Resilient Time Synchronization in 6G Networks: A Hot Standby Solution

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***Abstract*—While 5G strives to revolutionize connectivity, 6G promises to further intertwine the realms of the physical and digital worlds. In the context of 6G networks, ensuring resilience in time synchronization is imperative for the realization of envisioned innovative use cases. In this paper, we introduce resiliency in time synchronization for 6G networks with a hot standby grandmaster (GM) clock. In particular we focus on the integration of 6G with time-sensitive networking (TSN). Since it is not obvious as to where the two different GMs should reside in a 6G-TSN network, we present important considerations for choosing a GM location. We propose prospective time synchronization architectures and analyze them based on the standardized support for time synchronization. Finally, we provide some discussions on the proposed architectures and identify use cases where redundant hot standby GM would be beneficial.**

***Index Terms*—Time synchronization, 5G/6G, TSN, 5G-TSN, 6G-TSN, resilient time synchronization**

I. Introduction

The rapid advancement in technologies like cloud and edge computing is revolutionizing the availability of computing and data storage, hence enabling digital twins and cyber-physical systems. These developments are expected to converge towards a cyber-physical continuum. In particular, the 6G networks providing intelligently networked infrastructures will serve as a critical link between the physical and digital worlds. The proliferation of applications such as vehicle-to-everything, virtual and augmented reality, and adaptive manufacturing underscores an escalating demand for low-latency and deterministic communication [1]. This future landscape will be supported by massive multiple-input, multiple-output (MIMO), terahertz communications, quantum communications, fog computing, edge computing, machine learning, and artificial intelligence. While 5G laid the groundwork integrating solutions like time-sensitive networking (TSN), deterministic networking (DetNet), ultra-reliable low latency communication (uRLLC), and network slicing, the exigencies of 6G networks call for substantial enhancements to achieve true end-to-end (E2E) deterministic communication [2].

3GPP has a keen interest in enabling the current and upcoming verticals for industrial automation. A seamless and efficient integration with TSN is crucial for this goal. 3GPP has standardized the integration of 5G with TSN networks, where the 5G system (5GS) integrates with TSN as a time aware virtual TSN bridge. This integrated network is termed as 5G-TSN network. The TSN integration with 6G networks assumes the backward compatibility of 6G specifications. In the context of the future 6G-TSN networks, time awareness and synchronization will be crucial to achieve E2E deterministic communication [3]. It is envisioned for 6G networks that multiple technologies and devices must operate together in a coordinated manner to ensure optimal network performance and resource allocation [1]. Here the timing of events and data transmissions is carefully orchestrated to meet stringent requirements, such as low latency, high reliability, and synchronized coordination among multiple devices or processes. Moreover, synchronized timing fortifies network resilience, by combating anomalies and time-based threats efficiently.

As 6G-TSN networks are still in the early stages of development, there are several open challenges that need to be addressed for time synchronization in these networks. Coordinating synchronization across heterogeneous devices and technologies poses challenges due to variations in grandmaster's (GM) clock accuracy and synchronization protocols. Developing synchronization techniques that can effectively handle this heterogeneity is crucial. Additionally, synchronization mechanisms must accommodate device mobility and changing network topology while maintaining accurate and reliable synchronization [4]. Handling mobility-related challenges and ensuring synchronization continuity in dynamic environments prone to failures are open research areas.

In light of the above mentioned challenges to realize 6G-TSN use cases, continuous time synchronization in case of device or link failure over heterogeneous networks is addressed in this work. While the current 3GPP and IEEE 802.1 have standardized mechanisms for enabling resilience of synchronization using redundancy in paths and timing source. However, this redundancy has not yet been defined for 6G-TSN networks. In this paper, we employ redundancy in GM clocks (also know as a hot standby GM) to introduce resilience in time synchronization for 6G-TSN networks. We first provide an overview on standardized time synchronization mechanisms for 5G-TSN networks with a focus on resiliency measures. We then propose how redundancy of the timing source can be incorporated in the future 6G-TSN networks to improve reliability. In particular, we present the important considerations for choosing the GM clock. Additionally, we propose time synchronization architectures for 6G-TSN networks with redundant GMs. Finally, we analyze the proposed architectures based on the standardized synchronization requirements and identify use cases where redundant GMs would be beneficial.

