INVITED PAPER

Extending Accurate Time Distribution and Timeliness Capabilities Over the Air to Enable Future Wireless Industrial Automation Systems

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ABSTRACT | Many industrial automation systems rely on time-synchronized (and timely) communication among sensing, computing, and actuating devices. Advances in Ethernet enabled by time-sensitive networking (TSN) standards, being developed by the IEEE 802.1 TSN Task Group, are significantly improving time synchronization as well as worst case latencies. Next-generation industrial systems are expected to leverage advances in distributed time coordinated computing and wireless communications to enable greater levels of automation, efficiency, and flexibility. Significant progress has been made in extending accurate time synchronization over the air (e.g., 802.1AS profile for IEEE 802.11/Wi-Fi). Given the inherently unreliable, varying capacity and latency prone characteristics associated with wireless communications, proving the feasibility of worst case latency performance over the wireless medium is a major research challenge. More specifically, understanding what levels of capacity, reliability, and latency could be guaranteed over wireless links with high reliability are important research questions to guide the development of new radios, protocols, and time coordinated applications. This paper provides an overview of the potential applications, requirements, and unique research challenges to extend TSN capabilities over wireless. The paper also describes advances in wireless technologies (e.g., next-generation 802.11 and 5G standards) toward achieving reliable and accurate time distribution and timeliness capabilities. It also provides a classification of wireless applications and a reference architecture for enabling the integration of wired and wireless TSN capabilities in future industrial automation systems.

KEYWORDS | 5G; 802.11ax; industrial Internet of Things (IOT); next-generation Wi-Fi; time-sensitive networking (TSN)

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NOMENCLATURE

ACK	Acknowledgment.
AGV	Automated guided vehicle.
AIFS	Arbitration interframe space.
AP	Access point.

BLE	Bluetooth low energy.
BS	Base station.
CDMA	Code-division multiple access.
CIR	Channel impulse response.
CNC	Centralized network configuration.
CRAN	Cloud-RAN.
CSI	Channel state information.
CSMA	Carrier sense medium access.
CUC	Central user configuration.
DMRS	Demodulation reference signal.
FDMA	Frequency-division multiple access.
FPGA	Field-programmable gate array.
GSCMs	Geometry-based stochastic channel models.
HARQ	Hybrid automatic repeat request.
HCCA	HCF coordinated access.
HCF	Hybrid coordination function.
HMI	Human–machine interface.
IETF	Internet engineering task force.
IoT	Internet of Things.
IT	Information technology.
LDPC	Low-density parity check.
LPWAN	Low-power WAN.
LTE	Long-term evolution.
MAC	Medium access control.
MCS	Modulation and coding scheme.
MEC	Mobile edge computing.
MIMO	Multiple-input–multiple-output.
NACK	Negative-ACK.
NFV	Network function virtualization.
NOMA	Nonorthogonal multiple access.
5G NR	5G new radio.
OFDM	Orthogonal frequency-division multiplexing.
OFDMA	Orthogonal FDMA.
OPC UA	Open platform communication unified architecture.
OT	Operational technology.
PCF	Point coordination function.
PHY	Physical layer.
PIFS	PCF interframe space.
PLCs	Programmable logical controllers.
PPDU	PHY protocol data unit.
PTP	Precision time protocol.
QoS	Quality of service.
RAN	Radio access network.
SDMA	Space-division multiple access.
SDN	Software-define networking.
SDR	Software-defined radio.
SISO	Single-input–single-output.
SNR	Signal-to-noise ratio.
STA	Station.
TDD	Time-division duplex.
TDMA	Time-division multiple access.
TSCH	Time-synchronized channel hopping.
TSN	Time-sensitive networking.
TTI	Transmission time interval.
TWT	Target wake time.
URLLC	Ultrareliable low-latency communications.
USRP	Universal Software Radio Peripheral.
VLAN	Virtual local area network.
WWAN	Wireless wide area networks.

I. INTRODUCTION

New industrial applications are emerging, which require the time coordinated computing and communications over wireless links. For instance, smart factories, AGVs, and immersive virtual/mixed reality are few examples, which would greatly benefit from easy reconfigurability, cost reduction, and better user experience through the wireless operation. Some applications require precise synchronization to a reference time down to nanoseconds accuracy [1], deterministic (bounded) end-to-end latency, and extremely low packet loss probability. Latency requirements can vary in the microseconds to milliseconds range [2], depending on the application. It is also important to provision networks for the convergence of time critical and noncritical traffic in the same network. The IEEE 802.1 TSN Task Group develops standards to enable time synchronization, bounded latency, redundancy, preemption, and other features [3]. Most of the TSN standards have been restricted to wired (Ethernet) networks. Enabling time-critical industrial applications over wireless links would add value and open up new markets, such as software-defined machines and factories. However, given the inherently unreliable, varying capacity and latency prone characteristics associated with wireless connectivity, proving the feasibility of TSN performance over wireless, involve major challenges. More specifically, understanding what levels of capacity, reliability, and latency could be guaranteed over wireless links and in what environment conditions are important research questions to guide the development of new radios, protocols, and time-aware applications and networks.

This paper provides a new perspective on extending TSN capabilities over wireless links. This paper starts with an overview of industrial communication requirements and networks, including a brief review of the main wireless standards used in industrial environments today. Next, this paper summarizes the main TSN capabilities and standards, followed by an in-depth discussion of wireless challenges in channel dynamics, medium access, and interference. Existing and potential future extensions of TSN capabilities over wireless are described including time synchronization, time-aware scheduling, and reliability capabilities and their required adaptations for operation over the wireless medium. This paper also provides an overview of next-generation wireless technologies and standards and their new features to address time-critical applications. This paper concludes with a description of a future industrial wired-wireless network infrastructure, a roadmap of wireless applications, and the role of experimental platforms that can meet strict timing and reliability requirements in enabling feasibility demonstrations of wireless TSN capabilities.

II. STATE-OF-THE-ART COMMUNICATIONS AND NETWORKING FOR INDUSTRIAL AUTOMATION

A. Industrial Networks

Distributed computer networks have been used in industrial automation and control systems for decades. Different communication technologies have been adopted to serve different needs within industrial and manufacturing environments, as described in [4]. The industrial automation pyramid (Fig. 1) [5] has been used to describe industrial networks, applications, and their typical communication requirements through different layers as follows.

1) *Field Level:* The lowest level includes communication among sensor, actuators, and controllers and typically has the most stringent latency and reliability requirements. Throughput requirements are relatively low at this level. Fieldbus systems have enabled distributed automation and control loops. Many fieldbus technologies have been standardized [4] and widely deployed across manufacturing and industrial installations. Subsequently, Ethernet-based industrial networks have also been used at field level as they support extremely short cycle times (in the order of microseconds) and low jitter, such as PROFINET, EtherCAT, and SERCOS III. All these networks are encompassed by the IEC 61784 International Standard [6].
2) *Cell Level:* This level includes mostly communications between PLCs and between PLCs and industrial PCs. PLC-to-PLC communication may require time synchronization and various levels of real-time guarantees but at relaxed performance when compared to the field level. Cell-level communications have consolidated on Ethernet as the main transport media technology. Various real-time Ethernet standards (e.g., PROFINET, EtherCAT, SERCOS III, Tcnet, and Vnet are profiles under the IEC 61784 Standard [6]) have been developed and adopted by different industrial players. Communications between PLCs and industrial PCs is typically served by IP-based communication over Ethernet.

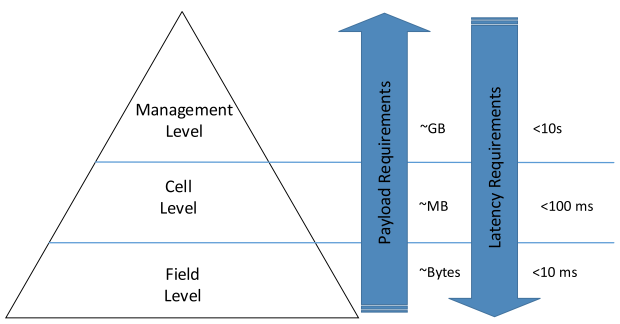

Fig. 1. ***Automation pyramid.***

3) *Management Level:* This level includes mainly the typical IT infrastructure that supports operational processes. More data are transferred at this level, but latency and reliability requirements are more relaxed. Some applications at this level involve human interaction, which can require real-time performance but not necessarily the same level of synchronization, latency, and reliability as expected at the field and cell levels.

Recently, there has been a trend toward enabling more flexible data exchange within industrial systems. This is mainly enabled by advances in networking and information services, such as OPC UA [7] that enables easier access to operational data, as well as applications of artificial intelligence, such as predictive and prescriptive analytics. As a result, the automation pyramid is expected to be transformed to enable more flexible data flows between different parts of the system.

Another emerging trend is the convergence of typical IT and OT, usually referred to as IT/OT convergence. Reuse of IT technologies in operational processes is expected to bring significant cost savings and enables the flexibility expected from future industrial networks in supporting a variety of applications. There are, however, many challenges, especially related to the convergence of time and safety critical real-time and other types of traffic in the same infrastructure.

Industrial applications vary tremendously depending on the particular manufacturing process or domain. The communication requirements of industrial applications have been defined in multiple real-time and nonreal-time classes [4]. In the remainder of this paper, we broadly classify industrial communication requirements in the following categories.

1) *Non Real Time:* Applications that do not require real-time communications. For instance, sensor networks and equipment data collection/reporting. Typically, these applications enable data visualization, analytics, and process improvements based on historical data.
2) *Soft Real Time:* Applications that involve real-time interactions between devices and/or human operators. These applications typically require low latency but not necessarily tight time synchronization, and they may tolerate some missed deadlines. These are not time- or safety-critical applications.
3) *Hard Real Time:* Applications that require accurate synchronization and timeliness (bounded latency) with very high reliability. These applications are also referred to as isochronous and are mainly at the field and cell levels. Some of these applications may also have safety requirements.

Wireless networks have been used primarily in nonreal-time applications and in a few soft real-time applications that are not safety critical. The next section provides an overview of existing wireless technologies and standards being used in industrial environments.

B. Wireless Networks in Industrial Environment

Compared to the installed base of wired-communication technologies, the deployment of wireless technologies is only at its infancy, especially when it comes to supporting time-sensitive applications. However, emerging artificial intelligence applications and the movement toward easier and more flexible access to data are driving more deployment (at least in experimental stages) of wireless technologies. Furthermore, as mobile and autonomous systems (e.g., AGVs and mobile robots) become more common, they will also drive the need for industrial grade and time-sensitive wireless communications. Some of the main wireless technologies that can be currently found in industrial environments are described next.

1) IEEE 802.15.4: The IEEE 802.15.4 standard [8] has been one of the most popular wireless technologies for IoT applications, especially in the nonreal-time category. It defines several PHY modes for operation in the 2.4-GHz and sub-GHz (868/916 MHz) unlicensed bands. There are also several MAC layer modes, but the most commonly implemented is based on CSMA in which devices sense the channel before transmission and backoff if the medium is busy. Several 802.15.4 chipsets are available in the market and most of them support sub-GHz and 2.4-GHz bands with data rates up to 250 Kb/s (for 2-MHz occupied channel bandwidth) in the 2.4-GHz operation.

The 802.15.4 standard has enabled the development of several industry ecosystems, including ZigBee [9] and Thread [10]. ZigBee is sometimes used as synonymous with 802.15.4, but ZigBee defines networking, transport protocols, and application profiles on top of the 802.15.4 radio. ZigBee and 802.15.4 have been used to enable industrial sensor networks [11], which are mainly within the nonreal-time category described in Section II-A. Many solutions consist of proprietary software modifications on top of the 802.15.4 radios. ZigBee and many 802.15.4 implementations also support mesh networking that enables deployments across large areas as well as redundancy to interference and link failures.

More recently, the 802.15.4g amendment [12] has added new PHY modes that achieve longer range and higher data rates, including an OFDM option. Another very relevant amendment of the 802.15.4 is the 802.15.4e, which has been designed to address industrial applications and is described in the next section.

2) IEEE 802.15.4e Time-Synchronized Channel Hopping: The 802.15.4e amendment [13] defines the TSCH access mode that has been motivated by higher reliability and power saving requirements from industrial applications. The TSCH mode operation is illustrated in Fig. 2. It requires time synchronization at the slot boundary across all devices in the network. In this mode, devices can be allocated different time slots and channels. The ability to switch channels on a slot basis can increase diversity and improve reliability. As demonstrated in [14], the

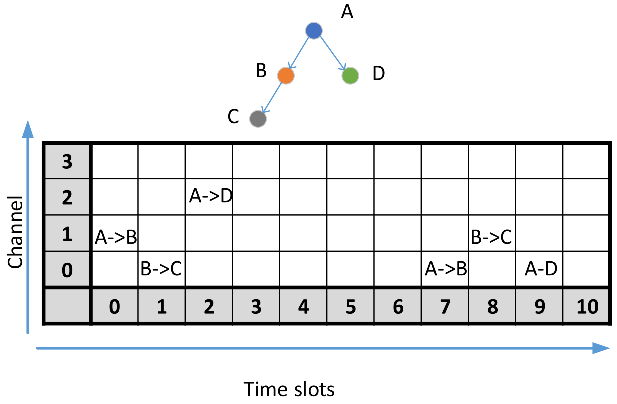

Fig. 2. ***TSCH operation and mesh example.***

TSCH mode can enable low power consumption with better control of latency compared to CSMA protocols used in typical 802.15.4 networks. This mode can also be used across a mesh network. Different links in the mesh may be assigned to different time slots and channels, as illustrated in Fig. 2. A similar operation mode has also been adopted in the Wireless HART standard [15]. It should be noted, however, that the levels of latency that can be expected from an 802.15.4 radio are constrained by the frame exchange sequence and data rates supported. For instance, a typical slot value is 10 ms, which enables the exchange of one data frame (<127 bytes) followed by an ACK frame. The TSCH mode may also be used with the more recent 802.15.4g mode, but most implementations so far have been using the basic 802.15.4 PHY at 2.4 GHz.

