Wi-Fi QoS improvements for industrial automation

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Abstract

Digitalization caused a considerable increase in the use of industrial automation applications. Industrial automation applications use real-time traffic with strict requirements of connection of tens of devices, high-reliability, determinism, low-latency, and synchronization. The current solutions meeting these requirements are wired technologies. However, there is a need for wireless technologies for mobility, less complexity, and quick deployment.

There are many studies on cellular technologies for industrial automation scenarios with strict reliability and latency requirements, but not many developments for wireless communications over unlicensed bands. Wireless Fidelity (Wi-Fi) is a commonly used and preferred technology in factory automation since it is supported by many applications and operates on a license free-band. However, there is still room for improving Wi-Fi systems performance for low-latency and high-reliable communication requirements in industrial automation use cases.

There are various limitations in the current Wi-Fi system restraining the deployment for time-critical operations. For meeting the strict timing requirements of low delay and jitter in industrial automation applications, Quality of Service (QoS) in Wi-Fi needs to be improved. In this thesis, a new access category in Medium Access Control (MAC) layer for industrial automation applications is proposed. The performance improvement is analyzed with simulations, and a jitter definition for a Wi-Fi system is studied. Then, a fixed Modulation and Coding (MCS) link adaptation method and bounded delay is implemented for time-critical traffic in the simulation cases to observe performance changes.

Finally, it is shown that the new access category with no backoff time can decrease the delay and jitter of time-critical applications. The improvements in Wi-Fi QoS are shown in comparison with the current standard, and additional enhancements about using a fixed modulation and coding scheme and implementation of a bounded delay are also analyzed in this thesis.

Keywords Wi-Fi, QoS, IEEE 802.11, MAC, TSN, end-to-end delay, jitter, industrial automation

Preface

This thesis study was conducted with Network Architecture and Protocols team at Ericsson Research in Jorvas, Finland.

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Contents

Abbreviations

5G	Fifth Generation
AC	Access Category
ACK	Acknowledgement
AIFS	Arbitration Inter Frame Spacing
AP	Access Point
AVB	Audio Video Bridging
BK	Background
BSS	Basic Service Set
CCA	Clear Channel Assessment
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CUC	Centralized User Configuration
CNC	Centralized Network Configuration
CS	Carrier Sensing
CSMA/CA	Collision Sense Multiple Access with Collision Avoidance
CSMA/CD	Collision Sense Multiple Access with Collision Detection
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	DCF Inter Frame Space
DSSS	Direct Sequence Spread Spectrum
E2E	End-to-End
EDCA	Enhanced Distributed Channel Access
FCS	Frame Check Sum
FDMA	Frequency Division Multiple Access
FHSS	Frequency Hopped Spread Spectrum
HCCA	HCF Controlled Channel Access
HCF	Hybrid Coordination Function
HT	High Throughput
IEEE	Institute of Electrical and Electronics Engineers
IFS	Inter-Frame Space
IoT	Internet of Things
IP	Internet Protocol
ISM	Industrial, Scientific and Medical
KPI	Key Performance Indicators
LLC	Logical Link Layer
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MPDU	MAC Protocol Data Unit
MSDU	MAC Service Data Unit
MIMO	Multiple Input Multiple Output
NAV	Network Allocation Vector
OFDM	Orthogonal Frequency Division Multiplexing

OFDMA	Orthogonal Frequency Division Multiple Access
PCF	Point Coordination Function
PHY	Physical Layer
PLC	Programmable Logic Controller
PLCP	Physical Layer Convergence Protocol
PMD	Physical Medium Dependant
PPDU	PHY Packet Data Unit
PSDU	PHY Service Data Unit
QoS	Quality of Service
SIFS	Short Inter Frame Space
SDN	Software Defined Network
SDU	Service Data Unit
SOF	Start Of Frame
STA	Station
TAP	Traffic Arrival Period
TCP	Transmission Control Protocol
TSN	Time Sensitive Networks
TXOP	Transmission Opportunity
UDP	User Datagram Protocol
VHT	Very High Throughput
VLAN	Virtual Local Area Network
VO	Voice
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network

1 Introduction

Since the beginning of industrialization, communication between human and machines has attracted tremendous attention. With the evolution of industrial technologies, more machines took the place of human communicating the machines directly, and this brought up the need for machine-to-machine communication technologies. Industrial automation, where the communication is the critical enabler, has been the focus of intense research over the last few decades. Main advantages of industrial automation are reducing production time, human error and employee cost while increasing uniformity and consistency in repetitive tasks, safety, efficiency, quality, and production volume. Information and communication technologies, Fifth Generation (5G) networks, wireless sensors and networks, digital manufacturing, Time-Sensitive Networks (TSN), artificial intelligence (AI), virtual reality (VR), robotics, machine intelligence, and advanced software are some of the outstanding technologies enabling and contributing to industrial automation. In particular, innovations and developments in communication technologies and networks accelerated the transition from conventional industrial solutions to industrial automation.

Industry 4.0, which is also known as the Fourth Industrial Revolution, is the 4$^{\text{th}}$ and the current phase of the industrial revolution which started in 1784 with mechanization and continued with the development of assembly lines and programmable logic controllers (PLC). Industry 4.0 is an initiative that was established by the German government to make a transition in manufacturing by digitalization in cooperation with universities and companies. It is a joint integration of two key concepts; ensuring real-time communication between machines and humans, cloud computing and Internet of Things (IoT) [1]. The main goal of Industry 4.0 is revolutionizing manufacturing and production by transferring all the factory machine processes and computations to the cloud, managing and controlling machines remotely. Most significant challenges in Industry 4.0 are real-time communication based on low-latency and high-reliable networks, robustness even with high network loads and merged data transport for both operational technologies and information technologies.

Industrial automation can be classified according to device number in the system, data throughput, reliability and latency requirements of the applications. The classification of the industrial applications varies depending on the criteria. In Neumann's study [2], industrial automation applications are divided into four classes according to their scheduling mechanisms as follows:

- **Soft real-time**, that has scheduling of User Datagram Protocol (UDP) / Transmission Control Protocol (TCP) layer and used in a factory floor and process automation.
- **Hard real-time**, that has scheduling on top of Medium Access Control (MAC) layer and used in control application with 1 to 10 ms cycle.
- **Isochronous real-time**, that is used for motion control with 250μs to 1 ms cycle time and less than 1μs jitter requirement for with clock synchronization.
- **Non real-time**.

Another classification in the paper by Buda [3] is considering industry automation as a hierarchical model. It starts with sensors and actuator in the bottom level and reaches to factory level with control, system and process automation levels in between. Also, as shown in Table 2, International Telecommunication Union [4] categorizes industrial automation depending on the application area and purpose in a factory. The most challenging requirements for high-performance industrial automation applications are the simultaneous connection of tens of devices, high-reliability, determinism, low-latency also, synchronization. Requirements of different classes in industrial automation result from the traffic model that is used in the application.

Table 2: Classification of industrial automation applications [4, 5]

Industrial application	**delay**	**Jitter**	**Cycle time**
Process control	100 ms	< 20 ms	10-100 ms
Factory automation	1-10 ms	$< 100\mu$s	1-100 ms
Motion control	1 ms	< 1 μs	< 1 ms
Remote control	5 ms	< 10 μs	$\sim 250\mu$s

Both wired and wireless technologies are deployed for industrial automation applications in the fields. For many years, 4-20 mA analog cables are used for communication in industrial facilities between devices and controllers [6]. In the 1990s, digitalization started to influence communication in industrial automation with fieldbus technology as a replacement for analog cables. Foundation Fieldbus, PROFIBUS, CAN, Modbus, CC-Link are some of the technologies that were introduced with fieldbus for the long life cycle need of industrial systems and they are still very popular today. The next development in industrial communication is using Ethernet as an enabler technology, and some examples of Ethernet-based technologies are EtherCAT, Ethernet/IP, PROFINET, POWERLINK and Sercos III [7]. TSN is the latest innovation in wired technologies and considered as the future of industrial automation. TSN is a collection of standards that are defined by Institute of Electrical and Electronics Engineers (IEEE) to enable deterministic data transmission on standard Ethernet. The studies on TSN show that the strict reliability and latency requirements of industrial automation applications can be met [8, 9].

However, wired technologies are deployed at the factory level, including TSN. Wired communication systems are more expensive, high maintenance and less flexible compared to wireless solutions. Looking at the future of industrial automation, it is expected that there will be an increase in TSN importance and deployment. The transition of industrial automation accelerates with TSN; hence, the integration of TSN with wireless networks is a significant point. There are many advantages of deployment of wireless technologies in industrial automation, but three of them stand out. The first advantage is not requiring cable installation and maintenance services. The maintenance services and replacements can cause interruptions and breakdowns in the system. The second significant advantage is a fast deployment of new devices and network configurations. In wired connections, the production lines or the other applications going on are needed to be stopped for the time being during the installation. The third one is the flexibility of the connection. Machines and devices can connect to more than one device and have the flexibility of connection points with a wireless system [10].

Fpr fast improvements in wireless technologies, many studies started to focus on cellular technologies, LTE and 5G, enabling industrial automation with wireless communication [11, 12, 13, 14]. It is promising that the challenging requirements of some industrial automation cases, such as delay of less than 1 ms, can be satisfied with LTE and 5G. Another enabler for wireless communication in industrial automation is Wireless Fidelity (Wi-Fi) devices that are widely deployed around the world today, and supported by many applications. IEEE 802.11 Wireless Local Area Networks (WLAN) are very pervasively deployed due to their ability to provide ubiquitous network access with high flexibility, cheap costs, and ease of installation and maintenance. Wi-Fi devices, which are certified based on IEEE 802.11 WLAN standards, run on the unlicensed spectrum. Wi-Fi is a candidate technology as Ethernet cable replacement in industrial automation scenarios. With IEEE 802.11 networks, the delay can be lowered with current standards in non-congested environments, 200 μs delay can be achieved with Wi-Fi for a basic sequence [15]. This addresses Wi-Fi to be a suitable technology for wireless TSN operations.

Predictability and determinism are the keys for real-time communication in networks. Real-time communication As mentioned above, low-latency in networks can be achieved with both cellular and unlicensed band wireless communications. However, determinism in wireless technologies is ongoing research. In spite of the application dependent throughput, network volume, and density requirements, low jitter is the a common goal for all real-time communication technologies since deterministic communication can be achieved only with significantly small jitter values. Jitter is defined as the variation in delay values, and when the unpredictability, variation, in delay is low, it implies that the determinism can be achieved. Both submissions [15] and [16] in IEEE working groups addressed the essentially of jitter studies for deterministic and reliable wireless communications.

Therefore, this thesis focuses on the research gap in jitter studies to enable Wi-Fi integration to industrial communication networks based on TSN. Due to the randomness and unpredictability in resource sharing mechanisms of 802.11 standard, it is not possible to meet the high requirements of factory automation, motion control, and robotics; however, as mentioned in [16], since TSN is not an improvement for just strict latency and reliability applications, additional domains such as process automation can profit from it, too. Hence, Wi-Fi devices can replace the Ethernet connection in process automation and resembling applications. The studies in this thesis take a step forward to analyze and improve the performance of Wi-Fi systems for industrial automation applications. For jitter performance improvements in IEEE 802.11 standard, QoS mechanism modifications in 802.11 MAC layer for TSN-like traffic is studied.

1.1 Motivation

The motivation for this thesis arises from the need for QoS improvement in wireless communications over unlicensed bands for real-time applications. Real-time applications generate traffic with varying characteristics depending on the application purpose. The most common traffic model in industrial applications is a periodic traffic with short cycle time, requiring low-latency and jitter so that the data in every cycle can be transmitted without overlapping, colliding or expiring. Traffic being transmitted in TSN is also a real-time data from real-time application with strict timing requirements.

In particular, the current standard IEEE 802.11 is not sufficient to serve to real-time applications with strict reliability and low jitter conditions. Therefore, it is sometimes considered impossible to serve time-critical operations in an unlicensed band with existing WLAN standards and Quality of Service (QoS) framework [17]. Wireless communications in unlicensed band cannot dedicate and ensure resources for users, and the wireless medium has to be shared with random processes. IEEE 802.11 requirement for randomness in radio resource sharing and transmission times conflicts with the requirement to transport traffic in a deterministic manner for industrial automation. For TSN-like traffic to be compatible with Wi-Fi technology, there is a need for modifications in the standards.

1.2 Objective of the Thesis

The objective of this thesis is improving jitter performance of IEEE 802.11 MAC layer from a TSN-like downlink traffic perspective. This thesis aims for MAC layer QoS improvements to allow WLAN standards to reduce the delay and jitter for TSN-like traffic for process automation applications. For the performance evaluation of the improvements, data rate, delay, jitter, packet losses and service ratio are used. The jitter definition in IEEE 802.11 standard is left for the application layer; however, jitter is one of the significant parameters for deterministic communications. Hence, the jitter definition for random access mechanisms, IEEE 802.11 standard, is also studied and defined in the scope of the thesis.

A design for TSN and Wi-Fi integrated system is proposed in this thesis. The overall architecture of the network is proposed where TSN-like traffic is generated by an industrial application and received with an Ethernet cable at Wi-Fi AP. The data is transmitted over the air to a Wi-Fi STA that the other end device is connected. The last hop of the TSN line, from the controller to the device, is replaced with a wireless link. The wireless connection is end-to-end (E2E) between the AP and the device. Downlink performance improvements are studied in this thesis where the purpose is sending the control frames from the controller to actuators, where the downlink transmission is a priority. Therefore, uplink traffic performance and physical layer improvements are outside of the scope of this work.

1.3 Structure of the Thesis

This thesis is organized as follows. Chapter 2 provides background on TSN and IEEE 802.11 technologies. It also gives details of TSN standards and IEEE 802.11 protocols, and insight about how data transmission is done. Chapter 3 introduces and describes the enhancements in the MAC layer of IEEE 802.11 standard in detail. Then in Chapter 4, the model for simulation and assumption are presented. Chapter 5 shows the results of the different scenarios and analyzes the performance improvements. Finally, Chapter 6 summarizes the conclusions and observations and presents future research topics that can be of interest.

2 Background on technologies

Among the technologies to meet the requirements of industrial automation applications, Time Sensitive Networks (TSN) is a set of standards promising to replace proprietary technologies. Nowadays, proprietary Ethernet protocols have been chosen for many industrial automation applications as a replacement for fieldbus communications.The next leap in Ethernet evolution is TSN which is a set of protocols that allows connecting all machines and hardware, capable of doing hard real-time communication for industrial automation.

Wi-Fi is a widely used technology for wireless communication in offices, homes, industries and many other areas. Wi-Fi plays an increasingly important role in the industry since more and more data is generated, transported and processed due to digitalization. Wi-Fi is a favorable technology in industrial applications like monitoring, configuring, controlling and data acquisition since it brings mobility for moving devices and easy deployment functionality in factory level while operating in an unlicensed spectrum.

This chapter gives background information on the current standards for TSN and Wi-Fi technologies. The start of TSN standardization, the network, and TSN traffic are described. Afterward, the background of IEEE 802.11, functions of Physical and MAC layer and QoS in Wi-Fi are explained.

2.1 Time Sensitive Networks

TSN is a set of standards that are developed by IEEE Time Sensitive Networking task group, IEEE 802.1Q, to provide deterministic data transmission on standard Ethernet [18]. This task group originates from Audio Video Bridging (AVB) task group that was working on the specifications to allow time-synchronized low-latency streaming services. The TSN task group was formed in 2012 by renaming the existing AVB Task Group and continuing its work. AVB task group worked on specifying the low-latency transmission over Ethernet. The need for AVB task group originated from the problem that the connections in audio and video devices were with analog cables and all standards needed a dedicated and single connection [19]. This requirement resulted in massive cable usage and confusions. There was a need for a technology that can meet the requirements of all audio and video applications like live audio playback [20]. Therefore, AVB task group was created in 2004 as a residential Ethernet study group, but afterward, in 2005, IEEE 802.1 bridging network working group was formed.

2.1.1 From Ethernet to TSN

Time Sensitive Networking task group originates from AVB and expands the standardization scope to a larger area of Deterministic Ethernet for use cases including industrial automation, automotive and cellular network fronthaul. The communication technologies used in industrial automation cases are all based on Ethernet. These comprise a different additional mechanism to satisfy delay requisites which makes the solutions disunited and incompatible. As a result, development for the future becomes impossible with disjoint technologies. Also, the use of devices from different vendors and different communication technologies in industries becomes more challenging and unifying communication between them in a synchronized manner gains more importance. Having a unified converging Ethernet protocol for industrial automation is the idea for TSN task group.

Ethernet is a LAN technology under IEEE 802.3 standardization. It was developed in the 1970s, after the invention of ALOHAnet, leveraging by introducing channel listening before transmitting due to many collisions detected. Shortly after the first patent of Ethernet by Xerox company, they wanted to make it an open standard for development and the IEEE committee took an initiative to standardize Ethernet. This led the way for Ethernet being the most widely installed LAN technology today. In 1985, IEEE 802.3 released the standard for Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications [21]. As the name of the standard suggests, Ethernet is not a protocol for networks; it is a family of network technologies for the PHY and MAC layer. According to Open Systems Interconnection (OSI) reference model, illustrated in Figure 3, Ethernet covers the Physical and lower Data Link Layer.

