The 5G Transparent Clock: Synchronization Errors in Integrated 5G-TSN Industrial Networks

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***Abstract*—Deterministic communication across integrated wired and wireless networks is currently one of the big topics in research and standardization. 5G and TSN integration efforts are at the forefront of enabling the convergence of wired and wireless networks for Industry 4.0.**
In this paper, we investigate how synchronization and syntonization errors affect the achievable end-to-end time synchronization accuracy in integrated 5G and TSN networks. We specifically focus on the impact of the 5G System modeling a TSN transparent clock according to 3GPP Release 17.

***Index Terms*—5G, TSN, wireless, synchronization, syntonization, simulation, ns-3, IEEE 802.1, Industry 4.0**

I. Introduction

One of the big promises of Industry 4.0 (I4.0) is to enable the "smart factory". Flexible production is an important aspect of this, meaning the ability to react to changing production needs, for example, through increasingly mobile (automated guided vehicles (AGVs), mobile robots) and modular manufacturing environments. In turn, communication concepts are needed that provide the necessary flexibility. The approach to enabling this, is to utilize a communication infrastructure that connects stationary and mobile devices through the convergence of wired and wireless technologies. These so-called converged networks will be able to provide the necessary degree of flexibility.

The strict real-time communication requirements are one of the key challenges for the network infrastructure in an industrial environment. These have to be met irrespective of the underlying technology.

Current standardization efforts focus on 5G and TSN as the respective wireless and wired communication technologies for converged networks in factories.

Time-Sensitive Networks (TSN) is a set of standards specified in the IEEE 802.1 working group. TSN provides a standard for reliable, deterministic, and low-latency wired communication. This is achieved mainly through a precise time synchronization with the generalised precision time protocol (gPTP) [1] [2] and various scheduling enhancements [3].

The 5th generation cellular standard (5G) is the current generation of the mobile communication standard defined by the 3GPP. The 5th generation is the first one to include industrial communication as a central use case for mobile communcation. The integration of 5G and TSN is already part of the 3rd Generation Partnership Project (3GPP) 5G specification since Release 16 [4]. An overview with details on 5G and TSN integration is given in our previous work [5]. In this paper, we analyze the time synchronization performance of IEEE 802.1AS in an integrated 5G-TSN network by simulation. We compare various parameterizations in order to get a better understanding of the expected time synchronization accuracy for different industrial use cases and to identify possible issues.

A. Related Works

There are a number of works investigating integrated 5G-TSN networks and the issues that arise with the convergence of wired and wireless networks. Gundall et al. [6] derive the necessary requirements for cooperative mobile robots in a factory. Based on these, the authors propose a concept to integrate 5G and TSN and validated this concept in a demonstrator. Schüngel et al. analyzed and simulated the performance of an integrated 5G and TSN network in [7]. Wei et al. [8] propose an enhancement to the IEEE 1588 synchronization procedure to mitigate the impact of asymmetric link delays in converged wired and wireless networks. In [9], Schüngel et al. propose a grandmaster selection algorithm for converged wired and wireless network. The 5G system architecture aspects of an integrated 5G-TSN network are specified in TS 23.501 [4].

Our contribution in this work is the inclusion of 5G device to device synchronization, as is currently being specified in 3GPP Rel. 17 [10]. One important aspect that has not been considered before, is the disparity between a normal TSN bridge and the 5G logical TSN bridge. We investigate the impact of synchronization and syntonization errors on the end-to-end time synchronization over the 5G System under consideration of this disparity.

