The Effects of Clock Synchronization in TSN Networks with Legacy End-Stations

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***Abstract*—In this paper, we present our ongoing work on proposing solutions to integrate legacy end-stations into Time-Sensitive Network (TSN) communication systems where the legacy end-stations are synchronized via their legacy clock synchronization protocol. To this end, we experimentally identify the effects of lacking synchronization or partial synchronization in TSN networks. In the experiments we show the effects of clock synchronization in different scenarios on jitter and clock drifts. Based on the experiments, we propose preliminary solutions to overcome the identified effects.**

***Index Terms*—TSN, synchronization, legacy support.**

I. INTRODUCTION

The IEEE Time-Sensitive Networking (TSN) task group established a set of standards to provide deterministic zero-jitter and low-latency transmission, fault tolerance mechanisms, advanced network management allowing dynamic reconfiguration, precise clock synchronization and flexibility in the traffic transmission. The latter two properties are particularly relevant to the adoption of TSN in the industry. On the one hand, the flexibility of the traffic allows the transmission of different types of traffic, which would enable the migration of legacy traffic to TSN. This would facilitate the adoption of TSN by the industry as many of the legacy systems and implemented solutions could be maintained, which would reduce adoption time and costs. On the other hand, certain types of TSN traffic, such as Time-Triggered (TT) traffic, require the path from the source to the destination, including all switches in the network, to be synchronized. However, this assumption does not hold in many existing industrial systems where end-stations often do not support TSN synchronization mechanisms due to their hardware or software limitations. In this work-in-progress, we seek for answers to the following main questions. *What are the effects of implementing a non-synchronized TSN network on the network performance?*, and in turn, *Is there any solution to reduce the effects?*

In order to answer the above-outlined research questions, we have set up an experimental network combining legacy end-stations that communicate via a TSN network and transmit TT traffic. We have selected TT traffic for this experiment as the effects of non-synchronized network on TT is more significant compared to other traffic. Through the experiments we detect the causes and consequences of the lack of synchronization in short and long term in the network. In addition, we propose preliminary solutions to improve the network performance that do not require any modifications in the legacy end-stations. Preventing any modifications in the legacy end-stations allows us to apply the proposed solutions on any TSN network where several legacy end-stations communicate through. An extensive performance measurement and analysis of the proposed solutions are ongoing.

The paper is organized as follows. Section II presents the related work. Section III describes the experimental setup, while Section IV presents the effects of non-synchronized TSN networks. Section V proposes preliminary solutions to the detected synchronization issues. Finally, Section VI concludes the paper and presents future directions.

II. RELATED WORK

One of the key features with TSN is the clock synchronization. Most of the works about clock synchronization over TSN are focused on integrating TSN with wireless or 5G networks. For example, the work in [1] implements a low-overhead beacon-based time synchronization mechanism to provide highly accurate synchronization to the wireless networks, thus they can be used in the context of highly deterministic TSN networks. Moreover, the works in [2] and [3] extend IEEE 802.1AS and IEEE 802.11, respectively, with the intention of integrating TSN with wireless networks, while [4] discusses the integration challenges of Wired TSN and Wireless Local Area Network (WLAN) technologies and proposes a Hybrid TSN device architecture. On the other hand, the work in [5] introduces the integration of TSN time synchronization (IEEE 802.1AS) that complies with 5G specifications, while the work in [6] proposes a cross-domain clock synchronization method based on data packet relay to solve the end-to-end cross-domain clock synchronization problems caused by the different 5G-TSN integrated network clock-domains. Finally, other works, such as [7], [8] and [9] have evaluated the performance of 5G-TSN networks focusing on the clock synchronization.

On the other hand, the work in [10] proposes a clock integration methodology between EtherCAT and TSN. However, this kind of clock integration requires specific solutions for each protocol to be integrated. This may hinders adoption of TSN by the industries due to the time needed to design and implementation of each solution, and makes compatibility between solutions difficult. For instance, if we have a legacy system with two different synchronization protocols (P1 and P2) and we want to integrate them with TSN, we would

Fig. 1. Network topology.

need a specific solution for the integration of P1 with TSN and another one for P2 with TSN which might not even be compatible with each other. For this reason, we believe that it would be more efficient to solve the problems generated by the lack of synchronization in a general way from the TSN network without any modifications in the legacy networks.

