QoS-aware UL-OFDMA for time-sensitive applications in Wi-Fi 6 networks

Ozgur Ozkaya, Jetmir Haxhibeqiri, Ingrid Moerman and Jeroen Hoebeke
IDLab, Ghent University - imec
name.surname@ugent.be

***Abstract*—Real-time applications are employed in today's private professional networks to support process handling and improve the efficiency of production. For supporting such applications, communication networks need to support deterministic communication with bounded low latency and high reliability. Time-sensitive networking (TSN) is used for such purposes, recently extended to wireless networks as well. To further improve the network catering to such real-time applications, it is crucial for end devices to expose their requirements to the network. On top of that, new wireless features like OFDMA, implemented in IEEE 802.11ax (Wi-Fi 6), can improve wireless time-sensitive networks (W-TSNs) by improving communication efficiency. This paper looks at reducing the overhead of OFDMA and integrating UL-OFDMA with wireless TSN to support time-sensitive flows. We show that when both features are integrated, it reduces the latency by $\sim$ 16 times compared to Wi-Fi with UL-OFDMA scenario while giving 50% better air time utilization compared to the wireless TSN scenario.**

***Index Terms*—wireless TSN, OFDMA, WiFi 6**

I. Introduction

In the fast-evolving world of private professional communications, time-sensitive networking (TSN) has become important as it supports communication between people, machines, and processes facilitating faster production, decreasing costs, and improving needed customization. With recent advancements in wireless technologies, TSN is spanning both wired as well as wireless domains, bringing the flexibility of the wireless domain to support even portable and mobile time-sensitive (TS) applications. As such, TSN serves as a cornerstone technology and refers to a set of standards developed by the IEEE 802.1 TSN task group. TSN facilitates deterministic communication by providing accurate time synchronization [1], traffic scheduling [2], and network management [3]. These compounds ensure that critical data is delivered on time, enabling seamless coordination between various components and systems, while the communication network is shared with other best-effort applications.

With the advancement of the IEEE 802.11 technology, the latest standard IEEE 802.11ax introduced a set of features that can be utilized for supporting time-sensitivity in wireless links. Amongst others, Orthogonal Frequency Division Multiple Access (OFDMA) and Multi-User Enhanced Distributed Channel Access (MU EDCA) can enable coordinated channel access for end devices by access points (APs). Such coordination improves channel access delays for devices with TS applications bringing determinism to wireless networks. In addition, OFDMA allows for efficient spectrum utilization and improved reliability in wireless networks [4]. Similarly, MU EDCA enhances channel access mechanisms, enabling better performance in multi-user environments [5].

Next to the developments on wired-wireless end-to-end TSN, the ability of applications to expose their requirements to the network stack as well as network devices is another important aspect of wireless TSN (W-TSN). Such application-network integration ensures optimal resource allocation and prioritization, leaving sufficient resources for best-effort traffic as well. By allowing applications to expose their requirements and interact intelligently with the network, APs or controllers can create adaptive and deterministic systems capable of meeting the diverse demands of diverse applications.

In this paper, we study the behavior of UL-OFDMA coordination in a W-TSN-enabled network where channel access for end devices is scheduled by the AP. The contributions of this paper are to show the effect of UL-OFDMA for TS applications, utilizing the QoS characteristics sharing from applications towards the network. On top of that, we've created a scenario where AP can create schedules in a dense network to fulfill TS application requirements while improving overall network performance. The rest of the paper is organized as follows: section II gives a background to scheduling and OFDMA, section III discusses the related work, section IV introduces the integration of application requirement sharing mechanism with UL-OFDMA, sections V describes the simulation setup and shows achieved results. Lastly, section VI concludes the paper.

II. Background

This section presents an overview of the key concepts, such as OFDMA and scheduling and gating mechanisms, helping to understand the motivations and objectives of this paper.

A. Scheduling and Gating Mechanism

The usage of TS communication has increased in many use cases in private professional networks. Deterministic communication, synchronization, and quality of service (QoS) form the foundation of such networks. TSN and its wireless extension aim to meet these requirements [6].

