Single Message Distribution of Timing Information for Time Synchronization in Converged Wired and Wireless Networks

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***Abstract*—Future factory automation scenarios require real-time capable communication networks and most recently expose great demand for mobile and scalable communication. A promising solution is the convergence of wired and wireless networks in order to merge the benefits of both wired and wireless technologies. The industry emphasizes TSN and 5G as technologies for future communication networks. The seamless integration of 5G with TSN as virtual TSN bridge is a focus topic of the 3GPP and IEEE standardization groups. However, the distribution of timing information through converged TSN/5G networks has not yet been investigated.**

In this work, we propose and analyze a single message mechanism for distribution of timing information in converged TSN/5G networks under consideration of 3GPP and IEEE standard documents.

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

I. Introduction

Industrial applications comprise precise and time-critical processes. The cyclic data exchanged between sensors, actuators, and controllers is crucial. Industrial communication networks require high availability, reliability, and bounded low latencies. Under the heading of Industrie 4.0 (I4.0) and Factory of the Future (FoF) novel requirements are raised such as mobility and scalability factors [1]. The new set of requirements for industrial communication networks can be satisfied by the convergence of wired and wireless technologies.

Time-Sensitive Networking (TSN) is a set of IEEE standards which adopt standard Ethernet at the media access layer to enable real-time capabilities [2]. The fundamental paradigm for a TSN network is a common sense of time between all nodes within the network. The network reference time is related to a dedicated master clock. It continuously distributes the reference time to all network nodes through the generalized Precision Time Protocol (gPTP) as specified in IEEE 802.1AS [3]. Since TSN is a wired communication technology, it naturally lacks mobility. A promising solution driven by both IEEE and 3GPP is the convergence of TSN and 5G networks. 5G is the fifth generation mobile communication standard specified by the 3GPP. The integration of 5G with TSN is intensively discussed by 3GPP and IEEE [4].

IEEE 802.1AS specifies the generalized Precision Time Protocol (gPTP) for the synchronization of TSN networks [3]. gPTP is a network protocol for synchronization of distributed clocks within a communication network. Hence, gPTP specifies the distribution of timing information within a TSN network and the handling of synchronization messages at TSN devices. The seamless integration of 5G with TSN as virtual TSN bridge (VTB) presents itself as standard conform TSN bridge. Thus, the specified mechanisms for time synchronization apply at the boundaries of the VTB towards the TSN network. The distribution of timing information within the VTB has not yet been specified [5].

Our contribution is a proposal for signaling timing information through the VTB using a single message leveraging the underlying synchronization of the 5G system (5GS) according to 3GPP TR 23.734 [5]. We give a comprehensive description of the necessary operations and analyze its performance improvements as well as its dependencies.

This work is organized as follows. In Sec. II we highlight the standardization efforts on time synchronization and TSN/5G integration. In Sec. III we continue with an analysis of time synchronization in TSN/5G networks and propose a novel mechanism for distribution of timing information in Sec. IV. In Sec. V we examine the synchronization accuracy in converged TSN/5G networks under the proposed scheme through simulation. Finally, we conclude our findings in Sec. VI.

II. Standardization Efforts Overview

In this section we provide an overview on the standardization efforts of IEEE and 3GPP towards converged real-time wireless networks. We focus on the synchronization scheme specified by IEEE 802.1AS [3] and the architecture of converged TSN/5G networks as discussed by 3GPP and IEEE.

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A. Overview on IEEE 802.1AS

IEEE 802.1AS specifies the gPTP for time synchronization in TSN networks. It defines mechanisms for propagation delay measurements and for frequency and time synchronization. gPTP defines two types of time-aware systems (TAS) that are 1) time-aware end stations (TAE) and 2) time-aware bridges (TAB). A TAS may be a slave or a master entity. There is only a single master entity per time-domain. Moreover, the master entity, referred to as grandmaster (GM) in scope of gPTP, serves as source of reference time for all slave entities within the time-aware network (TAN). A TAN is associated with one or more time domains. Thus, TASs may be members in different time domains at once.

In an industrial scenario there is a distinction between a universal time domain (UD) and working clock domain (WD) as can be seen in Fig. 1. The UD is established across the entire network. The timescale is typically given as international atomic time (TAI). The UD is used to align network wide processes, e.g. sequence of event tracking, and has relaxed requirements compared to the WD [6]. The WD is established across a smaller network section with less complex topologies. The WD is typically a free running clock hence without reference to an absolute timescale such as the TAI. The WD is used to align demanding processes, e.g. closed-loop control, and has stringent requirements.

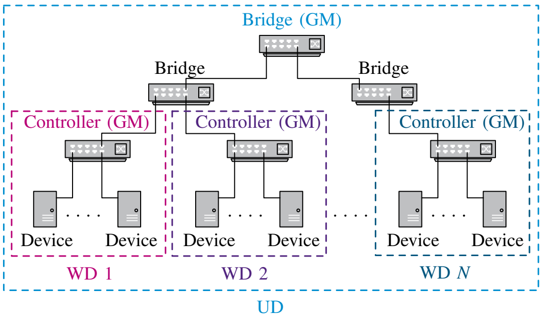

Fig. 1. Representative industrial network topology with several working clock domains (WD) and a single universal time domain (UD).