To the best of our knowledge, there is no work that analyzes the causes and consequences of the lack of synchronization in TSN networks integrated with legacy systems and consequently there is no work that proposes a general solution applicable to most of the legacy systems.

III. EXPERIMENTAL SETUP

We set up a small network consisting of two single-board computers (i.e., Raspberry Pi 3 Model B) running Raspberry Pi OS and a Multiport TSN kit switch from the company System-on-Chip Engineering (SoC-e)[1], see Fig. 1. The Raspberry Pi boards were configured to synchronize their software clocks with each other via the Network Time Protocol (NTP). Note that any clock synchronization protocol can be used between the end-stations since we are emulating scenarios where the TSN switch is unable to synchronize with the end-stations.

We define three experimental scenarios to investigate the effects of partially synchronized TSN networks in detail. The scenarios are described as follows.

1) Case 1- Unsynchronized end-stations: In this scenario, the end-stations are connected directly, i.e., the TSN switch does not exist in this scenario. The end-stations are not synchronized, therefore, we expect drift in the clocks. We measure jitter and clock drift of the end-stations to use them as references, i.e., a baseline, for the further experiments.

2) Case 2 - Synchronized end-stations: In this scenario, the end-stations are still connected directly without using the TSN switch, while they are synchronized via the NTP clock synchronization protocol. The main idea of this scenario is to investigate and analyze the impact of using the clock synchronization against the baseline experiment in Case 1. Therefore, we measure the jitter and clock drift in the end-stations that will be used to analyze the next experiment.

3) Case 3 - Synchronized end-stations in a switched network: In this scenario we add a TSN switch to the previous scenario. We configure the switch to forward the TT traffic. Note that the end-stations are connected via a TSN switch and NTP synchronization is used to synchronize them. However, the TSN switch cannot use its clock synchronization, as it is not supported by the end-stations. Therefore, enabling or disabling the TSN switch clock synchronization will not affect on the performance of this experiment. This scenario emulates scenarios in which legacy devices are connected via newly installed TSN switches. We measure the jitter and clock drifts in the end-stations to investigate the contribution adding a TSN switch to degrading the network performance.

4) Case 4 - Emulating long-term effects by clock drift: In this scenario, we keep the experimental setup as in Case 3 and we enforce clock drifts on the end-stations. We call this a synthetic drift, which can be negative or positive, i.e., receiver clock is faster or slower than the sender clock, respectively. The goal of this experiment is to investigate the effects of long-term clock drift on the performance of TSN networks with legacy end-stations that are synchronized via a legacy clock synchronization.

IV. RESULTS

This section shows and discusses the results of the above four mentioned cases. Note that the jitter and drift measurements are done via a software implemented on the end-stations to log the traffic time-stamps. The clock drift is presented only for the receiver end-station.

Table I shows the measured jitter and clock drifts in the experiments of Cases 1 to 3. In Case 1 we can observe that we have jitter on both sender and receiver end-stations. The sender jitter is due to the network stack and interface. Moreover, the receiver will inherit the same jitter as the end-stations are connected directly. However, in Case 2 when the synchronization is enabled, still without the TSN switch, the jitter on both sides increase. We believe that the increase in the jitter is due to involving synchronization software in the operating system. An important observation is that Case 2 has significantly less clock drift compared to Case 1, as it was expected, due to enabling the clock synchronization protocol.

Case 3 isolates the sender and received end-stations by the TSN switch in the middle, which in turns reduces the jitter in the receiver significantly. However, since end-stations do not support TSN synchronization, the receiver experiences a clock drift.

Fig. 2 shows the detailed jitter measurement in the receiver node when the end-stations are synchronized without the TSN switch connected, i.e., Case 2.

Fig. 3 shows the detailed jitter measurement in the receiver node when the end-stations are synchronized and the end-stations are connected via a TSN switch. As it can be seen, compared to Fig. 2 the jitter is constant with significantly less deviations in each measurement.