Traffic scheduling is an essential part of TSN. Scheduling in TSN is performed utilizing a gating mechanism on each queue of each station. Each gate will open and close in a cyclical way, allowing for deterministic channel access for each station. Figure 1 shows an example of how scheduling

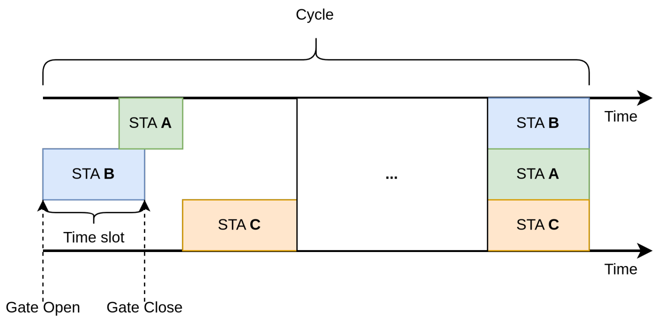


Fig. 1. Scheduling mechanism

works. Time slots are assigned to the stations and their queues. The beginning of these slots is called gate opening time. As can be seen in the figure these slots can be shared with other stations, can be dedicated, and can differ in length. In shared time slots, channel access is based on contention. Depending on the implementation, transmissions which start inside a time slot can exceed the time slot boundaries. This is also the case in our implementation in ns-3.

B. OFDMA

Orthogonal Frequency Division Multiple Access (OFDMA) was introduced in Wi-Fi with the latest standard IEEE 802.11ax [7]. OFDMA allows multiple users to simultaneously transmit data over the same frequency band reducing the network contention. In addition, this leads to better spectrum utilization and an increase in overall network capacity. All of this is enabled by dividing available bandwidth into smaller sub-carriers known as resource units (RUs), that can be dynamically assigned to different stations.

In UL-OFDMA, figure 2, each user is allocated a subset of sub-carriers for data transmission. First, AP will poll stations for their buffer state. Such information collection can be done in two ways: explicit and implicit [8]. When an explicit Buffer Status Report Poll (BSRP) is used, stations answer with a BSR sending their queue sizes of each access category (ACs). When implicit BSRP is used, stations add the queue information to the packets they send in UL. Based on this information AP will decide on RU assignment to each station. After the BSRP exchange, the MU-RTS Trigger/CTS frame exchange procedure may follow. This is optional and it allows an AP to start a TXOP and protect the TXOP exchange [7].

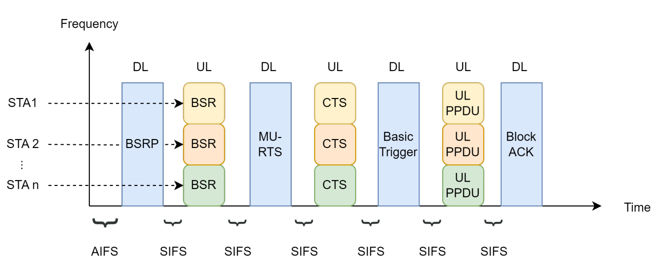


Fig. 2. Flowchart of a UL-OFDMA procedure

III. Related Work

Recently, both TSN and OFDMA have attracted interest from industry and researchers. In this section, state-of-the-art works are presented and discussed briefly.

Ahmed et al. [9] introduced the scheduled TXOP (S-TXOP) where a pre-configured resource allocation at the beginning of TXOP takes place. The S-TXOP is divided into smaller parts by AP and is used for different transmissions both in uplink and downlink. In this way, requirements for applications can be met and TS applications are supported in the network. However, gaining channel access by the AP remains probabilistic based on CSMA.

In [10] various UL-OFDMA scenarios are tested in a testbed scenario. Scenarios include EDCA, traffic scheduling, and UL-OFDMA with stream classification services (SCS). Similar to our solution, authors in [10] removed BSRPs utilizing such SCSs, resulting in low latency for applications compared to EDCA and UL-OFDMA without using SCSs. Authors in [11] propose a scheduler to achieve the required latency for Health Internet-of-Things (H-IoT) applications. To do this, AP also plays the role of the scheduler and assigns RUs based on the prioritization formula which is mainly related to ACs of traffic flow and actual queue size. The main goal of this work is to define different prioritization classes for different stations and assign RUs to answer the needs of H-IoT applications.