Fundamentally, Ethernet is a technology to connect devices for forming a basis of most LANs, also to connect the device or network to the Internet with a cable. Ethernet was initially designed to run over coaxial cables. Alternatively now, it uses twisted pair cables since they are resistant to noise, also optical fiber cables for higher speeds [22]. The network can be configured in two types of topology as star and bus, defining how network elements are connected to each other. Bus topology was used until twisted pair cables were in use. After that point, Ethernet became a more reliable network with star topology where all the nodes are connected to a central point.

Ethernet is a best effort network that attempts to deliver messages to destinations without errors, but there is not a single feature to deal with lost or corrupted frames. Hence, Ethernet does not guarantee the delivery of data. Ethernet initially assumed a shared medium only, half duplex, and one signal could be transmitted at a time; therefore, it is based on listen-before-talk mechanism. The transmitting device needs to listen to the channel before transmitting any signal to see if the channel is in use by another signal or it is free. CSMA/CD algorithm for medium access is the MAC algorithm for this purpose in Ethernet. Carrier Sensing (CS) is listening to the channel for a period before attempting to transmit. When the channel is idle, the transmitter sends the packet; if there is multiple access in the medium, there occurs a collision. In the case of collision, the devices connected to the same network sense it, and they stop transmitting. Collision detection mechanism starts a randomized procedure to wait and restart the transmission again in case of busy channel [22]. Due to the characteristics of the CSMA/CD algorithm and a best effort network, Ethernet does not guarantee that the packets are delivered, MAC level does not provide error recovery. Upper layer protocols are responsible for packet delivery to the destination according to the standard [23].

Over the time, there have been new inventions for Ethernet, to make it a possible candidate technology for emerging areas of use. With the invention of network switches, full-duplex operations and twisted-paired cables point-to-point communication was enabled in Ethernet and shared media problems were solved. On the other hand, the half-duplex mode is still in use in Ethernet technology, and it is also an enabler for Gigabit Ethernet.

An Ethernet packet, in Figure 1, is not just a payload, it consists of address information for MAC layer, Virtual LAN (VLAN) tagging and quality of service information and error checking information to detect problems in transmission. For the transmission of frames in Ethernet, they are put in a packet which has information to set up the connection, preamble and Start Of Frame delimiter (SOF).

7 B	**1B**	**6 B**	**6 B**	**4 B**	**2 B**	**42-1500 B**	**4 B**	**12 B**
Preamble	SOF	MAC Destination	MAC Source	802.1Q VLAN Tag	Ethertype/ Lenght	Payload	FCS	IFG

16 bits	**3 bits**	**1 bit**	**12 bits**
Tag Protocol Identifier	Priority Code Point	Drop Eligible Indicator	VLAN Identifier

Figure 1: Ethernet packet format [23].

Ethernet technology has been commonly used in enterprise networks since it is open, standard and can support many widely used protocols like TCP/IP, UDP. Even though Ethernet is also high bandwidth, inter-operable and low-cost of maintenance, it cannot support the requirements of real-time communication. The fundamental principle of Ethernet cannot comply with determinism. As explained in Chapter 1, deterministic networks are the critical point for real-time communications.

Deterministic Ethernet is the way to enable Ethernet in the real-time applications such as factory automation, process automation, and automobile networks. For Ethernet to be a deterministic network, features of time synchronization, scheduling, resource reservation for time-critical traffic, guaranteed end-to-end delay and coexistence with non-time critical traffic are fundamental requirements. The mentioned deterministic features assure that time-critical traffic can be delivered in the time limit that is scheduled. Adoption of Ethernet for car networks in 2011 created another big market for Deterministic Ethernet and made other industries using real-time communication see the benefits. Many industrial automation technologies already enable deterministic Ethernet; however, as mentioned above, they are not unified by one standard. TSN will make Ethernet deterministic without a fieldbus protocol while still using the standard Ethernet features.

TSN is expected to be a technology for demanding requirements in communications in a broad market. Provided that, it is designed as a modular technology with various components enabling real-time communication. Hence, TSN is not a single standard document but is a family of standards which have been in development by the IEEE 802.1 TSN Task Group. For different characteristics in the fields, TSN can be deployed with needed principles. TSN task group works to enable Ethernet to satisfy industrial automation applications' requirements as time synchronization, delay provisions, reserved bandwidth, redundancy, converged networks, flexibility of network topology, scalability, and security. There are developments under TSN qualifying it as a solution, described in Section 2.1.3, which can be called fundamentals of TSN.

Since TSN is a technology on Ethernet, it uses Ethernet packet format that shown in Figure 1. For TSN, the frames of one communication unit from one device to another gather in a flow. The transmission of a TSN packet is described in Section 2.1.2.

2.1.2 TSN components

In a system where the primary purpose is managing time-critical data, all the elements in the network should use the same time for time-aware traffic scheduling. For that reason, TSN topology is designed in a way to control timing for the whole network with centralized configuration approach.

To describe the network elements in TSN terminology, the core network of a TSN system consists of Centralized User Configuration (CUC), Centralized Network Configuration (CNC), TSN switches, Listener and Talker as depicted in Figure 2 [24]. CNC and CUC are Software-Defined Network (SDN) Controllers to configure the paths and connections between Listeners and Talkers. SDN Controllers are the nodes in the system that know everything about the traffic and paths. With this information, controllers create the paths and schedule the traffic flow in order to have deterministic behavior. Depending on the requirements in the system as reliability, delay, jitter, throughput; routing is changed and reconfigured accordingly.

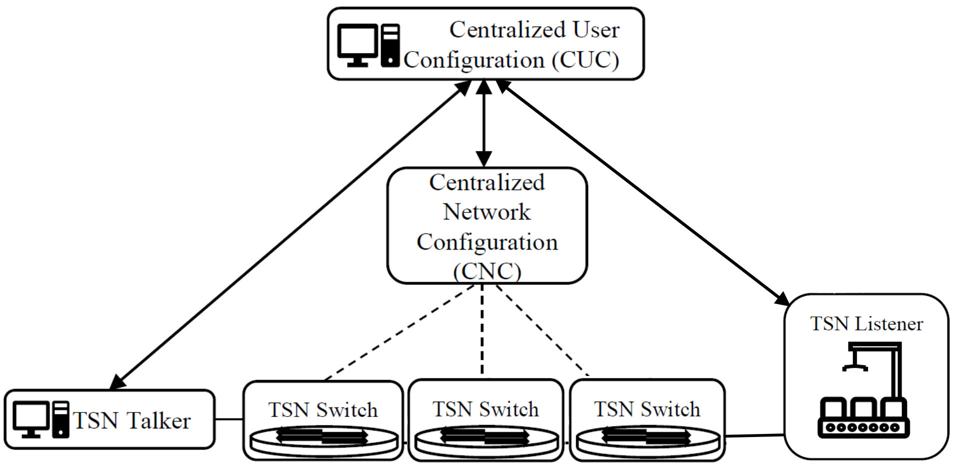

Figure 2: TSN topology with network elements.

- **CNC** is the main controller and manager of TSN network that knows everything about the network elements and configurations for control applications. It controls the transmission of TSN frames with the information that is received from CUC and switches for transmission and path configuration. After planning the paths, it sends requests the TSN switches for planned configuration.

- **CUC**'s primary function is to provide communication between the CNC and TSN Talkers and Listeners. The transmission requests of Listeners and Talkers are delivered through CUC. CUC makes a request to CNC for TSN flows with the application specified deterministic communication requirements.

- **TSN Talker** is the end device that is the source of the TSN traffic generation. The devices in the TSN network with deterministic communication request are called end devices, and both listeners and talkers in TSN network are end devices. TSN talkers can be any device that requests communication to another end device to actuate the received information.

- **TSN Listener** is an end device in the TSN network receiving the TSN packets from TSN Talker.

- **TSN Enabled Switches** are the bridges in the network with the functionality of transmitting and receiving Ethernet frames of a TSN traffic on planned schedule.

The communication between TSN Talker and Listener is provided in a deterministic manner with synchronized network elements as described above. Before any transmission in the network, CUC asks the CNC to scan the network and get the information of the connected devices and paths. TSN Talker requests to CUC for sending a TSN flow to the Listener. CUC requests from CNC to schedule transmission according to the size of the flow and delay requirements. After calculating the paths and proper scheduling for the packet, CNC reports it back to CUC. As a final step, CUC request from talker to start transmission accordingly.

In an industrial automation application, it is typical to use a ring topology for the network nodes between the SDN controllers and the end devices. The ring topology exists of two paths for traffic flow, and this provides diversity for the network. Then, one of the suitable paths with a schedule is chosen for transmission on the ring topology.

2.1.3 TSN standards

The main goal of TSN is adding a variety of functions and abilities to standard Ethernet IEEE 802.3 and IEEE 802.1 to make them more suitable for industrial automation applications. TSN technology is a centrally managed network and guarantees the delivery with minimized jitter using time scheduling for real-time applications. A time-sensitive system should ensure that high-priority traffic can predictably meet delay and jitter requirements, also in the cases of presence of same priority or best-effort traffic.

TSN consists of elements for a synchronized, deterministic, reliable, redundant and low-latency for real-time communications [25]. Time synchronization is needed for using a global sense of time and a schedule that is shared between network nodes. For a deterministic communication, the transmission should be predictable which addresses low jitter. Reliability ensures zero congestion, even with retransmissions, and diversity in the network. Redundancy is needed in all nodes to handle multiple path transmissions. As in many communication systems, minimizing delay is a goal in TSN, too. To reach the mentioned goals and assure real-time communication components, TSN has the set of standards described in Table 3.

Table 3: Main TSN Standards [26]

TSN Standard	Area	Title
IEEE 802.1AS	Timing and synchronization	Timing and synchronization for time sensitive applications
IEEE 802.1Qbu	Forwarding and queuing	Frame preemption
IEEE 802.1Qbv	Forwarding and queuing	Enhancements for scheduled traffic
IEEE 802.1Qcc	Central configuration method	Stream reservation protocol enhancements and performance improvements
IEEE 802.1Qci	Time-based ingress policing	Per-stream filtering and policing
IEEE 802.1CB	Seamless redundancy	Frame replication and elimination for reliability

For deterministic packet transmission in a network, the first requirement is that all the nodes in the network have the same understanding of time. Time synchronization in TSN enables a common clock for all nodes in the network for transmission scheduling via standard IEEE 802.1AS – timing and synchronization for time-sensitive applications with Precision Time Protocol. IEEE 802.1AS is a derivation of IEEE 1588 standard. The core of the time synchronization and Precision Time Protocol are timestamps on the physical layer. There is a master clock that is chosen in the network, and it exchanges packets with the other elements to change the time according to timestamps on the packets for time synchronization [27]. The standard is now under development for further features with name IEEE 802.1AS-Rev.

In standard Ethernet, when a packet is generated and arrives at Ethernet wire, all other packets are stopped and on hold till the end of the entire packet reception. This feature causes real-time traffic an unexpected delay and jitter. To overcome this problem, IEEE 802.11Qbu - Frame preemption is standardized. Frame preemption defines a mechanism that allows high priority traffic to interrupt the transmission of another type of traffic and transmit before waiting until the end of a packet, after the high priority packet transmission, the packet on hold continues [28]. This feature reduces the delay for high priority frames while increasing the efficiency of the network.

Since Ethernet is a best effort delivery system, there is no traffic prioritization; hence, prioritizing the traffic with delivery guarantee was standardized in AVB standards. However, a delivery guarantee is not enough for time-critical applications, predicted, and known delay boundaries are required. IEEE 802.1Qbv - Enhancements for scheduled traffic standard provides a mechanism for traffic prioritization using Time-Aware Shaper. Time-Aware Shaper knows about the schedule of the time-critical data and controls the gates of the queues for transmission. Depending on the scheduled traffic timings, gates are closed or open for time-critical data. If the gate is open for prioritized traffic, there is no other transmission even if there is no prioritized traffic due to some problem in the system [29].

Components in a time sensitive network are described in Section 2.1.2. The standard defining centrally managed network inspired by the SDN concept is IEEE 802.1Qcc - Stream reservation protocol enhancements and performance improvements. Stream ID, destination address and traffic class are classification parameters that are used for configuration in the network for controlling traffic, scheduling transmissions and paths [24].

There can be problems like congestion and packet drop due to an incorrect operation of a network element in a time-critical communication. IEEE 802.1Qci - Per-stream filtering and policing standard introduces methods to protect the rest of the traffic from the effects of a problem in reception or transmission of another stream. Methods describe a mechanism of filtering per stream with the gates in the reception port [30]. Gates in the reception port have the policing functions to check the sufficiency of each stream. These methods increase the robustness of the system and reduce ingress.

Redundancy is an essential characteristic of deterministic communication. In a standard Ethernet system, packet failures are solved by the application layer. If a failure or problem is detected, retransmissions are planned. In a time-critical application, re-transmission risks the bounded delay requirement of the failed packet and also future packets. IEEE 802.1CB - Frame replication and elimination for reliability standard explains a method that follows selectively replicating frames, transmitting in several paths and eliminating the duplicate in the receiver [31]. For time-critical data in TSN, rapid failure detection is essential, and this standard is a method to minimize retransmissions.

More TSN standards are published like path control and reservation - IEEE 802.1Qca, cyclic queuing and forwarding - IEEE 802.1Qch, forwarding and queuing enhancements for time-sensitive streams - IEEE 802.1Qav and YANG data model - IEEE 802.1Qcp [18]. Addition to the published standards, there are also task groups working on new amendments.

2.1.4 TSN traffic

Understanding the characteristics of the data traffic is crucial for the development of the communication systems. Enhancements in systems aim to serve the traffic matching specific requirements depending on the characteristics. Type and needs of applications shape the traffic characteristics. There are two important classifications to categorize traffic and describe the models. The first model is an event triggered traffic where the creation of the traffic is related to the previous event and the current status in the system. The new traffic is created after a condition is met in the system in an event triggered traffic model, and data is transmitted as soon as it is received in the system according to the availability in the system. In this model, scheduling and time limitations are not necessary, the state of the system is the essential condition. The second traffic model is a time-triggered model where the traffic is created based on a planned schedule. The traffic is generated periodically and scheduled beforehand. No matter the situation in the system is, new traffic is generated. Time-triggered models are mostly used for industrial automation applications since it is more robust in comparison with event-triggered traffic model since deterministic and real-time applications are used. In summary, the throughput of a time-triggered traffic model is less than event triggered traffic model since the traffic generation and transmission is not continuous all the time; however, traffic generation is not dependant on the system's status or affected by any disruption, it is on a planned timeline [32].

Industrial automation applications are deployed for a real-time system where the time triggered traffic is generated. Hence, TSN's target applications are real-time networks that require a guaranteed bounded end-to-end delay for critical data. It focuses on making sure that the data transmission between two end devices happen in a set and bounded time. Starting with the AVB standards, there were two traffic classes according to their delay requirement as Class A and Class B. The maximum end-to-end delay of AVB class A is 2 ms and AVB class B is 50 ms [33]. Further on, categorization of traffic classes depending on their priorities is explained in TSN standard [34] as shown in Table 4. The information of the priority level of a TSN packet is in the VLAN Identifier field of Ethernet packet.

Table 4: Categorization of data depending on their priority in TSN standard [34]

Priority	**Traffic classes**
0	Background
1	Best effort
2	Excellent effort
3	Critical applications
4	Video, delay $<$ 100 ms
5	Audio, delay $<$ 10 ms
6	Internetwork Control
7	Network Control Supports

The primary consideration of TSN is being capable of serving the deterministic requirements of real-time communication, which is also the time-critical traffic in industrial automation applications. For deterministic and low-latency networks, one of the main characteristics of the traffic is low jitter. The characteristics of time-triggered traffic require that the data transmission is completed in a scheduled period of time. For the transmission of frames in the bounded delay, the jitter should be as small as possible. Jitter requirements vary depending on the delay, precision and the period of the application and generated traffic.

On the other hand, jitter in communication systems can result from many components both in the network and traffic generation in the devices. In the ideal case, packets are created periodically without any jitter, but in reality, traffic generation is done by computation on an operating system. For the TSN traffic generation, the operating system should be very exact and real-time. Another source of jitter is the switches in the network. In every switch, there is also software that also needs to be exact. In the end, jitter is the accumulation of all these variations in the network. On top of the network, there is the application. If the protocol is a just best effort, jitter can also be created in the application layer. In a best effort case, the packets can arrive in a different order than they need to be served which can create jitter. Application protocol needs to deal with the resulting jitter. Additional to these reasons, hardware can also be the cause of jitter. The number of hops in the path increases the delay, and for a non-ideal case, also it contributes to jitter.

2.2 Wireless Local Area Networks

Wireless Local Area Network (WLAN) is a common technology for wireless access. IEEE 802 is the standardization committee for local, metropolitan, and other area networks aiming at developing and maintaining the PHY and MAC layers. Within this committee, IEEE 802.11 is a working group for Wireless LAN standardization. IEEE 802.11 follows the 802 reference model as depicted in Figure 3 and uses 48-bit universal addressing as a part of the IEEE 802 standards family. WLANs connect mobile hosts to the Internet and network and maintain connectivity while allowing mobility for users moving within a cell radius up to tens of meters [35].

