noname manuscript No.
(will be inserted by the editor)

Bringing Time-Sensitive Networking to Wireless Professional Private Networks

Filling gaps and bridging the innovation

Jetmir Haxhibeqiri · Xianjun Jiao · Esteban Municio · Johann M. Marquez-Barja · Ingrid Moerman · Jeroen Hoebeke

Received: date / Accepted: date

Abstract Private professional environments such as manufacturing industry, warehouses, hospitals, airports, among others, increasingly rely on end-to-end connected solutions to support and to improve their daily operational performance. This comes with a demand for real-time and deterministic communication, without evading the flexibility offered by wireless communication. Currently, wireless networks are lacking Time-Sensitive Networking (TSN) features, making them only suitable for non-time-critical communication. To support end-to-end wireless-wired deterministic communication in these private professional environments, it is necessary to introduce TSN features to the wireless network segments. In this paper, we list a number of considerations that have to be addressed before such communication may become a reality, including accurate time synchronization and fine-grained scheduling. Based on these considerations, we present a proof-of-concept realization of a TSN-capable Wi-Fi system, which enables end-to-end wireless-wired deterministic communication.

Keywords Time Sensitive Networking (TSN) · Wireless Networking · In-band Network Telemetry (INT) · Time Synchronization

This research was funded by the Flemish FWO SBO S003921N VERI-END.com (Verifiable and elastic end-to-end communication infrastructures for private professional environments) project, by the FWO project under grant agreement #G055619N and the Flemish Government under the "Onderzoeksprogramma Artificiële Intelligentie (AI) Vlaanderen" program.

J. Haxhibeqiri, X. Jiao, I. Moerman and J. Hoebeke
are with IDLab, Ghent University - imec
E-mail: jetmir.haxhibeqiri@ugent.be, xianjun.jiao@ugent.be, ingrid.moerman@ugent.be, jeroen.hoebeke@ugent.be

E. Municio and J. M. Marquez-Barja
are with IDLab, University of Antwerp - imec
E-mail: esteban.municio@uantwerpen.be, johann.marquez-barja@uantwerpen.be

1 Introduction

Connectivity is vital for the digital transformation that society is undergoing. It must evolve to keep up with the ever more and diverse demanding requirements of applications found in professional environments such as manufacturing industry, warehouses, hospitals, airports, among others. For instance, industry 4.0 is transforming digitally the conventional production processes by connecting machines, devices, people and processes [1,2]. Industrial communication networks are becoming the crucial point of smart production facilities providing reliable and rapid communication between processes to foster further flexibility, achieving sustainability, increasing customization and improving quality of production. In many industrial use cases, the communication network must fulfill strict communication requirements, such as: guaranteed network availability, real-time, low latency and low jitter end-to-end communication [1]. Not less important, such networks should also be energy efficient by limiting the end-to-end energy usage for communication purposes.

In such environments, private networks are preferred over public networks for both performance and accountability reasons. Over the years, different communication technologies were introduced (PROFINET, PROFIBUS [3], EtherCat [4]) to handle specific requirements for specific industrial applications in the wired network domain, resulting in a variety of communication protocols. To overcome this fragmentation, a set of Time-Sensitive Networking (TSN) standards have been initiated by the IEEE 802.1 TSN task group. These standards offer real-time, deterministic and low-latency communication in wired Ethernet networks [5]. Their scope is not limited to industrial settings, but also targets other time-critical use cases such as audio and video.

However, time-critical communication is not confined to wired networks only. In order to support end node flexibility and mobility, communication has to be extended to the wireless network domain. Each network segment along the end-to-end connectivity path must then support specific Quality of Service (QoS), with low end-to-end latency and jitter being the most important QoS parameters. But until now, wireless communication was mainly used for non-time-sensitive monitoring and open-loop control applications. New advancements in wireless networking technologies such as 5G URLLC [6] or Wi-Fi 6 [7] promise lower communication latencies down to 1 ms at radio level measured at layer 2 for small data payloads ($\sim$ 32 bytes) [6]. But fast wireless communication is only the first step towards end-to-end mixed wireless-wired TSN networks.

To really bring Time-Sensitive Networking features into the wireless domain a number of innovation gaps have to be bridged. This encompasses accurate end-to-end time synchronization mechanisms, unified traffic scheduling and solutions to verify end-to-end network performance on a per-flow and per-hop basis. In this paper we show how these gaps can be bridged to achieve end-to-end time synchronized networks capable of supporting a multitude of demanding, time-critical applications. Following a comprehensive overview of related work in Section 2, the way forward towards wireless TSN is discussed in Section 3. Section 4 describes the proof of concept implementation of our wireless TSN solution based on Wi-Fi, while Section 5 concludes the paper.