In [12] authors utilize additional EDCA parameters for APs to give an advantage on channel access contention over the other stations in the network. Having an AP with better EDCA parameters results in a high probability of winning channel access, while AP in return can utilize OFDMA to meet TS flow requirements. [13] proposed two algorithms to ensure TS traffic. Both algorithms aim to use the smallest, 26-tone RUs, to maximize the stations served and also meet the requirements of TS traffic. It solves the scheduling problem by checking the performance of previously used RUs. In some cases TS applications have more chances compared to non-TS, thus creating an unfair situation.

Works done in the literature are either non-deterministic or have overhead compared to our proposed solution. While usage of UL-OFDMA increases overheads such as BSRP and MU-RTS, probabilistic channel access for AP still hinders the full channel access determinism. Contrary to cited papers, in this paper we aim to create a deterministic W-TSN along with modifying UL-OFDMA in a way that shortens the total transmission time of the OFDMA procedure.

IV. Proposed UL-OFDMA and Application Requirements Sharing Mechanism

In this section, our proposed UL-OFDMA procedure and application requirements (AppReq) sharing mechanism are described in detail.

A. AppReq Sharing Mechanism

The importance of sharing application requirements is already mentioned in Section I. Doing so, the AP learns the needs of each TS application and utilizes such information as input for scheduling different stations in its Basic Service Set (BSS). As such, stations can be triggered at the right time by the AP, ensuring timely transmissions of the TS frames. To ensure that none of the other stations will utilize the channel at the beginning of the triggering slot, AP informs all the other stations in the network about the schedule changes. As a result, a dedicated time slot for TS applications, to be used for UL-OFDMA, can be created by considering only application requirements.

The steps of this procedure are given in Figure 3. When a station starts a TS application at first it sends the requirements of that application to the AP, a so-called AppReq request (1). The AppReq request packet includes the maximum latency limit, application data rate, packet size, and AC information. As time slots can be defined per station and per AC, AC is an essential parameter for scheduling. To reduce the overhead of transmitting AppReq, such data can be encapsulated with other Wi-Fi control packets as part of information elements (IE) or be included with other data packets going in uplink as IPv6 extension header [14]. After receiving the request, AP saves the information about the station and TS flow to be triggered in UL-OFDMA. Then it creates a schedule based on the request and sends back that schedule information to the station, called AppReq response (2). The AppReq response packet includes the communication cycle, start time inside the communication cycle, and duration of the dedicated time slot for relevant AC. After sending the AppReq response, AP broadcasts another packet (3) to ensure that all the other stations in the BSS get updated with the new schedule. This information can be included also as information element (IE) in the beacon packets to account for possibility of losses of broadcast packets. As such, all the stations are aware that there is a dedicated time slot for a TS operation only and they should clear the channel during that time slot. This is achieved by utilizing a gated mechanism for each AC, on top of the normal IEEE 802.11 channel access mechanism. If another station has a TS flow at the same AC, after the same packet exchange, AP includes it in the UL-OFDMA procedure and both of the stations can send their packets at the same time. The stations with the TS application close all the gates for their relevant AC. This means that they can send their packets only when they are triggered for UL-OFDMA by the AP.

B. AppReq-aided UL-OFDMA

For a single UL-OFDMA transmission, as explained in the previous section, there are a lot of pre-steps (such as BSRP and MU-RTS) for each OFDMA procedure hence, resulting in overhead in the wireless medium. In cases where hidden node issue is not common, the RTS-CTS mechanism gives an additional overhead. To avoid such overheads, we disabled the RTS-CTS mechanism. On top of that, we make use of the application requirements sharing mechanism to avoid the need for BSRPs and BSRs. This will ensure determinism for TS traffic flows by supporting them only with an updated UL-OFDMA scheme. After receiving an AppReq request, AP keeps track of station requests. When a gate opens, AP triggers

