Avnu Alliance® White Paper

Wireless TSN – Definitions, Use Cases & Standards Roadmap

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Executive Summary

Recent advances in 5G and IEEE 802.11 wireless connectivity technologies in providing low latency and high reliability have generated significant interest in extending TSN capabilities over wireless. Wireless communication systems are beneficial for many obvious reasons, including enabling flexibility and reducing wiring costs as well as enabling mobility. However, given the stochastic nature of wireless communications, enabling TSN capabilities that are interoperable and compatible with existing wired TSN standards is challenging. This white paper introduces the basic terminology, use cases, and standards for extending TSN capabilities over wireless networks.

About Avnu Alliance

The Avnu Alliance is a community creating an interoperable ecosystem of low-latency, time-synchronized, highly reliable networked devices using open standards. Avnu creates comprehensive certification programs to ensure interoperability of networked devices. The foundational technology enables deterministic synchronized networking based on IEEE Audio Video Bridging (AVB) / Time Sensitive Networking (TSN) base standards. The Alliance, in conjunction with other complimentary standards bodies and alliances, develops complete solutions in professional AV, automotive, industrial control and consumer segments.

Introduction

The main purpose of this document is to introduce the basic terminology, use cases, and standards for extending TSN capabilities over wireless networks. As described in a previous Avnu white paper [1], wireless communication systems are beneficial for many obvious reasons, including enabling flexibility and reducing wiring costs as well as enabling mobility. However, given the stochastic nature of wireless communications, enabling TSN capabilities that are interoperable and compatible with existing wired TSN standards is challenging. Recent advances in 5G and IEEE 802.11 wireless connectivity technologies in providing low latency and high reliability have generated significant interest in extending TSN capabilities over wireless.

The motivation for this white paper is to generate awareness and start defining work required in Avnu to enable wireless TSN extensions in alignment with wired TSN systems and operation models. The expectation is that this document will serve as an introduction to the applications, meeting wireless technologies, standards and open technical and market adoption challenges in extending TSN to wireless applications. This document will also serve as input to potential future Avnu work enabling evaluation, testing and certification of products that enable TSN extensions from wired to wireless domains.

The remainder of the document is organized as follows:

Section 1 – Defining Wireless TSN: Provides definitions and the terminology used to describe extensions of TSN capabilities to wireless.

Section 2 – Use-Cases for Industrial, Pro AV, and others: Describes examples of use cases that can directly benefit from wireless and summarizes their main requirements.

Section 3 – Wireless TSN technology deep-dive: Focuses on the two main wireless technologies, IEEE 802.11/Wi-Fi and 5G, their relevant capabilities and roadmap of features to enable TSN extensions over wireless.

Section 4 – Conclusion and considerations for the future: Wireless-specific considerations and gaps in current TSN standards and operation models are discussed as well as areas for enhancements.

Section 1: Defining Wireless TSN

The IEEE 802.1 Time-Sensitive Networking (TSN) task group develops standards for achieving accurate time distribution and timeliness with high reliability for time-sensitive streams, even in the presence of background traffic. A more detailed description of TSN standards can be found in [2]. Although a few of the IEEE 802.1 standards exist for wireless, most

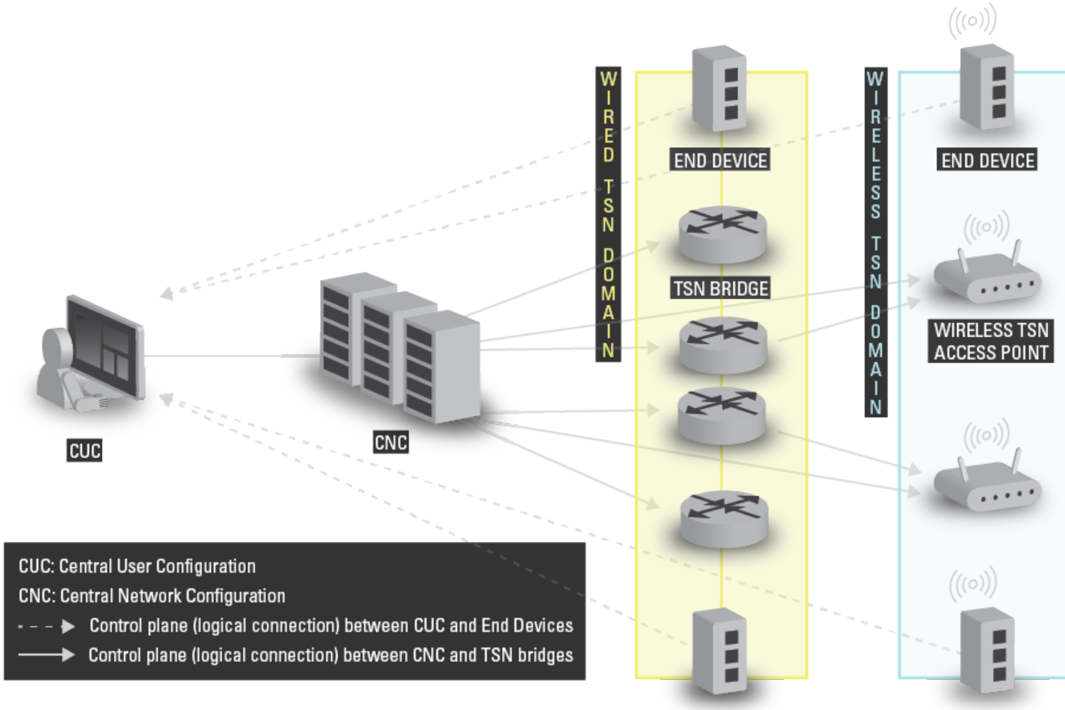

Figure 1: Example of a Wireless TSN domain in centralized TSN operation model.

implementations, market-specific profiling, interoperability testing and certification efforts -- which are enabled by Avnu -- have focused on Ethernet as the main transport media. As TSN-enabled devices and networks start to be deployed, enabling extensions of similar capabilities over wireless is a natural next step.

