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TUTORIAL

Evolution of Timing Services From 5G-A Toward 6G

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ABSTRACT 5G-Advanced and 6G networks will serve as critical infrastructure for society and will enable a new generation of immersive use cases, such as the metaverse, wherever people roam. Absolute time is an essential component to ensure critical use cases, synchronize media playout, and timestamp events to be used in machine learned contexts. Until now, timing on the go has mainly been acquired by satellite, e.g., Global Navigation Satellite System (GNSS), but a terrestrial timing solution using cellular networks is required to extend coverage to deep indoors and to offer resilient operation in GNSS-denied environments (e.g., due to GNSS signal interference, jamming and spoofing). In this paper, we detail the use cases for timing to be provisioned by 5G-Advanced and 6G networks. Then, we discuss the architectural enablers for timing as a service in current 5G and 5G-Advanced standard and timing resiliency enablers under discussion in the 3rd Generation Partnership Project (3GPP). Finally, we discuss the gaps and research challenges to be solved in 6G for future-proof timing solutions.

INDEX TERMS Time-of-day service, timing resiliency, 5G Advanced, 6G, architecture enablers.

I. INTRODUCTION

For cellular connectivity, the user equipment (UE) needs to know at which frequency and exact time instant it can exchange traffic with the base station, thus the UE and the base station are relatively synchronized to each other [1]. Further, cellular networks require absolute time synchronization (i.e., all nodes synchronized to an external source of time), for instance to ensure co-existence between operator's time division duplex (TDD) deployments and to use advanced radio features such as coherent transmissions.

Recent focus in 5G has been on extending the time synchronization support to the device, i.e. to synchronize the UE and attached device sub-systems to a known reference clock, e.g., typically the Coordinated Universal Time (UTC). Initially, focus has been on meeting the very strict accuracy demands of time synchronization for Industrial IoT (IIoT) and time-sensitive Ethernet networks and services [2], [3]. Later, the scope was expanded to support time synchronization for IP networks [4].

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5G time-of-day services with microsecond accuracy can empower low-cost and low-power timing devices and clocks. In this paper, we explain the many use cases for a time-of-day service provided by 5G/5G Advanced (5G-A) and future 6G networks. We then outline the enabling architectural components technologies, both those recently specified for 5G/5G-A and those expected as future enhancements to make 5G-A networks a fully viable technology alternative or supplement to Global Navigation Satellite System (GNSS)/ Global Positioning System (GPS) for providing time synchronization to UTC or any well-defined time reference. We then outline the main remaining gaps to be bridged in 6G architecture and technology research, to cover extended future use cases.

II. FUTURE USE CASES FOR TIME IN WIRELESS NETWORKS

The availability of a common absolute time understood by both wireless devices and network functions (e.g., typically UTC), has a wide range of usage as exemplified in the following subsections.

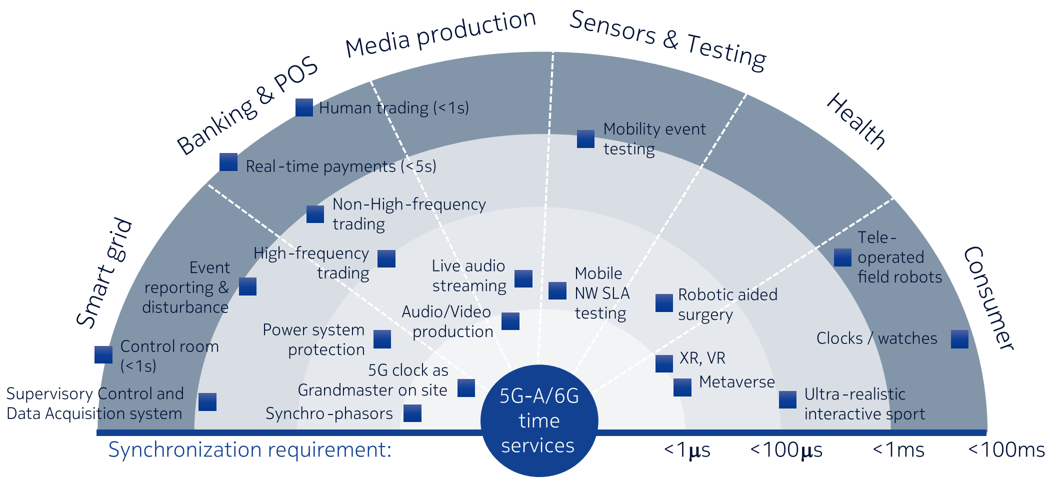

FIGURE 1. Wide area time-services use cases in 5G-A and 6G radar.

A. END-USER APPLICATIONS

A list of end-user use cases for absolute timing in wide area networks, including typical required synchronization accuracy numbers, are summarized in Fig. 1 as a radar chart. The radar captures the synchronization accuracy requirement range as semicircular areas and groups the use cases in different use case segments. For example, within the consumer segment, many upcoming XR (e.g., augmented, virtual, and mixed reality) services and holographic applications rely on synchronized media layers, where time synchronization is needed to align playout buffers. Additionally, to unleash the machine learning based optimizations, timestamping of captured real world events is an essential capability to extract meaningful correlations and actions. The combination of the synchronization accuracy requirement along with other use case Quality of Service (QoS) demands will determine if the time-service applies to 5G-A or 6G. That is, basic XR and VR support will be enabled by 5G-A networks, but it is not envisioned that full "metaverse" experiences become available until 6G is deployed. Note that besides those shown in Fig. 1 for wide area, there are many use-cases for time-services in 5G-A and 6G that will be based on dedicated installations, e.g., wireless time-sensitive networking in Industrial IoT, in-vehicle critical networks, etc.

