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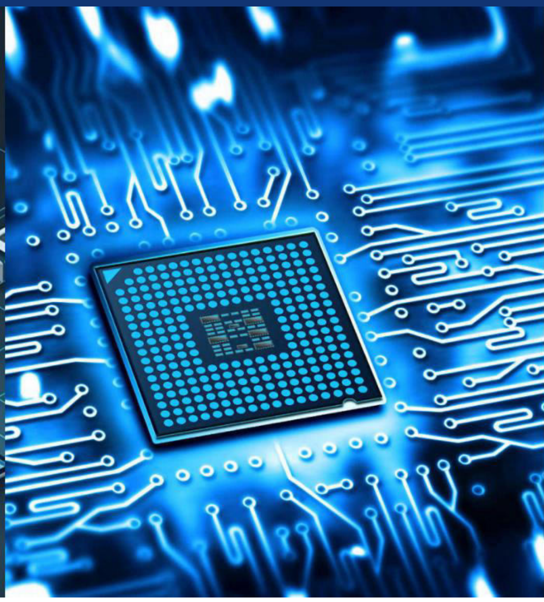


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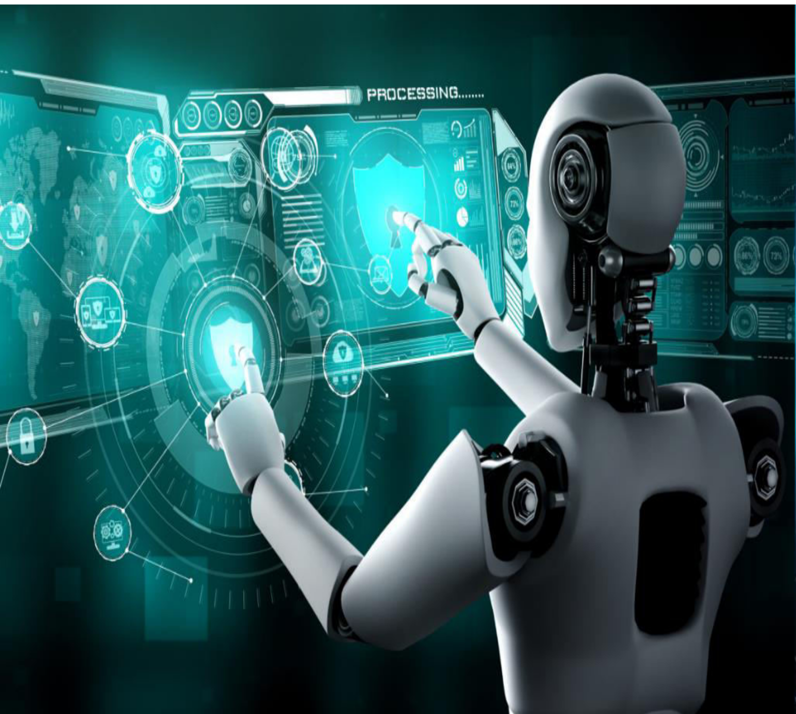

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Analysis of Time-Sensitive Networking (TSN) over 5G networks

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ABSTRACT: Many emerging applications require a higher level of flexibility, modularity, and efficiency but are dependent on advancements in communication infrastructure and distributed computing. Time-sensitive networking (TSN) standards aim at providing vendor agnostic, reliable, and deterministic communications over the Ethernet, but lack in flexibility and modularity provisions. In this context wireless communication systems are preferred given the obvious benefits in terms of increased flexibility, reduced deployment & maintenance costs, and inherent mobility support. However, the stochastic nature of the wireless medium poses several challenges in achieving these benefits. In this paper we comprehensively analyze the recent standardization efforts and developments in IEEE 802.11 and 5G to enable low-latency, deterministic communications and present the current status of their integration with wired TSN. Then, we present a set of use cases that may be enabled by wireless TSN including industrial automation,automotive,or audiovisual applications

KEYWORDS: real time, deterministic, reliable, time sensitive networking, TSN, 5G, Wi-Fi, IEEE 802.11

