Impactless Beacon-Based Wireless TSN Association Procedure

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***Abstract*—Time-sensitive networking (TSN) is widely used in industrial environments to support low-latency deterministic communications. Innovation to bring time-sensitive networking to wireless networks is getting traction. Besides enabling real-time and deterministic communications, Wireless Time-Sensitive Networks (W-TSN) should provide flexibility and easy deployment, key characteristic requirements for industrial networks. Nevertheless, current research in this field focuses on adapting wired TSN features to the wireless world, namely accurate time synchronization and traffic scheduling, essential processes for wireless end devices such as automated and impact-less association procedure are not considered until now. This work proposes a W-TSN impactless association procedure that provides time synchronization and traffic scheduling for prospect W-TSN clients during the association phase by utilization of beacons. As such, prospect clients can perform association procedure in a controlled fashion avoiding collisions with other, already-associated, W-TSN clients. The presented procedure is designed, implemented, and tested in a real-world scenario on top of a wireless Software Defined Radio (SDR) platform with the IEEE802.11 standard. The results show high accuracy synchronization on client frame transmissions even with challenging scheduling timeslots of 128 μs.**

***Index Terms*—wireless time-sensitive networking, association, time synchronization, scheduling.**

I. Introduction

Industry 4.0 heads us to environments crowded with wired and wireless sensors and actuators, where many industrial applications require real-time and safety-critical communication. As such, industrial communication networks should maintain strict communication requirements including real-time, deterministic low latency, and high reliability. To enable such network features, innovation on wireless network time-sensitive features and its integration with wired time-sensitive networking (TSN) is bringing us closer to an end-to-end wired-wireless deterministic communication vision.

To tackle the adoption of the time-sensitive network features, a set of standards named TSN were developed by the IEEE 802.1 group. TSN dates back to 2007 when the Audio Video Binding (AVB) task group was created with the aim of standardizing an Ethernet-based solution for audio and video transmission. Later, due to the industrial control communication gap to satisfy strict end-to-end requirements with high data transmission rates, the group expanded its scope becoming the Time-Sensitive Networking Task Group [1]. The main TSN standards include the Timing and Synchronization for Time-Sensitive Applications - IEEE 802.1AS [2], Enhancements for Scheduled Traffic - IEEE 802.1Qbv [3] and the Forwarding and Queueing Enhancements for Time-Sensitive Streams - IEEE 802.1Qav [4].

To achieve deterministic communication, TSN is based on two pillars: time synchronization and transmission agreements or schedules between data generators and the network. Keeping a unique and accurate time reference through the network allows clients to be fully time-synchronized and to determine the accurate schedule timing. In addition to this, by synchronizing transmission schedules, transmission reliability with bounded latency and no queue congestion loss is ensured. While variants of the Precision Time Protocol (PTP) are the most widely used for synchronization purposes, scheduling uses a cycle and time slices with a guard band system to ensure deterministic medium access fulfilling of application requirements [5].

At the moment, most advances in TSN networks have been focused on Ethernet-based wired networks. However, many industry use case scenarios demand access to nodes that cannot be easily accomplished by wires or even mobile nodes. Here, the flexibility and mobility possibilities offered by wireless communications represent a clear advantage. While the current works are focused on including wireless TSN (W-TSN) as an extension of a TSN wired network, yet big challenges such as wireless delays, lack of determinism, security, and transmission inefficiencies make it difficult for wireless to comply with TSN standards [6].

Another essential point is the wireless technologies that can support TSN features or integration with wired TSN. Standardization efforts to integrate wired TSN network with their wireless counterpart are being done for both 5G and WiFi, as two most widely used wireless technologies. 5G

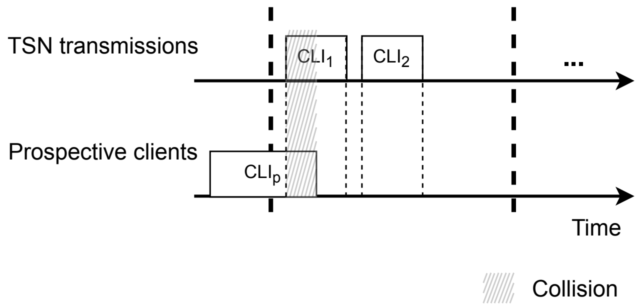

Figure 1. W-TSN association problem

currently supports integration with wired TSN, where the 5G network behaves as a TSN bridge between TSN nodes. Translation functions are standardized to map the data plane and control plane between both networks [7]. However, there are still gaps to be addressed in such integration such as: end-to-end TSN stream configuration, fully distributed network management and end-to-end time synchronization. On the other hand, the new features introduced to WiFi 6 (UL/DL OFDAM, MU-MIMO) [8] and others being introduced to WiFi 7 (multi-link operation, AP coordination) can be used to support determinism in the wireless segment, achieving seamless integration of the wired TSN with WiFi [9].

