# An Introduction To Wireless Time-Sensitive Networking

**Talha Kiani** (A paper written under the guidance of Prof. Raj Jain) Download

## Abstract

Many industries have a need for reliable, real time communication system. Many of these industry specific needs are satisfied by the IEEE 802.1 standards however the freedom of being wireless and mobile is critical in todays world. Providing bounded latency and zero packet loss is challenging considering the nature of wireless however careful planning combined with the advancements in wireless technology can make wireless time sensitive networking a reality.

## Keywords

Time Sensitive Networking, Wireless Time Sensitive Networking, Time Synchronization, Traffic Scheduling, Bounded Latency, Deterministic Communication

## Table of Contents

## 1. Introduction

The early version of ethernet as it was developed, did not distinguish between different types of traffic. Each frame was treated equally regardless of its priority, privacy, or importance. However, soon it became evident on the researchers that it was probably not the best policy. For example, multimedia packets such as audio and video can have different priorities based on the usage and may need to be transmitted based on their priorities. In 802.1D-1998 [IEEE98a] for the first-time traffic classes were partitioned into eight different priorities, allowing the division of urgent and less urgent traffic. Then later in 802.1Q-1998 [IEEE98b], Virtual LANs (VLANS) were introduced that allowed division of different packets of data on the same Local Area Network (LAN). These enhancements were crucial for the development of a variety of products and considerably improved and expanded the usefulness of ethernet. However, allowing the flow of multiple priorities through the same channel also introduced some unwanted side-effects such as added latency and uncertainty in the time taken for a frame to get from source to its destination. This is problematic particularly for the transport of time sensitive data.

Real time cooperation between agents requires the sharing of time critical information. Many industries including automotive, multi-media, healthcare, transport, and industrial automation have a need for reliable real-time communication. Although, many attempts were made to bridge the gap in real time communications using ethernet, the most notable addition was through the work of the Time Sensitive Networking (TSN) Task Group of IEEE 802.1. They were able to combine the synchronization performance of proprietary networks and the excellent worst-case latency of standard IT networks to put together the TSN standards. The TSN standards provide accurate time, data delivery with bounded latency, zero packet loss due to congestion, redundancy, and robustness in LAN's. It allows the use of standard ethernet as a real time communication network and enables the sharing of ethernet between multiple time-critical applications.

Wireless is the predominant networking medium in today's world and will remain so for the foreseeable future. However, unlike modern ethernet, Wireless can introduce substantial latency in frame transmission due to re-transmission, link rate changes or other bandwidth improvement techniques. All these factors introduce delay and cause uncertainty in transmission times. Therefore, given the unreliability and other interference related issues associated with wireless communications, implementing TSN standards over wireless and providing real time wireless communications is a major challenge.

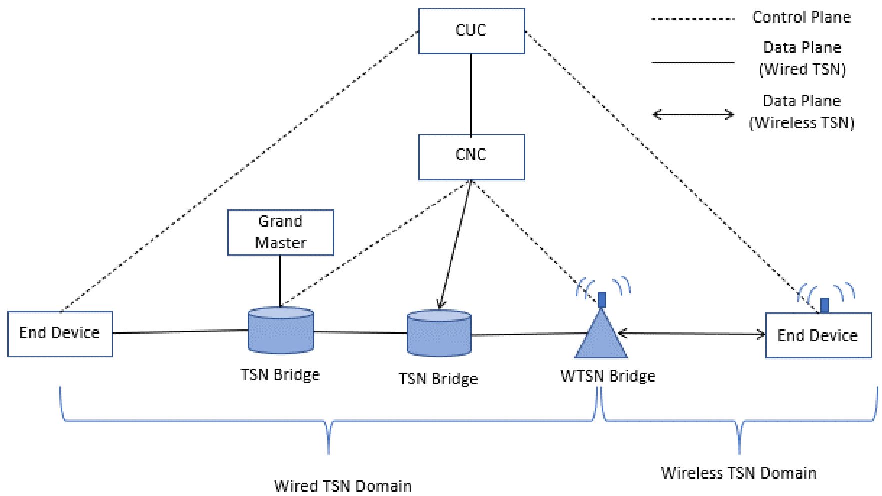


Figure 1: TSN over wired (Ethernet) and wireless (Wi-Fi) [network06]

In this paper we will be focusing on the time triggered communication aspects of TSN, why translation of TSN standards from wired to wireless networks is important and what are some of the challenges in extending TSN standards over the wireless domain. Next, we will talk about some of the recent developments in wireless technologies and how they can be a precursor to Wireless TSN standards. We will also briefly discuss some of the inspiring use cases of Wireless TSN in diverse industries, possible security threats and their mitigation. Lastly, we will conclude with a summary of the article.

