Experimental Analysis of Wireless TSN Networks for Real-time Applications

Zenepe Satka, Deepa Barhia, Sobia Saud, Saad Mubeen, Mohammad Ashjaei
Mälardalen University, Västerås, Sweden; firstname.lastname@mdu.se

***Abstract*—Wireless Time-Sensitive Networks (TSN) are needed to fulfill the requirements of real-time applications in areas where wired connections are not feasible. Wireless TSN combines the real-time capabilities of TSN with the flexibility of wireless connectivity opening a path for new use cases while providing determinism to time-critical scenarios such as autonomous vehicles. Industrial automation is integrating TSN with various wireless technologies such as WiFi, 4G, and 5G. This paper presents an ongoing work which aim is to experimentally analyze the performance of TSN when integrated with 4G, 5G, and WiFi in real-world scenarios. This will help both the researchers and industries to have a clear view of the network performance regarding the end-to-end latency requirements when designing their applications and use cases.**

***Index Terms*—Wireless Time-Sensitive Networking, TSN-5G, TSN-WiFi, TSN-4G.**

I. Introduction

Industrial automation nowadays is undergoing a tremendous change by the recent advances in technology that allow interconnection on a wider and more fine-grained scale [1]. The vehicle domain is moving towards digitization while sending larger amounts of data with different levels of Quality of Services (QoSs) on the network starting from the bounded low-latency to high-bandwidth requirements. Therefore, there is a great importance in developing a highly efficient and reliable network to fulfill the requirements of such applications and use cases [2].

Nowadays, Time-Sensitive Networking (TSN), introduced by the IEEE TSN group [1], is gaining the momentum by its advanced features to meet the bounded low-latency and high-bandwidth requirements over switched Ethernet. Among those advancements, we can mention the support for clock synchronization, resource reservation for different types of traffic, various traffic shapers, frame preemption, and network management mechanisms [3].

However, TSN is mainly developed for on-board communication, thus it is missing the flexibility of mobile connections. Hence, the recent research is focusing on wireless TSN to improve the TSN effectiveness by adding the benefits of mobile connection such as mobility and cost-effectiveness [4]. The integration of TSN with wireless technologies, such as WiFi or cellular networks, requires significant efforts due to the dissimilarities of such systems. They use different protocols and techniques for traffic transmission and prioritization, therefore several core challenges need to be addressed starting from the interoperability between wired and wireless components, synchronization, and QoS management, to mention a few.

Although there is an urgent need to integrate TSN with wireless technologies to unlock standards-based, scalable, and highly flexible use cases, it is not yet shown how will the performance of the converged networks be in real-world scenarios. This ongoing work aims to provide initial results on experimentally evaluating the integration of TSN with various wireless technologies such as WiFi and cellular network, concerning communication latency and end-to-end latency from the sender node to the receiver node. These initial results help developers and researchers to understand the benefits of each wireless technology when they are integrated with TSN networks. The envisioned final results will help the industry to choose among several wireless technologies depending on their QoS needs and vendor requirements. Based on the collected results, we plan to extend the evaluation to analytical performance evaluation that can support the network designers.

[1] https://1.ieee802.org/tsn

II. Background and Related Work

In this Section, we discuss the fundamental concepts of TSN and wireless technologies necessary to understand the rest of the paper, as well as the related work.

A. Background

1) Time Sensitive Networking: Time-Sensitive Networking (TSN) is a set of standards introduced to provide real-time capabilities and high bandwidth over switched Ethernet. These standards provide solutions for:

- Clock synchronization - Using Precision Time Protocol (PTP) to distribute timing information across the network [5].
- Resource management - TSN offers efficient resource allocation to meet the timing and reliability requirements of time-critical applications by configuring the TSN capabilities and managing the network and device resources.
- Mechanisms for bounded low latency - TSN introduces traffic classes (Scheduled Traffic, AVB class A, AVB class B, Best-Effort) and eight possible priority levels (0-7) to ensure that the packets are forwarded with the requested prioritization level to fulfill the QoS needs of the applications. Moreover, TSN utilizes frame preemption making sure that the packet with the highest priority is always sent on the network before any lower-priority packet, even in cases when there is ongoing transmission of the lower-priority packets.
- Network management mechanisms - TSN enables centralized network configuration of TSN devices allowing robust configuration and management of various TSN-specific parameters.