II. 5G - TSN integration Technical background

One of the key requirements for time-critical communication in factories is a strict time synchronization between the communicating devices. This is necessary in order to be able to correctly align operations. For example, one mobile robot rotating a work piece as necessary, while another robot welds it together. This only works if both devices share a common understanding of time, i.e., if they

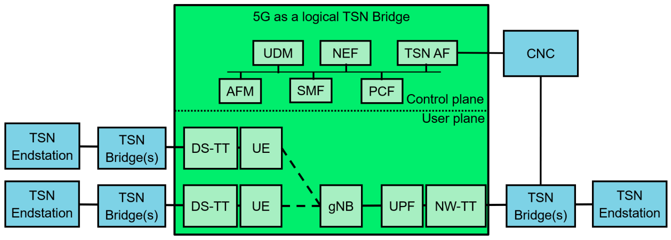

Fig. 1. 5G-TSN Integrated Architecture.

are synchronized.
The major challenge for this type of use case is to achieve a very strict synchronization accuracy ($< 1\,\mu$s [11] [12]) from any synchronized device to the master clock. Across two different communication technologies, the wired TSN and the wireless 5G networks. In [11], the 3GPP requires the time error component of the 5G System, the synchronization budget, to be $< 900\,$ns. The 5G System (5GS) can account for 90% of the allowed end-to-end synchronization error.

A. 5G as a logical TSN bridge

The integration of 5G and TSN, as specified in [4], has the 5G System expose the behaviour of a TSN Bridge to the TSN Network. This is shown in Fig. 1.
The user plane interactions with the TSN network are handled by the network-side and device-side TSN translator functions (NW-TT, DS-TT). The control plane interactions are handled by the TSN Application Function (AF).

1) User Plane: The TSN translator functions handle the interaction between the TSN and 5G networks. For the purpose of time synchronization in the integrated network, this mainly means timestamping and processing of precision time protocol (PTP) messages. The 5G network does not need to synchronize itself to the TSN time. Instead, the PTP messages are adjusted by the time spent in the 5G network, i.e., the residence time. Fig. 1 shows the 5G System in 5G-TSN integrated network. The residence time measurement relies on accurate timestamps at the ingress and egress ports of a TSN bridge. In the 5G logical TSN bridge, these timestamps, as well as other PTP-related operations such as updating the correction field (details in section II-B), are handled by the TSN translator functions.

2) Control Plane: The TSN central network controller (CNC) provides information about the TSN stream to the 5G network, specifically to the TSN AF. The stream information is necessary for tasks like the routing of TSN messages inside the 5G network, as well as the configuration of radio resources and other parameters to meet the quality of service (QoS) requirements for the respective TSN traffic streams. However, control plane specific issues are out of scope of this work.

B. IEEE 802.1AS gPTP

The distribution of timing information in an integrated 5G and TSN network is done via the gPTP protocol [1]. The gPTP protocol is a special case of the PTP protocol [2], where the available configuration and implementation options are limited in favor of meeting stricter performance requirements.
The gPTP time synchronization is done via the peer-to-peer delay mechanism, which works by combining two messaging procedures:

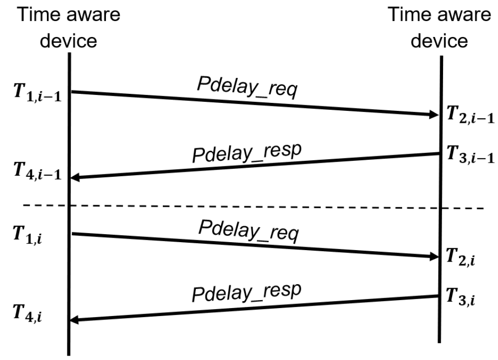

Fig. 2. gPTP Propagation Delay Procedure

1) Propagation Delay Procedure: The propagation delay procedure is shown in Fig. 2. Every time-aware device in the network periodically sends a Pdelay_Req message with a transmission timestamp $T_{1,i}$ to every neighboring device, where i denotes the i^{th} occurence of the message. The receiving device will make a receive timestamp $T_{2,i}$ and answer with a Pdelay_Resp message. This response contains both the receive timestamp $T_{2,i}$, as well as a transmission timestamp $T_{3,i}$. Finally, the initiating device receives the Pdelay_Resp message at the time $T_{4,i}$.
Now, the initiating device has all 4 timestamps stored. After the propagation delay procedure has been repeated at least once, the device can calculate the neighbor rate ratio (NRR) to its neighboring device, as shown in Eq. 1. If the clocks of both devices run at different frequencies, that offset can be compensated using this ratio.