## 2. Time Sensitive Networking And Its Components

Time Sensitive Networking is the evolution of IEEE 802.1 standard to bring capabilities such as low bounded latency, no packet loss, and deterministic transfer to the open network of ethernet [ni01]. The TSN standard relies on three key components to offer real time communication solution. These three basic components include time synchronization, scheduling, and selection of communication paths [wikipedia02]. Although all three of these are separate specification on their own, however only when used together they can meet the strict constraints of TSN. Let's take a closer look at these components.

### 2.1 Time Synchronization

For real-time communication with strict latency requirements, all devices in the network need to have a similar time reference and constantly synchronize their clocks amongst each other. Time synchronization is TSN is provided through the IEEE 802.1AS standard. It allows compliant ethernet switches to automatically synchronize times between them using the connected ethernet cable. This greatly simplifies the process of synchronization because the ethernet not only carries the data packets but also provides a common notion of time to the connected devices in the subnet [3]. IEEE 802.1AS standard provides sub-microsecond time precision and extension to support synchronization over wireless as well [wikipedia02].

### 2.2 Scheduling and Traffic Shaping

For scheduling, TSN uses the IEEE 802.1Qbv based time-aware scheduler which utilizes Time Division Multiple Access (TDMA) to configure slices of time on the network and transport different types of traffic. Each segment of time is assigned a different priority or type of traffic. With time synchronization between all the network devices, each device knows exactly when each frame should be processed and transmitted. Because of this, the devices can hold traffic to ensure that traffic with higher priority is processed first and bandwidth is available for time critical data [motion03]. An example of IEEE 802.1Qbv schedule is given in figure 1.

Traffic shaping is process of managing traffic for soft real-time communication. It enables different data types such as hard real time, soft real time, and background data to coexist on the same network [motion03]. It is possible for each traffic type to have different latency and bandwidth requirements.

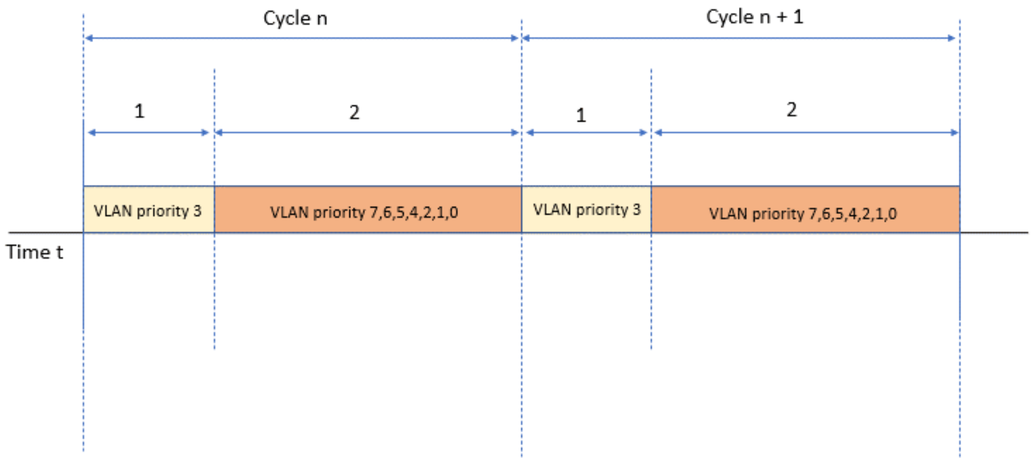


Figure 2: Example IEEE 802.1Qbv schedule [wikipedia02]

### 2.3 Path Selection

All devices participating in real time communications need to behave in a predictable fashion, therefore they follow the same methods of selecting communication paths and reserving bandwidth and time slots. Some of the most common path selection standards include IEE 802.1Qca Path Control and Reservation (PCR) and IEEE 802.1CB Frame Replication and Elimination for Reliability (FRER)[ieee802].

The PCR standard extends the application of Intermediate System to Intermediate System (IS-IS) to control bridged networks. It also provides path selection, bandwidth reservation, redundancy protection and distribution of control parameters for synchronization and scheduling[ieee802].

The FRER standard specifies procedures and protocols for bridges and end stations that identify and eliminate duplicate frames [mirabilis05]. This can be done in end stations and relay nodes [1.ieee802].