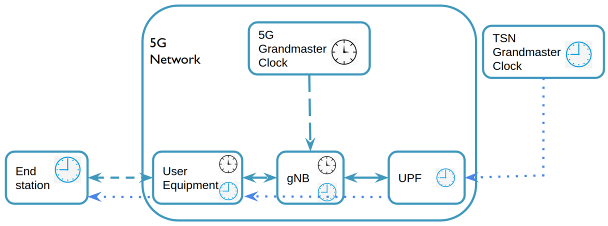
2 Related Work

Time-Sensitive Networking (TSN) is a set of standards defined by the IEEE 802 TSN task group [5] for supporting deterministic communication over Ethernet networks. It includes specifications for time synchronization [8], traffic scheduling [9], frame preemption [10], stream policing [11] and frame replication [12].

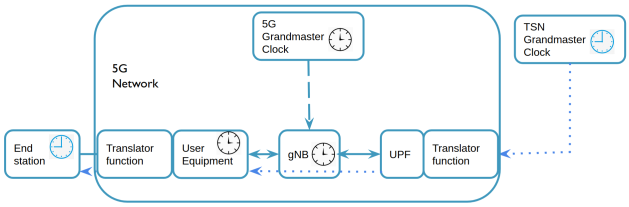
The IEEE 802.1AS standard or generalized Precise Time Protocol (gPTP) is used to synchronize time of all the devices within a single Ethernet network. This is achieved by propagating time information from the PTP grandmaster to all the other devices in the network. In addition to precise and accurate time synchronization, traffic needs to be organized in order to ensure deterministic communication. IEEE 802.1Qbv [9] is used as a time-aware scheduler to assign traffic streams to different traffic classes based on priority codes. Then, each traffic class is scheduled on a certain time slot during a cyclic time period, enforcing the separation of time-sensitive traffic from non-time-sensitive traffic. Another key feature in TSN networks is the network configuration and network performance verification, checking whether the network can meet the application's requested Quality of Service (QoS). While TSN configuration is standardized under IEEE 802.1Qcc [13], offering fully distributed, fully centralized or mixed (network centralized/ user distributed) configuration models, there are no standards how network performance verification is achieved. Network monitoring is generally limited by aggregated statistics collected by network devices, while network performance verification should be monitored between individual end-to-end applications.

In the wireless network domain, high-throughput technologies that also consider low latency communication include 5G Release 15 Ultra-Reliable Low-Latency Communication (URLLC) and IEEE 802.11ax (Wi-Fi 6). 5G URLLC targets a latency down to 1 ms and a reliability of 99.9999% for a packet error ratio of 10^{-4}. Low latency communication in 5G URLLC is achieved by reducing the transmission time interval based on the adopted numerology (shorter symbol time) and by scheduling transmissions in shorter time slots [6]. Moreover, URLLC includes preemption features where an URLLC transmission can interrupt an ongoing non-URLLC transmission to get faster access to the wireless medium, hence reducing latency. In Release 16 [14], the integration between Ethernet TSN and 5G networks is foreseen as a 5G TSN bridge, where an adaptation module interconnects the wired TSN protocol and 5G, while 5G parameters and procedures are not exposed towards the TSN network [15].

To achieve time synchronization with the 5G TSN bridge, two approaches are possible: *the boundary clock* approach (Figure 1a) and *the transparent clock* approach (Figure 1b) [15]. In the first approach, the 5G core and Radio Access Network (RAN) is connected directly to the grandmaster of the TSN



(a) Boundary clock approach



(b) Transparent clock approach

Figure 1: The 5G-TSN integration. End-to-end time synchronization approaches.

clock and the gNB provides TSN time information to the end stations. In the second approach, the RAN only transmits 5G system clock information. This means that two synchronization mechanisms should run in parallel, the 5G synchronization process and the TSN synchronization process [16]. The PTP related messages are timestamped using the 5G system reference time at the 5G TSN bridge ingress and egress ports by the TSN translation elements. Based on these timestamps, the residence time of PTP messages within the 5G TSN bridge is determined and timing information is corrected. Such a synchronization approach does not correct for timing errors caused due to propagation delays in the communication link, which are always lower than 1 μs [17]. The second approach has been adopted in Release 16 and does not give an end-to-end PTP-based synchronization. In terms of traffic handling, the 5G TSN bridge will map TSN traffic classes to 5G QoS profiles, with each profile having certain fixed parameters such as bridge delay, guaranteed bit rate, etc. [17]. Though, such mapping can be dynamically updated by the TSN central controller, the traffic handling is not unified between TSN network and the 5G bridge.

