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Improvements for Time Synchronization with 5G Transparent Clocks

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Abstract: Deterministic, time-sensitive communication over integrated wired and wireless networks is one of the key enablers for Industry 4.0 and future factories, with current efforts in research and standardization focusing on integrating 5G and TSN. However, enabling the required interaction between two separate and different networks also introduces new issues. We focus on the disparity of the 5G System behaving as a single logical TSN Bridge for the sake of this integration. In this paper we investigate how to reduce the time synchronization errors caused by the 5G Systems approach to interacting with the TSN network. An ns-3 based simulation of an integrated 5G – TSN network is used to validate the proposed improvements.

1 Introduction

Part of the vision of Industry 4.0 is the shift towards the "smart factory": Instead of single purpose and static manufacturing, a flexible and mobile factory environment that can be adjusted to react to changing priorities and needs is envisioned. Flexible and mobile production environments (e.g., involving automated guided vehicles or mobile robots) require a communication infrastructure that can provide the necessary capabilities. A communication infrastructure that is capable of deterministic and time sensitive wireless communication without having to completely replace existing hardware is needed. The focus of currently ongoing standardization efforts by the 3GPP have been on the integration of IEEE TSN [1] and 5G [2].
This integration is realized such that the 5G System presents itself as a TSN Bridge to the TSN Network [3]. The advantage is, that the TSN network does not need to be aware of the 5G System. No change to existing procedure is required. However, the differences between a traditional TSN Bridge and a 5G logical TSN Bridge may result in additional errors when synchronizing over a 5G network [4].
In this paper, we start with a problem description in Chapter 2 and following that, propose modifications to how the 5G System interacts with gPTP synchronization messages in order to mitigate the impact of these differences. A simulation, described in Chaper 3, is used to evaluate these modifications in comparison to the standardized approach. This evaluation is shown in Chapter 4. A conclusion to this work is then given in Chapter 5.

1.1 Related Works

A general overview of wireless ultra-reliable, low latency communication (URLLC) and its challenges was given by Mahmood et al. [5]. One of the key use cases for future factories, cooperative mobile robots, is examined by Gundall et al [6]. They propose an integration concept for 5G and TSN networks based on the requirements they derive in their work and validate their concept in a demonstrator. Schüngel et al. [7] investigate the time synchronization performance of an integrated 5G-TSN network according to 3GPP Release 16. The theoretical model they derive is validated with a simulation. However, these works do not consider the specific effects due to the disparity between a TSN Bridge and 5G logical TSN Bridge. We investigated these effects in [4].

Regarding synchronization procedures, the 3GPP assumes the 5G internal synchronization to be achieved via System Information Block (SIB) messages [8]. Synchronization in the TSN network uses (g)PTP [1]. Our contribution in this work is the mitigation of the synchronization error introduced due to the disparity between a TSN bridge and a 5G logical TSN bridge in regard to handling of (g)PTP messages by the 5G System.

2 Problem Description and Proposed Modifications

In this chapter, we will first describe the problem with 5G and TSN integrated networks and then go on to show our proposed approach to mitigating it.

2.1 Problem Description

In [4] we investigated the difference between a traditional TSN Bridge that is integrated as a transparent clock into a TSN network, and a 5G System that is integrated as a logical TSN Bridge (and transparent clock) into a TSN network.

Synchronization in a TSN network is achieved by timestamping of a periodically exchanged synchronization message between the master clock and any clock that is synchronized to it. This synchronization procedure is explained in detail in the IEEE standards documents IEEE 1588 [9] and IEEE 802.1AS [1]. In this comparison, the important part is the calculation of the residence time in a bridge. As shown in Equation 3, the residence time is calculated by subtracting the ingress timestamp from the egress timestamp and multiplying the result with the cumulative rate ratio (CRR) [1].

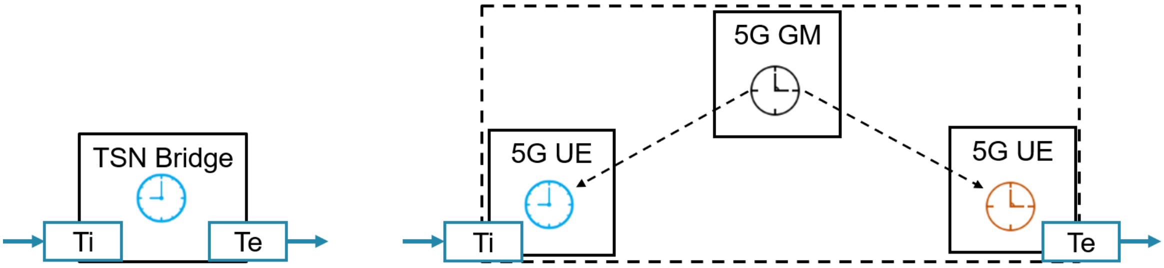

Figure 1: Difference in timestamping setup between TSN Bridge and 5G logical TSN Bridge

This method assumes that both ingress and egress timestamp are made based on the same, continuous time. While a TSN Bridge is a single device with a single clock, a 5G System is not. The ingress and egress timestamps are made by separate devices, with their own clocks, as shown in Figure 1.