1) Distribution of Timing Information: gPTP uses dedicated *Sync*- and *FollowUp*-messages to distribute timing information. The GM maintains the reference time scale and periodically distributes its timing information to all other nodes within the network. The principle of operation is given in Fig. 2. The GM v_{i-1} registers the timestamp $\tau_{s.E,i-1}$ of the *Sync*-message departure. It continues with an associated *FollowUp*-message which includes $\tau_{s.E,i-1}$. The receiving TSN bridge v_i registers the ingress timestamp $\tau_{s.I,i}$ of the *Sync*-message. Upon reception of the *Sync*-message, v_i can synchronize itself to the GM by determining the time offset $\theta_{i,0}$ (GM $v_{i-1} = v_0$, i.e. $i = 1$) according to the generic procedure (1):

$$\theta_{i,0} = \tau_{s.I,i} - rr_i \cdot (\tau_{s.E,0} + cf_{i-1} + \bar{pd}_{i-1,i}) \qquad (1)$$

where rr_i is the ratio between the clock rate of v_i and the GM $v_{i-1} = v_0$, cf_{i-1} is the correction field, and $\bar{pd}_{i-1,i}$ is the propagation delay on the link between v_{i-1} and v_i. At this point the correction field can be mitigated, i.e. $cf_{i-1} = 0$, as $v_{i-1} = v_0$ is the GM, i.e. $i = 1$, and no corrections were applied yet. Note that the calculation of the rate ratio rr_i and the propagation delay $\bar{pd}_{i-1,i}$ is described in IEEE 802.1AS [3]. For the peer delay measurement, two adjacent TAE exchange a set of messages from initiator to responder. For each message ingress and egress timestamps are registered. Then the initiating TAE compares the time interval from sending the first message to receiving the last message against the retention time at the responding TAE to find the mean propagation delay. Link asymmetry is omitted [3] [7]. The rate ratio is determined by comparing time intervals generated by different clocks at different rates [3] [7]. Further details on propagation delay and rate ratio determination are out of scope of this work as we are only considering the distribution of timing information in particular. The TSN bridge sends out *Sync*-messages to the connected TSN end-station v_{i+1}. Then it continues with an associated *FollowUp*-message. The *FollowUp*-message includes a correction field which is the sum of delays since origin of the *Sync*-message at the GM. It is determined using (2):

$$cf_i = cf_{i-1} + \bar{pd}_{i-1,i} + rr_i \cdot (\tau_{s.E,i} - \tau_{s.I,i}) \, . \qquad (2)$$

Upon reception of both *Sync*- and *FollowUp*-messages, the TSN end-station v_{i+1} can synchronize itself likewise to the TSN bridge v_i before using (1).

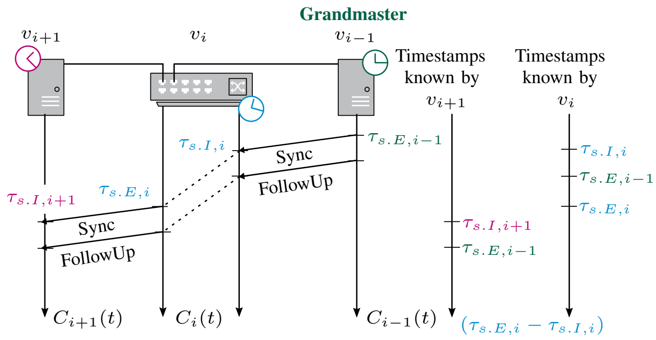

Fig. 2. Time synchronization through IEEE 802.1AS in a TSN network with two TSN end-stations v_{i+1} and v_{i-1}, and a TSN bridge v_i. v_{i-1} serves as GM for the single time domain and distributes the required timing information through *Sync*- and *FollowUp*-messages.

B. Architecture of Converged TSN and 5G Networks

The seamless integration of 5G with TSN for converged wired and wireless networks is discussed both within 3GPP and IEEE [4]. 3GPP provides an architectural model for converged 5G/TSN networks [5]. It introduces network- and device-sided TSN translator (TT), further denoted as NW-TT and DS-TT, to the 5GS. The NW-TT is integrated within the user plane function (UPF) and the DS-TT is integrated with the user equipment (UE) as depicted in Fig. 3. The wireless connection is served to the UE by the next generation NodeB (gNB). Note that we are only considering the user plane (UP) since gPTP messages are signaled through the UP anyway [5].

The 5GS with integrated NW-TT and DS-TT is considered as virtual TSN bridge (VTB).

The VTB appears as standard TSN bridge towards the TSN network. NW-TT and DS-TT are the logical ports of the VTB hiding the 5GS complexity. Hence, NW-TT and DS-TT have to adopt TSN bridge ingress and egress port operations towards the TSN network [4]. In 5G, UP data is tunneled via the GPRS Tunneling Protocol (GTP-U) through a Protocol Data Unit (PDU) session between UE and data network [8]. UP data supports different types of traffic such as IPv4, IPv6 or Ethernet. The GTP-U introduces an additional GTP header which holds quality of service (QoS) information [9].

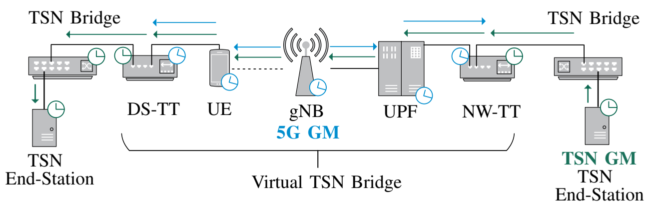

Fig. 3. Architecture of converged TSN/5G networks (user plane) with two separate time domains for TSN and 5G.