IEEE 802.11ax, branded as Wi-Fi 6, is the latest version of IEEE 802.11 technology. Its main advancements and improvements include the usage of orthogonal frequency division multiple access (OFDMA), uplink multi-user MIMO (MU-MIMO), higher modulation and usage of resource unit (RUs) concept [7]. OFDMA offers the possibility to support low latency communication by increasing the number of transmit opportunities and reducing the amount of contention (hence reducing random waiting times) compared to

Table 1: Comparison between 5G and Wi-Fi 6

Feature	**5G URLLC**	**Wi-Fi 6**
Synchronization	Accurate, non-E2E PTP	Inaccurate, special mechanisms required
Traffic handling	Possible, mapping between TSN classes to 5G QoS classes	Priority-based, non-deterministic
Monitoring	Aggregated only on network devices	Aggregated only on APs
Application-network interface	Extensive set of QoS identifiers	Limited set of QoS classes.
Architecture	Complex: TSN controller + 5G system bridge	Stand-alone WiFi
Spectrum	Licensed + Unlicensed	Unlicensed

longer waiting time of single-user OFDM of the previous IEEE 802.11ac generation. In order to support low-latency communication, Wi-Fi 6 has to be carefully optimized by keeping the time-sensitive traffic load low. According to [18], low-latency communication over Wi-Fi 6 (lower than 4 ms) can only be achieved under low network loads, while when the traffic load increases latencies as high as 25 ms are encountered. Moreover, in order to support URLLC traffic, proprietary solutions need to be in place for Wi-Fi 6 to cope with the traffic demands.

Wi-Fi 6 does not provide any time synchronization mechanism by itself, but a number of time synchronization mechanisms have been proposed already. They run on top of Wi-Fi and are either PTP-based with accurate timestamping support [19] or non-PTP-based [20]. In terms of traffic schedule handling, WiFi 6 can support a number of traffic classes based on priority level as standardized by IEEE 802.11-2016. Such traffic classification can be used to perform traffic shaping, but such mechanism is not specified neither standardised by the IEEE 802.11 group. The main challenge to achieve determinism over IEEE 802.11 is the random delay, introduced by the channel access mechanism.

From the application-network interaction perspective, 5G offers an extensive set of QoS identifiers and QoS parameters (such as guaranteed flow bit rate, guaranteed maximum flow bit rate, packet delay budget etc.). Contrary, Wi-Fi 6 can offer only prioritized QoS based on four different traffic access categories (AC). Wi-Fi 6 provides a minimal stand-alone architecture, while it does not provide any integration with wired TSN. 5G networks on the other hand have a complex network architecture and possibilities for integration with wired TSN in the form of a 5G TSN bridge. In Table 1 we have summarized the differences between 5G and Wi-Fi 6 for the different features needed to support deterministic communication over wireless networks.

3 Towards wireless TSN

The main challenge in supporting end-to-end TSN for professional private communication networks remains the incorporation of TSN features in the wireless network domain. As we have shown in Section 2, there are still a number of obstacles to overcome. The path towards wireless TSN starts with end-to-end accurate time synchronization as the first cornerstone in supporting all other needed features and functionalities. In the following subsections we will discuss all the features to be considered for realizing wireless TSN.

3.1 Accurate end-to-end time synchronization

Consideration 1: *Accurate end-to-end time synchronization using the same synchronization mechanism in both the wired and wireless network segments needs to be considered for integrating wireless and wired TSN.*

A synchronized common time base at each node in the professional private network is a crucial feature to support time-critical services and applications. With such a common time base, the optimal global scheduling of the network traffic at each node becomes possible, and time-triggered coordination of applications, such as physical actuators, becomes feasible. The better the time synchronization accuracy, the more efficient application coordination and network traffic scheduling can be achieved.

Although there are already some mature time synchronization solutions for the wired network in the product line, factory and vehicle, extending it to the wireless segment is still very challenging. The first challenge comes from the time variant fading of the wireless channel. This brings a higher packet loss rate, latency and jitter than what is encountered in wired networks. The time synchronization technique designed for the wired network needs to be further optimized in the more challenging wireless environment. The second challenge comes from the fact that most of the wireless network interface cards (NIC) lack the key features, such as precise time stamping and time measurement, needed by the time synchronization protocol.

The basic idea of the time synchronization is measuring the time difference between different nodes by exchanging time synchronization packets and aligning their local time afterwards. This measurement can hardly be done at the application level, because application's packets could be queued in the wireless NIC for an non-controllable period of time due to the uncertainty of the wireless channel. The travel time of the packet between the transmitter's baseband transmitting port and receiver's baseband receiving port is deterministic, which is the analog circuit delay plus the signal propagation delay. As such, the ideal place for performing the timestamping and measurement is the one that is as close as possible to the antenna.

To tackle the time synchronization challenge in the wireless segment, the wireless NIC implementation needs to be improved in the following aspects: offer more robust transmission and higher priority to the time synchronization packets by improving the local scheduling strategy and PHY parameters; do the timestamping and time measurement as close as possible to the baseband digital to analog converter)/analog to digital converter (DAC/ADC) and expose the results to the time synchronization protocol.