It is envisioned that TSN-enabled networks will extend from wired (Ethernet) to wireless domains. In the context of this document, the term "**Wireless TSN**" is used to refer to a wireless network that extends IEEE 802.1 TSN capabilities over wireless media. **Figure 1** illustrates the concept of a Wireless TSN domain extending a wired TSN-enabled network. The Wireless TSN links can enable wireless access to end devices and connect wired TSN networks, as illustrated in Figure 1. The architecture in the figure is an example of a centralized TSN-enabled network deployment, as described in the Avnu Best Practices for TSN-enabled industrial systems [3]. In the Professional Audio and Video (Pro AV) market, a distributed network architecture is used in which TSN capabilities are configured and managed using distributed protocols. In the distributed Pro AV architecture, the CNC is not present, and the CUC is replaced by the AVDECC Controller.

The 802.1 TSN family of standards can be grouped into four main areas, most of them directly related a performance vector:

Time Synchronization: the 802.1AS standard defines a profile of the IEEE 1588 Precision Time Protocol (PTP) to distribute time across the network. Time synchronization between hosts and network devices can be used by the application and by other TSN capabilities (e.g. Time-Aware 802.1Qbv Scheduling).

Bounded Latency: Providing bounded latency is one of the main features of a TSN-enabled network. Several 802.1 standards have been defined to enable queuing management, gating and traffic shaping (802.1Qav, 802.1Qbv) to ensure time-critical packets receive priority as they are being forwarded through the network. Frame preemption, defined by 802.1Qbu and 802.3br for Ethernet, provide low bounded latency while increasing the efficiency of the network.

Reliability: The bounded latency performance must be delivered with very high reliability. The TSN-enabled network must ensure every packet is delivered within a given latency bound with *no* packet losses and delays due to congestion. In addition, to account for device failure and/or media errors, packet replication and elimination capabilities were also defined (802.1CB) to enable redundant links and paths.

Resource Management: Configuring the TSN capabilities and managing the network and device resources is fundamental to assure end-to-end performance for time-critical flow across the network in presence of other traffic flow. By managing the resources in each node, the availability of buffers and timing of transmission can be guaranteed and the TSN latency and reliability goals can be assured. Therefore, several network management models, and protocols have also been defined (e.g. 802.1Qcc, 802.1Qca, 802.1Qat, ...). The main 802.1 TSN standards are listed in *Table I*.

The remainder of this document focuses on the extension of the main 802.1 TSN standards to wireless technologies. Not every wireless technology is capable of supporting TSN features. Therefore, given the recent advances and features available in IEEE 802.11/Wi-Fi and 5G standards, only these two technologies are considered as candidates to enable TSN-grade performance in this document.

Table I: IEEE 802.1 TSN Standards

IEEE Standard	Capability
1588, 802.1AS	Time synchronization
802.1Qca*	Path control and reservation
802.1Qav†	Credit-based traffic shaping
802.1Qbv*	Time-aware scheduling
802.1Qbu* and 802.3br	Frame preemption
802.1Qcc	Configuration models
802.1Qci*	Filtering and policing
802.1CB	Redundancy (frame replication and elimination)
802.1Qat*	Stream Reservation Protocol (distributed resource reservation)

Section 2 – Use-Cases for Industrial, Pro AV, and others

This section describes a few examples of applications that can directly benefit from TSN capabilities over wireless due to higher flexibility/reconfigurability, mobility and reduced maintenance costs. The use cases described in this section (Table 2) do not constitute a comprehensive list; rather they represent only a few examples relevant to Avnu activities and markets. Detailed descriptions of wireless use cases and requirements have been published by several industry organizations [5] and standards groups [6][7][8].