Summarizing, there are two key differences between a TSN Bridge and a 5G logical TSN Bridge:

- **Clocks:** The residence calculation does not consider that ingress and egress timestamps are made based on different clocks. The resulting difference in clock drift introduces an additional synchronization error.
- **Time:** TSN Bridges acting as transparent clocks are typically free flowing to avoid time jumps due to the synchronization procedure resulting in offset corrections. That is not possible in the 5G System. Both ingress and egress devices have to be synchronized to the 5G grandmaster (GM). The resulting offset corrections introduce an additional synchronization error. How a requirement for the 5G clocks to provide a monotonously increasing time would impact our proposed modifications is out of scope of this work.

In the following sections we will describe our proposed approach to adjusting the synchronization procedure to mitigate the impact of these issues.

2.2 Clock Drift

From Release 16 onward, the 5G GM, typically the gNodeB (gNB), allows the synchronization of 5G UEs by including reference time information in the periodically distributed SIB messages [8]. In contrast to the PTP procedure in IEEE 1588 [9] and IEEE 802.1AS [1], this procedure does not account for frequency drift between master and slave clocks. The error resulting from this clock drift is kept sufficiently small by using more stable oscillators and choosing an appropriately small synchronization period.

As the goal of our proposed approach is to compensate for the error caused by the difference in clock drift between ingress and egress devices, we need to know said clock drift. Therefore, we first propose a simple method to determine the clock drift between a 5G user equipment (UE) and the 5G GM based on the periodically distributed SIB messages.

The ratio of the frequencies of two clocks can be calculated by comparing the same time interval as measured by each clock. For the 5G System we propose to use the SIB messages to calculate the frequency ratio, based on the reference time stored in the message and the receive time at the 5G UE. The resulting calculation is shown in Equation 1,

$$NRR_{5G} = \frac{T^{i}_{\text{reference,gNB}} - T^{i-1}_{\text{reference,gNB}}}{T^{i}_{\text{receive,UE}} - T^{*i-1}_{\text{receive,UE}}} \qquad \text{Eq. 1}$$

where $T^{i}_{\text{reference,gNB}}$ is the reference time from the 5G gNB and $T^{i}_{\text{receive,UE}}$ is the receive time at the UE, both at the i-th instance of the periodic message.

However, as the receiving UE updates its clock offset with every received SIB message, the constant part of its clocks drift is compensated (as the times in Equation 1 are therefore also periodic). Due to these times being linked to the synchronization process, we can adjust the procedure to take this into account: The current receive time, $T^{i}_{receive,UE}$, is taken before the offset is corrected. After the neighbour rate ratio (NRR) and the new offset have been calculated, the receive time is adjusted by the new offset before being stored, as shown in Equation 2, where T^{i}_{offset} is the value of the UE clock offset after the i-th synchronization event:

$$T^{*i}_{\text{receive,UE}} = T^{i}_{\text{receive,UE}} - \left(T^{i}_{\text{offset}} - T^{i-1}_{\text{offset}}\right), \qquad \text{Eq. 2}$$

2.3 Residence Time

As stated above, the 5G System is integrated into the TSN network by having it behave like a transparent TSN Bridge. This means, the duration the synchronization message spent in the 5G logical TSN Bridge is measured and stored in the message. This duration is the residence time (see Equation 3), and it is calculated as the difference between the timestamps at the ingress and egress ports of the 5G System, multiplied by the CRR to get the residence time in the TSN GMs time base.

The CRR is the rate ratio between the TSN GM and the current ingress port. As this ratio cannot be calculated directly (unless the current ingress port is a direct neighbour of the TSN GM), the CRR is stored in the synchronization message and updated at every ingress port the message passes. As shown in Equation 4, the CRR at device n is the product of the NRRs between all previous devices along the synchronization path, up to NRR^{n} between the current and preceding device.

$$T_{\text{residence}} = \text{CRR} \cdot (T_{\text{egress}} - T_{\text{ingress}}) \qquad \text{Eq. 3}$$

$$\text{CRR}^{n} = \text{CRR}^{n-1} \cdot \text{NRR}^{n} \qquad \text{Eq. 4}$$

Figure 1 shows the simplified behaviour of the ingress and egress clocks compared to the 5G GM clock: The clocks drift relative to the 5G GM and relative to each other. This drift has both a constant and a time-variant component. In the 5G System, this drift is corrected by periodically repeating the synchronization procedure and adjusting the respective offset to the 5G GM. In regard to the resulting behaviour, Figure 1 also shows the times of the relevant events.