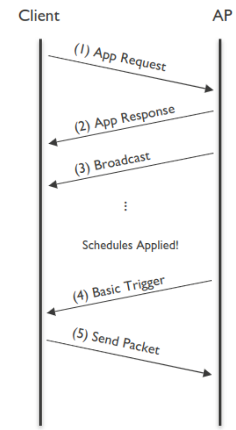


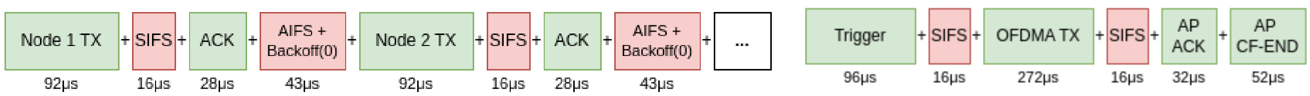
Fig. 3. Application-Requirement (APP-REQ) sharing to support dedicated UL-OFDMA

only the stations with an active TS application that have previously shared their requirements. In this way, multiple TS flows can be sent in UL in parallel utilizing UL-OFDMA without the need for BSRP exchange. After the removal of these 2 pre-steps, BSRP exchange and MU-RTS, UL-OFDMA traffic only consists of a basic trigger, TS data packets from stations, and lastly multi-user acknowledgment (ACK).

This approach also decreases the total transmission duration compared to standardized OFDMA implementation and Wi-Fi after a certain number of stations. The total transmission time of the updated OFDMA mechanism is shorter than a normal OFDMA procedure since BSRP and MU-RTS packets are dropped out. This is illustrated for 4 stations, either using normal Wi-Fi operation or polled in parallel using UL-OFDMA. Figures 4a and 4b show transmission times of packets and inter-frame spacings (IFS) in a scenario with 640 bytes packet size and 122.5 Mbps physical data rate parameters. When OFDMA is not used, there are more IFSs compared to when it is used. In some cases, due to contention and channel busy events where backoff is employed, the waiting time between packets can take up to one packet transmission time. In the case when OFDMA is not used and assuming no backoffs at all due to perfect synchronized transmissions (best case scenario), the total transmission time is calculated to $716\mu s$. For our proposed AppReq-aided UL-OFDMA mechanism, it is calculated as $484\mu s$. Thanks to being able to share application requirements, AP can remove pre-steps and can directly send the basic trigger. Moreover, AppReq packets are sent only once throughout the communication time, compared to BSRP information exchange which has to be performed periodically. In addition, the channel access time will also be reduced for stations that include TS applications.

V. Simulation Setup and Results

The AppReq-aided UL-OFDMA mechanism is implemented in ns-3 version 3.37. This implementation also consists of the main openwifi and W-TSN features [15]. In table I simulation parameters are given.



(a) Air-time usage without OFDMA transmission

(b) Air-time usage with proposed UL-OFDMA transmission

Fig. 4. Transmission time for four stations w/wo employing OFDMA.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Stations	12
WiFi Standard	802.11ax
Data Mode and Bandwidth	HeMcs3, 80MHz
TS App Data Rate	1 Mbps
TS Traffic Type	CBR
TS Traffic packet size	640 bytes

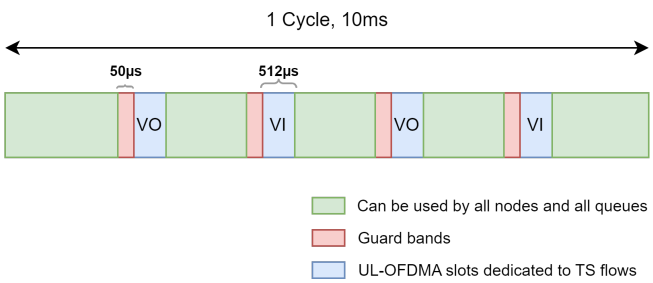


Fig. 5. Schedule used in W-TSN with UL-OFDMA. UL-OFDMA slots are dedicated to AP to initiate the UL-OFDMA procedure for TS flows.