## 3. Wireless Time Sensitive Networking

Although a few of the IEEE 802.1 (TSN) standards apply to wireless networks, most efforts have been focused on ethernet as the main transport medium. However, wireless being the most predominant media in homes and enterprises. It is only natural that TSN capabilities are transferred over to the wireless domain as well. The term "Wireless Time Sensitive Networking" (WTSN) is used to refer to wireless networks that implement the TSN standards.

To enable seamless operation and interoperability from wired TSN to wireless TSN and support end-to-end TSN for wireless network domain, there are still some major challenges. The typical random-access protocols used in wireless impose a serious limitation to meeting the bounded latency requirement in TSN. Similarly, interference from other devices can also impact time sensitivity. In the following subsections we will discuss some of the features to be considered for realizing wireless TSN and some possible impediments.

### 3.1 Accurate End-To-End Time Synchronization

As we saw earlier, a synchronized common time base is very important to support time critical services and applications. Although we have some very reliable time synchronization methods available for ethernet but extending them to wireless is challenging. The first challenge comes from slow fading (changes in signal strength between a transmitter and receiver as the distance between them increases) in the wireless channel. This causes increased latency, higher packet loss and jitters in the transfer. Secondly, most of the wireless network interface cards (NIC) lack key features such as precise time measurement and time stamping required for synchronization.[jetmir21]

### 3.2 Unified End-To-End Traffic Scheduling

Traffic engineering techniques to differentiate between traffic flow based on priority and importance have successfully been deployed in wired networks, where packet collisions can be avoided. These approaches can effectively schedule and shape traffic for most of the common applications. However, the inherent half-duplex nature of wireless and prioritization solutions such as enhanced distributed channel access (EDCA) at the Wi-fi Medium Access Control (MAC) layer, do not provide the deterministic performance required by TSN and real time systems.[jetmir21]

### 3.3 Key Performance Indicators To Evaluate Wireless Time Sensitive Networking

Up until now the major focus of wireless networking was to increase network capacity, however with the introduction of new features such as TSN, new Key Performance Indicators (KPIs) need to be defined to better understand the network performance and power consumption.[jetmir21]

## 4. Advancements in Wireless Technologies and Wireless Time Sensitive Networking

Recent advancements in the wireless domain have resulted in technologies with higher throughput and lower latency. 5G Ultra-Reliable Low-Latency Communication (URLLC) and IEEE 802.11ax (Wi-fi 6) are two promising developments. Both 5G URLLC and Wi-fi 6 can play a crucial role in making WTSN a reality. Table 1 below draws a comparison between some of the key features in 5G and Wi-fi 6.

Table 1: Comparison between 5G and WI-FI 6 [jetmir21]

| **Feature** | **5G URLLC** | **WI-FI 6** |
|---|---|---|
| **Synchronization** | Accurate | Inaccurate |
| **Traffic Handling** | Possible, mapping between TSN classes to 5g QoS classes | Priority-based, non-deterministic |
| **Monitoring** | Aggregated only on network devices | Aggregated only on APs |
| **Application-network interface** | Extensive set of QoS identifiers | Limited set of QoS classes |
| **Architecture** | Complex: TSN controller + 5G system bridge | Stand-alone WiFi |
| **Spectrum** | Licensed + Unlicensed | Unlicensed |

Let's take a deeper look at some of the exciting features in these technologies and how they can support Wireless TSN.

#### 4.1 5G Ultra-Reliable Low-Latency Communication

5G URLLC can achieve low latency communication down to 1 ms by scheduling transmissions in shorter time slots and by reducing the transmission time interval based on shorter symbol time [1.ieee802]. Also, URLLC transmission can interrupt an ongoing non-URLLC transmission to get faster access to wireless medium and reduce latency [jetmir21] .

Next, 5G URLLC can potentially utilize the 5G TSN bridge for synchronization based on the boundary clock approach [texas13] and the transparent clock approach [texas13] to achieve time synchronization requirements for TSN [jetmir21] .

#### 4.2 Wi-fi 6

Wi-fi 6 is the latest version of IEEE 802.11 technology and its capabilities can also enable lower latency bounds with high efficiency. Some of its major improvements include the usage of orthogonal frequency division multiple access (OFDMA), higher modulation and uplink multi-user multiple-input and multiple-output (MU-MIMO) concept.

OFDMA can schedule multiple devices to transmit simultaneously thereby increasing the number of transmission opportunities, reducing contention and random waiting times compared to previous versions.

