Empirical Evaluation of a 5G Transparent Clock for Time Synchronization in a TSN-5G Network

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***Abstract*—Time synchronization is essential for industrial IoT and Industry 4.0/5.0 applications, but achieving high synchronization accuracy in Time-Sensitive Networking (TSN)-5G networks is challenging due to jitter and asymmetric delays. 3GPP TS 23.501 defines three 5G synchronization modes: time-aware system, boundary clock (BC), and transparent clock (TC), where TC offers a promising solution. However, to the best of our knowledge, there is no empirical evaluation of TC in a TSN-5G network. This paper empirically evaluates an 5G end-to-end TC in a TSN-5G network, implemented on commercial TSN switches with a single clock. For TC development, we compute the residence time in 5G and recover the clock domain at the slave node. We deploy a TSN-5G testbed with commercial equipment for synchronization evaluation by modifying the Precision Timing Protocol (PTP) message transmission rates. Experimental results show a peak-to-peak synchronization of 500 ns, meeting the industrial requirement of ≤ 1 μs, with minimal synchronization offsets for specific PTP message transmission rates.**

***Index Terms*—Transparent Clock, Time Synchronization, 5G, Time-Sensitive Networking.**

I. Introduction

Time synchronization distribution is an essential service for the Industrial Internet of Things (IIoT), playing a crucial role in the evolution towards Industry 4.0 and 5.0. Applications in these sectors depend on precise synchronization for reliable communication, low latency and operational efficiency to optimize automation and interaction between robots, sensors and machinery, as well as accurate sensor data analysis. The Time Sensitive Networking (TSN) standard, defined by IEEE 802.1 [1], enables synchronization accuracy below 100 μs [2], ensuring deterministic and reliable operation. However, the growing need for mobility in industrial, Internet of Things (IoT) and robotics sectors presents new challenges, as TSN was conceived for wired networks. As a solution, 3GPP Release 16 proposes integrating Fifth Generation (5G) with TSN to provide wireless communication and mobile flexibility without compromising synchronization requirements.

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TSN functionalities such as IEEE 802.1 Qbv, IEEE 802.1 Qcc and IEEE 802.1 Qci rely on accurate time synchronization. However, 5G introduces challenges that degrade synchronization accuracy, such as high levels of jitter, asymmetries in Uplink (UL) and Downlink (DL) delays, variable processing times in devices like the Next-Generation Node B (gNB) and User Plane Function (UPF), and retransmissions. TS 22.104 [3] establishes the 5G System (5GS) requirements for industrial and IIoT networks, specifying a maximum time synchronization error of 900 ns and support for up to 32 simultaneous working clock domains. These domains provide high-precision time to the devices within them, allowing TSN devices to manage multiple clock domains simultaneously. While a global clock domain provides the date and time to the devices belonging to that domain. In some cases, the working and global clock domains may overlap. Meanwhile, 3GPP TS 23.501 [4] defines several configurations to enable TSN synchronization in the 5GS, which can be implemented as a time-aware system using the IEEE 802.1AS standard [5], [6], which uses the generic Precision Time Protocol (gPTP) protocol, or configured as a Boundary Clock (BC) or Transparent Clock (TC) following the IEEE 1588 standard [7].

Several studies have addressed the challenges of time synchronization distribution in TSN-5G network. For example, Striffler et al. [8] analyze frequency drift and timing errors when 5GS operated as a TC, which can lead to non-compliance with time synchronization requirements. While Wang et al. [9] propose solutions to mitigate the effects of multi-gNB competition, retransmissions, and mobility in a 5GS modeled as TC. Shi et al. [10] investigate synchronization errors in 5GS configured as BC, focusing on the uncertainty due to reference time granularity and propagation delay estimation. Val et al. [11] demonstrate that, despite Wi-Fi variability, TSN-compatible synchronization accuracies are achieved through hardware-level modifications, although this approach is currently infeasible for commercial 5G networks.