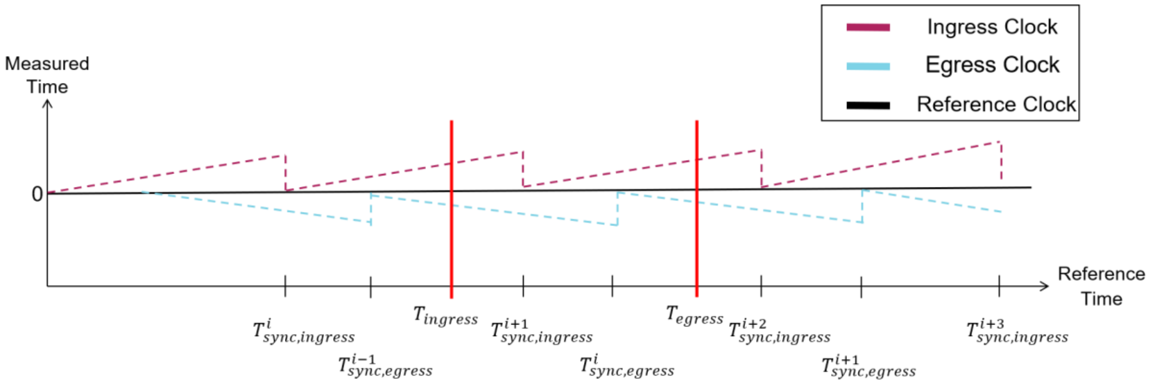

Figure 2: Simplified synchronized clock behavior relative to a reference clock with relevant events

$T^{i}_{\text{sync,ingress}}$ - the time of the i-th synchronization event at the ingress (or egress) UE

T_{ingress} - the ingress (or egress) timestamp used for the residence time calculation

In addition to these (known) times, our proposed approach requires knowledge of the relative clock frequencies of the involved devices:

$\frac{f_{\text{TSN}}}{f_{\text{5G,ingress}}}$ - the rate ratio between the previous TSN device and the ingress UE

$\frac{f_{\text{5G,GM}}}{f_{\text{5G,ingress}}}$ - the rate ratio between the 5G GM and the ingress UE

$\frac{f_{\text{5G,GM}}}{f_{\text{5G,egress}}}$ - the rate ratio between the 5G GM and the egress UE

The rate ratio between the ingress UE and the previous TSN device is known at the ingress UE and calculated via the peer delay mechanism as described in IEEE 802.1AS [9]. The rate ratios between the UEs and the 5G GM is not typically known, here we use the approach we propose in Chapter 2.2 to calculate these ratios.

In general, the approach described here aims to convert both the ingress and egress timestamps to the 5G GMs time base. By having a common understanding of time for both timestamps, the residence time can then be calculated and converted to the TSN GMs time, similar to a TSN Bridge.

First, the ingress timestamp is adjusted before it is stored in the synchronization message, as shown in Equation 5 and Equation 6.

$$T^{\text{corrected}}_{\text{ingress}} = T^{*i}_{\text{sync,ingress}} + \left(T_{\text{ingress}} - T^{*i}_{\text{sync,ingress}}\right) \cdot \frac{f_{\text{5G,GM}}}{f_{\text{5G,ingress}}} \qquad \text{Eq. 5}$$

$$T^{*i}_{\text{sync,ingress}} = T^{i}_{\text{sync,ingress}} - \left(T^{i}_{\text{offset,ingress}} - T^{i-1}_{\text{offset,ingress}}\right) \qquad \text{Eq. 6}$$

The CRR has to be adjusted in two steps, first at the ingress UE and then again at the egress UE, in order to accurately reflect the two devices of the 5G logical TSN Bridge. At the ingress UE, the rate ratio to the previous TSN bridge and the inverse of the rate ratio to the 5G GM are used to update the CRR (see Equation 7).

$$\text{CRR}^{n}_{\text{temporary}} = \text{CRR}^{n-1} \cdot \frac{f^{n-1}}{f_{\text{5G,ingress}}} \cdot \frac{f_{\text{5G,ingress}}}{f_{\text{5G,GM}}} \qquad \text{Eq. 7}$$

where CRR^{n-1} is the CRR after the previous TSN device (stored in the synchronization message).