C. Time Synchronization in Converged TSN and 5G Networks

The VTB supports time synchronization through IEEE 802.1AS in order to be a standard compliant TSN bridge. Therefore, the VTB may adopt either boundary or a transparent clock behavior [5], i.e. between both TT. As a boundary clock node, the VTB would not traverse any gPTP messages through the 5GS. Instead the 5GS would synchronize itself to an external GM. The Class B TSN profile for industrial automation [10] requires the support of at least two time domains. Thus, for a scenario with multiple time domains, the 5GS has to manage and update a mapping of its local clock to each time domain regarding frequency and time offset, yielding to an additional management effort proportional to the number of time domains.

In contrast, the VTB as transparent clock does not synchronize itself to an external GM but it signals gPTP messages from slave port to master ports[1] and applies corrections using the 5GS timescale. This assumes that all 5GS components, including NW-TT and DS-TT, are synchronized to the 5GS timescale [5]. Hence, the transparent clock behavior promises simplicity and generate less performance degradation than boundary clocks. For scenarios with multiple time domains there is no additional management effort introduced because the transparent clock, e.g. the determination of the residence time, is independent of the time domains.

Towards TSN, both NW-TT and DS-TT adopt the boundary clock behavior. They synchronize themselves to the TSN GM and participate in peer delay measurements. It is important that NW-TT and DS-TT maintain the TSN timescale as they inject data to the TSN network and for instance must keep to the defined traffic schedule (IEEE 802.1Qbv) or they must support sequence of events tracking [11]. In conclusion, 3GPP TR 23.734 [5] encompasses the following aspects about synchronization in converged TSN/5G networks:

- The VTB either adopts boundary or transparent clock behavior;
- All 5GS components are synchronized to the 5GS timescale which is provided by the gNB;
- Synchronization traffic is signaled through the 5G UP;
- Upon reception of *Sync*-messages, the receiving TT registers an ingress timestamp τ_I;
- After transmission of *Sync*-messages, the sending TT registers an egress timestamp τ_E.

However, the signaling of gPTP messages through the 5G UP remains unspecified. We close that gap by proposing a single message mechanism for distributing timing information in between TTs through the 5G UP.

III. Distribution of Timing Information through Virtual TSN Bridge

In regular TSN networks, gPTP messages are sent from peer to peer only. They are not signaled internally from ingress to egress port of a time-aware bridge (TAB). However, in case of converged TSN/5G networks, gPTP messages are signaled through the UP of the 5GS as part of the VTB. As a matter of fact, this brings three major challenges.

First, as the VTB is designed as standard compliant TAB, it is subjected to the maximum residence time requirement of 10 ms [3]. Within 10 ms, the VTB has to receive the *Sync*- and the *FollowUp*-message, signal the timing information from one boundary TT to the opposing one through the 5GS UP, and send the corresponding *Sync*- and *FollowUp*-messages (with updated correction field) through its master ports.

Second, we consider the transmission of user data through 5G. In wireless systems, data is scheduled to available transmission resources. In advanced wireless communication systems, i.e. 5G, data is scheduled over time slots, and over frequency carriers. Thus, the allocation of transmission resources is rather complex as it also depends on the current transmission channel state which varies over time. Due to uncertain channel characteristics, it is difficult to schedule traffic ahead of time. Scheduling optimizations are typically done in the time-domain, i.e. on a per-time slot basis. In the time-domain, 5G organizes the transmission into frames of 10 ms. A frame consists of 10 subframes of 1 ms each. A subframe has slots. The number of slots per subframe depends on the configured subcarrier spacing [6]. Therefore, the scheduling of data in 5G introduces an additional delay as data may be allocated to a later frame or subframe. Indeed, gPTP messages (*Sync* or *FollowUp*) may be delayed such that the residence time requirement for a TSN bridge of less than 10 ms [3], is violated.

Third, unlike regular TSN traffic, gPTP messages are missing prioritization. This is not an issue for regular TSN

[1]Considering a single time domain, a time-aware bridge with n ports has 1 slave port through which it receives synchronization messages and $n-1$ master ports through which it distributes timing information to adjacent systems. The port states, i.e. master or slave, is determined by the best master clock algorithm (BMCA)

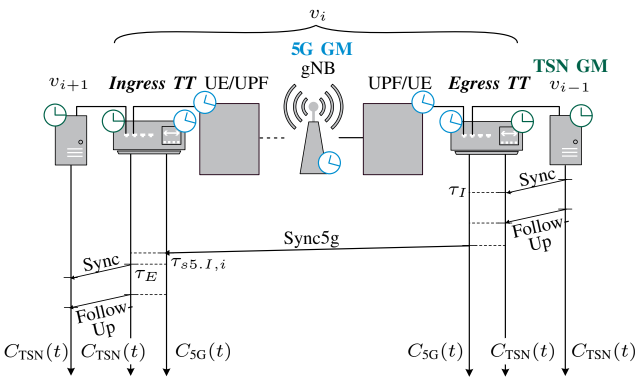

Fig. 4. Single message distribution of timing information through converged TSN/5G networks with 5GS as transparent clock, TTs as boundary clocks. At the boundaries of 5G, i.e. TTs, the distribution of timing information operates with two messages according to IEEE 802.1AS. Within the 5G network timing information is distributed using only a single message.

networks as gPTP messages are transmitted from peer to peer only. However, for the signaling inside the VTB, gPTP messages require a prioritization in order to be scheduled properly. As a matter of fact this is important in order to prefer gPTP message over best-effort traffic. Otherwise, the transmission of gPTP message may be delayed such a way that the residence time becomes larger than the gPTP timeout at connected TAS which is usually around $3 \cdot T_s = 375$ ms[2].