To our knowledge, there is no empirical evaluation of the TC in an integrated TSN-5G network. Therefore, the objective of this paper is to empirically investigate the distribution of TSN time synchronization in a TSN-5G network when the 5GS is configured as an End-to-End (E2E) TC. Our main

contributions are as follows:

- We analyze the various configurations of 5GS to support TSN synchronization transport, considering its implementation in commercial single-clock equipment.
- We implement the E2E TC on commercial TSN switches. This implementation comprises two processes: the computation of the residence time introduced by the 5GS and the recovery of the TSN clock domain at the slave node.
- We deploy a TSN-5G network testbed with commercial equipment to evaluate time synchronization performance.
- We performed an experimental evaluation of the time synchronization accuracy on the implemented testbed.

Our results indicate a peak-to-peak time synchronization of 500 ns, meeting industrial requirements ($\leq 1\ \mu s$). Also, we note that, at certain Precision Time Protocol (PTP) message transmission rates, time offsets can be observed that may affect the time synchronization but do not exceed the requirements. These results are independent of whether the synchronizing transmitter (master node) is synchronized to an external reference (Global Navigation Satellite System (GNSS)) or operates with its internal clock (Free-running (FR)).

The rest of the paper is structured as follows: Section II presents the background and an analysis of time synchronization options in TSN-5G networks. Section III describes the model and architecture of the integrated network. Section IV details the design and operation of the TC, along with PTP messages analysis and offset calculation. Section V describes the testbed and experimental setup. Section VI presents and discusses the results obtained. Finally, Section VII concludes with the main contributions.

II. Background and Analysis of Time Synchronization Options

In the TSN-5G integrated network, there are two synchronization processes running in parallel, the 5G time synchronization process and the TSN time synchronization process [2], [12], as shown in Figure 1. The 5G synchronization process provides the temporal reference from the 5G Grandmaster (GM) to the 5GS devices, such as the UPF, gNB and User Equipment (UE). In paralell, the TSN synchronization process provides the TSN GM temporal reference to the TSN network devices. The two synchronization processes are considered to be independent, providing flexibility in the design and implementation of the synchronization process. Both processes are detailed below, but first we describe the 5GS architecture in the integrated TSN-5G network proposed by 3GPP.

A. Architecture of 5GS in the TSN-5G networks

According to 3GPP TS 23.501 [4], the 5GS acts as a PTP instance in the TSN network. As shown in Figure 1, the external network consists of end stations and TSN bridges, whose time reference is provided by a PTP or gPTP GM. In the 5G domain, a 5G GM synchronizes the gNB, which distributes the time reference to the UE over the radio link and to the UPF via the PTP-compliant 5G transport network. To integrate 5G with TSN, the UPF implements a TSN Translator

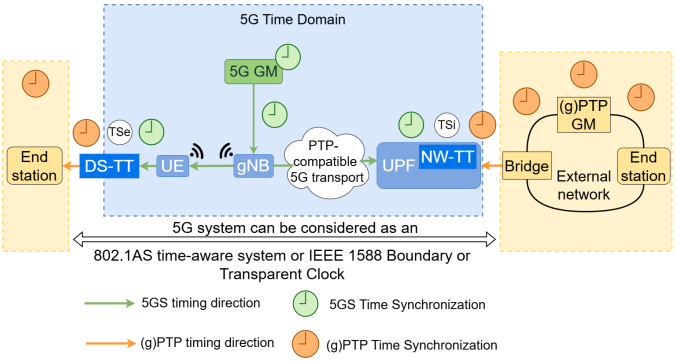


Fig. 1. Architecture of the integrated TSN-5G network [4]

(TT) (Network-Side Time Sensitive Networking Translator (NW-TT)) that interfaces with the external TSN bridge, while the UE connects to another TT (Device-Side Time Sensitive Networking Translator (DS-TT)) and this connects to a TSN end station. These TT ensure interoperability, allowing the 5GS to operate as a logical bridge in various modes without direct alignment with the TSN GM.