The 6TiSCH working group of the IETF has defined an IPv6 compatible layer to enable configuration and exchange of schedules in a TSCH network [16]. 6TiSCH and Wireless HART have received increasing interest from industrial sectors but mostly restricted to sensor networks (nonreal time) applications. A review of the state of the art and open-source implementation of 6TiSCH/TSCH has been provided in [17].

3) Bluetooth: Bluetooth [18] is a very successful technology for local connectivity between phones and other consumer devices (e.g., headset, speakers, wearables, and car infotainment) operating in the 2.4-GHz band. Bluetooth uses a frequency hopping PHY and only supported 1-Mb/s data transfer in its earlier releases (Bluetooth 1.2 and earlier). More recent releases support higher rates with an enhanced data rate version (Bluetooth 2.0) and even further with a high-speed version (Bluetooth 3.0). BLE, defined in Bluetooth 4.0, enables lower power, small size data for low duty cycle types of applications. Bluetooth and, more recently, BLE (mainly for its low-power characteristics) have been getting more attention from industrial IOT solution developers. Bluetooth has also recently added mesh capabilities [19], which was one of the gaps required to enable IoT applications, especially compared to 802.15.4 radios. Bluetooth can play a role in many HMI and wearable applications in industrial environments, and with mesh capability, it may also be able to support more industrial sensor network type of applications.

4) IEEE 802.11 Wi-Fi: Wi-Fi is a widely adopted technology in consumer, enterprise, and industrial markets, mainly for general IT connectivity. Since its original standard in 2007, the IEEE 802.11 working group [20] defined several major releases (a, b, g, n, and ac). Current 802.11 deployments are mainly based on 11n and 11ac, which use OFDM and MIMO capabilities to achieve very high data rates, usually on the order of hundreds of Mb/s in practical scenarios. The next major release is 802.11ax [21], which is described in more detail later in this paper, given its capability to enable multiple-user transmissions simultaneously, which can help control latency and increase reliability. The 802.11 MAC is based on CSMA with enhancements for QoS defined by the 802.11e amendment [22] which enables traffic prioritization through four main access categories (voice, video, best effort, and background). Although the 802.11 MAC has defined options for operation in a contention-free polling-based mode, e.g., PCF and HCCA, these options have not been supported in practice by mainstream Wi-Fi vendors.

Wi-Fi has also been used in industrial applications, mainly with proprietary adaptations to off-the-shelf 802.11 radios [23], [24], such as 802.11n. A comprehensive analysis and evaluation of 802.11n for industrial applications have been provided in [25].

Some of the most common industrial applications where Wi-Fi has been used are AGVs and remote HMI. Given the ubiquitous presence of Wi-Fi in industrial environments, expanding its applicability to a wider range of industrial applications, including hard real-time ones, has great potential to enable fast IT/OT convergence and flexibility in the manufacturing processes. There are many challenges and opportunities to be addressed in the next-generation 802.11 technologies, as will be discussed in the following sections.

5) Cellular Technologies: Recently, there has been increased interest in cellular technologies, especially in the context of machine-to-machine communications. Cellular technologies have been used mainly in industrial systems that are distributed across wide areas and involve vehicular mobility. For instance, remote monitoring and control for smart grid and oil pipelines are some of the applications that would benefit from cellular solutions. Proprietary radio technologies have been used in electricity distribution systems for decades, but cellular systems based on 3GPP standards [25], such as General Packet Radio Service (GPRS) and 3G, have also become more common recently. 3GPP standards have also defined new capabilities to adapt LTE for IoT applications, including Category M and narrowband IOT. The goal of these recent updates is to reduce cost, power consumption, and extend coverage, but they do not provide real-time performance.

Table 1 IEEE 802.1 TSN Standards

IEEE Standard	Capability
1588, 802.1AS	Time synchronization
802.1Qca	Path control and reservation
802.1Qbv	Time-aware scheduling
802.1Qbu and 802.3br	Frame preemption
802.1Qcc	Central configuration model
802.1Qci	Filtering and policing
802.1CB	Redundancy (frame replication and elimination)

LPWAN technologies operating in unlicensed bands (868/916 MHz) such as SigFox [27] and LORA [28] are a new category of networks that have been getting increased attention in the IOT space. However, LPWAN is useful for applications that require very low throughput over wide areas without hard latency and reliability requirements (mostly nonreal time).

In the future, cellular technologies, more specifically 5G standards, are expected to address a wider range of industrial use cases (from nonreal time to hard real time). We discuss 5G candidate technologies to support real-time applications in more detail in Section V-B.

C. IEEE 802.1 TSN

TSN mechanisms and standards have been developed [1] to enable time synchronization, control congestion, and packet loss due to media or device failure, mainly assuming Ethernet as layer 2 transport. A subset of the TSN standards and capabilities is listed in Table 1. More detailed discussions on TSN standards can be found in [29] and other articles in this special issue. TSN standards are enabling the convergence of various real-time standards and protocols used at the field and cell levels (as described in Section II-A) toward a unified family of networking standards defined by the IEEE 802.1 TSN working group.

The TSN mechanisms discussed in this paper include the following sets.

1) *Time Synchronization:* 802.1AS is a profile of the PTP defined by IEEE 1588 to enable precise time synchronization across the network, which is the foundation for other TSN capabilities.
2) *QoS Provisioning:* The time synchronization is leveraged to define a global time-aware schedule (defined by the 802.1Qbv standard) to control congestion and provide deterministic latency. A frame preemption mechanism (802.1Qbu and 802.3br) has been introduced to reduce latency for high priority frames. The 802.1CB standard introduces redundancy through frame duplication and elimination, which is needed to reduce the impact of packet loss due to link and/or device failure.
3) *Traffic Identification:* TSN devices must differentiate time-sensitive streams from other flows.

The IEEE 802.1Q standard describes the fundamentals to identify and differentiate time-sensitive types from other types of traffic. To support traffic differentiation, 802.1Q specifies a VLAN tag field, which is added to the header of the Ethernet frames. Furthermore, 802.1Q defines traffic classes (up to eight traffic classes per Ethernet port), each traffic class associated with a dedicated queue.

4) *Network Configuration:* The 802.1Qcc [30] and 802.1Qca [31] standards define a CNC model and stream reservation capabilities, respectively, that can be used to compute the global communication schedule for the network (based on the 802.1Qbv standard). 802.1Qci provides additional policing and filtering mechanisms to ensure nodes follow the configured schedules and avoid malicious behavior.

These and other TSN mechanisms, not discussed here, have been developed to control congestion and packet loss in Ethernet networks. The traffic identification (802.1Q), 802.1AS-based time synchronization, and stream reservation (802.1Qca) capabilities have already been extended to 802.11 (e.g., timing measurement capability defined in 802.11-2012), but other QoS capabilities to control congestion to reduce latency and jitter, as well as increase reliability have not been explored in existing wireless standards.

The following sections describe different properties of wireless networks and their impact on congestion and packet loss, and capabilities to deliver TSN-grade service.

III. CHALLENGES FOR WIRELESS TSN

As described in the previous section, TSN standards address two fundamental problems:

1) latency and jitter caused by network congestion;
2) packet losses due to media and/or hardware failures.

Given that wired (Ethernet) links have constant capacity and extremely low packet error rate, bandwidth reservations/scheduling (e.g., 802.1Qca and Qvb) can guarantee latency/jitter, and preemption (802.1Qcu) can avoid interference from the best effort traffic and guarantee low latency and jitter with high reliability. In addition, redundant paths (802.1CB) can address losses due to media and hardware failure. Wireless media has two fundamental differences from wired communications as follows.

1) Variable capacity, which is a function of the quality of the links.
2) Typically higher PER, due to stochastic properties of the channel and interference.

The above-mentioned unique characteristics of wireless communications impose several challenges in providing deterministic latency and reliability guarantees expected by time-sensitive applications. The next sections describe some of the major challenges and state-of-the-art wireless techniques that can help address the issues and provide more stable/predictable wireless performance.

A. Wireless Channel Variations

Unlike wired media, the wireless channel capacity is dynamic (depending on fading, interference, range, and other factors). Provisioning resources with high reliability and bounded latency is not always possible. Understanding the wireless channel behavior in specific deployment environments is key to assess achievable latency, reliability, and capacity. Multiple measurement campaigns have been conducted in the past to understand and model different types of environments [34]–[38]. As a result, channel models have been proposed to help in the development of new wireless technologies [41]–[44].

In IEEE 802.11 standards, wireless channel behavior is modeled for both 2.4 and 5 GHz for SISO and MIMO systems in indoor scenarios [32]. Path loss is modeled using a free-space loss term up to a breakpoint distance ($d < d_{BP}$) and an additional loss term after the break point distance ($d \geq d_{BP}$). In addition, a log-normal shadow-fading term with the standard deviation $\sigma_{BP,d}$ is also considered. Multipath is statistically characterized by generating different clusters, typically between 2 and 6 [32]–[38]. In each tap of a cluster, power, angular spread, angle of arrival, and angle of departure are added to fit experimental and/or ray-tracing data [43], [44]. To model channel conditions in outdoor scenarios in the upcoming 802.11ax standard, ITU-R channel and Doppler modes [41] have been adopted.

In 3GPP-based cellular networks, more advanced channel models are used [42], [43]. These channel models are typically known as GSCMs, simulating multipath by randomly placing the location of scattering clusters. GSCMs provide features such as short-time evolution of channel coefficients (e.g., updating delays, departure and arrival angles, and polarization), scenario transitions, variable mobile speeds, and geometric polarization.

None of the aforementioned channel models have been parameterized to represent realistic indoor and outdoor industrial (e.g., factory) scenarios, where heavy multipath is expected in wireless transmissions. In [49], a measurement campaign conducted in different industrial environments is described, and the collected data are analyzed to show the averaged CIR, channel gain, delay spread, and Rician K-factor under different operational conditions. Three scenarios are considered: an automotive factory, a stem generation plant, and a machine shop.

Fig. 3 shows a comparison of the path gain between the machine shop and the different IEEE path-loss models shown above. As stated before, current models do not capture the behavior of industrial environments accurately, and updated models are required. The ReiCovAir project [50] has been conducting measurement campaigns to provide parameters for the Quadriga GSCM [44] to represent industrial scenarios.

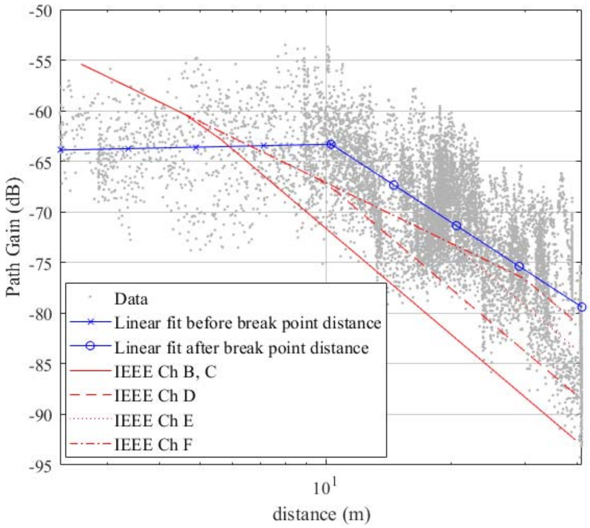

Fig. 3. *Measured path gain in the machine shop [49] versus averaged IEEE channel model path gain [−L(d)] in the 5.4-GHz band.*

Channel models are generic enough to statistically represent a plethora of propagation environments. However, a better understanding of wireless channels specific to an environment is required before the deployment of a wireless network to guarantee latency-bounded high-reliable communications. For this purpose, ray-tracing tools can be used to model wireless channels corresponding to a well-defined environment [52], providing coverage maps, fading statistics, power delay profiles, root-mean-square delay, and coherence bandwidth. This information can be used in the design, evaluation, and deployment phase of wireless networks in industrial environment to provide the required QoS.

B. Channel Access Latency

Most wireless systems involve some form of channel access procedure as multiple devices attempt to share the medium. In LTE, for example, the grant acquisition and random access procedures are the two major sources of delay [53]. In Wi-Fi, the listen-before-talk channel access procedure also becomes the major source of delay. The listen-before-talk procedure has also been used in LTE to access unlicensed spectrum, and it is expected to increase the channel access delay with an increasing number of devices [54]. The randomness in listen-before-talk protocols is an issue for hard real-time applications. Therefore, novel approaches are needed to support ultralow-latency services with deterministic access to the medium and low jitter. It is important, however, to understand different ways in which the wireless channel is used to multiplex users.

1) Multiple-Access Techniques: Multiple-access techniques are a fundamental part of any wireless system and play a key role in determining channel access latency. Techniques differ in how the channel (resource) is defined and shared, and different approaches include: FDMA, TDMA, CDMA, OFDMA, SDMA, and NOMA.