IV. Single Message Mechanism for Distribution of Timing Information

We propose a single message scheme for distribution of timing information through a VTB, i.e. i between NW-TT and DS-TT, as shown in Fig. 4. The proposed mechanism is supported by the underlying synchronization of the 5GS components, including NW-TT and DS-TT according to 3GPP TS 23.734 [6].

Using only a single message to distribute timing information from TT to the opposing TT brings several advantages. It reduces the scheduling effort for the transmission through the 5G UP and may improve robustness against packet loss. At the 5GS, incoming frames cannot be transmitted immediately since they have to wait for available radio resources which leads to a delay. This scheduling delay can be mitigated if only a single message is sent. Apart from that, using a single message also reduces the amount of total data to be sent through 5G which may be an important aspect, since transmission resources, especially in crowded areas such as factory halls, are limited goods.

A. Operation

The single message scheme is illustrated in Fig. 4. It uses a single *Sync5g*-message instead of dedicated *Sync*- and *FollowUp*-messages. TTs are distinguished as egress and ingress TT depending on whether they transmit or receive the *Sync5g*-message, thus depending on their relative location towards the GM. Figures 5 and 6 show the model of operation for both egress and ingress ports of a TT. Note that we consider the architecture depicted in Fig. 4 where egress TT exposes only a single slave and master port. The egress TT may also support multiple master ports towards other TSN devices, i.e. not towards 5G. Then the distribution of timing information follows IEEE 802.1AS.

1) Egress TT: In reference to Fig. 5 the egress TT operates as follows. When the egress TT receives a *Sync*-message through its slave port towards TSN, it registers an ingress timestamp τ_I. This ingress timestamp is relative to the timescale shared through all components of the VTB (e.g. $C_{5G}(t)$ in reference to Fig. 4). Upon reception of the corresponding *FollowUp*-message, the egress TT can extract the attached timing information that is the precise origin timestamp, the correction field, and the rate ratio. Then it can synchronize itself to the TSN GM. Moreover, it signals the acquired information, including the ingress timestamp τ_I, with a single message, i.e. the *Sync5g*-message, through the 5GS to the ingress TT.

2) Ingress TT: Upon reception of the *Sync5g*-message, the ingress TT registers the auxiliary ingress timestamp $\tau_{s5.I,i}$ and extracts the attached timing information that is the precise origin timestamp, the correction field, the rate ratio, and the ingress timestamp. It synchronizes itself to the TSN GM by determining the time offset $\theta_{0,i}$ towards the GM:

$$\theta_{0,i} = \tau_I - rr_i \cdot (\tau_{s.E,0} + cf_{i-1} + \bar{pd}_{i-1,i}) \ . \tag{3}$$

The rate ratio can be adopted from the egress TT as both TTs share a common sense of time due to their underlying synchronization through the 5GS. Then the ingress TT initiates the transmission of *Sync*-message through all its master ports. It registers the egress timestamp τ_E and thus is able to compute the correction field value according to (4):

$$cf_i = cf_{i-1} + \bar{pd}_{i-1,i} + rr_i \cdot (\tau_E - \tau_I) \ . \tag{4}$$

It concludes with the transmission of the corresponding *FollowUp*-message.

B. Optimized Distribution of Timing Information

Now we want to emphasize the single *Sync5g*-message approach and compare it to the traditional dual message scheme. The *Sync5g*-message to be signaled through the VTB includes the following information:

- Precise Origin Timestamp;
- Correction Field;
- Rate Ratio;
- Mean Propagation Delay;
- Ingress Timestamp.

An overview on the corresponding data sizes is consolidated in Tab. I. The *Sync5g*-message uses the *FollowUp*-message format at its core and attaches additional quantities that are *1)* propagation delay and *2)* ingress timestamp of size $M_{\bar{pd}} = 12$ Byte and $M_{\tau_I} = 10$ Byte as can be seen in Fig. 7. The egress TT may add the propagation delay directly to the correction

[2]According to IEEE 802.1AS *syncReceiptTimeout* multiplied *syncInterval* [3] where the default values are 3 and 125 ms

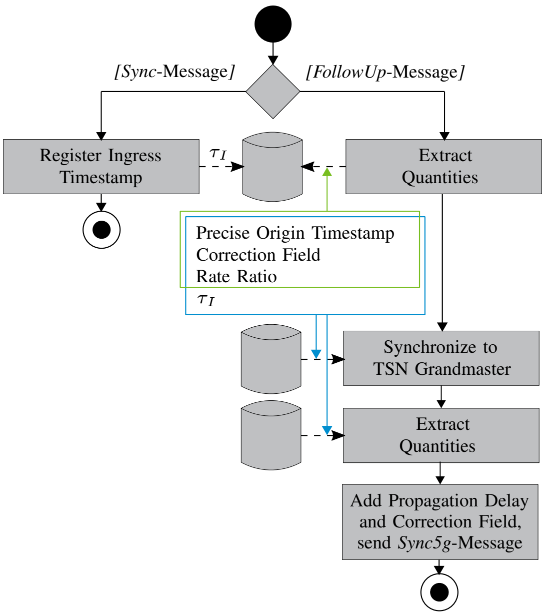

Fig. 5. *Egress TT*: *Sync5g*-message transmission: Proposed scheme for single message distribution of timing information at TT towards the TSN GM, i.e. recipient of *Sync*- and *FollowUp*-messages and transmitter of *Sync5g*-message.