$$\mathrm{NRR}_i = \frac{T_{3,i} - T_{3,i-1}}{T_{4,i} - T_{4,i-1}} \tag{1}$$

The link delay $T_{\text{delay},i}$ between both devices can be calculated as the average of the link delay in both directions, as shown in Eq. 2. The timestamps in this equation are made by two different clocks, therefore the NRR is used to compensate any frequency offsets.

$$T_{\text{delay},i} = \left(\mathrm{NRR} \cdot (T_{4,i} - T_{1,i}) - (T_{3,i} - T_{2,i})\right)/2 \tag{2}$$

2) Synchronization Procedure: The synchronization procedure across a 5G logical TSN bridge is shown in Fig. 3. The master clock periodically sends out a Sync message, including a transmission timestamp $T_{1,i}$, to all endstations. Any PTP-capable device on the way simply forwards this message after adding both the delay (as previously calculated) and the residence time, the time spent in the device, to the correction field of the Sync message. The cumulative rate ratio (CRR), the product of the NRRs of all devices in the communication path, is also updated.

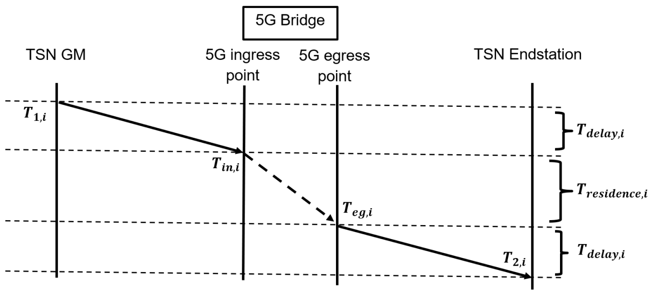

Fig. 3. gPTP Synchronization over a 5G logical TSN Bridge

The residence time $T_{\text{residence},i}$ is calculated as the difference between the egress timestamp $T_{\text{eg},i}$ and the ingress timestamp $T_{\text{in},i}$ of a device, shown in Eq. 3. The CRR is used compensate for frequency offsets between the master clock and clock making the ingress timestamp $T_{\text{in},i}$.

$$T_{\text{residence},i} = \text{CRR} \cdot (T_{\text{eg},i} - T_{\text{in},i}) \tag{3}$$

Finally, the endstation will make a receive timestamp $T_{2,i}$ upon reception of the Sync message. The offset $T_{\text{offset},i}$ between the master clock and the synchronizing endstation is then calculated in Eq. 4 as the difference between the measured transmission delay based on the timestamps, $T_{1,i}$ and $T_{2,i}$, and the calculated sum of link delays and residence times.

$$T_{\text{offset},i} = T_{2,i} - T_{1,i} - \sum (T_{\text{delay}} + T_{\text{residence},i}) \tag{4}$$

C. 5G logical TSN bridge

One key difference between a traditional TSN bridge and a 5G logical TSN bridge lies in the physical clocks used for the synchronization procedures. The residence time measurement in Eq. 3 assumes that both the ingress and egress timestamps are made with the same pyhsical clock. As can be seen in Fig. 1, in a 5G logical TSN bridge, the ingress and egress ports are on different devices, with physically different clocks. While both clocks are synchronized to the same 5G master clock, typically the gNodeB (gNB), they will have different synchronization errors, different frequency offsets and different frequency drift rates. These errors impact the achievable time synchronization accuracy in an integrated 5G-TSN network.

We assume the 5G ingress and egress devices to be synchronized to the same master clock via a periodic procedure [13] [14]. We define the resulting error on the residence calculation $E_{\text{residence}}$ in Eq. 6. This error has two components. First, the relative frequency error between the ingress and egress clocks $f^{5\text{G}}$ in ppm. Second, the duration since the last 5G synchronization event $T^{5\text{G}}_{\text{sync}}$.

$$E_{\text{residence}} = \left(t - T^{5\text{G}}_{\text{sync}}\right) \cdot f^{5\text{G}} \tag{5}$$

$$max(E_{\text{residence}}) = \min\left(T^{\text{TSN}}_{\text{sync,interval}}, T^{5\text{G}}_{\text{sync,interval}}\right) \cdot f^{5\text{G}} \tag{6}$$

This error is maximised if the duration since the last 5G synchronization event is maximised, which is the minium of the 5G and TSN synchronization intervals.