2.2.1 Evolution of IEEE 802.11

WLANs operate in unlicensed Industrial, Scientific and Medical (ISM) frequency bands that were designed by the Federal Communications Commission (FCC). Primary ISM frequency ranges are 900 MHz, 2.4 GHz, 3.6 GHz, 5 GHz, and 60 GHz. Some of the Wi-Fi technologies like IEEE 802.11b/g operate in 2.4 GHz band, IEEE 802.11a/h/ac operate in 5 GHz band, and IEEE 802.11n operates in both 2.4 GHz and 5 GHz bands. The high demand for WLANs leaded companies to form a non-profit association called Wireless Fidelity (Wi-Fi) in 1999, named as Wireless Ethernet Compatibility Alliance back then. Wi-Fi Alliance is the organization that certifies devices for operability with IEEE 802.11 standards and interoperability with other devices and Wi-Fi is the trademark of the certification.

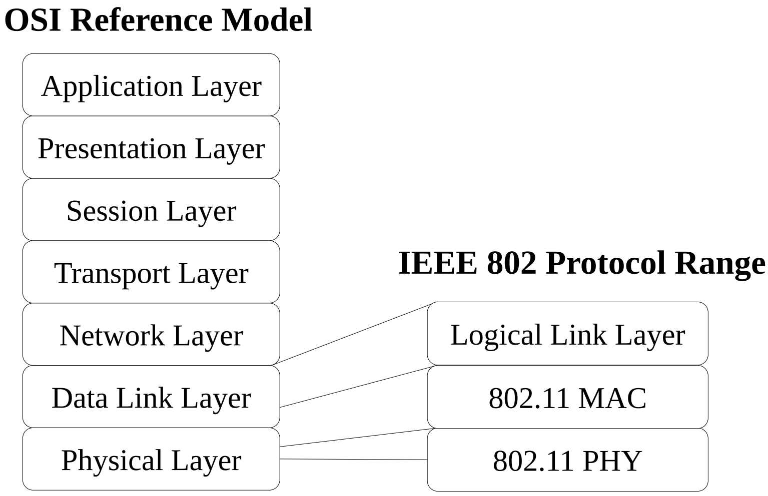

Figure 3: IEEE 802 reference model.

IEEE 802.11 standard has a lot of amendments and many more under development. As explained in Section 2.2.4, IEEE 802.11 uses a listen-before-talk method for medium access configuration, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). All WLAN standards have a similar protocol at the MAC layer. Until the standardization of IEEE 802.11e, the original MAC remained unchanged; only physical layer enhancements have been studied. Standardization of WLANs started with IEEE 802.11 in 1997. The Wi-Fi standard supported two-bit rates 1 and 2 Mbps. It included three different PHY layer techniques, not interoperable; infrared (IR), 2.4 GHz Frequency Hopped Spread Spectrum (FHSS), and 2.4 GHz Direct Sequence Spread Spectrum (DSSS). In 1999, IEEE 802.11b was ratified with providing 11 Mbps data rate in 2.4 GHz band using the same MAC level scheme, but the PHY level enhancements, and IEEE 802.11a supporting 54 Mbps data rate in 5 GHz band using OFDM based transmission. In 2003, a third modulation standard IEEE 802.11g was released, which extends IEEE 802.11b PHY layer to support data rate 54 Mb/s in the 2.4 GHz band using OFDM based transmission scheme as IEEE 802.11a. Interest in high data rates led the way to form High Throughput (HT) task group for standardization of IEEE 802.11n, which started it 2003 and finalized in 2009. IEEE 802.11n introduces Multiple Input Multiple Output (MIMO) antennas, supports both 20 and 40 MHz channels in both 2.4 and 5 GHz bands enabling data rate from 54 Mbps to 600 Mbps [36].

Since the developments in IEEE 802.11 family continues and there are new amendments ratified continuously, fast implementation of the latest technology in chipsets and devices is challenging. Many networks were based on IEEE 802.11n, which was a more significant improvement than previous IEEE 802.11 standards until IEEE 802.11ac was standardized in 2013. IEEE 802.11ac is most recent Very High Throughput (VHT) amendment that is offering a theoretical maximum rate of 6.93 Gbps (accumulated). For the time being, the available network products and chipsets in the market incorporate IEEE 802.11ac. The next amendment focusing on high throughput is the IEEE 802.11ax which provides enhancements for dense network deployments introduces more centralized control than IEEE 802.11ac and utilizes OFDMA techniques for multi-user access. However, since the latest available products and chipsets are based on IEEE 802.11ac, and IEEE 802.11ax is still under development, IEEE 802.11ac is considered in this thesis.

2.2.2 Network topology

In communication networks, there needs to be a topology standardized for the specific technology to describe the configuration of devices and elements of the network. IEEE 802.11 defines two types of elements in a network, a station (STA) as a device that contains an IEEE 802.11 conformant MAC and PHY interface to the wireless medium, and access point (AP) is a networking device that allows a STA to connect to a wired network that can form a WLAN. In IEEE 802.11 terminology, the wireless STAs associated with an AP and the communication going through AP to a wired network is called Basic Service Set (BSS). IEEE 802.11 standardizes two network topologies based on BSS configuration [37] as shown in Figure 4:

- *Independent Basic Service Set (IBSS):* STAs are connected peer-to-peer where there is no node functioning as a bridge or base station, meaning the BSS consists of only STAs. This network topology is also categorized as an ad-hoc network.
- *Extended Service Set (ESS):* Two or more basic service sets are connected by the physical medium that is used to connect access points, which is a wired medium in WLAN cases.

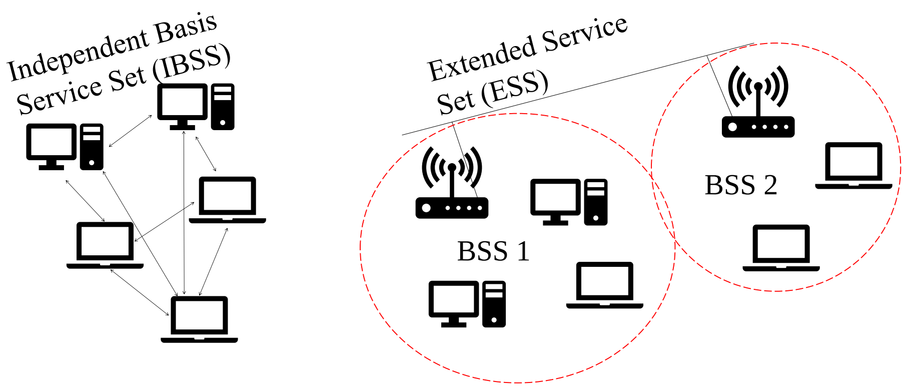

Figure 4: Defined network topologies in IEEE 802.11.

Some of the wireless communication topologies are categorized as a star, mesh, cluster tree, line, star-mesh, point-to-point, and ring representing the flow of the data in a network [38]. Considering the data flow descriptions by IEEE 802.11, the star topology is the most commonly preferred topology in WLANs due to the isolation of point-to-point communication between AP and STA. Each STA is connected to AP and AP is connected to the wired environment.

2.2.3 Physical layer

The Physical layer of IEEE 802.11 networks defines a series of encoding and transmission schemes for wireless communications between the device and the medium. It is the layer in a communication system protocol stack where the data in transmission is converted into bits using complex coding and modulations. The primary services and functions of the Physical layer in IEEE 802.11 network are as the following:

- Establishing and terminating the communication between the device and medium.
- Realizing the resource sharing among users.
- Modulation and coding of the signal that is received from communication medium for transmitting to upper layers and from the medium to upper layers.

IEEE 802.11 defines several PHY layer technologies as IR, FHSS, DSSS and OFDM. The enhancements in the PHY layer technologies continue with the upcoming standard IEEE 802.11ax. The next amendment focusing on high throughput is the IEEE 802.11ax which provides enhancements for dense network deployments, introduces more centralized control than IEEE 802.11ac and utilizes OFDMA techniques for multi-user access. Each technology defines channelization and how to share the time and frequency for communication.

Physical layer and MAC layer of IEEE 802.11 are designed as shown in the in Figure 5. PHY layer is divided into three sub-layers; Physical Layer Convergence Protocol (PLCP) sub-layer, Physical Medium Dependent (PMD) sub-layer and PHY Management. PLCP manages the frame transmission between MAC and physical level, by mapping data units into a suitable PMD format and providing channel access information for MAC layer. PMD layer is responsible for providing the information about Modulation and Coding Schemes (MCS) for transmission of the data unit in the wireless medium [39].

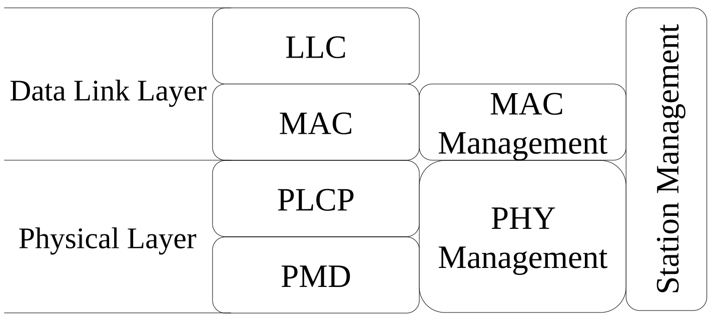

Figure 5: Physical and MAC layer in IEEE 802.11.

PHY layer in IEEE 802.11 is responsible for Carrier Sensing (CS), Clear Channel Assessment (CCA), transmitting and receiving the data. PLCP in STA performs CS continuously, and when the medium is busy because of a transmission, the information in PLCP header and preamble is read and used for receiving or transmitting the data. PLCP senses the medium before attempting any transmissions and reports the medium's state to the MAC layer for deciding on the transmission process. After the MAC layer sends the decision of transmitting, PLCP revoked PMD to transmitting mode. After sending the PHY Service Data Unit (PSDU) with the determined data rates, PLCP reports back to MAC layer the end of the transmission to stop transmission mode and also changes PMD mode to receiving. For receiving a packet, PMD recognized the power level of the signal higher than the threshold value and clear channel assessment indicates the medium is busy. In this case, PLCP reads the header of the frame and if it is error-free reports it MAC layer to notify frame reception. When the final byte of the frame is received, PLCP reports MAC layer the end of reception [40].

2.2.4 IEEE 802.11 MAC layer services

MAC is the layer between physical and transport layers in a wireless communication system. It is responsible for deciding when a node accesses a shared medium, resolving any potential conflicts between competing nodes, prioritization, in other words, correcting communication errors occurring at the physical layer and performing other activities such as framing, addressing, and flow control.

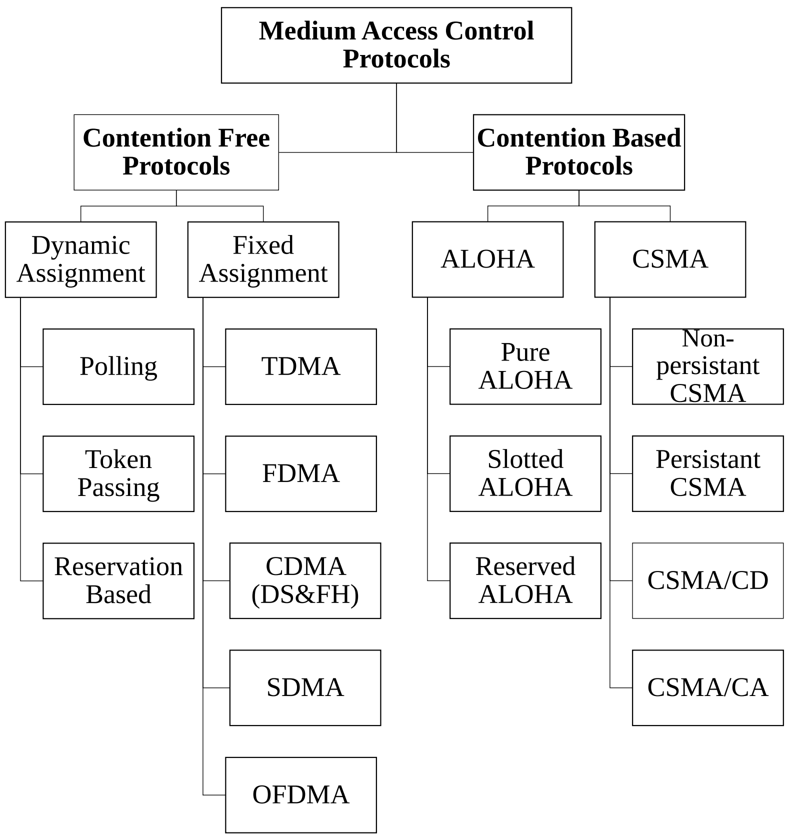

Figure 6: MAC layer multiple access schemes.

In a wireless medium, users request to share scarce radio resources. The task of MAC layer is to transmit data from the physical layer to upper layers in uplink operation and from upper layers to the physical layer in downlink operation which requires a configuration for access to wireless medium and sharing radio resources. There are several methods for radio access categorized according to their mechanism to share the medium as shown in Figure 6 [41].

Two main categories of MAC mechanisms are contention-free and contention-based. Contention-free access is used for the systems when there is a need for dedicated resources for users. In contention-free protocols, by ensuring that each user is allocated to a resource, collisions are avoided. Fixed resource allocation is possible in a different domain as time (TDMA), frequency (FDMA), codes (CDMA), space (SDMA) and both time and frequency (OFDMA). Dynamic assignment methods allow nodes to access the medium on demand with polling; where the controller asks every node is they have anything to transmit one by one, token passing; where a frame for allowing a transmission is passed around, and reservation-based protocols; where the node reserves a time slot for transmission beforehand. In contention-based protocols, the nodes start transmission without resource allocation beforehand. Therefore, there can be collisions due to transmissions at the same time. There are two different methods to prevent collision as ALOHA (Abramson's Logic of Hiring Access) and CSMA. ALOHA is a mechanism where the nodes send a packet whenever they have a packet to send and are variations of ALOHA as Pure, Slotted and Reserved. CSMA is a mechanism like Listen-before-talk, where each node senses the channel before transmission and CSMA has variations of non-persistent, persistent, collision detection and collision avoidance [42].

A successful standard Ethernet - IEEE 802.3 was a good reference for IEEE 802.11 MAC layer. Ethernet uses CSMA/CD where the station senses the channel before transmission if the channel is idle transmission starts and if the channel is busy it waits till channel is idle. Also during the transmission, if there is any collision, the station sends a message to all stations about a collision. However, in a wireless medium, it is not as fast as Ethernet line to detect a collision and abort transmissions. However, CSMA/CD is not a suitable mechanism for a wireless medium. Detecting the collision during over the air transmission is not possible in wireless communications and reporting to other nodes in the system that the collision happened is waste of resources. Therefore, the IEEE 802.11 working group developed a MAC configuration for WLANs, CSMA/CA. Collision avoidance is provided with waiting for a random time after sensing the medium as idle while continuing sensing the medium. If the medium is idle until the end of random time, transmission begins [43].

The first IEEE 802.11 standard supported two types of coordination functions, Distributed Coordination Function (DCF) protocol and an optional Point Coordination Function (PCF) Protocol. The fundamental access scheme for IEEE 802.11 systems, CSMA/CA, is implemented in the MAC layer as DCF and a new packet in the system follows the steps as in Figure 7. In DCF, STA senses the medium for a fixed period of time before transmission attempt, which is DCF inter-frame space (DIFS). If the medium is idle at the end of DIFS, STA starts backoff operation.

Carrier sensing in DCF is done in both physical and MAC layer and the medium is idle if both senses the channel as idle. If the medium is busy at any point of channel sensing during DIFS, STA starts waiting until the channel is idle again and waits for another DIFS and random duration of backoff afterward.

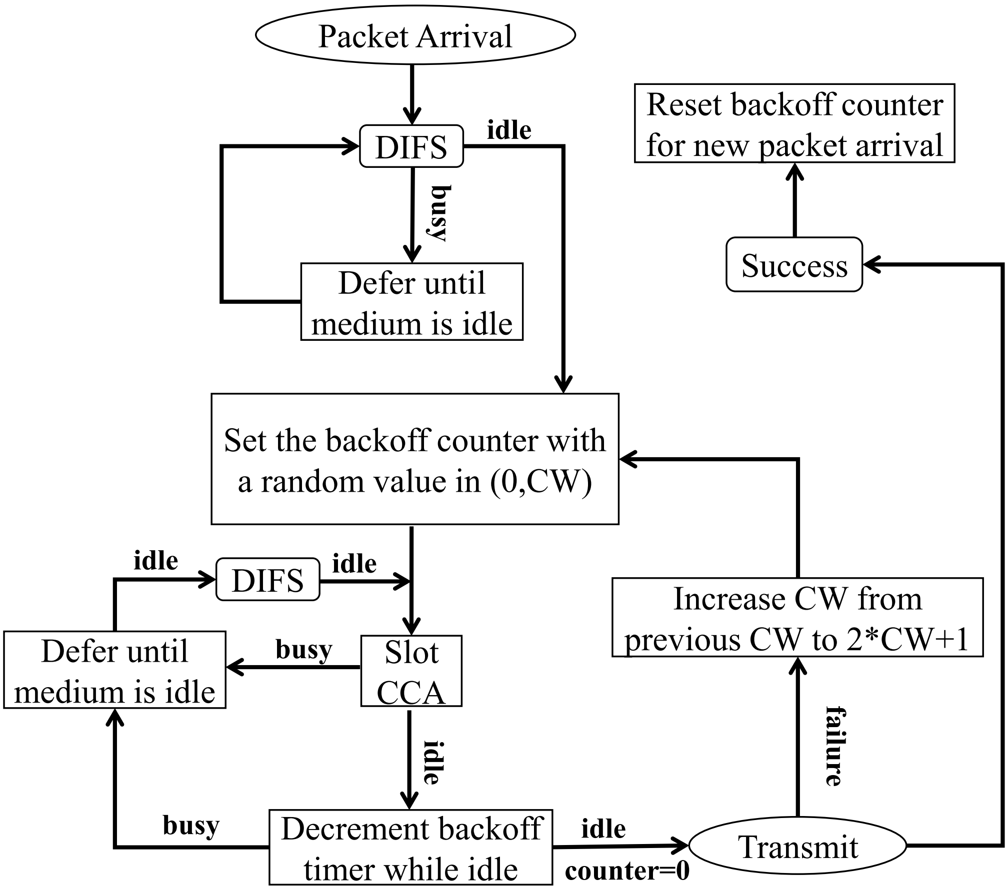

Figure 7: Channel Access in DCF.