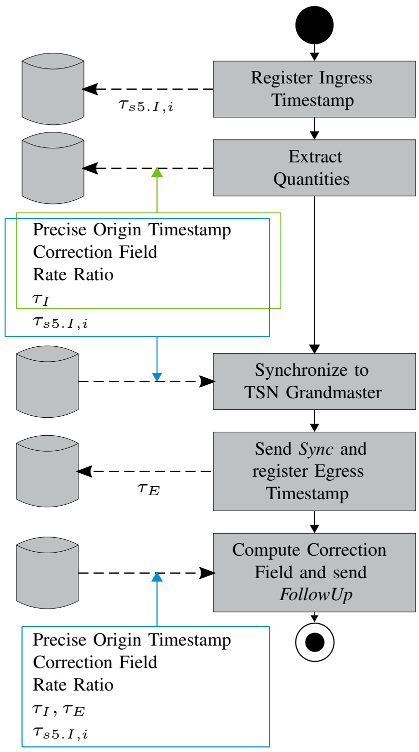

Fig. 6. *Ingress TT*: *Sync5g*-message reception: Proposed scheme for single message distribution of timing information at TT opposing to the TSN GM, i.e. recipient of *Sync5g*-message and transmitter of *Sync*- and *FollowUp*-messages

field so that the *Sync5g*-message does not have to include the propagation delay in a separate message field, thus saving $M_{\bar{pd}} = 12$ Byte. On that basis, the proposed *Sync5g*-message

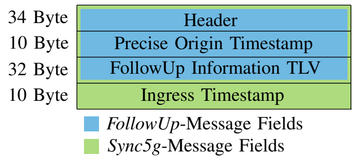

Fig. 7. Evolution of the *Sync5g*-message format from *FollowUp*-message format as specified in IEEE 802.1AS [3].

format yields to a total message size given in (5)[3]:

$$M_{1\text{-Message}} = M_{Sync5g} = M_{FollowUp} + M_{\tau_I} = \underline{\underline{86 \text{ Byte}}} \qquad (5)$$

where $M_{FollowUp} = 76$ Byte. In contrast, the conventional *Sync*- and *FollowUp*-messages accumulate up to a combined size of $(M_{Sync} + M_{FollowUp}) = 120$ Byte with $M_{Sync} = 44$ Byte [3]. It has to be noted that neither the *Sync*- nor *FollowUp*-message carry the propagation delay or the ingress timestamp. Thus, in case of a dual message distribution of timing information, i.e. leveraging both *Sync*- and *FollowUp*-message, additional data has to be attached. Likewise to the single message approach, the propagation delay may be added to the correction field directly. This yields to a total data effort following (6):

$$M_{2\text{-Message}} = (M_{Sync} + M_{FollowUp}) + M_{\tau_I} = \underline{\underline{130 \text{ Byte}}} \,. \qquad (6)$$

Under consideration of IEEE 802.3 Ethernet transport, the standard Ethernet header size (including frame check sequence) of $H_{\text{Eth}} = 18$ Byte has to be accounted for. Hence, the total data effort for both single and two message mechanism follows (7) and (8):

$$F_{2\text{-Message}} = M_{2\text{-Message}} + 2 \cdot H_{\text{Eth}} = \underline{\underline{166 \text{ Byte}}} \qquad (7)$$

$$F_{1\text{-Message}} = M_{1\text{-Message}} + H_{\text{Eth}} = \underline{\underline{104 \text{ Byte}}} \,. \qquad (8)$$

User data that is sent via the 5G UP is tunneled through a GTP-U tunnel [9]. The 5G UP packet includes the user data, i.e. T-PDU, a GTP-U header and outer IP/UDP headers [8]. The additional GTP-U and IP/UDP headers introduce additional data of $G_{\text{GTP}} = 8$ Byte and $G_{\text{IP/UDP}} = 28$ Byte such that the total size of the associated UP packet results as:

$$P_{2\text{-Message}} = F_{2\text{-Message}} + 2(G_{\text{GTP}} + G_{\text{IP/UDP}}) = \underline{\underline{238 \text{ Byte}}} \quad (9)$$

$$P_{1\text{-Message}} = F_{1\text{-Message}} + G_{\text{GTP}} + G_{\text{IP/UDP}} = \underline{\underline{140 \text{ Byte}}} \,. \quad (10)$$

The total amount of data which has to be sent through the VTB is reduced from 238 Byte to 140 Byte which corresponds to a reduction of > 41 %. Besides, only a single message has to be scheduled and sent through the 5GS.