Second, the egress timestamp is adjusted, and the residence time is calculated according to Equation 8 and Equation 9.

$$T^{\text{corrected}}_{\text{egress}} = T^{*i}_{\text{sync,egress}} + \left(T_{\text{egress}} - T^{*i}_{\text{sync,egress}}\right) \cdot \frac{f_{\text{5G,GM}}}{f_{\text{5G,egress}}} \qquad \text{Eq. 8}$$

$$T^{*i}_{\text{sync,egress}} = T^{i}_{\text{sync,egress}} - \left(T^{i}_{\text{offset,egress}} - T^{i-1}_{\text{offset,egress}}\right) \qquad \text{Eq. 9}$$

$$T_{\text{residence}} = \text{CRR}^{n}_{\text{temporary}} \cdot \left(T^{\text{corrected}}_{\text{egress}} - T^{\text{corrected}}_{\text{ingress}}\right) \qquad \text{Eq. 10}$$

After the residence time calculation in Equation 10, the final CRR is calculated according to Equation 11 and stored in the synchronization message.

$$\text{CRR}^{n} = \text{CRR}^{n}_{\text{temporary}} \cdot \frac{f_{\text{5G,GM}}}{f_{\text{5G,egress}}} \qquad \text{Eq. 11}$$

3 Simulation

In this chapter, we give a short overview of the simulation used to test our proposed modifications.

The simulation we use is built in ns-3 [10], and is based on the interactions of the TSN and 5G devices with the PTP synchronization messages. The 5G System part of this simulation is based on the 5G LENA model [11]. The major components to enable these interactions are the clocks, unique to each device, and a timestamping mechanism (as PTP is timestamp-based). More details on this simulation can be found in [4].

3.1 Clocks

Each clock entity is based on the simulation time t provided by ns-3 and therefore capable of perfectly accurate timekeeping. In order to model real-world clocks, errors are added on top of the simulation time. As ns-3 is an event-based simulator, the clock entity updates the time at every event where it is accessed. The resulting time T^i, at the i^{th} event, is calculated based on the difference in simulation time since the i-1st event and the error $c(t^i)$ of this clock (see Equation 12). This error is modelled as the sum of the constant frequency offset f and the time-variant frequency drift rate f' (see Equation 13). If the clock is synchronized to a master clock, the offset T^i_{offset} is added on top in Equation 14.

$$T^i = T^{i-1} + (t^i - t^{i-1}) \cdot (1 + c(t^i)) \tag*{Eq. 12}$$

$$c(t^i) = f + \int_{t^{i-1}}^{t^i} f' \cdot \sin(t)\, dt \tag*{Eq. 13}$$

$$T^i_{\text{sync}} = T^i + T^i_{\text{offset}} \tag*{Eq. 14}$$

3.2 Timestamping

The synchronization procedure implemented here is based on the (g)PTP synchronization described in IEEE 802.1AS [1]. Synchronization messages are timestamped at every ingress and egress port they pass. The timestamp T^i_{TS} is based on the (erroneous) time provided by the local clock entity connected to that port, and an additional error is added for the timestamping event itself (see Equation 15). This time error (TE) is based on the IEC/IEEE 60802 Use Cases document [12] and has both a constant part cTE and a dynamic (random) part dTE.

$$T^i_{\text{TS}} = T^i_{\text{sync}} + cTE + dTE \tag*{Eq. 15}$$

3.3 Scenario & Procedure

The simulation scenario is shown in Figure 2. The TSN GM synchronizes the TSN Endstation via a line of Bridges and a 5G network (modelled as a logical TSN Bridge). We assume all Bridges to be transparent clocks, meaning they forward the synchronization messages but do not synchronize their own clocks to the TSN GM. Every TSN Bridge periodically performs the Peer Delay procedure as described in IEEE 802.1AS [1] to determine the delay and rate ratio to its neighbours. Only the TSN GM periodically sends out the synchronization message that is forwarded to the TSN Endstation.

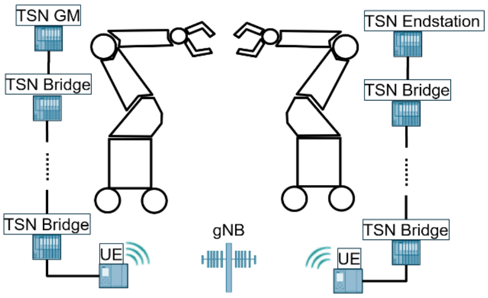

Figure 3: Two cooperative mobile robots as basic scenario for the simulation

4 Results

In this chapter, we look at the performance of our proposed modifications to the 5G-TSN synchronization procedure. First, we detail our choice of parameterization and then discuss the resulting data.

4.1 Setup & Parameters

As described in Chapter 3.3, the simulation models the synchronization procedure according to IEEE 8021AS [1]. The performance of the proposed modifications is based on the achieved synchronization accuracy for a variety of parametrizations. The general simulation parameters are shown in Table 1.