I. INTRODUCTION

The Time-Sensitive Networking (TSN) is a set of IEEE 802.1 standards designed to provide deterministic and low-latency communication over Ethernet networks. TSN ensures real-time data transmission by implementing features like time synchronization, traffic shaping, and resource reservation. When combined with 5G networks, TSN enhances ultra-reliable and low-latency communication (URLLC), making it a key technology for industrial automation, autonomous vehicles, and mission-critical applications. 5G networks, with their advanced capabilities such as network slicing, massive device connectivity, and URLLC, complement TSN by offering highspeed wireless communication with minimal delays. The integration of TSN over 5G enables realtime, deterministic networking in wireless environments, which was traditionally limited to wired Ethernet. This combination is particularly useful in Industry 4.0, smart factories, intelligent transportation systems, and remote healthcare, where precise timing and reliable data delivery are critical. By leveraging TSN over 5G, industries can achieve seamless end-to-end communication between wired and wireless networks while ensuring strict timing constraints. The synchronization mechanisms of TSN, coupled with 5G's high reliability and low latency, enable applications that demand precise control, such as robotic automation and teleoperation. Additionally, TSN ensures Quality of Service (QoS) by prioritizing time-sensitive traffic, reducing jitter, and avoiding data loss. Another critical aspect of TSN over 5G is its impact on Quality of Service (QoS) and traffic engineering. Traditional wireless networks face challenges such as packet loss, network congestion, and high jitter, which can severely impact time-sensitive applications. However, TSN over 5G mitigates these issues through strict traffic prioritization, bandwidth reservation, and redundancy mechanisms like Frame Replication and Elimination (FRER). These features ensure that critical data is delivered on time, even in the event of network failures or congestion. Additionally, 5G network slicing allows for dedicated network resources to be allocated specifically for TSN-based applications, preventing interference from other network traffic. The motivation for integrating Time-Sensitive Networking (TSN) with 5G networks stems from the growing demand for ultra-reliable, low-latency, and deterministic communication in critical applications such as industrial automation, autonomous transportation, smart cities, and telemedicine. While TSN has traditionally ensured real-time data transmission in wired networks, the need for wireless flexibility without compromising timing precision has become crucial. 5G networks, with features like Ultra-Reliable Low-Latency Communication (URLLC) and network slicing, provide the ideal foundation to extend TSN capabilities into mobile and dynamic environments. This integration enables seamless, end-to-end communication between wired and wireless systems, making it particularly valuable in smart manufacturing, real-time control systems, vehicle-to-everything (V2X) communication, and remote healthcare. The ability of TSN to prioritize time-sensitive

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traffic, reduce jitter, and ensure synchronized data transmission enhances network efficiency and reliability, addressing challenges in mission-critical industries.

II. BACKGROUND

The communication technology landscape for applications requiring deterministic communication is highly dominated by proprietary or standardized but not interoperable wired communication systems. Examples include PROFIBUS], EtherCAT [20], SERCOS III [21], and many more [1], [18]. A clear downside of current industrial fieldbuses for deterministic communications is that the solutions are not interoperable and cannot coexist in the same network. To this end, the IEEE 802.1 TSN TG has been working to establish a set of standards to provide deterministic and more reliable communications over standard Ethernet [4]. This effort is also mainly aimed to enable seamless interoperability among different industrial devices, enable their coexistence over the same fieldbus, and unify their communication interfaces. Besides wired communication systems, wireless communication technologies have also been considered and deployed in industrial environments for monitoring and openloop control applications. Among others, some wireless solutions based on IEEE 802.15.4 PHY have been proposed, e.g., Zigbee [13], WirelessHART [14], wireless networks for industrial automation - process automation (WIA-PA) , and Smartmesh IP . These standards define their own medium access control (MAC) to achieve different features, such as real-time communications, or high reliability. However, the limitations of the IEEE 802.15.4 PHY in terms of bit rate or reliability makes its use unfeasible for emerging high-performance applications. Some industrial applications use the digital enhanced cordless telephone (DECT) technology, given its deterministic medium access. However, it requires improvements on communication robustness and reliability . Recently, the DECT technology has received an upgrade in the form of DECT-2020 new radio (NR). It defines an advanced radio interface technology to support both URLLC and massive machine type communication (mMTC) [18]. However, it supports short-range communications with limited data rates and marginally meets the minimum reliability requirements [19].

III. TIME SENSITIVE NETWORKING

In the last decade the institute of eletronics and electrical engineers (IEEE), the international electrotechical commission (IEC), and the internet engineering task force (IETF) have proposed new standards to enable deterministic communications to the Ethernet standard. The IEEE 802.1 TSN TG evolved from the IEEE 802.1 audio-video bridging (AVB) TG to cover the expanded goals and meet the demands of. the industrial control community and the automotive community . Such demands have resulted in mechanisms such as time-aware scheduling to guarantee packet delivery with bounded latency, high reliability, and low latency fluctuations (jitter). The IEEE 802.1 TSN TG has focused efforts not only on defining and proposing new standards but also on extending and improving the already available standards like the IEEE 802.1Q [19] and the IEEE 802.1AS for accurate time synchronization .

