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Heterogeneous Synchronization in Converged Wired and Wireless Time-Sensitive Networks

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***Abstract*—The integration of 5G with Time-Sensitive Networking (TSN) promises to support the novel requirements of future industrial communication. A key aspect for the industrial application of converged TSN/5G networks is synchronization. Different synchronization scenarios can be identified which are directly affiliated with a particular grandmaster location. The state-of-the-art scenario is a network-sided grandmaster. We propose an novel synchronization scenario which uses a common grandmaster for both the wired and wireless networks. This uniforms the synchronization in converged networks. Our proposed approach achieves a largely improved synchronization towards device-sided devices while introducing only a minor additional error towards network-sided devices. We present and compare our proposal with the state-of-the-art synchronization scenarios, and conduct a formal analysis to estimate the synchronization quality per scenario and simulations to verify the results.**

***Index Terms*—5G, Ethernet, factory automation, TSN, real-time communication, synchronization, wireless communication**

I. Introduction

A current trend in the industry and academia is the endeavor for an unification of communication technologies in order to develop a single technology that is capable to serve diverse real-time and non-real-time applications. A solution discussed by industry and standardization groups to address the novel requirements is Time-Sensitive Networking (TSN). TSN is a set of IEEE 802.1 standards which adopts Ethernet to enable real-time capabilities. In line with the targets of Industry 4.0, wireless technologies will also become an indispensable aspect of future industrial communication at a large scale. The fifth generation cellular network technology (5G) is a promising technology to approach the lack of mobility and scalability in wired networks. 3GPP groups pursue the interest to enable 5G real-time features to make it suitable for industrial applications. Therein, a key aspect is the seamless integration with TSN to establish converged TSN/5G networks.

The integration of TSN and 5G is heavily discussed by both 3GPP and IEEE yielding the integration of 5G with TSN as virtual TSN bridge (VTB) [1]. The VTB enables a seamless integration of 5G with TSN by concealing the 5G complexity using dedicated TSN translators (TTs). These provide a TSN compliant interface towards the TSN network. A key feature is the support of synchronization through the generalized Precision Time Protocol (gPTP) according to IEEE 802.1AS [2]. From an architectural perspective, the TSN/5G integration as VTB is thoroughly defined. However, only particular synchronization scenarios are discussed. A detailed study of different synchronization scenarios, that are affiliated with specific Grandmaster (GM) [2] locations, is lacking. The discussed scenarios refer to a network- or device-sided GM which requires a dedicated system to serve the network as GM. This implies the involvement of heterogeneous synchronization mechanisms considering integrate TSN/5G network and the access of a GM to a source of time, e.g. GPS. A study of the engagement of heterogeneous synchronization and its effect on industrial applications remains open.

In this work we are studying the synchronization in converged TSN/5G networks and investigate the engagement of heterogeneous synchronization mechanisms. We propose a novel approach of using a common GM for both, 5G and TSN networks, that largely unifies the synchronization in converged TSN/5G networks. The remainder of this work is organized as follow. In Sec. II we present the state-of-the-art synchronization mechanisms. In Sec. III, we describe our proposal of a 5G-sided GM. A formal analysis of the individual synchronization mechanisms and their integration is carried out in Sec. IV. In Sec. V, the analytical results are verified with simulation and our proposed approach is compared with the state-of-the-art synchronization to confirm potential benefits. The following conclusion in Sec. VI finalizes this work.

II. Overview on Synchronization Mechanisms

In this section we provide an overview on the individual synchronization mechanisms that are used in converged TSN/5G networks. The presented synchronization mechanisms serve the purpose of time synchronization and thereby to establish a shared notion of time [3]. The 5G integration with TSN is discussed by 3GPP and IEEE to be transparent such that 5G can be deployed seamlessly into green-field or brown-field scenarios. As can be seen from Fig. 1, the desired transparency is established by the introduction of network- and device-sided TTs which are referred to as NW-TT and DS-TT [1], [4]. Together with both TTs the 5G User Plane (UP) is considered as VTB. The TTs mask the 5G complexity and provide a standard interface towards the TSN network.

From a TSN end-to-end perspective, i.e. from network- to device-sided TSN end-stations, heterogeneous synchronization

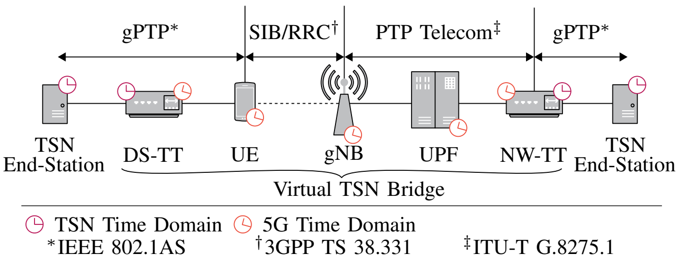

Fig. 1. Synchronization mechanisms in converged TSN/5G networks.

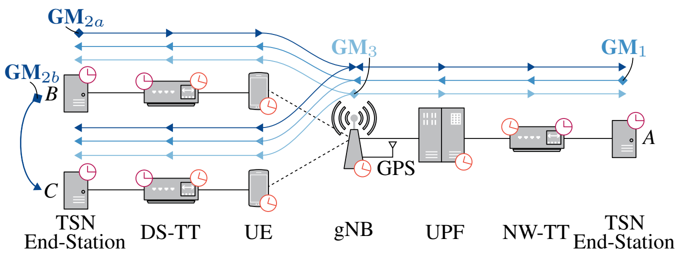

Fig. 2. Synchronization scenarios in converged TSN/5G networks: 1) GM_1: NW GM - DL synchronization, 2a) GM_{2a}: DS GM - UL synchronization, 2b) GM_{2b}: DS GM - SL synchronization, and 3) GM_3: 5G-sided GM

mechanisms are involved. The synchronization of TSN is handled separately from the synchronization of the VTB/5GS components. TSN leverages the gPTP for synchronizing its network components. Within 5G the synchronization is distinguished between the 5G Radio Access Network (5G RAN) and the 5G Core (5GC). Within the 5G RAN, the User Equipment (UE) is synchronized by the Next Generation NodeB (gNB) through a built-in reference time indication that leverages either System Information Blocks (SIBs) or Radio Resource Control (RRC) messages [3], [5], [6]. In the 5GC, the gNB synchronizes the remaining components, that are the User Plane Function (UPF) and the NW-TT, through a PTP telecommunication profile (PTPtele) [6]. Therefore, the synchronization mechanisms can be separated into PTP based mechanisms, that includes gPTP and PTP/PTPtele, and the 5G built-in reference time indication.