* Incorporated into IEEE 802.1Q-2018

† Incorporated into IEEE 802.1Q-2011

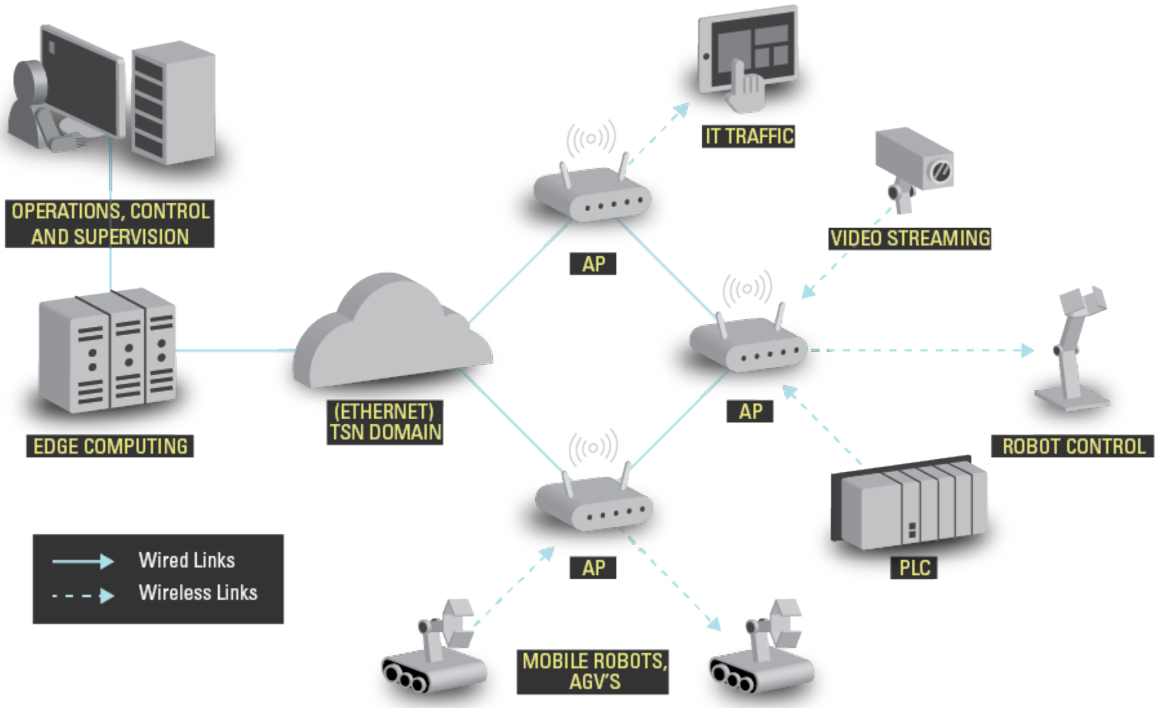

Figure 2: Wireless Use Cases in Industrial

Industrial Use Cases

The industrial segment has the most diverse set of use cases and requirements for wireless TSN. This segment has received significant interest and has motivated the development of the 5G Ultra-Reliable Low Latency Communications (URLLC) mode. Several industrial use cases have been captured in detail by 3GPP [6], 5G ACIA [5], and IEEE 802.11 [7] standard groups. Closed loop control is one of the most widely applicable use cases given its generic control loop model (input + compute + actuation), but specific latency and reliability requirements varies significantly depending on the application. Mobile robots are also an important use case as wireless is fundamental for mobility and flexibility and reconfigurability of tasks and routes. Mobile robots' latency and reliability requirements are compatible with capabilities of the latest wireless technologies. A few industrial use cases are illustrated in Figure 2.

Use cases related to control of Power Grid components have also been described in the IETF DetNet group [8]. One unique aspect to be considered in some electrical power grid systems is the required coverage area, which may vary from local (e.g. substation) to wide areas (distribution and transmission). Industrial control systems require the highest level of determinism and reliability and rely exclusively on IEEE 802.1Qbv for scheduling.

Pro AV Use Cases

Professional Audio and Video (Pro AV) use cases can also benefit from wireless technologies. In many Pro AV scenarios, cabling is complex and costly. On a typical tour, several kilometers of Ethernet cables are needed and are transported from venue to venue for a total of 60-100 shows. Most issues arise from defective cable connections, which are hard to identify. Replacing cables with wireless connection can significantly reduce the overall cost of deployment and operation of Pro AV systems.

Figure 3 illustrates the main components in a Pro AV system for a live performance scenario. Depending on the Pro AV application, a combination of wired and wireless networks may be used. Currently, UHF bands are used in professional wireless audio links with highly specialized RF solutions. However, as dedicated spectrum resources become scarce, there is significant interest in leveraging standards-based wireless connectivity technologies, especially solutions such as 5G URLLC given the promised latency and reliability performance.

Low Latency Interaction Use Cases

Emerging real-time applications that may also benefit from wireless TSN capabilities are gaming and augmented/virtual reality. applications also share some of the same requirements for bounded latency and low jitter.

Potential future use cases for wireless

Other use cases that require TSN-enabled networks, such as automotive and transportation applications, may also benefit from wireless. For instance, the wiring harness within vehicles, airplanes, and trains add significant production costs. If wireless technologies can provide the required time-sensitive media performance, it would bring value to such systems. However, due to stringent latency, safety requirements and regulations, use cases that have safety critical requirements are beyond the scope of this document and the current wireless standards in 802.11 and 5G. Use cases that require under 100 microsecond level cycle times are also considered