The TSN standards have been designed to enable modular systems, whereby the implementations for a specific application can be tailored to meet its hardware and software requirements. Another motivation behind the development of TSN was to provide a standardized technology that is open – not affiliated to any organization or company [12]. Hence, allowing interoperability between standard conforming industrial devices from any vendor. This added advantage of interoperability on top of deterministic and high reliability communications has pushed the development on TSN forward. TSN in its essence enables the convergence of IT and OT systems, which were previously kept separate given the difference in their communication, safety, and security requirements. TSN also supports direct convergence with higher-layer protocols (e.g., open platform communications unified architecture (OPC-UA) [11], [12]), since TSN is implemented self-contained on the data link layer (layer 2 of the OSI model). To reach the targeted capabilities, the TSN technology is based on five key features: accurate time synchronization, traffic shaping and scheduling, ultra-reliability, resource management, and flexible network configuration models. Such features are defined across different standard or amendments, as summarized . Since the TSN family of standards gather many mechanisms which result in different capabilities, different standardization bodies are working together to TSN profiles for specific application areas. The goal is to ease the configuration of TSN network and provide a reference for the vendors by defining mandatory and optional TSN features. TSN profile standards include IEEE 802.1BA-2011 for AVB networks , IEEE 802.1CM-2018 TSN for fronthaul , and its amendment on synchronization enhancements IEEE 802.1CMde [15]. The ongoing standardization efforts for TSN profiles includes IEC/IEEE 60802 TSN profile for industrial automation, P802.1DG TSN profile for automotive in-vehicle Ethernet communications, P802.1DF TSN for aerospace onboard Ethernet communications, and P802.1DF TSN profile for service provider networks [4]. In the following subsections we overview the most relevant TSN standards classified according to the feature they provide**.**

A. TIME SYNCHRONIZATION

The IEEE 802.1AS, [16] standard defines the procedure to achieve a common sense of time shared among all networked devices including switches, bridges, and end stations in the TSN network. This shared sense of time is a fundamental premise not only for the correct functioning of other TSN mechanisms (e.g., TAS) but also for coordinated functioning of different end stations. The IEEE 802.1AS provides a generic precision time protocol (gPTP) profile for accurate time synchronization, using IEEE 1588v2 precision time protocol (PTP) . PTP uses the master-slave paradigm, where a device with the most accurate time source is selected as the grandmaster (GM). The GM's clock is then used to provide time reference to other devices in the network. PTP sends periodic sync and followup messages from the clock master (CM) egress ports to the clock slave (CS) ingress ports. This mechanism synchronizes the local clocks of the networked devices with each other. In order to ensure more stringent synchronization, the standard also introduces redundancy in GM devices and synchronization hierarchies by supporting multiple gPTP domains. The redundant domain is used when the performance of the first domain degrades.

B. TRAFFIC SHAPING AND SCHEDULING

A TSN stream is defined as a data flow with a given QoS requirements between two end stations. Based on the QoS, Each flow is uniquely identified by using the priority code point (PCP) field (traffic class) and the VLAN ID (VID) within the IEEE 802.1Q tag in the Ethernet header. IEEE 802.1Q defines up to eight traffic classes per Ethernet port, where a dedicated queue is associated with each traffic class. Each queue can then be controlled by different TSN mechanisms that results in different QoS provisioning, such as TAS (IEEE 802.1Qbv amendment) for time triggered communications, or credit based shaper (CBS) (IEEE 802.1Qav amendment) for priority-based transmissions. IEEE 802.1Qav ensures fair distribution of frames to queues by shaping the network traffic so as to control the latency and bandwidth of the reserved streams. It defines a transmission credit to each queue, whereby a queue is eligible for transmission if the transmission credit is non-negative and no frames from any other queue are being transmitted. The credit is increased for a non-empty queue if no frame is transmitted, and decreased when a frame is transmitted.

C. ULTRA RELIABILITY

Reliability is an important requirement for many TSN applications. Although, cyclic redundancy check can detect errors and notify the sender for re-transmission, it causes delays that are not tolerable by time critical flows. enabling fault tolerance in the network increases reliability and supports deterministic communication. TSN comprises some standards to enhance the reliability of the network and add fault tolerance. Those standards are described as follows. The IEEE 802.1CB standard for frame replication and elimination provides proactive redundancy in order to decrease packet loss probability. It identifies packets belonging to a stream, replicates them for transmission over possibly disjoint paths, and removes the duplicate frames at the destination . The IEEE 802.1CB is similar in properties and compatible to the well-known parallel redundancy protocol (PRP) and high-availability seamless redundancy (HSR) protocols, thus providing inherent interoperability.

D. RESOURCE MANAGEMENT

Resource management is a key aspect to achieve deterministic and reliable communication. It defines mechanisms and services to manage resources including bandwidth, scheduling patterns, and communication paths. The following standards in TSN contribute towards resource management. The IEEE 802.1Qat standard for stream reservation protocol (SRP) provides protocols to ensure resource availability along the entire path between the source and destination. It achieves this by allowing resource allocation and reservation at each switch, thus ensuring end-to-end latency and bandwidth guarantees.