II. Standardized time synchronization mechanisms

In this section, we present standardized mechanism for the time synchronization in 5G-TSN networks. We provide details on resiliency and redundancy support specified by 3GPP and IEEE 802.1 standardization bodies. We also present the limitations of the current time synchronization mechanisms.

A. Time synchronization in 5G-TSN networks

In the context of synchronization, 5GS can operate in various modes: as a time-aware system [IEEE 802.1AS], a boundary clock , a peer-to-peer transparent clock, or an end-to-end transparent clock [IEEE 1588]. In the 5GS-TSN network, distinct synchronization mechanisms work together to achieve E2E time synchronization, as shown in Fig. 1. On the one hand, the components of the 5GS (e.g., the user equipment (UE), user plane function (UPF), and gNodeB (gNB)) are synchronized using the internal 5GS synchronization mechanisms based on the 3GPP TS 38.331 and ITU-T G.8275.1 to the internal 5GS clock, which receives time from a global navigation satellite system (GNSS). On the other hand, the TSN nodes (i.e., end stations and bridges) are synchronized according to the precision time protocol (PTP) profile generic precision time protocol (gPTP) [IEEE 802.1AS-2020], to a GM clock residing either in the TSN network or in the 5G network. The gPTP is supported by the two functional entities at the boundaries of the 5GS, namely the device side TSN translator (DS-TT) located on the device side of the 5GS at the UE and the network side TSN translator (NW-TT) located on the network side of the 5GS at the UPF. The internal 5GS synchronization mechanisms are used to synchronize the UE/DS-TT [TS 38.331] and the NW-TT [G.8275.1]. The synchronization between gNB and UE/DS-TT is also referred to as access stratum time distribution. The synchronization mechanisms between UE and DS-TT are not specified by the 3GPP. The 3GPP has specified a time error contribution between the ingress and egress of the 5GS for the synchronization messages to be no more than 900 ns [TS 22.104]. The GM location introduces correlations among the different synchronization mechanisms [5]. Hence, 3GPP has standardized three different options for a GM to synchronize the TSN nodes in 5G-TSN networks [3].

First, *downlink synchronization* (as shown in Fig. 1 in dark blue) was standardized by 3GPP in Rel-16. In this configuration the GM for TSN nodes resides on the network side of the 5GS connected to the UPF. The downlink GM synchronizes all the TSN devices within its time domain connected both to the network-side of the 5GS and to the device-side of the 5GS, as shown in Fig. 1. The synchronization error for TSN nodes, which lie beyond the 5GS and are part of downlink synchronization, is impacted by the 5GS residence time accuracy. This accuracy relies heavily on the 5GS internal clock based synchronization of NW-TT and DS-TT.

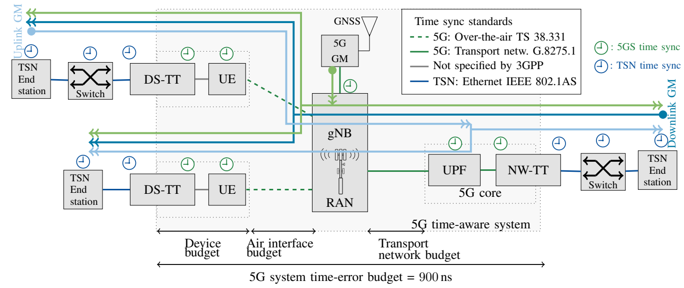

Fig. 1. Time synchronization in 5G-TSN network where 5GS operates as a time-aware system. Time synchronization for downlink GM (dark blue), uplink GM (light blue) and 5G GM (green) are provided. The GMs are represented with small colored dots.