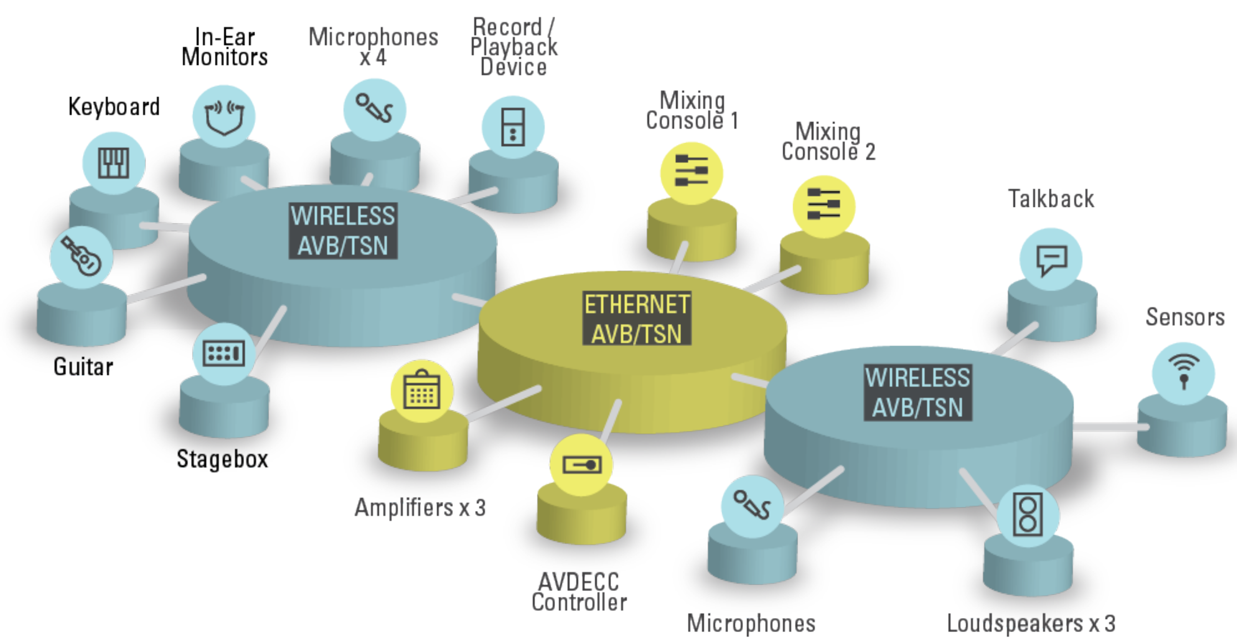

Figure 3:Example ProAV scenario for live performance.

These applications were described in detail in the IEEE 802.11 Real Time Applications (RTA) report [7]. High latency and jitter cause lag, which significantly degrades use experience. AR/VR out of scope for wireless. Such use cases may be considered in the future as wireless technologies evolve.

Table 2: Example Use Cases

Use case	Description	Benefit of wireless	Main KPIs
Closed Loop Control	Synchronous communications between sensors, PLCs (Programmable Logic Controllers) and actuators. Used in various industrial applications.	Flexibility of deployment, reconfigurability, mobility, maintenance cost reduction	IEEE 1588 synchronization Typical packet size: small (20 -50 Bytes) Bounded latency: application dependent (1 – 10 ms) Reliability: 99.9 to 99.9999%
Power Grid	Communication links used to selectively isolate faults on high voltage lines, transformers, reactors and other important electrical equipment.	Wire replacement, maintenance cost reduction	IEEE 1588 synchronization Typical packet size: small Bounded latency: 4 – 8 ms (for 60Hz lines) for the most critical messages (IEC 61850) Reliability: 99 to 99.9%
Mobile Robots	Communication between mobile robots, automated guided vehicles (AGV), and guidance control including process data, video/image, and emergency stop.	Mobility and reconfigurability	Typical packet size: 15 Bytes to 150Kbytes Bounded latency: 10 – 100 ms Reliability: 99 to 99.9%
Pro AV	Conference rooms, live performances (medium and large venues).	Cable replacement, maintenance cost reduction and improved fault-tolerance	IEEE 1588/802.1AS synchronization Packet size range: 68 to 1522 Bytes Data rate: 6.144Mbps per audio channel @ 192KHz Bounded latency: 0.25 – 2 ms Reliability: 99.99% Potentially hundreds of end points in the same network

Section 3 – Wireless TSN technology deep-dive

Given the benefits and advances in wireless connectivity technologies, it is a natural step to consider the extension of TSN capabilities to wireless media. As illustrated in **Figure 1**, it is envisioned that the transition to wireless will be gradual. Initially, a wired TSN-enabled network will be extended to the wireless domain in order to support the use-cases where wireless provides clear benefits.

In order to leverage the IEEE 802.1 TSN standards and ecosystem developed around them, it is important to enable seamless operation and interoperability from wired to wireless TSN domains. This section discusses some of the challenges in mapping TSN capabilities to wireless as well as the progress in wireless standards to support and integrate with TSN standards.

Mapping TSN capabilities to wireless

IEEE 802.1 TSN standards are defined to operate over IEEE 802 LAN (MAC/PHY) transport. Ethernet (802.3) has been the main LAN transport option assumed in most of the 802.1 TSN standards. The unique characteristics of wireless media and communication protocols impose several challenges to achieving TSN-grade performance. A detailed discussion on wireless TSN challenges can be found in [9]. The fundamental differences between wireless and wired (Ethernet) communications are:

1) The variable capacity of wireless links, which is a function of the environment and communication protocol choices;

2) The Packet Error Rate (PER) is typically higher in wireless due to the stochastic nature of the channel and interference.

TSN capabilities such as bandwidth reservation and scheduling are very effective in providing low latency/jitter over Ethernet. When applied to wireless media, such capabilities need to consider the wireless link characteristics (e.g. achievable data rates and PER), which may vary over time.

Therefore, it is expected that some of the TSN standards need to be aware of the basic characteristics of the underlying communication links (wired or wireless).

The broadcast nature of the wireless medium is another important aspect to be considered. On one hand, it may open up the possibility to reach more devices with a single transmission. On the other hand, it is more susceptible to interference. Therefore, coordinated medium access is very important as well as resilience to interference.

Although most of the TSN standards and solutions developed so far are based on Ethernet, some of the fundamental TSN capabilities, such as 802.1AS-based time distribution, have already been extended to operate over 802.11 and integration with 5G standards is also being developed. The remainder of this section provides an overview of the existing 802.1 TSN standards and capabilities that can operate over wireless (802.11 and 5G) and ongoing efforts in expanding the wireless TSN capabilities.