III. Simulation Implementation

In this section, we will show how our simulation was implemented and explain our assumptions and simplifications. The simulation is built in Network Simulator 3 (ns-3) [15], an event based simulator. We compare the synchronization accuracy for different 5G-TSN integration scenarios und parameterizations. The simulation is built upon three major components.

A. Clock

We define a simple clock model (Eq. 7), where T_0 is the bias, f is the frequency offset and $f'(t)$ is the time-dependent frequency drift rate.

$$T(t) = T_0 + (1 + f + f'(t)) \cdot t \tag{7}$$

The perfectly accurate simulation time is used as a basis for the clock instance. The frequency offset and frequency drift rate are calculated and added to the simulation time whenever the clock is accessed. The offset, used to correct the time when synchronizing to a master clock, is then added separately. The model is shown in Eq. 10, where T_i is the time of the simulated clock at the discrete simulator event i and $c(t_i)$ is the clock error, the sum of the frequency offset f and the frequency drift rate f', integrated from t'_{i-1} to t'_i. The frequency offset is constant, while the frequency drift rate is modeled to have sinusoidal behaviour. If the the clock is being synchronized to a different master clock, the synchronized time $T_{sync,i}$ is calculated by simple addition of the offset (Eq. 4).

$$T_i = T_{i-1} + \left(t'_i - t'_{i-1}\right) \cdot (1 + c(t'_i))) \tag{8}$$

$$c(t'_i) = f + \int_{t'_{i-1}}^{t'_i} f' \cdot \sin t \, dt \tag{9}$$

$$T_{sync,i} = T_i + T_{\text{offset},i} \tag{10}$$

B. gPTP & Timestamping

For the gPTP model, we implemented a timestamping mechanism as well as the previously described messaging procedures.

The timestamping procedure models hardware timestamping. The timestamping model, shown in Eq. 11, is based on the error model described in [12]. Instead of considering effects like PHY jitter and clock granularity separately, each PTP instance contributes a time error to the synchronization. This time error has two components. A constant time error component cTE, and a dynamic time error component dTE. When creating a timestamp, this time error is added to the time of the device's clock $T_{sync,i}$.

$$T_{\text{TS},i} = T_{sync,i} + \text{cTE} + \text{dTE}_i \tag{11}$$

C. Simulation Scenario & Setup

The general simulation scenario, shown in Fig. 4, models the cooperative interaction of two mobile robots. A typical use case for future factories, that requires precise time synchronization of two wired networks across a wireless link.

We model each mobile robot as a TSN endstation, connected

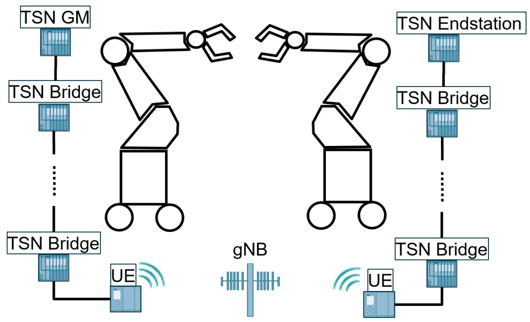

Fig. 4. Simulation Overview - Scenario

to a 5G UE via a variable number of TSN Bridges (here: transparent clocks). Every device, both TSN and 5G, is based on the ns-3 Node class. For every node, a clock instance according to section III-A is initialized. The rest of the setup differs between TSN and 5G devices:

1) TSN: The TSN nodes are connected using the Carrier Sense Multiple Access (CSMA) channel model. ns-3 does not provide a real ethernet model, however the CSMA channel model supports layer 2 communication and is a sufficiently close approximation of ethernet for our purpose.