Besides considering these challenges when leading TSN foundation elements into wireless, it is also imperative to consider procedures such as the association of new nodes to the wireless TSN network. Apart from being the first interaction between the network and the clients, the association is a key step that has an impact on the user and network performance and has special relevance in W-TSNs [10]. Furthermore, a simple and reliable association procedure will always be essential for the right initial distribution of the network resources. End device association in W-TSN has an obvious goal, letting new clients join the network without affecting ongoing traffic flows of other already connected devices. An illustration of this is presented in Figure 1. Let us consider CLI_1 and CLI_2 the already designated wireless transmission timeslots of associated clients. Then, as prospective clients, in this case, CLI_p, do not have any means of time synchronization and scheduling, their association procedure can happen at any time, colliding with the scheduled traffic from other devices. To remedy this, the proposed solution brings TSN features such as synchronization and scheduling to prospect clients, before and during the association stage.

Therefore, the contribution of this study is a beacon-based association procedure for W-TSN which includes synchronization and scheduling methods for non-associated W-TSN clients. The association procedure is scheduled by the network and initiated by the client. As such, traffic collisions between W-TSN clients and prospect clients during the association phase are avoided. The proposed solution is evaluated in a real test-bed scenario using an open-source WiFi-based platform, openwifi, which is an IEEE 802.11 compatible Software Defined Radio (SDR) platform.

This paper is organized as follows. First, in section II, we present W-TSN tendency and wireless association related works, then in section III, key concepts of the operational phase scheduling system used in this work are presented. In section IV, we describe each part of the impact-less association procedure solution. In section V, the evaluation of results including synchronization accuracy, schedule overlapping, and delay are shown. Finally, section VI concludes this work.

II. Related Works

To understand better the research landscape, this section analysis related works based on two aspects: the general research work that has been done in W-TSN and specific studies related to supporting time synchronization and traffic scheduling during the association phase. It is important to mention that to the best of our knowledge there are no studies about W-TSN association, hence the next presented works relate with the specific features we propose to achieve association.

The TSN task group is focused on enabling TSN features on wired networks such as time synchronization [2], traffic scheduling [3], improved reliability [11] and resource management [12]. On the other hand, with the target to integrate wired TSN with wireless networks, the research community has commenced looking at ways how TSN features can be applied to wireless networks as well.

As such, in [13], the authors push W-TSN synchronization by introducing a low-overhead beacon-based synchronization mechanism for IEEE 802.11. This method includes follow-up beacons to account for beacon delays, achieving down to 10 μs synchronization accuracy. Equally important, in [14] the authors present a communications W-TSN model which proposes conversion methods to face transmission delays and transmission uncertainties. The authors propose to include sensitivity levels at data frames to achieve a multi-priority scheduling mechanism for frames. Another essential point is the network configuration. Here, works such as [15] take the first steps towards scheduling in W-TSN that satisfies end-stations requirements based on a fully centralized configuration model. The authors present a set of entities and interfaces and validate the model using the Digital Enhanced Cordless Telecommunications ultra-low energy (DECT ULE) wireless protocol.

Closer to our work, authors in [16] examine the use of carrier sense multiple access (CSMA) based superframes which carry schedule and synchronization for the discovery stage, while shifting to time division multiple access (TDMA) on the operation stage. Although in our work we also use CSMA/collision avoidance (CA) to transmit association frames, these transmissions are scheduled, avoiding collisions with already associated clients. Further, the use of superframes as control traffic may increase the network overhead.

Other studies such as [17] present a hybrid alternative that applies superframes for communications and beacons for time synchronization. Beacon transmission variations are handled by a proportional-integral filter which by its nature would require a convergence time and thus would increase association time affecting user experience and applications that involve mobility.