Wi-fi 6 can support a number of different types of traffic based on priorities which can be used to implement scheduling and traffic shaping in WTSN. Although, there does not currently exist a time synchronization mechanism for Wi-fi 6 currently. However, several time synchronization techniques based off Wi-fi have been proposed which can be useful in extending TSN over the wireless domain.[jetmir21]

## 5. Use Cases of Wireless Time Sensitive Networking

Wireless TSN will be important to the next-generation applications in a variety of diverse industries from healthcare to transport, from entertainment to manufacturing and many more. Let's take a brief look at some of the possible use cases of Wireless TSN.

### 5.1 Health Care

Latest IT advancements such as higher video resolution, artificial intelligence and cloud computing will open doors for abundance of innovations in remote diagnosis, treatment, and recovery for a wide range of medical applications. Wireless TSN is important due to the critical and sometimes extremely strict network requirements of low latency and reliability for medical use cases such as tele-surgery or tele-monitoring.

### 5.2 Entertainment

The entertainment industry has exciting use cases for Wireless TSN such as real time high quality 4k/8K streaming, cloud gaming, virtual reality, and other interactive applications.

### 5.3 Industrial Manufacturing

Accurate synchronization between network sensing and actuating nodes is critical for industrial manufacturing. In fact, requirements for time accuracy to be to the nearest microsecond is not un-common in the industry. Increased speed and precision for machines require deterministic network latency, increased sample rate and improved time accuracy for the sensors and actuators to perform their actions at the scheduled time. With better networking capabilities, industrial manufacturing efficiency and product quality can be improved.

### 5.4 Transport

Realtime traffic information is starting to be crucial for drivers. However, what will truly revolutionize transportation are fully autonomous vehicles and automated guided vehicles which require zero to very minimum human interaction. These next generation vehicles require fast and reliable communication and processing systems. Wireless TSN will play a crucial role in ensuring high reliability and low latency for the future transport systems.

## 6. Security

Wireless TSN networks are considerably envisioned to be the backbone of networks in the future. Such networks have bounded latency and deterministic communication in TSN, which can make them susceptible to attacks. In the following subsections we will explore and analyze some potential security issues and eventually see how we can be protected.

### 6.1 Threats

Some of the most common threat vectors include:

- Delay Attack: Attacker maliciously delays TSN data flow traffic.
- Path Manipulation: Attacker manipulates the paths being used.
- Attack on Time Sync Mechanism: Attacker disrupts TSN synchronization.
- Reconnaissance: Attacker gathers information about TSN flows, bandwidth, schedules.
- Replication: Increased attack surface: Attacker gains access to more points in the network that can potentially be attacked.
- Inter-segment attack: Attacker injects traffic from one segment, affecting the performance of other segments.

All of these attacks can disrupt the flow of traffic and cause the network to behave abnormally. Their impacts range from denial of service to resource exhaustion, increased buffering in bridges to modifying network flows and from modifying streams to crashing the application.[tal18]

#### 6.2 Protection

Although traditional security solutions such as firewalls will remain a key mechanism for securing a TSN network. The real time properties of TSN, have an impact on the design of some of these security measures. For example, if we can not check the data packets passing through the firewall in real time, that can create additional transmission delay which the TSN standard is very strict about. Therefore, we have to employ firewall technology that is guaranteed to work in real time.

The 802.1 Security Task Group has defined some standardized solutions and protocols for port authentication key agreement, integrity, and confidentiality. IEEE 802.1X-2010 provide port authentication and key agreement. Hop-by-hop frame integrity and optionally confidentiality is provided by 802.1AE-2006. 802.1AR defines secure device identity based on device identifiers. [soheil18]

## 7. Summary

The growing need for real time and deterministic communication in various professional environments demands that time sensitive networking should be extended to wireless domain as well. Several challenges still need to be addressed related to the application of TSN standards to the wireless network. This paper mentioned a few considerations that have to be addressed to achieve end-to-end wireless TSN. These considerations include accurate end-to-end synchronization, unified end-to-end traffic scheduling, introducing KPIs to measure wireless TSN performance. In addition, we also talked about some of the upcoming innovations in the wireless technology with higher throughput and lower latency and how they can be crucial in extending TSN to the wireless domain. Lastly, we discussed some of the exciting use cases of wireless TSN in different industries and the security risks and benefits of wireless TSN.