The integration of 5G with TSN inevitably yields the correlation of the individual synchronization mechanisms. The emerging dependencies are specific to the present synchronization scenario, i.e. the GM location. Figure 2 shows the different GM locations that are: 1) network-sided (NW) GM, 2) a device-sided (DS) GM, and 3) a 5G-sided GM.

1) Network-Sided Grandmaster: A NW GM leads to a synchronization scenario that is also referred to as Downlink (DL) synchronization. As can be seen from Fig. 2, the GM is located at the TSN network towards the network-side of the 5GS, i.e. it is a NW device. The resulting synchronization scenario integrates seamlessly with the VTB and is the state-of-the-art approach consolidated in the 3GPP Rel. 16 specifications [1]. The DL synchronization leverages the underlying synchronization of the VTB components through the 5GS. A `Sync` message that traverses the VTB, i.e. the 5G UP, is timestamped at the ingress NW-TT and at egress DS-TT. The timestamps are in scale of the 5G time. With that the VTB is able to find the residence time of the `Sync` message and thus is able to calculate the correction field of the corresponding `Follow_Up` message. The synchronization error of devices beyond the VTB, i.e. for DL synchronization that are DS devices, is affected by the accuracy of the VTB residence time which depends on the underlying synchronization of the NW-TT and DS-TT through 5G. The individual synchronization mechanisms of TSN and 5G do not engage with each other except for the residence time calculation.

2) Device-Sided Grandmaster: A DS GM yields a synchronization that is also denoted as Uplink (UL) synchronization. As shown in Fig. 2 the GM is located at the TSN network towards the device side of the 5GS. In context of UL synchronization, the synchronization of a NW device is similar to the DL synchronization only in reverse direction (independent from DL/UL symmetry). However, considering the synchronization of a DS end-station through the 5G infrastructure this brings up the issue of practically combining UL and DL synchronization. A `Sync` message emerges from the DS GM and traverses the VTB. For the UL synchronization it is timestamped likewise to the DL synchronization but in opposite order. For the combined UL and DL synchronization, the `Sync` message is governed to the UPF where it is switched into the DL direction. As already discussed for the DL synchronization, the synchronization error of devices, i.e. NW devices or other DS devices, that are connected to the DS GM through VTB infrastructure depends on the accuracy of the VTB residence time. Likewise to the DL synchronization, the individual synchronization mechanisms engage only for the residence time calculation. UL synchronization is subject to the 3GPP Rel. 17 activities [7].

Another synchronization scenario emerges from a DS GM that is the Sidelink (SL) synchronization. As depicted in Fig. 2, a DS device is synchronized to a DS GM without using the 5G infrastructure. Rather both systems communicate directly over the SL. The SL itself is part of the 3GPP Rel. 17 discussions, such that the SL synchronization, is for further study [7].

3) 5G-Sided Grandmaster: With a 5G-sided GM both TSN and 5G networks refer to the same timescale. As shown in Fig. 2, the 5G-sided GM is located within the VTB conveniently at the gNB and is synchronized through GPS by design [1]. The resulting synchronization scenario seamlessly integrates with the converged TSN/5G network since the VTB acts as GM from a TSN network point of view. The boundary TTs conceal the heterogeneity of the synchronization mechanisms used within the VTB. However, there is a strong engagement of the different synchronization mechanisms within the VTB which yields the following challenges that are specific to a 5G-sided GM:

1) At the boundary of the 5GC towards the TSN network, i.e. the NW-TT, the PTPtele, that is used within the 5GC, has to be mapped to the gPTP, that is used by the external TSN network. 2) At the boundary of the 5G RAN towards the TSN network, i.e. the UE, the synchronization through RRC messages or SIBs has to be mapped to gPTP. The question

emerges, how the UE synchronizes the DS-TT and how the DS-TT broadcasts `Sync` messages towards connected devices. 3) For the participation in the Best Master Clock Algorithm (BMCA), the TTs have to provide the clock information to the external network. The logical local clock of the VTB is the 5GS clock provided by the gNB [1]. However, some of the clock information elements are affected by the internal transport of the timing information from the gNB to the VTB boundary, i.e. NW-TT and DS-TT. It is not defined how to proceed with that.

Although the synchronization scenarios for both NW and DS GMs are addressed in the ongoing specification, the 5G-sided GM scenario remains open. In the following section we propose integration strategies for a 5G-sided GM.

III. Proposed Integration Strategies for a 5G-Sided Grandmaster

In this work we study twofold integration strategies for a 5G-sided GM that are *A.* shallow integration and *B.* deep integration strategies. The shallow integration leverages the VTB concept to enable a convenient 5G-sided GM scenarios that is in line with current standardization efforts of 3GPP and IEEE, whereas the deep integration follows a more transparent approach which requires an engagement within the VTB. This section concludes with an overview on the benefits of our proposed integration strategies.