2) Wireless TSN: Wireless TSN refers to the integration of TSN with wireless technologies such as WiFi, or cellular networks, to enable reliable and predictable communication in the wireless domain. Not every wireless technology is capable of supporting TSN features, hence according to IEEE 802.11/Wi-Fi and 5G standards, these are the two most promising candidates to support the TSN performance [6]. However, in this work we consider 4G as it is coexisting at the same network with the public Non-Standalone 5G network, and there are still industries leveraging 4G in their use-cases.

B. Related Work

1) Integration of TSN with Wi-Fi: The authors in [7] investigate the integration of TSN with a Wi-Fi network focusing on the QoS of Wi-Fi for downlink with MAC layer modifications while analyzing the jitter and delay performance of the network. They introduce a higher priority access category in the Wi-Fi MAC layer with parameters tuned for time-critical traffic flow, and based on simulations they show that the packet delays are reduced to less than 50% for 90% of the packets, and jitter is reduced to zero for 80% of the packets. Similarly, the authors in [8] investigate the integration of TSN with Wi-Fi, and from their emulated model they show that the majority of the packets in the network were lost due to the access point as it did not have the shaping capabilities needed to efficiently deliver TSN frames. On the other hand, the authors in [9] demonstrate the TSN data path redundancy capability over Wi-Fi by leveraging multiple Wi-Fi radios on the same device. The results show that such prototype implementation can maintain low latency performance under unmanaged interference of wireless networks.

2) Integration of TSN with 5G: The research on the integration of TSN with 5G started in 2018 [4]. The researchers have been working on addressing the main core challenges of TSN-5G integration such as time synchronization, security, and several architecture properties such as interoperability and/or dependability to enable the transmission of time-critical data with low latency and high reliability. The authors in [10] investigate the time synchronization in integrated TSN-5G networks by using the Precision Time Protocol (PTP) which utilizes a shared clock between TSN and 5G system and share the clock information to each node via dedicated messages. On the other hand, the authors in [11] focus on network configuration and resource management mechanisms for the TSN-5G network.

To the best of our knowledge, the state of the art is missing a comparative analysis of wireless TSN networks in real-world scenarios. Therefore, in this work, we aim to provide an experimental analysis of the integration of TSN with wireless technologies, while comparing the transmission delays and end to end delays of each wireless TSN network.

III. Prototype Design

This section presents the prototype we used to model the integration of TSN with other wireless technologies. The prototype consists of three nodes as shown in Fig. 1. Node A is communicating with Node B via the wireless network which can be WiFi, 4G, or 5G, and Node B is communicating with Node C via the TSN network. Task scheduling functions were implemented to execute at specific time intervals, and these tasks are periodic. Each node has two tasks, namely “send” and “receive” which permits bidirectional communication if necessary. For instance, depending on its task scheduling, Node A can function as either a sender or receiver.

In our experiments, we focus on two types of latencies. Firstly, we analyze and compare the communication latency which is the transmission time of a frame from one node to another traversing a certain network. Secondly, we analyze the end-to-end latency from Node A to Node C, which is comprised of processing times that a node acquires during task execution presented as t_{p1}, t_{p2}, and t_{p3} in Fig. 1, and the end-to-end communication latency of the overall network from the sender node to the receiver node. Consequently, the end-to-end latency of wireless TSN network (t_{E2E}) can be represented as:

$$t_{E2E} = t_{p1} + t_{wireless} + t_{p2} + t_{TSN} + t_{p3} \tag{1}$$

From Eq. 1, the communication latency over wired TSN (t_{TSN}) is deterministic and can be calculated based on the frame size and the TSN network speed as presented in [12].