Parameter	Value
Simulation runs	100
Simulation duration	100s
TSN synchronization interval	125 ms [13]
TSN PDelay interval	31.25 ms [13]
5G synchronization interval	[10 ms, 40 ms, 80 ms] [8]
TSN clock frequency offset	50+U(-5,5) ppm [13]
TSN clock frequency drift	3 ppm/s (sinusoidal) [13]
TSN cTE	U(-10,10) ns [12]
5G cTE	U(-275,275) ns [14]
dTE	U(-20,20) ns [12]

Table 1: General Simulation Parameters

4.2 5G Clock Drift

First, we look at our proposed approach to determining the clock drift between a 5G UE and the 5G GM. The accuracy of the clock drift calculation depends on the accuracy of the respective timestamps. As shown in Table 1, we assume the 5G synchronization to be accurate within 275 ns according to [14]. As the clock drift calculation is based on the same timestamps as the synchronization itself, we can assume the same accuracy to apply here. Equation 16 gives us a theoretical upper limit, depending on the chosen synchronization interval $T_{sync,interval}$.

$$\max\left(E_{\mathrm{5G,NRR}}\right) = \frac{T_{\mathrm{sync,interval}}}{T_{\mathrm{sync,interval}} + 2 \cdot 275\mathrm{ns}} \qquad \text{Eq. 16}$$

For example, for $T_{\mathrm{sync,interval}} = 10\mathrm{ms}$, that results in a maximum calculation error of 55 ppm. As this maximum error is very unlikely to occur, we additionally take the median of a sliding window of the calculated drift values (similar to common practice in IEEE networks [13]). This reduces outliers and therefore increases the accuracy.

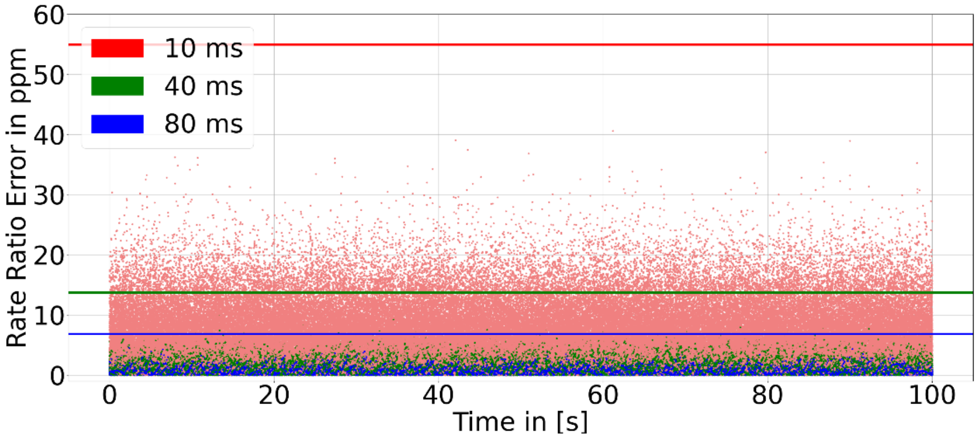

Figure 4: Absolute 5G UE-gNB rate ratio error for different 5G synchronization intervals

Figure 4 shows the achieved accuracy as the difference between the calculated drift and the actual drift applied in the simulation, for different synchronization intervals. The bold lines mark $\max(E_{5G,NRR})$ for the respective synchronization interval. The error is shown to be limited to roughly half the theoretical maximum. While the relative error is quite significant at up to 40 ppm for $T_{\mathrm{sync,interval}} = 10\mathrm{ms}$, it is limited to 7 ppm and 3 ppm for $T_{\mathrm{sync,interval}} = 40\mathrm{ms}$ and $T_{\mathrm{sync,interval}} = 80\mathrm{ms}$, respectively. While that is still far less accurate than the drift determination in a TSN network, it is sufficiently accurate to provide a benefit in our proposed 5G residence time calculation modification.

4.3 5G Residence Time

We evaluate our 5G residence time calculation modification by comparing the calculated residence time to the actual residence time in the simulation. As mentioned in Chapter 2, the residence time calculation in a 5G logical TSN Bridge has two issues:

1. The ingress and egress timestamps are added by separate devices, with possibly different clock drift behaviour and time errors.
2. For the CRR, only the NRR of the ingress device is taken into account. The separate egress device is not.