E. NETWORK CONFIGURATION

A TSN network consists of a set of interconnected fullduplex (TSN) Ethernet switches (forming a multi-hop topology); and a set of (computational) TSN nodes (each connected to one or more TSN switches). The configuration of such network is a complex task and it depends on the TSN network architecture models. Three models currently exist: fully centralized, hybrid, and fully distributed, as defined in the 802.1Qcc amendment [58]. Therefore, the network configuration relates to the TSN configuration models and the network topology where it is applied to. For the fully centralized model, a centralized user configuration (CUC) entity is defined along with the centralized network configuration (CNC). The UNI is defined between the CNC and the CUC to exchange the information related to the user specific communication requirements.

IV. WIRELESS TSN

The ongoing work on wired TSN promises deterministic latency along with high reliability. However, wired networks lack flexibility given the high maintenance and installation costs of wired connections and minimal support for mobility. With the advancement of industrial technologies, a new vision (often termed as industrial internet of things (IIoT)) is emerging where all industrial assets are interconnected with each other including the cloud, the information systems, and the business processes. Wireless technologies are the key enablers to realize this vision for factories of the future. The benefits of adding wireless includes inherent support for mobility, possibility to monitor harsh environments, flexible and modular production systems that support mass customization, and ability to self-configure after failures

A. ENABLING WIRELESS TSN INTEGRATION

Deterministic latency and high reliability performance are the prerequisites of any communication technology in the IIoT. The deterministic latency and high-reliability are mostly fulfilled by wired fieldbuses, though wireless protocols struggle to fulfill them. The main challenge comes from the errorprone nature of the wireless channel and the fact that the wireless media is shared by all the devices. With the advancement of industrial technologies, a new vision (often termed as IIoT) is emerging where all industrial assets are interconnected with each other including the cloud, the information systems, and the business processes. Industrial assets include sensors, actuators, robots, machines, and control systems (see Section VII-A for a brief overview of IIoT applications). We focus on the challenges at MAC and PHY layers, given that industrial communication systems are typically focused on these layers along with the application layer . The components and functions of a fully centralized TSN network must include TSN enabled switches, end devices (EDs), TSN clock, CUC, and CNC. To support IIoT use cases for additional advantages of mobility and flexibility, extending TSN capabilities over a wireless network is essential.

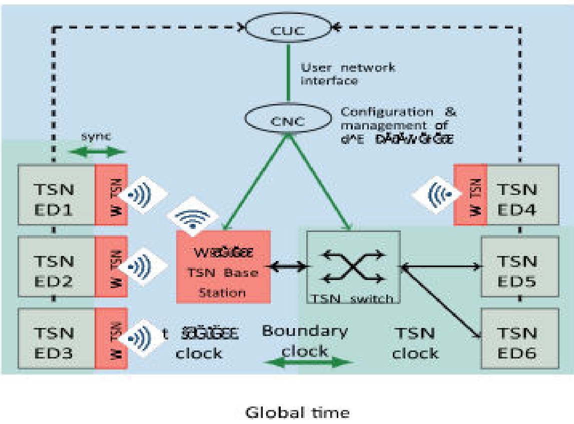

FIGURE 1: Simplified wireless TSN network fully centralized

On the PHY-layer, TSN capabilities can be extended over a wireless network through interfacing between the wired EDs and the wireless EDs. This can be established either through a wireless bridge such as the 5GS (5G core and BS), providing wireless interfaces such as connecting APs, or through a wired connection such as Ethernet to a WiFi BS. Here, we use the general term BS to address the media conversion from the wired to the wireless domain and vice versa. Two types of BSs can be identified, namely, a simple BS and a complex BS. Simple BSs are placed at the ED ends and allows allows interfacing between wired and wireless TSN EDs, e.g., ED1- ED4 to a wireless channel, as presented in Fig. 1. A complex BS translates the serial TSN Ethernet communication to the wireless domain. This BS has to act as a wireless bridge with the possibility to analyze or compile Ethernet data and respectively send/receive the data in defined time slots using the corresponding wireless channels. The mapping between Ethernet data and wireless channel time slots (irrespective of the technology) is to be configured as part of the link layer functions.

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The link layer allows to link packets of the Ethernet stream according to their identification to specific time slots in wireless channels. However, the forwarding of the traffic with low, deterministic latency, requires tight time synchronization between the domains. In Fig. 1, the wireless domain is depicted in blue and wired in green where time synchronization of the two domains can be performed using a boundary clock.

