The Future of Smart Factory: Wireless Time-Sensitive Networks for Industry 4 Applications

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Abstract: The integration of Time-Sensitive Networking (TSN) in Ethernet networks with IEEE 802.11ac wireless network offers attractive features for hybrid communication network such as handling real time applications, flexibility, expansion and mobility in Industry 4.0 context. Nonetheless, considerable issues arise regarding incompatibility between the two technologies such as the synchronization and traffic prioritization processes. This paper suggests two mechanisms between IEEE 802.11 ac and TSN to address these challenges: the first one is developing the access point (AP) to introduce a bounded master clock utilizing a software-based timestamping mechanism for the synchronization of wireless devices with TSN wired part. While, the second point employs a traffic prioritization mapping in the AP between TID value in QoS control field and PCP value in VLAN Tag of IEEE 802.1 frame. The results indicated that the traffic of the highest priority time-sensitive application has been fully received within the application's end-to-end delay requirements (≤1 ms) when applying these mechanisms even in a network flooding with low priority data application. However, the traffic received without integration mechanisms suffers from lost data with respect to the time-sensitive application at the case when the whole bandwidth of the link has been allocated to the lower-priority application.

Keywords: TSN, IEEE 802.11 ac, Traffic Identification, Priority Code Point, Precision Time Protocol, Smart Factory.

1. Introduction

Time-Sensitive Networking (TSN) which was proposed by the IEEE 802.1 group in 2012, has gained momentum due to the advanced capabilities to achieve the requirements of strict real time applications and heavy data applications in smart factory concepts based on switched Ethernet technology[1]. However, TSN lacks the adaptability of mobile connections, which are essential for a wide variety of the smart factory applications, such as Automated Guided Vehicle (AGV) applications, Augmented Reality (AR) applications, etc.[2]. Consequently, the existing implementation of Time-Sensitive Networks (TSNs) in these environments encounters challenges: the placement of devices on the factory becomes increasingly dynamic, in addition to wired Ethernet communication conflicts to meet mobility demands, and making wireless communication becomes more beneficial than its wired equivalent. As a result, there are significant efforts performed to integrate wireless networks with TSN in order to enhance their efficiency by incorporating the advantages of wireless network, such as mobility and cost-effectiveness [3]. Wireless technology is a prominent choice to handle the previous points in certain industrial environments in comparison to the other wireless communication techniques, such as Wireless HART, Bluetooth, ZigBee, and so on. Wireless technology offers important advantages such as extensive transmission range with a radius of several hundred meters; economical and accessible internet and network connectivity; respectable throughput; and excellent openness and scalability [4]. Successive revisions of the IEEE 802.11 standard, such as IEEE 802.11ac (Wi-Fi 5) and IEEE 802.11ax (Wi-Fi 6) respond to the growing demand for faster and more efficient wireless communication. These standards have improved dependability and quality of service (QoS) mechanisms to serve different priority applications and meet industrial applications' expanding requirements, allowing for simple installation and reconfiguration of devices and systems, making it adaptable to changing industrial layouts and processes[5]. In the same context, a large amount of effort has been required due to the

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differences between these two types of systems, which use various protocols and methodologies for data transmission, which means several fundamental challenges that need to be solved, such as the synchronization between TSN wired and wireless components, traffic prioritization, and frame format of data [6]. Many works have been presented in the field of integration between wireless technology and TSN; the work in [7] utilized OMNeT++/NeSTiNg Simulation Models to investigate the feasibility of applying Time Sensitive Networking (TSN) standards to the Wi-Fi 802.11ac standard. It highlighted the difficulties of attaining determinism in wireless networks owing to factors such as interference and packet collisions. The results indicated that improvements to Wi-Fi are essential to more effectively support time-sensitive applications, including improving traffic prioritization and establishing mechanisms to regulate bandwidth for various traffic kinds. in [8], the authors investigated how to integrated Time-Sensitive Networking (TSN) with wireless technologies, like Wi-Fi, 4G, and 5G, to ensure reliable real-time communication in contexts where wired connections are not possible. The work offered experimental results that compare communication latency for TSN integrated with various wireless technologies, supplied empirical data to inform the selection of appropriate technologies for real-time applications. The work in [9] examined the integration of Time-Sensitive Networking (TSN) with Wi-Fi technology to improve wireless connectivity for real-time applications, especially in industrial automation. The study emphasized Wi-Fi's potential, particularly with forthcoming standards such as IEEE 802.11be, to facilitate low-latency communication while managing time-sensitive traffic. The results show that although Wi-Fi cannot ensure complete determinism due to its unlicensed nature, the application of prioritizing methods and dynamic access strategies can markedly decrease latency and enhance reliability for applications across diverse sectors, such as industrial automation and healthcare. The work in [10] proposed a methodology for integrating IEEE 802.11ad technology with Time-Sensitive Networking (TSN) to improve low-latency and reliable data transmission in industrial settings. The work concentrated on enhancing network configurations to reduce the quantity of Access Points (APs) while guaranteeing adequate synchronous service periods (SPs) for time-critical communications. The result demonstrated that the application of a binary linear programming model and two heuristic approaches effectively resolved the issues associated with implementing TSN over Wi-Fi. The results indicated that the synchronization between TSN attributes and the Wi-Fi MAC layer is essential for enhancing performance. The work in [11] presented a comparative analysis between the integration of 5G and Wi-Fi with Time-Sensitive Networking (TSN) in industrial environments. The results indicated that each technology has its own benefits; while 5G is considered as an appropriate choice for high-density applications that necessitate precise timing and reliability, Wi-Fi, on the other hand, provides an economical option, is easier to implement and is appropriate for specified workspaces. In comparison to the mentioned works, the contributions of this work provide a comprehensive framework including suitable mechanisms for integrating Wi-Fi networks with TSN, which can be summarized in the following two key points:

- Suggesting an appropriate mechanism for synchronizing process between the TSN network and the Wi-Fi network by develop the access point to act as a bounded master clock for the wireless devices.
- Proposing a mechanism for establishing traffic priority at the access point to facilitate the generation of an IEEE 802.1Q Ethernet frame containing PCP value derived from the TID value in the wirelessly received frame prior to transmitting the Ethernet frame to the TSN switch.

The rest of the paper has been organized as follows: Section 2 presents TSN and Wi-Fi technologies. Section 3 explains the TSN – IEEE 802.11ac Integration, section 4 states the problem. Section 5 presents the methodology of the work; section 6 describes the model and assumptions while section 7 indicates the results and discussion. Lastly, section 8 provides the conclusion.

2. Time Sensitive Networks (TSN) and IEEE 802.11 ac Technology

A. Time Sensitive Networks

A Time Sensitive Network (TSN) is a communication network that carries out a time-bound transfer of data using the standard Ethernet technology. TSN has been developed by a research group within the IEEE working group under the IEEE 802.1 standard. It operates within the second layer (MAC Layer) of OSI Layers Ref.) in which a 4-bytes tag has been added to the standard Ethernet header. TSN has different standards to meet its functionalities, such as IEEE 802.1Qbv, IEEE 802.1Qbu, and others [12]. IEEE 802.1Q, a standard, uses a strict priority (SP) algorithm as the default method for transmission selection in the TSN switch for eight distinct traffic classes, each allocated a unique priority level. The priority levels are established based on the value of the Priority Code Point (PCP) field in the 802.1Q tag of a new Ethernet frame, eight types of services can be defined due to this field, and the SP algorithm always serves the highest priority traffic firstly and so on. Table 1 explains the fields of VLAN tag [13].

Table 1. VLAN tag Fields.

Name of Field	Field Size	Description
TPID (Tag Protocol Identifier)	16 bits	Indicate that the frame has a VLAN tag. Always (0x8100)
PCP (Priority Code Point)	3 bits	0-7 (traffic classes)
DEI (Drop Eligible Indicator)	1 bit	Identifies frames that may be dropped in congestion. Default (0)
VID (VLAN Identifier)	12 bits	Identifies the VLAN Default (0)

B. IEEE 802.11ac- Wireless fidelity (Wi-Fi)

Wi-Fi, which stands for wireless fidelity, is one of the most popular wireless technologies that are based on the IEEE 802.11 family of standards. Local arear networks typically use these protocols for devices networking and Internet access with coverage area reaching a few hundred meters. These standards have been utilized all over the world in home and small office networks to link devices and to provide Internet access with wireless routers and wireless access points in public locations like coffee shops, restaurants, hotels, airports, factories, and other similar establishments [4]. IEEE 802.11ac (Wi-Fi 5) is a wireless networking standard certified in 2013 that belongs to the IEEE 802.11 family. It substantially improves wireless communication by offering high data rates, which can reach more than 1 Gbps, increased capacity, and superior performance in crowded environments. The effects of interference from other devices have been minimized in this standard by using the 5 GHz band which led to enhance overall performance [14]. The PHY and MAC layers have been modified to obtain additional enhancements such as channel bandwidth, hence 802.11ac accommodates channel widths of 20, 40, 80, and 160 MHz to provide significantly greater data speeds. In terms of spatial streams, 802.11ac accommodates up to 8 spatial streams, hence enhancing the aggregate data throughput. Moreover, it supports beamforming and MIMO technology where Multi-User, Multiple-Input Multiple-Output (MU-MIMO) is an advancement of MIMO technology that facilitates concurrent downlink delivery of distinct streams to many clients inside the same channel. MU-MIMO is applicable only during downlink transmissions from the access point to client devices. The 802.11ac standard defines a procedural framework for the application of beamforming technology. Beamforming is intended to enhance bandwidth efficiency and extend the range of the wireless network. Traditional 802.11 access points employed omnidirectional antennas. Omnidirectional antennas keep radio channels busy in all directions. Beamforming directs energy toward a client, hence enhancing the signal-to-noise ratio and data rate. The QoS Control field (introduced in 802.11e) is another mechanism in IEEE 802.11 ac that applies QoS to network applications as its traffic class which is defined in Wi-Fi Multimedia (WMM). It is 16- bits wide and contained in QoS Data frames. The interpretation of these bits may differ slightly based on the frame type, but here is the most thorough view for Data frames as explained in Table 2 [15]:

Table 2. Description of QoS Control Field in IEEE 802.11 ac MAC Header

Name of Field	Field Size	Description
TID	(4 bits) 0-3	Traffic ID (0-7) AC (8-15) Reserved
EOSP	(1 bit) 4	End of Service Period
Ack Policy	(2 bits) 5-6	Policy for Acknowledgment
Reserved	(1 bit) 7	Not used must be 0

3. TSN – IEEE 802.11ac Integration

In this work, the hybrid network is defined as a communication network that combines TSN-based Ethernet with Wi-Fi 5. However, TSN includes end users and switches, while a wireless network consists of wireless nodes that are connected to the TSN wired network via an access point, which linked to one of the Time-Sensitive Network switches, as shown in Fig. 1.