If the channel is busy again during DIFS or backoff time, the STAs defers until the channel is idle and starts DIFS again. If the medium stays idle during DIFS and then backoff time and when it reaches zero than STA can transmit. If the STA cannot access the medium during the first backoff, backoff counter stops and waits for DIFS time for the channel to be idle again and start the backoff counter again. If the counter reaches zero and medium is idle, STA transmits the packet. If there is a failure in transmission, CW is increased to 2*CW -1 and backoff counter increases. All STAs have a Contention Window (CW) value for determining backoff counter. The backoff counter is determined as a random integer drawn from a uniform distribution over the interval [0, CW]. Backoff in a IEEE 802.11 system helps to randomize the medium access. Once a STA gets access to the channel and starts transmitting, it keeps a short inter-frame spacing (SIFS) between frames in a sequence to keep the medium busy for other STAs trying to access the channel. Therefore, during the transmission opportunity, SIFS is always smaller than DIFS. After the transmission of a packet, ACK is sent to the STA. The ACK frame is transmitted after a SIFS since it is shorter than DIFS and again other STAs cannot get the opportunity to transmit in between. If the ACK is not received, it means that the transmission is failed because of some problem during the transmission and depending on the network configurations, it can be transmitted [44].

The inter frame timings of IEEE 802.11 are depicted in Figure 8. SIFS is a short timing for messages that need to be transmitted immediately and other channel sensing the channel is idle. This spacing is used for ACK and MAC layer CS with Network Allocation Vector (NAV). NAV is a mechanism to overcome hidden node problem with an exchange of Request-to-Send (RTS) and Clear-to-send(CTS) messages. PIFS is a spacing that is used when AP and STA are in a contention free period. It is used for Beacon frames, but not in use for many devices. DIFS is the frame spacing when DCF is used. New coordination functions and inter-frame spacing values for MAC layer are introduced with IEEE 802.11e, an amendment for QoS in IEEE 802.11 networks, is described in the next section.

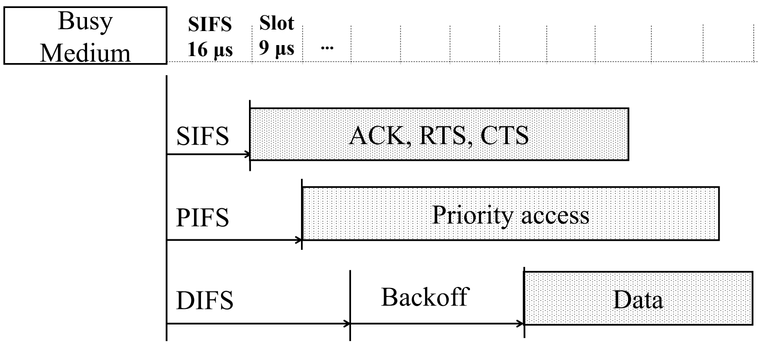

Figure 8: Inter frame spaces in IEEE 802.11 [43].

In IEEE 802.11 networks, the MAC layer is responsible for packet transmission between LLC and PHY layer. When a packet is received for upper layers, the MAC layer creates a new packet with adding related fields. The packet format of the MAC layer in IEEE 802.11ac is shown in Figure 9.

Bits: 4	**1**	**2**	**1**	**8**
TID	EOSP	ACK Proxy	MSDU	TXOP Limit/Queue Size/Buffer State

Bytes: 2	**2**	**6**	**0 - 6**	**0 - 6**	**0 - 2**	**0 - 6**	**0 - 2**	**0 - 4**	**variable**	**4**
Frame Control	Duration /ID	Address 1	Address 2	Address 3	Sequnce Control	Address 4	QoS Control	HT Control	Payload	FCS

MAC Header

Figure 9: MAC Frame Format [44].

In short, the MAC layer adds information to the MAC Service Data Unit (MSDU) in the form of headers and trailers to create the MAC Protocol Data Unit (MPDU). The first information in the MAC layer is frame control that contains interpretation information of the other fields of the MAC header. QoS Control field is described in Section 2.2.5. HT control frame has the information of HT or VHT specifications of the frame. The frame check sum (FCS) is used to determine if the MAC frame is decoded correctly in the receiver.

2.2.5 Quality of Service in IEEE 802.11

Wi-Fi is a best effort network, like Ethernet, that tries to send the packets as soon as possible without any assurance of reliability, delay bounds, or throughput. Best effort networks are based on providing equal opportunity to transmit to all users in the system without categorizing. However, quality of service requirements of the traffic vary a lot depending on the various application and traffic types. Digitalization and increasing demand on using of new multimedia contents like video, voice over IP, video conferencing, real-time connection and time-sensitive critical applications require differential QoS features [45]. This changes necessitated all communication systems to adapt a QoS framework to serve different categories of data with a particular requirement. Wi-Fi systems give equal access opportunity to all users and cannot prioritize any data category from others. Therefore, there was a need for improving IEEE 802.11 system to enable QoS in the network.

The IEEE 802.11e working group designed the QoS improvements in IEEE 802.11 networks in 2005 [36]. The IEEE 802.11e amendment [46] provides prioritization for up to eight classes for users. It describes a new mechanism, Enhanced Distributed Channel Access (EDCA) protocol, with changing three main operations in DCF. Four Access Categories (AC) defined as voice, video, best effort, and background are implemented for traffic categories for different STAs. For prioritizing different ACs in MAC layer, DIFS parameter is specialized for each AC with different the Arbitration Inter Frame Spacing (AIFS), and also CW_{min} and CW_{max} values are defined separately for each access categories. The mapping of user priorities from is shown in Table 5.

IEEE 802.11e introduces Hybrid Coordination Function (HCF) which is a new mode that allows new QoS features to operate within a cell while also supporting operability with the legacy non-QoS mechanism by improving the original PCF and DCF. HCF includes two new channel access methods as HCF Controlled Channel Access (HCCA) and Enhanced Distributed Channel Access (EDCA). HCCA is an improved version of PCF. EDCA is a QoS improved DCF with AC specified AIFS, CW_{min}, and CW_{max} parameters. In HCF, for each frame exchange with either EDCA or HCCA, there is a contention free period, Transmission Opportunity (TXOP), for defining the duration which a station can send or receive data without contending for the medium. TXOP interval defines medium access duration with a starting time and a maximum duration. The TXOP limits for AC in IEEE 802.11ac are 0 for both AC_BK and AC_BE, meaning that they can only transmit one frame in each transmission opportunity, 22.56ms for AC_VI and 11.28ms for AC_VO. QoS

Table 5: Access categories and user prioritization mapping in IEEE 802.11e

Priority	**Traffic class**	**Access Category**
1	BK	AC_BK - Background
2	-	
0	BE	AC_BE - Best effort
3	EE	
4	CL	AC_VI - Video
5	VI	
6	VO	AC_VO - Voice
7	NC	

specifications of the packet are in the QoS control field in a MAC frame [44].

In EDCA mechanism, four access categories are directed to four priority queues based on traffic class based. All frames to transmit are placed into one queue of appropriate AC. The queues in IEEE 802.11 MAC layer work with a single first-in-first-out (FIFO) transmission [47]. When a packet is at the head of the queue, it starts competing for the channel access. The mechanism for channel access follows the same steps as in DCF, but different parameters of AIFS, CW_{min} and CW_{max} per AC. The calculation of AIFS and the values in IEEE 802.11ac of separate AIFS, CW_{min} and CW_{max} are shown in Equation 1 and Table 6. In IEEE 802.11ac, aSlotTime is defined as 9μs and aSIFSTime as 16μs.

$$\mathbf{AIFS[AC]} = aSIFSTime + AIFSN[AC] * aSlotTime \tag{1}$$

Table 6: CW and AIFSN parameters for AC in IEEE 802.11ac [44]

AC	$\mathbf{CW_{min}}$	$\mathbf{CW_{max}}$	**AIFSN**
AC_BK	15	1023	7
AC_BE	15	1023	3
AC_VI	7	15	2
AC_VO	3	7	2

Before stating transmission, a random access process of CCA and backoff is operated independently in each queue. The random access process follows the same order of operations as DCF, as described in Figure 7. The difference is that instead of DIFS, different access categories use different AIFS times and backoff times are calculated according to different values of ACs as illustrated in Figure 10. If two packets from different AC complete a successful random access process at the same time, internal collision resolution grants the higher priority packet to transmit, and the other packet continues the process as if a physical collision occurred during transmission [48].

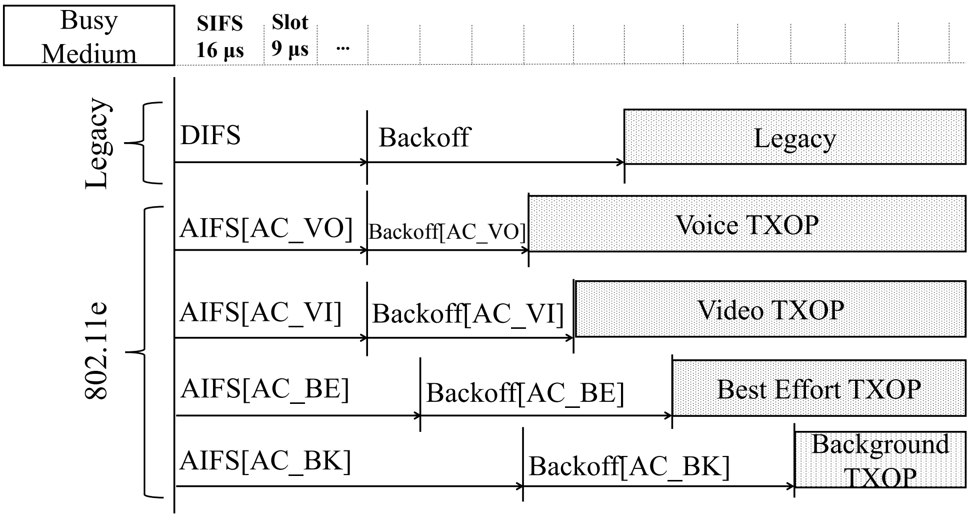

Figure 10: EDCA random access processes [43].

Some other new features of IEEE 802.11e are using Block Acknowledgements (BlockACK) and No Acknowledgement (NoACK). With BlockACK, sending multiple frames without for an ACK after every transmission is possible. BlockACK is sent after the stream of frames are over with the list of the received frames. This way, it helps to reduce the channel occupation time by ACKs. NoACK feature is where the frames do not need an ACK after the transmission. This feature is important for some time-critical applications since it increases the channel availability.

2.2.6 Major features of IEEE 802.11ac

Very High Throughput (VHT) working group was formed in 2008 to improve the performance of IEEE 802.11, and in December 2013 IEEE 802.11ac amendment was ratified. Primary drivers for the development of WLANs were the needs for better QoS, supporting more users in a network and faster data transmission by introducing improvements and new features. The latest revealed version of IEEE 802.11 in 2016 includes the final version of IEEE 802.11ac and the revision 2013.

IEEE 802.11ac brings higher data rates and more capacity, increases robustness, introduces MU-MIMO, and reduces delay, power consumption and interference with enhancements in both PHY and MAC layers. IEEE 802.11ac improves the techniques that are used in IEEE 802.11n, and some of the differences of IEEE 802.11ac from IEEE 802.11n are shown in Table 7. The first important PHY layer feature of IEEE

802.11ac is that it operates only in the 5 GHz frequency channel. The task group for IEEE 802.11ac was working for the frequencies below 6 GHz, which means 2.4 and 5 GHz operation of WLANs. The interference in 2.4 GHz because of other technologies using the same unlicensed band is the biggest reason for IEEE 802.11ac to support operation at 5 GHz, but also the number of non-overlapping channels in 5 GHz band is higher than 2.4 GHz band and extending the use of 5 GHz band in product is another reason [50].

Table 7: Differences between IEEE 802.11n and 802.11ac

IEEE 802.11n	**IEEE 802.11ac**
Channel width of 20 and 40 MHz	Supports 20, 40, 80 and 160 MHz
Frequency band 2.4 and 5 GHz	Supports on 5 GHz
BPSK, QPSK, 16-QAM, and 64-QAM	Supports also 256-QAM
Only single user transmission	Adds multi user transmission
MIMO up to 4 spatial streams	Supports up to 8 spatial streams

IEEE 802.11ac uses OFDM-based transmission like the previous amendments from the first standardization of OFDM in IEEE 802.11a and IEEE 802.11n. In the amendment IEEE 802.11ac, 20 MHz channel consists of 64 FFT samples meaning that there 4 of them are pilot sub-carriers. Pilot carriers do not carry any data, but they are used for making the coherent detection robust against frequency offsets and phase noise. The sub-carriers in the middle of the channel are nulled to reduce problems in analog baseband circuits, and the sub-carriers at the highest and lowest edges of the bandwidth are nulled to avoid interference from adjacent channels. The carriers on the edges of the channel are also called guard channels since they carry zero energy [51]. IEEE 802.11ac supports channel bandwidth of not just 20 and 40 MHz like in IEEE 802.11; it adds 80 MHz channel bandwidth and optional 160 MHz band. Channelization of wider bandwidth provides higher speeds.

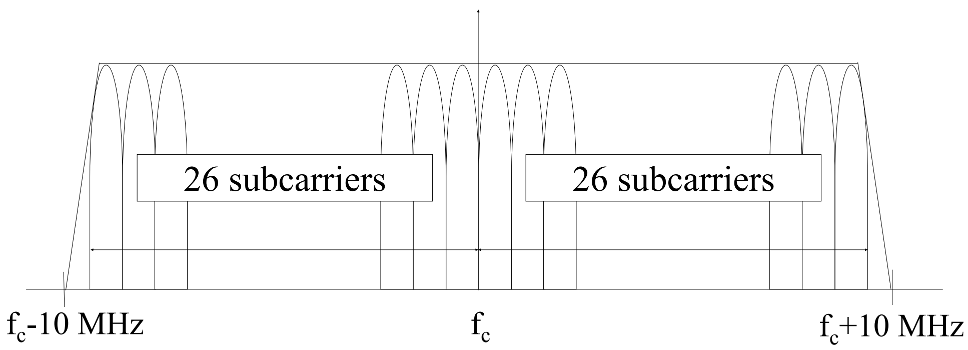

Figure 11: OFDM sub-carriers in 20 MHz channel in 5 GHz IEEE 802.11ac.

In data transmission, Modulation and Coding Scheme (MCS) is one of the key parameters of the data rate. It represents a set of modulation and coding rate. Modulation defines how many bits can be transmitted with a carrier. It is possible to transmit more bits with a higher modulation scheme while requiring more power level. Coding rate represents the ratio of data bits to the sum of data and redundant bits for error correction. High code rates increase the number of data bits per transmission while risking the error ratio. IEEE 802.11n offers more than 70 MCS options; on the other hand, there are ten options in IEEE 802.11ac as shown in Table 8 which makes the MCS selection process simpler. IEEE 802.11ac also offers new MCS options with 256-QAM [52].

Table 8: MCS and FEC of IEEE 802.11ac

MCS	**Modulation**	**FEC Rate**	**Data Rate (Mbps)**			
			20 MHz	40 MHz	80 MHz	160 MHz
0	BPSK	1/2	7.2	15	32.5	65
1	QPSK	1/2	14.4	30	65	130
2	QPSK	3/4	21.7	45	97.5	195
3	16-QAM	1/2	28.9	60	130	260
4	16-QAM	3/4	43.3	90	195	390
5	64-QAM	2/3	57.8	120	260	525
6	64-QAM	3/4	65	135	292.5	585
7	64-QAM	5/6	72.2	150	325	650
8	256-QAM	3/4	86.7	180	390	780
9	256-QAM	5/6	N/A	200	433.3	866.7

One of the most important PHY layer enhancements in IEEE 802.11ac is the improvement about MIMO, that was introduced by IEEE 802.11n, by supporting up to eight spatial streams and enabling Multi-User MIMO (MU-MIMO). MU-MIMO creates a significant change in how Wi-Fi networks planned since it enables the use of the same channel by more than one STA that is connected to same AP.

Even though IEEE 802.11ac amendment mostly focuses on improvements in the PHY layer, it also introduces some MAC features. One of the MAC layer enhancements is mandatory use of frame aggregation. IEEE 802.11n introduced an optional frame aggregation feature to reduce channel occupation caused by random access process. IEEE 802.11ac makes the frame aggregation mandatory even if a STA want to transmit only one frame since with the high data rates in IEEE 802.11ac, aggregation still reduces the channel occupation duration [53].

There are many more enhancements introduced by IEEE 802.11ac. Some of the new PHY layer features are dynamic channel bandwidth management; a single method closed loop transmit beamforming. There are also more MAC layer enhancements as spatial diversity multiple access, as a result of MU-MIMO, a new encryption option Galois Counter Mode Protocol and power save mode with new TXOP [54].