IEEE 802.11/Wi-Fi Capabilities and TSN support

Given that 802.11 is one of the 802 LAN transport options, the extension of 802.1 TSN protocols over 802.11 is by default well-aligned with the overall TSN reference architecture [9]. Nevertheless, extensions of the 802.1 TSN protocols need support of the 802.11 MAC/PHY to properly operate. This section describes some of the standards that have already been developed for extending TSN over 802.11 and some of the recent advances (e.g. 802.11ax) and ongoing efforts (e.g. 802.11be) to further extend TSN capabilities available over 802.11.

Time Synchronization (802.1AS) over 802.11

Time synchronization is a fundamental TSN capability, which is used by TSN-enabled applications and to enable other TSN capabilities (e.g. Time-Aware scheduling). The IEEE 802.1AS standard defines a profile of IEEE 1588 for 802.3 and 802.11 networks. 802.1AS used the 1588 as the basis to define a generalized PTP (gPTP) and it also defined select configuration options available from 1588. The extensions to distribute time over 802.11 are enabled by the Timing Measurement (TM) and Fine Timing Measurement (FTM) capabilities included in the IEEE 802.11-2016 standard. Figure 4 illustrates the distribution of a single reference time between wired (Ethernet) and wireless (802.11) TSN enabled by the 802.1AS extensions over 802.11 as defined in the 802.11-2012 specification.

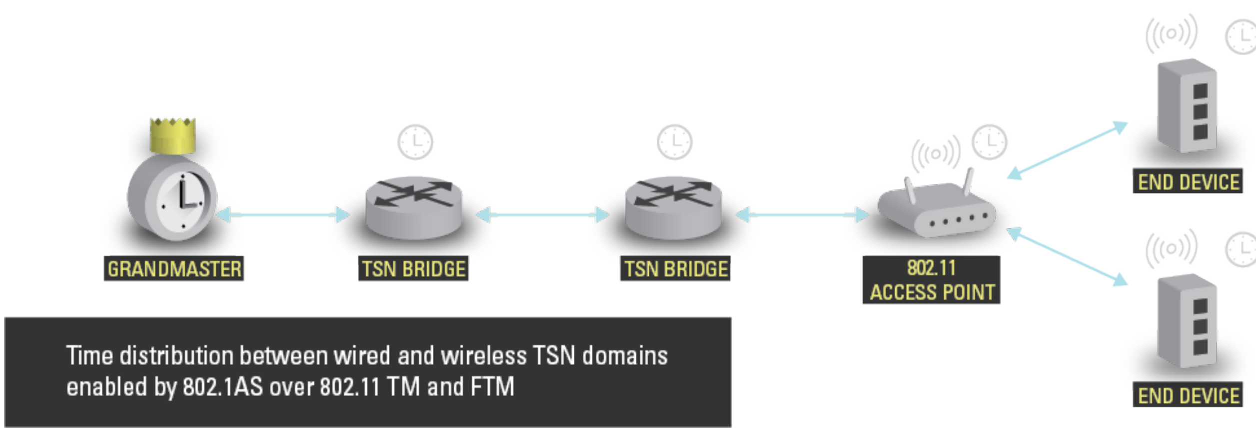

Figure 4: 802.1AS over 802.11 – TM frame exchange.

Traffic classification, shaping and scheduling over 802.11

In addition to time synchronization, another fundamental TSN capability is the ability to identify and differentiate time-sensitive traffic streams. IEEE 802.1Q-2014 defines the mechanisms to classify time-sensitive streams and differentiate them from other traffic across the TSN-enabled nodes and end stations. The 802.1Q traffic classification is based on the concept of VLAN tag. Traffic specification and classification mechanisms defined in the IEEE 802.11-2016 specification (TSPEC and TCLAS) support VLAN tag traffic stream differentiation as defined in the 802.1Q, therefore enabling seamless traffic classification mapping from wired to wireless domains.

Once time-sensitive traffic is identified, delivering the required bandwidth and latency across the network is the next challenge. Several traffic shaping mechanisms have been defined by the 802.1 TSN working group for meeting bandwidth and latency requirements. The credit-based traffic shaping (802.1Qav), originally defined for audio/video systems, and time-aware traffic scheduling (802.1Qbv) are the main options used in current (wired) TSN-enabled networks.

Given that traffic streams can be uniquely identified from Ethernet to Wi-Fi domains, it is possible to apply traffic shaping mechanisms to 802.11 networks if such mechanisms are configured appropriately for operation on top of the 802.11 MAC/PHY.

For instance, the concept of 802.1Qbv time-aware scheduling can be applied over the 802.11 MAC to prioritize traffic and avoid congestion delays. A time-aware schedule must consider the feasible data rates that can be achieved across each wireless link as well as overhead due to medium access procedures. Therefore, the minimal latency bounds as well as number of traffic streams that can be supported over an 802.11 TSN link will differ from a wired (Ethernet) TSN link. A discussion on time-aware scheduling over 802.11 can be found in [7].

One of the main challenges in mapping traffic shaping mechanisms to 802.11 is the random delay introduced by the traditional medium access procedure, CSMA/CA (Carrier Sense Multiple Access Collision Avoidance), used in previous 802.11 standards. The scheduling capabilities introduced in the IEEE 802.11ax specification (Wi-Fi 6) enables the AP to trigger (schedule) communications for the 802.11 devices in the network. When combined with OFDMA (Orthogonal Frequency Division Multiple Access) and MU-MIMO (Multi-user Multiple Input Multiple Output) capabilities, the trigger-based operation allows scheduling of simultaneous transmissions from multiple devices more efficiently. This new capability can eliminate latency issues caused by competing devices trying to access the medium, therefore enabling a scheduled operation with low latency bounds and high reliability.

