Simulating and Validating openwifi W-TSN in ns-3

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***Abstract*—As industries increasingly rely on advanced networking solutions, Time-Sensitive Networking (TSN) has emerged as an essential tool, ensuring smooth and reliable communication in mission-critical applications. However, while TSN does a lot for industrial systems, there is still a whole world of not-utilized potential in wireless communication. To extend wired TSN with wireless capabilities, imec's openwifi platform has been extended with TSN features. To speed up the implementation of new Wi-Fi features in the openwifi platform, as well as to test their feasibility in larger-scale network scenarios we implemented the key TSN features of openwifi in the ns-3 simulator. In this paper, we evaluate how the selection of transmission opportunity (TXOP) duration affects network performance in shared time slots, as well as the impact of different shifts between shared time slots. The ns-3 implementation is validated against openwifi as well.**

I. Introduction

Industrial communication networks form the bedrock of industrial operations, providing communication between different processes, machines, and workers. Such communication needs to support the stringent requirements of diverse industrial applications in terms of communication latency, jitter, and reliability. To provide low bounded latency and high reliability, the network should support end-to-end accurate time synchronization, traffic separation, and control over such features. In the last decade, time-sensitive networking (TSN) has become popular in industrial environments for its ability to support such deterministic features over Ethernet networks.

TSN refers to a set of networking protocols and standards developed by the IEEE 802.1 TSN task group. TSN provides standards for accurate time synchronization, traffic scheduling, and network management. With TSN capabilities, the same network can be shared by best-effort and time-critical traffic types, ensuring bounded latency and high reliability for the latter ones.

While Ethernet-based wired networks are widely deployed in industrial environments, they cannot be used for cases where nodes are portable or mobile. To harvest the wireless flexibility for industrial communication, TSN features are becoming an inherent part of wireless communication as well. Both Wi-Fi based networks as well as cellular networks (5G URLLC mode) support certain features that can be used for TSN over wireless. In [1] the feasibility of bringing TSN features to the openwifi [2] platform is shown. openwifi [2] is the first opensource Wi-Fi implementation that provides TSN features including wireless node synchronization and traffic scheduling. For further development of the openwifi platform in terms of new TSN features, it is of paramount importance to be able to simulate certain features before their implementation in real platforms. In addition to this, the feasibility of certain features can be tested and evaluated in larger scale scenarios for their impact on TSN key performance indicators (KPIs). In this paper, we show the implementation of an initial set of TSN features of openwifi in ns-3 and its validation against a real setup. The contribution of this paper is twofold on the one hand we add the TSN capabilities of openwifi to the ns-3 simulator. On the other hand, we evaluate the impact of the effects of TXOP and slot shifting.

In recent literature, considerable attention has been given to investigating novel approaches for improving the performance and efficiency of wireless networks. In [3], authors work on enhancing QoS in industrial automation using TSN by adding a new access category for certain packets. In [4], a new TXOP scheduling scheme for 802.11 LANs is introduced that focuses on allocating transmission resources based on congestion and other information such as buffer status and channel quality. While existing studies have addressed aspects of QoS enhancement and TXOP scheduling schemes in LANs the specific impacts of TXOP and slot shifting remain untouched.

II. openwifi and W-TSN key features

openwifi is the first open-source Wi-Fi chip that implements the Wi-Fi physical layer (currently 802.11a/g/n) as well as lower and higher MAC protocol. In addition, it has implemented initial TSN features in the wireless link, namely accurate time synchronization [5], schedule distribution [1], and centralized management of the network [6]. openwifi scheduling is implemented as a gate control mechanism, similar to IEEE 802.1Qbv [7], on top of the carrier sense multiple access (CSMA) channel access mechanism and enhanced distributed channel access (EDCA) queues. As such, openwifi is fully compatible with off-the-shelf Wi-Fi.

To be able to simulate openwifi TSN features in a network simulator, we have incorporated TSN features in ns-3 version 3.37 on top of IEEE 802.11ax standard. This helps in studying other Wi-Fi features for TSN before they become available in the openwifi platform. In ns-3, synchronization among nodes is done by a central clock shared by all nodes with synchronization accuracy similar to the one achieved in openwifi, namely 1.3 μs. A gated mechanism to open and close certain queues on a certain node is implemented utilizing the MAC queue and channel access mechanism in ns-3. In Wi-Fi, when a packet comes into the MAC queue in most of the cases a clear channel assessment (CCA) is performed. In our design, we first check the gating mechanism.