A. Shallow Integration

The shallow integration strategy is in line with the VTB concept as can be seen from Fig. 3. Towards the external TSN networks the synchronization boundaries remain to be the NW-TT and DS-TT. The actual GM is located within the 5GS, i.e. conveniently the gNB is the GM as it is synchronized through GPS, and remains concealed to the external TSN networks. The interfacing of the actual GM is handled at the boundaries of the VTB. The shallow integration strategy implements independent GMs at the boundary NW-TT and DS-TT. These are denoted as Network GM (N-GM) and Device GM (D-GM). Both N-GM and D-GM are related to the same source of time that is provided through the actual GM, i.e. the gNB. This strategy addresses the previously discussed issues as follows:

1) Towards the NW TSN network, the NW-TT supports gPTP and serves as N-GM. Its source of time is the actual GM within the 5GS, i.e. the gNB. In that sense the N-GM establishes an interface between the actual GM and the NW TSN network. This can easily be configured using the `timeSource` attribute of its PTP dataset [2]. It would be set as `PTP` [2] under consideration of a PTP based synchronization in the 5GC, e.g. through PTPtele. 2) Similarly to the NW considerations, the DS-TT supports gPTP and serves as D-GM towards the DS TSN network and establishes an interface to the actual GM. The `timeSource` attribute of the D-GM depends on the synchronization between UE and DS-TT. Under consideration of Fig. 1 the attribute would be defined as `PTP` [2]. 3) With the concealment of the actual GM by the NW-TT and DS-TT, by means of N-GM and D-GM, the raised issue of non-transparent clock information provisioning of the actual GM is not addressed. The DS-TT and NW-TT provide their clock information and in that way withhold information on the 5GS internal transport of timing information and on the actual source of time.

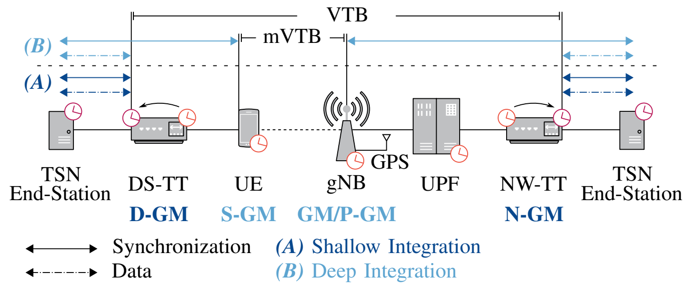

Fig. 3. Shallow and deep integration strategies for a 5G-sided GM. Concept of mVTB compared to VTB.

B. Deep Integration

Different to the shallow integration, the deep integration strategy engages with the VTB concept. Therefore, we introduce a modified VTB (mVTB) that, from a synchronization point of view, shifts its boundaries to the gNB and the UE in comparison to the boundaries of NW-TT and DS-TT established by the VTB. A representative illustration of the deep integration strategy through the implementation of a mVTB is given in Fig. 3. For the deep integration strategy the 5G/TSN integration differs from a synchronization and a data point of view. From the data perspective, the transparent 5G/TSN integration as VTB [1], with the defined boundaries of NW-TT and DS-TT, remains. However, for the synchronization some complexity of the VTB is revealed to the external TSN networks and new boundaries are defined as gNB and UE. A more transparent integration as mVTB is established. In comparison to the shallow integration strategy, an identical view on the 5G/TSN integration is shared from both a data and synchronization perspective. The deep integration strategy addresses the earlier discussed issues as follows:

1) The PTPtele is configured to be compliant to gPTP. This includes peer-to-peer operation, two-step clock mode, and message rates [2], [8]. With that, the gPTP domain of the NW TSN network is extended up to the gNB which serves as GM. For the deep integration strategy the gNB is also referred as Primary GM (P-GM). The P-GM acquires its source of time via GPS, and thus the P-GM `timeSource` attribute would be given as `GPS` [2]. 2) The UE establishes a Secondary GM (S-GM) that synchronizes the DS TSN network. Similar to the hot-standby GM introduced by the IEEE 802.1AS for redundant synchronization [2], the S-GM is a standalone GM whose source of time is the P-GM that is given by the gNB. However, the synchronization of the S-GM through the P-GM is not conducted through gPTP, instead the 5G built-in service for reference time indication is used. Hence, the S-GM `timeSource` attribute would be given as `TERRESTRIAL_RADIO` [2]. With that basically two separate gPTP domains emerge: one for the network-side, served by

the P-GM, and one for the device-side, served by the S-GM. 3) With the expansion of the NW and DS gPTP domains to the novel boundaries of the mVTB, the provision of the clock information becomes more transparent. Towards the network-side, the gNB simply provides its local clock information. The influence of transporting the timing information through the 5GC is then transparently given in the `stepsRemoved` field of the clock information element [2]. Towards the device-side, the UE similarly provides its local clock information as it serves as S-GM.

C. Potential Benefits of the Proposed Integration Strategies

The synchronization through a 5G-sided GM under our proposed integration strategies exposes major benefits compared to both DL and UL synchronization. In general, by using only a single GM for both TSN and 5G, we leverage the already existing infrastructure of 5G to access the source of time, e.g. GPS. A 5G-sided GM involves less intermediate systems towards DS devices than the state-of-the-art scenarios. Therein it promises to show an improved synchronization of DS devices [9]. The separation of gPTP domains for the network- and the device-side is inspired by the IEEE 802.1AS redundant synchronization [2]. It provides an improved stability in the event of handover or connection losses such that device-side devices are not required to re-select the GM which can affect the synchronization. Our proposed shallow integration strategy is a standard compliant approach of establishing a 5G-sided GM simply through configuration of the TTs. The proposed deep integration strategy delivers a simplified synchronization for converged TSN/5G networks as gPTP is applied to the entire wired domain, whereas the synchronization in the wireless domain is handled by the built-in service of 5G. The mVTB enables a more transparent BMCA as it represents the entire synchronization hierarchy starting from gNB rather than hiding complexity as the VTB does.