3 Enhancements on MAC layer

As explained in Chapter 1, the integration of a Wi-Fi system in a TSN network is studied in this thesis. The need for a wireless link in industrial automation cases arises from many advantages like mobility, less complexity, and quick deployment. For a wired network in an industrial automation scenario, the most beneficial link to be wireless is the link reaching the end device because the end devices can be mobile, far or plenty. Therefore, the last hop in a TSN network topology, which is the link between the last TSN switch and Listener, is replaced by a wireless link connecting both the TSN switch and Listener to a Wi-Fi access point, as illustrated in Figure 12.

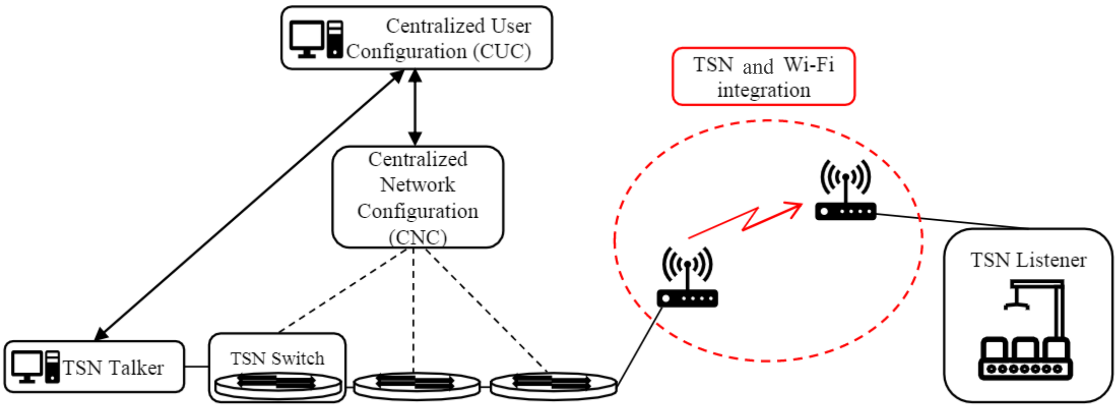

Figure 12: Proposed topology for TSN and Wi-Fi integration in factory automation.

This proposed deployment indicates that the TSN traffic flowing from a TSN Talker to a Listener with bounded delay requirement needs to be transmitted over a Wi-Fi link while satisfying the same requirements. However, deterministic, time-aware networking with resource allocation is on the contrary with the fundamentals of a Wi-Fi system. To make IEEE 802.11 standards compatible with the features of TSN, there need to be radical changes.

The PHY and MAC are the two layers of the IEEE 802.11 reference model that requires modification for performance improvements depending on the research area. There are limitations in both MAC and PHY layers for industrial automation use cases in the current VHT Wi-Fi standard, IEEE 802.11ac. One of the fundamental limitations in the PHY layer for industrial automation traffic is the transmission time. The transmission time of a packet depends on the PHY layer parameters of the channel width, guard interval, and MCS selection. Following the packet formats of the PHY layer in Figure 13 and MAC Layer in Figure 9, possible transmission time ($\mathrm{T_{tx}}$) of a single spatial stream in a Wi-Fi system with IEEE 802.11ac amendment is calculated as in the Equations (2).

$$\mathbf{T_{tx}} = T_{\text{PHY}} + N_{\text{symbol}} * (T_{\text{Symbol}} + T_{\text{GuardInterval}}) \tag{2}$$

As illustrated in Figure 11, in a 20 MHz channel in 5 GHz frequency band, there are 52 data sub-carriers out of 64 sub-carriers. Each sub-carrier carries one symbol, and that symbol duration is 3.2 μs. According to the IEEE 802.11ac standard, there are two possible guard intervals, a long interval of 0.8 μs and a short interval of 0.4 μs. Short guard intervals can result in higher error rates, but they can be used to increase the throughput. For time-sensitive data, long guard intervals can be considered. Therefore, 4 μs is needed for transmission of each symbol. The number of data bits per symbol is a selection of MCS and channel bandwidth. The best MCS for fast transmission in IEEE 802.11ac is MCS 9 with 256-QAM and 5/6 coding rate. With 256-QAM modulation, each symbol carries 8 bits, and with 5/6 coding rate, the number of bits per carrier (N_{bc}) is 40/6 bits. In one OFDM symbol, $52 * N_{bc} = 1040/3$ bits can be carried. In a PHY layer packet, there are mandatory PHY and MAC layers parameter fields for the transmission in addition to the payload. The shortest transmission time of a packet consists of 32 μs PHY layer preamble and 196 bits of MAC header and FCS. Since the data field of PPDU is smaller than the capacity of one symbol, padding is needed for filling one symbol. In this case, it would take minimum 36 μs as a best-case scenario for the transmission of a packet without payload. For a faster transmission, a wider channel of 160 MHz can be used with short guard interval but the transmission time of small size would not change.

← Legacy Preamble →			← VHT Preamble →						
8 µs	**8 µs**	**4 µs**	**8 µs**	**4 µs**	**4 µs**	...	**4 µs**	**4 µs**	**variable**
L-STF	L-LTF	L-SIG	VHT-SIG-A	VHT-STF	VHT-LTF1		VHT-LTFN	VHT-SIG-B	Data

Figure 13: VHT PPDU format in IEEE 802.11ac [43, 44].

Transmission time is calculated with the best possible MCS in both 20 MHz width without payload, and MAC layer operations of AIFS, backoff time, SIFS and ACK duration are not included. The transmission time of a packet using the current PHY layer and MAC layer frame formats and mechanisms gives an indication that for serving applications with strict and small delay requirements like 1 ms delay and small jitter like 1 μs in a Wi-Fi system, many enhancements and modifications are required. The current standards have many limitations and room for new developments to satisfy the requirements of time-critical applications. Since this thesis aims to take an initial step to study performance enhancements for the current standard, the goal is to improve IEEE 802.11ac systems MAC layer for a better QoS for time-critical traffic.

Enhancements on both PHY and MAC layer of IEEE 802.11 can improve the system's performance. For improvements in the PHY layer, introducing new MCS, link adaptation algorithms, MIMO, and many other areas can be studied. On the other hand, MAC layer improvements are studied in this thesis. The main concern for TSN and Wi-Fi integration is the coexistence of TSN and other traffic categories; prioritizing the TSN traffic. These concerns direct the research towards QoS mechanism in MAC layer. To provide a better service in both ends, QoS enhancements that serve the traffic according to the application types characteristics are crucial. The research focus in this thesis resembles how TSN technologies improve Ethernet to be a deterministic technology, is working on how Wi-Fi can be more deterministic. There are various ways to improve the performance in a deterministic manner like timing and synchronization, scheduling and path reservation, traffic prioritization and resource dedication. For enabling these operations, a first step of the design is classifying TSN traffic as a new and high priority access category.

3.1 Introducing a new access category

The key medium access mechanism in ISM bands is the listen-before-talk behavior. IEEE 802.11 standards are for ISM bands and the underlying mechanism for wireless medium access, CSMA/CA, only allows one node to transmit at a time. As a result of this mechanism, nodes requesting access to the medium compete. Using Wi-Fi technology, and its underlying random access mechanism, in conjunction with industrial Ethernet systems for industrial automation applications, tend to produce jitter. The random access process introduces a different value of delay when serving packets over the wireless medium due to randomization in channel access mechanism, meaning that the packets do not arrive at the receiver at fixed times. The varying delay values create the jitter. Thus, small jitter values cannot be obtained with the current random access process of Wi-Fi.

IEEE 802.11 MAC layer QoS mechanisms cause two significant problems in TSN traffic transmission process; not accessing the medium on time for transmission within bounded delay due to competition and high jitter values due to random backoff time before starting to transmit. As a solution, a new access category with higher priority in IEEE 802.11 MAC layer is proposed and simulated in this thesis. The proposed design for improving QoS for TSN-like traffic over Wi-Fi is a modification of the current standard by introducing an additional way of handling the queues as shown in Figure 14. The origin of the improvement is inspired from IEEE 802.11e EDCA amendment, where traffic flows are categorized into four access categories and prioritization is provided with different MAC level service parameters AIFS, CW_{min}, CW_{max} and TXOP for each Access Category.

The QoS parameters of the new access category are $CW_{min} = 0$, $CW_{max} = 0$, AIFSN = 0 and TXOP = 11.28 ms. These parameters describe a transmission as the following; when a new TSN packet is received in MAC layer, channel sensing starts with AIFS duration of just SIFS, 16 μs according to IEEE 802.11ac standard, and if the channel is idle at the end of this period, TSN packet is transmitted to the wireless medium without waiting for any backoff time. As a result, when a TSN packet and a packet of another access category is received in the MAC layer, TSN packet gets to transmit before due to shorter AIFS duration. Also, not waiting for a randomized backoff duration minimizes the possible jitter. If the medium is busy during AIFS for TSN packet, then the packet waits until the channel is idle and senses again for AIFS duration before transmitting to the wireless medium.

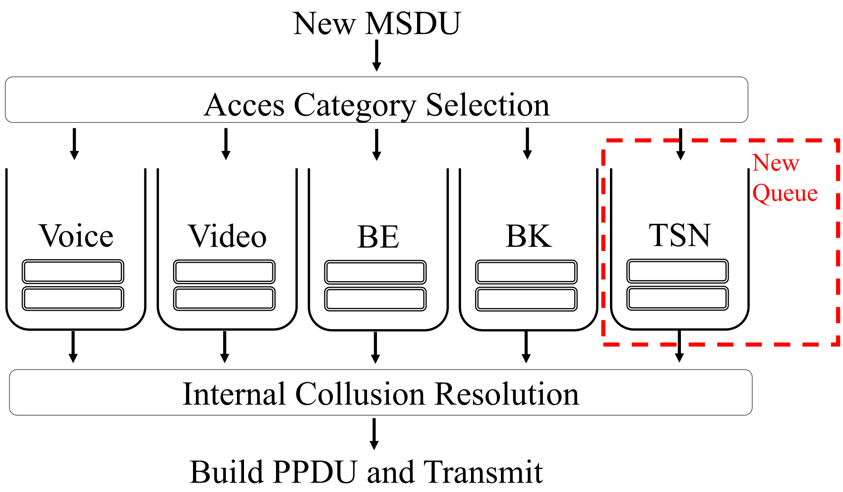

Figure 14: Proposed access category integration to EDCA.

Additional improvements in the proposed design to provide a better QoS for TSN packets are using a fixed MCS instead of Minstrel link adaptation algorithm in IEEE 802.11 and a bounded delay limit for discarding the TSN packets which waited in the system for a long time.

- **Using fixed MCS**

  Wi-Fi systems use link adaptation algorithms for achieving an optimal data rate according to the quality of the radio channel. There are several popular algorithms for link adaptation, but the Minstrel algorithm is the most widely used algorithm in commercial products of IEEE 802.11 [55]. Data rate configuration in IEEE 802.11 system is based on channel width, MCS, guard interval and the number of spatial streams.

  Basic Minstrel algorithm optimizes MCS selection for optimum data rate. The algorithm works as the following; first, AP and STA agree on a channel configuration. Second, according to the channel configuration, the algorithm picks an $\mathrm{MCS_h}$ for the highest possible data rate and tries sending the packets with the MCS values in the range $[1, \mathrm{MCS_h}]$. Third, according to the calculated data rate of the packets, it creates a table of MCS values resulted in highest data rates. Then, depending on the average shifting parameter of Minstrel algorithm, it stops at an MCS that best for the channel condition [56].

  Even though link adaptation algorithms help to increase and to optimize increasing and optimizing the data rate in WLANs, for time-sensitive traffic transmission, it creates a problem. The transmissions before choosing the best MCS may cause packet losses and also changing the MCS causes delay variation, creating jitter. Therefore, to decrease packet losses and ensure the packet transmission, a fixed MCS is used in some simulation cases instead of Minstrel algorithm. A fixed MCS value is chosen as 0 since it is the most robust and reliable MCS.

- **Bounded delay**

  Bounded delay is an important condition for real-time applications, and hence, for TSN. As the name implies, there is a time period in which the packet should be transmitted and received at the end device. In a Wi-Fi system, it is not possible to guarantee the packet transmission in a certain time period because the radio resources are not dedicated to any STA. Therefore, bounded delay requirement is challenging to met. Since the TSN traffic needs to be delivered in a bounded delay limit, if the packets are kept waiting in the system since the Wi-Fi system cannot serve them as fast as possible, there is no need to send them after the time period for delivery is expired.

  In some of the simulation cases, a bounded delay limit is implemented in MAC layer transmitter. Before starting channel sensing for transmission, the timestamps of the packets are checked to decide if the packet is in the system for longer than the bounded delay limit or not. If the delay is longer than the limit, the packet is discarded. Bounded delay limit is a constraint for a Wi-Fi system since it causes packet losses. However, it helps reducing the memory consumption in the system and to save more computational and wireless resources.

To observe the performance of proposed improvements in a Wi-Fi system, several simulations with various configurations are performed. For evaluating the performance in the simulations, analysis focuses on the statistics of important QoS parameters. The crucial QoS parameters for MAC layer performance in Wi-Fi are explained in the next subsection 3.2.

3.2 Key performance indicators for result analysis

Quality of Service (QoS) is the capability of the network to provide differentiated service for chosen traffic in the network. For WLANs, several enhancements can be achieved with improving QoS in the network. The need for dedicated bandwidth for critical applications, controlled jitter, and delay that is required by real-time applications, low network congestion, enhanced network configuration, and traffic prioritization can be supported by QoS developments [57].

The performance evaluation parameters for QoS are also called Key Performance Indicators (KPI). To evaluate the QoS performance of communication networks, KPIs that can be categorized into three as timelines, bandwidth, and reliability [58]. Depending on the service requirements of the traffic, different indicators can be used to assess the performance.

For QoS evaluation of prioritizing a time-critical application in IEEE 802.11 networks, delay and jitter are the most crucial timeline KPIs to consider. Since all the packets in real-time applications are essential in real-time traffic, packet losses during the transmissions are not wanted; therefore, it is also a crucial indicator. The data rate is a helpful indicator to observe systems efficiency and bandwidth usage. The mentioned KPIs for QoS in communication networks are explained below.

- **Data rate**

  The data rate is the measurement of transmitted bits per second. Many applications and services require a minimum data rate because if it falls under the minimum requirement, it can cause slow functionality in the application or even applications to stop working. Data rate varies depending on the load in a system.

- **Delay**

  Delay, which is also called latency, in transmission is defined as the time difference between the instances when a packet is sent from the transmitter and when it is received at the receiver. Delay can result from many components. If the network is overloaded, it takes a longer time than expected for a packet to be transmitted or the path configuration can be changed to a longer one with less load, which causes delay.

  End-to-end delay requirement became more important with the development of 5G networks. The definition of end-to-end is the duration between the transmission of a packet from the application layer at the source node and the successful reception at the application layer at the destination node plus the equivalent time needed to carry the response back. The delay in each protocol layer should be decreased for minimizing end-to-end delay.

- **Jitter**

  In communication systems, jitter is defined as a variation in delay of transmission. Delay of a packet can vary because of the queue length in the system, depending on the load. The path between the nodes in the network can be different for each packet, which can also create a variation in delay. Any source that creates a delay can also cause jitter in a transmission.

  Since jitter is defined as the variation of delay from the expected value, fitting this definition in a Wi-Fi system is not possible. Due to the random channel access principle of Wi-Fi, calculating an expected delay for the packet beforehand is not possible. Therefore, a jitter definition for Wi-Fi system is described in subsection 3.3.

- **Packet Loss**

  In a network, packet losses can occur during transmission due to some problems. Errors in data transmission like data load corruptions and network congestion like packet arrivals in a node when the buffers are full can the problems causing packet losses. Packet loss can be calculated as the ratio of lost packets to received packets. Depending on the application layer protocol, retransmission of lost packets can be asked, and this causes additional delay in the system for other packets.

3.3 Jitter definition for Wi-Fi

As mentioned in the jitter description above, defining jitter as dependent on an expected delay value is not possible for Wi-Fi systems. The delay in Wi-Fi systems is not predictable beforehand; hence, jitter definition is left for the application layer in IEEE 802.11 and 803.2 standards. For wired communication, as the definition in TSN also follows, expected delay in a transmission route can be calculated, and the jitter is the difference between expected value and real delay. However, in a random access wireless communication system, it is not possible to predict the delay without actually sending the packet over the air. Therefore, controlling the jitter in a Wi-Fi system is more challenging. For satisfying the requirements of real-time applications in a Wi-Fi system, jitter caused by the wireless hop should be minimized, and there is a need for jitter definition for development in Wi-Fi system's performance.

The approach for jitter definition is based on the delay variations. Since the delay is not known before packet transmission, it is calculated depending on the previous packet transmissions like in the Real-Time Protocols [59]. For the calculation of jitter in IEEE 802.11 standard, delay values are used. The definition in Equation 3 is for end-to-end jitter calculation in the application layer.