In [18], the authors use beacons for synchronization and scheduling delivery, which is time-frequency division multiple access (TFDMA) based. Although our proposed procedure also uses beacons for synchronization and scheduling, we differentiate between the association and the operational stage. The goal of this is to propose a low-overhead sufficient time synchronization mechanism and shared scheduling during the association phase while switching to a higher accuracy time synchronization method during the operation stage.

Finally, the concept of overloading fields in an AP beacon is far from being new. In [19] we find a theoretical study of the so-called beacon-stuffing. This broadcasting mechanism does not require an association and due to its simplicity, has different applications such as transmitting network information, synchronization, and other non-technical uses. In [20] a practical implementation is presented; however, contrary to this work, we use the vendor element instead of a second SSID to broadcast shared schedule information to be used for association.

In summary, numerous studies have been presented about time synchronization and traffic scheduling, especially in TDMA-based systems. Nevertheless, those do not contemplate an association phase that needs to be performed in the presence of dynamically assigned timeslots and without disrupting traffic therein.

III. W-TSN Scheduling

To understand better the proposed solution in the next section, in this section we will give a brief introduction on the way how traffic scheduling is achieved and maintained during the operational phase of an wired TSN node. Besides this, we present the traffic scheduling mechanism in the wireless TSN end nodes in openwifi SDR platform [21].

In order to ensure and maintain low-latency and deterministic communication, medium access of nodes and traffic flows have to be scheduled in time. In Ethernet TSN this is achieved by IEEE 802.1Qbv standard [3] that is used as a time-aware scheduler to assign traffic streams to different traffic classes based on priority codes. A gating system is defined for each multiple-queues Ethernet port that organizes the access of each queue to the transmission medium. The communication time of each Ethernet port is divided in time cycles with certain time length, where each queue will get its portion of the time slice, with some of them assigned the same shared time slice while others will have a dedicated time slice for low-latency communication. Then, each traffic class is mapped to a certain queue and scheduled on a certain time slice during a cyclic time period. This ensures the separation between different traffic classes by enforcing deterministic communication for traffic classes assigned to queues with dedicated time slice(s).

Following the IEEE 802.1Qbv concept and understanding the shared usage of the wireless medium, a scheduling mechanism was implemented in the openwifi SDR platform [21]. Due to the shared nature of the wireless medium, the W-TSN scheduling mechanism needs to be synchronized between the wireless nodes in order to avoid channel collisions and ensure deterministic behavior e.g., when one queue from a certain node is transmitting, the other queues in the same node as well as in the other nodes of the same wireless cell need to be closed to avoid traffic collision. Such W-TSN scheduling system is based on a gated system that controls the channel access of 4 hardware queues of openwifi. For achieving accurate gate opening and closure, the gate is controlled by the time synchronization function (TSF) timer of the wireless node. Thus, the TSF timer must be synchronized between nodes [22], [23].

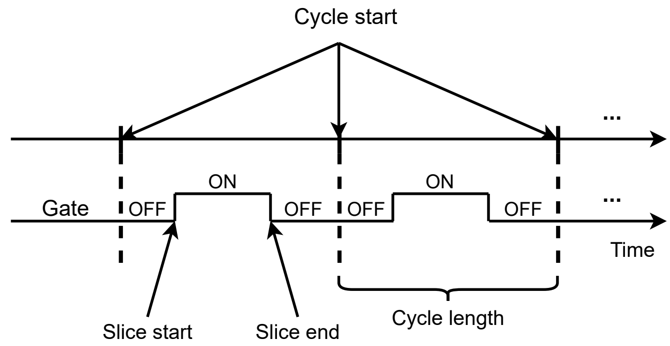

Figure 2. W-TSN scheduling system

For its normal operation, the gating system requires three inputs: cycle length, slice start, and slice end for each queue. As it is shown in Figure 2, the cycle is restarted every cycle length. Then, relative to each cycle start, slice start is the time when the gate for certain queues opens (ON), and slice end when it closes (OFF). This way, the transmission of every queue in the node is strictly controlled.

IV. W-TSN Association Design

In this section, we present a detailed description of how beacons are loaded at the AP with the pre-synchronization and pre-scheduling information to support the association phase, and how this data is captured and processed by the prospective clients to mitigate traffic collisions. In addition, the detailed W-TSN association procedure is described as well.