IV. Analysis of the Integration of Heterogeneous Synchronization Mechanisms

In this section we give a system model definition that establishes a consistent mathematical formulation for the following analysis of the individual synchronization mechanisms, that are PTP based synchronization and the 5G built-in reference time indication, and the analysis of the integration of those synchronization mechanisms.

A. System Model

For our analysis of the individual synchronization mechanisms we define a consistent system model. A system, i.e. any network component of a TSN network or a 5GS, is associated with a clock i. We use a consistent mathematical notation. An erroneous value $\tilde{x} = x + \delta x$ consists of the ideal value x and an error component δx. The difference between two values of the same kind x_i and x_j is denoted as $\Delta x_{i,j} = x_i - x_j$.

A clock i is ideal when it emits an ideal continuous clock signal $C_i(t) = t$ that is a function of the universal time t according to (1). However, in real world applications clocks emit a discretized signal as they are implemented as an oscillator driven counter [10]. Real oscillators are not ideal and introduce impairments that result in frequency instabilities. A common approach to model real world clocks, that is known from the literature, is to use a second order polynomial [10]. It features a frequency offset ρ_i, that consists of the constant clock skew ρ_i' and the time-variant clock drift $\rho_i''(t)$, and a clock offset θ_i, i.e. an offset in the time domain [10].

$$\tilde{C}_i(t) = \big(1 + \rho_i(t)\big)t + \theta_i \quad \text{with} \quad \rho_i(t) = \rho_i' + \rho_i''(t)t \tag{1}$$

A timestamp $\tau_i(t) = C_i(t)$ is a defined point in time that is derived from a clock signal $C_i(t)$. Timestamps are used to measure intervals and to compare the timely behavior of different systems. In order to model the timestamp generation, different sources of error are considered. Apart from the inaccuracy introduced by the associated clock signal, a timestamp is exposed to two major sources of inaccuracy that are the granularity $G(t)$ and the Physical Layer (PHY) jitter $J(t)$ [9], [11]. A timestamp shows a granularity due to the limited oscillator frequency of the associated clock [11]. The PHY jitter emerges when a timestamp is triggered by a message transmission/reception, hence when a frame traverses the PHY in both up- and downlink directions [11]. Considering the depicted impairments the timestamp generation results from

$$\begin{aligned} \tilde{\tau}_i(t) &= \tilde{C}_i(t) + G(t) + J(t) \\ &= \big[\big(1 + \rho_i(t)\big)t + \theta_i\big] + G(t) + J(t) \end{aligned} \tag{2}$$

where timestamp granularity $G \in [-1/f_{\text{osc}}, 0]$ depends on the oscillator frequency f_{osc} of the associated clock [11]. The synchronization mechanisms are used to align the timely behavior of different clocks. The presented mechanisms are able to compensate the clock skew ρ_i' and offset θ_i to a certain degree by applying the correction $\mathcal{C}_i$. However, the correction $\mathcal{C}_i$ is prone to errors such that the correction errors are given as $\delta\rho_i'$ and $\delta\theta_i$. The correction error depends on the synchronization mechanism. Since the clock drift is not addressed by the specified synchronization mechanisms [10], e.g. gPTP or 5G built-in reference time indication, the clock drift is neglected for the following considerations, i.e. $\rho_i''(t) = 0$. Accordingly, the timestamp generation (2) under the consideration of $\mathcal{C}_i$ can be separated into the ideal timestamp $\tau_i(t)$ and the timestamp error $\delta\tau_i(t)$

$$\begin{aligned} \tilde{\tau}_i(t) - \mathcal{C}_i &= \tilde{\tau}_i(t) - (\rho_i' - \delta\rho_i') - (\theta_i - \delta\theta_i) \\ &= \underbrace{\big[\ t\ \big]}_{\tau_i(t)} + \underbrace{\big[\delta\rho_i' t + \delta\theta_i + G(t) + J(t)\big]}_{\delta\tau_i(t)} \ . \end{aligned} \tag{3}$$

Examining the synchronicity between different clocks i and j can be done by comparing the corrected timestamps $\tau_i(t) - \mathcal{C}_i$ and $\tau_j(t) - \mathcal{C}_j$ that are generated by either clock at the same universal time t. Then the asynchronicity is given by the difference of the individual error components according to (4), where the difference of the clock skew correction errors $\Delta\delta\rho_{i,j}'$ is limited to the synchronization interval, i.e. correction interval, $T(t) \in [0, T_{\text{Sync}}]$.

$$\Delta\delta\tau_{i,j}(t) = \Delta\delta\rho_{i,j}' T(t) + \Delta\delta\theta_{i,j} + \Delta G_{i,j}(t) + \Delta J_{i,j}(t) \tag{4}$$

B. Analysis of PTP Based Synchronization

The synchronization error in TSN networks or other PTP based networks, e.g. the 5GC, between a GM and a system to be synchronized follows from the erroneous application of the timing information along its transportation through the network. As discussed before, the GM broadcasts its reference time through the network. The systems to be synchronized adapt the reference time under consideration of corrections that are applied at each intermediate system between themselves and the GM. The individual corrections include the correction of the previous system, the ingress propagation delay, and the residence time of the timing information at the current system under consideration of the rate ratio. In reference to IEEE 802.1AS [2] the correction error results as

$$\begin{aligned}\delta \text{cf}_i = \delta \text{cf}_{i-1} + \text{rr}_{i-1}\delta \bar{\text{pd}}_{i-1,i} + \delta \text{rr}_{i-1} \cdot (\bar{\text{pd}}_{i-1,i} + \delta \bar{\text{pd}}_{i-1,i}) \\ + \text{rr}_i \delta \Delta\tau_{s,i} + \delta \text{rr}_i \cdot (\Delta\tau_{s,i} + \delta\Delta\tau_{s,i}) \ .\end{aligned} \tag{5}$$