So far, we considered only a single time domain and a single UE. IEC/IEEE 60802 [10] suggests that Class A[4] devices have

[3] Note that M_{τ_I} and $M_{\bar{pd}}$ are only exemplary values. M_{τ_i} may be derived from $M_{\tau_1} = 10$ Byte. $M_{\bar{pd}}$ may be derived from $M_{\text{UInteger96}} = 12$ Byte according to IEEE 802.1AS. The values may vary in real implementations.

[4] Class A is feature rich device class as opposed to Class B.

to support $N_{\text{domain}} \geq 4$ individual time domains at least. Each time domain leverages dedicated synchronization messages [5], thus the number of messages that have to be sent through a VTB scales with the number of time domains. This requires a strict assignment of ingress timestamp τ_I and time domain (to which triggering message belongs). For our proposed single message approach this is no issue since the ingress timestamp is embedded into the *Sync5g*-message anyway. Assuming converged TSN/5G networks with $N_{\text{domain}} = 4$ time domains and the default synchronization interval $T_s = 125$ ms [10]. Then the data rate consumed by synchronization of a single device alone results for both single message and dual message distribution as:

$$R_{\text{2-Message}} = \frac{N_{\text{domain}}}{T_s} \cdot P_{\text{2-Message}} = \underline{\underline{60.93 \text{ kBit/s}}} \tag{11}$$

$$R_{\text{1-Message}} = \frac{N_{\text{domain}}}{T_s} \cdot P_{\text{1-Message}} = \underline{\underline{35.84 \text{ kBit/s}}} \ . \tag{12}$$

Furthermore, 5G supports up to N_{UE} UEs per gNB. Thus, the synchronization traffic scales proportionally to the number of connected UEs and established time domains. Then the total data rate introduced by the synchronization traffic results as:

$$R_{\text{2-Message}}(n_d, n_u, t_s) = \frac{(n_d \cdot n_u)}{t_s} \cdot P_{\text{2-Message}} \tag{13}$$

$$R_{\text{1-Message}}(n_d, n_u, t_s) = \frac{(n_d \cdot n_u)}{t_s} \cdot P_{\text{1-Message}} \tag{14}$$

$$\text{with} \quad n_d \geq N_{\text{domain}} = 4 \quad \text{and} \quad n_u \geq N_{\text{UE}} \ . \tag{15}$$

C. Dependency on 5GS Synchronization

The presented proposal for single message distribution of timing information leverages the underlying synchronization of the 5GS. We use both the ingress and the egress timestamps, τ_I and τ_E, to determine the residence time at the VTB. Both timestamps are relative to the same timescale, i.e. the 5GS timescale as provided by the gNB. However, both timestamps are generated at disjoint 5GS components, namely the boundary NW-TT and DS-TT, with physically different clocks. It becomes apparent that the residence time accuracy, i.e. the accuracy of the corrections applied at the VTB, directly depends on the synchronicity of NW-TT and DS-TT.

The residence time is affected by air interface related aspects, i.e. it is increased and decreased, for instance time-variant (and asymmetric) propagation delays, scheduling delays and packet re-transmissions due to packet loss [12] [13]. Nevertheless, the residence time accuracy is not being deteriorated as it is determined through ingress and egress timestamps which are registered at the very boundaries of the VTB and such already compensate for jitter within the 5GS.

Assuming that the underlying synchronization of the 5GS is capable to compensate the time and frequency offset of NW-TT's and DS-TT's clock. This may be accomplished by using an appropriate synchronization protocol for instance the PTP telecom profile according to ITU-T G.8275/Y.1369.1 [14]. Then we have to consider the drifting frequency offset ρ' as main source of error. The resulting time offset error at a TT due to drifting frequency follows:

$$\delta\theta_{\text{TT}} = T_s^2 \cdot \rho' \tag{16}$$

where T_s is the synchronization interval. Assuming the worst-case scenario where both TT show the opposing maximum frequency drift according to IEC/IEEE 60802 [10], the residence time error δrt of the VTB results as:

$$\delta rt = \left(T_s^2 \cdot \rho'\right) - \left(T_s^2 \cdot (-\rho')\right) = 2 \cdot T_s^2 \cdot \rho' \ . \tag{17}$$

Now using the default synchronization interval $T_s = 125$ ms after IEEE 802.1AS [3] and the maximum allowed frequency drift $\rho' = 3 \cdot 10^{-6}/\text{s}$ according to IEC/IEEE 60802 [10] we are able to obtain the worst-case residence time error due to drifting clock frequencies of NW-TT and DS-TT:

$$\max(\delta rt) = 2(125 \cdot 10^{-3} \text{ s})^2 \cdot 3 \cdot 10^{-6}/\text{s} = \underline{\underline{93.75 \text{ ns}}} \ . \tag{18}$$

Note that the worst-case scenario only occurs right before the clock is synchronized. An obvious way to reduce the resulting error is to lower the synchronization interval.

Up to this point we only considered the frequency drift as source of error for the residence time. However, in realistic scenarios there are several sources of error due to physical effects. As Loschmidt *et al.* [15] found, clock granularity and physical layer jitter are major sources of error in real-world scenarios as they heavily impact the timestamping accuracy.

We need to clarify that the presented sources of error occur due to the usage of disjoint systems with physically different clocks. Indeed, those errors apply for any other mechanism that uses the suggested ingress and egress timestamps [5] and are not limited solely to our proposal. Therefore we claim that our proposal show no disadvantages compared to any other mechanism that uses ingress and egress timestamping according to 3GPP TR 23.274.