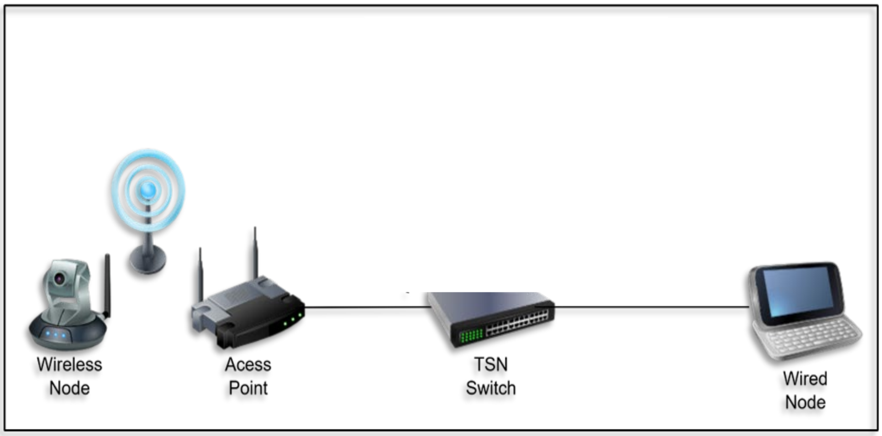


Fig. 1. TSN – Wi-Fi Integration

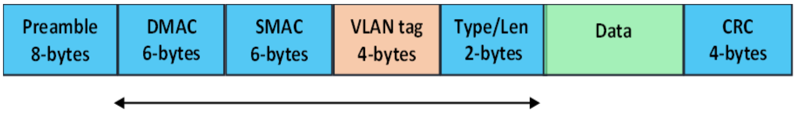
Several challenges must be taken under consideration in order to successfully integrate TSN networks with Wi-Fi networks, such as the issue of synchronization between the components of these networks and the issue of variations in data formats and data traffic classification techniques, which have been discussed in the following subsections.

A. Synchronization

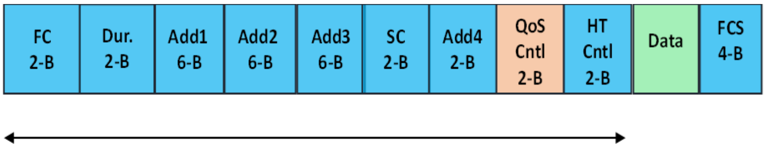
The IEEE 802.1AS generalized precision time protocol (gPTP) is a TSN standard derived from IEEE 1588 that is more efficiently designed for applications that require precise timing. The 802.1AS protocol, like IEEE 1588, synchronizes a series of nodes connected by Ethernet cables and intermediate devices [16]. It accomplishes this by automatically selecting a grandmaster clock using the Best Master Clock method (BMCA)[17]. The grandmaster clock functions as the primary time provider for slave devices (devices that are not designated as the 1588 grandmaster). Conversely, it is important to consider that IEEE 802.11ac technology does not guarantee a precise synchronization mechanism among the network's wireless components.

B. Traffic Prioritization and Frame Format

TSN and Wi-Fi technologies each categorize their traffic differently. TSN depends on the PCP value in VLAN tag of the MAC header to categorize the traffic produced by its nodes. On the other hand, Wi-Fi utilizes the TID field in the QoS Control field of the MAC header for traffic classification. Therefore, mapping must be addressed to handle the integration between the two technologies. Fig. 2 illustrates the format of the MAC header, with (a) representing IEEE 802.1 and (b) representing IEEE 802.11ac.



a. IEEE 802.1 MAC header



b. IEEE 802.11 ac MAC header

Fig. 2. MAC header of IEEE 802.1 and IEEE 802.11ac

4. Problem Statement

The access point serves as an entrance for data traffic between the TSN network and the Wi-Fi network. However, the existing access point fails to integrate both networks due to its inability to synchronize the associated wireless elements as accomplished by the TSN components. Furthermore, when the access point receives a frame with a specific priority, it processes the information of the data link layer. Upon transmitting the data encapsulated in a traditional Ethernet frame, it does not insert a VLAN tag into this frame. Consequently, when the frame arrives at the TSN switch, then the switch directs it to queue 1 due to the absence of the capability to read a PCP field. Thus, the switch treats it as background traffic, despite its high priority at the source. In the next section, the proposed methodology has been introduced to solve these problems; see Fig. 3.