Similar to the the correction error, the rate ratio error results from the concatenation of previous errors or rate ratio and neighbor rate ratio detection. From IEEE 802.1AS [2] we can derive the rate ratio error as follows

$$\begin{aligned}\delta \text{rr}_i = (\text{rr}_{i-1} + \delta \text{rr}_{i-1}) \cdot (\text{nrr}_{i,i-1} + \delta \text{nrr}_{i,i-1}) \\ - (\text{rr}_{i-1} \cdot \text{nrr}_{i,i-1})\end{aligned} \tag{6}$$

where neighbor rate ratio can be calculated using the clock skews of the neighbored clocks $\text{nrr}_{i,i-1} = (1+\rho'_i)/(1+\rho'_{i-1})$. Using both (5) and (6) we are able to formulate the erroneous clock offset of any clock towards the GM

$$\begin{aligned}\delta\theta_{i,0} = (\text{rr}_i + \delta \text{rr}_i)\delta\tau_{s.I,i} + \delta \text{rr}_i \tau_{s.I,i} - \big(\delta\tau_{s.E,0} + \text{rr}_{i-1} \\ \cdot \delta \bar{\text{pd}}_{i-1,i} + \delta \text{rr}_{i-1}(\bar{\text{pd}}_{i-1,i} + \delta \bar{\text{pd}}_{i-1,i}) + \delta \text{cf}_{i-1}\big) \ .\end{aligned} \tag{7}$$

C. Analysis of the 5G Built-In Reference Time Indication

The synchronization error in the 5G RAN between gNB and UE results from an erroneous reference time indication using the 5G built-in service. As stated before, the gNB indicates its reference time to the UE. The UE adapts the indicated reference time under consideration of the present propagation delay. The propagation delay is provided to the UE using Timing Advance (TA) commands [3], [5], [6], [12]–[14]. Since TA commands refer to the round trip time (RTT), the propagation delay can be estimated using half of the TA value. This yields the erroneous clock offset

$$\begin{aligned}\Delta\tilde{\theta}_{\text{UE,gNB}} &= \tilde{\tau}_{\text{UE}}(t) - \big(\tilde{\tau}_{\text{gNB}}(t) + \tilde{\text{pd}}_{\text{gNB,UE}}\big) \\ &= \tau_{\text{UE}} + \delta\tau_{\text{UE}} - \Big(\tau_{\text{gNB}} + \delta\tau_{\text{gNB}} + \frac{\text{TA} + \delta\text{TA}}{2}\Big)\end{aligned} \tag{8}$$

where $\tilde{\text{pd}}_{\text{gNB,UE}} = \frac{\tilde{\text{TA}}}{2}$. The UE error component results from detection errors $\epsilon_{\text{UE,DL,RX}}$ at the receiver that are introduced due to limited sampling capabilities of it [13]. The UE error component is defined as $\delta\tau_{\text{UE}} = \epsilon_{\text{UE,DL,RX}}$. The gNB error component emerges from a limited frame timing accuracy, that introduces a time alignment error ϵ_{TAE}, and from the erroneous transport of the timing information between the source of time, e.g. GPS, and the gNB which leads to a time indication error ϵ_{TI} [13]. The gNB error component is formulated as $\delta\tau_{\text{gNB}} = \epsilon_{\text{TAE}} + \epsilon_{\text{TI}}$. The final error component is given by the propagation delay estimation and compensation through TA. Due to the fact that TA refers to the RTT, using half of the TA to compensate the propagation delay leads to the negligence of the DL/UL asymmetry which introduces an asymmetry error ϵ_{asym}. The TA calculation includes the reception errors at either receiver of the UE and the gNB that are denoted as $\epsilon_{\text{UE,DL,RX}}$ and $\epsilon_{\text{gNB,UL,RX}}$ [13]. The TA shows a limited granularity which leads to a granularity error ϵ_{TAG}. The adjustment of the UL transmission through the TA is also subject to inaccuracy ϵ_{TAA} [13]. The resulting error is defined as $\delta\text{TA} = \epsilon_{\text{UE,DL,RX}} + \epsilon_{\text{gNB,UL,RX}} + \epsilon_{\text{TAG}} + \epsilon_{\text{TAA}}$. The overall clock offset error between gNB and UE under consideration of propagation delay compensation through TA follows as

$$\begin{aligned}\Delta\delta\theta_{\text{UE,gNB}} = \frac{1}{2}\big(\epsilon_{\text{UE,DL,RX}} - \epsilon_{\text{asym}} - \epsilon_{\text{gNB,UL,RX}} \\ - \epsilon_{\text{TAG}} - \epsilon_{\text{TAA}}\big) - \epsilon_{\text{TAE}} - \epsilon_{\text{TI}} \ .\end{aligned} \tag{9}$$

D. Analysis of Integrated Synchronization Mechanisms

Following the independent discussion of the PTP based synchronization and the 5G built-in reference time indication, we will now analyze their integration in conjunction with the different synchronization scenarios, that are present in converged TSN/5G networks as shown in Fig. 2.