TABLE I
OVERVIEW ON MESSAGE SIZES

Description	Symbol	Size [Byte]
Ingress Timestamp τ_I	M_{τ_I}	10
Propagation Delay $\bar{pd}$	$M_{\bar{pd}}$	12
Sync-message	M_{Sync}	44
FollowUp-message	$M_{FollowUp}$	76
Sync5g-message	M_{Sync5g}	86
Total Message Size, Dual Message	$M_{\text{2-Message}}$	130
Total Message Size, Single Message	$M_{\text{1-Message}}$	86
Ethernet Header	H_{Eth}	18
Total Frame Size, Dual Message	$F_{\text{2-Message}}$	166
Total Frame Size, Single Message	$F_{\text{1-Message}}$	104
GTP Header	G_{GTP}	8
IP/UDP Header	$G_{\text{IP/UDP}}$	28
Total Packet Size, Dual Message	$P_{\text{2-Message}}$	238
Total Packet Size, Single Message	$P_{\text{1-Message}}$	140

V. SIMULATION

In Sec. III and IV we discussed the distribution of timing information through converged networks for the schemes of dual and single message distribution. Now, we compare the synchronization accuracy achieved under both schemes through simulation of converged networks. We use the discrete event simulator OMNEST [16] to simulate converged networks with regard to worst-case clock and link models for evaluation of the inherited synchronization accuracy.

We simulated the converged TSN/5G scenario as presented in Fig. 4 with two TAE, i.e. v_{i-1} and v_{i+1}, and a VTB v_i which connects both TAE. v_{i-1} serves as TSN GM. The relevant simulation parameters are listed in Tab. II. Our clock model accounts for phase offset and drift [17] [18], physical layer (PHY) jitter, and limited timestamp resolution [18] which are configured as worst-case given by IEEE 802.1AS [3] and IEC/IEEE 60802 [10]. We use the specified gPTP default intervals for synchronization and peer delay measurements [3]. The presented findings result from 100 simulations of 200 s each whereas we omitted the first 100 s in order to ensure that we do not see distortions from initializing filters, e.g. filter for rate ratio or peer delay measurements. Our study of the synchronization accuracy of TAE v_i is based in the synchronization error p_i:

$$p_i = \tau_i - \tau_{gm} \ . \tag{19}$$

Here, τ_{gm} is the precise origin timestamp with applied corrections and τ_i is a timestamp registered right before clock adjustment through gPTP [7] [18].

TABLE II
SIMULATION PARAMETERS

Description	*Parameter*
Packet Loss Rate	$R_{\text{lossless}} = 0$, $R = 10^{-2}$
Link Delay	$D = 50$ ns
Phase Offset	$\theta \sim \mathcal{U}(-50, 50)$ ms
Phase Drift	$\rho' \sim \mathcal{U}(-3, 3) \cdot 10^{-6}$/s
Physical Layer Jitter	$\delta phy \sim \mathcal{N}(0, \frac{5}{3})$ ns, $P(\lvert\delta phy\rvert < 5) = 99.8\%$
Timestamp Resolution	$\Delta_r = 40 \cdot 10^{-9}$ s
Sync-Interval	$T_s = 125$ ms
Pdelay-Interval	$T_p = 1$ s
Simulation Time	$T_{\text{sim}} = 200$ s
Repetitions	$N_{\text{reps}} = 100$

In Sec. V-A we compare both dual and single message schemes with regard to the synchronization accuracy that emerges from v_{i+1} as it is affected by the time distribution scheme used within the VTB v_i. We continue in Sec. V-B with an evaluation of the synchronization accuracy in a scenario where the VTB introduces a residence time error due to asynchronous NW-TT and DS-TT.

A. Comparison of Dual and Single Message Schemes

For the comparison of both dual and single message schemes we make the following assumptions:

- NW-TT and DS-TT are synchronous, i.e. ingress and egress timestamps τ_I and τ_E are based on the identical time reference (simulation time). The VTB residence time is free of errors. This is not an issue as both time information distribution schemes leverage the underlying synchronization through 5G and an additional consideration of the VTB residence time error does not contribute any additional information to the comparison of the dual and single message schemes.
- For the dual message scheme, the loss of one of the associated *Sync*- or *FollowUp*-messages yields a missed synchronization opportunity.
- Packet loss inherited by the radio link is applied identically to each packet.

First, we simulate an ideal radio link within the VTB, i.e. without any packet loss $R_{\text{lossless}} = 0$. The simulation results showed that the synchronization accuracy of v_{i+1} is not affected by the scheme used to distribute the timing information through the VTB. We achieve a synchronization accuracy of:

$$\bar{p}_{\text{lossless}} = \underline{\underline{1.1 \text{ ns}}} \quad \text{and} \quad \sigma_{\text{lossless}} = \underline{\underline{20.1 \text{ ns}}} \ . \tag{20}$$