B. CHALLENGES TO SUPPORT WIRELESS TSN

To support wireless TSN, several research challenges can be foreseen, which are mostly related to the wireless medium. First, the wireless medium, specifically, under the unlicensed frequencies is contention based and poses the challenge of channel access due to the listen before talk procedure. However, guaranteed access to the wireless channel is essential to enable deterministic communications. The demanding question is to design mechanisms that enable guaranteed channel access in unlicensed frequency spectrum. A related issue of the wireless medium is the inherent interference from other channels. The interference and signal distortion issues pose challenges in achieving ultra-reliability. In the first place, interference from nearby wireless devices that communicates with the same protocol may be avoided by a good protocol design (e.g., using coordination between devices). Interference from wireless devices using other protocols are more complex and mechanisms to minimize interference are required. For instance, in the case of a factory, the mechanisms to minimize interference could be shielding the walls of the factory or implementing a strict access control of devices so no one transmits in the operation bands of the industrial devices. Also, the Wireless TSN can implement functionalities to detect interference and move to other bands, as is the case in cognitive radio approaches. Apart from the inherent problems of interference in unlicensed bands, common wireless propagation phenomena also poses a significant hurdle in the achievable reliability and latency. Therefore, the propagation phenomena in the target environments must be taken into account in the design and implementation of the protocol, and in the deployment of the wireless network infrastructure.

To enable TSN integration with wireless technologies, several challenges are to be addressed. These include enabling time synchronization, time-aware scheduling, providing the ultra-reliability targets required by the applications [12], [13], [17]. Moreover, exposing the wireless QoS capabilities from the wireless TSN to the wired TSN domain and its integration with the TSN configuration and management is another challenge. A crucial feature of TSN is to support vendor independent network configuration. These can be configured through protocols such as NETCONF to ensure that configuration of the TSN features is performed according to standard methods. However, in case of any changes such as installation of additional sensors, a manual re-configuration is required. Therefore, the challenge is the design of reconfigurable system that allows changes in the network yet enabling smooth network functioning. A re-configurable system, however, also requires defining interfacing and interaction between the sensors, the wired TSN domain and the wireless TSN domain. The configuration setting is also to be reflected at the wireless system in a dynamic manner for automatic deployment and configuration of an end-to-end hybrid wired-wireless TSN system. In the following sections, we detail how some of these challenges can be addressed by IEEE 802.11 and 5G.

V. ENHANCEMENTS TO SUPPORT TSN IN IEEE 802.11AX/BE - WI-FI 6/7

During the past few years, the IEEE 802.11 standardization groups have been working on the 802.11ax standard (WiFi 6) [9]. Efforts have not only been focused on providing higher throughput, but also on enhancing some other aspects such as latency, reliability, and flexibility. The most relevant features are the modification of the orthogonal frequency 802.11 FTM scheme AP (CM) STA (CS) t t 0 FTM req t1 FTM t 0 2 ACK t4 t 0 3 FTM(t1,t4) ACK FIGURE 2. Synchronization schemes considered in 802.11ax for wireless TSN operation. division multiplexing (OFDM) numerology, the introduction of orthogonal frequency division multiple access (OFDMA), and the definition of the TF and target wake time (TWT) mechanisms. The new 802.11ax mechanisms enable significant latency reduction and enhanced efficiency, though IEEE 802.11ax does not still reach the performance figures in some important TSN aspects, such as time-aware scheduling and ultra-reliability [13]. The new 802.11be standard (Wi-Fi 7) is under definition and its final specification will be released in two to three years . An expected novelty for 802.11be is the introduction of the low-latency operation mode . The low-latency mode may provide the QoS required by TSNcapable systems and so enabling wireless TSN [16]. Through this section, we first comprehensively analyze all the current existing mechanisms in 802.11ax and the new mechanisms that are yet to come in 802.11be that can be used to enable wireless TSN. Then, taking into account that the integration of wired TSN and 802.11 is yet to be defined, we propose a possible 802.11-based TSN architecture that includes the configuration of the 802.11 mechanisms to enable wireless TSN and the integration of such mechanisms with wired TSN.

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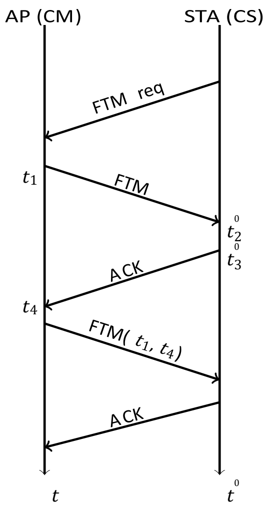

FIGURE 2. Synchronization schemes considered in 802.11ax for wireless TSN operation.

A. TIME SYNCHRONIZATION

The problem of time synchronization using 802.11 has been widely studied in the literature. Two elements are key to successfully enable time synchronization for wireless TSN: the technologies/protocols involved in the actual wireless time synchronization and its coexistence with other wireless TSN mechanisms (e.g., traffic shaping and scheduling).