1) Network-Sided Grandmaster: For the DL synchronization in a NW GM scenario, the synchronization messages are transmitted through the VTB over the 5G UP. The boundary NW-TT and DS-TT determine the residence time of the `Sync`-message and accordingly apply correction to the corresponding `Follow_Up`-message leveraging their underlying synchronization through the 5GS [1], i.e. originating from the gNB. In order to find the overall synchronization error $\Delta\delta\tau_{B/C,A}(t)$ of DS devices, e.g. *B* or *C*, towards the NW GM *A*, we have to consider different error components as shown in (10). The synchronization errors $\Delta\delta\tau_{\text{NW-TT,gNB}}(t)$ and $\Delta\delta\tau_{\text{DS-TT,gNB}}(t)$ of the NW-TT and DS-TT towards the 5G GM, i.e. the gNB, represent the 5G internal erroneous synchronization. Additionally, we have to consider the incorrect timing information transport and correction from the NW GM *A* to the DS *B* and *C*. This includes the synchronization error $\Delta\delta\tau_{\text{NW-TT},A}(t)$ between *A* and the NW-TT, and the synchronization error $\Delta\delta\tau_{B/C,\text{DS-TT}}(t)$ between the DS-TT and *B* and *C*.

$$\begin{aligned}\Delta\delta\tau_{B/C,A}(t) &= \Delta\delta\tau_{\text{NW-TT,gNB}}(t) + \Delta\delta\tau_{\text{DS-TT,gNB}}(t) \\ &\quad + \Delta\delta\tau_{\text{NW-TT},A}(t) + \Delta\delta\tau_{B/C,\text{DS-TT}}(t) \\ \Delta\delta\tau_{\text{DS-TT,gNB}}(t) &= \Delta\delta\tau_{\text{DS-TT,UE}}(t) + \Delta\delta\tau_{\text{UE,gNB}}(t)\end{aligned} \tag{10}$$

2) Device-Sided Grandmaster: For the UL synchronization in a DS GM scenario, the timing information transport is likewise but in opposite direction independent from the DL/UL symmetry. The overall synchronization error of a NW device *A* towards a DS GM *B* can be adopted from the NW GM scenario according to (11). However, as stated before, a DS GM is also capable of synchronizing another DS device, i.e. *C*, that belongs to a different UE. In order to find the resulting synchronization error $\Delta\delta\tau_{C,B}(t)$ according to (12), we have to consider the incorrect synchronization $2 \cdot \Delta\delta\tau_{\text{DS-TT,gNB}}(t)$

of the different DS-TTs through the underlying 5G mechanisms as well as the timing information transport from *B* to its associated DS-TT and to *C* from its associated DS-TT. The formulation in (12) assumes that the timing information transport is switched at gNB level. Depending on the currently discussed implementation of multicast message handling in 5G a switching at the UPF or NW-TT is also conceivable which would introduce an additional error.

$$\Delta\delta\tau_{A,B}(t) = \Delta\delta\tau_{B/C,A}(t) \tag{11}$$

$$\Delta\delta\tau_{C,B}(t) = 2 \cdot \Delta\delta\tau_{\text{DS-TT,gNB}}(t) + \Delta\delta\tau_{\text{DS-TT},B}(t) + \Delta\delta\tau_{C,\text{DS-TT}}(t) \tag{12}$$

3) 5G-Sided Grandmaster: For a 5G-sided GM scenario, the synchronization of a NW device *A* becomes trivial since only PTP based synchronization mechanisms are involved. The synchronization error of *A* to the 5G GM, i.e. the gNB, results from the concatenation of three PTP systems that are the UPF, the NW-TT, and the TSN end-station *A* itself. For the synchronization of a DS device, e.g. *B* or *C*, the emerging synchronization error $\Delta\delta\tau_{B/C,\text{gNB}}(t)$ follows (13). It involves the synchronization error $\Delta\delta\tau_{\text{DS-TT,gNB}}(t)$ of the DS-TT towards the gNB, and synchronization error $\Delta\delta\tau_{B/C,\text{DS-TT}}(t)$ of *B* or *C* to the DS-TT to the erroneous timing information transport and correction. The presented estimation is valid for both the shallow and the deep integration strategy of a 5G-sided GM.

$$\Delta\delta\tau_{B/C,\text{gNB}}(t) = \Delta\delta\tau_{\text{DS-TT,gNB}}(t) + \Delta\delta\tau_{B/C,\text{DS-TT}}(t) \tag{13}$$

V. Assessment of the Integration of Heterogeneous Synchronization Mechanisms

In this section we first study the PTP based synchronization mechanisms and the 5G built-in reference time indication mechanism separately. We proceed with the assessment of the integration of those heterogeneous synchronization mechanisms in context of the highlighted synchronization scenarios. This section encompasses an analytical estimation of the worst-case synchronization errors and a concluding simulative verification of the presented estimations.

A. Assessment of PTP Based Synchronization

In order to estimate the worst-case synchronization error for PTP based synchronization, we are using the generic description of the asynchronicity of different clocks (4) in conjunction with the erroneous rate ratio (6) and erroneous clock offset (7) calculations under the assumption that the erroneous rate ratio represents the clock skew correction error of a PTP system. For the parameterization we use the requirements that are specified for gPTP according to Tab. I [2].

For the estimation of the worst-case synchronization error of concatenated PTP systems, we used an numerical approach due to the recursive impairments shown in (5), (6), and (7). We studied 100 concatenated PTP systems under the worst-case parameterization according to Tab. I [2]. We considered a uniformly distributed clock skew $\rho' = \mathcal{U}(-100, 100)$ ppm per PTP system. We then conducted 1000 estimations under the probabilistic clock skew parameterization and averaged

TABLE I
Requirements for PTP based synchronization.

Residence time [ms]	10
Propagation delay pd [ns]	800
PHY jitter $\|J\|$ [ns]	5
Timestamp granularity G [ns]	40
Clock skew $\|\rho'\|$ [ppm]	100
Neighbor rate ratio error $\|\delta\text{nrr}\|$ [ppm]	0.1
Synchronization interval T_{Sync} [ms]	125

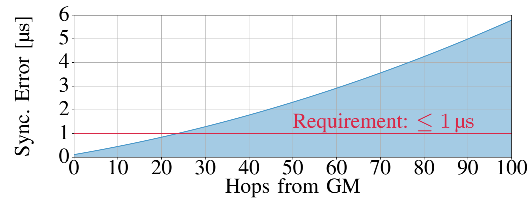

Fig. 4. Estimated worst-case (absolute) synchronization error of concatenated PTP systems in contrast to the synchronization requirement of 1 µs for less than 6 hops from the GM [2].

the resulting synchronization per PTP system. The estimated worst-case synchronization error per PTP system is given in Fig. 4. The graph shows a non-linear synchronization error propagation with an increasing distance from the GM.