FDMA, TDMA, and CDMA are well-known techniques that have been applied in several versions of 3GPP cellular standards. Variations of these techniques have also been applied to other wireless systems. For instance, frequency- and time-division concepts have been used over Wi-Fi to reduce the latency caused by the random channel access [55], [56]. One strategy is to support multiple users over different Wi-Fi channels [55]. Other solutions control the number of devices that are allowed to access the channel within a service period (time slot) [56] or based on transmission attempts [57]. The total number of devices can be divided into several groups. Each group is assigned a time slot and allowed to compete for the channel only during the assigned time slot. Unless the number of devices within each time slot is strictly controlled, collisions can lead to higher latencies and jitter. On the other hand, CDMA allows multiple users to transmit independent information using orthogonal spreading coding over the same channel simultaneously. CDMA was used in 2G and 3G cellular standards and its performance is known to be interference-limited [58].

OFDMA and SDMA have been adopted in more recent cellular and Wi-Fi standards. Downlink multiuser (MU) MIMO was the first SDMA technique introduced in Wi-Fi, as part of the IEEE 802.11ac amendment. The basic idea is to enable transmission of different data to multiple devices over the same channel simultaneously by using multiple antennas. In other words, devices are separated into different spatial streams. The next-generation 802.11ax standard will support MU MIMO capabilities in both downlink and uplink (UL) directions. OFDMA separates users in resource units (a combination of frequency and time resources) and it is the main access technique in LTE/4G and upcoming 5G standards. A new MU OFDMA access mode will also be part of the upcoming 802.11ax standard, and it has potential to reduce the latency by avoiding contention (see Section V-A). The AP can send downlink data to multiple devices or trigger MU UL transmissions in the same PPDU.

NOMA has emerged more recently as a potential approach to reduce latency as it enables a device to access the medium immediately without channel contention [59]. It can reduce the latency with negligible reduction in reliability when the number of devices is very large. However, the receiver has to be equipped with the capability to do successive interference cancellation, which is not trivial in current wireless chipsets. NOMA has not yet been adopted in major wireless standards, but the technology has been discussed in the context of 5G and next-generation 802.11 standards.

Other approaches have also been used to reduce channel access latency on top of the basic multiple-access techniques. For instance, multichannel access strategies [60] have been introduced in unlicensed bands to increase the

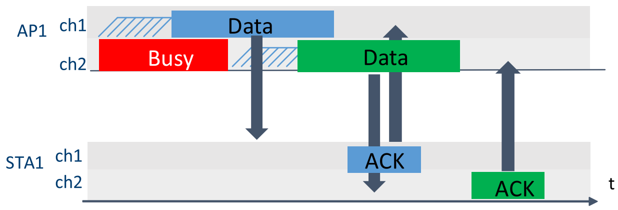

Fig. 4. *Multichannel access.*

probability that a device will get access to the medium and, as a result, reduce latency and increase reliability. As shown in Fig. 4, the basic idea is to enable the device to access multiple channels and initiate multiple data transmissions independently, in ch1 and ch2 as shown in Fig. 4. However, in order to acquire transmission opportunities in different channels, the device has to be equipped with multiple radios to sense and contend for access simultaneously in multiple channels.

It is important to note that most approaches discussed in this section can be used alone or in combination to reduce channel access delay with different tradeoffs to be considered. Latency-specific optimizations should also take into account the unique and dynamic characteristics of wireless channels and links.

2) Centralized Coordination and Scheduling: It is very hard to control latency through distributed random access, especially under congestion. Therefore, the central coordination of medium access through scheduling is a key capability that has been used in existing and upcoming wireless systems to address strict QoS requirements. In 3GPP systems, access is centrally managed by a NodeB (eNodeB or gNodeB depending on 3GPP specification version). Central coordination is also possible in 802.11 networks that are managed by the same entity (e.g., this would be feasible within a factory). Scheduling by the Wi-Fi AP has become an important problem with the adoption of the OFDMA mode in 802.11ax (see Section V-A1). Scheduling algorithms are important regardless of the underlying multiple-access technique used. Traditionally, scheduling approaches have considered throughput and fairness, but new optimizations may be needed in order to meet stringent latency and reliability requirements with high efficiency. When operating in a centralized scheduling mode, it is also important to consider approaches to distribute the scheduling information to devices in the network. 3GPP systems support persistent scheduling, in which devices are assigned deterministic access opportunities once admitted. This minimizes overhead and ensures that the worst case latency can be supported (provided that enough resources are available). In 802.11, scheduling information is transmitted by the AP before every transmission opportunity, but persistent scheduling could be considered in the future extensions, especially given that OFDMA is already supported.

C. Interference and Coexistence

Interference and coexistence between the known and potentially unknown systems (e.g., jammers) are not a problem in wired medium but need to be addressed in order to enable wired equivalent TSN performance over wireless links. The problem is made more challenging with the requirement to support both TSN and non-TSN traffic in a converged network over unlicensed spectrum.

Any wireless link is inherently susceptible to interference. Although in the nontime-sensitive operation, using multiple retransmission attempts is a common method to assure payload delivery, opportunities to retransmit packets in hard real-time applications are limited due to latency constraints. This makes interference avoidance and mitigation a primary method to ensure payload delivery in adverse conditions.

In unlicensed bands, channel conditions may be greatly impacted by the presence of other devices working in the same band (other Wi-Fi, LTE-U, Bluetooth/BLE, ZigBee, security cameras, wireless microphone, etc.). Another area of concern is self-interference from other devices in the same network due to scheduling conflicts, overall network density, or device failures. RF emissions from industrial sources, such as microwave ovens, electrical machinery, welding arches, power plants, cablings, and so on, may create interference. However, emissions (noise) generated by such industrial sources is dominantly contained in the subgigahertz band, and may have little or no effect in higher bands (e.g., 2.4 and 5 GHz). Real experiments in industrial environments done as part of the RelCovAir project [50] support such a conclusion.

The dynamic nature of potential interference sources requires constant monitoring of the wireless medium in order to detect impurities, identify their sources, and adapt the network accordingly. In order to maintain the required QoS expected by TSN applications, the network has to be adapted fast, ideally before the next scheduled transmission is impacted.

IV. NEW APPROACHES TO EXTEND TSN CONCEPTS TO WIRELESS

This section describes approaches to extend TSN capabilities over wireless networks. Fig. 5 shows a typical reference protocol stack where the hard real-time application can use direct access to the TSN capabilities at layer 2. Currently, Ethernet (IEEE 802.3) is the main media that supports the TSN capabilities, and IEEE 802.11 supports some capabilities (e.g., time synchronization over 802.11 described in Section III-B). There are ongoing research and preliminary standardization efforts in 802.11 to extend TSN capabilities and in 3GPP to introduce TSN capabilities over next-generation standards. A recent industry effort has also explored the use cases and potential capability roadmap for Wireless TSN [51]. Given that both 802.11 and 802.3 are based on the same family of IEEE 802 standards, extending TSN capabilities over 802.11 is

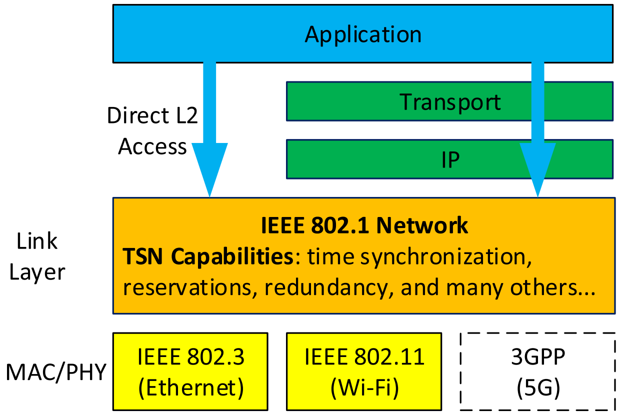

Fig. 5. ***TSN reference protocol stack.***

a natural and seamless step. 3GPP/5G standards, on the other hand, are based on a different protocol stack, and more work is required to enable the integration with IEEE 802 networks.

A. Wireless Network Management Model

In order to guarantee performance in any network (wired or wireless), one must control/manage access to network resources based on the application/user requirements (e.g., traffic profiles). It is not practical to expect TSN-grade performance in an open wireless environment. Therefore, the wireless network should be managed by a single entity that can plan the deployment and resolve potential interference between overlapping networks (e.g., Wi-Fi APs) at the deployment and configuration stages. Another requirement is that all devices can implement a minimal set of required features to operate under a managed network model as described in [3], which includes CUC and CNC. The CUC collects information about the critical traffic streams, and the CNC uses this information to perform admission control, define and deploy resource allocation strategies to meet the required time-sensitive performance. Fig. 6 illustrates the TSN management model (also defined in the 802.1Qcc standard [30]). The Wireless TSN domain is expected to seamlessly extend the wired TSN domain. As such, wireless devices and APs should be configured by the same CUC and CNC entities. The TSN managed network operating model is applicable in industrial and enterprise scenarios where a single entity (IT) manages the network. It is also important to ensure that infrastructure and end devices support interoperable methods and protocols to enable management, control latency, and reliability.

B. Wireless Time Synchronization

There are several mechanisms to achieve time synchronization in wireless networks. In particular, the 802.1AS standard defines a PTP profile over 802.11, which is enabled by the timing measurement capabilities included in the 802.11-2012 standard. A detailed description of the 802.1AS over 802.11 can be found in [61]. Fine time measurement capabilities have also been introduced in 802.11 to increase the accuracy of time synchronization (on the order of hundreds of nanoseconds). A survey of time synchronization mechanisms over 802.11 can be found in [62]. An implementation of 802.1AS time synchronization over 802.11 has been demonstrated in [63].

In 3GPP cellular networks, there is tight PHY-level synchronization between mobile devices and BS, but synchronizing the radio and applications to the same clock has not been done. This is one of the new areas for improvement that are being considered as part of 5G development for URLLC, but standards have not been developed yet.

C. Time-Aware Scheduling

The 802.1Qbv time-aware scheduling introduces gates synchronized to a common reference clock to control the opening/closing of queues that share a common egress port within an Ethernet switch. A global scheduler defines the times when each queue opens or closes, therefore eliminating congestion and ensuring that frames are delivered within the expected latency bounds.

Fig. 7 illustrates one model where the 802.1Qbv concept is applied to an 802.11 radio. Once a queue is open, a transmission selection module selects a data frame to send and delivers it to the 802.11 MAC layer. Typically, the 802.11 MAC follows a random access procedure, which could introduce random delays to the transmissions, as discussed earlier (Section II-B4). One challenge is to reduce such random access delay at the MAC layer in order to ensure that the time-aware schedule timings are satisfied. One potential solution is to use the time-division multiplexing technique to control the wireless medium access so as to leverage the global reference time between wireless devices.

The scheduler would need to assign time slots to wireless devices aligned with the end-to-end latency

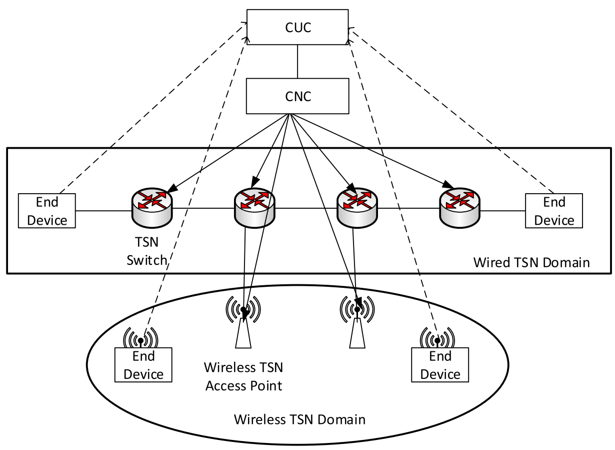

Fig. 6. ***TSN network management model.***

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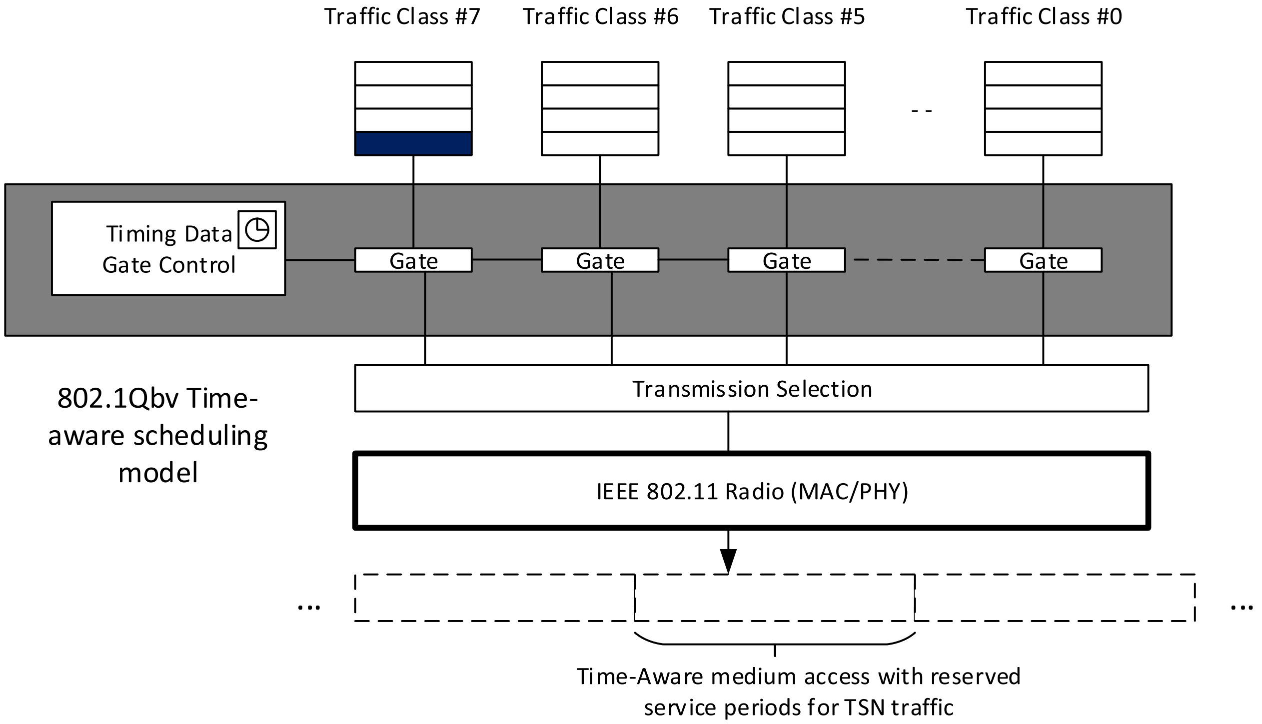