3.2 Unified end-to-end traffic scheduling

Consideration 2: *Unified, end-to-end, fine-grained traffic scheduling based on absolute timing and contemplating the wireless channel sharing issue should be considered. Such scheduling, rather than considering only the priority of traffic flows and wireless devices, should be based on time shaping as well.*

Traditionally, there have been many traffic engineering techniques to ensure certain QoS differentiation between flows, such as the queuing disciplines based on prioritization (e.g., PRIO, Hierarchy Token Bucket (HTB), Hierarchical Fair Service Curve (HFSC), etc.) [21]. When deployed in wired networks, where packet collisions are avoided thanks to modern full-duplex links, these approaches can effectively shape and prioritize traffic for most of the common Internet applications. However, such prioritization-based approaches do not provide the deterministic performance required by TSN and real-time systems, where packets need to arrive exactly at the moment it is expected. This is because switches, even without suffering from packet collisions, may need to forward traffic coming from different unknown sources, through an interface in a "serial" manner, which results in the loss of time-critical predictability. For wireless networks this problem is even more dramatic. Despite prioritization solutions such as Enhanced Distributed Channel Access (EDCA) at the WiFi MAC layer [22], strict time-critical predictability cannot be ensured. On top of the previously mentioned forwarding uncertainty that exists in wired networks, wireless networks also have to deal with the half duplex nature of their links.

The best known solution to ensure time-critical predictability in both wired or wireless domains is to schedule the traffic. A synchronized, time-slot based network can leverage end-to-end schedules built from network information and application profiles to offer deterministic performance for TSN systems. End-to-end schedules allow for orderly packet transmissions, coordinating the forwarding procedure in the switches (i.e., packet arrivals are now considered by the schedule) and avoiding packet collisions in the wireless domain (i.e., now different nodes will transmit only on their respective slots).

3.3 Network performance verification and in-band monitoring

Consideration 3: *Network performance verification should be low-overhead and offer the possibility for adjustable fine-grained per-flow, per-hop and end-to-end monitoring.*

An important aspect of an end-to-end TSN is the ability to perform network performance verification. Currently, the Quality of Service (QoS) of the

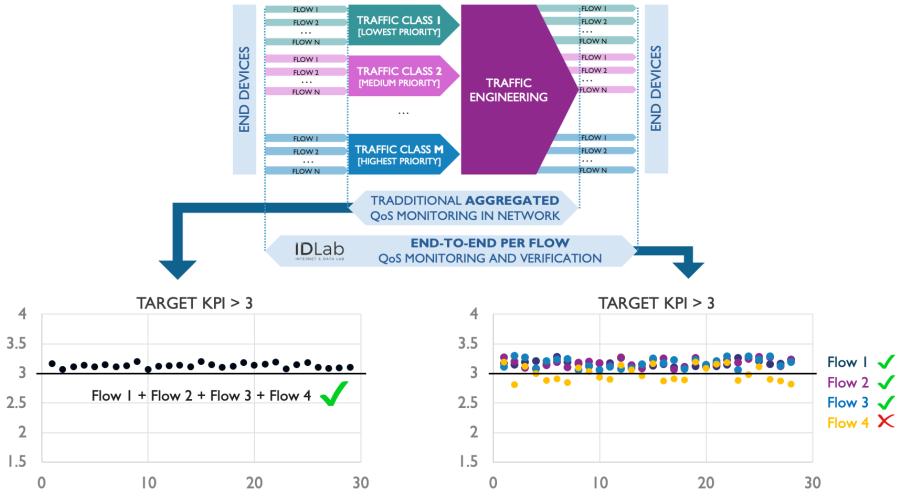


Figure 2: In-band network telemetry versus aggregated QoS monitoring.

network is determined by the traffic classes, where all the traffic flows in a certain traffic class are treated in the same way. Also such QoS monitoring mechanism is limited to aggregated statistics from network devices only, leaving out the actual performance experienced by the end applications. In such cases, under certain circumstances, the individual traffic flows may still underperform compared to their actual individual requirements as shown in Figure 2.

Moving towards E2E TSN means that one should consider the network performance verification mechanisms as well. To this end, the network performance monitoring mechanism should be able to distinguish between different traffic flows and collect information on flow basis. In such scenario, the individual traffic flows' performance can be compared directly to individual application requirements, as seen in Figure 2 and determine exactly which traffic flow underperformed. In addition to flow-based monitoring, such technique should offer the possibility to collect information on each network hop, end-to-end and in different points inside the network stack (e.g. TCP stack measurements). Moreover, the offered monitoring granularity should be adjustable over time based on network and application events and needs.

3.4 New key performance indicators (KPIs) to evaluate TSN networks

Consideration 4: *New KPIs to asses the network performance in terms of time synchronization accuracy, end-to-end traffic handling, power consumption as well as monitoring performance need to be defined and considered for end-to-end TSN networks.*

Table 2: Definition of new key performance indicators (KPIs) for end-to-end TSN

KPI	**Description**
	Time synchronization KPIs
E2E time synchronization error [s]	Remaining time difference between the system time of grandmaster and any device in the network
Time synchronization error [s]	Remaining time difference between the master and a slave in a single network hop
	Traffic related KPIs
E2E communication latency [s]	Communication latency between two applications running in two different nodes in the network.
E2E communication jitter [s]	Difference between two consecutive E2E communication latency measurements.
QoS setup time [s]	Time elapsed since the network controller receives the application requirements until the network is configured to maintain such QoS requirements.
QoS retainability [%]	Time percentage that certain QoS is full filled during the flow active time.
	Monitoring KPIs
Monitoring Age of Information [s]	Time elapsed since the information was collected in the network
Monitoring compute--communicate footprint [%]	It measures the impact of monitoring compute power versus communication overhead.
	Power consumption KPIs
E2E energy consumption [J/b]	Energy consumption for successfully transmitted application traffic bit between end-to-end application.