A. AP Beacon Overloading

The IEEE 802.1Qcc [12] standard specifies the TSN management possibilities which range from fully centralized to distributed model solutions. In the case of the centralized model, the Centralized Network Configuration (CNC) entity would dynamically manage the schedules for the nodes in the network. To extend such functions to the W-TSN network, W-TSN-enabled APs and client schedules are managed by the CNC. For each wireless cell, CNC will determine also a shared time slice inside the cycle that is reserved to be used only by the prospective clients to perform impact-less association procedure. In a decentralized W-TSN management

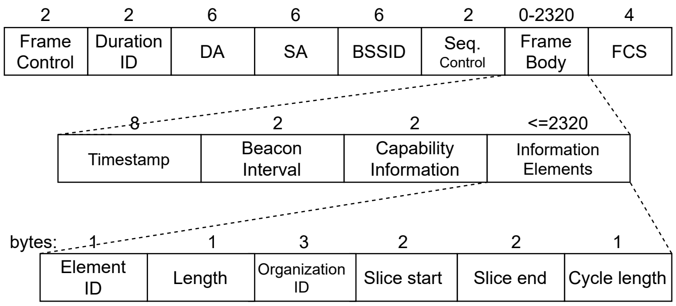

Figure 3. Beacon stuffing using the vendor specific element

case, AP should be aware of schedules assigned to all the wireless clients connected to it, or at least should be aware of the unassigned time slots.

As already stated, by using AP beacons we aim to attain pre-synchronization and pre-scheduling for not yet associated W-TSN clients. For achieving pre-synchronization of W-TSN clients we use the already available *Timestamp* field of the beacon. This timestamp is held from the AP's local time synchronization function (TSF) and added to the beacon at the driver level. This process generates delays that require compensation at the client-side to improve synchronization accuracy, which will be described further in subsection IV-B.

In addition to the TSF field, a beacon frame, among other elements, contains Information Elements (IE) that carry relevant information to clients. In this case, to carry non-standard defined information and keep coexistence with non-W-TSN clients the vendor-specific element was used. As it is described in section III, each W-TSN client will have a gating system like IEEE 802.1Qbv that needs to be configured accordingly. During the association phase, the gating system of the prospective client needs to be configured to allow traffic transmission only on the shared time slot that is reserved to be used for association procedure only. As such, the prospective client needs to know the cycle length of the AP, and the slice start and end of the association time slot. Such information (*Slice start, Slice end, Cycle length*) are added in five octets of the IE of the beacon as shown in Figure 3.

B. Beacon Processing by Clients

Thanks to the openwifi SDR platform [21], it is possible to shape the SDR driver according to our needs. Once the prospective client receives the beacons transmitted by the AP, it extracts the beacon TSF and uses it to overwrite its TSF, achieving thus time pre-synchronization. After that, the client extracts pre-schedule fields and configures its gating system accordingly. Once the gating system is configured the associating procedure can start ensuring no impact on other traffic in the wireless cell. During the whole association process, the client will continue to keep the pre-synchronization based on the received beacons. As part of the beacon packet processing, two fundamental mechanisms have been introduced to enhance pre-synchronization accuracy:

a) *Timestamp delay compensation:* The received timestamp or TSF includes delays that require to be corrected by the client. Since the beacon TSF is set at the driver level, such delays are related to channel access delay for beacon transmission, the transmission time of the beacon, and the communication delay between the driver level and the physical layer itself. In Equation 1, δ represents the total corrected delay that is added to the received beacon TSF.

$$\begin{aligned} \delta &= DIFS + B_T + P \\ &= 28 + \frac{148 * 8}{6} + 19.7 \\ &= 28 + 197.33 + 19.7 \\ &= 245.03 \mu s \end{aligned} \tag{1}$$

The first delay element is the DCF interframe space (DIFS), which is a mechanism to assign priorities to frames in the distributed coordination function. It is the minimum time the beacon frame would wait before being transmitted and changes depending on the applied standard. In our case we employ 802.11g, hence it is 28 μs [24]. B_T is the beacon transmission time, which is calculated considering the beacon frame size of 148 bytes and the default data rate of 6 Mbps at which beacons are transmitted. Finally, the client processing time P, to process and filter beacon frames at the driver was measured and also considered.