The gPTP procedures are defined in a separate class and installed on each node. We differentiate between ordinary and transparent clocks. This determines how a node interacts with the different gPTP messages. Every TSN node will initiate the peer delay messaging process to its neighbors. Only the ordinary clock acting as the master clock will initiate the synchronization messaging process.

2) 5G: The 5G devices have to act as a gateway between the TSN and 5G networks. To achieve that, they are made up of two nodes. One node is connected to the CSMA channel and acts as the wired (ethernet) port. The other node acts as the 5G module and is connected to the wireless channel. Both nodes share the same local clock instance and essentially act as one device. The TSN translator functionalities are also defined in a separate class and installed on these 5G nodes.

The 5G internal communication uses the 5G LENA module [16]. This module focuses on the PHY and MAC layers, based on the 3GPP Rel. 15 non-standalone version of 5G. Higher layers reuse the existing LENA lte module.

The 5G LENA module provides a wireless channel implementation and supports different frame structures and frequency bands. For the 5G-internal traffic, UDP/IP communication is used. The specific configuration setup used for our 5G LENA implementation is given in Table I.

TABLE I
5G LENA CONFIGURATION

Parameter	Value
Central Frequency Band	28 GHz
Bandwidth	400 MHz
5G Numerology	0 ... 3
Packet Size	44 Byte

IV. SIMULATION RESULTS

In this section, we look at the impact of various parameters on the achievable end-to-end time synchronization accuracy in a converged 5G-TSN network. First, we consider only synchronization errors for the 5G ingress and egress devices. Secondly, we also include syntonization errors between the 5G ingress and egress devices. Finally, the impact of the 5G internal synchronization on the rate ratio calculation is included as well.

TABLE II
SIMULATION PARAMETERS - GENERAL

Parameter	Value
Simulation Runs	100
Simulation duration	100 s
Synchronization Interval	125 ms [17]
PDelay Interval	31.25 ms [17]
Clock Frequency Offset	50 + $\mathcal{U}(-5, 5)$ ppm [17]
Clock Frequency Drift Rate	3 ppm/s (sinusoidal) [17]
cTE TSN	$\mathcal{U}(-10, 10)$ns [12]
cTE 5G	178 ... 488 ns [18] [19]
dTE	$\mathcal{U}(-20, 20)$ns [12]

A. Impact of synchronization errors

First, we analyze the end-to-end time synchronization accuracy in our converged network under the assumption that the 5G UEs are perfectly syntonized to the 5G master clock. The general simulation parameters are listed in Table II, the parameters specific to the imperfect synchronization simulation are listed in Table III.

Considering only imperfect synchronization of the 5G devices, the 5G System simply behaves like a normal TSN transparent clock with a larger cTE, which is determined by the used numerology. The 5G System adds an additional synchronization error, where the value is equal to the relative synchronization error between the ingress and egress ports.

Fig. 5 shows the maximum time synchronization error for different numbers of TSN bridges and different sub-carrier spacing (SCS)s in the 5GS. For time synchronization, it is only important that the required accuracy can be met. Hence, we consider the maximum instead of the average synchronization error.

The behaviour is as expected. Each additional TSN bridge adds a small error to the network as a whole. Increasing the SCS results in a lower synchronization accuracy between the two 5G UEs, as can be seen by the offset between results.

The cdf for a number of different deployments is shown in Fig. 6. This example uses 5G Numerology 2, 60 kHz SCS. For small numbers of TSN Bridges, the variance is very low, due to the major error component in this case being the 5G-internal synchronization error. Increasing the number of TSN bridges increases the variance.