1) Wireless time synchronization The attainable wireless time synchronization depends mainly on three variables: the messaging scheme of the synchronization protocol, the timestamping technique / available clock, either SW or hardware (HW) timestamps/clock, and the specific wireless conditions. The largest error source is the timestamping and clock, whereas the messaging scheme and the wireless channel phenomena are typically a source of small time synchronization error. Two main families of time synchronization messaging schemes exist: one way messaging based on the broadcasting of time frames (e.g., beacon frames) or two-way, when the slaves acknowledge the time frames. The latter is able to compensate the channel delay thanks to the two-way exchange, whereas the former cannot. In the particular case of 802.11, the timing measurements (TM) and fine timing measurements (FTM) define two nearly identical messaging schemes to enable precise time synchronization. Fig. 2 represents the FTM frame exchange, which is described as follows. First, an STA sends a FTM request message to start the synchronization procedure. The AP answers the request with a FTM frame. The STA receives the FTM and answers an 802.11 acknowledgment (ACK). During the frame exchange, a set of timestamps is collected, which represent the frames ingress and egress times. The frame exchange is repeated several times (depending on the FTM configuration) to take more timestamps. Finally, the timestamps are used by the STA to compute the synchronization error and frequency drift and compensate its internal clock time. The frame exchange is periodically performed to continuously correct small variations in the clock drift.

2) Coexistence of time synchronization and other traffic streams

Apart from the performance itself, the coexistence of the time synchronization with other traffic streams is also a relevant matter of study. It is extremely important that the timing messages do not impact the scheduling of the TSN flows. At the same time, the traffic from the TSN flows should not block the timing messages. The natural option would be using the 802.11 FTM. However, an unauthenticated and non-synchronized STA may cause interference to the wireless TSN traffic flows when it attempts to send FTM request frame to synchronize its timer to the network base time. A hybrid synchronization using the 802.11 beacon frames and the FTM scheme could be a suitable solution. In the first step, in an unsynchronized state, the STAs could perform a coarse-grain synchronization exploiting 802.11 beacons. In the second step, after the coarse synchronization, it could switch to the 802.11 FTM.

B. TRAFFIC SHAPING AND SCHEDULING

802.11 default medium access is contention-based where every node of the network can gain access to the wireless medium at any time. Such medium access is not deterministic and cannot virtually provide any level of QoS. Nonetheless, 802.11 includes other operation modes that enable traffic classification and contention-free based medium access. Regarding traffic classification, 802.11 includes a medium access scheme named enhanced distributed channel access (EDCA) [9], which includes four traffic classification profiles: video, voice, background tasks, and best-effort. Even though these traffic profiles are not aligned with the TSN needs, they may be redefined or extended for the TSN needs, given that, real applications may roughly require three traffic priorities (hard real-time, soft real-time, and best-effort). Besides, other mechanisms such as internet protocol (IP) classification [13] are also being considered to perform traffic classification in 802.11be. Nonetheless, TSN sub-standards are defined just for the second layer of the communication stack and thus the use of IP may constraint the design of custom stacks for specific applications

Concerning the time-aware operation and QoS, 802.11ax supports several methods to prevent undesired transmissions from the STAs connected to a wireless TSN-capable AP and to ensure almost deterministic transmissions. Nonetheless, it is worth mentioning that since 802.11 is based on the listenbefore-talk procedure, the transmissions will always present a jitter (even for free channel conditions).

VI. ENHANCEMENTS TO SUPPORT TSN IN 5G

The 3GPP standardization body is continuously working on the evolution of 5G cellular technology. The 3GPP Release15 focuses on enhanced mobile broadband (eMBB), while in Release-16 and forthcoming Release-17 URLLC gains importance. Besides URLLC, 5G offers network slicing and edge computing that may interest future industrial applications. Moreover, the 5G NR defines a flexible frame structure and mini-slot transmissions based on different numerologies to support low latency communication . The IIoT is a major vertical focus area for Release-16 with features including enhanced support for URLLC, time sensitive communication (TSC), non-public networks (NPN), high accuracy positioning, and NR on unlicensed bands . The 3GPP Release-16 extends support to TSN for applications that demand reliable and deterministic communications. The 5G-TSN integration is applicable to TSN fully centralized configuration model (IEEE 802.1Qcc) whereby the fully distributed and the hybrid (centralized network/distributed user) models are not supported . The 5GS integrates with TSN as a logical bridge where the 5G core and access network procedures remain hidden from the TSN network . The 5GS architecture as a TSN logical bridge is presented in Fig. 6. The 5G core consists of the control plane and the user plane. The control plane carries signaling and control traffic, whereas the user plane carries user traffic . The signaling and control traffic is referred to as the exchange of information that enables user equipment (UE) access to the network such as authentication, resource allocation, mobility, etc. The user traffic is the actual data that is to be exchanged in corresponding QoS flows. The control plane has functions such as the access and mobility management function (AMF), session management function (SMF), and policy control function (PCF), while the user plane function (UPF) falls under the user plane. The PCF provides policy rules to SMF that include QoS policy and charging control, network slicing, and roaming & mobility management. The SMF performs the session management functions such as allocation of IP addresses to UEs, signaling of QoS and policy information to RAN via the AMF, and selection & control of UPF for traffic routing.