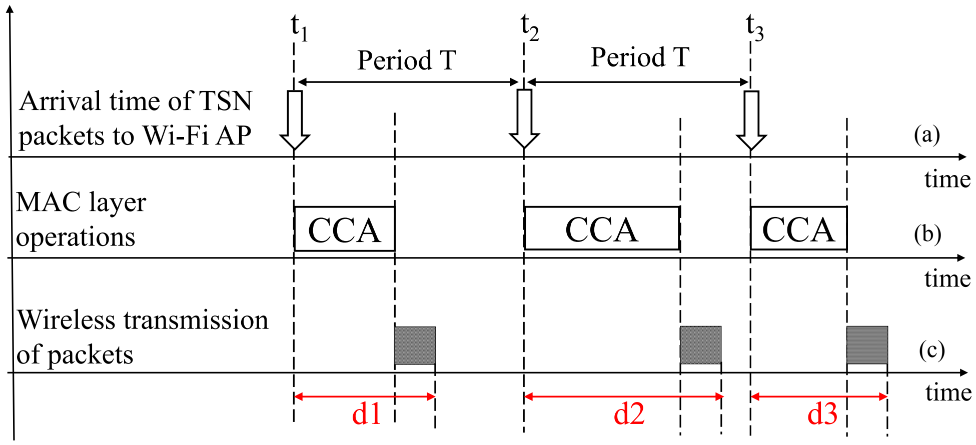

Figure 15: Transmission of a TSN packet in MAC layer.

$$\begin{aligned} d_1 &= t_{\mathrm{r}1} - t_{\mathrm{t}1} \\ d_2 &= t_{\mathrm{r}2} - t_{\mathrm{t}2} \\ j_2 &= |d_2 - d_1| \\ &\cdots \\ \mathbf{j_n} &= |d_{\mathrm{n}} - d_{(\mathrm{n}\text{-}1)}| \end{aligned} \tag{3}$$

For the equation, let's assume that the traffic in TSN is periodic and the packets arrive in Wi-Fi AP without any jitter at times t_1, t_2, t_3 and so on as depicted in Figure 15. Then, the delay of each packet is calculated as their reception time at the receiver minus the transmission time from the AP. Next, the delay difference between two consecutive packets is the calculated as jitter (j). From this definition, it is obvious that if the consecutive delay values are different, the jitter value is different from zero.

To keep end-to-end delay in a limit, the variations on expected delay should be minimized; in best case scenario, should be zero. Therefore, the randomness in the Wi-Fi system should be minimized. The delay in a Wi-Fi system is a combination of channel sensing, backoff, retransmissions and packet transmission time. Moreover, jitter from the randomness in channel access mechanism and retransmission possibility. With the new QoS access category for TSN in MAC layer, the aim is minimizing the randomness for TSN packets while inactivating backoff process and optimizing the system for fewer retransmissions.

4 Simulation methodology and design

Simulations are the computer programs imitating the operation of a real-world system or processes over time. They are key solutions to various real-world problems and used to describe and analyze the behavior of a system. Simulations help to learn and test the behavior of a system before starting implementation.

Simulations are preferred in research and development due to their various advantages. One outstanding advantage is that they can provide fast feedback on the system behavior, opportunity to analyze and evaluate the correctness before physical implementation. In this way, they are both efficient and flexible about giving feedback and also cost saving. Although the ease of design, compliance, and expertise, all the advantages lead to one main asset, cost saving [60].

System and model are the two main elements when designing a real-world simulation. The system is the equipment, environment and the process of the simulation idea. Model is the set of assumptions about the behavior the system in real life. Both existing and conceptual systems can be modeled with a simulation [61].

4.1 Simulation methodology

Communication networks are complex systems having a variety of scenarios. Monte Carlo methods are a way of simplifying the complexity of a communication system by randomizing the input parameters in the system. The input parameters are defined with statistical distributions and the output driven by the randomized inputs creates variety in the results. Therefore, Monte Carlo simulation methodology is commonly used in telecommunication.

In this thesis, an event triggered system level Monte Carlo simulation is used. This methodology requires defining the events, input, and output in the system beforehand. Monte Carlo simulations use random number generators with defined probability density functions in order to simulate the desired system. They design a simulation driven by the events occurring at random discrete time points and changing the state of the system. Since it is an event-based method, simulation assumes that there is no change in the system between two consecutive events and does not simulate those time periods. The main idea of Monte Carlo methods is to obtain a large number of samples based on repeated random sampling and give a statistical analysis of the results.

4.2 Simulation design and implementation

A system level simulation with a link to system interface that is focused on modeling the PHY and MAC layer details is used for this thesis. A system level simulation is widely used for performance evaluation of a system in real operation. Communication networks are also complex systems with various network elements and users of real operations. On the other hand, designing a simulation with the details of all network elements would take extremely long duration and requires a very high computational power. Therefore, designing each part of the simulation separately and connecting those parts with interfaces is more efficient and controllable. The parts of the system are link level simulations designing a point-to-point communication between network elements. In a communication network, link to system level interface provides the performance information of each level to the system level simulation.

The simulation design that is used for this thesis is described in Figure 16. The figure shows one side of the transmission where TSN packets are created in devices and send over the Wi-Fi link to the end device. In the simulation, after packets are received in the Wi-Fi Access Point (AP), packets are transmitted through the application, network, and Logical Link Control (LLC) layers and Service Data Units (SDU) are received in the MAC layer. In the MAC layer, MSDUs (MAC Service Data Unit) are assigned to the different queues depending on their QoS parameters, Access Category (AC) information. When the random access and backoff process is completed successfully for an MSDU, it is transmitted to the PHY layer as an MPDU (MAC Packet Data Unit). Then the packets are transmitted over the air. The reception process follows a similar manner in the reverse direction. A Station (STA) receives the packet from the PHY layer and transmits it to the application layer.

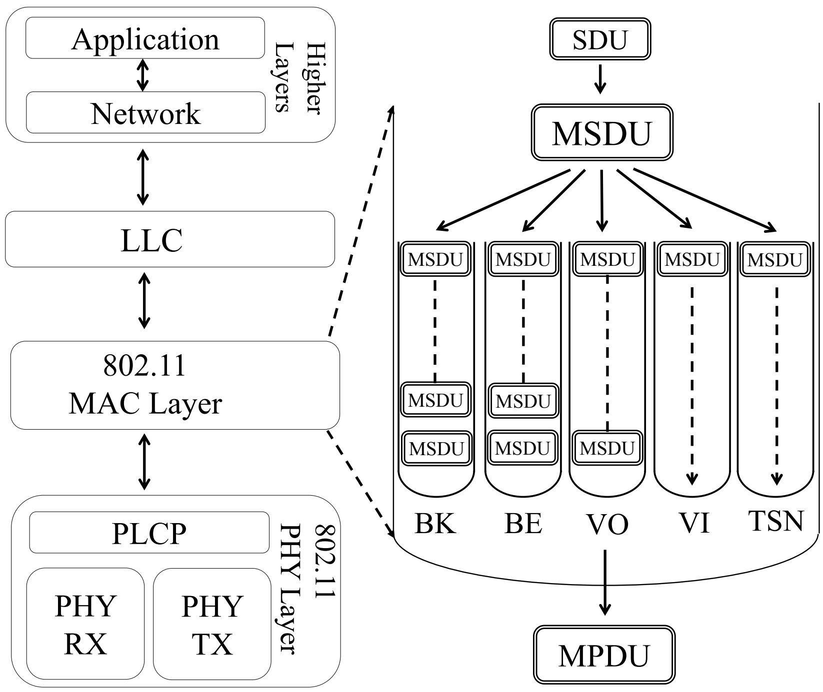

Figure 16: Protocol stack and MAC layer of the simulator.

4.2.1 Simulation parameters

One of the most crucial configurations in simulations is collecting relatively enough number of samples for reliable statistics. Simulations are run for 200 s, 4 times with different initial numbers for the random number generator to achieve enough number of random and different samples in results. Samples in the first 10% of the simulation time are discarded from the statistics to collect samples after the system is in a stable state. The number of the samples depends on the simulation case and number of events.

This thesis focuses on an industrial automation case where Wi-Fi is used as a wireless communication technology between the end devices. As shown in Figure 12, both TSN Talker and TSN Listener are connected to a Wi-Fi AP which is a part of the simulation configuration. For the system simulation of a downlink TSN traffic use case, a factory environment with a number of users and an AP is designed. Only one BSS with one Wi-Fi AP and 20 STAs is simulated as shown in Figure 17. The radius of a hexagonal BSS cell is chosen to be 30 meters, and the AP is located in the center of the cell. STAs are randomly distributed within the cell boundaries, and they are stable during the whole simulation time. There are two types of STAs in the system; the first one is a STA which receives and uses TSN traffic, called TSN STAs, and the second one is STA that uses Background (BK) traffic, called BK STAs. There are 10 TSN STAs and 10 BK STAs in the cell. The traffic models of both ACs are similar with two main differences. First one is the packet size difference where TSN traffic packets are 64 bytes, and BK traffic packets are 200 bytes. The second one is the traffic arrival (TAP) period meaning the time difference between the packet arrivals at Wi-Fi AP. For BK traffic TAP is 100 ms in all simulation cases and for TSN traffic, simulations are run for a number of TAP values as 1, 4, 5, 10, 50 and 100 ms to observe the limitations in the Wi-Fi system for a shorter TAP. One of the references for TSN traffic characteristics is Cisco's paper [26], where the measurements of a TSN traffic tested show that TSN packets are 64 bytes and generated every 1 ms.

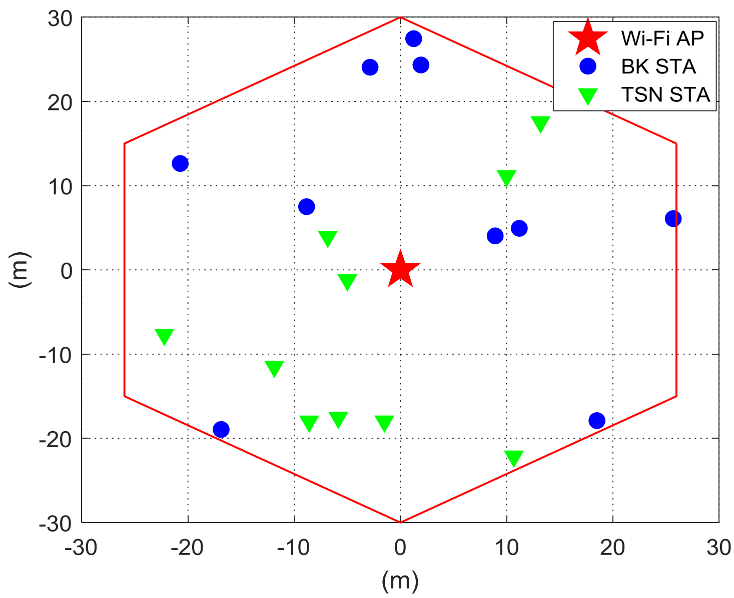

Figure 17: Simulation layout with Wi-Fi AP and STAs at a time instance.

For the factory layout, a suitable indoor propagation model of IEEE 802.11 is chosen, and the details of the model parameters are given in Table 9. F model indoor propagation option is used for the simulations since it is described in IEEE references [62] for open spaces, halls, airports, and factories. The breakpoint distance is 30 meters for this model meaning that all STAs have a LOS channel condition for the designed factory layout.

Table 9: Channel model

IEEE 802.11 path loss model for indoor propagation parameters		
Channel model	F	
Breakpoint distance	d_{BP} = 30 m	
Path loss model	for d $\leq d_{BP}$, $L(d) = L_{FS}(d_{BP}) + SF$	
	for d $> d_{BP}$, $L(d) = L_{FS}(d_{BP}) + 35\log(d/d_{BP}) + SF$	
Free space path loss	$L_{FS}(d) = 20\log_{10}(d) + 20\log_{10}(f) - 147.5$	
Shadow fading loss	$p_{SF}(x) = (1/\sqrt{2\pi}\sigma_{SF}) \times \exp(-x^2/2\sigma^2{}_{SF})$	
Path loss slope	before d_{BP}	after d_{BP}
	2	3.5
Shadow fading std. dev.	3 dB	6 dB
Channel condition	LOS	NLOS

The PHY and MAC layer parameters in the simulations are based on IEEE 802.11ac standard. Since IEEE 802.11ac standard is for only 5 GHz ISM band operation, the center frequency in the simulations is chosen accordingly, and a single channel operation is used in 20 MHz channel to avoid random access process in channelization of wider bandwidth operation. MAC layer parameters are chosen as given in Table 10. Block Acknowledgements (Block ACK) is not used either for TSN or BK traffic. Block ACK can cause retransmissions of TSN packets since they do not receive the ACK immediately which increases the delay. For channel sensing in MAC level in the simulation, only CCA is used. RTS/CTS technique is not included since the simulations are for downlink traffic, where the AP is sending data to STA, meaning that there is no competition going on between the STA to access the AP once they are paired. Therefore, in this scenario of factory level for downlink traffic, there is no hidden node problem requiring RTS/CTS. TSN packets are not aggregated in the simulation cases since it all packets should be delivered as soon as they arrive in AP. It is assumed that the packets are transmitted from the application layer to the MAC layer and in the opposite direction without any delay in the middle layers. The only cause of the delay in the transmission is in the PHY and MAC layers. Minstrel link adaptation algorithm is the most common one in IEEE 802.11 networks. For BK traffic, Minstrel link adaptation algorithm is used in all cases, and it changes for TSN traffic depending on the simulation case. Rest of the parameters for ACs are same as in the IEEE 802.11ac given in Table 6 and for TSN as described in Subsection 3.1.

Table 10: MAC layer configuration in simulations

<table>
<tr><th colspan="3">MAC layer parameters</th></tr>
<tr><td>Acknowledgements</td><td colspan="2">normal ACK</td></tr>
<tr><td>Random access process</td><td colspan="2">only CCA - No RTS/CTS</td></tr>
<tr><td>Packet aggregation</td><td colspan="2">Single packet in A-MPDU</td></tr>
<tr><td>Higher layer delay</td><td colspan="2">0</td></tr>
<tr><td>Link adaptation</td><td>for BK Traffic;
Minstrel</td><td>for TSN traffic;
Minstrel
or fixed MCS=0</td></tr>
</table>

Evaluation Metrics

The performance evaluation of the simulations is observed with several metrics. As described in Subsection 3.2, delay, jitter, data rate, packet losses and additionally packet waiting time in the queue are the metrics used in the simulations. When defining the metrics, it is important to specify where they are calculated in the system. A downlink traffic packet transmission flow is depicted in Figure 18 which also shows where the performance indicators are calculated.
Delay, jitter, and data rate are calculated in the application layer when the packet is received in the STA and it is composed of the packet transmission and ACK duration. It is calculated as the difference in the timestamps of reception in the AP application layer and reception in the STA application layer. Jitter is calculated in the application layer like delay as described in Section 3.3. The data rate is calculated as the packet size over the delay. Service ratio is also calculated in the application layer as the ratio of packets created in the AP application layer and received packets in the application layer of STA. Number of dropped PDUs is a performance indicator for the case where there is a bounded delay limit for TSN packets and the packet delays are checked when they are received in the MAC layer before assigning them into a queue. Packet waiting time in the queue is calculated in the MAC layer of AP as the time difference between SDU received in MAC layer and transmitted to the PHY layer as MPDU.

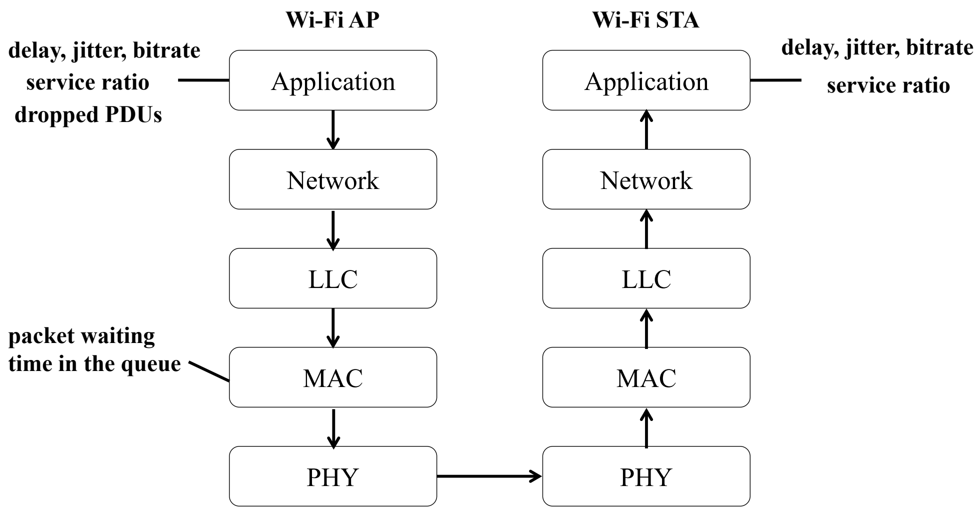

Figure 18: A downlink case protocol layer representation with evaluation metrics

Delay and jitter assumptions in the simulation

In the simulations, it is assumed that all network elements are synchronized, which is based on the synchronization standard in TSN networks IEEE 802.1AS. Therefore, it is possible to create a traffic model that is periodic without any jitter. In the simulation topology, the TSN traffic from PLC is received with a wire at Wi-Fi router and then transmitted over the air. It is known that the TSN traffic has jitter value is in the microsecond scale, approximately 1 μs. The jitter resulting from TSN is very small compared to the Wi-Fi jitter, as proved with mathematical analysis in Figure 19; therefore, delay of the data on the physical Ethernet cable is neglected. In Equation 4, t_{PLC} is the time when the packet is transmitted from PLC, t_W is the time when the packet is received in Wi-Fi router, t_D is the time when the packet is received at the destination, d represents the delay and j represents the jitter of a packet.