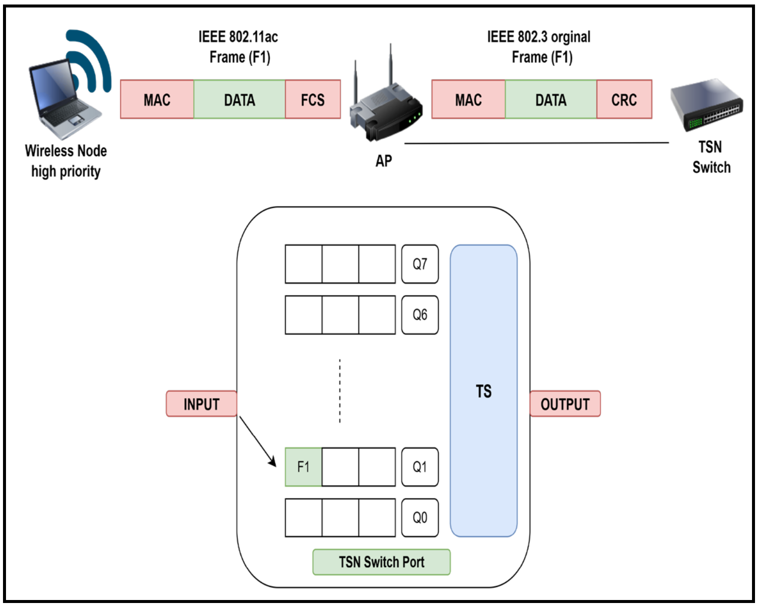


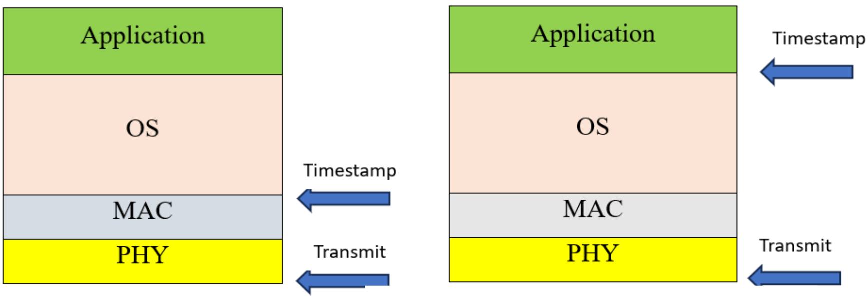
Fig. 3. Problem Statement of Traffic Prioritization and Frame Format

5. Methods and Materials

The methodology of this work is based on two approaches: the first proposes a solution for the synchronization issue between the wireless and wired parts of the network, while the second suggests a mechanism to resolve traffic prioritization and frame format challenges between these two network types. It is worth to mention that applying the suggested mechanisms to more realistic industrial networks which include more industrial applications will negatively impacts the clarity of the performance of these mechanisms for the integration between TSN and Wi-Fi networks

A. Timestamping

This work suggests software timestamping (TS) to synchronize wireless devices over PTP. The system clock of the access point is identified firstly as the slave clock due to the master clock which, has been selected in TSN part. Then, the access point receives the time from the master clock, it operates according to the boundary clock concept where the access point acts as a new master clock. The wireless clients' system clocks are considered slave clocks and synchronize with the access point via Wi-Fi. The master clock is synchronized using a PTP clock, linked via TSN. Two types of timestamps exist: hardware timestamping and software timestamping, as shown in Fig. 4.



a. Hardware Timestamp b. Software Timestamp

Fig. 4. Types of Timestamping

Hardware timestamping utilizes dedicated hardware components, such as Network Interface Cards (NICs), to capture precise timestamps with minimal delay, making it highly accurate and suitable for time-sensitive applications. On the other hand, the software timestamping relies on the operating system and software processes to log timestamps, which enables clock synchronization among networked devices particularly in wireless settings where hardware timestamping may be impractical or prohibitively expensive. Software timestamping records the exact time when a PTP event message is handled by the protocol stack [18]. Fig. 5 illustrates the messages transferring in the case of PTP based software.

Fig. 5 demonstrates that the Master clock (access point which works as bounded clock) transmits a sync message to the slaves. The timestamp based on software (t1) has been recorded at the moment of transmitting the packet. If the master is unable to insert t1 in real-time due to software latency, it transmits a Follow_Up message containing t1. The slave obtains the sync message. The software timestamp (t2) is recorded upon the packet's receipt. The slave transmits a Delay_req message to the Master, it records the software timestamp (t3) upon sending the request. The master gets the Delay_req and records the timestamp (software timestamp t4). The master responds with a Delay_resp message that includes (t4). Finally, the slave calculates the delay using (t1-t4) then adjusts its local clock to match the master clock.