The AF influences traffic routing in the user plane and interacts with the PCF for policy control. The 5GS virtual bridge comprises the user plane tunnel between the UE and UPF, the NW-TT side port to support connectivity to the TSN domain, and DS-TT side port associated to the protocol data unit (PDU) session that provides connectivity to the TSN network. Only a single PDU session per DS-TT port for a given UPF can be established. However, all PDU sessions that connect to the same TSN network through a particular UPF are grouped under one 5GS virtual bridge. Nevertheless, multiple 5GS virtual bridges can be established using different UPFs that may exist in a 5GS to support redundant traffic transmission . In the forthcoming Release-17 support for fully distributed TSN configuration and UE-UE TSN communication is under consideration . Another viewpoint of adding TSN functionalities in the 5GS instead of TSN-5G integration may also prevail in future [15]. In the following subsections we present the mapping of TSN standards as integration to 5GS for the centralized configuration model.

A. TIME SYNCHRONIZATION

Time synchronization being the fundamental prerequisite for TSN is supported by 5GS through establishing Ethernet type PDU sessions between the end stations and TSN switches . Irrespective of the TSN time synchronization, 5G entities such as UE, gNB, UPF, DS-TT, and NW-TT are all synchronized via the 5G internal synchronization process (see Fig. 6). Although 5G and TSN synchronization processes run in parallel, they are independent of each other. The 5G fronthaul synchronization between the radio resource head (RRH) (gNB) and the baseband unit (BBU) is serviced via enhanced common public radio interface (eCPRI) , while timing information to the UE is distributed by the gNB through multicast or unicast messages . gNB as a CM, synchronizes the UE and the UPF. The synchronization accuracy requirement of less than 1 µs between the gNB and the UE is specified . Specifically, gNB-UE synchronization accuracy between 470 ns and 540 ns is achievable with 15 kHz sub-carrier spacing (SCS). The synchronization accuracy can further be improved with wider SCS . In addition, some evaluations suggest that the synchronization accuracy requirement can be achieved without applying UE propagation delay compensation if the inter-site distance (ISD) is smaller than 200 m with dense cell, because the delay is in the range of tens of nanoseconds. Additional details on 5G synchronization process can be found in and are out of the scope of this paper.

B. TRAFFIC SHAPING AND SCHEDULING

The 5G capability of URLLC enables integration of TSN traffic shaping and scheduling. The URLLC service is provided through several components including integrated frame structure, flexible scheduling, efficient control and data resource sharing, and advanced channel coding schemes. URLLC is, however, possible due the development and implementation of 5G NR that supports sub-6 GHz and mmWave carrier frequency ranges. NR supports mini-slots comprising 2, 4, or 7 OFDM symbols whose transmission can start instantly with priority and preemption support. Such transmission capabilities facilitate URLLC and are beneficial for time-critical applications. In the DL, a URLLC packet can follow either an instant or a reservation-based scheduling scheme . Instant scheduling can interrupt an ongoing transmission via preemption indication sent by the gNB to the UE informing that the resources indicated contain URLLC data. In the reservation-based scheduling scheme, resources are reserved in advance for URLLC transmission TSN traffic arriving at the 5GS bridge through a corresponding PDU session is mapped with appropriate QoS flow configuration characteristics. The QoS flow between the UE and UPF can be characterized in terms of resource type, priority level, packet delay budget (PDB), packet error rate (PER), averaging window, and maximum data burst volume (MDBV). The resource types can be guaranteed bit rate (GBR), non-GBR, or delay critical GBR [11]. Averaging window represents the duration over which the guaranteed flow bit rate (GFBR) and maximum flow bit rate (MFBR) are calculated. GFBR is the guaranteed bit rate to be provided to a QoS flow while MFBR limits the highest expected bit rate for the QoS flow over an averaging window. Based on the QoS characteristics, 5G quality indicator (5QI) values have been standardized, however, this can also be pre-configured, or assigned dynamically.

VII. ADVANTAGES

• Provides low-latency and deterministic communication for real-time applications.
• Ensures precise time synchronization across wired and wireless networks.
• Enhances reliability for industrial automation and critical infrastructure.
• Supports seamless integration of TSN-enabled devices with 5G networks.
• Enables efficient network resource allocation and traffic prioritization.
• Facilitates network slicing to manage time-sensitive traffic separately.
• Improves scalability for large-scale industrial and smart city applications.
• Enhances quality of service by reducing jitter and packet loss. • Enables wireless flexibility while maintaining deterministic performance.
• Promotes innovation in automation, healthcare, and intelligent transportation.