The impact of the constant and dynamic Time Errors (see Table 1) on the 5G residence time is limited to

$$\max(E_{5G,TE}) = \pm 2 \cdot (\mathrm{cTE}_{\max} + \mathrm{dTE}_{\max}) \qquad \text{Eq. 17}$$

which results in $\max(E_{5G,TE}) = \pm 590\mathrm{ns}$. The impact of the relative clock drift between the ingress and egress UEs depends on the synchronization period of both the 5G and TSN networks and is therefore limited to

$$\max(E_{5G,\mathrm{drift}}) = \min(T_{\mathrm{sync,interval}}^{\mathrm{TSN}}, T_{\mathrm{sync,interval}}^{5G}) \cdot f^{5G} \qquad \text{Eq. 18}$$

For example, a clock frequency offset of ± 10 ppm and a clock frequency drift rate of ± 3 ppm/s at a $10\mathrm{ms}$ 5G synchronization period result in $\max(E_{5G,\mathrm{drift}}) = 260\mathrm{ns}$.

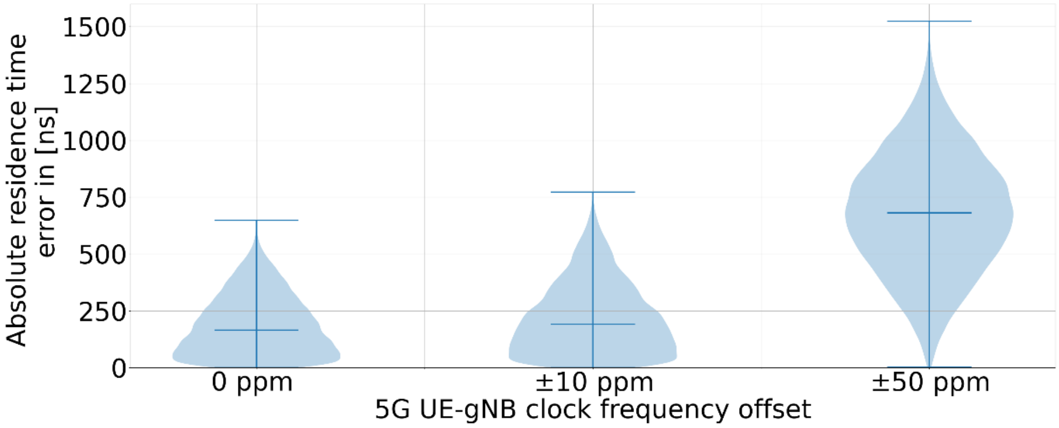

Figure 5: 5G residence time error without modifications for various UE-gNB frequency offsets

Figure 5 now shows the residence time error for the unmodified 5G system with a 5G synchronization interval of 10ms and for different clock frequency offsets between ingress and egress UEs. The violin plots show the full distribution of the data sets, with the extrema marked by horizontal lines.

The behaviour is as expected based on the error components explained above. For clocks that are stable relative to the 5G GM and each other, the impact of ignored egress clock drift is low. However, if the egress clock is allowed to drift relative to the ingress clock (or 5G GM), the resulting error increases significantly.

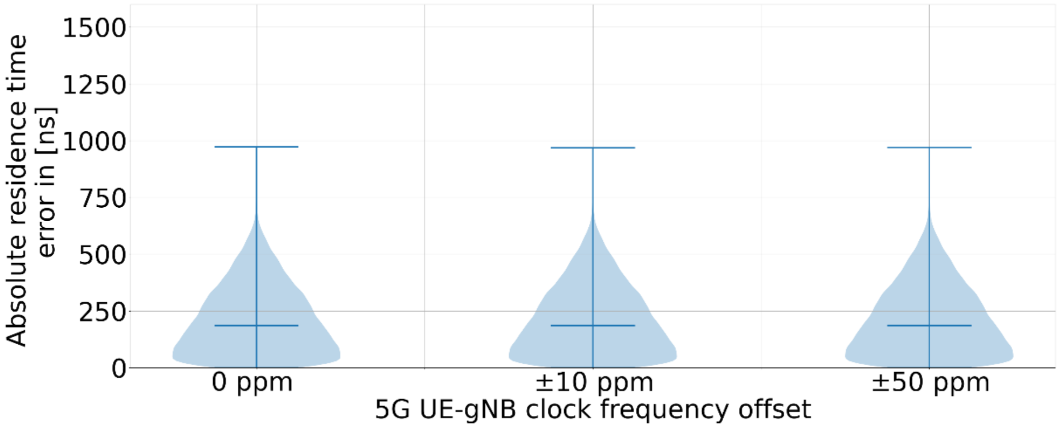

Figure 6: 5G residence time error with modifications for various UE-gNB frequency offsets

In comparison, Figure 6 shows a consistent residence time error independent of the relative clock frequency offset. That is due to the clock frequency offset being compensated by the modified residence time calculation, the residence time error is decoupled from the clock drift. However, for low clock frequency offsets, the error is larger than the unmodified calculation. That is due to the error in determining the rate ratio between the 5G UE and 5G GM, that may exceed the actual rate ratio for very stable oscillators. This may be improved by reducing the uncertainty in the transmit and receive times used to calculate the rate ratio, for example by enabling more precise hardware timestamping at the 5G radio antennas.