b) *Early/late beacon detection:* The default beacon transmission interval is 102.4ms. However, as it is shown in Figure 4, TSF differences of consecutive beacons arriving at the client are not always constant. The cause of this is related to the variable nature of the CSMA/CA channel access and channel conditions when the beacon transmission is initiated. Even though the beacons do not follow the backoff mechanism they have to obey the clear channel assessment mechanism. Thus, when the channel is busy with another transmission the beacon transmission has to be delayed. Hence, using all received beacons for pre-synchronization could lead to synchronization errors and thus unsynchronized transmissions by the client.
The role of such early/late beacon detection mechanism is to filter out ineffective beacons. This simple filter operates in a moving window scheme by using the arrival time difference of pairs of received beacons and checking if this difference is within a defined range (R). To define R, the *Beacon Interval* - B_I field is extracted from the received beacon frame and a deviation value x is added as shown in Equation 2. If the received beacon pair meets the condition, the last beacon internal timestamp is used to set the TSF of the client.

$$R = B_I \pm x \tag{2}$$

Unlike other filtering proposals such as the proportional-integral, this filter does not require a convergence time, which is imperative for a prompt W-TSN association procedure.

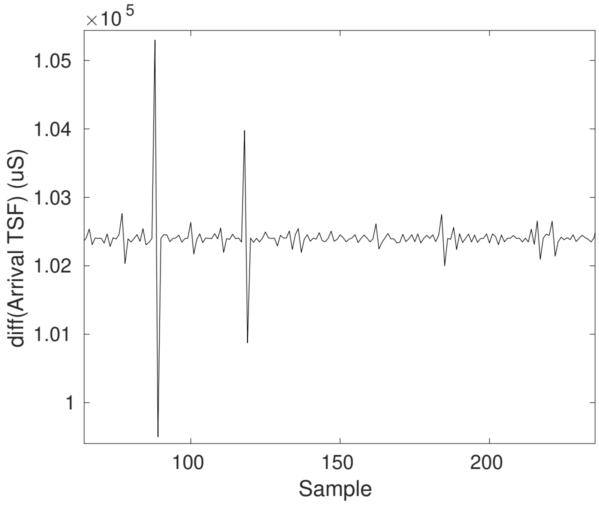

Figure 4. Beacon arrival timestamp difference variations at client

C. W-TSN Association Procedure

As it is shown in Figure 5, the client willing to join the network will start association by running wpa_supplicant[1] in Linux userspace. To avoid early transmissions, passive scanning is done and the transmission gates of all queues are closed by default. Here, it is important to mention that control traffic from the AP, i.e. beacons are not controlled by the AP's transmission schedule, therefore beacons are freely transmitted. As a result of the scanning, beacon frames are captured by the client's driver. Then, the early/late beacon detection filter is applied. Then again, the remaining beacons are used for setting the pre-schedule and pre-synchronization. Finally, the client transmits the authentication and association request in the authorized time slice.

As stated before, once the association stage is concluded, for the operational stage, the CNC will assign a unique schedule to the new client that is shared in-band [25] and PTP-over-wireless [23] is used for improved time synchronization accuracy after the client has been associated.

V. Results

The described mechanisms to achieve impactless association procedure were evaluated experimentally in a real test setup. The next section will compare both beacon pre-synchronization strategies: when all beacons are used for synchronization and when early/late beacon detection is used to filter delayed beacons. In both cases, the timestamp delay compensation was used. Finally, the impact-less transmission of packets during the association phase using the pre-schedule approach is evaluated by setting different pre-schedules.

A. Test Setup

As previously said, the described association procedure was implemented using IEEE802.11 in an FPGA-based SDR platform. For testing the proposed solution, the openwifi IEEE802.11/Wi-Fi baseband chip/FPGA design was used, implemented in the Software Defined Radio (SDR) ADRV9361-Z7035 that combines the Analog Devices AD9361 integrated RF Agile Transceiver™ with the Xilinx Z7035 Zynq®-7000. For Ethernet interface addition, the carrier card ADRV1CRR-BOB/FMC is used [26].