Fig. 7. *802.1Qbv time-aware scheduling over the 802.11 MAC.*

requirements for each data frame. The wireless part of the schedule would need to be communicated to the AP and its associated devices. Furthermore, given the varying capacity of the wireless channel (as discussed earlier in Section III-A), the scheduler would also need to ensure that each device would be able to complete its transmission within the allocated slot with the required reliability. As described in [64], the extension of the Qbv traffic-shaping concept over 802.11 would require modification in the 802.11 MAC layer to enable distribution of the Qbv schedule between managed STAs and also to ensure that the 802.11 queues are controlled to meet the Qbv schedule.

D. Wireless Link Reliability

It is challenging to provide wireless links with high reliability due to fading and interference from other wireless devices (in the same or in neighboring networks) or interfering emissions from other systems. The problem is illustrated in Fig. 8, where an AP installed on the ceiling of the factory serves two STAs on the factory floor, which could be sensor (I/O device) or actuator. If a device is far away from the AP, or there is a big obstruction between the AP and the device (e.g., AP 1 and STA 1 shown in Fig. 8), the reliability of the link can degrade significantly. Also, if other interfering devices (e.g., Bluetooth and other Wi-Fi devices operating in the same 2.4-GHz band) are brought into the area, they may interfere and cause a link (e.g., AP 1 and STA 2 shown in Fig. 8) to experience higher packet loss.

Several techniques can be used to improve reliability, which include the following.

1) *Transmit Power Control:* Link reliability can be consistently enhanced with higher receiver signal strength, which can be achieved by increasing the transmit power of the transmitting device as long as the power is within the linear power amplification range. However, increased transmit power may generate interference to other users and may prevent spatial reuse of the channel. As shown in Fig. 9, both AP1 and AP2 are operating on the same channel. If the transmit power of the AP1 is increased from P_{tx1} to P_{tx2}, its communication and interference ranges will increase, which may generate interference to STA2, when STA2 is receiving data from AP2. In addition, there are regulatory limits on both the transmit power density and the total transmit power over the unlicensed bands. Therefore, smart

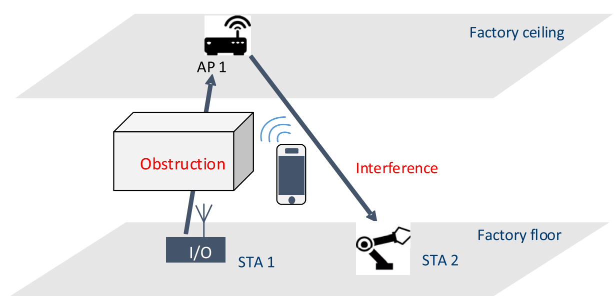

Fig. 8. *Example of wireless control loop.*

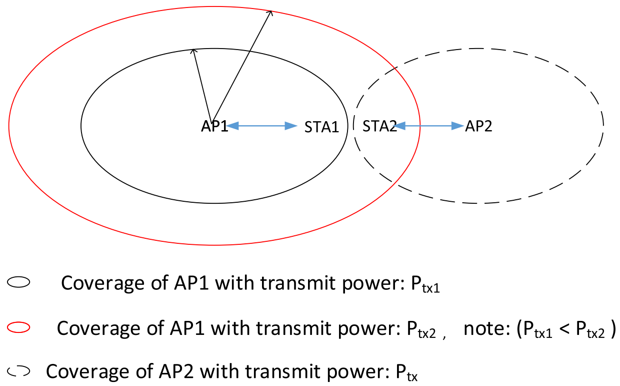

Fig. 9. ***Transmit power control and spatial reuse.***

transmit power control algorithms could play a more significant role by adjusting the power to improve reliability while considering spatial reuse, which can improve efficiency and ultimately contribute to mitigate interference.

2) *Optimal Time–Frequency Resource Scheduling:* Reliability can also be improved by scheduling transmissions with good time–frequency resources. For example, in the downlink multiple-user OFDMA modes (used in both LTE and 802.11ax), the AP can use CSI for each device to schedule the data transmissions over the best time–frequency resource unit. However, accurate CSI also adds overhead, which may impact system capacity.

3) *Spatial Diversity or Beamforming [65] With Multiple Antennas:* Spatial diversity and beamforming [66]–[68] are signal processing techniques for directional signal transmission or reception. They can provide remarkable improvement in terms of power efficiency and can be used either at the transmitter by precoding the transmit signal or the receiver side by decoding the receive signal to achieve antenna array gain. However, accurate CSI is essential for the transmitter to do precoding or for the receiver to do decoding to maximize the antenna array gain.

4) *PHY Waveform Design:* OFDM has been widely adopted in wireless standards (e.g., LTE, 802.11, and 5G) because of its high spectral efficiency, robust fading mitigation, efficient digital signal processing implementation, and granular resource allocation. However, the high out-of-band emission is one of the main shortcomings, which will generate serious interference to other users over adjacent channels. Many approaches have been proposed to mitigate this problem. The existing approaches, including windowing [69], filtering [70], subcarrier weighting [71], carrier cancellation [72], mapping antipodal symbol pairs onto adjacent subcarrier [73], precoding [74], [75], and so on, can be used to mitigate the interference to other users over adjacent channels. As a result, the capacity of the overall system can be improved with high reliability. Another unique aspect that must be considered in the PHY design is the need to support short packets common to many industrial automation applications. Most standard PHY designs so far (e.g., 802.11 and LTE) have focused mainly on large packets, which may be suboptimal when the size of the data is comparable to the size of the control information added to the packet. The challenges involved in supporting short packets with low latency and high reliability, as well as new design directions, are discussed in [76]. Luvisotto *et al.* [77] propose a new design approach for supporting small packets with lower latency by reducing some of the overheads in the 802.11 OFDM PHY.

5) *Adaptation of Modulation and Coding Scheme to Channel Conditions [78]:* Lower MCS provides higher reliability but increases the latency. Therefore, how to adapt the MCS according to the channel condition to optimize the reliability subject to the latency bound becomes very important. If the estimated CSI is better than the actual CSI, higher MCS will be used for the data transmission, which may lead to packet loss. If the estimated CSI is worse than the actual CSI, lower MCS will be used for the data transmission, which will add unnecessary transmission delay. Therefore, there is a high requirement for the accuracy of the CSI. A dynamic rate adaptation algorithm leveraging the multirate features in 802.11 for industrial scenarios has been proposed and evaluated in [79].

6) *Redundancy:* Frame Replication and Eliminations is introduced in the IEEE 802.1CB to improve reliability. Similar concepts can be adopted in wireless networks. Multiple-link aggregation is already supported in both the LTE and 802.11 standards; however, current solutions focus only on increasing the throughput and do not take into account hard real-time and reliability requirements. Therefore, adaptations are needed to take into account the unique characteristics of wireless channels and links and ensure that multiple links can deliver the same packets within strict latency requirements to increase reliability.

Providing latency and reliability guarantees expected by hard real-time industrial applications over wireless networks involve many challenges. Existing wireless standards are not yet capable to fully support such stringent requirements, but this is also seen as an opportunity for the next-generation wireless technologies and standards, which are discussed next.

V. NEXT-GENERATION WIRELESS CAPABILITIES FOR TSN

Wireless communication standards are evolving, and new capabilities are being introduced; those are conducive to TSN support over wireless networks. This section discusses the main advances relevant to industrial systems in major wireless standards including 802.11ax, 5G, and WigGig.

A. IEEE 802.11ax: The Next-Generation Wi-Fi

Next-generation Wi-Fi being defined by the IEEE 802.11ax Task Group introduces several features and capabilities that can significantly improve the support for industrial automation applications. We summarize these enhancements in the following sections.

1) Scheduled Access and Multiuser OFDMA: The draft 802.11ax amendment [80] has defined scheduling capability for Wi-Fi APs. Devices can now be scheduled for accessing the wireless channel in addition to relying only on the traditional contention-based channel access. Such scheduled access enables more controlled and deterministic behavior in Wi-Fi networks.

Multiple users can be scheduled across frequency by using MU OFDMA or in the spatial dimension by using MU MIMO capability. As shown in Fig. 10, a trigger frame (TF) can initiate transmission from multiple users in the same UL PPDU in the UL direction. The trigger-based access gives the AP much more control of the channel, and it can remove contention between devices for UL transmissions. By removing contention delays, the scheduled MU access can significantly reduce the transmission latency.

For example, assuming 20-MHz channel bandwidth and 256-bytes packet size, single-user (SU) transmissions from 9 STAs will take approximately 1.3 ms using 256 QAM in IEEE 802.11ac (the current main 802.11 mode in the market). By contrast, in the 802.11ax trigger-based UL transmission, the same amount of data exchange will take approximately 0.758 ms.

Fig. 11 shows the theoretical number of UL TSN users that could be supported within a given latency bound based on the 802.11ax trigger-based UL MU OFDMA mode, as shown in Fig. 10. The 802.11ax MU transmission mode is compared to the 802.11ac SU transmissions multiplexed in time. In this example, we assumed SISO transmission, 64 QAM, and 256-byte packet size. In practice, it is important to note that MCS selection should take into account the tradeoff between latency and reliability. Although selecting the lower (more reliable) MCS can increase reliability, it also increases latency. For small packets (typical in industrial control applications), the latency increase may not be significant in absolute numbers but it should be considered nevertheless. The MCS selection should also take into account channel conditions to enable operation at the lowest possible latency with high reliability. In order to calculate channel access latencies, in this analysis, we used default voice access category (AC_VO) parameters for 802.11ac. Each device waits for the (AIFS $= 18\ \mu s$) followed by an average backoff window of 7 slots (63 μs) given the 9-μs slot time. In the case of the 802.11ax OFMDA mode, since there is no contention between devices, we assumed the AP contends for the channel using (PIFS $= 25\ \mu s$) followed by an average backoff window of 7 slots. We also assumed a 2-MHz resource unit size for 802.11ax.

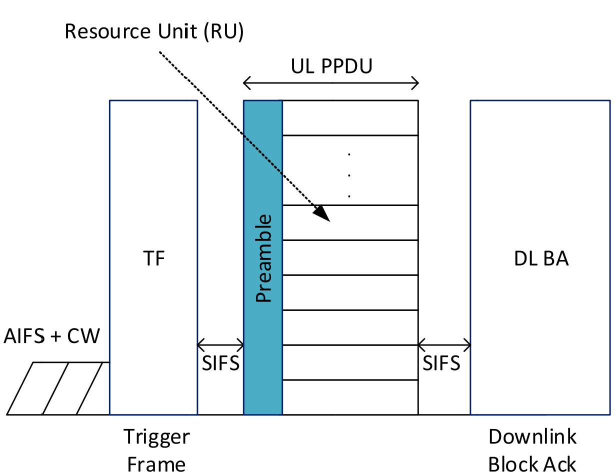

Fig. 10. ***Trigger-based MU UL transmission in IEEE 802.11ax.***

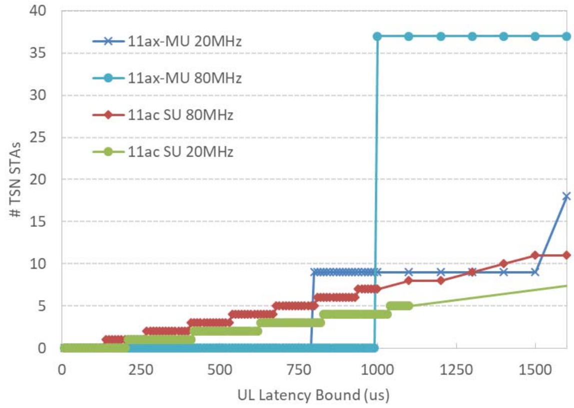

Fig. 11. ***UL capacity for TSN streams as a function of the target latency bound with 802.11ac and 802.11ax.***

In the case of 802.11ac, the capacity increases gradually with the latency bound as the time budget allows for more users to be added. With 802.11ax, multiple users can be served in the same PPDU resulting in higher capacity compared to the SU 802.11ac mode for certain latency bounds. It is also worth noting the strict limitations on the number of users per channel (9 users in 20 MHz and 37 users in 80 MHz) and a minimal amount of time required to complete an 802.11ax trigger-based UL transmission. As a result, the 802.11ax capacity does not increase gradually with the latency bound. With a 20-MHz channel, the 802.11ax OFDMA mode cannot ensure latency below 0.810 ms. However, once that threshold is crossed, the MU transmissions allow 9 devices to be supported with such a latency. The next step in capacity increase occurs at about 1.5 ms, at most 18 devices supported with such latency bound.