If the node doesn't have an open slot at the moment, the CCA and channel access functions are delayed until the next time the gate opens. Another feature implemented in ns-3 is the dynamic inter-frame spacing applied on a per time slot basis. In case the time slot is dedicated to a certain node and certain queue, it could be beneficial to not use DCF inter-frame spacing (DIFS) or arbitrary inter-frame spacing (AIFS) at the beginning of the time slot. Similarly, in shared time slots where the number of nodes is not high, the contention window can be set to lower values for faster channel access for the nodes. Thus, contention window values should be able to change on a time slot basis as well. Other parameters that are not yet part of the openwifi TSN feature set are dynamic transmission opportunity (TXOP), dynamic transmit power as well as dynamic receiver sensitivity changes on a time slot basis. For the upcoming Wi-Fi 7 coordinated spatial re-use (C-SR) feature, the last two features are a must for large scale testing. The features that have currently been implemented in ns-3 are listed below:

- **Gate start and duration**: defines the starting time and duration for a gate opening.
- **Dynamic TXOP limit**: defines the duration of TXOP limit on a time slot basis.
- **AIFS value**: Defines the AIFS value of a node on a time slot basis.
- **Dynamic minimum and maximum contention window value**: defines contention window values to be used in the backoff mechanism on a time slot basis.
- **Dynamic receiver sensitivity:** defines a node's sensitivity while receiving packets at a certain time slot.
- **Dynamic transmit power**: defines a node's transmission power while sending packets at a certain time slot.

III. Effects of Shared Time Slots and TXOP Limit on Latency

TXOP is a feature not yet implemented in openwifi. In this section, we will validate the impact of the TXOP limit on communication latency when time slots are shared between different nodes. In addition to TXOP, we validate the effect of different offsets between shared time slots on the transmissions of the packets.

A. *Shared time slot impact*

Having a well-defined schedule can increase the overall performance of a network significantly. A network with shared and dedicated time slots leads to a decrease in congestion and delays while keeping the network operational. Also, serving time-critical applications becomes possible which is essential for an industrial network.

The impact of shared time slots and offsets between them are evaluated in ns-3 as well as in an openwifi toy scenario. In both tests, there are 2 clients, as senders, and 1 AP. Tests are done for 3 different scheduling scenarios. In the first scenario, equal length time slots of 128 μs are applied to the nodes, sufficient to transmit a single packet every cycle, with time slots shifted for only 20 μs. Slot shifting means that the second node can access the channel for a shifted amount of time after the first node. In this case, the shift was chosen to be smaller than the AIFS of 34 μs in the voice access category. In the second scenario, the second node's time slot value is increased to 228 μs, while the shift is kept the same. In the last scenario, dedicated time slots are applied to the nodes with 128 μs duration. A cycle of 65 ms is used for all the scenarios.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Number of nodes	1 AP, 5 Clients
Type of traffic	UDP
Physical data rate	61.3 (HeMCS1)
App data rate	1 Mbps
Packet size	512 Bytes
Traffic type	Constant bit rate (CBR)

Packet generation has an interval of a random value between 125 ms and 140 ms. That means a packet is generated every 2 cycles. Also, the airtime of a complete transmission is very important. A full transmission includes AIFS in the beginning, actual packet airtime, SIFS from AP's side, and layer two acknowledgment. The sum of all these values is calculated as 138 μs, which is higher than the given time slot. The behavior of the network explained above is evaluated in both setups (ns-3 and openwifi) and compared to validate our simulation.

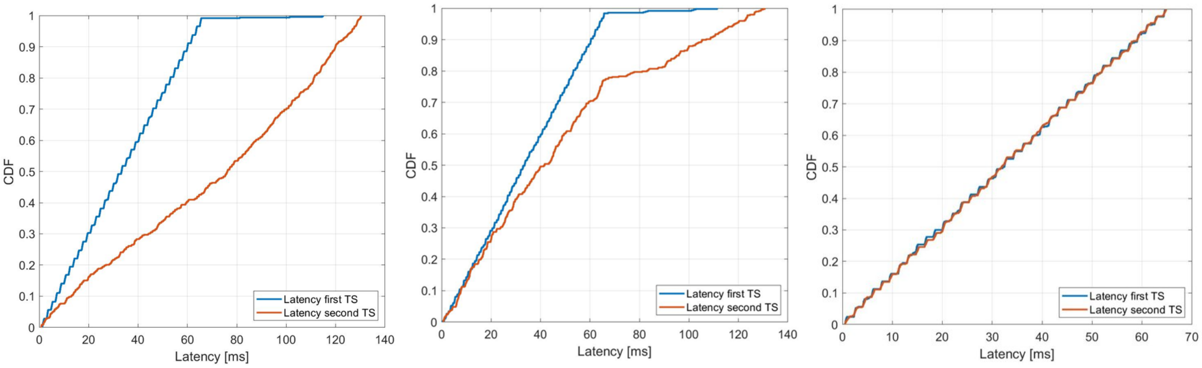
B. *TXOP limit effect*

When larger time slots are assigned to multiple nodes in a TSN communication cycle, it can be used by a single node to transmit its packets or it can be used by multiple nodes to transmit fewer packets based on contention. Limiting TXOP duration can control the amount of packets one node can transmit, impacting the overall latency of the communication.