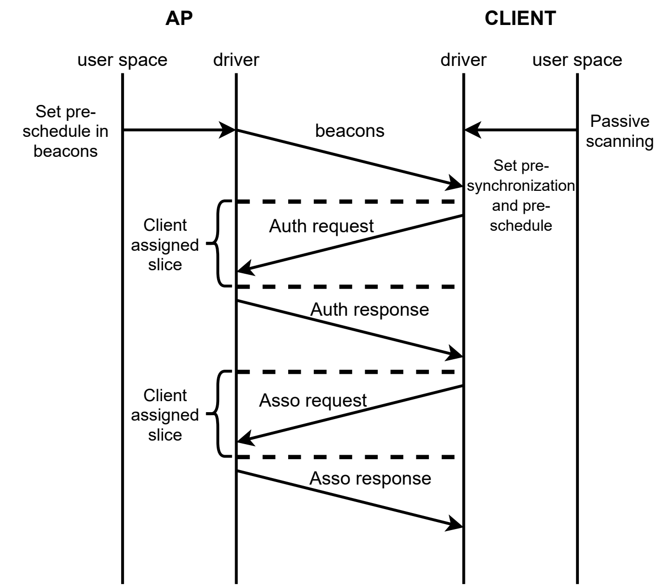

Figure 5. Association procedure

Although 802.11g standard is used for testing as 802.11ax is still in development [26], the proposed procedure is standard agnostic. Usage of 802.11ax will bring more degrees of freedom employing OFDMA as well. However, during the association phased the resource utilization can happen only on the time domain. Reserving certain OFDMA sub-carriers for performing association procedure is not an option, since UL OFDMA requires for the AP triggers and accurate time synchronization. During the association phase such synchronization is not yet active, neither AP does not know the actual prospect client timing for initiating the trigger.

The infrastructure mode wireless network consisted of two nodes; one access point (AP) and one client/station, both connected to a PC acting as a CNC for the AP as it can be seen in Figure 6.

B. Pre-synchronization

Using the architecture presented in Figure 6, once the association was completed, to test pre-synchronization, ping frames are transmitted from the client to the AP. The pre-synchronization and pre-scheduling are kept even after the association phase just for testing purposes. The beacons were overloaded with a slice start of 0μs, slice end of 128μs, and cycle length of 65536μs, which presents a challenging association configuration, where the assigned slice length is only 0.19% of the cycle length.

At the AP, packets were filtered to ensure only ping requests would be captured. On every received frame, the *frame arrival*

[1] https://w1.fi/wpa_supplicant/

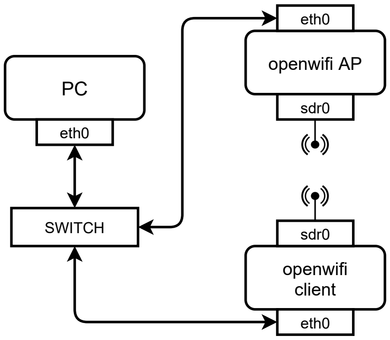

Figure 6. Testing hardware architecture

TSF was logged. To track the arrival TSF into a cycle-based measurement, Equation 3 was used.

$$T_{Of} = mod(T_{Ar}, C_L) \tag{3}$$

where T_{Of} represents the arrival time within the cycle in μs, T_{Ar} the frame arrival TSF, C_L the designated cycle length, and $mod()$ is the modulo operation.

The first evaluation is performed without enabling early/late beacon detection mechanism. Figure 7 shows the time offset(T_{Of}) in the cycle when the ping requests were received by the AP, and the amount of difference between the received beacon TSF and the current TSF at the client-side. When such difference is negative it means that the beacon was delayed, thus introducing an error in the TSF synchronization at the client-side, which is corrected by the next beacon (the high positive peaks in the continuous graph in Figure 7). It is seen that most of the ping requests are received within the assigned slice; however, the relationship between delayed frames and timestamp differences is evident. These variations are the consequence of slight delays in beacon transmissions as was described in Section IV-B. Such delays might cause transmission of association frames outside the predefined time slice, causing packet collisions with already scheduled traffic from other nodes.

Figure 8 presents the results when the early/late beacon detection mechanism was used. The delayed beacons are no longer used for updating the TSF at the client, thus TSF variations are highly reduced, and ping requests present well-aligned inside the assigned slice. To define the *range* from equation 2, tests with *x=10* μs*, x=5* μs*, and x=2* μs were performed. For each, the number of outliers considering the slice end threshold was measured, concluding that *x=2uS* is the *range* with the best overall performance.