B. The 5G synchronization process

The 5G time synchronization process is based on the internal distribution of the 5G GM reference across the 5GS transport network and the 5GS Radio Access Network (RAN) [13]. A straightforward solution in the 5G transport network is to install GNSS receivers in each gNB, which offers ± 100 ns accuracy [13], meeting the 5GS timing requirements. However, this method comes with high deployment and maintenance costs, indoor installation difficulties and vulnerability to jamming. Alternatively, synchronization protocols over packet networks, such as IEEE 1588 [7], with adapted profiles defined by ITU-T (e.g., G.8275.1 (PTP-aware) and G.8275.2 (non-PTP-aware)).

In the 5G RAN, synchronization between the 5G GM and the UE is achieved through the gNB, as defined in TS 38.331. The gNB continuously updates the 5G GM reference [2], [13], [14] and periodically transmits it to the UE via System Information Block (SIB) or unicast Radio Resource Control (RRC) messages, identified via a System Frame Number (SFN). The SIB9 message, which contains the time information in GPS and UTC formats, is transmitted at the boundary between two SFNs, enabling synchronization of the devices. In addition, the 5G reference must be adjusted according to the cell size to compensate for DL propagation delay and minimize reception uncertainty. Accurate delay calculation and obtaining the SIB9 reference are essential aspects, although they are not addressed in this study. For more information, see [13], [14].

C. The TSN synchronization process

TS 23.501 [4] defines several modes in which the 5GS can be configured to operate as one PTP instance [2], enabling TSN time synchronization in an integrated TSN-5G network. Specifically, these clock modes are:

- **5GS as a Time-Aware System:** The 5GS behaves as an IEEE 802.1AS-compliant node [5], participating in time synchronization using the gPTP protocol. NW-TT and DS-TT synchronize with both GM clocks (TSN GM and 5G GM), thus requiring two clocks, and manage gPTP messages (transmitted in Layer 2 (L2)) to ensure synchronization [2].
- **5GS as BC:** The 5GS is configured as a BC according to the IEEE 1588 standard [7], actively participating in synchronization. That is, the 5GS maintains the PTP domain timescale and synchronizes the connected PTP time receivers (e.g., DS-TT, TSN Slave, etc.), acting as the time source. This mode provides higher accuracy and robustness, allowing network scalability and lower impact of jitter and propagation delay in multi-device scenarios, but is more complex.
- **5GS as TC:** The 5GS behaves as a TC according to the IEEE 1588 standard [7], without actively participating in time synchronization, but measures the residence time of PTP messages within the network and uses it to correct them before forwarding them. The TTs manage the PTP messages and calculate the delay within the 5GS.

  There are two types of TC: Peer-to-Peer (P2P) or E2E. In P2P TC [15] the 5GS measures the delay between two directly connected neighboring node using Peer Delay Messages and calculates the residence time of the PTP messages within the 5G network. The sum of the residence time and the link delay along the path is reported to the PTP time receiver [6]. The E2E TC calculates the total E2E delay between the PTP transmitter and receiver by exchanging PTP messages. In the 5GS the residence time is calculated and the sum of the residence time over the entire path is added in the correction field of the PTP messages. This sum of residence times is relayed to the PTP time receiver. This way, the PTP receiver can calculate the total compensation based on the sum of residence times in the correction field of the messages.

  Therefore, P2P TC compensates for the latency between neighboring nodes while E2E TC compensates for the latency of the entire E2E path. P2P TC requires IEEE 1588 compatibility on all network devices, E2E TC does not.