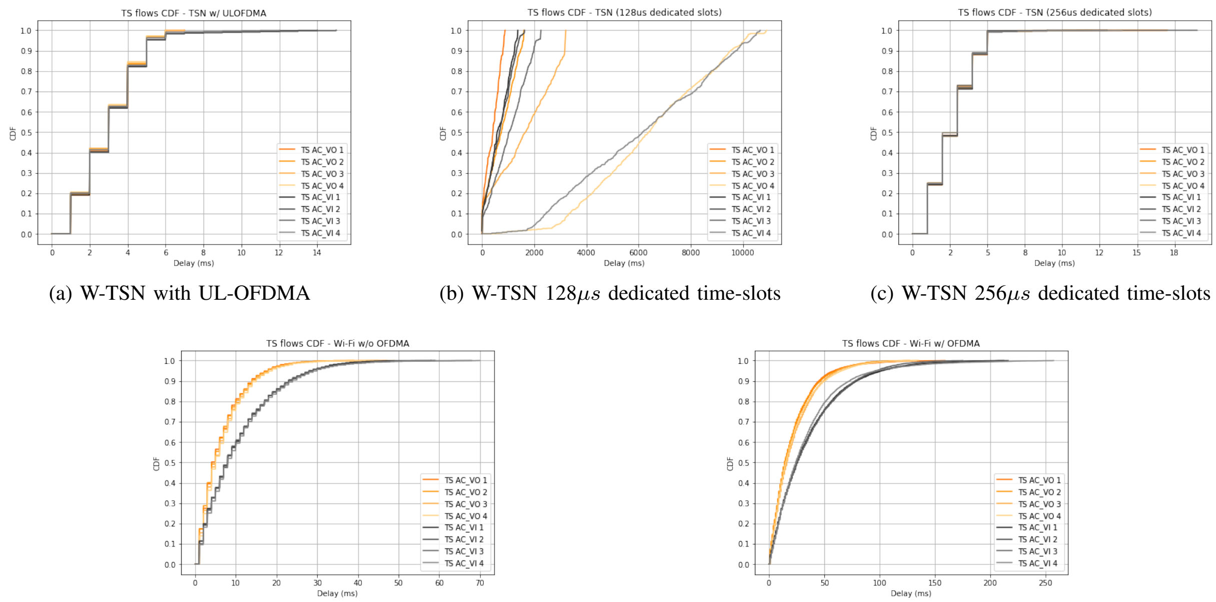
There are a total of 12 stations in the network placed randomly in a 10x10 meter area. The psychical data rate is set at 122.5 Mbps. Tests are done in 5 different cases. The first one is a network that supports W-TSN scheduling in wireless as well as UL-OFDMA. In this case, we tested our proposed OFDMA in relation to TSN scheduling. The second one is W-TSN without UL-OFDMA support. In this scenario, dedicated slots are assigned to each TS flow. The lengths of dedicated time slots are calculated based on the first case to ensure fairness between scenarios. The time slots reserved for UL-OFDMA in the first scenario, shown in figure 5, are divided equally for each TS flow. Thus, in the second case, $512\mu s$ reserved for UL-OFDMA is divided by 4 and each TS flow has a $128\mu s$ dedicated time slot one after another. The third case is again W-TSN without UL-OFDMA but the dedicated time-slot length for each TS flow is 2 times longer than in the previous case. The remaining last 2 cases are non-W-TSN Wi-Fi with and without OFDMA support, respectively. In Wi-Fi with OFDMA case, AP has an access request interval of 10ms which is the value of a cycle in the W-TSN scenarios. AP tries to access the channel following each successful OFDMA procedure plus the interval.

Regarding the traffic types, eight TS flows are considered in the conducted simulations. Four of them are of voice AC type and four of them are of video AC type. TS applications have a 1 Mbps data rate and a 640-byte packet size. These parameters lead to $\sim$2 packets generation per cycle for a constant bit rate (CBR) traffic type. We expect to have a max of 10ms (1 cycle) delay in these TS flows. In addition to TS traffic flows, we add one baseline non-TS UDP traffic flow that is sent by one of the stations and would be present in the simulation all the time. Baseline traffic has Possion distribution and 500-byte packet size. The other three stations send non-TS UDP video packets to the AP with a Poisson distribution. The packet size of the traffic flows is 1000 bytes.

In all of the W-TSN scenarios (scenarios 1 to 3), pre-defined schedules are used. When AppReq is used schedules are distributed by the AP, when not used schedules are assigned to each station manually just for the sake of simulation. In the case of wireless W-TSN with UL-OFDMA support, AP distributes the schedule given in Figure 5. Stations without a TS flow can use all the time slots except dedicated slots for other TS traffic flows. On the other hand, stations with TS flows close their respective AC queues all the time. Also, during guard bands initiating a channel access is not possible but ongoing traffic is not interrupted even when the next gate is opened. These guard bands are added to ensure the transmission of TS traffic.