B. Assessment of the 5G Built-in Reference Time Indication

For the estimation of the worst-case synchronization error between UE and gNB, we use the generic description of the asynchronicity of different clocks (4). The associated clock offset calculation follows the representation of the 5G built-in reference time indication (9) whereas the clock skew is derived from the given requirements. For the parameterization we use the time and frequency requirements given in Tab. II that are subject to 3GPP specifications [13]. The timestamp granularity for both gNB and UE is adopted from the PTP based synchronization. Although the DL/UL asymmetry may introduce an error for the 5G built-in reference time indication (different to a DS GM which is independent from the DL/UL asymmetry), it is neglected, i.e. $\epsilon_{\text{asym}} = 0$, since it exposes only a minor contribution to the overall error due to the fact that we currently consider only relaxed mobility constraints for factory environment as it is practice in ongoing discussions [13]. We assume that the transport of the timing information between the source of time and the gNB is ideal, i.e. $\epsilon_{\text{TI}} = 0$. The resulting estimation of the worst-case synchronization error per subcarrier spacing configuration is presented in Tab. III. For a larger subcarrier spacing, and therefore a larger numerology, we observe a lower synchronization error. This results from the principle that a larger numerology yields a finer granulation of the transmission/reception in time. This leads to more stringent timing requirements but also reduces the TA adjustment and granularity errors [13], [14].

C. Assessment of Integrated Synchronization Mechanisms

In order to assess the integration of the heterogeneous synchronization mechanisms for different synchronization scenarios, we leverage the formal descriptions (10), (11), (12),

TABLE II
REQUIREMENTS FOR THE 5G BUILT-IN REFERENCE TIME INDICATION.

Subcarrier Spacing [kHz]	15	30	60	120
DL reception error at UE $\lvert\epsilon_{\mathrm{UE,DL,RX}}\rvert$[ns]	260	260	160	100
UL reception error at gNB $\lvert\epsilon_{\mathrm{gNB,UL,RX}}\rvert$[ns]	100	100	92	92
TA adjustment error $\lvert\epsilon_{\mathrm{TAA}}\rvert$[ns]	130	130	65	16
TA granularity error $\lvert\epsilon_{\mathrm{TAG}}\rvert$[ns]	260	130	65	32
Time alignment error $\lvert\epsilon_{\mathrm{TAE}}\rvert$[ns]	65	65	65	65
UE frequency error $\lvert\delta\rho'_{\mathrm{UE}}\rvert$[ppm]	0.1			
gNB frequency error $\lvert\delta\rho'_{\mathrm{gNB}}\rvert$[ppm]	0.1			
Synchronization/SIB9 interval T_{Sync}[ms]	80			

TABLE III
ESTIMATED WORST-CASE SYNC. ERROR BETWEEN UE AND GNB.

Subcarrier spacing [kHz]	15	30	60	120
Sync. error [ns]	±476	±411	±292	±221

TABLE IV
WORST-CASE ERROR PER SYNCHRONIZATION SCENARIO.

Estimated Worst-Case Error				
Subcarrier spacing [kHz]	15	30	60	120
1) Network-Sided GM: *A*				
Sync. error of *B/C* [µs]	±0.88	±0.81	±0.69	±0.62
2) Device-Sided GM: *B*				
Sync. error of *A* [µs]	±0.88	±0.81	±0.69	±0.62
Sync. error of *C* [µs]	±1.32	±1.19	±0.95	±0.81
3) 5G-Sided GM: gNB				
Sync. error of *A* [µs]	±0.18	±0.18	±0.18	±0.18
Sync. error of *B/C* [µs]	±0.62	±0.56	±0.44	±0.37
Simulated Worst-Case Error				
Subcarrier spacing [kHz]	15	30	60	120
1) Network-Sided GM: *A*				
Sync. error of *B/C* [µs]	±0.70	±0.64	±0.52	±0.46
2) Device-Sided GM: *B*				
Sync. error of *A* [µs]	±0.70	±0.64	±0.52	±0.46
Sync. error of *C* [µs]	±1.11	±0.99	±0.75	±0.63
3) 5G-Sided GM: gNB				
Sync. error of *A* [µs]	±0.11	±0.11	±0.11	±0.11
Sync. error of *B/C* [µs]	±0.60	±0.54	±0.41	±0.35

and (13) given in Sec. IV-D complementary to the previously presented estimation for the individual mechanisms and their parameterization. The annotations of NW and DS devices are again related to Fig. 2. The purpose of this assessment is to estimate the worst-case synchronization errors that are inherited by the different synchronization scenarios and to compare these in particular.

The estimated worst-case synchronization error for the different synchronization scenarios is presented Tab. IV. The results are given in relation to the subcarrier spacing since the 5G built-in reference time indication is involved in all but one synchronization scenarios that is the synchronization of a NW device *A* through the 5G-sided GM. The provided estimations definitely support the expectations as discussed in Sec. II. As expected, the synchronization of a DS device through a NW GM and vice versa delivers equivalent worst-case synchronization errors since DL and UL are assumed to be symmetric. The estimated worst-case synchronization error does not exceed the requirement of 1 µs even for relaxed subcarrier spacing configurations. However, this impression shifts when a DS device *C* is synchronized through a DS GM *B*. For a subcarrier spacing of 15 kHz or 30 kHz the estimation violates the required 1 µs of synchronization precision. Even for a subcarrier spacing of 60 kHz the estimated error barely complies with the required synchronization error. It is expected that the synchronization of *C* through *B* shows the worst synchronization precision since it involves both UL and DL transmission in the 5G RAN, and thus it depends on the synchronicity of separate DS-TTs.