2) Improved Reliability in the Physical Layer: The 802.11ax allows smaller resource units to be assigned to individual devices, thanks to the support for OFDMA. Compared to the smallest channel width of 20 MHz in the previous generation (802.11ac), only 2 MHz can be the smallest resource unit in 802.11ax. This translates to almost 8-dB reduction in noise power [81], which can lead to much better SNR and vastly improved packet error rate. The MU diversity achievable through OFDMA can lead to higher throughput, which, in turn, reduces the transmission latency. It should be noted that smaller resource units result in longer transmission durations, which may impact the minimal latency that can be achieved, as demonstrated in Fig. 11. However, the latency reduction due to MU transmission, which can avoid long and random contention periods, is still a major benefit of 802.11ax.

The 802.11ax PHY also offers flexible guard interval durations to combat intersymbol interference in various multipath channel conditions. Larger guard intervals (e.g., 1.6 or 3.2 μs) compared to the 0.8-μs guard interval in 802.11ac can provide significantly better protection against heavy multipath fading environment in a factory floor.

Recently, the 802.11ax Task Group extended the scope of the project to include operation in the 6-GHz band, which is proposed for unlicensed operation in the U.S. [82]. The 802.11ax operation in this new band is expected to face less interference, which could play a key role in enabling adoption of Wi-Fi-based solutions for industrial systems. Legacy Wi-Fi systems (802.11b/n/ac) will not operate in this new band, only 802.11ax and future extensions will be enabled to access the new band. Therefore, one could envision an enhanced 802.11ax version in the 6-GHz band for better supporting hard and soft real-time applications (see Section VI).

3) Target Wake Time: The 802.11ax also includes the concept of TWT, a new power saving mechanism that enables devices and the AP to agree on a schedule defining when the devices would be awake to communicate. Although it was mainly proposed for power management, the TWT mechanism can be used to schedule TWT service periods, which is another tool to control collisions [82]. A TWT service period is a period in which one or more devices expect to be serviced, and they are expected to enter sleep mode outside the TWT. As such, a central scheduler can define TWT service periods for groups of devices. Even if devices may not need to use power save modes, implementation specific features can be included to ensure they can only transmit during the allowed TWT service period. In this way, it is possible to control the number of devices that contend for the channel during each period. Furthermore, the AP can use the OFDMA capability to periodically schedule multiple devices during TWT service periods, as illustrated in Fig. 12. The TWT feature, thus, can be leveraged together with the OFDMA mode to implement scheduled access and achieve more predictable latency for industrial automation systems. Within each TWT service period, multiple users can be scheduled by the AP using the TF, which is followed by UL MU data (UL MU data can contain up to nine resource units for a 20-MHz channel, as shown in Fig. 12) after short interframe space (SIFS) time, and a downlink MU block ack (DL MU BA) from the AP after another SIFS time (see Fig. 12).

B. 5G Ultrareliable Low-Latency Communications

Supporting the future industrial automation and factory deployment over wireless connectivity is one of the primary use cases driving the design of the next-generation 3GPP standards, also called 5G [53], [84]. A new term URLLC mode is coined to describe the communication requirements for a wide range of applications and services needing extremely low latency and ultrahigh reliability, including those of industrial automation systems. A description of the principles and building blocks for supporting 5G URLLC is provided in [85].

The 5G air interface has incorporated low-latency frame structure and numerology, high-reliability, and low-latency features in the PHY, low-latency signaling, and protocol for the MAC and upper layers. It has also introduced architectural enhancements in the network and the protocol stack to reduce latency and increase reliability. Industrial application requirements, capabilities/limitations in LTE, and potential enhancement areas for 5G are described in [86]. 5G air interface and network architecture enhancements for industrial applications are also discussed in [87]. The relevant features in the latest 5G specifications are summarized next.

1) Low-Latency Frame Structure and Numerology: The air interface of 5G systems, referred as 5G NR, introduced a flexible frame structure [88], illustrated in Fig. 13, where the slot duration is not fixed as it was in LTE. Compared to the fixed 1-ms TTI in LTE, the slot duration in 5G NR can be as low as 0.125 ms for data transmission. The low-latency slot durations are made possible by enhanced OFDM numerology where wider subcarrier spacing leads to smaller OFDM symbol duration.

In addition to the smaller slot length, the 5G NR standard allows minislots to be allocated for short transmissions. Compared to a slot, which is comprised of 14 OFDM symbols, the minislots can have 2, 4, or 7 OFDM symbols only.

The 5G NR frame structure allows faster uplink/downlink switching and HARQ timing intervals for TDD access in order to reduce the latency in potential retransmissions of time-critical data.

5G NR also supports a self-contained subframe structure where data transmission, associated control signaling, and ACK/NACK feedback can all take place within a single subframe. This feature can be very useful in supporting low-latency applications requiring a very short turnaround time.

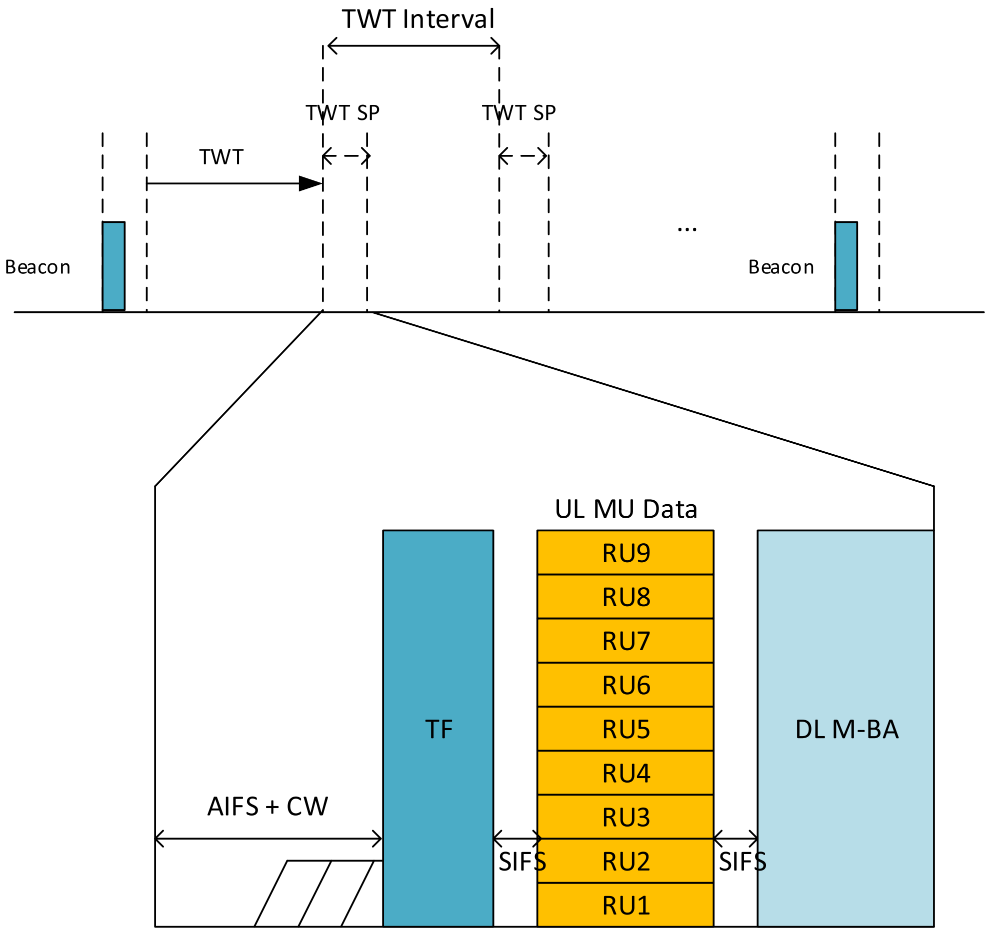

Fig. 12. ***TWT-based scheduled access in IEEE 802.11ax.***

2) PHY Enhancements for High Reliability and Low Latency: To achieve higher reliability and robustness, 5G NR has introduced support for Polar codes [90], [91] and LDPC [92] codes in addition to the convolutional and turbo codes supported in previous generations. For small packet sizes, prevalent in industrial automation applications, the Polar code has significant performance improvement [93] over turbo and convolutional codes. In addition, Polar codes have been shown to have no noticeable error floor, which is an important criterion to reach extremely high level of error tolerance.

The 5G standard enables better support for massive MIMO techniques [94] that may harness spatial diversity from more than 32 antennas to massively increase the transmission reliability. Although the concept of massive MIMO is not new, the previous generations, including LTE, did not have necessary reference signaling and protocol support to harness its potential.

The 5G NR PHY also supports mmWave communication in higher frequency bands (e.g., 28 GHz). The larger channel bandwidth and the directional communication in the mmWave PHY can be leveraged to provide very high reliability as well as low latency in industrial automation and factory deployment use cases where line-of-sight communication could be viable.

3) Low-Latency Signaling and Protocol: Control signals and protocol messages associated with resource scheduling and initial access can be a major contributor to latency in LTE and previous 3GPP standards [95], [96]. The 5G NR standard has introduced the concept of grant-free access in the UL by which devices can avoid time-consuming UL resource request and grant mechanism for hard real-time data [97].

PHY reference signaling enhancements such as front-loaded DMRS in 5G NR enables lower data decoding latency in low-mobility scenarios [85], [98].

Further protocol enhancements such as omitting HARQ, removing cipher and header compression, and prioritization for mission-critical data can enable low-latency applications [99].

4) Architectural Enhancements: 5G NR has introduced major architectural enhancements both in the RAN and core network [100]. CRAN-based design of 5G access network [101] introduces flexibility in dynamically assigning computing and communication resources necessary to

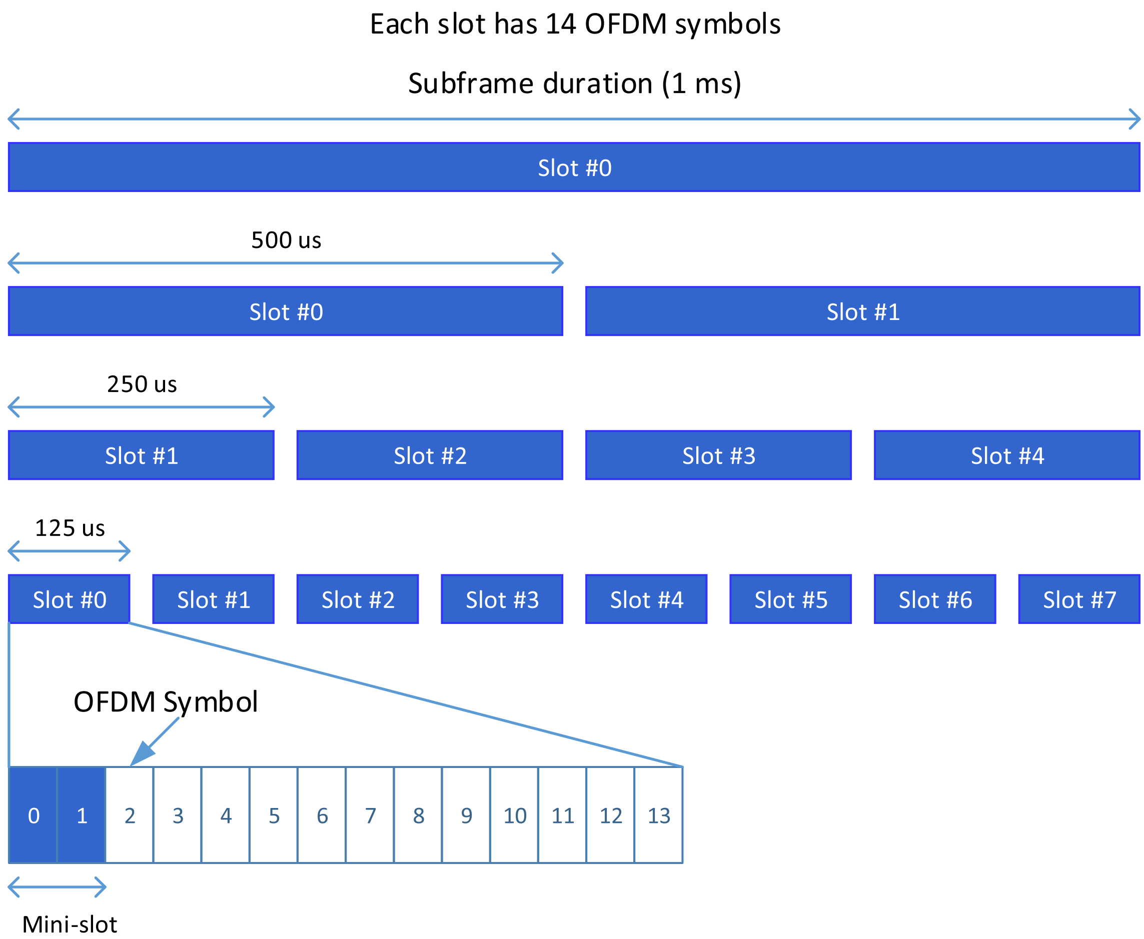

Fig. 13. ***Scalable slot structure in 5G NR with options for minislot [89].***

continually provide low latency and high reliability as the traffic mix, network load, and wireless channel conditions evolve over time.