The credit-based (802.1Qav) traffic shaping mechanism may also be extended to 802.11TSN standards extended over 802.11. Integration of credit-based traffic shaping with 802.11ax scheduling would require periodic transmission opportunities to achieve a given bandwidth defined by the 802.1Qav mechanism.

Figure 5 shows the basic 802.11ax Trigger-based scheduling sequence. The number of users that can be supported in a single frame transmission varies with the channel bandwidth used (Wi-Fi can operate with 20, 40, 80, 160 MHz, and 320 MHz support will be enabled the next generation 802.11be specification). The lowest latency achievable also depends on the modulation and coding scheme (MCS) selected. For a simple 20 MHz operation, up to 9 users can transmit simultaneously and the whole exchange can take approximately 700 microsec for a 100Bytes data packet. Lower latencies and/or higher capacity can be achieved with wider channel bandwidths.

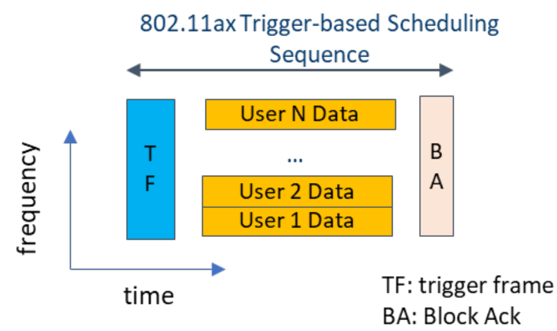

Figure 5: 802.11ax Trigger-based scheduling

Given the new scheduling capabilities in 802.11ax, it is feasible to provide latency bounds with high reliability with 802.11ax in a managed network environment. As described in [10], 1 msec latency bound with 99.999% reliability can be achieved with the proper configuration and latency-optimized scheduling capability.

In addition to scheduling capabilities, 802.11ax also includes support for operation at the new 6GHz band, which is expected to be opened for unlicensed use by the Federal Communications Commission (FCC) in the U.S. and other organizations around the world. The 6GHz operation is a key capability as it adds almost 1GHz of new spectrum, which will not be subject to interference from legacy 2.4GHz and 5GHz devices.

TSN support and integration in next-generation 802.11be

The next major Wi-Fi release after 802.11ax is already being defined by the 802.11be Task Group. Addressing worst-case latency and jitter requirements, as well as enabling better integration with 802.1 TSN standards, is part of the scope of the 802.11be project.

The 802.11be specification is expected to be completed around 2023, and the main new features that can be leveraged to achieve TSN performance goals are: wider bandwidth (320 MHz), multi-link/channel operation, multi-AP coordination, and priority access for time-sensitive streams. Multi-link/channel operation can enable isolation of time-sensitive traffic from other network traffic, helping reduce congestion. Multi-AP capabilities can be used to improve reliability, for instance, by leveraging spatial diversity gains to enable multiple APs to improve the reliability of the links.

TSN capabilities integration with 5G

The 3GPP Rel-16 [11] started to introduce TSN support over 5G and more work is expected to continue in the 3GPP Rel.17 specification. Different from 802.11, the 5G system is not a native 802 LAN technology, and as such cannot be directly integrated with Ethernet TSN standards at Layer 2. Therefore, the 3GPP approach to integration is an over-the-top one where TSN-related functionality is confined to TSN Translator (TT) functions at the 5G System (5GS) ingress and egress points. This approach has minimal impact on the RAN specification. The 3GPP Rel-16 centralized TSN integration architecture is illustrated in **Figure 6**. As can be seen, the TT functions at the device and core network (CN) sides provide gateway capabilities for TSN features across the 5GS.

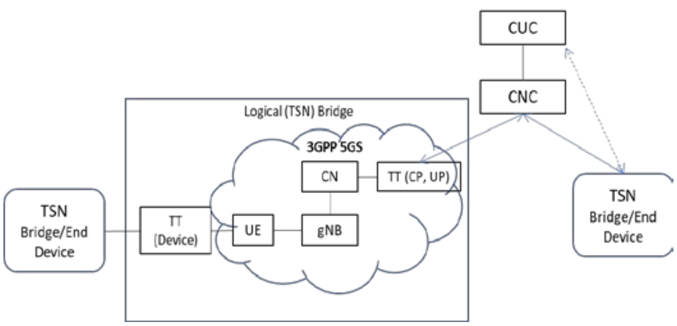

Figure 6: 3GPP Rel-16 5GS-TSN integration architecture

Time synchronization across a 5GS

The 3GPP Rel-16 defined the capability to distribute time from a Grand Master in the TSN domain across the 5GS to a TSN device connected to the 5G UE [12]. The TSN time domain information is distributed between the TT functions in the network and device sides using the 802.1AS standard protocol. The 5GS is not synchronized with the external TSN domain, but it can keep the internal network elements synchronized with its own 5G clock so that the 802.1AS messages are timestamped correctly at the TT functions and any 5G specific time corrections are applied. The 3GPP Rel-16 architecture for integration of TSN time synchronization [12] is shown in **Figure 7**. Future work in 3GPP Rel-17 is expected to include support for the case where the TSN Grand Master resides on the side of the 5G device (UE).