In this paper, we opt for the E2E TC mode in 5GS, as it allows transmission of multiple working clock domains from different GMs, a key requirement in industrial environments. The IEEE 802.1AS standard, requiring L2 transmission, has limitations for integration into commercial equipment. However, it has been demonstrated that an IEEE 802.1AS network can operate as distributed clock (BC, ordinary or TC) according to IEEE 1588 [15], facilitating the transport of multiple clock signals between domains. Moreover, the TC by operating independently, without the need to synchronize its own clocks simplifies the integration of 5GS into existing TSN networks or enables the incorporation of new 5G operators, thus ensuring greater flexibility in the deployment of TSN-5G network.

III. System Model

We consider the TSN-5G system model as illustrated in Figure 2. The TSN system includes a TSN Master, synchronized with the TSN GM, which distributes the time reference

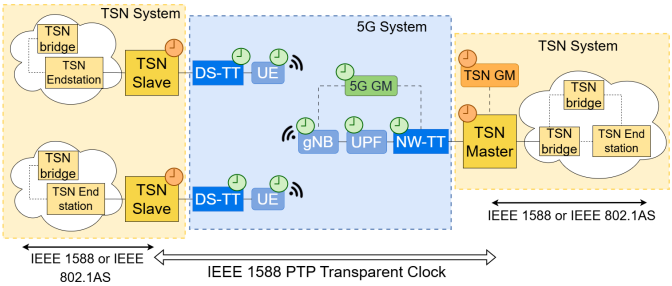


Fig. 2. TSN-5G system model for time synchronization

to other TSN bridges and/or TSN end station. This synchronization is extended to a TSN Slave in another TSN domain, interconnected through the 5G network. This TSN Slave, once synchronized, distributes the synchronization to other TSN bridges or TSN end stations. The 5GS incorporates a 5G GM, which directly provides the time reference to the gNB and NW-TT, both connected through the UPF. Since commercial equipment does not integrate a UPF with NW-TT, the NW-TT is synchronized with the 5G GM and connected directly to the TSN Master. While the DS-TT, also synchronized to the 5G GM via the UE, connects to the TSN Slave. This differs from the model in Figure 1, as in this case the NW-TT and UPF are separate devices, and both the NW-TT and DS-TT are directly connected to the TSN Master and TSN Slave, respectively.

Time synchronization in the TSN-5G network is based on IEEE 1588 compliant PTP frame transmission [7]. In this paper, we use the E2E TC clock mechanism for time synchronization. We define $\mathcal{F}$ as the set of PTP flows traversing the TSN-5G network. Each PTP flow $f_i \ \forall \ i \in \mathcal{F}$ represent a bidirectional communication between a PTP transmitter node, synchronized with a GM and a PTP receiver node, not synchronized with the GM. We refer as a PTP transmitter node to the TSN Master and as a PTP receiver node to the TSN Slave. These PTP flows ensure that the PTP transmitter and the PTP receiver maintain the same time reference as the GM. Therefore, each flow $f_i \ \forall \ i \in \mathcal{F}$ is transmitted from the TSN Master to the TSN Slaves, traversing the 5G network. In our case, we focus on a single PTP flow f_i to evaluate synchronization. This f_i transmits a series of $p_{\mathcal{E}}^{f_i}$ PTP packets between the TSN Master and the Slave using the E2E TC mechanism detailed in Section IV. For clarity, henceforth, the superindex f_i will be omitted, meaning $p_{\mathcal{E}}^{f_i} = p_{\mathcal{E}}$ in all variables, since only a single PTP flow is considered.

In this scenario, as previously explained, two synchronization processes coexist [12]: TSN synchronization and 5G synchronization. We consider that each device within the TSN-5G network has a single clock. The clocks of the TSN Master and Slave are synchronized with the TSN GM reference, while the TTs are solely synchronized with the 5G GM. In 5G synchronization, the 5G GM reference is transmitted through the gNB to the UE and the UE transmits it to the DS-TT. In this paper, we do not focus on the 5G clock recovery by the UE and its subsequent transmission to the DS-TT, therefore,

we assume perfect recovery from SIB9 for synchronization at the UE and subsequently at the DS-TT.