## 8. References

[IEEE98a] IEEE Std. 802.1D-1998, "IEEE Standard for Local Area Network MAC (Media Access Control) Bridges,"IEEE SA, June 1998; https://standards.ieee.org/findstds/standard/802.1D-1998.html

[IEEE98b] IEEE Std. 802.1Q-1998, "IEEE Standards for Local and Metropolitan Area Networks: Virtual Bridged Local Area Networks," June 1998; https://standards.ieee.org/findstds/ standard/802.1Q-1998.html

[ni01] "NI-DAQmx-Based TSN Synchronization Accuracy Explained",https://www.ni.com/en-us/support/documentation/supplemental/17/ni-daqmx-based-tsn-synchronization-accuracy-explained.html, [What is TSN, Its Impact, NI-DAQmx-Based TSN]

[wikipedia02] "Time-Sensitive Networking",https://en.wikipedia.org/wiki/Time-Sensitive_Networking#:~:text=Scheduling%20and%20traffic%20shaping%20allows,end%2Dto%2Dend%20latency , [TSN background and it components]

[motion03] "What is time-sensitive networking (TSN)?", https://www.motioncontroltips.com/what-is-time-sensitive-networking-tsn/,[TSN Synchronization, scheduling and shaping]

[ieee802] "802.1Qca - Path Control and Reservation",https://www.ieee802.org/1/pages/802.1ca.html, [What is Intermediate System to Intermediate System (IS-IS)]

[1.ieee802] "P802.1CB - Frame Replication and Elimination for Reliability",https://1.ieee802.org/tsn/802-1cb/ , [Frame Replication and Elimination for Reliability]

[controleng04] "Extending TSN capabilities over 5G and other wireless networks",https://www.controleng.com/articles/extending-tsn-capabilities-over-5g-and-other-wireless-networks/ , [Extending TSN over wireless 5G]

[jetmir21] Jetmir Haxhibeqiri, Xianjun Jiao, Esteban Municio, Johann M. Marquez Barja, Ingrid Moerman, Jeroen Hoebeke, "Bringing Time Sensitive Networking to Wireless Professional Private Networks", Springer, August 2021, Pages [7-13], https://www.marquez-barja.com/images/papers/Haxhibeqiri2021_Article_BringingTime-SensitiveNetworki.pdf

[texas13] Texas Instruments, "AN-1838 IEEE 1588 Boundary Clock and Transparent Clock Implementation Using the DP83640", Phyter, April 2013, Pages [4-8],https://manualzz.com/doc/24167345/texas-instruments-ieee-1588-boundary-clock-and-transparen...

[tal18] Tal Mizrahi, Andrew Hacker, Henrik Austad, "Security Considerations in DetNet / TSN", IEEE 802.1 / IETF Joint Workshop, November 2018, Pages [2-18],https://www.ieee802.org/1/files/public/docs2018/detnet-tsn-mizrahi-security-1118-v01.pdf

[soheil18] Soheil Samii, Helge Zinner, "Level 5 by Layer 2: Time-Sensitive Networking for Autonomous Vehicles", IEEE Communications Standards Magazine ( Volume: 2, Issue: 2, June 2018), Pages[62-68]], https://ieeexplore.ieee.org/document/8412465

[mirabilis05] "Time Sensitive Network Standard Technology For Deterministic Traffic",https://www.mirabilisdesign.com/time-sensitive-network/, [TSN for Deterministic traffic] [network06] "Adoption rate of wireless TSN is expected to ramp UP quickly for Industrial IoT applications", https://networkbuilders.intel.com/blog/adoption-rate-of-wireless-tsn-is-expected-to-ramp-up-quickly-for-industrial-iot-applications, [Adoption rate of wireless TSN]

## 9. List of Acronyms

| **Acronym** | **Definition** |
|---|---|
| VLANS | Virtual LANs |
| LAN | Local Area Network |
| TSN | Time Sensitive Networking |
| TDMA | Time Division Multiple Access |
| PCR | IEE 802.1Qca Path Control and Reservation |
| FRER | IEEE 802.1CB Frame Replication and Elimination for Reliability |
| IS-IS | Intermediate System to Intermediate System |
| NIC | Wireless Network Interface Cards |
| EDCA | Enhanced Distributed Channel Access |
| MAC | Medium Access Control |
| KPIs | Key Performance Indicators |
| URLLC | Ultra-Reliable Low-Latency Communication |
| Wi-fi 6 | IEEE 802.11ax |
| OFDMA | Orthogonal Frequency Division Multiple Access |
| MU-MIMO | Multi-User Multiple- Input and Multiple-Output |

---

Last modified on December 7, 2022
This and other papers on recent advances in Wireless and Mobile Networking are available online at
http://www.cse.wustl.edu/~jain/cse574-16/index.html
Back to Raj Jain's Home Page