Until now the core focus of wireless system design was in increasing network capacity, expressed in aggregated throughput and the number of parallel users. With the introduction of new features in the wireless network segment to offer end-to-end TSN, new KPIs need to be defined to better capture the network performance according to application requirements as well as the performance of each network feature (time synchronization, scheduling and monitoring). In addition to this, new KPIs regarding power consumption of the network and end devices for improved network energy sustainability should be defined. In Table 2 we have listed a number of KPIs needed for end-to-end TSN.

It has to be pointed out that the traffic related KPIs that deal with end-to-end communication latency cover all the delays experienced by the packet in the network, including propagation and transmission delays, network stack and processing delays in the network nodes, as well as queuing delays in switch and AP queues. As the clocks of any node in the network are absolutely synchronized we use the same notion of time in all network nodes. Thus, the end-to-end communication latency is measured between the point where the packet enters the communication stack of the source node and the point where it leaves the communication stack in the destination node. Similarly, the end-to-end power consumption KPI considers all the power consumed for carrying the packet from one application to the other. This will include the packet transmission power consumption on each link and packet processing power consumption at each node in the path.

4 Proof of Concept (PoC) Wireless TSN

To achieve the vision of truly end-to-end wireless-wired Time-Sensitive Networks, a wireless TSN proof-of-concept has been designed that takes into account the above considerations. The proof-of-concept has been built on top of our Wi-Fi based SDR, openwifi [23]. In the following subsection we will describe each of the added time-sensitive features and how they are integrated with the wired TSN.

4.1 Wi-Fi based solution

We have implemented the necessary TSN features on the openwifi chip/FPGA and integrated them with the PTP program via the openwifi Linux driver. For the usual PTP user, running the PTP time synchronization service over openwifi is the same way as running it over Ethernet.

The PTP program on the master node and slave node perform synchronization by periodically exchanging 4 types of messages: Sync, Sync Follow Up, Delay Request and Delay response. According to the PTP protocol design, the local timestamp of the event when the packet (Sync and Delay Request) leaves and enters the wireless NIC is needed. In our implementation, the timestamp at the moment when the Wi-Fi preamble is transmitted or received is recorded and reported to the PTP program. For the rest, the PTP program does the necessary data processing (averaging, tracking, etc) to achieve the time synchronization. According to the characteristic of the wireless medium, PTP packets could also be treated with special settings in the openwifi driver: assigned to the high priority queue in FPGA; assigned with more robust modulation and coding scheme (MCS); sent with adjusted contention window (CW) and backoff setting; etc.

In addition to end-to-end time synchronization, TSN should support end-to-end fine-grained traffic scheduling too. This is crucial in the wireless segment due to its half-duplex operation and in order to avoid channel contention between different devices. For the wired network segment we use the IEEE 802.1Qbv time aware shaper [9]. In the wireless network segment, we implemented a similar scheduling mechanism as IEEE 802.1Qbv, where to each queue in the wireless nodes (be it an end device or an access point) a certain time slot during the cycle period is assigned. As the time is absolutely synchronized between all nodes in the network, so is the scheduling cycle time on the different devices. Based on the traffic flow requirements, transmissions from a certain node can be scheduled on contention-free time slots during the scheduling cycle.

For network performance verification we used in-band network telemetry (INT) monitoring that collects information end-to-end and per-flow and per-hop basis. INT monitoring information is added as an IPv6 extension header to the data packets, without breaking the communication between non-INT enabled nodes [24]. The INT monitors both wireless and wired network seg-

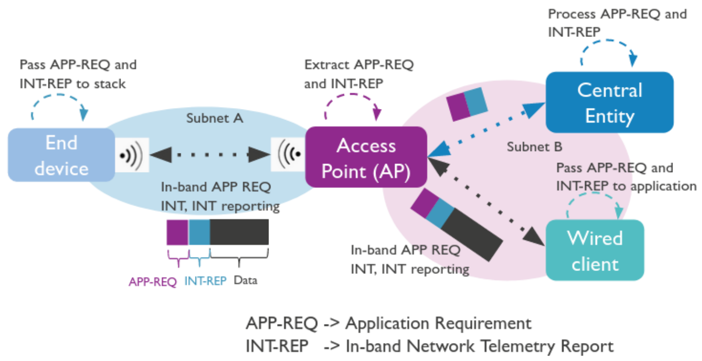


Figure 3: In-band passing of application requirements, monitoring reports and monitoring data.

ments without introducing any additional monitoring traffic [25] and avoiding additional channel contention in the wireless link. In addition to wireless link information such as RSSI, MCS, data rate, retransmission flag and channel used, INT also monitors the end-to-end communication latency.