On the other hand, the communication latency of wireless networks is not deterministic as the potential interference caused by other devices or physical obstacles can reduce the overall quality of the connection hence introducing extra delay to the transmission. In our experiments, we consider the wireless networks without providing any isolation on the interference as we want to compare their performance in normal network conditions. Hence, in this initial step of our work, we measure the communication latency from each wireless network in different wireless TSN scenarios and compare the measured outcome.

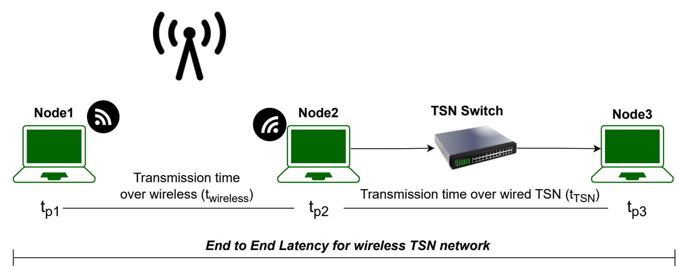

Fig. 1: Wireless TSN prototype design.

IV. Experimental Evaluation

A. Experimental Setup

Our experimental scenarios are implemented using socket programming. Tasks such as Send and Receive are scheduled to execute after every 1 and 2 seconds, respectively. The socket is initialized for both tasks. The workflow of the sender task is in such a way that it first binds the local IP address and port, listens and makes connections, sets the message, and then sends it further. On the receiver end, the socket connects it to the IP address of the sender. Once it connects to the sender, it starts receiving messages. The communication latency is estimated by gathering the time stamps from sender and receiver tasks.

The periodicity for task scheduling is kept the same for both TSN and 4G or WiFi. Node 1 sends text messages with 52 size bytes and zero offset over the 4G network to Node 2 after every 1 second. On Node 2, the message is converted to an Ethernet frame, assigned Scheduled Traffic class priority, and sent it eventually over the TSN network to Node 3. These traffic characteristics such as periodicity are kept the same for all the scenarios.

At the beginning of the study we run our experiments using Windows OS in each of the Nodes presented in Fig. 1. As expected, we notice the extra increase in end-to-end latency introduced by the operating system, as Windows is not designed as a real-time OS, therefore it can not guarantee real-time requirements for different tasks on the system. However, to show the impact of the OS we present the results for the end-to-end latency for TSN-4G and TSN-WiFi in Fig. 5 and Fig. 6, respectively.

The important observation from the results in Fig 5 is that the TSN-4G network takes higher computation time and the maximum value is approximately around 6466ms. One of the factors contributing to the latency is the serial communication used in this scenario. Serial communication provides a limited serial reading function that takes a bit longer time in seconds to read the frames stored in the memory. Other than that several factors contribute to the end-to-end latency in 4G such as network speed, and interference from other devices and obstacles.

The values for 4G communication latency vary between 117.36 ms and 796.12 ms whereas values for TSN-4G end-to-end latency vary between 5789.87 ms and 6466.79 ms as shown in Fig. 2. For the TSN switch, the frame transmission time is evaluated to be 0.0072 ms and remains the same due to its deterministic behaviour. The average value for communication latency and for end-to-end latency is observed as 515.61 ms and 6183.10 ms, respectively.

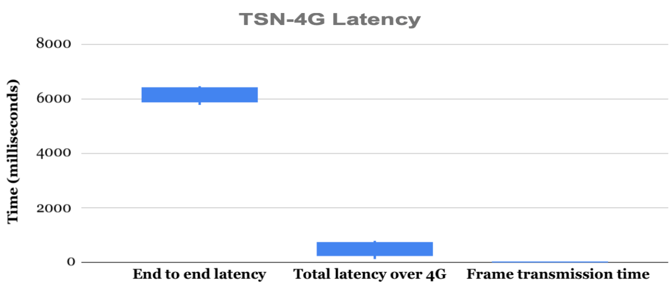

Fig. 2: Communication Latency Over 4G.