URLLC

An important 5G capability to enable TSN-grade performance is the Ultra-Reliable Low Latency Communications (URLLC) mode, which was defined in 3GPP Rel-15. Together with the flexible 5G frame structure concept, the URLLC mode enables low latency (e.g. 1msec) with high reliability for short packets, as discussed in [9]. In addition, QoS enhancements for multiple simultaneous active configured grants and semi-persistent scheduling have also been defined.

5G-ACIA

An industry group has been formed, the 5G-ACIA (Alliance for Connected Industries and Automation), to help coordinate the 3GPP standards development and industry adoption of 5G technologies in industrial markets. 5G-ACIA is also expected to help in the evaluation of 5G technologies and exploration of spectrum needs operator models for industrial 5G networks.

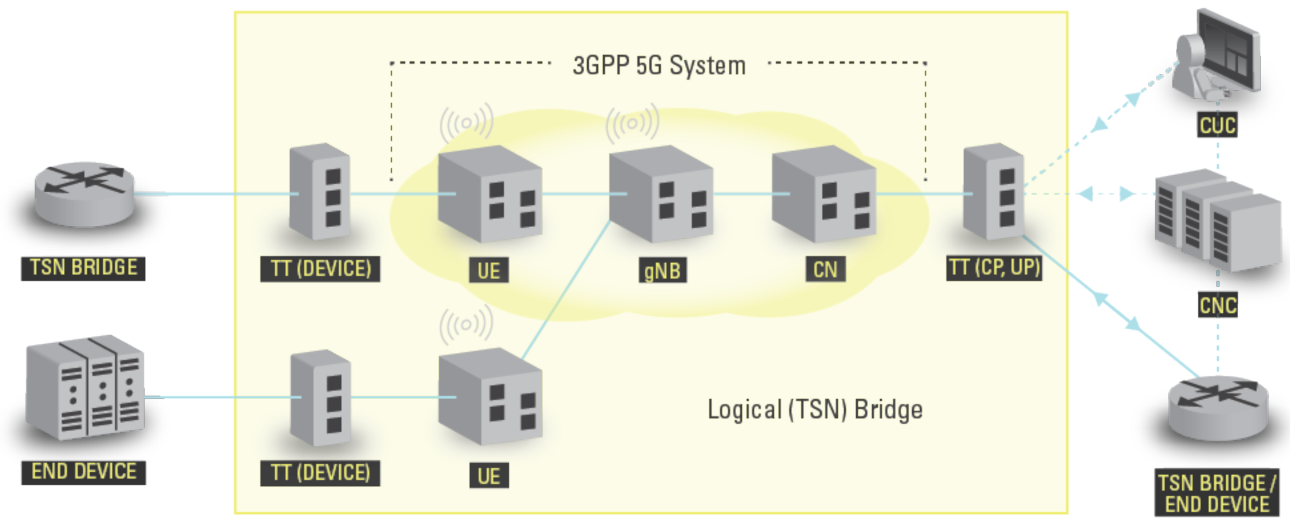

Figure 7: 5G architecture for TSN time synchronization integration

Section 4 – Conclusion and considerations for the future

Most of the 802.1 TSN standards are designed with the assumption of operation over wired (Ethernet) links, which have constant capacity, high speed and very low packet error rates. As TSN capabilities are extended over wireless, some assumptions may have to be re-considered. For instance, the assumption that the link speed is constant may not apply to wireless. Also, the broadcast nature of the wireless medium imposes new medium access and interference challenges. This section discusses some of the potential standard gaps and areas for further work to integrate wireless and wired TSN standards.

Wired-Wireless TSN integration model and abstraction interface

As multiple wireless standards develop TSN-enabling capabilities (e.g. IEEE 802.11 and 3GPP), it is expected that future TSN domains will be extended with both 802.11 and 3GPP-based wireless solutions. In order to leverage existing TSN standards and ecosystem, it is important to define a common model to integrate wireless technologies with a TSN domain. A new abstraction interface for wireless TSN should define clear service requirements and capabilities expected from wireless standards, such as IEEE 802.11 and 5G.

Wireless TSN configuration and management

Configuration and management of TSN features need to consider the capabilities of the underlying communication links, especially in the case of wireless, as such capabilities can change over time. For instance, the CNC task to define and configure a time-aware schedule for a set of time-sensitive streams across the network assumes a constant data rate for each Ethernet link in order to compute the proper gate operation schedule across the bridges. As wireless links are introduced, the CNC needs to consider the possibility of dynamic changes in link speed/bandwidth due to external conditions (e.g. wireless channel dynamics, interference, etc.). There is a need to dynamically manage time-aware scheduling involving wireless links.

Scheduling also happens within the wireless network (e.g. Wi-Fi AP and 5G gNB) for radio level decisions (e.g. bandwidth and MCS assignment) that will ultimately determine the latency and reliability performance. How such wireless scheduling will interface and coordinate with the overall TSN network scheduling is one of the areas that still need further work.

Availability, Security, and Fault-tolerance

Interference is typically the number one concern when it comes to wireless TSN extensions. The susceptibility to malicious jamming is often raised as a concern as well. Although the scale of the threat needs to be considered in each specific wireless deployment and application, it is important to enable tools to mitigate the potential impact of interference (malicious or not) in a wireless TSN domain. Because TSN is based on Ethernet and wireless standards (IEEE 802.11/Wi-Fi and 5G), networks can take advantage of security best-practices and standards that have been developed for Ethernet, 802.11 and 3GPP systems. An additional layer of security for TSN can also be added with precise timing mechanisms that facilitate early detection of a network breach as defined in the IEEE 802.1Qci specification. The 802.1Qci capability identifies the time-sensitive streams and uses timing and schedule information to accept or discard packets. The right packet must arrive in the right time window on the right port to be accepted. This capability also needs to be extended to wireless networks.