Second, *uplink synchronization* (as shown in Fig. 1 in light blue) was standardized by 3GPP in Rel-17. In this configuration the GM for TSN nodes resides on the device side of the 5GS. The uplink GM synchronizes all the TSN devices within its time domain connected both to the network-side of the 5GS and to the device-side of the 5GS, as shown in Fig. 1. Here the gPTP messages to synchronize the other TSN devices on the device side need to traverse the wireless link (air interface, shown with green dashed line in Fig. 1) between UE and gNB twice. Similar to downlink synchronization, the synchronization error is closely related to the accuracy of residence time estimation, which relies on the 5G internal clock. Note that for the air interface, the time error increases significantly which leads to cases where it may exceed the required time error budget of 900 ns. To remedy this, 3GPP has proposed to add the air interface propagation time to the time reference. In this way, the air interface propagation delay is taken into account in the synchronization, and therefore the time error can be minimized [6].

Finally, *time synchronization as a service* allows external networks (e.g., a TSN network) to access the 5G timing by requesting the application function (AF) using time synchronization application programming interfaces (APIs) introduced in Rel-17 [3GPP TS 23.501]. Two different types of time synchronization services are supported via a UE. Either a gPTP time distribution method, where gPTP messages are forwarded via the user plane between a GM and a timeReceiver. Or an access stratum time distribution method where the 5G clock is disseminated using control plane signaling over the air interface.

B. Support for resiliency and limitations

As the quality of 5GS clocks is constantly improving, it is becoming less dependent on the GNSS or even can be considered as a terrestrial backup for GNSS. With Rel-18, 3GPP has introduced a timing resiliency service for an external network, which monitors the performance of the 5G time synchronization and provides a status report. If a status change (degradation, failure or improvement) is detected, the next generation-radio access network (NG-RAN) sends either a high level status report or detailed clock quality metrics to the UE using the service [3GPP TR 23.700]. This support for timing resiliency allows for the detection of faults and degradation in quality of the time synchronization.

IEEE 802.1AS employs the best timetransmitter clock algorithm (BTCA) as defined by IEEE 1588 for dynamically selecting a GM in a time-aware network. The BTCA compares the clock quality attributes to choose a GM. As soon as a GM fails or stops sending timing information, BTCA is initiated and a new GM is chosen. The time synchronization as a service allows for the 5GS clock to be used as a GM for the external networks (e.g., a TSN network) by exposing the 5GS clock quality metrics such that the 5GS clock can take part in the BTCA used in gPTP. The BTCA in the event of a failure introduces a downtime period until a suitable replacement is identified. Consequently, BTCA's response to device or link failures is characterized to be slow, which can be detrimental in time-critical applications. Additionally, BTCA is unable to detect instability of a GM clock, hence leading to a ping-pong effect to find the best GM.

Both 3GPP and IEEE 802.1 standards provide support for multiple GMs and multiple time domains to support industrial applications requiring universal time and a working time and to introduce fault tolerance. Different domains are identified by their domain number. IEEE 802.1AS-2020 requires a mandatory domain 0 (for backward compatibility with IEEE 802.1AS-2011) and additional domains are optional, where the IEEE 802.1 industrial automation profile [P60802] defines that the minimum number of domains supported by an end station depends on its device class. In 3GPP the maximum number of domains that can be supported by a network is limited to 32. So far these working domains are independent of each other (i.e., the different GMs do not synchronize to each other). Additionally, 3GPP also supports local configuration for determining the GM and the synchronization spanning tree.