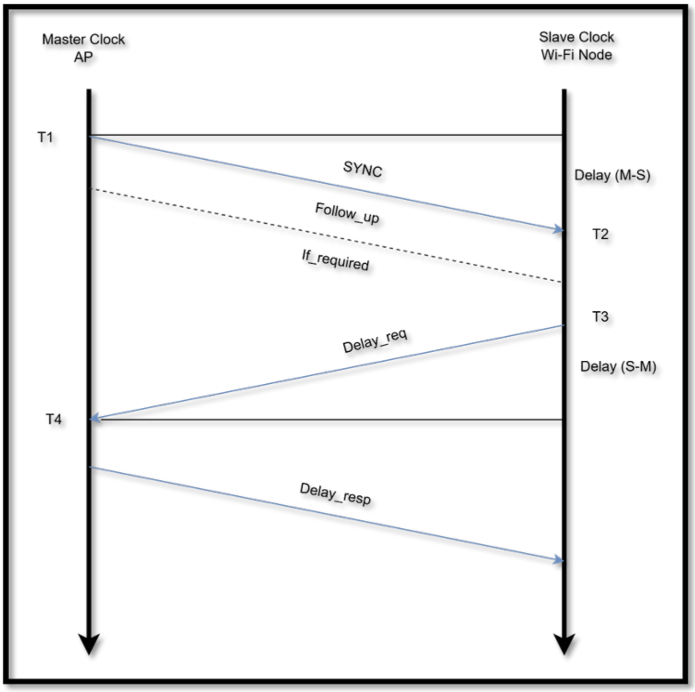


Fig. 5. Software PTP

B. Traffic Prioritization Mapping

The second phase of the adopted methodology aims to upgrade the access point that links the wireless and wired parts of the network by proposing a mechanism to map the TID field value in the QoS control field of the wireless network frame's MAC header with the PCP field in the MAC header of the TSN wired network frame. The proposed mechanism has been done by the following steps:

- Make a mapping table between TID and PCP values within the access point as shown in Table 3.
- Extracting the TID value from the MAC header which is received wirelessly by the access point.
- Mapping TID to the PCP value as table entries.
- Embedded functionality in the access point to insert VLAN tags with the mapped PCP into the MAC header of frames, which will be transmitted via wired connections to the TSN switch to be corresponding to the IEEE 802.1Q standard. The rest of the fields for the VLAN tag have been assigned with the default values which indicated in Table 1. The flowchart of this mechanism has been explained in Fig. 6.

Table 3. Mapping between TID and PCP Fields

TID	PCP	Traffic Class
0	0 (lowest)	Best Effort
1	1	Background
2	2	Excellent effort
3	3	Critical Application
4	4	Video
5	5	Voice
6	6	Internetwork Control
7	7 (highest)	Network Control

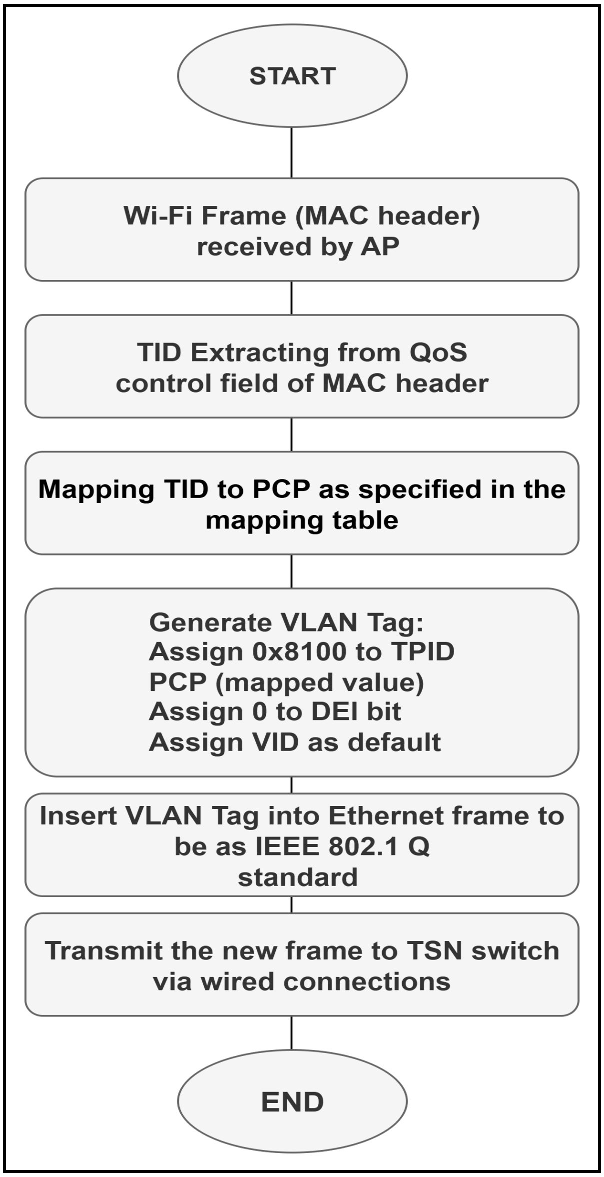


Fig. 6. Flowchart of Suggested Mechanism for Traffic Prioritization Mapping

6. Model Description and Assumptions

An industrial network model has been constructed with two different priority applications in the smart factory context, the first application consists of two nodes: the controller node (Node A), which sends high-priority control data to move a robotic arm on the other side of the network. This application has strict requirements related to availability, which must not be less than 99.9999%, and latency, which must be less than (1ms) [19], while the other application that has been considered as an excellent effort application with low-priority traffic consists of two nodes: EE node (Node B) and the backup server. As well as, there are two TSN switches, which represent as the backbone network that connects these nodes. This work presents three scenarios that have been explained later within the OMNeT++ environment utilizing the INET Framework, which encompasses both wired and wireless network components, alongside the Nesting Framework [20], for modeling Time-Sensitive Networks. The following subsections clarify the adopted scenarios:

A. TSN Wired Network Scenario

In this scenario, the model has been assumed to be a fully wired time-sensitive network, wherein node A generates high-priority data, such as control signals for the robotic arm, while node B transmits low-priority data, such as effort traffic to the backup server. Fig. 7 illustrates the model for this scenario.