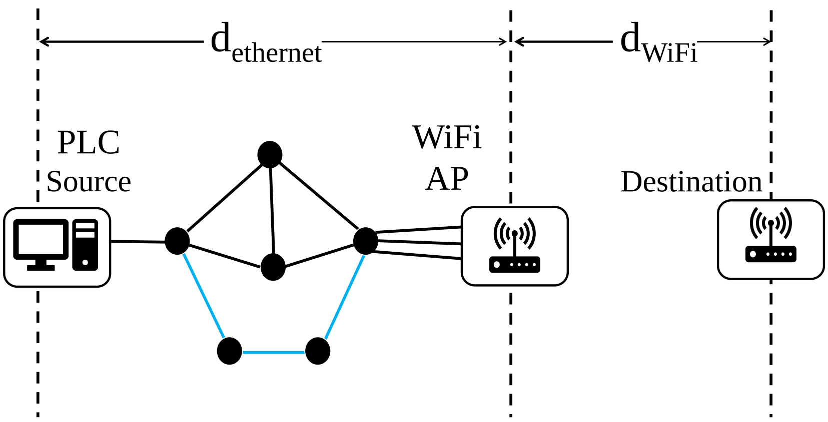

Figure 19: Delay and jitter of received TSN traffic.

The results of the jitter analysis of TSN traffic, depending on the periodicity, jitter varies from 100μs to 1ms. Since the difference on the scale is big, the jitter of the received TSN traffic at Wi-Fi router is assumed to be 0.

$$
\begin{aligned}
t_{\text{D}} - t_{\text{PLC}} &= d_{\text{packet}} \\
t_{\text{W}} - t_{\text{PLC}} &= d_{\text{Ethernet}} \\
t_{\text{D}} - t_{\text{W}} + d_{\text{Ethernet}} &= d_{\text{packet}} \\
j_{\text{packet}} &= |d'_{\text{packet}} - d_{\text{packet}}| \\
j_{\text{packet}} &= |(t'_{\text{D}} - t'_{\text{W}}) + (t_{\text{D}} - t_{\text{W}}) + (d'_{\text{Ethernet}} - d_{\text{Ethernet}})| \\
j_{\text{packet}} &= |(d'_{\text{Wi-Fi}} - d_{\text{Wi-Fi}}) + (d'_{\text{Ethernet}} - d_{\text{Ethernet}})| \\
\mathbf{j_{packet}} &= j_{\text{Wi-Fi}} + j_{\text{Ethernet}}
\end{aligned} \tag{4}
$$

4.2.2 Simulation Cases

There are four simulation cases with different enhancements implemented in the system to be able to observe and compare the performance. The differences between simulation cases are described in Table 11. The main differences are the access category, link adaptation and the bounded delay of TSN traffic. In all simulation cases, several TSN traffic arrival period (TAP) are simulated to observe the limits of the proposed modifications on Wi-Fi system when the cycle time of the traffic gets shorter for some industrial automation applications.

Table 11: Simulation cases

Parameter	**Case 1**	**Case 2**	**Case 3**	**Case 4**
AC of TSN traffic	AC_VO	AC_TSN	AC_TSN	AC_TSN
Link adaptation	Minstrel	Minstrel	Fixed MCS=0	Fixed MCS=0
Bounded delay	No limit	No limit	No limit	2 ms
AC of Background traffic	AC_BK	AC_BK	AC_BK	AC_BK

5 Simulation results and analysis

In this section, simulation results of several simulation cases as described in Table 11 are analyzed and discussed. TSN traffic is simulated in a Wi-Fi system based in the IEEE 802.11ac standard in our proposed system as depicted in Figure 12. The simulation results of system performances are analyzed with MATLAB.

Our analysis of results starts with a baseline system where there are background (BK) and TSN traffic stations (STA) and TSN traffic is carried over Voice Access Category (AC) in the MAC layer (Case 1 in Table 11). Then, the analysis move to the result of the simulation where the new access category for time-sensitive traffic is integrated into the Wi-Fi system and TSN traffic is carried on in coexistence with BK traffic (Case 2 in Table 11). Also, performance comparison between the current IEEE 802.11ac standard and proposed enhancements are shown. Further analysis is followed by the results of the systems with the implementation of fixed MCS (Case 3 in Table 11) and bounded delay limit (Case 4 in Table 11).

5.1 Simulation results of case 1 and case 2

First, our analysis starts with the results of simulation Case 1. The delay results of TSN packets in simulation Case 1, where the TSN packets are served with Voice AC QoS parameters are shown in Figure 20. Each curve in the plots represents a different TSN Traffic Arrival Period (TAP). By looking at the plot on the left, it is observed that the current Wi-Fi system can serve TSN packets with up to 4 ms TAP, for TAP shorter than 4 ms, the performance of the system is unstable. The delay of 1 ms TAP packets increases in a linear manner, which is a result of the packets accumulating in the MAC layer queue since they wait longer than TAP to be transmitted.

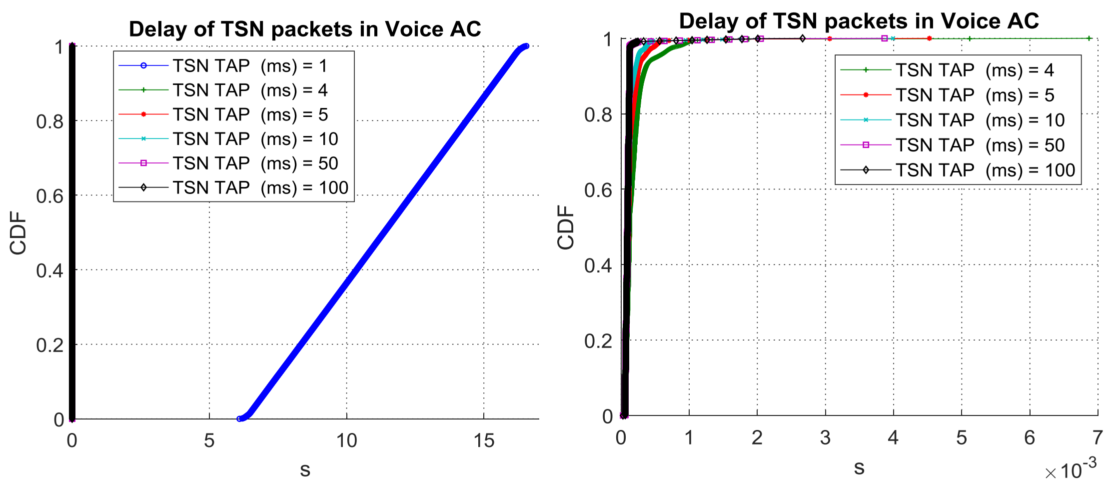

Figure 20: Delay results of TSN packets in simulation Case 1. Each curve in the plots represents a different Traffic Arrival Period (TAP).

Therefore, as the system is in an unstable state, delay requirement of industrial automation applications cannot be met when TSN packets have shorter TAP than 4 ms in coexistence with Background (BK) traffic of 100 ms TAP. The plot on the right shows the delay of 4, 5, 10, 50 and 100 ms TAP TSN packets. The delay values of all TAPs increases like-step function due to random backoff time. The difference between the steps of the curves is 9 μs which is the slot time in AIFS. Although they all follow the same like-step function trend, the possibility for higher delay values is higher for the shorter TAP. The CDF curves of delay start increasing exponentially after the delay reaches 124.2 μs. Both the like a step function and exponential characteristics of the delay curves points out the variation in the delay and results in jitter that are shown in Figure 21.

The jitter results of the TSN packets in Voice AC are shown in Figure 21. The plot on the left focuses on the jitter up to 90% probability, and the right one focuses on the remaining. The results show that for 4, 5, 10, 50, 100 ms TAP TSN packets, the jitter is 0 with 0.1 probability. 0 jitter result means that two consecutive packets have the same delay value, with a probability of 0.1 in this simulation case. In the current Wi-Fi system, this can be a result of two possible cases. First is that both packets have the same MCS and same backoff time or second, they have different MCS, but also different backoff time complementing each other to the same delay value. The plot on the right shows that for 0.02 probability of the last range of CDF curve, the jitter increases linearly and some packets can have jitter values higher than 1 ms that may reach up to 5.23 ms. Also, it can be seen that packets with different TAP have the same trend in the increase of jitter resulting from a regular delay variation of slot time.

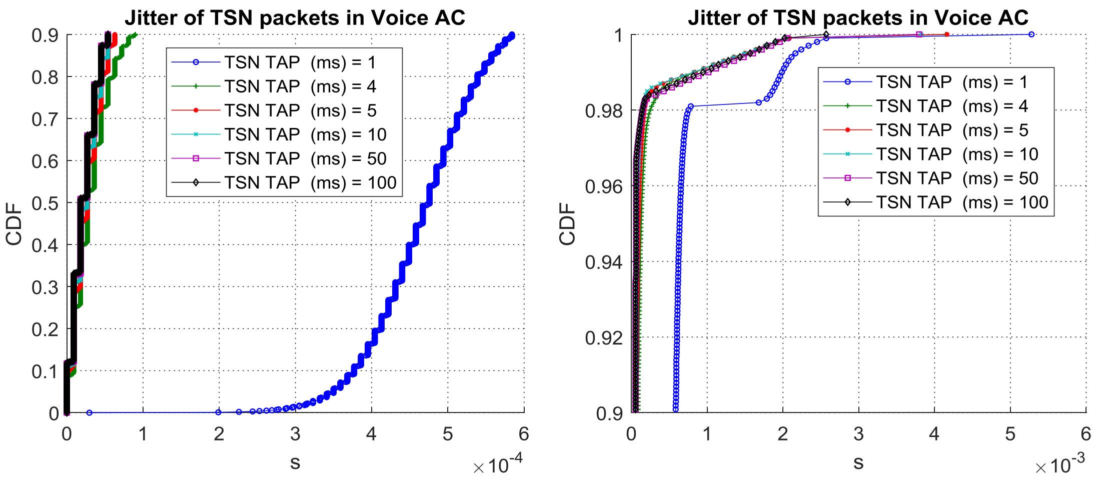

Figure 21: Jitter results of TSN packets in Voice AC in simulation Case 1.

The second set of the analysis is for simulation Case 2, where the new access category for TSN traffic is implemented in the MAC layer. The delay results of TSN packets in simulation Case 2 are shown in Figure 22. The plot on the left shows a similar result like Case 1 in Figure 20. The system can support TSN packets with TAP up to 4 ms. Even though the system is unstable for 1 ms TAP packets, the delay is less with the new AC compared to Voice AC. The plot on the right shows a focused view of delay results from 0.6 to 1 CDF probability values and delay values up to 5.2 ms for 4, 5, 10, 50 and 100 ms TAP. It can be seen that the delay results of 4, 5, 10, 50, 100 ms TAP follow the same trend with small differences. However, while the probability of STA having the minimum delay is 60.3% for 4 ms TAP, 74% for 5 ms and 84% for 10 ms TAP packets, it is over 85% for 50 and 100 ms TAP packets. Also, the tail of the CDF curve reaches a higher value as the TAP gets shorter since the medium is utilized more with more packets at a time. The tails in the CDF curves are for a small percentage of packets, but they are important for the overall system performance since, all packets needs to have a strict time requirement in TSN.

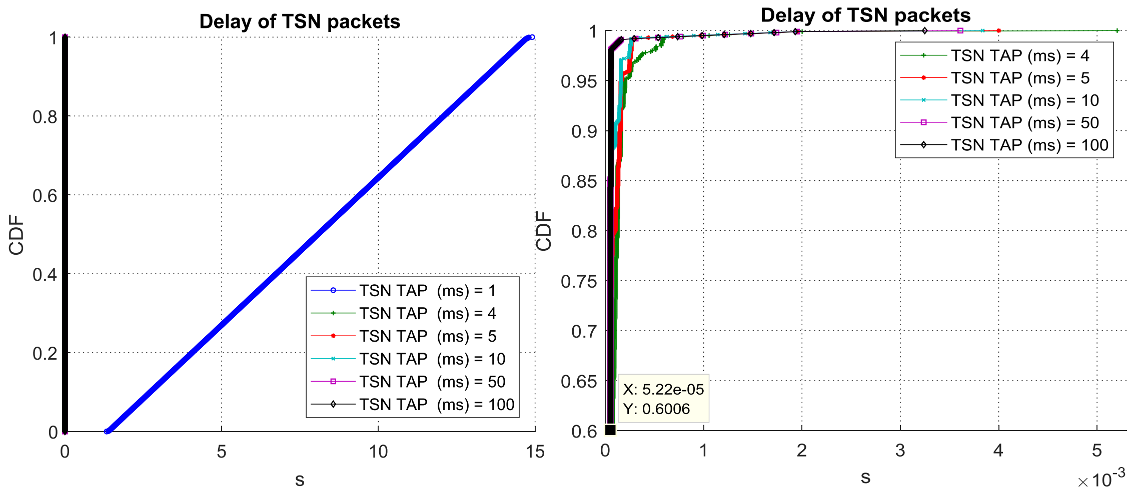

Figure 22: Delay results of TSN packets in simulation Case 2.

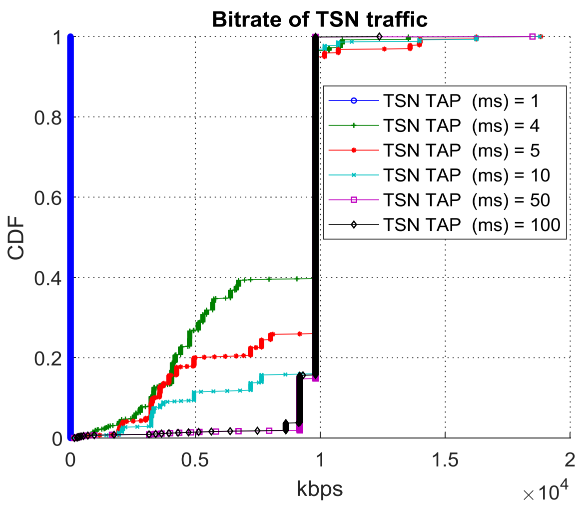

Figure 23: Bitrate of TSN packets in simulation Case 2.

The minimum delay, which can be seen in the plot on the right in Figure 22, is 52.2 μs for 4, 5, 10, 50 and 100 ms TAP packets with 0.6 probability. The data rate in Figure 23 shows the same trend as delay results where the maximum data rate is 9808 kbps. The represented delay results are calculated in the application layer of the simulator. This explains the delay value in Figure 22 since TSN packets are 64 bytes, 64 bytes/9808 kbps = 52.2 μs. Considering that Minstrel link adaptation algorithm is used in this simulation case, some higher data rates and smaller delay values are also achieved for a small percentage of packets, but the algorithm reaches an optimal value of 9808 kbps.

Jitter results of TSN packets in simulation Case 2 are shown in Figure 24. The plot on the left shows the jitter up to 90% probability, and the plot on the right shows the jitter in the remaining. It is observed from the left plot that 90% of the packets with 4, 5, 10, 50, 100 ms TAP are transmitted without any jitter. As explained in the delay analysis, 1 ms TAP packets cannot be supported by the system; however, the jitter results follow a resembling trend with the rest of the results. For all TAP values, there is a tail in the CDF curve which indicates that there is a relatively small percentage of packets experiencing a high jitter value. It can be observed that the highest value of the jitter depends on the TAP.

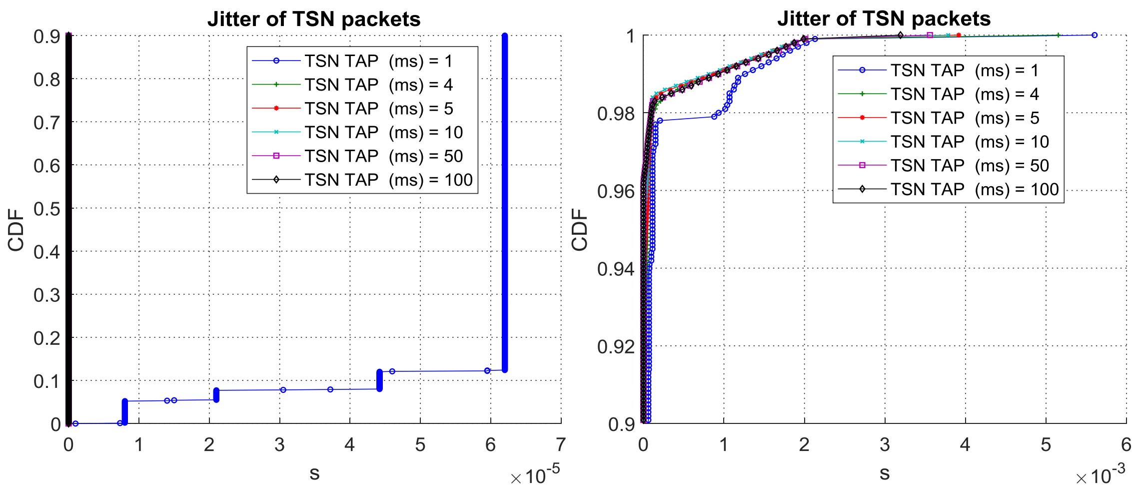

Figure 24: Jitter results of TSN packets in simulation Case 2.

In Figure 25, the mean waiting time of the packets in MAC layer queues results of simulation Case 1 and 2 are shown. MAC layer queue waiting time for a packet is calculated as the time between SDU arriving in the MAC layer and creation of MPDU. When TSN traffic is carried over the new access category, mean waiting time for the packets is reduced more than 50% for packets with all TAPs.