Second, we consider a lossy radio link within the VTB. We assume a high packet loss rate of $R = 10^{-2}$, e.g. corresponding to a 5G quality of service (QoS) index (5QI) value of 1 which is used for conversational voice, to compare both schemes under worse transmission conditions. The simulation results for both dual and single message schemes are shown in Fig. 8. Given the presented simulation parameters, the single message scheme achieves a better synchronization accuracy of ± 80 ns compared to the dual message scheme with an accuracy of ± 90 ns. A statistical analysis proves that the single message scheme achieves a better synchronization accuracy under consideration of the average and the standard deviation:

$$\bar{p}_{\text{2-Message}} = \underline{\underline{1.45 \text{ ns}}} \quad \text{and} \quad \sigma_{\text{2-Message}} = \underline{\underline{20.92 \text{ ns}}} \tag{21}$$

$$\bar{p}_{\text{1-Message}} = \underline{\underline{1.3 \text{ ns}}} \quad \text{and} \quad \sigma_{\text{1-Message}} = \underline{\underline{20.37 \text{ ns}}} \ . \tag{22}$$

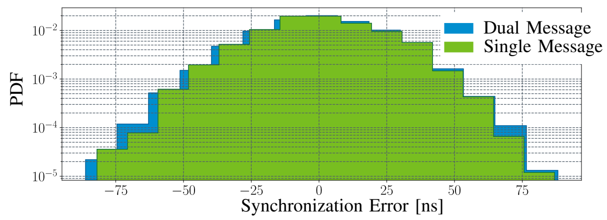

Fig. 8. Synchronization accuracy of TAE v_{i+1} for both *dual* and *single* message schemes.

It has to be noted that the packet loss rate is applied uniformly to each packet. It is assumed that a lost packet, whether *Sync*-, *FollowUp*-, or *Sync5g*-message, leads to a missed synchronization opportunity. The dual message scheme suffers more from this assumptions than a single message scheme as it exposes a greater vulnerability towards packet loss. The number of missed synchronization opportunities is proportional to the number of lost packets. In reality we might observe burst packet losses such that a bunch of subsequent packets, e.g. *Sync*- and *FollowUp*-messages, are lost in conjunction. The number of missed synchronization opportunities becomes disproportionate to the number of lost packets. Under consideration of burst packet losses, we would observe a less relevant benefit of the single message scheme. Accordingly, we will address burst packet loss models are in scope of future studies.

B. Time Synchronization Accuracy

In order to evaluate the synchronization accuracy in a worst-case converged TSN/5G scenario, we use the simulation parameters from Tab. II and make the following assumptions:

- The single message scheme for the distribution of timing information is used.
- NW-TT and DS-TT are synchronous, i.e. the VTB residence time is free of errors, but we introduce an artificial uniformly distributed error in range of ± 93.75 ns according to (18).

The simulation results are provided in Fig. 9. As expected, we see that the synchronization error deviation broadens such that we achieve an accuracy within ± 165 ns. This result can be explained using the worst-case parameters of residence time error ± 93.75 ns and synchronization accuracy ± 80 ns (under the single message scheme with $R = 10^{-2}$) which lead to a worst-case accuracy of ± 173.75 ns. The theoretical worst-case scenarios is very unlikely due to probabilistic effects considered in the presented simulation. From the statistical evaluation we see that the average synchronization error is actually lower than for our previous simulations due to the fact that different errors cancel out each other. Therefore, we emphasize the standard deviation which is significantly larger compared to the previous simulations.

$$\bar{p}_{\text{1-Message}} = \underline{\underline{-0.47 \text{ ns}}} \quad \text{and} \quad \sigma_{\text{1-Message}} = \underline{\underline{58.37 \text{ ns}}} \,. \tag{23}$$

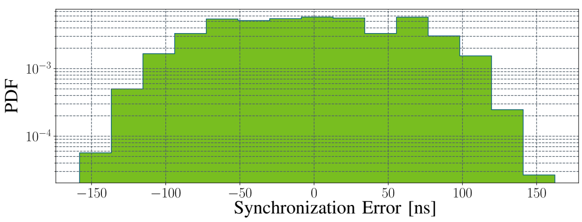

Fig. 9. Synchronization accuracy of TAE v_{i+1} under the *single* message scheme with asynchronous NW-TT and DS-TT and a lossy radio link.

It becomes obvious that the synchronization accuracy of a disjoint TAS which is connected through 5G, e.g. v_{i+1}, suffers directly from the residence time error introduced by asynchronous NW-TT and DS-TT. In order to improve the synchronization of disjoint TAS it is relevant to refine the synchronicity of NW-TT and DS-TT, i.e. the 5GS components.

VI. Conclusion

In this work, we proposed a single message mechanism for distribution of timing information in converged TSN/5G networks. We provided a detailed description of the necessary operations and presented a possible message structure. We discussed the key benefits of the single message mechanism in regard to data rate reduction of > 41 % and reduced scheduling effort for the integrated 5GS. We found that the single message scheme provides a slightly improved robustness against packet error. Moreover, we analyzed its disadvantageous dependency on the underlying synchronization of the 5GS components. We found that mechanisms which use ingress and egress timestamps from disjoint systems may suffer from asynchronous NW-TT and DS-TT. Therefore, in order to improve the synchronization performance, i.e. the accuracy of the applied corrections at the VTB, we have to improve the synchronization quality of the 5GS including both NW-TT and DS-TT.

So far, we have examined the impact of the proposed single message scheme on the synchronization performance in converged TSN/5G networks. We plan to investigate the synchronization performance in realistic converged TSN/5G networks and want to include more simulations results. With that we want to examine different integration scenarios and network designs.

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