A. Results

Figure 6 shows the cumulative distribution function (CDF) values of communication delay. The first case results when wireless W-TSN is used in combination with the proposed AppReq-aided UL-OFDMA mechanism are shown in Figure 6a. All of the voice packets and 99% of the video packets are sent within the first communication cycle, meaning that only less than 1% of the video packets are sent in the second cycle. It is seen in the logs that when an application starts a management packet exchange occurs between the station and AP and this can continue in UL-OFDMA slots. Since this happens only at the beginning, the rest is not affected too much as can be seen from the 99th percentile values. 99th percentile of all voice flows is 6ms and for all video flows it ranges between 6ms and 9ms. This leads to achieving the goal of both ACs sending packets in one cycle in 99% of cases. In the second case, W-TSN is used and schedules are manually applied to all stations in the network. Stations with TS flows have their dedicated time slots for their applications' AC. Since transmission started in the previous slot can continue even when the next gate is opened, a snowball effect can occur affecting transmission in upcoming time slots negatively,



(a) W-TSN with UL-OFDMA

(b) W-TSN $128\mu s$ dedicated time-slots

(c) W-TSN $256\mu s$ dedicated time-slots

(d) WiFi without UL-OFDMA

(e) WiFi with UL-OFDMA

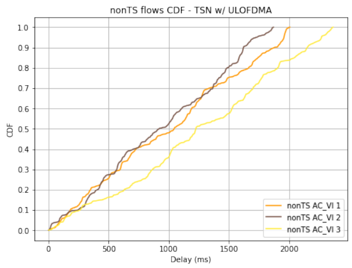
Fig. 6. Delay values of TS flows in a CDF format for all cases.

meaning causing stations not to be able to send their packet. As a result, delay values go up to seconds. TS AC_VO 1 and TS AC_VI 1 flows are the first ones in the dedicated time slots chain. Since they have a guard band before them, they have higher chances of accessing the channel resulting in lower delays compared to other TS flows as shown in Figure 6b. However, as each TS flow has only limited time to send packets, $128\mu s$, it can happen that such time slot is wasted due to possible channel busy events by other stations. Also, if these two flows do not access the channel at the beginning of their respective time-slots, they can create a snowball effect too, resulting in high delay values for the rest of the TS flows. In the third W-TSN case when stations have doubled dedicated time slots, most of the packets are sent in one cycle with a 99th percentile of 5 ms for both TS flows (Figure 6c). In this case, the TS flow requirements are met as in our proposed method, but twice as much time is reserved for TS flows compared to the first two cases. Thus, non-TS flows are affected negatively from that since they have reduced air time in a communication cycle than before.

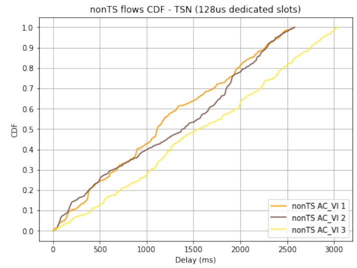
Figure 6d and 6e show the results when WiFi without W-TSN scheduling extension is used. In the case when OFDMA is not used, EDCA parameters show their effects resulting in voice packets having lower delays compared to video packets. The 99th percentile for all voice flows ranges between 25ms and 27ms and for all video flows between 38ms and 43ms, which are higher than W-TSN with App-Req aided UL-OFDMA mechanisms support. Also, the worst-case delay reaches up to 70ms. In the case of WiFi with OFDMA, again voice packets have lower delay values compared to video packets but overall delays are higher than in the Wi-Fi without OFDMA case. The main reason for this is OFDMA. AP acts like a station in the network and tries to gain channel access with an interval of 10ms. Thus, contention increases among the network resulting in higher delay values for all flows. W-TSN with UL-OFDMA has reduced latency for $\sim$ 16 times smaller compared to Wi-Fi with UL-OFDMA.