In addition to monitoring, individual applications can encapsulate their application requirements in the same way as INT monitoring information is encapsulated within data packets. Then, the first network device along the path (being it AP for wireless end devices, or a switch for wired end devices) will process such requirements and pass them to the central controller, as shown in Figure 3. This way, the end devices do not need to communicate directly with the central controller. Based on the application requirements the network controller will (re)configure the network (i.e. update schedules) in an end-to-end fashion to support the requirements.

4.2 Results

In order to validate our Wi-Fi based TSN design, we use the w-iLab.2[1] testbed for setting up a network containing a multi-hop wired-wireless topology. For the wireless part, we used openwifi SDR nodes [23] while for the wired part we used a TSN enabled commercial switch[2]. The PoC solution is assessed with respect to the time synchronization error (assessing the time synchronization mechanism performance) and end-to-end communication latency (assessing the scheduling mechanism performance). In addition to this, the obtained results are benchmarked to results obtained when Wi-Fi COTS devices are used in the wireless segment of the network instead of SDR nodes.

[1] https://doc.ilabt.imec.be/ilabt/wilab/overview.html
[2] https://www.nxp.com/docs/en/fact-sheet/LS1021ATSNRDA4FS.pdf

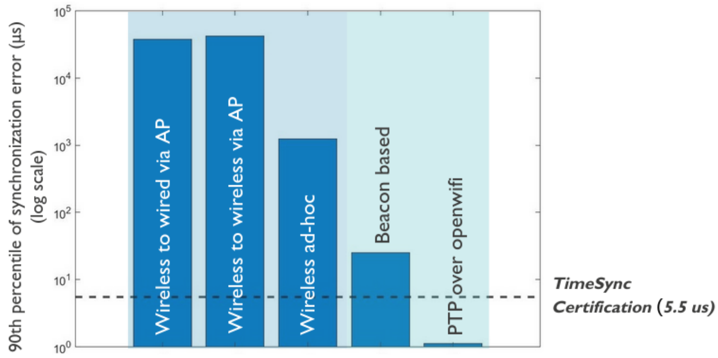
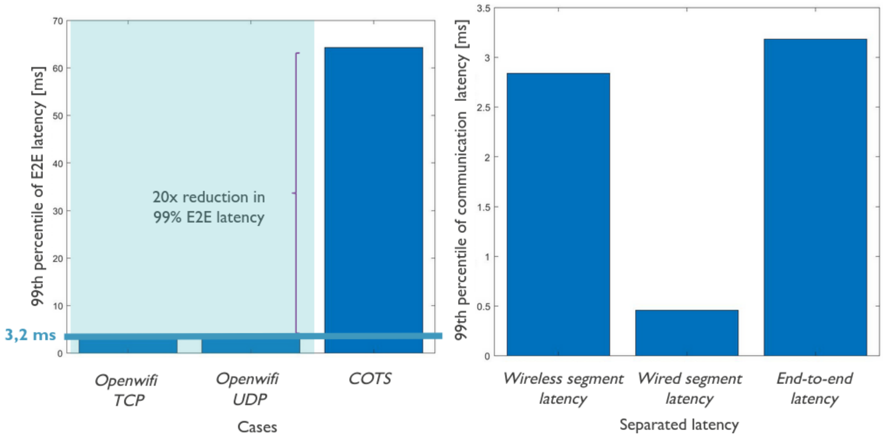


Figure 4: Time synchronization error for different time synchronization cases.

4.2.1 Time synchronization accuracy

We assessed the performance of the PTP based implementation over openwifi boards in terms of achieved synchronization error. The Wi-Fi Alliance has announced the *Wi-Fi TimeSync* certification program that specifies the requirements for the performance of a time synchronization mechanism between multiple Wi-Fi devices [26]. The certification requires the 90^{th} percentile of the absolute time synchronization error to be lower than 5.5 μs for 90% of the observed time (i.e., 120 *sec*).

In Figure 4 we show the 90^{th} percentile of time synchronization error for different cases using a logarithmic scale. In the first three cases (the three left bars), Wi-Fi 6 COTS devices were used in different network topology scenarios. As Wi-Fi COTS devices do not support hardware timestamping of PTP messages, the achieved time synchronization accuracy is low, with time synchronization errors ranging from several milliseconds for an ad-hoc topology, to several hundreds of milliseconds in case of managed mode. On the other hand, due to the ability of hardware timestamping in the openwifi boards, the PTP synchronization achieves a high time synchronization accuracy, with the 90^{th} percentile of the time synchronization error being lower than 1.3 μs. This is well below the *Wi-Fi TimeSync* certification requirements threshold of 5.5 μs. When the time synchronization requirements are more relaxed, and Wi-Fi end-devices need to be COTS devices, we can make use of a beacon based synchronization mechanism [20] that achieves a 90^{th} percentile of time synchronization error smaller then 25 μs. Such a synchronization error is higher than the *Wi-Fi TmeSync* certification requirements, but is still 2-3 orders of magnitude better than the offered synchronization accuracy when COTS devices are used in both AP and end devices.