In TSN synchronization, the $p_{\mathcal{E}}$ include a timestamp. Specifically, each p_e $e \in \mathcal{E}$ contains a timestamp that records the moment the TSN Master sends the packet e. However, due to delays caused by software and hardware packet processing in the TSN Master, the timestamp in p_e may lack precision. Then, the transmission timestamp of p_e is included in p_{e+1}, recording the precise moment (t_1) when p_e exits the TSN Master. When the TSN Slave receives p_e, it records the timestamp (t_2).

In addition, $p_{\mathcal{E}}$ packets when traversing the 5G network experience variable delays (jitter), compromising the timing accuracy and affecting the correct operation of the TSN nodes. This present a challenge to accurately estimate the time reference. To address this issue, the delay experienced by the $p_{\mathcal{E}}$ while traversing the 5G network is calculated. This delay is referred to as the residence time in the 5G network (d_{res}). Its calculation involves generating timestamps for certain p_e packet at the TTs. The NW-TT generates an ingress timestamp (t_{in}) based on the 5GS reference time, while the DS-TT generates an egress timestamp (t_{eg}) also based on the 5GS reference time. The residence time (d_{res}) is defined as:

$$d_{res} = t_{eg} - t_{in} \tag{1}$$

Since the 5G network is asymmetric in its links, meaning the UL and DL delays differ depending on the radio channel's characteristics, a specific residence time is defined for each link. The residence time for the UL is denoted as $d_{res,up}$, and for the DL as $d_{res,down}$.

Each TSN node incorporates an internal oscillator that may introduce noise to the device's internal clock due to physical disturbances, causing clock skew. To mitigate this clock drift, PTP messages are generated with cycle T.

IV. Transparent Clock Design

We focus on the distribution of time synchronization in an integrated TSN-5G network, implementing E2E TC mode in the 5GS. With this approach, 5G devices do not need to synchronize with the TSN GM time reference, as the 5G common time reference is used to accurately calculate the residence times ($d_{res,up}$, $d_{res,down}$) of $p_{\mathcal{E}}$ traversing the network. As explained in Section III, it is essential that the NW-TT and DS-TT share the same time reference derived from the 5G GM. This allows that the TC mechanism to operate in a manner equivalent to a standalone switch, ensuring consistency in the calculation of residence times from the timestamps generated on devices located at opposite ends of 5GS. Any failure to propagate a common time reference could lead to inconsistencies or invalid synchronization results between TSN systems at the edges. The following section details the PTP messages exchanged and the procedure to be followed to calculate the offset and residence time.

A. Messages, procedures and offset calculation

The E2E TC solution implemented in the 5GS exchanges PTP messages between the nodes of the distributed architecture, as illustrated in Figure 3. The TSN Master initiates

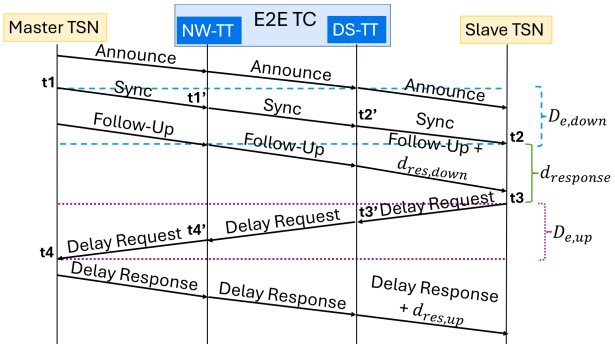


Fig. 3. End-to-End Transparent Clock messages exchange

synchronization by transmitting "Announce" messages, followed by "Sync" and "Follow-Up". The TSN Slave then sends "Delay Request" and receives a "Delay Response" in reply. This exchange enables the measurement of the residence time on the 5GS, through the time stamping and delay estimation capabilities of the NW-TT and DS-TT, and the recovery of the TSN clock domain at the TSN Slave. Both functionalities are key to the operation of the TC and to perform TC on commercial switches, we have implemented both functionalities in these devices. Each functionality is detailed below:

1) Calculation of the 5GS residence time: NW-TT and DS-TT assign timestamps to the "Sync" packets at the ingress ($t_{1'}$) and egress ($t_{2'}$) of the 5GS, respectively. These timestamps determine the DL residence time ($d_{res,down}$), as detailed in equation (2). The value of $d_{res,down}$ is temporarily stored in DS-TT until the arrival of the "Follow-Up" packet, where DS-TT updates the Correction Field (CF) with the value of $d_{res,down}$. This procedure allows the TSN Slave to compensate for the delay introduced by the "Sync" packets within the 5GS for its estimates of the total link delay. An analogous process is applied for the "Delay Request" and "Delay Reply" packets, allowing the UL residence time ($d_{res,up}$) estimation using the timestamps of "Delay Request" and the CF update in "Delay Reply", as shown in Figure 3. The UL and DL residence time are calculated as:

$$\begin{aligned} d_{res,down} &= t_{2'} - t_{1'} \\ d_{res,up} &= t_{4'} - t_{3'} \end{aligned} \tag{2}$$

2) Clock recovery at the TSN Slave: several operations are necessary [7]. First, we decouple the delay of the PTP packets sent from the TSN Master to the TSN Slave from the variable residence time of the 5GS. That is, due to the residence time calculation, the 5GS introduces variable jitter in the UL and DL, generating different delays for PTP packets. We call $D_{e,down}$ the DL delay of the "Sync" packet, while $D_{e,up}$ is the UL delay of the "Delay Request" packet. The sum of both delays determines the $p_{\mathcal{E}}$ transmission delay ($D_{\mathcal{E}}$). $D_{e,down}$, $D_{e,up}$ and $D_{\mathcal{E}}$ are calculated as:

$$D_{e,down} = t_2 - t_{2'} + t_{1'} - t_1 = t_2 - t_1 - d_{res,down} \tag{3}$$

$$D_{e,up} = t_4 - t_{4'} + t_{3'} - t_3 = t_4 - t_3 - d_{res,up} \tag{4}$$

$$D_{\mathcal{E}} = D_{e,down} + D_{e,up} \tag{5}$$

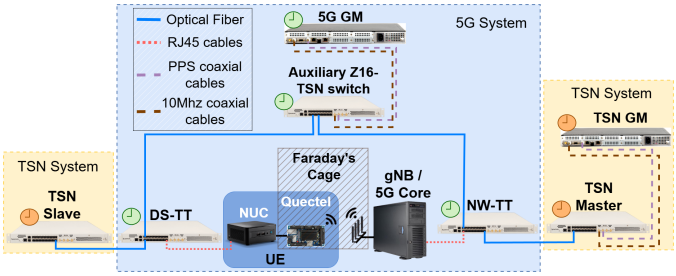


Fig. 4. TSN-5G testbed

$d_{res,down}$ and $d_{res,up}$ mitigate the associated problem of having different latencies in UL and DL. The TSN Slave requires a response time ($d_{response}$) after receiving the "Sync" before generating the "Delay Request", as shown in Figure 3. This $d_{response}$ is calculated as:

$$d_{response} = t_3 - t_2 \tag{6}$$

The TSN Slave calculates the time offset (β) with respect to the TSN Master from all timestamps, the residence time and the response time, as follows:

$$\beta = (t_2 - t_1) - \frac{D_{\mathcal{E}}}{2} - d_{res,down} \tag{7}$$

Thus, the TSN Slave compensates for its clock offset to set the TSN GM time. This procedure compensates for latency variability in the propagation of time references in 5GS, ensuring accurate synchronization throughout the network, essential for industrial applications and the IIoT. Both functionalities have been implemented in commercial equipment that make up the TT and the TSN Slave.