Table 12 gives the details of TSN packets delay and jitter results when they are carried over Voice (VO) AC and TSN AC. The mean delay, jitter, and corresponding 95% confidence intervals based on the normal distribution of the delay and jitter results are given in the table. The mean delay values show that TSN AC improves the average system performance for TSN traffic 47% for packets with TAP less than 5 ms and 40% for packets with a higher TAP. The mean jitter comparison shows that

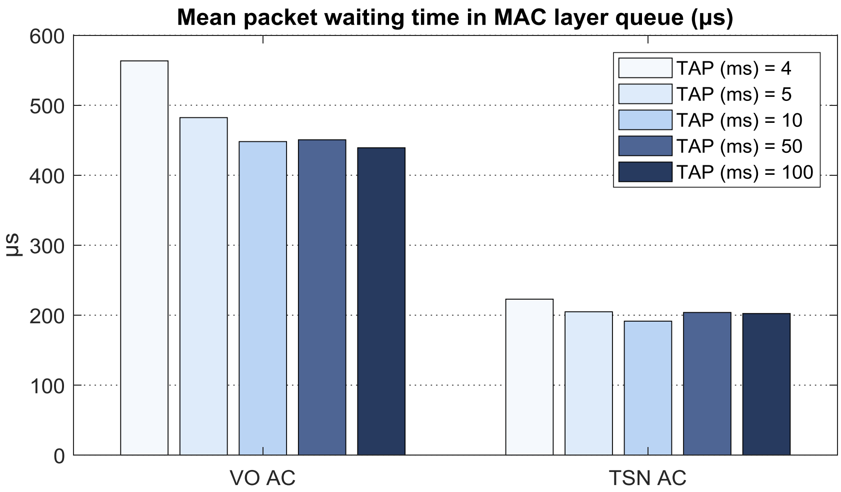

Figure 25: Packet waiting times in MAC layer queue in simulation Case 1 and 2.

TSN AC decreases the jitter results by almost 60%. The delay confidence interval of 95% confidence level shows that the results may vary in a nanosecond scale where the delay values are in μs. This shows that there are enough samples and the results are reliable. The confidence intervals for both simulation cases are similar since the simulation time and the number of samples are the same. Additionally, a narrow confidence interval implies that the system is in a stable state during simulation time, since a warm-up time at the beginning of simulation is not used in results.

Table 12: Mean delay and jitter comparison of Case 1 and 2

Cases	Mean delay(μs)			Mean jitter(μs)		
	TAP = 4 ms	10 ms	50 ms	4 ms	10 ms	50 ms
Case 1	186.35	121.74	104.67	56.33	45.06	44.8
95% confidence interval	±0.276	±0.189	±0.0343	±0.0313	±0.0216	±0.0546
Case 2	98.35	73.14	62.94	22.28	19.14	18.38
95% confidence interval	±0.1547	±0.1254	±0.028	±0.0136	±0.012	± 0.0514

5.2 Simulation results of case 3

Moving to the analysis of the simulation results of Case 3, where fixed MCS = 0 is used instead of Minstrel link adaptation algorithm, main differences compared to Case 2 are observed in delay values shown in the plot on the left in Figure 26. Since link adaptation algorithm, Minstrel in the simulation Cases 1 and 2, optimizes the data rate according to changing conditions in the medium, delay results are smaller compared the case with a fixed MCS = 0. The probability of delay being minimum 203.4 μs is 0.3, and the plot on the left shows the delay results from 0.3 to 1 CDF probability. Minimum delay increases from 52.2 μs to 203.4 μs and the maximum delay of 4 μs TAP packets increases by 2 μs, 5 ms TAP packets by 1.2 μs and for other TAP packets, delay results are similar to Case 2. Besides, the system is unstable when TSN packets are with 1 ms TAP The most robust MCS = 0 is chosen for higher reliability since it is one of the significant requirements of industrial automation applications. The plot on the right in Figure 26 shows the CDF curve of jitter results in Case 3. The plot on the right shows a focused view of jitter results from 0.78 to 1 since the jitter is 0 with 0.78 probability for packets with 4, 5, 10, 50 and 100 ms TAP. Comparing the jitter results with Case 2, it varies more, and the highest value it reaches is higher as expected from the increased delay.

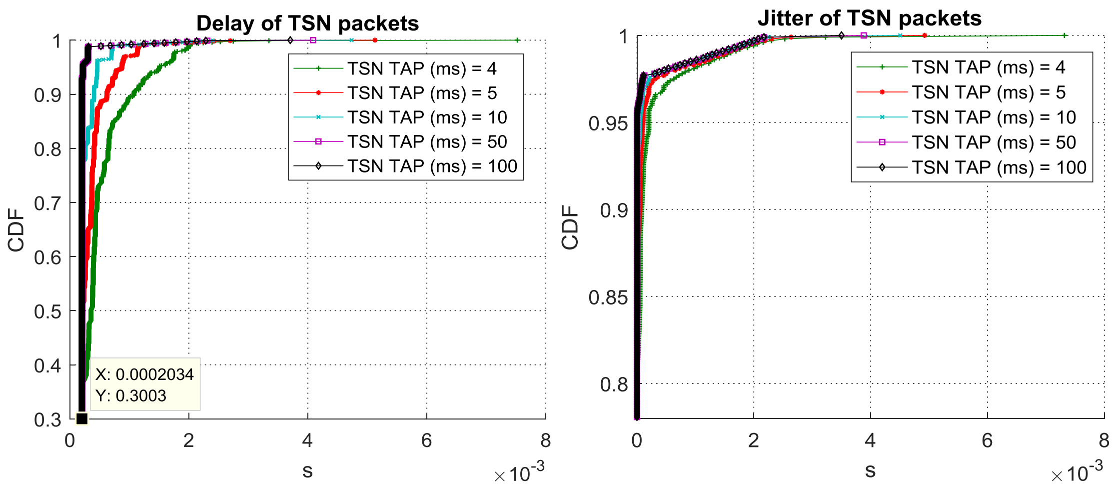

Figure 26: Delay and jitter results of TSN packets in simulation Case 3.

5.3 Simulation results of case 4

Results of the simulation Case 4 show how a bounded delay limit changes the performance of the Wi-Fi system. As in the previous simulation cases, the system is unstable when TSN packets have 1 ms TAP. Bounded delay implementation in the system is to test the Wi-Fi performance in case the restriction is required by the traffic model of industrial automation use case. The bounded delay causes packets to be discarded before transmission. Even though delay limit is a constraint for a Wi-Fi system since it causes packets to be dropped, it helps to reduce the memory consumption in the system and saving more computational and wireless resources. Since the implementation of bounded delay is in the Wi-Fi AP transmitter, the delay results of the packets include the transmission time on top of the delay limit of 2 ms. The Figure 27 shows the delay and jitter results of the TSN packets in simulation Case 4. The plot on the left shows a focused view of delay results from 0.3 to 1 CDF probability. The minimum delay value is the same as Case 3. The plot on the right in Figure 27 shows the jitter results of the TSN packets in simulation Case 4. The plot is a focused view from 0.8 to 1 CDF probability since jitter is 0 with 0.81 probability for packets with 4, 5, 10, 50 and 100 ms TAP. Because of the bounded delay limit, jitter results also have a cutoff at 2 ms. From both delay and jitter results, it can be seen that the results get better; however, bounded delay causes other system performance changes.

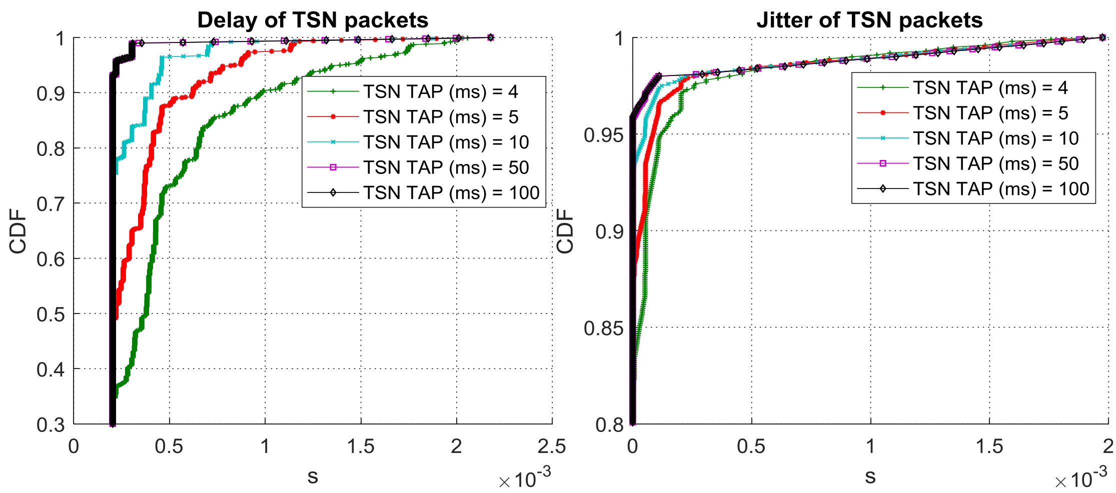

Figure 27: Delay and jitter results of TSN packets in simulation Case 4.

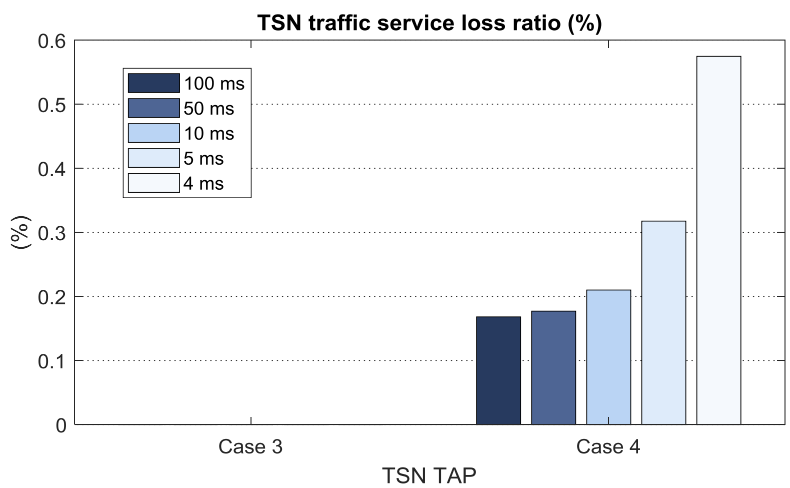

Figure 28: TSN traffic service loss percentage at the application layer in simulation Case 3 and 4.

The service ratio, which is an application layer calculation for the ratio of transmitted and received packets decreases compared to the system without a bounded delay. Figure 28 shows the TSN packets service loss ratio of Case 3 and 4. The service ratio for simulation Case 3 where MCS = 0 is used for TSN traffic, is 100 % for TSN packets with 4, 5, 10, 50, 100 ms TAP. In case 4, there is a service loss of 0.58%, 0.32%, 0.21%, 0.18% and 0.17%. The main advantage is as the name implies, all the received packets are within the required time limit and therefore, jitter is reduced. The bounded delay causes discarding packets both in the first transmissions and at retransmissions as shown in Figure 29 while it is zero for simulation cases without bounded delay.

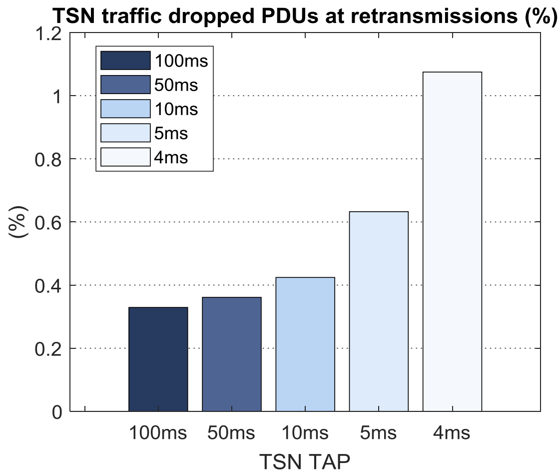

Figure 29: TSN traffic percentage of dropped PDUs at retransmissions in simulation Case 4.

Table 13 gives the details of the delay and jitter results of TSN packets in simulation Cases 3 and 4. The mean delay, jitter, and corresponding 95% confidence intervals based on the normal distribution of the delay and jitter results are given as in Table 12. It is observed that the mean delay values are close to each other in these two cases, even though Case 4 has a bounded delay limit. Based on this, it can be concluded that the a small percentage of the packets experience a high delay value, which has a small effect on the mean. On the other hand, both the delay and the jitter results of Case 3 and 4 are different from each other, and the results of Case 4 are better meaning that the bounded delay can improve the delay and jitter performance.

When the results in Table 12 and 13 are compared, one of the main differences is the mean delay values, caused by the link adaptation algorithm in Case 1 and 2. The mean delay is more than 4 times of the Case 2 results in Case 3 and 4. However, the jitter results do not differ as delay results.

Table 13: Mean delay and jitter comparison of Case 3 and 4

Cases	Mean delay(μs)			Mean jitter(μs)		
	TAP = 4 ms	10 ms	50 ms	4 ms	10 ms	50 ms
Case 3	488.62	262.42	221.45	57.503	33.38	30.03
95% confidence interval	±0.659	±0.375	±0.177	±0.0254	±0.02038	±0.0581
Case 4	474.77	257.79	217.68	33.04	24.30	22.51
95% confidence interval	±0.641	±0.37	±0.178	±0.0323	±0.01372	± 0.0096

6 Conclusion and future work

In this thesis, a new Access Category (AC) in the MAC layer is proposed for improving QoS in a Wi-Fi system for industrial automation applications. The thesis focuses on a use case where the industrial automation application is TSN traffic and traffic is one way, downlink. The new AC in MAC layer with no backoff time, a fixed MCS method and a bounded delay limit implementation for real-time traffic in a Wi-Fi are proposed solutions. As real-time traffic, TSN traffic is used for reference.

The proposed AC is implemented in a system level simulator with a link to system interface for analysis. The simulations are performed with the current configuration of IEEE 802.11ac standard and with the proposed improvements for performance comparison. The system performance is analyzed in the cases where TSN traffic is categorized in Voice AC in a system with current standard and in the new AC. Then, to improve the system performance for industrial applications, a fixed MCS=0 link adaptation and a bounded delay for TSN traffic are simulated.

6.1 Conclusions

First of all, the simulation results show that the proposed enhancements in IEEE 802.11 MAC layer for industrial automation applications improves the QoS performance. QoS in the Wi-Fi system is evaluated with delay, jitter and service ratio indicators and the average results show that the jitter and delay are reduced almost 50% in comparison with the system when TSN traffic is categorized in Voice AC.

The proposed enhancements improve the average jitter performance of the system by 60% while supporting minimum 4 μs TAP packet in coexistence with background traffic. One of the important QoS parameters for packets is the waiting time in the queue. It is observed that with introducing a new AC for TSN traffic in Wi-Fi, the waiting time in the queue is reduced more than 50 % for the packets. Wi-Fi can provide a deterministic network for critical real-time TSN traffic.

The analysis of the simulations using a fixed MCS=0 shows that it helps to decrease the number of retransmissions for TSN traffic, but it also increases the delay resulting in higher jitter results. For a scenario where there are more STAs and the area of deployment is bigger, using MCS=0 for time-critical packets helps to reduce the jitter. The bounded delay brings a limitation to a Wi-Fi system causing some packets to be discarded before transmission and reducing the service ratio. However, it increases the overall system capacity instead of serving packets that are kept waiting in the queues and, new packets can be served.

With the simulations, it is conceptually proved that a time-critical and background traffic can operate simultaneously in a Wi-Fi system until a limit in the cycle time of time-critical traffic is reached. The proposed enhancements can improve the Wi-Fi system for time-critical traffic up to 4 ms arrival period.

6.2 Future work

This thesis takes a step for Wi-Fi system deployment in industrial automation case for time-critical traffic. The focus is MAC layer improvements in Wi-Fi for a downlink traffic case. Future work could continue for uplink performance improvements. Also, a system with more cells can be simulated for analyzing interference.

Future work can also be focused on the other applications' requirements for Wi-Fi integration. For a WLAN system to support all TSN components, there needs to be modifications in all levels of the communication system. Only one solution cannot support all requirements of the system; therefore, there need to be more modifications in all layers of a communication system.

In this work, the enhancements on the MAC layer and simulation are based on the latest VHT standard IEEE 802.11ac. On the other hand, the standardization groups are working on a new amendment IEEE 802.11ax since 2014, and it is expected to be completed by early 2019. The new specifications in IEEE 802.11ax can be studied for better performance and updating the improvements.

Another study could continue to link adaptation algorithm; it has a significant impact on the system's performance. A new link adaptation algorithm to optimize the channel for time-critical traffic can be studied.

Even with the optimized parameters for TSN traffic, the CCA processes for all access categories queues stops simultaneously due to a wireless channel being busy or priority level of the queued packets. After a while, when the channel is idle again, the CCA processes of all the access categories start a competition. All in all, the queue with the highest priority might not get served first. Therefore; a TDMA medium access method can be studied for Wi-Fi.

There are some limitations in the system analysis which can also be improved with new software. The results evaluated in an overall system performance manner. However, as can be seen from the CDF probabilities, there are cases where the average system performance is good, but there are tails caused by some packets with outlying results. For the analysis of the results, there are limitations about the tools since the precision in each step can be different. Jitter results are in the scale of microseconds to milliseconds and can differ sensitively.

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