(a) End-to-end communication latency

(b) Separation of communication latency on each network segment.

Figure 5: Communication latency comparison in a 3-hop wireless-wired network topology.

4.2.2 End-to-end communication latency

By scheduling different traffic flows in separate contention-free time slots we can avoid the random delays in accessing the wireless channels due to contention. In this scenario we used a three hop wired-wireless network topology where all devices in the network were time synchronized using PTP and each device applied scheduling (as described in Section 4.1). In the network, we run two different traffic flows, one of them being time sensitive and requiring end-to-end deterministic communication latency.

In Figure 5a we show the 99^{th} percentile of the end-to-end communication latency and its benchmarked value when Wi-Fi COTS devices are used in the network setup. When COTS devices are used, there is no possibility to do any type of scheduling in the wireless network segment, implying that different traffic flows (time sensitive and other non-time sensitive) will compete for the channel access introducing random delays to communication latency. In the scheduled case, the end-to-end communication latency is solely impacted by the cycle length and the way how time schedules are assigned in different network hops. However, such schedule organization is deterministic and will provide a certain upper bound to the communication latency that will not be exceeded under any network circumstance. As seen in Figure 5a, in the scheduled case the end-to-end latency is 20 times lower than in the unscheduled case.

Using INT monitoring we can measure the latency on each hop and determine which hop or network segment contributed the most on the end-to-end latency. In Figure 5b we show the contribution of each network segment on

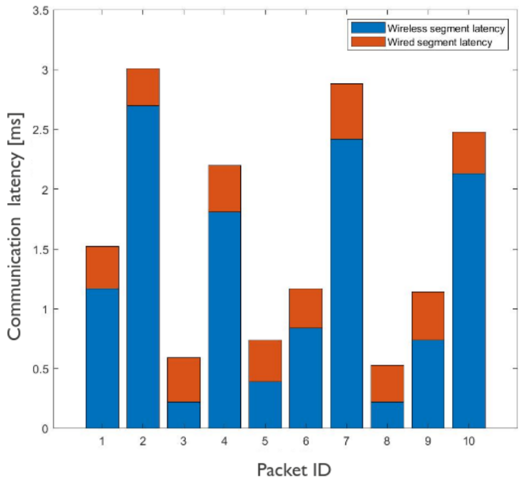


Figure 6: Communication latency per packet basis (first 10 packets).

end-to-end latency. As the packet is timestamped at the point when it enters the communication stack the measured segment latency includes the queuing delay in the sending side as well as transmission and propagation delays in the link. Due to its lower data rates compared to the wired segment, as well as longer waiting times in the source node (the worst case waiting time can be as high as the scheduling cycle time), the wireless segment contributed the most in the end-to-end latency.

Figure 6 presents the communication latency of the first 10 packets of the time sensitive data flow. Here we can clearly see the impact of the scheduling cycle length. As the packet generation by the application is random, it might happen that the packet is generated just after the scheduled time slot has ended (e.g. packets 2, 7 or 10). In that case, the packet has to wait at the sending side for the whole scheduling cycle, which in our case was 3 ms. On other occasions, when the packet is generated just before the scheduled time slot, the queue waiting time at the sending side will be lower (e.g. packets 3, 5 or 8) resulting in a lower communication latency in the first hop (in the wireless segment). As it can be seen, further improvements can be achieved by synchronizing the application generation time with the actual schedule at the end device.

5 Conclusion

The growing need for real-time and deterministic communication in various professional environments such as industrial facilities, signals that Time-Sensitive Networking (TSN) should become an inherit part of the wireless network segment as well. A number of challenges still need to be addressed related to the application of TSN features in the wireless network, commencing with accurate time synchronization and fine-grained wireless scheduling. Based on such observations, this paper listed a number of considerations that have to be tackled to achieve end-to-end wired-wireless TSN. These considerations include accurate time synchronization, unified wired-wireless fine-grained scheduling, in-band network performance verification and new KPIs for better tackling performance of each network feature. In addition to this we presented a PoC Wi-Fi based solution that is able to offer deterministic communication even in wireless network segment with time synchronization error lower than 1.3 μs, and end-to-end communication latency of 3 ms in three hop wired-wireless TSN.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest.