V. Testbed and Experimental Setup

We implemented a TSN-5G testbed to evaluate time synchronization performance, illustrated in Figure 4, where we only considered PTP traffic. The TSN systems are composed of TSN Master and TSN Slave nodes, implemented on commercial TSN switches (Z16 from Safran). These devices integrate time-sensitive networking features according to the specifications set forth in [1]. TSN Slave contains modifications to implement the TSN clock recovery functionality, as detailed in Section IV-A. For PTP packet encapsulation and exchange, these devices use the User Datagram Protocol (UDP) protocol over IPv4 in unicast mode with the E2E mechanism, a modality widely adopted in 5G networks with commercial devices. In this UDP/IPv4 mode, the source and destination IP addresses of the PTP packets are the addresses assigned to the TSN Master and TSN Slave ports, respectively. The PTP packet transmission rate varies depending on the experiment. The TSN Master is synchronized with the TSN GM, implemented by a time and frequency reference server (Safran's Secure Sync). The time synchronization between the TSN GM and the TSN Master is performed by coaxial cables, using the Pulse Per Second (PPS) and 10 MHz signals.

TABLE I
Overview of $p_{\mathcal{E}}$ rate settings per TC experiment

Test ID	Announce	Sync	Follow-Up	Del. Req.	Del. Resp.	Sync. Mode
0	1 p/2s	1 p/2s	1 p/2s	1 p/2s	1 p/2s	GNSS
1	1 p/s	1 p/s	1 p/s	1 p/s	1 p/s	
2	2 p/s	2 p/s	2 p/s	2 p/s	2 p/s	
3	2 p/s	2 p/s	2 p/s	2 p/s	2 p/s	FR

5GS consists of the TTs, also implemented with commercial TSN switches (Safran's Z16), both modified to implement TC. These TTs are synchronized with the 5G clock provided by a second Safran Secure Sync server, which acts as the 5G GM. Since the 5G GM only has a single PPS and 10 MHz output, an auxiliary TSN switch (Z16-TSN) is required to distribute the time reference to the TTs. This switch is synchronized with the 5G GM via coaxial cables connected to the PPS and 10 MHz signals, see Figure 4. Subsequently, the switch transmits the time reference to the NW-TT and DS-TT via L2, using an E2E mechanism with a PTP message transmission rate of 1 packet/s. The 5GS also consist of a Base Station (BS) and a 5G core, both integrated in a PC with two 50 MHz PCLe SDR Amarisoft cards and an AMARI NW 600 license. The BS operates in the frequency band *n78*, using a Sub-Carrier Spacing (SCS) of 30 kHz and a Time Division Duplex (TDD) mode, with a TDD pattern of 1,0. The UE consists of a Quectel RM500Q-GL modem connected to an Intel NUC 10 NUC10i7FNKN, which acts as a Customer Premise Equipment (CPE). This device contains an Intel i7-10710U processor with 16 GB of RAM and 512 GB of SSD memory, and runs Ubuntu 22.04.

All experiments are performed inside a LABIFIX Faraday cage, where the BS antennas are connected to a SDR via SMA connectors and the Quectel modem is connected via USB. This cage avoids radiation within the licensed frequency bands. The connections between the rest of the equipment are made using 1 Gbps optical fiber, except for the connections between the NW-TT and DS-TT to the gNB and UE, respectively, which use 1 Gbps RJ-45 cables, as shown in Figure 4.

VI. Experimental Results

We have performed two experiments to evaluate the performance of TC and the accuracy of TSN time synchronization. The first experiment analyzes the synchronization between the TSN Master and the TSN Slave when varying the PTP packet transmission rates. The second experiment compares the time synchronization when the TSN Master is synchronized to the TSN GM, locked to a GNSS reference, versus when operating in FR, using its own internal clock. In both cases, we measured the offset between the TSN Master and TSN Slave clocks for 20 min with a high precision counter. Table I summarizes the configurations used in the experiments.