Also, it can be seen that two frame arrival lines are visible in the slice. This normal behavior is produced by frames generated and ready to be transmitted while the gate was closed. When the gate opens, there is an initial constant delay (DIFS + physical header reading) before the frame gets received at the AP. Then the process repeats while the gate is still open and the second ping request is received with the second TSF offset inside the assigned time slice.

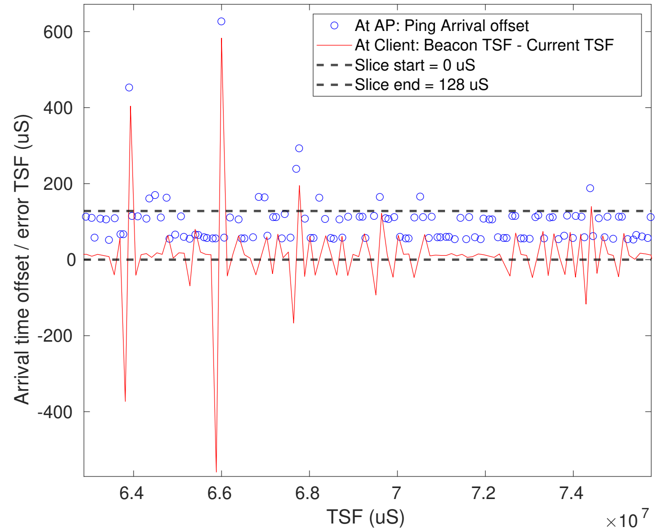

Figure 7. All beacon pre-synchronization

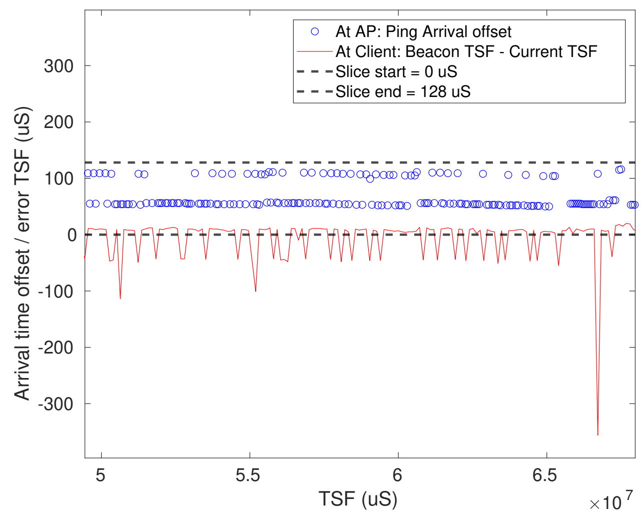

Figure 8. Early/late beacon detection pre-synchronization with *x=2uS*

Finally, as an overview, considering the slice end of 128μ s, Figure 9 shows a clear advantage of early/late beacon detection over all-beacon pre-synchronization. No outliers are presented, and the median value is lower by more than 50μs, ensuring association frames will be received on time at the AP.

C. Pre-schedule

Pre-schedule tests are resumed in Figure 10. Here, early/late beacon detection was used for all the measurements. This Figure combines four different measurements, each with a different slice location and a cycle length of 8192μs. Again, the arrival timestamp of ping request frames received from the client is logged at the AP, by translating it to time offset inside the cycle using Equation 3.

As it is seen, the different ping request frames are received inside the assigned slice of 2048μs.