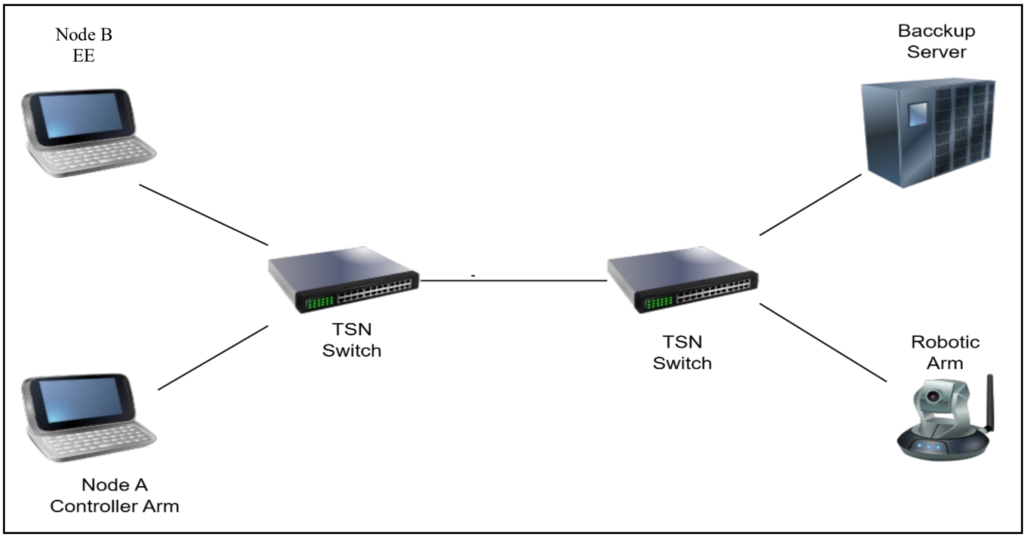


Fig. 7. TSN Model Scenario

Table 4 Describes the Items and Assumptions for this scenario

Table 4. Main Attributes of the TSN wired Scenario

No.	Item	Description
1	Node A	Control data with packet size of 354 bytes
		Packet Interarrival Time = 400 µs
		PCP in VLAN-TAG = 7 (high)
2	Node B	EE traffic with packet size of 1500 bytes
		Packet Interarrival Time = 125 µs
		PCP in VLAN-TAG = 2 (low)
3	Data rate of Ethernet link	100Mbps
4	Switch processing time	5us

B.TSN-IEEE 802.11ac Network Scenario without Suggested Access Point

In this scenario, a part of the network in the previous scenario has upgraded to a wireless network, which includes node A (controller Arm), along with a standard access point connected to a TSN switch, as shown in Fig. 8.

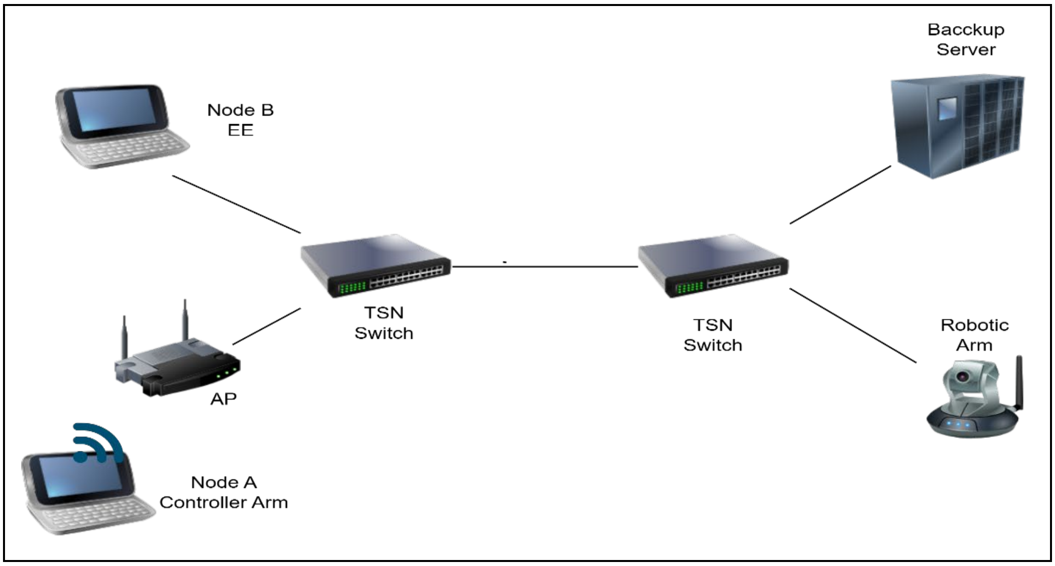


Fig. 8. TSN – IEEE 802.11 ac Model

Table 5 outlines the main assumptions for the wireless part of the network, which align with those of the TSN wired part and the two nodes described in Table 4. The only exception is the packet interarrival time of node B, which has been adjusted from 123 µs (98.5 Mbps traffic sent) to 135 µs (90 Mbps traffic sent) in order to evaluate network performance.