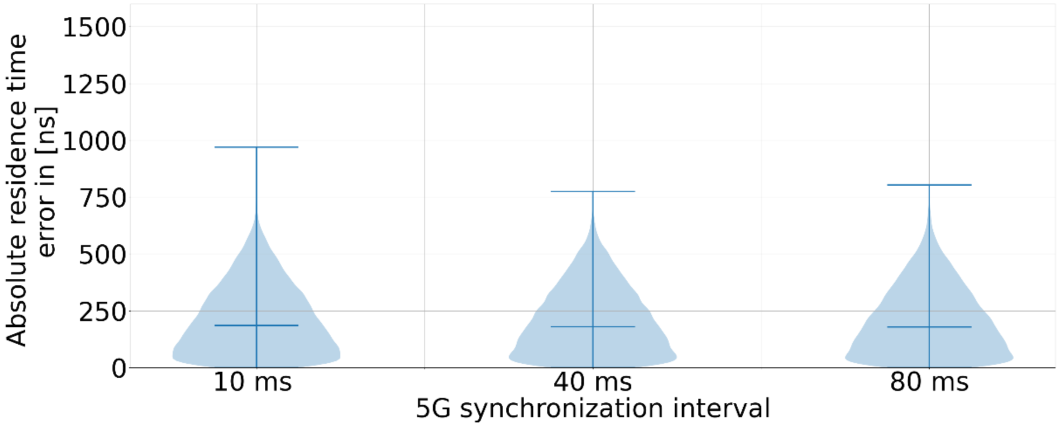

Figure 7: 5G residence time error with modifications for various 5G synchronization intervals

Figure 7 shows the residence time error for different 5G synchronization intervals. We can see that the large error in determining the rate ratio for a short 5G synchronization interval, as shown in Figure 4, results in a large residence time error, as shown in Figure 6. This error is reduced when increasing the 5G synchronization interval, due to the smaller resulting rate ratio error.

We also note that the CRR is used to calculate the residence time in TSN GM time at every TSN Bridge along the path to the synchronizing TSN Endstation. Regarding the CRR calculation, the 5G ingress and egress devices could be considered neighbouring devices. Thus, the error due to not including the 5G egress devices' clock frequency offset relative to the 5G ingress devices clock frequency offset is propagated until the TSN Endstation, resulting in an error for every further residence time calculation.

Considering that the CRR is the product of the NRR of all preceding devices, as shown in Equation 4, the error resulting from removing one device (device n-1 in Equation 19 and 20) from the CRR would be equal to the inverse of the missing NRR.

$$\mathrm{CRR}^{\mathrm{n}} = \frac{f_{GM}}{f^1} \cdot \frac{f^1}{f^2} \cdot \ldots \cdot \frac{f^{n-2}}{f^{n-1}} \frac{f^{n-1}}{f^n} \qquad \text{Eq. 19}$$

$$\mathrm{CRR}^{\mathrm{n}} \cdot \frac{f^{n-1}}{f^{n-2}} = \frac{f_{GM}}{f^1} \cdot \frac{f^1}{f^2} \cdot \ldots \cdot \frac{\cancel{f^{n-2}}}{\cancel{f^{n-1}}} \cdot \frac{\cancel{f^{n-1}}}{\cancel{f^{n-2}}} \cdot \frac{f^{n-1}}{f^n} \qquad \text{Eq. 20}$$

In the case of the 5G egress clock frequency offset not being included, we assume the error to be equal to $\frac{f_{5G,egress}}{f_{5G,ingress}}$, the inverse of the NRR at the 5G egress device. Figure 8 shows the resulting error on the residence time calculation for TSN devices before (here noted as "Baseline") and after the 5G Systems' impact on the stored CRR. The resulting error aligns with our expectation: $\pm 10\mathrm{ppm}$ frequency offset and $\pm 3\mathrm{ppm/s}$ frequency drift result in a $26\mathrm{ns}$ error for a $1\mathrm{ms}$ residence time.