The network parameters are shown in table I. The simulation area is 6m x 6m where nodes are distributed randomly with the AP located at the center. 5 clients send UDP packets in UL with an application rate of 1 Mbps and a packet size of 512 bytes. This means between 2 and 3 packets are generated per cycle per node.

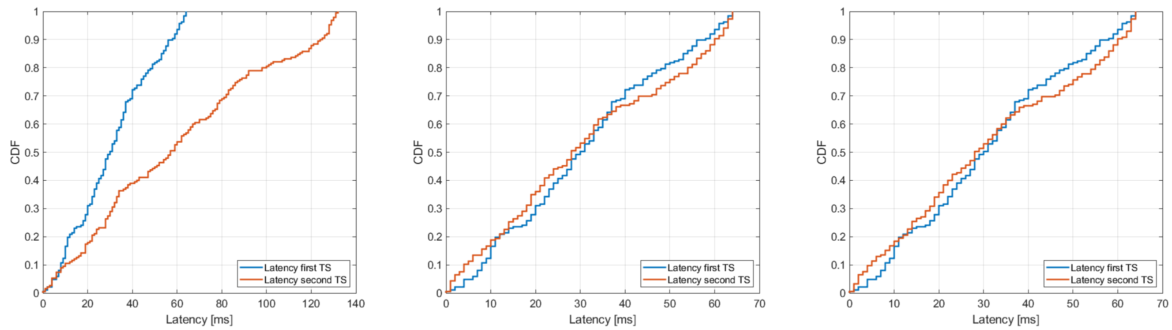
Two different schedules are tested. In the first scenario, all time slots are shared from the beginning of that slot. In the second case, the time slot lengths are the same, however, each consecutive node has a shifted starting time for that slot for 10 μs compared to the time slot of the previous node. Transmission can start at any time during the schedule, meaning that in some cases the end of the transmission can bypass the schedule boundaries. A time slot of 2 ms is assigned to each node every cycle of 10 ms.

To account for the impact of each schedule type and the impact of TXOP, we change the TXOP limits for each node in 3 different ways. In the first case, each node has a $TXOP = 0$ limit. All nodes send their packets one by one during a time slot. This will lead to high contention since every node will try to access the channel after each transmission. In the second case, each node uses a $TXOP = 384\mu s$. The number 384



(a) Equal time slot test with offset < AIFS (b) Different time slot test with offset < AIFS (c) Dedicated time slot test

Fig. 1. openwifi experiment results



(a) Equal time slot test with offset < AIFS (b) Different time slot test with offset < AIFS (c) Dedicated time slot test

Fig. 2. ns-3 experiment results

is chosen because we do not want the sum of the TXOP limit of nodes to exceed the time slot, which is 2ms. In ns-3 TXOP limits should be multiples of 32. As a result, the highest possible TXOP limit, for this scenario, is chosen. In this case, nodes have the same opportunity to send their packets in a time slot. They use this duration to send their packets sequentially with a short inter-frame spacing (SIFS) after each layer 2 acknowledgment. In the last case, all the nodes have different random TXOP durations, the sum of which does not exceed the time slot length of 2 ms. From 1st client to the last client the amount of TXOP limits are 256μs, 512μs, 384μs, 448μs, and 320μs respectively. Lastly, every TXOP limit scenario is tested using a non-shifted and shifted schedule case.

IV. Results

A. Shared time slot impact

Figure 1 and figure 2 show the cumulative distribution function (CDF) of communication latency of experiments run in openwifi and ns-3, respectively. When the shift between time slots is smaller than the AIFS, the second node cannot transmit in the first time slot (as it is occupied by the transmission of the previous node) and consequently has to wait for the next cycle to transmit its packets. As such, the maximum communication latency can go as high as two communication cycles, 130 ms, respectively for the second node. This behavior is seen both in openwifi as well as ns-3 simulations in Figure 1a and 2a. In the second case, the shift is still smaller than the AIFS, but the second time slot is larger accounting for transmitting two packets. When the transmission from the first node has ended, the second one can still access the channel within the same cycle. The communication latency is smaller than the cycle length for the second node as well. In the case of openwifi, since we do not have full control over when the packet is generated, if the first node starts to transmit the packet just at the end of its time slot, then the second node will lose its possibility to transmit in the same cycle. Thus there is a percentage $(\dim 20\%)$ of packets transmitted in the second cycle. In the last case, results are very similar to each other. All the nodes can access the channel thanks to dedicated time slots and they can send their packets within a cycle, hence under 65ms.