TABLE I
SENDER AND RECEIVER JITTER AND DRIFT FOR CASES 1-3

	Case 1		Case 2		Case 3	
	Sender	Receiver	Sender	Receiver	Sender	Receiver
Jitter (ms)	43.59	43.62	60.05	59.56	89.93	0.17
Drift (us)	N/A	0.50	N/A	-0.06	N/A	-8.00

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[1] MTSN Kit: a Comprehensive Multiport TSN Setup. [Online]. Available: https://soc-e.com/mtsn-kit-acomprehensive-multiport-tsn-setup/

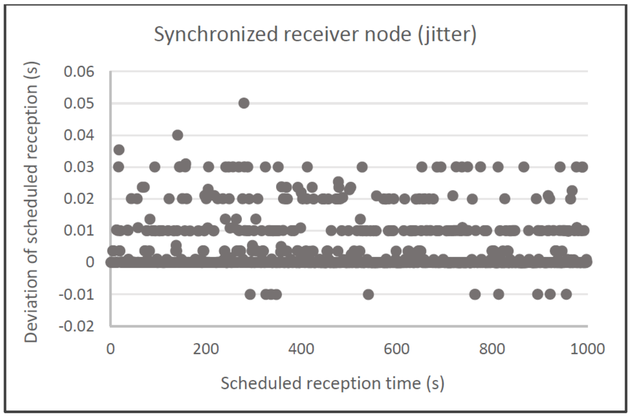

Fig. 2. Measured jitter in synchronized end-stations without the TSN switch.

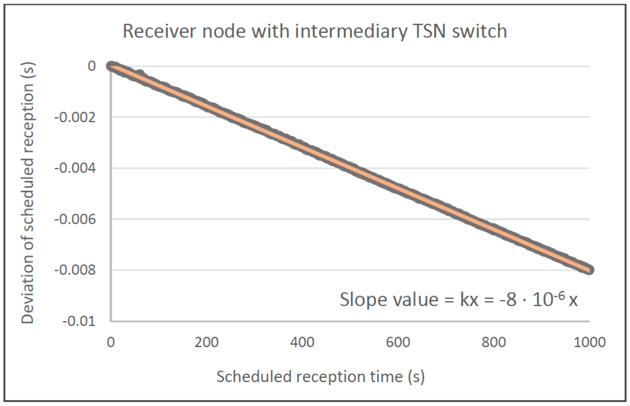

Fig. 3. Measured jitter in synchronized end-stations with the TSN switch.

The experiments of Cases 1-3 show how the receiver jitter may disappear when the legacy end-stations are connected via a TSN switch, yet synchronized with a legacy clock synchronization protocol.

Fig. 4 depicts the effects of long-term negative drift, i.e., faster clock in the receiver end-station. As it can be seen in the figure, the negative drift does not extend infinitely but is reset periodically. When enough drift accumulates after a while, messages miss the transmission time-slot in which they are scheduled, leaving a period with no message. Fig. 5 shows the behavior described above in which the receiver end-station has faster clock.

Fig. 6 shows the effects of long-term positive drift, i.e., when the receiver clock is slower. As it is shown in the figure, positive drift causes messages to be lost at a linear rate. Since messages arrive at the switch faster than it forwards them, messages accumulate in the buffer. However, the buffer is not infinite, hence messages that arrive once the buffer is full are discarded. Fig. 7 shows the behavior described above.

V. Preliminary Solutions

This section proposes preliminary solutions to reduce the impact of partial synchronization. The detailed investigation of the solutions and their performance analysis is an ongoing work. The solutions consider four different scenarios where each scenario requires a different solution, as follows.

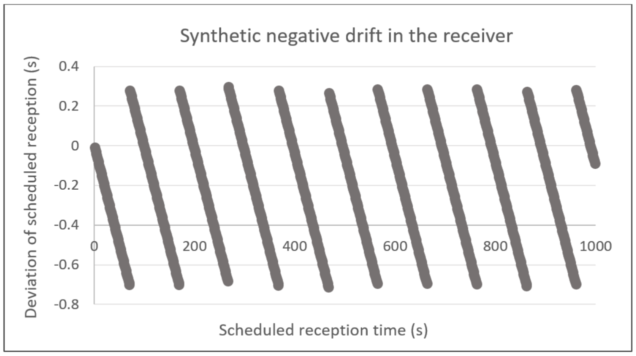

Fig. 4. Synthetic negative clock drift in the receiver.