VIII.APPLICATIONS

1.INDUSTRIAL AUTOMATION

A number of use cases for industrial automation can be identified where wireless TSN will make a significant impact. These may include closed-loop control, HMI and production IT, and functional safety to mention a few. The closed-loop control include very low latency, tight synchronization, and minimum jitter . The process monitoring use case employs multiple sensors to collect and analyze data. The data collected can be used for predictive maintenance, processes optimization, or condition monitoring .

2.AUTOMOTIVE

The number of sensors in a car are increasing exponentially given the new advanced driver assistance systems (ADAS) and autonomous driving (AD) functions along with stateof-the-art infotainment systems. Different types of sensors and actuators are used including environmental monitoring sensors, cameras, ultrasonic, light detection and rangings (LIDARs), and radio detection and rangings (RADARs). Sensor data, audio/video transmission, and control messages present different latency and reliability requirements to the communication network.

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A. RAILWAY INDUSTRY

The European railway industry has positioned to be a key player in the transport sector in the upcoming years. To this aim, the Shift2Rail Multi-Annual Action Plan has identified several challenges that need to be tackled. One of them is the evolution of the current wired train control and monitoring system (TCMS) to a wireless architecture . TCMS network operates in a two-level network architecture that comprises the train backbone, which connects different consists networks. The next-generation TCMS will apply wireless technologies at both backbone and consist levels, thus implementing wireless train backbone (WLTB) and wireless consist network (WLCN) solutions. These networks present diverse and stringent real-time requirements . TSN has been chosen as a perfect candidate for the wired domain network , whereas both 5G and 802.11 have been chosen as the convenient solutions for WLTB and WLCN respectively.

4. AUDIOVISUAL

Audiovisual use cases incorporate both visual and audio interactions to create a real-time virtual environment. It requires high data rates for video transmission, low latency, and accurate time synchronization to avoid jitter in the audio and video data. Several applications are under this use case. For instance cloud gaming is becoming popular and requires high traffic rate to ensure appropriate video resolution, low latency in the range of few ms and even lower jitter to ensure adequate user experience. In particular, 5G could be interesting to enable high-end graphics over hand-held devices with minimum consumption power. Other applications, such as augmented reality (AR) and virtual reality (VR), are also emerging audovisual trends. On the VR side, some VR glasses rely on external processing devices to compute the graphics.

5.AEROSPACE

Communication within an aircraft consists of different traffic classes from time-critical to best-effort traffic. Hence correct scheduling according to communication constraints is important. TSN has been envisioned as a cabin backbone bus for cabin communication in aircrafts' or in NASA Orion project for the multi-purpose crew vehicle. Moving to a wireless TSN can be desirable for the above use cases as it would not only reduce the weight of the vehicle by removing wires but also lower the maintenance and reconfiguration costs.

IX. CONCLUSION

In this paper we present the standardization activities and developments in 802.11 and 5G to enable wireless TSN. In particular, we focus on analyzing 1) the enabling mechanisms in both 802.11 and 5G for time synchronization, traffic shaping and scheduling, ultra-reliability, resource management, and flexible network configuration models and 2) the current state of the integration of both 802.11 and 5G with wired TSN. Additionally, we present wireless TSN use cases in different domains along with their QoS requirements in terms of latency, reliability and throughput.. Currently, wireless TSN is in its infancy, and there still are many open questions till we can reach open standardization. The 802.11 working group has been considering new mechanisms to enable wireless TSN like operation over 802.11.

Some existing mechanisms already enable few TSN features over 802.11ax (e.g., time synchronization) though several open questions are still to be solved for the next standard release. The probability of interfering transmissions is by far the most serious hurdle to achieve ultra-high reliability and guaranteed latency, especially for communications in unlicensed bands. However, even if 802.11be specification is able to solve these challenges, its adoption will strongly depend on the specific implementations of chip makers and in the integration model between 802.11 and wired TSN. Therefore, the most critical and often overlooked challenge is the definition of the mechanisms to enable the seamless integration of wired TSN and 802.11be. Regarding 5G, the open questions among others include the integration of TSN configuration and management with 5G management and orchestration capabilities, TSN domain synchronization through 5G internal clock, and the integration of TSN distributed and hybrid models with 5G as the standards become available.

Moreover, apart from of 5G TSN integration, another research direction could be provisioning of deterministic communications within 5G which would require modifications in the core and RAN entities of the 5GS. Nevertheless, the developments of wireless TSN are gaining interest and momentum among researchers, the question is when will it be realized for industrial use cases. Certainly, newer challenges will then emerge.

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