B. TXOP limit effect

It is seen that when no TXOP limit is used, then the average latency for each node is high, being around 450 ms. However, in the case of the shifted schedules, the latency for the first

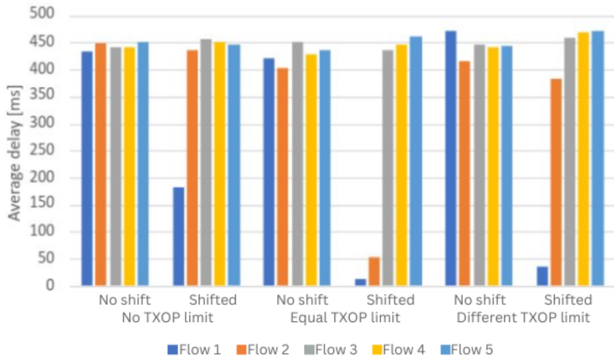


Fig. 3. Delay results for the network.

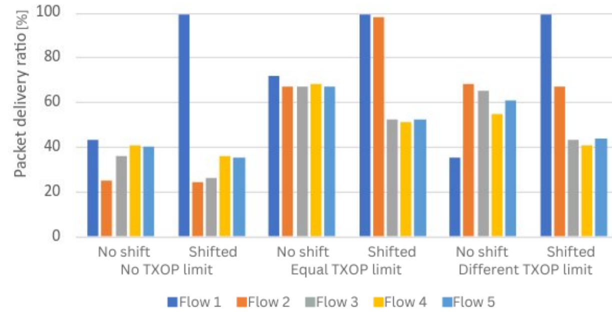


Fig. 4. PDR results for the network.

node is significantly lower than the one of the other nodes. For the same tests, the PDR values from Figure 4 are low ($\dim$ 40 %). On the other hand, the PDR value for the first node in case of shifted schedule is 100%, as the first node always gets the channel without any contention for the first packet. The reason for these high delay values comes from the fact of having a very congested network and a short time slot. While generating 2 to 3 packets per cycle, 5 nodes are competing for the same channel within a very limited time. Thus, packets are being buffered leading to high delays and losses.

When we use an equal TXOP duration for each node, at first we see that the average delay values remain the same as in the first case. However, PDR values of equal TXOP duration test are higher compared to the previous test, due to the fact of lower contention in the time slot. Having a shifted schedule helps the first node to have a higher PDR as well as a lower delay. In this case, the first client has 100% PDR and the second client has around 99% PDR. With less than 10 ms delay and less than 50 ms delay respectively. It is obvious that in the case of a shared time slot, having even a small shift at the beginning of the time slot will improve a lot for the first node. This is due to the fact that the first client can clear its queue and doesn't have any packet to send for some time slots. When that happens, the second client can use the channel to send its packets. The last scenario is when nodes use different TXOP durations: $256\mu s$, $512\mu s$, $384\mu s$, $448\mu s$, and $320\mu s$, for nodes one to five, respectively. In this case, to negate the advantage of the shifted schedule, the lowest TXOP duration is given to the first client. When no shift in schedule is used, average delay values remain as with other tests. PDR values are diverse having been affected by the TXOP duration. The first node has the lowest TXOP duration hence it has the lowest PDR. The second node has the highest TXOP duration and also has the highest PDR in this case. The values for the other nodes are lying in between those two. In the shifted schedule experiment, the first client has less than 50 ms delay and 100% PDR. Compared to the previous case it has slightly more delay. But for the second node results are too different from the previous case. The reason for that is that the first node cannot clear its queue as frequently as before.

V. Conclusion

Scheduling in wireless TSN is a challenge with trade-offs between latency and capacity. In this paper, the simulation results show the impact of strategies on slot overlaps and TXOP settings. These features are useful in reducing contention in shared time slots in a W-TSN use case. Validation showed the same results in most of the cases in ns-3 as well as in the openwifi platform, validating the TSN features implementation in ns-3. In future work, we will validate new Wi-Fi features (like coordinated spatial reuse and coordinated OFDMA) feasibility for TSN over wireless.

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