On the other hand, the results from the TSN-WiFi scenario shown in Fig 6 are much lower than those presented in the previous scenario. The maximum communication latency and end-to-end delay are observed at approximately 615 ms and 1319 ms respectively. The frame execution time for the TSN switch remains the same for all the messages shown in green colour and is low and constant concerning communication and end-to-end delays.

The values for WiFi communication latency vary between 122.87 ms and 615.06 ms whereas values for TSN-WiFi end-to-end latency vary between 398.67 ms and 1319.98 ms as shown in Fig 3. The average value for communication latency and for end-to-end latency is observed as 301.24 ms and 645.4 ms, respectively.

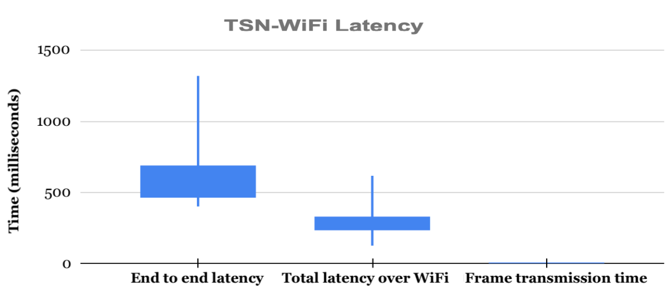

Fig. 3: Communication Latency Over WiFi.

In the second phase of our work, we implemented a real-time operating system, named Rubus, in each of the nodes presented in the prototype design. We send real-time traffic from Node A to Node C and measure the end-to-end latency using 4G, 5G, or WiFi on the wireless side. The results are improved with a huge factor as the real-time OS makes sure that the latency constraints are met. Some results are presented in Fig. 4.

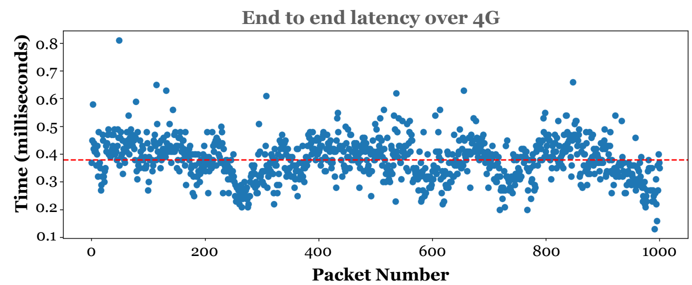

Fig. 4: The end-to-end latency in TSN-4G scenario using real-time OS on the nodes.

As this is an ongoing work, we are still working on the realization of the TSN-5G scenario, to provide a comprehensive comparison between different wireless technologies when present in wireless TSN scenarios.

V. Summary and Ongoing Work

This work aims to experimentally analyze the transmission delays and end-to-end latency of wireless TSN networks while taking into consideration different wireless technologies. From this initial results, we notice that TSN-WiFi network performed better then TSN-4G network in terms of communication latency, and end-to-end latency. In TSN-4G scenario, the average value for communication latency and for end-to-end latency is observed as 515.61 ms and 6183.10 ms, respectively. In TSN-WiFi scenario, the average value for communication latency and for end-to-end latency is observed as 301.24 ms and 645.4 ms, respectively.

The results shown before are taken from non-real-time scenarios to present the extra increase in end-to-end latency introduced by Windows OS. In the TSN-4G scenario, there is an observation that AT read command used for serial communication takes a non-negligible time for reading the messages which results in the higher end-to-end latency for TSN-4G. Moreover, when considering real-time traffic and Rubus OS in the sender and receiver nodes, the maximum and minimum communication latency over 4G for a packet of 52 bytes becomes 0.8 ms and 0.2 ms, respectively.