In order to address the above-mentioned limitations of BTCA, the process of selecting and configuring multiple GMs is specified in the IEEE 802.1ASdm standard leveraging the TSN profile for industrial automation [P60802]. The hot standby amendment proposes a static configuration of two independent GMs by an external entity, such as a management entity (e.g., centralized network configuration (CNC)) using the external port configuration option. Consequently, the BTCA is no longer used to select a GM within a domain. The two independent GMs are termed as primary and hot standby GM. The hot standby GM synchronizes itself with the primary GM before transmitting timing messages within its domain. This procedure ensures that the time provided by both GMs remains within a tolerance range, resulting in consistent time provision. The end station uses the primary time domain for its application as long as the hot standby system is in the redundant state (i.e., both time domains are available). The standard proposes an optional split functionality that transfers synchronized time from a synchronized GM to an out-of-sync GM. Thus, the split functionality allows the hot standby mechanism to recover from a non-redundant state to a redundant state (i.e., two active GMs).

While both the 3GPP [7] and IEEE 802.1 [8] standardization bodies acknowledge the need for continuous time synchronization by introducing support for multiple GMs and multiple synchronization paths, limitations persist as mentioned above. Hence, in the context of 6G networks looking into a solution similar to IEEE 802.1ASdm, i.e., a hot standby GM could be of interest to reduce the downtime period in case of failures for the time-critical applications.

III. Resilient time synchronization architectures

By provisioning resilient time synchronization, 6G networks can unlock their full potential for emerging use cases in the converged wired-wireless network landscape. Redundancy plays a crucial role in achieving resilience and fault tolerance, guaranteeing continuous time synchronization even in the event of failures. In this study, we focus on bringing the 3GPP and IEEE 802.1ASdm standards together to enable redundancy in timing sources as means of ensuring resilient time synchronization for the future 6G networks. Even though the IEEE 802.1ASdm standard clarifies details about how the two domains (primary and hot standby) will work together, there are several questions that still remain open when incorporating hot standby GM to a 6G-TSN network. First, as the two GMs are statically defined by an external management entity, what attributes need to be considered when choosing a GM in a network? Second, considering the 6G-TSN networks, specifically when wired and wireless technologies come together, where the two GMs should be located? In this paper, we approach these questions by providing considerations for selecting a GM and presenting some time synchronization architectures for the placement of two GMs in the 6G-TSN networks.

A. Important considerations for GM selection

For a clock to qualify as a GM, two critical attributes come into play: the precision of its timing source (such as an oscillator, atomic clock, or GPS) and its granularity. Traditional terrestrial networks have relied on GNSS receivers to access highly accurate time. GNSS receivers derive their time from the atomic clocks onboard the satellites. In general, atomic clocks possess the capability to provide clock frequencies with unparalleled accuracy, surpassing the capabilities of any other physical device, such as a quartz crystal oscillator [9]. Clock granularity pertains to the oscillation period of a physical clock and determines the maximum attainable resolution for time measurements. On the one side, not every device can be connected to expensive GNSS receivers to allow access to accurate time given the high maintenance and deployment costs. Additionally the performance of GNSS receivers is limited in indoor environments. On the other side, the clock granularity can be physically limited by its oscillator's frequency.

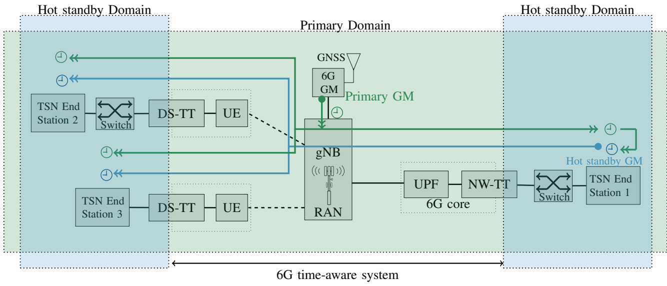

Fig. 2. 6G GM as primary GM and network-side TSN end station as hot standby GM.