Table 5. Main Assumptions of the TSN – IEEE 802.11 Model

No.	Item	Description
1	Wireless technology	IEEE 802.11 ac
2	Frequency band	5 GHz
3	Wi-Fi 5 data rate	693Mbps
4	Modulation	BPSK
5	Channel Bandwidth	20 MHz
6	Transmitting Power	20 dBm
7	Receiver Sensitivity	-85 dBm

C. TSN - IEEE 802.11 ac Network Scenario with Suggested Access Point

This scenario assumes the suggested mechanism to upgrade the access point for handling traffic prioritization in TSN and 802.11ac, using the same prior model and assumptions shown in Table 5. Although this proposed mechanism offers benefits for integrating TSN and 802.11ac, it will introduce extra processing delay to the overall application latency, which may violate the requirements of time-sensitive applications in terms of end-to-end delay.

7. Results and Discussion

The results of the TSN wired model have been illustrated in Fig. 9 and 10 respectively. Fig. 9. presents the recorded traffic received for each application alongside the corresponding traffic sent, while Fig. 10 displays the delay time for each application. As shown in Fig. 9, the traffic received for the highest priority application (HPA), which is represented by node A, is equal to the traffic sent by this node, due to the service being directed to this application (as per the IEEE 802.1Q standard), which consumed 7.4 Mbps of the total bandwidth of the link, which is approximately equal to (98.5 Mbps), and the rest of the bandwidth, which is approximately equal to 91.1 Mbps has been directed to serve the lower priority application (LPA), which is represented by node B which is less than the traffic sent by this node that equal to 97.5 Mbps. As a result, there is a discrepancy between the traffic received and sent for Node B. Fig. 10 illustrates the end-to-end delay time of the LPA application, which is significantly greater than that of the HPA application due to a longer waiting period in the queue before receiving service from the TSN switch scheduler.