A. Experiment 1: Impact of PTP message transmission rate

The measured offset results of the TC mechanism, with the GM synchronized to a GNSS, are presented in Table II

TABLE II
OVERVIEW OF TC SYNCHRONIZATION PERFORMANCE FOR $p_{\mathcal{E}}$ SETTINGS

Test ID	Mean (ns)	Max (ns)	Min (ns)	Std. Dev. (ns)	Mode
0	-18.70	269.92	-279.80	108.58	GNSS
1	-21.13	124.89	-179.89	61.83	
2	238.28	437.09	29.80	80.80	
3	-70.01	167.15	-268.26	76.78	FR

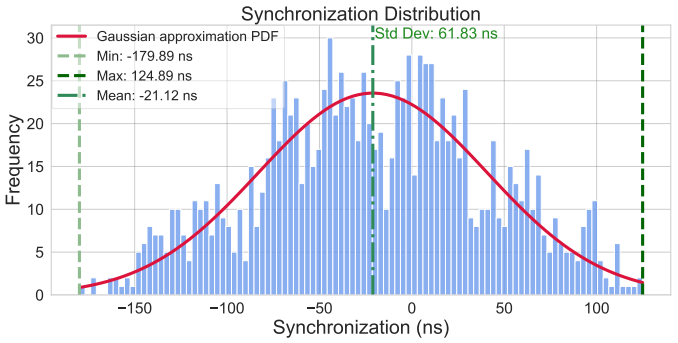


Fig. 5. Synchronization distribution for 1 packet/s rate

for the tests *"0"* to *"2"*, showing the average, maximum, minimum and standard deviation of the offset in each case. In particular, the measured offset at a rate of 1 p/s is illustrated in Figure 5, whose distribution follows approximately a Gaussian distribution. Similar behavior is observed for the rest of the tests. The data demonstrate very good synchronization performance for the E2E TC mechanism, with overall jitter below 500 ns and offset in the range of hundreds of nanoseconds. The best performance is obtained in the test *"1"*, while lower transmission rates generate slower offset correction, degrading accuracy. Conversely, higher rates cause packet accumulation in the TTs, which alters the residence time measurement at 5GS, inducing errors in the TSN Slave clock correction. Remarkably, all test meets the synchronization requirements of industrial applications, validating the effectiveness of our the distributed E2E TC system, even in a high variability and non-deterministic medium, such as 5GS.

B. Experiment 2: Performance comparison of TSN GM

The measured offset results when TSN Master operates in FR are presented in test *"3"* of Table II, showing a Gaussian-like distribution, similar to that illustrated in Figure 5. Comparison of results with test *"2"* shows an equivalent temporal accuracy. Although FR seems to offer slightly better stability, this could be attributed to the absence of adjustments to the internal oscillator of the TSN Master to follow the GNSS reference, which avoids additional fluctuations. However, this does not imply higher accuracy as it is not compared to the global time reference. Since the 5GS introduces significant latency variations, the differences in offset between FR and GNSS are negligible. Thus, we conclude that the E2E TC mechanism operates equivalently under both references without significant impacts on synchronization.

VII. CONCLUSION

This paper empirically evaluates an E2E TC in a TSN-5G network, implemented on commercial TSN switches with a single clock. The solution contains the computation of the residence time within 5GS (NW-TT and DS-TT), and the recovery of the TSN clock domain at the slave node. We have deployed a TSN-5G testbed with commercial equipment to analyze time synchronization at different PTP message rates. The results show a peak-to-peak accuracy of 500 ns, meeting industrial requirements, and show that certain transmission rates can induce offsets without exceeding the allowed margins, regardless of the reference (GNSS or FR). This work represents a first step to demonstrate the feasibility of E2E TC in an integrated TSN-5G network. Future research will explore synchronization under traffic load and extraction of the SIB9 reference to align the UE with the 5G GM clock of gNB.

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