In the core network, SDN-based partitioning of control and data plane [102] allows for lower latency in both the control and data planes. In addition, the architectural support for NFV and network slicing allows for consistently provisioning required network resources for hard real-time applications during network congestions and load fluctuations [103]. MEC and caching at the 5G network edges can reduce the latency by bringing the computing power and content near the client devices [104].

C. mmWave Communications in WiGig

Wireless communications in the mmWave bands are also emerging as a new alternative to enable very high throughput and low-latency communications. As indicated in the previous section, 5G NR defines new operation modes in licensed mmWave bands, such as 28 GHz in the United States. On the other hand, WiGig systems based on the IEEE 802.11ad [82] and its upcoming evolution, being defined in the 802.11ay [105] amendment, operate in the 60-GHz unlicensed band. WigGig can be considered for applications, such as wireless virtual reality, backhauling, and cable replacement in static scenarios. Fig. 14 illustrates the capacity in terms of TSN users (streams) that could be supported for a given latency bound with various modes of the 802.11ad standard. The analysis considers different PHY data rates as illustrated in Fig. 14 and the contention-free polled access mode in the 802.11ad MAC, in which each transmission is assigned a dedicated service period. The 27-Mb/s data rate in 802.11ad is the base rate using omnidirectional mode used in some of the control/management frame exchanges. As can be seen, the higher data rates enable much lower latency bounds to be supported compared to 802.11ac/ax (see Fig. 11). For instance, a 90-μs latency bound could be achieved with 802.11ad (at 3850 Mb/s) for nine TSN users, whereas the minimal supported latency bound with 802.11ax (20 MHz) would be around 750 μs for the same nine TSN users. The higher data rates in 802.11ad can significantly reduce latency, but other factors should be considered in order to have a practical solution. On the one hand, mmWave links are expected to face less coexistence issues compared to lower unlicensed bands. On the other hand, the short

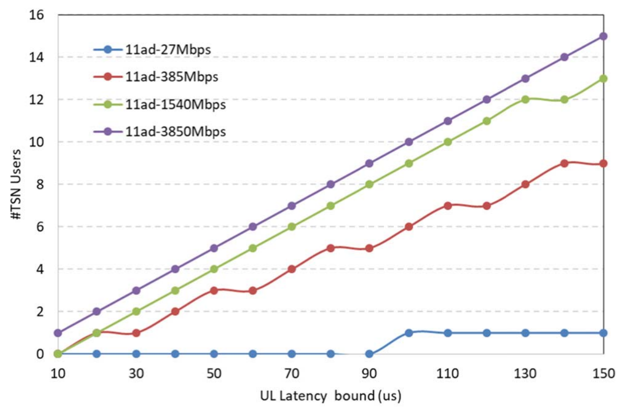

Fig. 14. *TSN user capacity with 802.11ad (60 GHz) as a function of the latency bound.*

range and directionality of mmWave links bring additional challenges, such as the overhead required for beam training and blockage issues, which impact both latency and reliability.

The use cases that can be served with a short-range highly directional mmWave solution need to be carefully considered.

D. Integration With Wired TSN Infrastructure

Despite the advances in both 802.11 and 3GPP standards to address latency and reliability requirements, there are still gaps to enable the integration of these technologies with a wired TSN infrastructure, as illustrated in Fig. 6. Since 802.11 is natively an 802 technology, it shares several layers with 802.3 (Ethernet), which makes the integration seamless. In fact, 802.11 links can already be seen as part of an 802.1 TSN network (as defined by the recently approved 802.11ak amendment). TSN compatible (802.1AS) time synchronization is already supported in 802.11. The next step for 802.11 is the support for additional TSN capabilities, such as time-aware shaping, redundancy, and preemption.

On the other hand, 3GPP 4G and 5G networks are not native 802 technologies at the link layer, i.e., they do not share the same IEEE 802-based link layer as Ethernet and Wi-Fi. As illustrated in Fig. 5, TSN capabilities are built on top of 802 MAC layers and the first common layer that 3GPP networks share with IEEE 802-based networks is the IP layer. Therefore, new standardization activities are needed to enable the integration of 3GPP-based 5G networks with 802.1 TSN networks. This problem has been identified and the work is being considered as part of the evolution of 5G standards. One of the work items is to enable transmission of 802-base link layer frames (Ethernet frames) over 5G links. Support for 802.1AS-based time synchronization across 5G links is another basic TSN capability needed to enable seamless integration with wired TSN infrastructure.

Once TSN capabilities are enabled over wireless (both Wi-Fi and 5G networks), integrating the management of wireless and wired TSN capabilities within the TSN infrastructure will need to be further explored. The dynamic aspects of wireless links impose new challenges for network provisioning compared to wired links, which are very stable in capacity and reliability. A much more proactive management approach may be needed to ensure that TSN-grade performance can be maintained across wired and wireless links.

As discussed in this section, mainstream wireless technologies are evolving to incorporate capabilities to better support real-time industrial applications. In the next section, we describe a vision for integrating multiple applications and connectivity technologies in an industrial wireless network infrastructure.

VI. INDUSTRIAL WIRELESS INFRASTRUCTURE AND APPLICATIONS

We envision a multiconnectivity infrastructure that combines wired and wireless technologies in multiple modes to enable the convergence of hard real-time, soft real-time, and nonreal-time applications, as illustrated in Fig. 15. Ethernet TSN can provide a backbone across the factory floor to enable deployment, configuration, and management of TSN properties. Wireless TSN would extend the infrastructure to mobile and portable devices (controllers, sensors, actuators, and AGVs). A combination of next-generation 802.11 and 5G standards across spectrum bands (e.g., <6 GHz and mmWave) could address a wide range of deployment scenarios and latencies, as well as support convergence (multiple classes of traffic). There is also a need for time-aware networking protocols to manage access control, resource reservation, routing, and coexistence across the envisioned industrial wireless infrastructure.

A. Time-Sensitive Applications Classification and Wireless Roadmap

As wireless networks and standards evolve and include new capabilities to provide better QoS, including TSN support, more applications are expected to migrate to wireless networks. This transition to wireless will likely be slow and gradual, given the stringent performance requirements. Applications that involve moving parts and mobile devices [robots, AGVs, and augmented/virtual reality (AR/VR)] will likely be the first to take advantage of new wireless TSN capabilities. A classification of industrial applications with their corresponding latency and reliability requirements is described in [106] and illustrated in Fig. 16. Class A could be supported by current wireless technologies (LTE and 802.11ac and ax) with proper enhancements for admission control, latency-optimized scheduling, and introduction of time-aware (802.1Qbv) concepts. Class B applications (AR/VR, HMI, soft real-time, and select hard

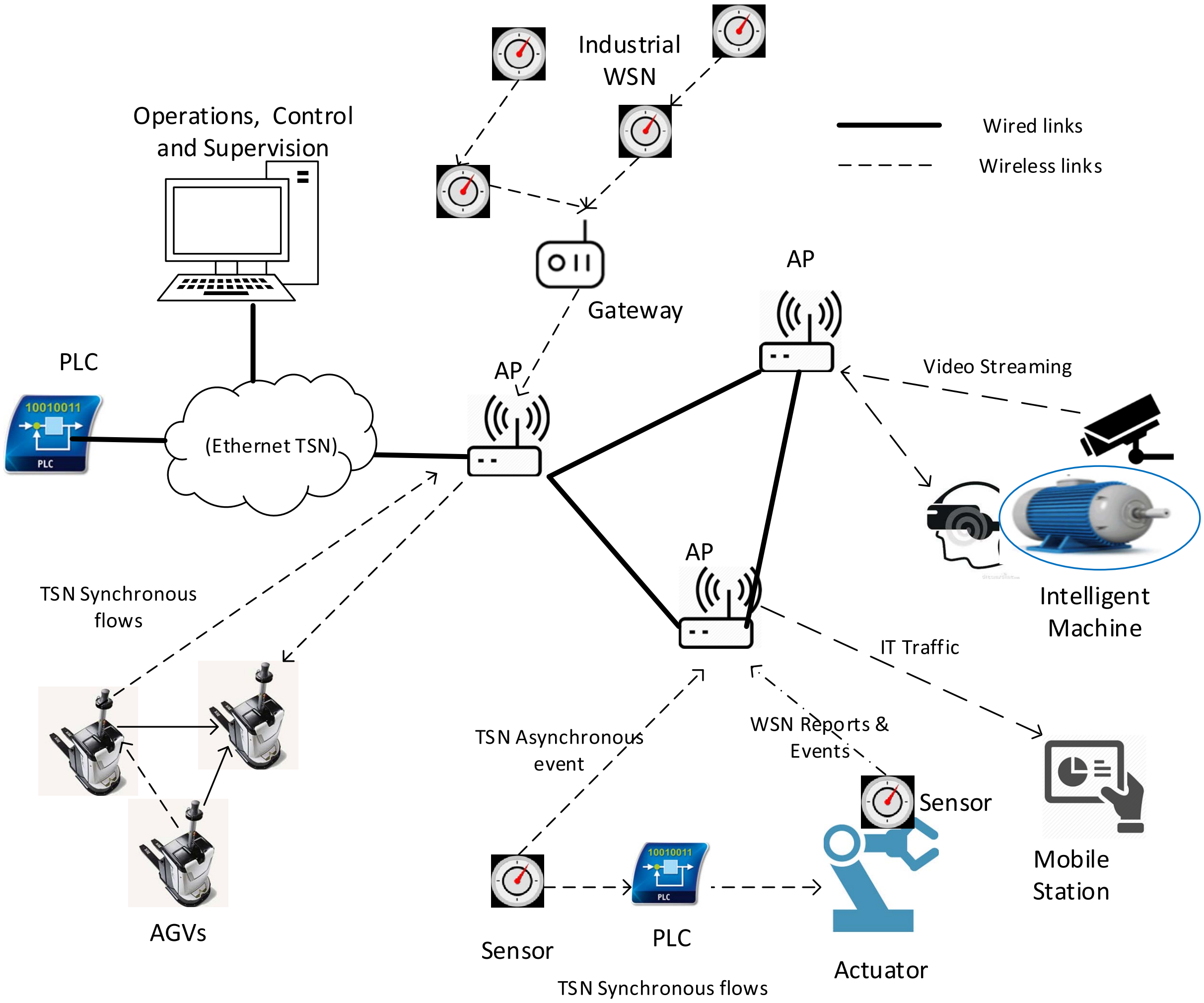

Fig. 15. ***Industrial wireless network.***

real-time control) will require single-digit milliseconds with higher reliability compared to Class A. These applications will require careful network planning and optimizations that are being introduced in upcoming standards, such as 802.11ax and 5G URLLC mode. Finally, Class C applications (hard real-time control with very low cycle times, such as motion control) may be supported in future, but many challenges still remain to be solved, as discussed in Section III, and will likely require the next generation of enhancements to 5G and 802.11ax. The 802.11 Extreme High Throughput study group has already started defining requirements and new technologies, such as distributed MIMO, multi-AP coordination, and low-latency enhancements that could enable Class C applications over wireless in the new 802.11be amendment, the next major release after 802.11ax.

Other nonreal-time (e.g., industrial sensor networks) and soft real-time applications (remote HMI) that are not time sensitive should also leverage advances enabled by TSN capabilities in future industrial wireless networks.

B. Wireless Experimental Platforms

Feasibility demonstration using hardware platforms is a required step before wireless technologies can be adopted in soft and hard real-time industrial applications. Experimentation with 802.11/Wi-Fi is relatively easier than with 3GPP technologies, mainly due to the lower cost and availability of off-the-shelf platforms. However, in order to experiment with time synchronization and other TSN features that control latency and reliability over the wireless medium, it is fundamental to have access to lower level MAC and PHY layer implementations. Typically, Wi-Fi vendors do not open their firmware in most off-the-shelf solutions. Although it is possible to find open-source software for upper layers (upper MAC, link layer, and above), lower MAC (e.g., the CSMA and backoff algorithms), and PHY features are usually proprietary.