Figure 7 represents delay values for non-TS flows. In the first two W-TSN scenarios, figure 7a and 7b, a total of 2ms time slot in a 10ms cycle is reserved for TS applications. Meaning that 20% of the cycle is taken away from non-TS flows. In the third case, W-TSN with doubled dedicated time slots, this value goes up to 40% since TS time slots are doubled. This, of course, results in high delay values for non-TS flows in W-TSN cases as can be seen in figure 7c. When it comes to WiFi without W-TSN scheduling and OFDMA, non-TS applications perform better than in W-TSN in terms of delay with a max of 70ms. In the case of Wi-Fi with OFDMA, AP acts like a station as mentioned previously, and increases the load in the network. This results in very high delay values as lots of packets are stacked in the queue.

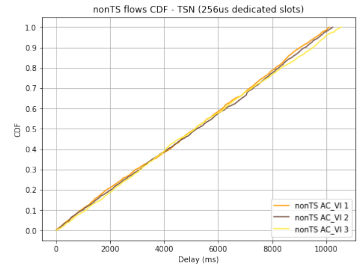
PDR results are presented in figure 8. In the case when W-TSN is used with the proposed AppReq-aided UL-OFDMA and W-TSN with doubled dedicated time-slot case, TS flows have 100% PDR. However, when $128\mu s$ time slots are used for TS flows, the last stations to have a dedicated time slot have a lot of packet loss. This is due to the snowball effect explained previously. Because one packet transmission time is already longer than the $128\mu s$ time slot. As a result of this, the last stations in the schedule likely miss their chances. When it comes to Wi-Fi without W-TSN support, with or without OFDMA, PDR values drop to 96%. The packet losses in Wi-Fi occur due to the channel being highly utilized. When OFDMA is used, channel utilization goes up to 82% which means the



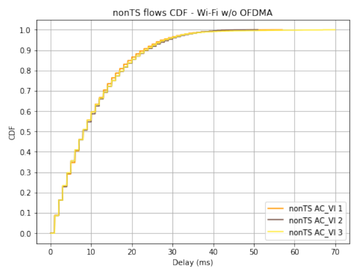
(a) W-TSN with UL-OFDMA



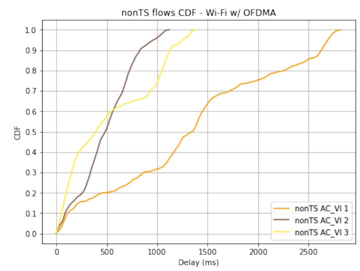
(b) W-TSN 128μs dedicated time-slots



(c) W-TSN 256μs dedicated time-slots



(d) Wi-Fi without OFDMA



(e) Wi-Fi with OFDMA

Fig. 7. Delay values of non-TS flows in a CDF format for all cases.

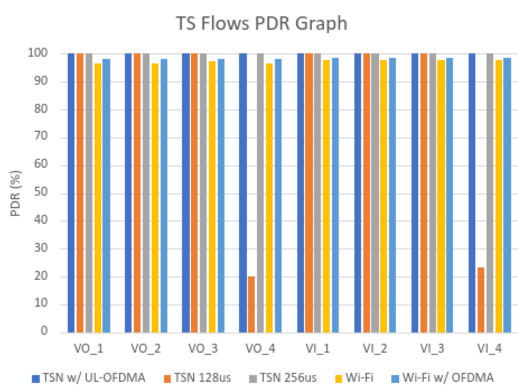


Fig. 8. PDR values of TS flows in all 5 cases.

network is very highly congested. The PDR results of non-TS flows are almost similar within most of the cases, greater than 98%, except the W-TSN case where time slots for TS flows are doubled. Reserving too much time for TS flows shows its negative effect on PDR values too, dropping down to 90%.

VI. Conclusion

W-TSN and OFDMA are getting more attraction over time as features to be used for supporting TS traffic flows in wireless networks. In this work, we used W-TSN scheduling in addition to the AppReq-aided UL-OFDMA mechanism to support TS flows, while sharing the network with non-TS flows. Results show that when the UL-ODFMA pre-steps are removed, OFDMA still fulfills TS-flow requirements reducing the overhead in wireless. Such reduced overhead is utilized by non-TS flows for better performance. Combining UL-OFDMA with W-TSN brings deterministic to the network being able to fulfil TS application requirements. There is still room for improvement in scheduling. Hence, automated scheduling systems with the help of artificial intelligence, large-scale networks, and mesh networks can be considered for W-TSN and OFDMA.

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