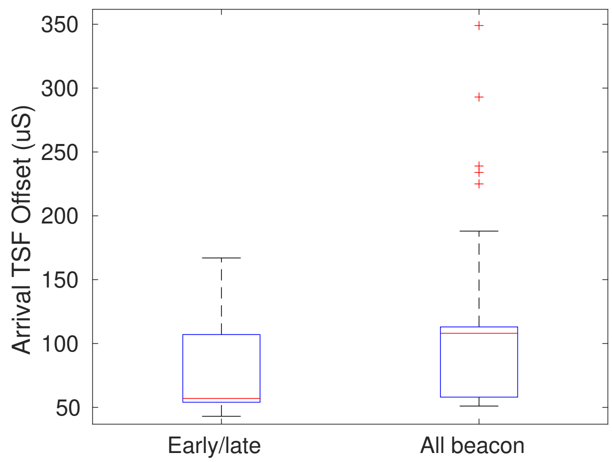

Figure 9. Comparison of pre-synchronization methods

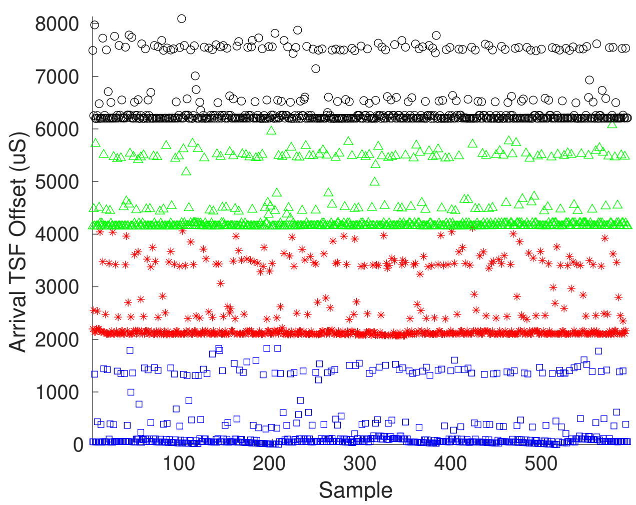

Figure 10. Arrival offsets with different slice location

When introducing additional clients that require association, arrival offsets will remain within the assigned slice. However, the addition of prospective clients might increase the association time as contention to access the medium within the slice will occur and transmissions might have to be postponed until the next cycle.

D. Association procedure timeline

As explained in Section IV, once the client is associated with the AP, the operation stage initiates, requiring an improved time synchronization method (e.g. moving to PTP synchronization). Figure 11 presents this so-called transition from early/late beacon detection based pre-synchronization to PTP synchronization (yellow area). The blue circles represent the ping TSF arrival offset, while the synchronization error is presented in red. The synchronization error during the pre-synchronization phase is calculated as the difference of current TSF and beacon TSF, while during the operational phase it gives the synchronization error reported by PTP. From the transition point, shown by the arrow, it is apparent that PTP, which includes 2-way delay measurements as well, provides the client with higher synchronization accuracy that adds stability to ping arrival offsets.

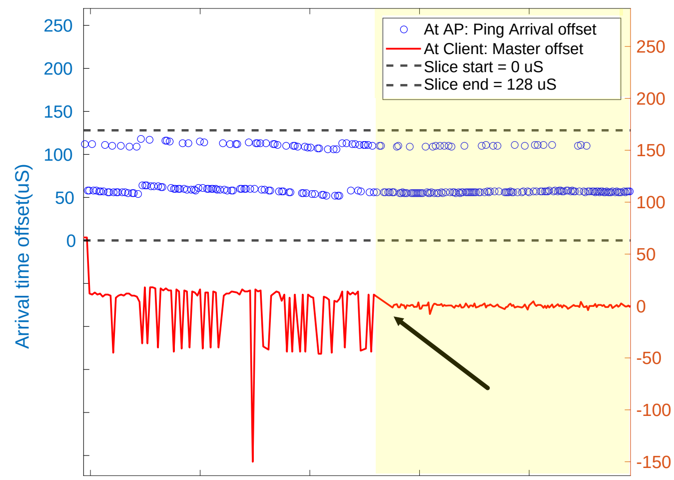

Figure 11. Association process synchronization transition

VI. Conclusion

In this paper, we presented a feasible W-TSN association method using beacons. This novel association design was developed and tested in real-world conditions over an SDR platform using the openwifi 802.11 software. Schedule and synchronization, key elements of TSN networks, are provided to prospect clients during the association phase. The standard-compliant solution, apart from providing the association schedule, enhances beacon-based synchronization by filtering delayed beacons. This procedure approach eliminates possible traffic collision between prospect W-TSN clients and already connected W-TSN clients, improving the general determinism of the network. Using our W-TSN testbed, extensive testing was conducted. Short timeslots of 128uS were used to demonstrate that prospective clients can utilize even the smallest schedules. Furthermore, the different timeslots locations were tested to establish the ability that the network has to dynamically adjust the association timeslot depending on the network schedule.

Depending on the application, the successful join of a client is not always the most important task, but also the association time plays an important role. Apart from working on an enhanced version of the beacon filtering to reduce the number of discarded beacons, we are studying how the link quality between the prospective client and the AP, the association timeslot length, and the number of users willing to associate would delay the association process.

Acknowledgment

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