The 5G-sided GM shows the best estimated synchronization precision. Towards a NW device *A* it involves only PTP based synchronization achieving a very low estimated synchronization error. Towards a DS device *B* or *C* it shows an reduced estimated synchronization error of approximately 30 % to 40 % in contrast to a NW GM. This improvement is achieved since the 5G-sided GM scenario does not depend on the synchronicity of NW-TT and DS-TT to each other as it is the case for the NW GM. In return to improved synchronization precision of DS devices a small error is introduced towards NW devices in comparison with a NW GM.

The assessment of the different synchronization scenarios shows that the 5G-sided GM achieves an improved precision for the synchronization of DS device over the remaining scenarios. Now we want to assess what practical value emerges from such an improved synchronization precision. A major restriction, that emerges from a large synchronization error, is that only a limited number of devices can be concatenated while maintaining the synchronization requirement. This may be a decisive prospect for industrial automation applications as they typically implement line topologies [15]. In order to study this perspective, we estimated how many devices (PTP systems) can be concatenated to a DS device *B* or *C*, without violating the required synchronization precision, per scenario using our findings from Sec. V-A.

The results are provided in Fig. 5. The graph shows the estimated worst-case synchronization error of additional hops concatenated to *B* or *C* for different subcarrier spacing configuration. The hatched area identifies the hops which expose a worst-case synchronization error that exceeds the required 1 µs precision. The results clearly show that the 5G-sided GM scenario is most capable of concatenating further devices to a DS device. Whereas only 1 to 8 additional devices are supported for a NW GM, a 5G-sided GM supports 8 to 15 additional devices. Again a DS GM delivers the worst performance, only supporting up to 3 additional devices for the most sophisticated subcarrier spacing.

D. Verification of the Estimated Synchronization Errors

In order to verify our estimated synchronization error for the different synchronization scenarios, we simulated them according to the converged TSN/5G network as shown in Fig. 2 using the discrete event simulator OMNEST. We used the INET framework for its Ethernet implementation, a 5G simulation framework based on SimuLTE [16], and our own

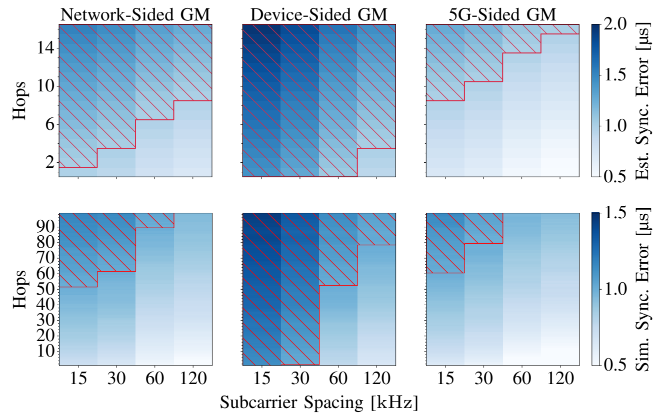

Fig. 5. Estimation (upper) and simulation (lower) of the expandability of a TSN/5G network with additional hops beyond a DS device, e.g. *B* or *C* in reference to Fig. 2. The hatched area marks where the estimated worst-case error exceeds the specified requirement of 1 µs towards the GM.

implementation of gPTP and NW-TT and DS-TT modules based on IEEE8021AS [17] and NeSTiNg [18]. For our simulation, we used a probabilistic parameterization of the PTP system clocks in reference to Tab. I using a uniform distribution in order to evoke a worst-case synchronization error propagation. Similarly, we choose the parameters for the 5G component clocks according to Tab. II. After 100 runs of 100 s each, the resulting synchronization error for the different synchronization scenarios are given in Fig. 5. The corresponding worst-case synchronization errors are listed in Tab. IV. As can be seen, the simulated results are in line with our estimations. The synchronization errors for any synchronization scenario agree with the estimated worst-case error. The simulated worst-case errors do not meet the estimations, i.e. the simulated errors is smaller than the estimations, since these are very unlikely to occur due to probabilistic effects which may lead to mutual error cancellations. Due to the very low probability of worst-case errors, many more simulation runs would be necessary to approximate the conducted estimations closer. In order to show the estimated behavior with a limited number of simulation runs, we simulated 100 concatenated devices according to the requirements that are discussed in [19]. However, the simulation validates the general behavior of our estimations.

VI. Conclusion and Future Work

In this work we discussed the synchronization in converged TSN/5G networks and identified the synchronization integration strategies that are 1) a network-sided GM, 2) a device-sided GM, and 3) a 5G-sided GM that involve heterogeneous synchronization mechanisms. We proposed integration strategies for a 5G-sided GM, and estimated the worst-case synchronization error for the different synchronization scenarios and investigate potential impact on industrial applications.

The main achievement of this work is the study of the novel strategies to integrate 5G-sided GM. We showed that the proposed integration strategies provide a significant benefit regarding the worst-case synchronization performance and possible improvements regarding the configuration and deployment in industrial environments. Potential applications of the proposed 5G-sided GM emerge in the industrial automation sector. We showed that the overall reduced worst-case synchronization error yields an improved device-sided expandability. By doing so, our proposed approach is capable to support more devices concatenated to the device-sided devices than the state-of-the-art strategies while meeting the corresponding synchronization requirements. In return, the 5G-sided GM introduces only an additional minor synchronization error compared to the network-sided GM.

For our future work, we plan to investigate the synchronization in real factories. This involves the study of novel aspects of synchronization, e.g. mobility or multipath propagation.

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