SDR hardware and software platforms have been used to enable research and development with MAC and PHY layers of common wireless standards (e.g., 802.11, Bluetooth,

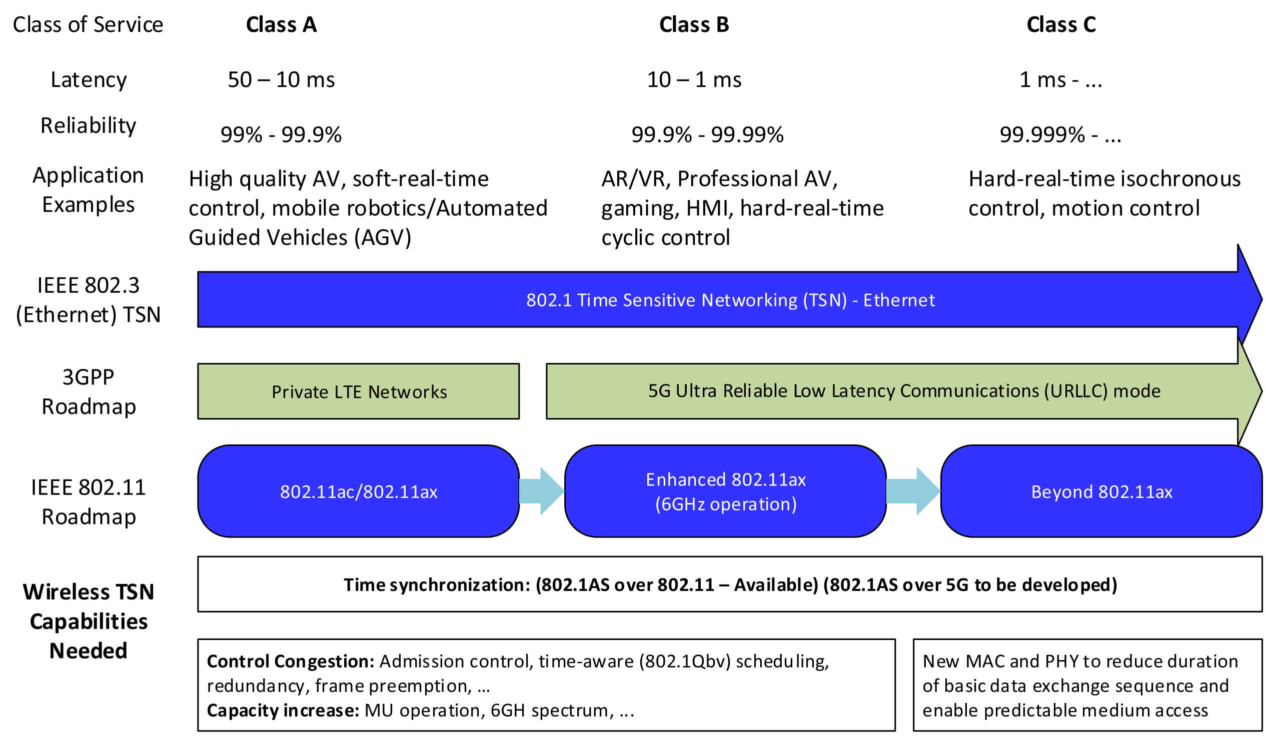

Fig. 16. ***Time-sensitive applications and roadmap of wireless technologies [106].***

802.15.4, and LTE). For instance, platforms such as USRP [107], WARP [108], and GNU Radio [109] have been leveraged by both industry and academia to implement and validate MAC/PHY research ideas. Architecturally, an SDR platform consists of a front-end module and a signal processing module that is typically implemented in FPGA or a combination of FPGA and system on chip (SoC). A number of integrated front-end solutions can be found in the market [110], [111], which are very common in current SDR platforms and can offer up to 100-MHz wide instantaneous spectrum, up to the 6-GHz band. SDR platforms may support a number of software development toolchains, the most common are provided by NI instruments [112] or MathWorks [113].

Most work done to date with SDR implementations of wireless standards has not considered stringent synchronization, latency, and reliability requirements. Meeting hard real-time requirements in an FPGA-accelerated radio implementation involves several tradeoffs in complexity, cost, latency, and reliability. Adding more features in the FPGA fabric may help reduce latency, but complexity in design, debugging, and cost are important factors to consider. A low-latency SDR system (called Tick) has been recently developed [114], which provides programmability and ensures low latency through an accelerator-rich architecture and a number of hardware and software codesign techniques. Furthermore, currently available SDR wireless implementations are based on older wireless standards (e.g., WARP implementation of 802.11a and g [108], Tick implementation of 802.11a/g and ac [114]). Very little is available when it comes to upcoming standards, such as 802.11ax and 5G, which include several capabilities relevant to hard real-time applications, as described previously.

Fig. 17. ***Wireless experimental research platform using Intel-Altera FPGA [63].***

We have recently demonstrated an 802.11ax baseband experimental implementation (with select features) on an Intel Arria 10 FPGA platform [115] integrated with an off-the-shelf analog front end in [63]. This SDR platform (Fig. 17) is an initial step toward enabling the validation of next-generation 802.11ax features. It also enables the development of techniques to optimize latency in FPGA and application-specific implementations. For instance, several latency optimizations were developed using this platform, including parallelization techniques for binary convolutional codes, low-latency streaming Fourier transforms, and tightly pipelined transmit and receive processing chains.

The development of wireless TSN technologies is still in the initial exploratory research stage, but as research and standards evolve, new experimentation platforms, especially SDR-based, will be required to validate the research in practice. Today's SDR hardware and software tools will need to be enhanced to enable new wireless capabilities as well as implementation optimizations that can address the strict TSN requirements.

VII. CONCLUSION

Wireless connectivity can enable flexibility, scalability, and lower costs in next-generation factories. However, there are major research challenges to achieve stringent levels of time synchronization and timeliness required to enable TSN capabilities and applications over mobile (wireless) domains. Next-generation wireless capabilities and standards are being introduced, which can enable faster communications with better control of channel access, therefore reducing randomness aspects of today's consumer wireless systems. Demonstrating the feasibility of wireless TSN will require new experimental wireless platforms that meet stringent timing and reliability requirements. Up until now, wireless networks and time-sensitive-distributed control systems have evolved independently. Enabling hard real-time application over wireless may also require a new end-to-end and cross-disciplinary research approach where time-coordinated distributed computing and connectivity are optimized jointly. ■

REFERENCES

[1] "Time-aware applications, computers, and communication systems (TAACCS)," NIST, Tech. Note 1867, Feb. 2015. [Online]. Available: http://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1867.pdf

[2] "Networking for industrial machine building, V. 1.0," Avnu Alliance, White Paper, Dec. 2014.

[3] *Time Sensitive Networking Working Group*, IEEE 802.1.

[4] C. Pereira and P. Neuman, "Industrial communication protocols," in *Springer Handbook on Automation*. 2009.

[5] A. W. Colombo, S. Karnouskos, and T. Bangemann, "Towards the next generation of industrial cyber-physical systems," in *Industrial Cloud-Based Cyber-Physical Systems*. Cham, Switzerland: Springer, 2014. doi: 10.1007/978-3-319-05624-1_1.

[6] *Industrial Communication Networks—Profiles—Part 2: Additional Fieldbus Profiles for Real-Time Networks based on ISO/IEC8802-3*, document IEC 61784-2, International Electrotechnical Commission, Nov. 2014.

[7] OPC Foundation. [Online]. Available: https://opcfoundation.org/about/opc-technologies/opc-ua/

[8] *IEEE 802.15 WPANs Task Group 4*. [Online]. Available: http://www.ieee802.org/15/pub/TG4.html

[9] ZigBee Alliance. [Online]. Available: www.zigbee.org

[10] Thread. [Online]. Available: www.threadgroup.org

[11] X. Li, D. Li, J. Wan, A. V. Vasilakos, C.-F. Lai, and S. Wang, "A review of industrial wireless networks in the context of Industry 4.0," *Wireless Netw.*, vol. 23, no. 1, pp. 23–41, 2017. doi: 10.1007/s11276-015-1133-7.

[12] *IEEE 802.15 WPAN—Task Group 4G (TG4G) Smart Utility Networks*. [Online]. Available: http://www.ieee802.org/15/pub/TG4g.html

[13] *IEEE 802.15 WPAN—Task Group 4e (TG4e)*. [Online]. Available: http://www.ieee802.org/15/pub/TG4e.html

[14] S. Duquennoy, B. Al Nahas, O. Landsiedel, and T. Watteyne, "Orchestra: Robust mesh networks through autonomously scheduled TSCH," in *Proc. ACM SenSys*, 2015, pp. 337–350.

[15] *WirelessHARTTM*, Standard IEC 62591, 2016. [Online]. Available: https://webstore.iec.ch/publication/24433

[16] *Ipv6 Over the TSCH Mode of 802.15.4e*. [Online]. Available: https://datatracker.ietf.org/wg/6tisch/about/

[17] T. Watteyne *et al.*, "Industrial wireless IP-based cyber–physical systems," *Proc. IEEE*, vol. 104, no. 5, pp. 1025–1038, May 2016.

[18] Bluetooth SIG. [Online]. Available: https://www.bluetooth.com/

[19] *Bluetooth Mesh Networking*. [Online]. Available: https://www.bluetooth.com/specifications/mesh-specifications

[20] *IEEE 802.11 Wireless Local Area Networks*. [Online]. Available: http://www.ieee802.org/11/

[21] *IEEE P802.11—Task Group AX*. [Online]. Available: http://www.ieee802.org/11/Reports/tgax_update.htm

[22] IEEE Standard 802.11e, (QoS Enhancements Amendment to IEEE Standard 802.11), 2005.

[23] *Industrial WLAN (Scalance W-Siemens)*. [Online]. Available: https://w3.siemens.com/mcms/industrial-communication/en/scalance/pages/default.aspx

[24] *ABB—Tropos*. [Online]. Available: https://new.abb.com/network-management/communication-networks/wireless-networks

[25] F. Tramarin, S. Vitturi, M. Luvisotto, and A. Zanella, "On the use of IEEE 802.11n for industrial communications," *IEEE Trans. Ind. Informat.*, vol. 12, no. 5, pp. 1877–1886, Oct. 2016.

[26] 3GPP. [Online]. Available: www.3gpp.org

[27] Sigfox. [Online]. Available: www.sigfox.com

[28] LoRa Allicance. [Online]. Available: https://lora-alliance.org/about-lorawan

[29] *Theory of Operations for TSN-Enabled Systems: Applied to Industrial Markets, Rev. 1.0.*, Avnu Alliance Best Practices, Feb. 2017.

[30] *P802.1Qcc—Stream Reservation Protocol (SRP) Enhancements and Performance Improvements*. [Online]. Available: https://1.ieee802.org/tsn/802-1qcc/

[31] *IEEE Standard for Local and Metropolitan Area Networks—Bridges and Bridged Networks—Amendment 24: Path Control and Reservation*, IEEE Standard 802.1Qca, 2015.

[32] G. Breit, *TGac Channel Model Addendum*, IEEE Standard P802.11, Mar. 2010.

[33] J. Medbo and P. Schramm, *Channel Models for HIPERLAN/2*, ETSI/BRAN document 3ERI085B.

[34] A. A. M. Saleh and R. A. Valenzuela, "A statistical model for indoor multipath propagation," *IEEE J. Sel. Areas Commun.*, vol. SAC-5, no. 2, pp. 128–137, Feb. 1987.

[35] Q. H. Spencer, B. D. Jeffs, M. A. Jensen, and A. L. Swindlehurst, "Modeling the statistical time and angle of arrival characteristics of an indoor multipath channel," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 347–360, Mar. 2000.

[36] R. J. M. Cramer, R. A. Scholtz, and M. Z. Win, "Evaluation of an ultra-wide-band propagation channel," *IEEE Trans. Antennas Propag.*, vol. 50, no. 5, pp. 561–570, May 2002.

[37] J.-G. Wang, A. S. Mohan, and T. A. Aubrey, "Angles-of-arrival of multipath signals in indoor environments," in *Proc. IEEE Veh. Technol. Conf.*, Apr. 1996, pp. 155–159.

[38] C.-C. Chong, D. I. Laurenson, and S. McLaughlin, "Statistical characterization of the 5.2 GHz wideband directional indoor propagation channels with clustering and correlation properties," in *Proc. IEEE Veh. Technol. Conf.*, vol. 1, Sep. 2002, pp. 629–633.

[39] *TGn Channel Models*, IEEE 802.11-03/940r4, Vinko Erceg.

[40] *TGac Channel Model Addendum*, IEEE 802.11-09/0308r12, Greg Breit.

[41] R. Porat, *TGah Channel Model*, IEEE Standard 802.11-11/0968r3.

[42] S. Jaeckel, L. Raschkowski, K. Börner, and L. Thiele, "QuaDRiGa: A 3-D multi-cell channel model with time evolution for enabling virtual field trials," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 3242–3256, Jun. 2014.

[43] S. Jaeckel, L. Raschkowski, K. Borner, L. Thiele, F. Burkhardt, and E. Eberlein, "QuaDRiGa-quasi deterministic radio channel generator, user manual and documentation," Fraunhofer Heinrich Herz Inst., Berlin, Germany, Tech. Rep. v2.0.0, 2017.

[44] [Online]. Available: http://quadriga-channel-model.de/

[45] P. Kösti *et al.*, "IST-4-027756 WINNER II D1.1.2 v.1.1: WINNER II channel models," Tech. Rep., 2007. [Online]. Available: http://www.ist-winner.org

[46] P. Heino *et al.*, "CELTIC/CP5-026 D5.3: WINNER+final channel models," Tech. Rep., 2010. [Online]. Available: http://projects.celtic-inititiative.org/winner+

[47] *Study on 3D Channel Model for LTE*, document 3GPP TR 36.873 v12.5.0, 2017.

[48] *Study on Channel Model for Frequencies from 0.5 to 100 GHz*, document 3GPP TR 38.901 v14.1.0, 2017.

[49] R. Candell *et al.*, "Industrial wireless systems: Radio propagation measurements," Tech. Note (NIST TN) 1951, Jan. 2017, p. 125.

[50] [Online]. Available: https://www.celticplus.eu/project-reicovair/

[51] *Industrial Wireless Time Sensitive Networking Roadmap*, Avnu Alliance, Dec. 2017.