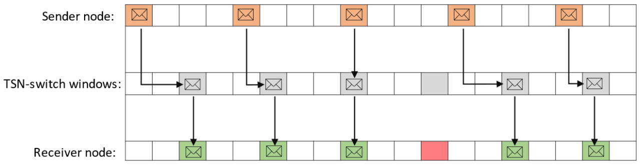

Fig. 5. Synthetic negative clock drift behavior.

1) *Spatial and temporal homogeneous drift::* This scenario corresponds to a network in which all end-stations are synchronized using a legacy clock synchronization protocol. This enforces that all end-stations have the same and constant clock drift. In this case, it is sufficient to measure the clock drift and apply it as a coefficient to the TSN traffic schedule.

2) *Spatial heterogeneous and temporal homogeneous drift::* In this scenario, unlike the previous one, there are subsets of synchronized end-stations that are not synchronized with each other. This occurs when several systems with specific synchronization protocols are integrated into a single TSN network. In this case, the same solution as in the previous scenario can be used, although each subset must be assigned to routes that do not share output ports. This is because, due to the small changes in period caused by drift, the hyper-period resulting from the combination of more than one subset of end-stations would lead to an infinite schedule synthesis.

3) *Spatial homogeneous and temporal heterogeneous drift::* In this scenario, there is a single drift involved. However, this may vary over time due to the course of time or environmental conditions. In this case, it is not sufficient to measure the drift only once and apply it to the schedule. Instead, the switches must periodically measure the drift and apply it as a multiplicative coefficient to the traffic schedule.

4) *Spatial and temporal heterogeneous drift::* This scenario presents unsynchronized end-station subsets and time-varying drift. As in the previous two scenarios, traffic from different unsynchronized subsets must be routed so that they do not share output port. In addition, the drift must be periodically measured at the port level rather than at the switch level, and

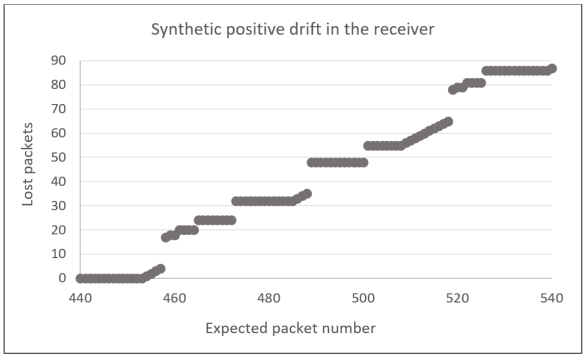

Fig. 6. Synthetic positive clock drift in the receiver.

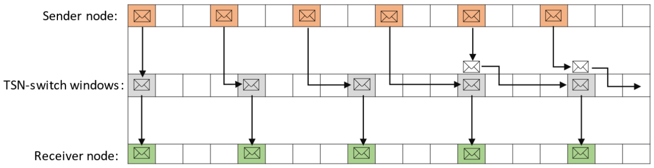

Fig. 7. Synthetic positive clock drift behavior.

each specific drift must be applied to the traffic schedule of the corresponding port.

VI. CONCLUSIONS

Thanks to the TSN characteristics, including deterministic zero-jitter and low-latency transmission, and precise clock synchronization, its integration with other legacy systems seems feasible. This would facilitate the adoption of TSN by the industry since it would allow maintaining a large part of the implemented devices and solutions. However, such integration presents different challenges, especially from the synchronization point of view. This paper has analyzed the consequences of the lack of synchronization or partial synchronization. We have setup four experiments to identify the effects of having legacy end-stations communicating via a TSN switch that are synchronized via a legacy clock synchronization protocol. We also experimentally have shown the effects of long-term clock drifts on TT traffic transmission, both in the case of faster and slower clock in the receiver end-station. In order to solve the identified effects we have proposed preliminary solutions that cover several scenarios. The ongoing work aims at investigating more complex networks where multiple TSN switches are used. In addition, we aim at implementing the solutions to experimentally validate them.

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