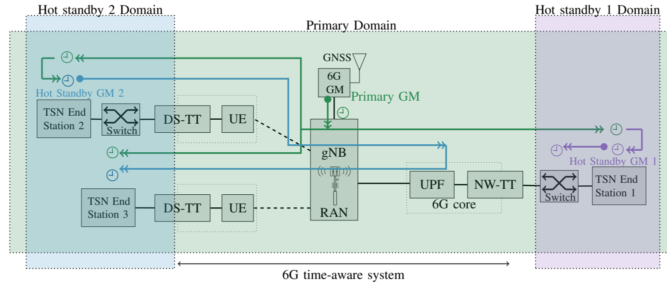

Fig. 3. 6G GM as primary GM and one hot standby GM on device-side TSN end station and another hot standby GM on network-side TSN end station.

Apart from the clock's intrinsic time keeping properties, the synchronization quality also depends on the quality of the communication link between the local clock and the GM. Wireless links are inherently more error prone as compared to wired links. Hence, the synchronization accuracy achieved at an end-station connected via a wireless link to its GM is lower than for an end-station connected via a wired link to its GM. As we move towards large scale industrial networks, the overall network topology and the location of an end-station in relation to its GM also affects the synchronization quality in the network. The synchronization error accumulates over multiple hops. Hence, end-stations farther away from the GM have worse time synchronization accuracy.

The effect of GM location on the subsequent time synchronization quality in the network has been studied previously for TSN and 5G-TSN networks. Gutiérrez et al. [5] demonstrated the cumulative effects of PHY jitter and clock granularity as synchronization information propagates farther from the GM. Specifically in a TSN network, their findings reveal that synchronization accuracy deteriorates from $0.6\,\mu$s to about $2\,\mu$s for the last end station in a chain of 100 hops. In the context of a 5G-TSN network, Schüngel et al. have introduced an enhanced BTCA designed to consider the relative positioning of the GM [6]. This algorithm incorporates network-related information in its decision-making process to account for the impact of architectural aspects when selecting a GM. The authors have also analyzed the synchronization quality in a 6G-TSN network, considering different GM locations [10]. They found that the error introduced by the integration of 5G with TSN, introduces an additional error to the time synchronization that is equivalent to ≈ 36 additional hops. Jeon et al. propose to use a pre-defined ordered list of GMs to reconfigure the GM to avoid accumulation of error given consecutive exchange of messages in traditional BTCA [11].

B. Time synchronization architectures with hot standby GM

Next we present the proposed hot standby architectures in the light of 3GPP and IEEE 802.1 standards and the above mentioned considerations for selecting a GM. In order to ensure resilient time synchronization, the TSN nodes in the 6G-TSN network are synchronized via a primary and a hot standby GM at the same time. Hence the following architectures present possible options for a primary GM and a hot standby GM. In particular, we provide details on where the primary GM and the hot standby GM could reside in a 6G-TSN network. Additionally, we also provide details on how the system would behave in case either of the GM fails. The ability of the 6G GM to provide synchronized time with high accuracy is considered out-of-scope for this paper. Here it is important to note that, the GM in a TSN network is a time aware system which could either be a TSN end-station or a TSN bridge fulfilling the requirements of a GM as mentioned above. We present the options where the GM in a TSN network would reside on a TSN end station.

1) Both primary and hot standby GM on network-side TSN end-stations: – In this architecture, it's worth noting that both, the primary and hot standby GMs, may lack access to a high-quality timing source (e.g., the 6GS clock). Moreover, given that the 6G-TSN network is specifically configured for use cases involving mobility or scenarios where an Ethernet implementation is unfeasible, an unlikely event of disruption of the 6G virtual bridge (e.g., a loss in connectivity) would result in the end-stations on the device-side losing synchronized time from both GMs, and would eventually drift away based on the quality of their local clocks.

2) Both primary and hot standby GM on device-side TSN end-stations: – This architecture has similar drawbacks as the architecture option 1. Additionally, with both GMs on device-side TSN end-stations, it would mean a higher time error for device-side TSN end-stations given the air interface (as discussed in Section II).