This is still ongoing work and the scenarios have been simplistic until now, but the authors are continuing the work and experimentally analyse the performance of wireless TSN networks in multiple scenarios when there are multiple connected nodes in the network, and also including in the analysis the performance of integrated TSN-5G network for real-time applications.

Acknowledgement

The work in this paper is supported by the Swedish Governmental Agency for Innovation Systems (VINNOVA) through the DESTINE, PROVIDENT and INTERCONNECT projects and KKS foundation through the projects DPAC, HERO and FIESTA.

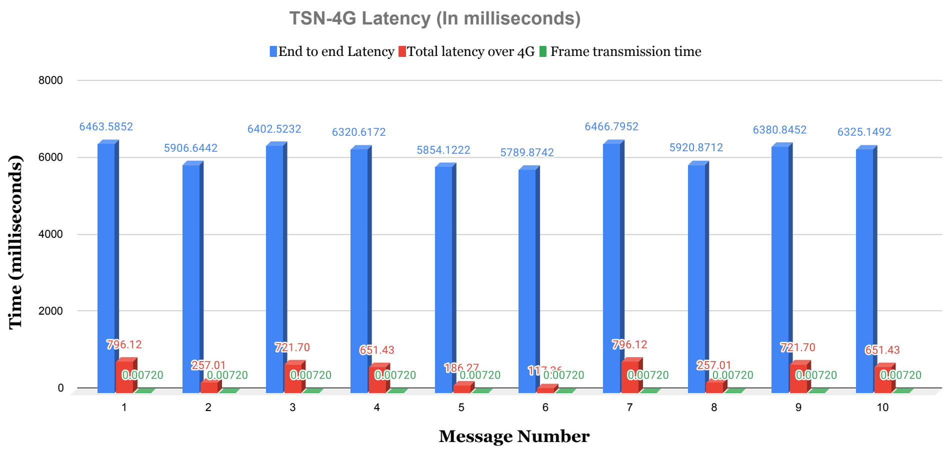

Fig. 5: The end-to-end latency in TSN-4G scenario using non-real time OS on the nodes.

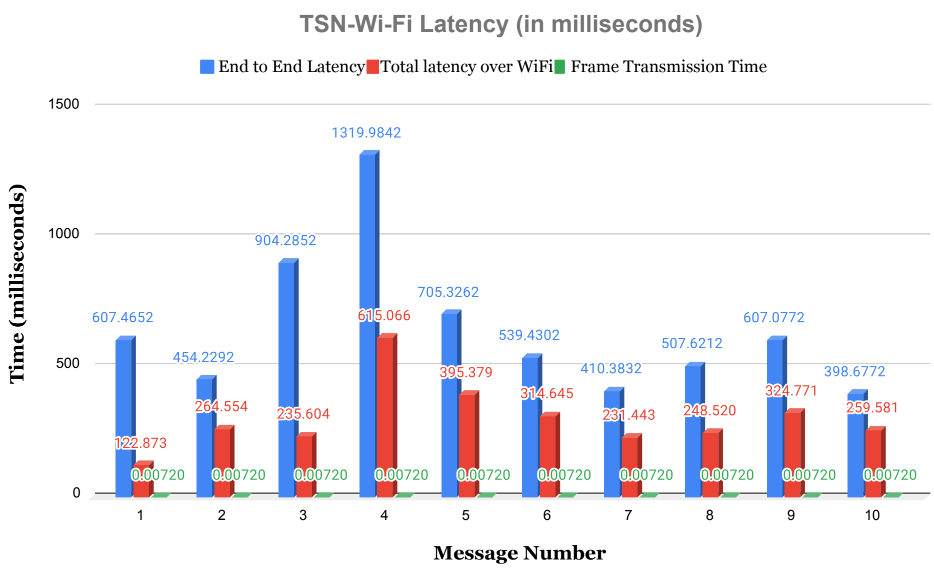

Fig. 6: The end-to-end latency in TSN-WiFi scenario using non-real time OS on the nodes.