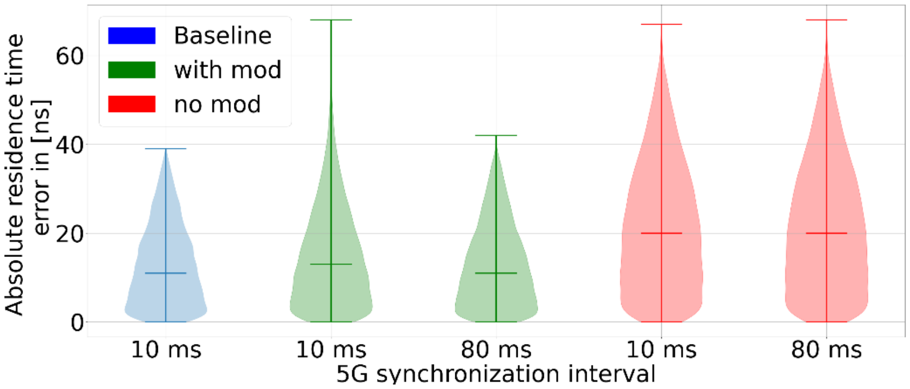

Figure 8: TSN residence time error after the 5G System for $T_{\mathrm{sync}}^{5\mathrm{G}} = 10\mathrm{ms}$ and $\pm 10\mathrm{ppm}$ 5G clock frequency offset

5 Conclusion

In this work, we propose a modification to the residence time calculation in a 5G logical TSN Bridge in order to compensate for the difference to a traditional transparent TSN Bridge. We show that the performance is comparable for very stable 5G clocks and short 5G synchronization intervals. For longer 5G synchronization intervals and less stable clocks in the 5G UEs, our modified approach to the residence time calculation stays relatively stable, while the unmodified approach fails. As mentioned in the introduction, the flexibility provided by wireless communication is an important part of future factories. More wireless communication devices will be required, therefore one of the relevant factors in deciding whether 5G and TSN will succeed in enabling Industry 4.0 will be the device cost. These modifications may enable the use of cheaper hardware for integrated 5G-TSN networks, though further research is required before use in industrial communication devices is possible.

For future work, a way to determine the clock drift more accurately inside the 5G Network should be investigated, as it was shown to be a limiting factor regarding the achievable accuracy. In addition, we did not consider the impact of requiring the clocks to always provide a monotonously increasing time. The current approach, based on the clocks' offset, will have to be adjusted to the different clock behaviour in such a case. This question will have to be addressed for full viability in industrial use cases.

6 Bibliography

[1] *802.1AS-2020: IEEE Standard for Local and Metropolitan Area Networks - Timing and Synchronization for Time-Sensitive Applications,* IEEE, 2020.

[2] *TS 23.501 System architecture for the 5G System (5GS),* https://www.3gpp.org/DynaReport/23501.htm: 3GPP, 2021.

[3] T. Striffler, N. Michailow und M. Bahr, „Time-Sensitive Networking in 5th Generation Cellular Networks - Current State and Open Topics," in *IEEE 2nd 5G World Forum (5GWF),* 2019.

[4] T. Striffler und H. D. Schotten, „The 5G Transparent Clock: Synchronization Errors in Integrated 5G-TSN Industrial Networks," in *INDIN 2021: IEEE International Conference on Industrial Informatics*, 2021.

[5] A. Mahmood, M. I. Ashraf, M. Gidlund und J. Torsner, „Over-the-Air Time Synchronization for URLLC: Requirements, Challenges and Possible Enablers," in *15th International Symposium on Wireless Communication Systems (ISWCS)*, 2018.

[6] M. Gundall, C. Huber, P. Rost, R. Halfmann und H. D. Schotten, „Integration of 5G with TSN as Prerequisite for a Highly Flexible Future Industrial Automation: Time Synchronization based on IEEE 802.1AS," in *Annual Conference of the IEEE Industrial Electronics Society (IECON-2020),* 2020.

[7] M. Schüngel, S. Dietrich, D. Ginthör, S. P. Chen und M. Kuhn, „Analysis of Time Synchronization for Converged Wired and Wireless Networks," in *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, 2020.

[8] *TS 38.331 NR; Radio Resource Control (RRC) protocol specification (Release 16),* https://www.3gpp.org/DynaReport/38331.htm: 3GPP, 2021.

[9] *1588-2019: IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems,* IEEE, 2019.

[10] *The ns-3 network simulator,* http://www.nsnam.org/, 2021.

[11] N. Patriciello, S. Lagen, B. Bojovic und L. Giupponi, *An E2E simulator for 5G NR networks,* Simulation Modelling Practice and Theory, 2019.

[12] *Use Cases IEC/IEEE 60802,* IEC and IEEE, 2018.

[13] G. M. Garner, *New Simulation Results for Time Error Performance for Transport over an IEC/IEEE 60802 Network Based on Updated Assumptions,* 2020.

[14] *R2-2010837 Reply LS on propagation delay compensation enhancement,* 3GPP, 2021.