3) Network-side TSN end station as primary GM and device-side TSN end station as hot standby GM: – This architecture has a similar disadvantage as architecture options 1 and 2 in terms of timing source quality. However, in case there is a disruption of the 6G virtual bridge, each part of the TSN network would still have access to the synchronized time.

4) 6G GM as hot standby GM and network/device-side TSN end station as primary GM: – This architecture is interesting but has some limitations. Considering the recommendation in the IEEE 802.1ASdm standard, the hot standby GM should synchronize to the primary GM before transmitting timing messages. Since the 6G GM is also used to synchronize the other 6G elements like the gNB, UPF and other UEs for their proper functioning, this option would not be feasible. Hence keeping two timing sources, that are not synchronized to each other would not provide the benefits aimed with redundancy of GMs.

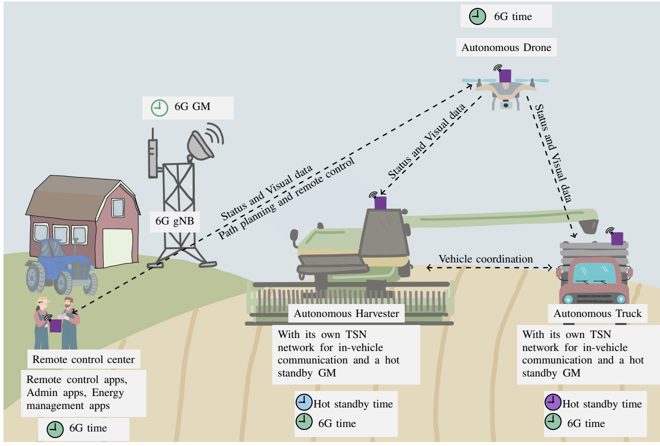

Fig. 4. Smart farming use case scenario with autonomous vehicles assisted harvesting.

5) 6G GM as primary GM and network-side TSN end station as hot standby GM: – This architecture benefits from the higher quality (access to GNSS time) 6G clock. On one hand, in a case of failure of the primary (6G) GM (e.g., loses access to GNSS time), the gNB can still support time synchronization for a certain time while being in a holdover state. On the other hand, having the hot standby GM on the network side helps keeping the time-error low for device-side TSN end-stations given the timing messages only travel once over the air interface, as shown in Fig. 2.

6) 6G GM as primary GM and device-side TSN end-station as hot standby GM: – In this architecture, the hot standby GM synchronizes the TSN end-stations using the uplink synchronization as mentioned in Sec. II.A. This architecture has similar benefits of having the 6G GM as primary GM. Whereas, with the hot standby GM on the device-side TSN end station, it could result in a higher time-error for other device-side TSN end stations, as the timing messages have to traverse the wireless link twice.

7) 6G GM as primary GM and one hot standby GM for the network-side TSN end stations and one hot standby GM for the device-side TSN end stations: This architecture is different from all above mentioned as it enables three different time domains with one primary GM and two different hot standby GMs, as shown in Fig. 3. Both hot standby GMs will first synchronize to the 6GS GM. Hence in this case if the primary (6G) GM fails, both device side TSN end stations and network side TSN end stations would still be synchronized to their own hot standby GMs.

IV. Discussions and Use Cases

Considering the argumentation provided above, one could choose the most suitable placement for the two GMs for a 6G-TSN network based on the application or use case scenarios. Given the high quality clock of a 6G GM, it would be desirable to use it as the primary GM. Additionally, as it is not desired that the 6G GM synchronizes to an external (non-6G) clock, it becomes a natural choice for it to never be a hot standby GM, given that, according to the IEEE 802.1ASdm, the hot standby GM should first synchronize to a primary GM. The hot standby GM could be a TSN end-station, since in order to maintain the continuous time synchronization it needs to first synchronize to the primary GM. Additionally, having different hot standby GMs for different sections of the network seems to be ideal in order to keep the lowest time error. Additionally, the optional split functionality in the IEEE 802.1ASdm standard should be set to FALSE, for the use cases which would employ architectures where one of the GMs is the 6G GM. This would stop the hot standby GM to try to synchronize the 6G GM with its clock once the 6G GM or 6G connection is restored.