[52] J. Moreno, M. Domingo, L. Valle, J. R. Lopez, R. P. Torres, and J. Basterrechea, "Design of indoor WLANs: Combination of a ray-tracing tool with the BPSO method," *IEEE Antennas Propag. Mag.*, vol. 57, no. 6, pp. 22–33, Dec. 2015.

[53] H. Chen *et al.* (2017). "Ultra-reliable low latency cellular networks: Use cases, challenges and approaches." [Online]. Available: https://arxiv.org/abs/1709.00560

[54] *Evolved Universal Terrestrial Radio Access*

(E-UTRA); Physical Layer Procedures (Release 14), document 3GPP TS 36.213 v14.1.0, Technical Specification Group Radio Access Network, Dec. 2016.

[55] B. Anjum, "Optimizing channel access for bandwidth versus latency in 802.11ac WLANs," in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, Garden Grove, CA, USA, Feb. 2015, pp. 113–128. doi: 10.1109/ICCNC.2015.7069328.

[56] E. Khorov, A. Lyakhov, A. Krotov, and A. Guschin, "A survey on IEEE 802.11ah: An enabling networking technology for smart cities," *Comput. Commun.*, vol. 58, pp. 53–69, Mar. 2015.

[57] Y. Kim, G. Hwang, J. Um, S. Yoo, H. Jung, and S. Park, "Throughput performance optimization of super dense wireless networks with the renewal access protocol," *IEEE Trans. Wireless Commun.*, vol. 15, no. 5, pp. 3440–3452, May 2016.

[58] S. Hara and R. Prasad, "Overview of multicarrier CDMA," *IEEE Commun. Mag.*, vol. 35, no. 12, pp. 126–133, Dec. 1997.

[59] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, "Non-orthogonal multiple access (NOMA) for cellular future radio access," in *Proc. IEEE Veh. Technol. Conf. (VTC Spring)*, Jun. 2013, pp. 1–5.

[60] G. J. Sutton *et al.*, "Enabling ultra-reliable and low-latency communications through unlicensed spectrum," *IEEE Netw.*, vol. 32, no. 2, pp. 70–77, Mar./Apr. 2018. doi: 10.1109/MNET.2018.1700253.

[61] K. Stanton, "Distributing deterministic, accurate time for tightly coordinated network and software applications: IEEE 802.1 AS, the TSN profile of PTP," *IEEE Commun. Standards Mag.*, vol. 2, no. 2, pp. 34–40, Jun. 2018.

[62] A. Mahmood, R. Exel, H. Trsek, and T. Sauter, "Clock synchronization over IEEE 802.11—A survey of methodologies and protocols," *IEEE Trans. Ind. Informat.*, vol. 13, no. 2, pp. 907–922, Apr. 2017.

[63] K. Sung *et al.*, "Enabling time-critical applications over next generation 802.11 networks," in *Proc. IEEE INFOCOM*, 2018.

[64] D. Cavalcanti *et al.*, *Time-Aware Traffic Shaping Over 802.11*, document 11-18-1542-00, Sep. 2018. [Online]. Available: https://imat.ieee.org/802.11/dcn/18/11-18-1542-00-0000-time-aware-traffic-shaping-over-802-11.pptx

[65] B. D. van Veen and K. M. Buckley, "Beamforming: A versatile approach to spatial filtering," *IEEE ASSP Mag.*, vol. 5, no. 2, pp. 4–24, Apr. 1988.

[66] D. Zhu, B. Li, and P. Liang, "A novel hybrid beamforming algorithm with unified analog beamforming by subspace construction based on partial CSI for massive MIMO-OFDM systems," *IEEE Trans. Commun.*, vol. 65, no. 2, pp. 594–607, Feb. 2017.

[67] Z. Chen, H. Li, G. Cui, and M. Rangaswamy, "Adaptive transmit and receive beamforming for interference mitigation," *IEEE Signal Process. Lett.*, vol. 21, no. 2, pp. 235–239, Feb. 2014.

[68] H. Ma and P. Ma, "Beamforming design of decode-and-forward cooperation for improving wireless physical layer security," in *Proc. 15th Int. Conf. Adv. Commun. Technol. (ICACT)*, PyeongChang, South Korea, Jan. 2013, pp. 41–49.

[69] A. Sahin and H. Arslan, "Edge windowing for OFDM based systems," *IEEE Commun. Lett.*, vol. 15, no. 11, pp. 1208–1211, Nov. 2011.

[70] D. Noguet, M. Gautier, and V. Berg, "Advances in opportunistic radio technologies for TVWS," *EURASIP J. Wireless Commun. Netw.*, vol. 2011, p. 170, Dec. 2011. [Online]. Available: http://jwcn.eurasipjournals.com/content/2011/1/170

[71] I. Cosovic, S. Brandes, and M. Schnell, "Subcarrier weighting: A method for sidelobe suppression in OFDM systems," *IEEE Commun. Lett.*, vol. 10, no. 6, pp. 444–446, Jun. 2006.

[72] S. Brandes, I. Cosovic, and M. Schnell, "Sidelobe suppression in OFDM systems by insertion of cancellation carriers," in *Proc. IEEE 62nd Veh. Technol. Conf. (VTC)*, Sep. 2005, pp. 152–156.

[73] X. Zhou, G. Y. Li, and G. Sun, "Low-complexity spectrum shaping for OFDM-based cognitive radio systems," *IEEE Signal Process. Lett.*, vol. 19, no. 10, pp. 667–670, Oct. 2012.

[74] C.-D. Chung, "Spectrally precoded OFDM," *IEEE Trans. Commun.*, vol. 54, no. 12, pp. 2173–2185, Dec. 2006.

[75] J. Fang and I.-T. Lu, "Precoder designs for jointly suppressing out-of-band emission and peak-to-average power ratio in an orthogonal frequency division multiplexing system," *IET Commun.*, vol. 8, no. 10, pp. 1705–1713, Jul. 2014.

[76] G. Durisi, T. Koch, and P. Popovski, "Toward massive, ultrareliable, and low-latency wireless communication with short packets," *Proc. IEEE*, vol. 104, no. 9, pp. 1711–1726, Sep. 2016.

[77] M. Luvisotto, Z. Pang, D. Dzung, M. Zhan, and X. Jiang, "Physical layer design of high-performance wireless transmission for critical control applications," *IEEE Trans. Ind. Informat.*, vol. 13, no. 6, pp. 2844–2854, Dec. 2017.

[78] U. Oruthota, F. Ahmed, and O. Tirkkonen, "Ultra-reliable link adaptation for downlink MISO transmission in 5G cellular networks," *Information*, vol. 7, no. 1, pp. 1–18, 2016.

[79] F. Tramarin, S. Vitturi, and M. Luvisotto, "A dynamic rate selection algorithm for IEEE 802.11 industrial wireless LAN," *IEEE Trans. Ind. Informat.*, vol. 13, no. 2, pp. 846–855, Apr. 2017.

[80] *IEEE P802.11/D2.0 Draft Standard for Information Technology—Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks—Specific Requirements: Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; Amendment 6: Enhancements for High Efficiency WLAN*, IEEE 802.11 Working Group, Oct. 2017.

[81] *The Sixth Generation of Wi-Fi*, IEEE Standard 802.11ax, Cisco, 2018.

[82] *Unlicensed Use of the 6 GHz Band*, document ET Docket 18–295, Notice Proposed Rulemaking, Oct. 2018.

[83] *Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band*, IEEE 802.11 Working Group, IEEE 802.11ad, Dec. 2012.

[84] *Service Requirements for the 5G System; Stage 1*, document 3GPP TS 22.261 V16.4.0, Jun. 2018.

[85] P. Popovski *et al.*, "Wireless access for ultra-reliable low-latency communication: Principles and building blocks," *IEEE Netw.*, vol. 32, no. 2, pp. 16–23, Mar. 2018.

[86] B. Holfeld *et al.*, "Wireless communication for factory automation: An opportunity for LTE and 5G systems," *IEEE Commun. Mag.*, vol. 54, no. 6, pp. 36–43, Jun. 2016.

[87] P. Schulz *et al.*, "Latency critical IoT applications in 5G: Perspective on the design of radio interface and network architecture," *IEEE Comm. Mag.*, vol. 55, no. 2, pp. 70–78, Feb. 2017.

[88] *Study on New Radio Access Technology Physical Layer Aspects*, document 3GPP TR 38.802 V14.2.0, Sep. 2017.

[89] "5G new radio," Nat. Instrum., Austin, TX, USA, White Paper, 2018.

[90] E. Arikan, "Channel polarization: A method for constructing capacity-achieving codes for symmetric binary-input memoryless channels," *IEEE Trans. Inf. Theory*, vol. 55, no. 7, pp. 3051–3073, Jul. 2009.

[91] S. Korada, E. Şaşoğlu, and R. Urbanke, "Polar codes: Characterization of exponent, bounds, and constructions," *IEEE Trans. Inf. Theory*, vol. 56, no. 12, pp. 6253–6264, Dec. 2010.

[92] T. J. Richardson and S. Kudekar, "Design of low-density parity check codes for 5G new radio," *IEEE Commun. Mag.*, vol. 56, no. 3, pp. 28–34, Mar. 2018.

[93] M. Sybis, K. Wesolowski, K. Jayasinghe, V. Venkatasubramanian, and V. Vukadinovic, "Channel coding for ultra-reliable low-latency communication in 5G systems," in *Proc. IEEE 84th Veh. Technol. Conf. (VTC-Fall)*, Montreal, QC, Canada, Sep. 2016, pp. 1–5.

[94] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.

[95] S. Mohan, R. Kapoor, and B. Mohanty, "Latency in HSPA data networks," Qualcomm, San Diego, CA, USA, Tech. Rep., 2011.

[96] C. Serrano, B. Garriga, J. Velasco, J. Urbano, S. Tenorio, and M. Sierra, "Latency in broad-band mobile networks," in *Proc. IEEE Veh. Technol. Conf. (VTC-Spring)*, Barcelona, Spain, Apr. 2009, pp. 1–7.

[97] A. Azari, P. Popovski, G. Miao, and C. Stefanovic, "Grant-free radio access for short-packet communications over 5G networks," in *Proc. IEEE Global Commun. Conf.*, Singapore, Dec. 2017, pp. 1–7.

[98] M. Hook, "5G in reality," in *Proc. Keynote Eur. Conf. Netw. Commun.*, Oulu, Finland, 2017.

[99] P. Marsch, Ö. Bulakci, O. Queseth, and M. Boldi, *5G System Design: Architectural and Functional Considerations and Long Term Research*. Hoboken, NJ, USA: Wiley, 2018.

[100] *System Architecture for the 5G System (Release 15)*, document 3GPP TS 23.501, 2017.

[101] P. Rost *et al.*, "Cloud technologies for flexible 5G radio access networks," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 68–76, May 2014.

[102] H.-H. Cho, C.-F. Lai, T. K. Shih, and H.-C. Chao, "Integration of SDR and SDN for 5G," *IEEE Access*, vol. 2, pp. 1196–1204, Sep. 2014.

[103] M. Simsek, A. Aijaz, M. Dohler, J. Sachs, and G. Fettweis, "5G-enabled tactile Internet," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 3, pp. 460–473, Mar. 2016.

[104] S. Wang, X. Zhang, Y. Zhang, L. Wang, J. Yang, and W. Wang, "A survey on mobile edge networks: Convergence of computing, caching and communications," *IEEE Access*, vol. 5, pp. 6757–6779, 2017.

[105] Y. Ghasempour, C. R. C. M. da Silva, C. Cordeiro, and E. W. Knightly, "IEEE 802.11ay: Next-generation 60 GHz communication for 100 Gb/s Wi-Fi," *IEEE Commun. Mag.*, vol. 55, no. 12, pp. 186–192, Dec. 2017.

[106] D. Cavalcanti *et al.*, *Controlling Latency in 802.11*, document 11-18-1160-00. [Online]. Available: https://mentor.ieee.org/802.11/dcn/18/11-18-1160-00-0wng-controlling-latency-in-802-11.pptx

[107] USRP. [Online]. Available: https://www.ettus.com/

[108] WARP. [Online]. Available: https://mangocomm.com/products/kits/warp-v3-kit

[109] GNU Radio. [Online]. Available: https://www.gnuradio.org/

[110] Analog Devices. *AD 9361 Agile Transceiver*. [Online]. Available: http://www.analog.com/en/products/ad9361.html

[111] Analog Devices. *AD 9371 Wideband Transceiver*. [Online]. Available: http://www.analog.com/en/applications/technology/sdr-radioverse-pavilion-home/wideband-transceivers/ad9371-family.html

[112] NI SDR. [Online]. Available: http://www.ni.com/en-us/innovations/wireless/software-defined-radio.html

[113] MathWorks SDR. [Online]. Available: https://www.mathworks.com/discovery/sdr.html

[114] H. Wu *et al.*, "The tick programmable low-latency SDR system," in *Proc. Mobile Comput. Commun. (MobiCom)*, Snowbird, UT, USA, Oct. 2017.

[115] "Arria 10 device overview," Intel-Alter, White Paper, Jan. 2015. [Online]. Available: https://www.intel.com/content/www/us/en/programmable/products/boards_and_kits/dev-kits/altera/arria-10-soc-development-kit.html

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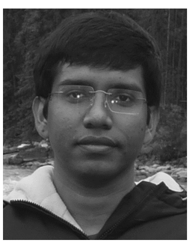

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