Redundancy has been a part of wireless standards (e.g. through coding schemes) to account for channel errors. But additional redundancy mechanisms that explore frequency/space diversity (e.g. multiple channels and antennas) may need to be considered in order to achieve fault-tolerance against interference and cybersecurity attacks. Proactive multi-link and channel redundancy mechanisms need to be tightly coordinated with bandwidth reservation and time-aware scheduling mechanisms to ensure latency bounds.

Mobility and roaming challenges

Mobility is a unique benefit of wireless connectivity. It enables flexibility of deployment and easy reconfiguration of devices and applications. However, mobility adds new challenges as devices change their attachment point to the network (Wi-Fi Access Point or 5G gNsB). Current roaming procedures in both cellular and Wi-Fi networks try to minimize connectivity disruptions, but they do not yet consider stringent latency and high reliability requirements in TSN domains. Providing TSN-grade latency and packet loss performance during roaming will be an important feature for future wireless connectivity standards.

Initial wireless TSN deployments are expected to be instituted within constrained areas, such as a factory floor, warehouse or enterprise. Therefore, the practical mobility and speed requirements will likely encompass indoor or campus-like outdoor use cases. Given the current and upcoming wireless capabilities in both Wi-Fi and 5G, use cases that require high speed mobility across wide areas are not yet considered practical for wireless TSN-grade performance.

Next steps towards wireless TSN

This section proposes specific next steps to address gaps in standards and technology areas in order to enable adoption of wireless TSN in the market.

- **Further study of scheduling capabilities and performance in wireless networks (802.11ax/Wi-Fi 6 and 5G)**: It is important for the TSN community to gain a deeper understanding on how wireless networks can schedule time-sensitive traffic. This work will require contributions from experts on wireless standards and it can result in documentation of the main capabilities, configuration parameters and interfaces to wireless networks that can impact latency bounded and reliable data delivery. It is also important to understand the achievable performance bounds and tradeoffs that need to be considered in wireless. This work can be performed as a follow up to this white paper within Avnu's Wireless TSN study group and can be published as a technical report.

- **Abstraction Interface for wireless TSN**: New abstractions and interfaces between existing TSN functions (e.g. scheduling implemented in the CNC, network management and configuration) and wireless networks (e.g. 802.11 and 5G) may need to be defined. Clear inputs,

outputs, and tasks and responsibilities are needed to ensure predictable and reliable time-aware delivery of scheduled traffic across wired and wireless domains enabled by different wireless technologies. A common interface to interact with wireless domains abstracting the underlaying wireless connectivity technology will facilitate the deployment and extension of TSN networks over wireless. The work may also include defining new wireless-specific parameters (e.g. as addition to existing 802.1Qbv YANG model) and it could be done in collaboration between the Avnu Alliance and IEEE 802.1 groups.
This work could also influence wireless standard organizations, such as IEEE 802.11 and 3GPP.

- **Enhancements for discovery and configuration of wireless TSN links**: As discussed previously, the overall TSN configuration and management entities must be aware of wireless TSN links as their wireless-specific characteristics. Extensions to existing link layer discovery (e.g. LLDP) and configuration protocols for wireless TSN may need to be considered to ensure the TSN management is wireless-aware. The initial step in this area is to identify gaps in existing standards, and it could be taken within Avnu. This work may also generate input to potential activities in other organizations, such as the IEEE 802.1, 802.11 working groups, and 3GPP.

- **Wireless TSN test plan**: The process of adopting and deploying wireless TSN capabilities within a TSN domain is expected to be gradual. It is very important to understand the performance and unique management aspects of each wireless TSN capability, and how they interact as part of the overall TSN system. Therefore, a gradual plan to test existing TSN capabilities extended to wireless is needed with clear test cases, assumptions and deployment scenarios. Time synchronization and traffic shaping capabilities (e.g. 802.1Qbv, Qav) could be tested in a first step, followed by capabilities that enable reliability and increased efficiency. Test cases could be developed within Avnu and in collaboration with other wireless technology organizations.

Conclusion

This white paper provided an initial overview of the use cases that can benefit from TSN extensions to wireless. The paper also introduced the basic architecture to enable integration of wired and wireless TSN domains. Wireless can enable flexibility of deployment, re-configuration and reduced costs in several industrial and ProAV use cases. However, it is important to highlight that there are areas where wireless may not be practical at this stage, especially in applications involving safety constraints and very low (microsec level) cycle times.

TSN capabilities have already started to be extended to wireless domains. For instance, time synchronization can be extended from a wired (Ethernet) domain to an 802.11/Wi-Fi domain using 802.1AS standard. Similarly, 5G standards define a mechanism to enable distribution of TSN time across a 5G network. New capabilities to schedule data transmissions with low latency and high reliability have also been introduced in 802.11ax/Wi-Fi 6 and 5G URLLC modes.

Existing wireless capabilities can support proof of concepts in the area of time synchronization and time-aware scheduling over wired and wireless domains and further work to define wireless specific test procedures is recommended. Configuration and management of wireless TSN capabilities is another area that can be further developed within the scope of Avnu. Areas for further work from a wireless standards standpoint have also been identified, which can be useful for groups like IEEE 802.11 and 3GPP.

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