B. Impact of syntonization errors

When synchronizing clocks for time sensitive communication, these clocks are often syntonized as well. Syntonize

TABLE III
SIMULATION PARAMETERS - IMPERFECT SYNCHRONIZATION

Parameter	Value
Number of TSN Bridges	2 ... 100
5G SCS	[15, 30, 60, 120] kHz

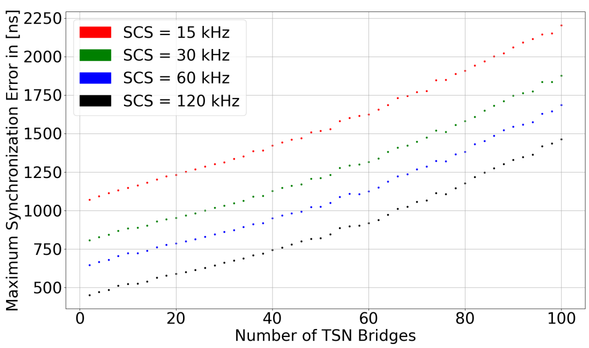

Fig. 5. Impact of synchronization errors

meaning, adjusted to operate at the same frequency. Assuming perfect syntonization is of course not realistic. We will therefore analyze the impact of imperfect syntonization of the 5G UEs on the end-to-end time synchronization performance. The simulation parameters are listed Table IV.

Imperfect syntonization means, that there may be a difference in frequency offset and frequency drift rate between the ingress and egress port clocks of the 5GS. As described in Section II-C, both these clocks are synchronized to the same master clock (typically the gNB), but the clocks will drift apart relative to each other. Fig. 7 shows how the 5G-internal synchronization interval and the frequency offset between ingress and egress port affect the synchronization accuracy without any NRR calculation errors. The red line shows the maximum synchronization error without syntonization errors for comparison. The resulting errors align with our expectations based on Eq. 6, e.g., for $f^{5G} = 6$ppm and $\min\left(T^{TSN}_{\text{sync,interval}}, T^{5G}_{\text{sync,interval}}\right) = 125\,\text{ms}$ the maximum additional error introduced by the imperfect syntonization of

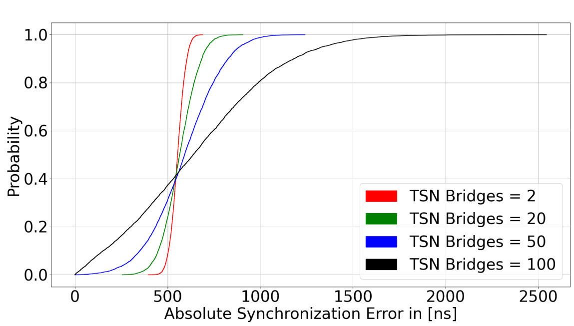

Fig. 6. CDF of the Synchronization Error with imperfect 5G synchronization

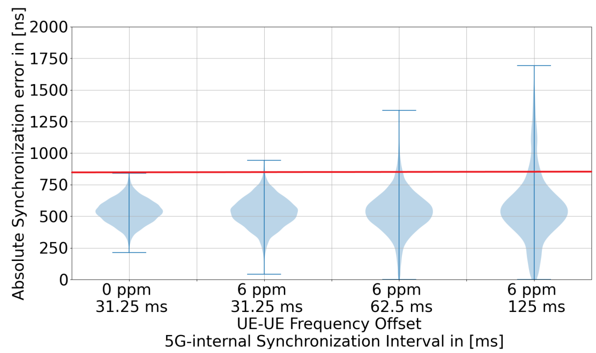

Fig. 7. Impact of syntonization errors

the 5G devices is $max(E_{\text{residence}}) = 750\,\text{ns}$. This error can overlap constructively or destructively with any other errors, hence the improvement of the lower bound of the overall synchronization errors.

This highlights one of the issues with the 5G logical TSN bridge. The residence time calculation (see Eq. 3) is based on the assumption, that the ingress and egress timestamps are made by the same, free-flowing, clock. While we can assume the 5G devices to be syntonized to the 5G master clock, even small frequency errors result in large errors in the residence time calculation.