References

1. Martin Wollschlaeger, Thilo Sauter, and Juergen Jasperneite. The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0. *IEEE industrial electronics magazine*, 11(1):17–27, 2017.
2. Morteza Ghobakhloo. Industry 4.0, digitization, and opportunities for sustainability. *Journal of Cleaner Production*, 252:119869, 2020.
3. International Electrotechnical Commission et al. Industrial communication networks - fieldbus specifications. *IEC 61158 series.*
4. International Electrotechnical Commission et al. Industrial communication networks-profiles-part 2: Additional fieldbus profiles for real-time networks based on iso/iec 8802-3. *Standard IEC*, pages 61784–2, 2014.
5. Ieee time-sensitive networking (tsn) task group.
6. Zexian Li, Mikko A Uusitalo, Hamidreza Shariatmadari, and Bikramjit Singh. 5g urllc: Design challenges and system concepts. In *2018 15th International Symposium on Wireless Communication Systems (ISWCS)*, pages 1–6. IEEE, 2018.
7. Aruba. Ieee 802.11ax,. White Paper, 2019.
8. IEEE Standards Association. *IEEE Standard 802.1AS-2020, "IEEE Standard for Local and Metropolitan Area Networks—Timing and Synchronization for Time-Sensitive Applications in Bridged Local Area Networks"*, June 2020.
9. IEEE Standards Association. *IEEE Standard 802.1Q-2018, "IEEE Standard for Local and metropolitan area networks: Bridges and Bridged Networks"*, July 2018.
10. IEEE Standards Association. *IEEE 802.1Qbu-2016 "IEEE Standard for Local and metropolitan area networks, Bridges and Bridged Networks, Amendment 26: Frame Preemption"*, August 2016.
11. IEEE Standards Association. *IEEE 802.1Qci-2017 "IEEE Standard for Local and metropolitan area networks, Bridges and Bridged Networks, Amendment 28: Per-Stream Filtering and Policing"*, September 2017.
12. IEEE Standards Association. *IEEE 802.1CB-2017, "IEEE Standard for Local and metropolitan area networks-Frame Replication and Elimination for Reliability"*, October 2018.

13. IEEE Standards Association. *IEEE P802.1Qcc-2018, "Standard for Local and metropolitan area networks - Bridges and Bridged Networks - Amendment:Stream Reservation Protocol (SRP) Enhancements and Performance Improvements"*, October 2018.
14. 3GPP. *Technical Specification 23.501, "System Architecture for the 5G System", v16.5.1*, August 2020.
15. Tobias Striffler, Nicola Michailow, and Michael Bahr. Time-sensitive networking in 5th generation cellular networks-current state and open topics. In *2019 IEEE 2nd 5G World Forum (5GWF)*, pages 547–552. IEEE, 2019.
16. Istvan Godor, Michele Luvisotto, Stefano Ruffini, Kun Wang, Dhruvin Patel, Joachim Sachs, Ognjen Dobrijevic, Daniel P Venmani, Olivier Le Moult, Jose Costa-Requena, et al. A look inside 5g standards to support time synchronization for smart manufacturing. *IEEE Communications Standards Magazine*, 4(3):14–21, 2020.
17. 5G-ACIA, White Paper. *Integration of 5G with Time-Sensitive Networking for Industrial Communications*, January 2021.
18. NOKIA, White Paper. *5G and Wi-Fi6 radio: options for operational technology*, 2020.
19. Aneeq Mahmood, Reinhard Exel, Henning Trsek, and Thilo Sauter. Clock synchronization over ieee 802.11—a survey of methodologies and protocols. *IEEE Transactions on Industrial Informatics*, 13(2):907–922, 2017.
20. Jetmir Haxhibeqiri, Xianjun Jiao, Muhammad Aslam, Ingrid Moerman, and Jeroen Hoebeke. Enabling tsn over ieee 802.11: Low-overhead time synchronization for wi-fi clients. In *2021 22nd IEEE International Conference on Industrial Technology (ICIT)*, volume 1, pages 1068–1073, 2021.
21. Bert Hubert, Thomas Graf, Greg Maxwell, Remco van Mook, Martijn van Oosterhout, P Schroeder, Jasper Spaans, and Pedro Larroy. Linux advanced routing & traffic control. In *Ottawa Linux Symposium*, volume 213. sn, 2002.
22. Ieee standard for information technology–local and metropolitan area networks–specific requirements–part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications - amendment 8: Medium access control (mac) quality of service enhancements. *IEEE Std 802.11e-2005 (Amendment to IEEE Std 802.11, 1999 Edition (Reaff 2003)*, pages 1–212, 2005.
23. Xianjun Jiao, Wei Liu, and Michael Mehari. open-source ieee802.11/wi-fi baseband chip/fpga design, 2019.
24. Jetmir Haxhibeqiri, Pedro Heleno Isolani, Johann M. Marquez-Barja, Ingrid Moerman, and Jeroen Hoebeke. In-band network monitoring technique to support sdn-based wireless networks. *IEEE Transactions on Network and Service Management*, 18(1):627–641, 2021.
25. Jetmir Haxhibeqiri, Ingrid Moerman, and Jeroen Hoebeke. Low overhead, fine-grained end-to-end monitoring of wireless networks using in-band telemetry. In *2019 15th International Conference on Network and Service Management (CNSM)*, pages 1–5, 2019.
26. Wi-fi certified timesync technology overview, 2017.