References

[1] M. Wollschlaeger, T. Sauter, and J. Jasperneite, "The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0," *IEEE Industrial Electronics Magazine*, vol. 11, no. 1, pp. 17–27, 2017.

[2] O. Seijo, X. Iturbe, and I. Val, "Tackling the Challenges of the Integration of Wired and Wireless TSN With a Technology Proof-of-Concept," *IEEE Transactions on Industrial Informatics*, vol. 18, no. 10, pp. 7361–7372, 2022.

[3] M. Ashjaei, L. Lo Bello, M. Daneshtalab, G. Patti, S. Saponara, and S. Mubeen, "Time-Sensitive Networking in automotive embedded systems: State of the art and research opportunities," *Journal of Systems Architecture*, vol. 117, p. 102137, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1383762121001028

[4] Z. Satka, M. Ashjaei, H. Fotouhi, M. Daneshtalab, M. Sjödin, and S. Mubeen, "A comprehensive systematic review of integration of time sensitive networking and 5G communication," *Journal of Systems Architecture*, vol. 138, 2023.

[5] N. Kerö, A. Puhm, T. Kernen, and A. Mroczkowski, "Performance and Reliability Aspects of Clock Synchronization Techniques for Industrial Automation," *Proceedings of the IEEE*, vol. 107, no. 6, pp. 1011–1026, 2019.

[6] Dave Cavalcanti and Stephen Bush and Marc Illouz and Genio Kronauer and Alon Regev and Ganesh Venkatesan , "Wireless TSN - Definitions, Use Cases & Standards Roadmap," Avnu Alliance white paper, 2020, accessed: 2023-05-24. [Online]. Available: https://avnu.org/wirelessTSN/

[7] E. Genc and L. F. Del Carpio, "Wi-Fi QoS Enhancements for Downlink Operations in Industrial Automation Using TSN," in *2019 15th IEEE International Workshop on Factory Communication Systems (WFCS)*, 2019, pp. 1–6, Sundsvall, Sweden.

[8] A. B. D. Kinabo, J. B. Mwangama, and A. A. Lysko, "Towards Wi-Fi-based Time Sensitive Networking Using OMNeT++/NeSTiNg Simulation Models," in *2021 International Conference on Electrical, Computer and Energy Technologies (ICECET)*, 2021, pp. 1–6, Cape Town, South Africa.

[9] J. Fang, S. Sudhakaran, D. Cavalcanti, C. Cordeiro, and C. Chen, "Wireless TSN with Multi-Radio Wi-Fi," in *2021 IEEE Conference on Standards for Communications and Networking (CSCN)*, 2021, pp. 105–110, Thessaloniki, Greece.

[10] I. Godor, M. Luvisotto, S. Ruffini, K. Wang, D. Patel, J. Sachs, O. Dobrijevic, D. P. Venmani, O. L. Moult, J. Costa-Requena, A. Poutanen, C. Marshall, and J. Farkas, "A Look Inside 5G Standards to Support Time Synchronization for Smart Manufacturing," *IEEE Communications Standards Magazine*, vol. 4, no. 3, pp. 14–21, 2020.

[11] Z. Satka, I. Álvarez, M. Ashjaei, and S. Mubeen, "Work in progress: A centralized configuration model for tsn-5g networks," in *2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA)*, 2022, pp. 1–4, Stuttgart, Germany.

[12] L. Lo Bello, M. Ashjaei, G. Patti, and M. Behnam, "Schedulability analysis of time-sensitive networks with scheduled traffic and preemption support," *Journal of Parallel and Distributed Computing*, vol. 144, pp. 153–171, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0743731520303087