Next we discuss different use cases including smart farming, adaptive manufacturing, exoskeletons, extended reality (XR), teleoperated surgery, and autonomous driving, where redundancy of the timing source would be highly beneficial to achieve the desired operational targets and support E2E deterministic communications. *Smart farming* leverages technology to optimize agricultural operations. Accurate and continuous time synchronization is critical for scenarios with coordinating harvesting using unmanned ground vehicles and drones. In such scenarios, the drone would be used to observe the field for possible humans and animals as harvesting takes place. Based on the observations of the drone and the control information from the remote control center, the behavior of the harvester is controlled [12]. The placement of different hot standby clocks for this scenario is depicted in Fig. 4. Here the autonomous ground vehicles, the autonomous drone, and the remote control center are synchronized to the 6G time via the primary GM residing at the 6G gNB. Additionally, each autonomous ground vehicle receives timing messages from a hot standby GM residing within its own in-vehicle TSN network. In this scenario, redundancy of the GM would help not only to protect wildlife, but would also be greatly beneficial to achieve maximum resource efficiency.

In *adaptive manufacturing* environments, where robots and machinery operate in close proximity, continuous time synchronization is paramount. Reliable timing ensures that collaborative robotic movements and interactions are precisely coordinated. Redundant time sources enhance reliability, ensuring that automated processes continue smoothly even in the event of time synchronization disruptions from one of the time sources.

Exoskeletons worn by industrial workers, to reduce physical load during intensive work, demand accurate and continuous time synchronization [12], [13]. Exoskeleton scenarios where part of the control system is off-loaded to the edge/cloud become particularly sensitive to loss of time synchronization during task transitions (e.g., walking/load lifting). Even though the exoskeleton's control system includes specific safety loops designed to detect any faults and/or unexpected behaviors via the embedded sensors within its own TSN network. The presence of the hot standby clock could increase the system robustness and availability by preventing potential risks caused by the loss of time synchronization. In other scenarios, a cooperative task could require multiple operators wearing the exoskeleton, or even an operator and an autonomous machine in the factory, to work in synergy to perform a certain task. In these scenarios, the hot standby clock would support continuous assistance even in rapidly changing dynamics of the task.

In *XR* applications like virtual reality (VR) and augmented reality (AR), along with bounded latency, continuous synchronization is vital to ensure virtual objects align seamlessly with real environments, enhancing immersion. Especially in scenarios where computations performed in the edge/cloud need to be fused with relative motion estimation or head motion compensation performed locally at the XR device, a loss in time synchronization could degrade the user experience [4], [12].

Teleoperated surgery is an interesting use case to provide life-saving health care in extreme conditions and also helps remove any geographic or economic boundaries [14]. In this scenario, redundancy of the timing source would ensure precise and continuous coordination and communication between robotic components.

The rise of *autonomous and self-driving cars* is propelling the digitization of embedded devices and vehicle functions, reshaping in-vehicle networks to resemble private 5G networks [15]. Here introducing redundant timing sources would ensure high availability of vehicle-to-infrastructure (V2I) and vehicle-to-everything (V2X) technology.

V. Conclusions

This paper highlights the importance of redundancy in GMs to achieve resilient time synchronization in 6G-TSN networks to support E2E deterministic communication. We present key considerations for the placement of GM clocks and propose different time synchronization architectures with a hot standby GM for the 6G-TSN networks. We analyze the presented architectures in the context of current 3GPP and IEEE 802.1 standards. We find that choosing 6G clock as a hot standby GM is not optimal. This is because a hot standby GM needs to first synchronize to the primary GM and it is not desirable for the 6G clock to take timing from an external (non-6G) clock. Additionally, choosing a GM connected to the network via a wireless link could increase the time error. Moreover, the optimal placement of the two GMs depends on different use case scenario requirements.

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