TABLE IV
SIMULATION PARAMETERS - IMPERFECT SYNTONIZATION

Parameter	Value
Number of TSN Bridges	20
5G Synchronization interval	[31.25, 62.5, 125] ms
5G UE frequency offset	0 ppm
5G UE frequency drift rate	± 3 ppm/s
5G SCS	60 kHz

C. *Impact of rate ratio calculation errors*

The 5GS-internal synchronization procedure means that the 5G UE time offset will change periodicaly. Typically, the clocks in a transparent clock are not being synchronized, i.e. they are free flowing. The result of this difference is shown in Fig. 8. In red is shown the calculated NRR for two perfectly syntonized clocks - the clock frequencies are the same, only timestamping errors introduce some variance. In green is shown the calculated NRR for an imperfectly syntonized clock - the clock drifts relative to its master clock, the offset is adjusted periodically with a synchronization procedure. Whenever the offset has to be adjusted, the propagation delay calculation produces an error. This effect can be seen in Eq. 1. The offset change lets the difference between $T_{3,i}$ and $T_{3,i-1}$ appear smaller or larger than it is in reality, resulting in a different NRR value. Fig. 9 now also includes the NRR calculation errors due to the 5G re-synchronization. The average distribution remains similar, however significant outliers are introduced.

As the CRR is used to compensate for frequency offsets

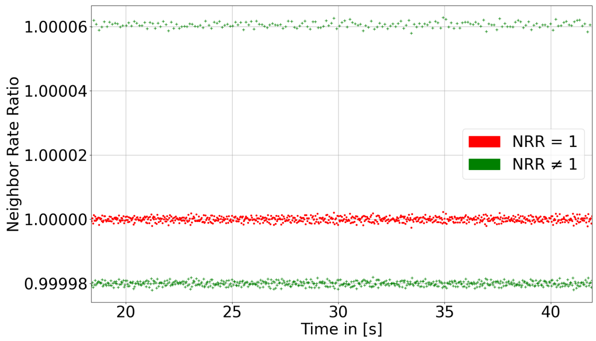

Fig. 8. Effect of 5G synchronization on NRR calculation

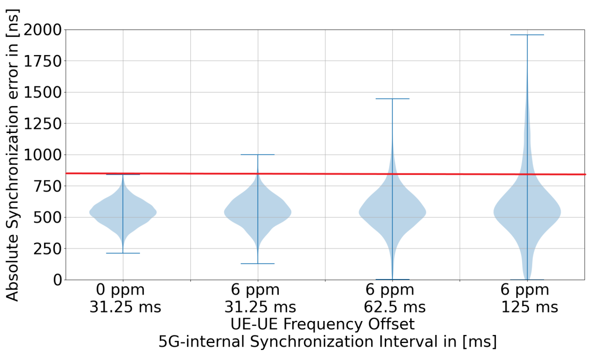

Fig. 9. Impact of rate ratio errors

between the master clock and any other clock (Eq. 3), an error in the NRR calculation can cause a significant error for the overall synchronization.

Similarly to the impact of the 5G synchronization on the residence time with syntonization errors in the ingress and egress clocks, the error in the NRR calculation depends on the time since the last re-synchronization event.

In contrast to the effect of the frequency error described before, the impact of an erroneous rate ratio calculation can typically be mitigated with limited effort. As described in [17], outliers can be filtered by discarding calculated values that exceed the acceptable error margin. In addition, instead of always using the latest calculated rate ratio, the median of a sliding window of a set of rate ratio values is taken.

V. Conclusion

In this work, we examined the time synchronization performance in an integrated 5G - TSN network for 5G UE to 5G UE communication in the 5GS. We specifically analyzed the impact of two separate synchronization procedures, for the TSN network and the 5G network, under consideration of different synchronization and syntonization errors.

We found that, due to the disparity between a traditional TSN transparent clock and the 5GS emulating a transparent clock, even small frequency offsets between ingress and egress of the 5GS can result in significant synchronization errors. With the already strict synchronization requirements for industrial use cases, the impact of these synchronization errors can be prohibitive.

For our future work, we will investigate possible approaches to minimize the impact of syntonization errors between 5G devices on time synchronization in integrated 5G - TSN networks.

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