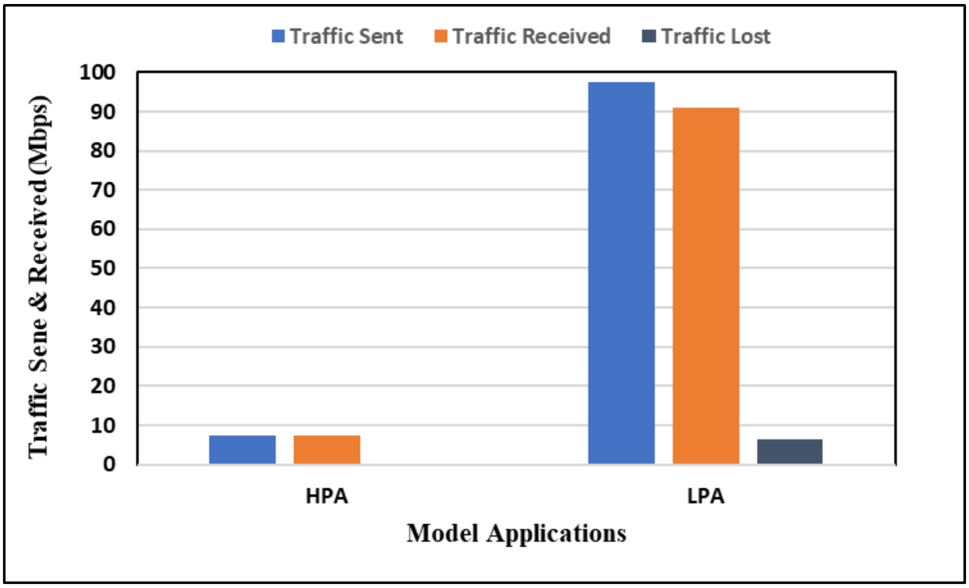


Fig. 9. Traffic Sent, Received and Lost for Model Applications

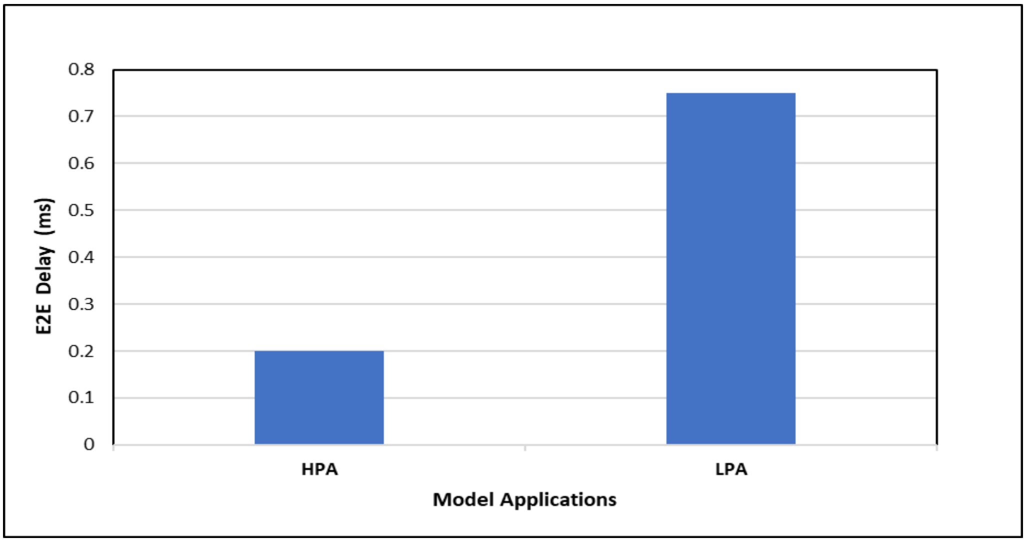


Fig. 10. End to End Delay for Model Applications

Table 6 illustrates the results of the hybrid (TSN-Wi-Fi 5) model in the second scenario, excluding the utilization of the proposed AP. The results indicate that, despite Node A having the highest priority, the switch directs the frames from this node to Queue No. 1 due to the access point's failure to transmit the Ethernet frame in accordance with the IEEE 802.1Q standard. Consequently, the scheduler serves queue No. 3, which contains the data from Node B (LPA), first before serving the rest of the lower-priority queues. If the total traffic sent from the two nodes does not exceed the link data rate, both nodes will receive complete service from the scheduler without problems, as shown in Table 6. However, as the traffic sent from node B increases, which the scheduler prioritizes as the highest priority application, the service will focus on serving the messages from this node. As the traffic sent from node B increases and reaches the link data rate, the traffic received from node A decreases, leading to a significant increase in delay time until service is completely cut off for node A, thereby reserving service exclusively for node B.

Table 6. Traffic Sent, Received, Lost and E2E Delay for Model Applications without Suggested Access Point

HPA (Node A)				LPA (Node B)			
TS (Mbps)	TR (Mbps)	TL (Mbps)	E2E Delay (ms)	TS (Mbps)	TR (Mbps)	TL (Mbps)	E2E Delay (ms)
7.4	7.4	0	0.29	90	90	0	0.4
7.4	7.2	0.2	5	91.25	91.25	0	0.4
7.4	6.45	0.95	5.7	92	92	0	0.4
7.4	5.8	1.6	6.3	92.7	92.7	0	0.4
7.4	5.1	2.3	7.1	93.3	93.3	0	0.4
7.4	4.4	3	8	94.1	94.1	0	0.4
7.4	3.6	3.8	9	94.8	94.1	0	0.4
7.4	2.9	4.5	12	95.5	95.5	0	0.4
7.4	2.2	5.2	16	96.3	96.3	0	0.4
7.4	1.4	6	23	97.1	97.1	0	0.4
7.4	0.7	6.7	48	97.8	97.8	0	0.4
7.4	0	7.4	----	98.5	98.5	0	0.7

*TS=Traffic Sent, TR=Traffic Received, TL= Traffic Lost.

Table 7 offers the performance evaluation in terms of traffic received and end-to-end delay after addressing the suggested mechanism at the access point to manage traffic prioritization between the TSN wired and Wi-Fi networks. The results indicate that the frames that have been received by the access point have been converted to the IEEE 802.1Q standard format prior to transmission to the switch, which categorizes them into the queues based on the Priority Code Point (PCP) value. As the PCP value for node A is 7 then, the scheduler serves node A before servicing node B ensuring that, regardless of any increment in the traffic sent from node B, node A transmits all its data to the receiver with a delay of 0.55 ms. The drawback of this approach is the processing time spent at the access point, which will contribute about 0.05 milliseconds to the overall end-to-end delay time of the transmitted frames of the two nodes.

Table 7. Traffic Sent, Received, Lost and E2E Delay for Model Applications with Suggested Access Point

HPA (Node A)				LPA (Node B)			
TS (Mbps)	TR (Mbps)	TL (Mbps)	E2E Delay (ms)	TS (Mbps)	TR (Mbps)	TL (Mbps)	E2E Delay (ms)
7.4	7.4	0	0.35	90	90	0	0.45
7.4	7.4	0	0.45	91.25	91.1	0.15	0.48
7.4	7.4	0	0.5	92	91.1	0.9	0.65
7.4	7.4	0	0.55	92.7	91.1	1.6	0.69
7.4	7.4	0	0.55	93.3	91.1	2.2	0.7
7.4	7.4	0	0.55	94.1	91.1	3	0.7.2
7.4	7.4	0	0.55	94.8	91.1	3.7	0.75
7.4	7.4	0	0.55	95.5	91.1	4.4	0.77
7.4	7.4	0	0.55	96.3	91.1	5.2	0.81
7.4	7.4	0	0.55	97.1	91.1	6	0.85
7.4	7.4	0	0.55	97.8	91.1	6.7	0.96
7.4	7.4	0	0.55	98.5	91.1	7.4	1.25

8. Conclusion

This research paper examined the integration of IEEE 802.11ac with Time-Sensitive Networking (TSN) systems, highlighting the synchronization and traffic prioritization issues. Two primary contributions have been presented: a synchronization technique utilizing software timestamping, wherein the access point functions as a bounded master clock, and a traffic mapping strategy that converts the TID field in Wi-Fi frames into PCP values within VLAN tags for TSN compliance. The results indicated that these mechanisms enable high-priority traffic to sustain low end-to-end delays and high traffic receipts, even under the load of lower-priority traffic. The suggested modifications to the access point incur only slight additional processing delays, which are necessary to achieve improvements in network performance. In conclusion, Wi-Fi networks may successfully expand TSN functionalities into the wireless domain, accommodating the increasing need for mobility in industrial environments. However, integrating TSN with wireless networks may lead to security threats that need to be addressed, which could be viewed as a future direction for this work.

9. Acknowledgment

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10. References

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