B. TIMING RESILIENCY

Another use is for cellular networks to be an alternative solution or backup for satellite/GNSS based time for applications. Wireless networks also provide excellent indoor coverage where GNSS reach is often limited and expensive to establish. Further, wireless networks are not directly vulnerable to many risk factors of satellite systems [5], e.g., solar storms, non-terrestrial attack vectors, etc. However, wireless networks themselves rely largely on e.g., GNSS provided timing today to operate, and a prerequisite is that they become robust to temporary or long-term failure of GNSS. Solving that issue, commercial 5G-A/6G networks can fulfill needs as per timing resiliency initiatives intended to protect critical infrastructure, e.g., [6].

C. INTEGRATION TO TIME-SENSITIVE AND INDUSTRIAL NETWORKS

For 5G-A and 6G to wirelessly extend time-sensitive networks, e.g., based on IEEE Time Sensitive Networking (TSN) [7] or IETF Deterministic Networking (DetNet) [8], support for absolute time-synchronization and compatibility with standard time-synchronization protocols such as IEEE Std 802.1AS [9], is a pre-requisite.

D. SPECTRUM SHARING AND CO-EXISTENCE

Accurately time-synchronized wireless networks and devices can participate in much more effective spectrum sharing and co-existence schemes, adding time-domain multiplexing on top of spatial and frequency domain separation schemes. This enables more aggressive utilization of spectrum and a much higher density of private wireless networks and co-existence of different access technologies to the same spectrum.

E. EXTENDED QOS/QOE MONITORING

Absolute time-synchronization, including timestamping capabilities in the device, enables highly accurate one-way delay measurements that enable dynamic monitoring and optimization of network parameters versus end-user experience.

III. ARCHITECTURAL ENABLERS IN 3GPP 5G/5G-A

The following time synchronization methods are supported in 5G/5G-A:

1) Direct provisioning of the 5G/5G-A System (5GS) clock (e.g., epoch/UTC) to the UE.
2) Use of generalized Precision Time Protocol (gPTP) to integrate to IEEE TSN and Ethernet networks.

3) PTP time synchronization method for 5GS to offer timing support for IP or Ethernet networks.

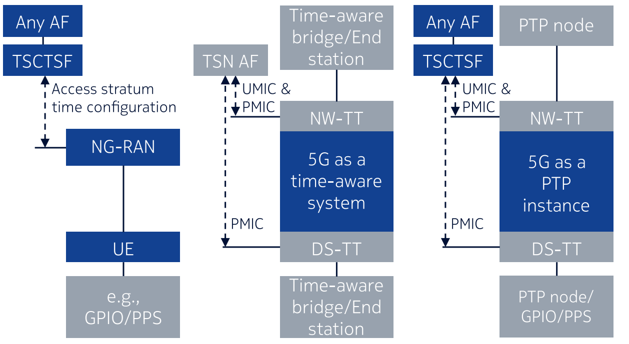

FIGURE 2. 5G/5G-A time synchronization architectures. Scenario 1) illustrates direct time synchronization over the air interface. Scenarios 2) and 3) illustrate gPTP and PTP time synchronization over the user plane. Dark blue boxes are within 3GPP scope. Gray boxes are defined in 3GPP but most of the functionality follows IEEE/non-3GPP specifications.

Besides 5GS clock, methods 2 and 3 also support external time-domains, with grand masters located both at the network and the UE side (e.g., both downlink and uplink time synchronization). To enable above time synchronization methods the necessary architectural enablers are summarized in Fig. 2 and explained in the subsequent paragraphs.

A. DIRECT TIME SYNCHRONIZATION OVER THE AIR INTERFACE

The 5G Next Generation - Radio Access Network (NG-RAN) can provide epoch/UTC time directly to the device or UE over the air interface, as illustrated in Fig. 2 scenario 1. To avoid ambiguities related to time of transmission and reception, the Reference Time Information (RTI) is provided in reference to a certain air interface event (a System Frame boundary) easily identifiable by the UE. Additionally, the RTI includes an uncertainty field that indicates how accurate the reference time information provided by the network is. The RTI can be delivered to the UE using broadcast to the whole cell, via the System Information Block 9 (SIB9), or via dedicated Radio Resource Control (RRC) messages targeted for a single device. The use of RTI achieves time synchronization accuracy for the 5G clock down to sub-μs level [10]. For wide area scenarios where the UE and the NG-RAN node may be far away, additional mechanisms compensate propagation delay on the radio interface [11]. Uncompensated access to the epoch/UTC broadcast timing can be achieved even without an active subscription to the network, although accuracy might be then limited to 5-10 μs. As a result, a myriad of devices with different synchronization capabilities can be supported, as summarized in Table 1. Note that the achieved synchronization accuracies in practice will depend on both UE and network implementation.

TABLE 1. Synchronization solutions for standalone devices.

Device Type	5G subscription required	Synchronization methods	Accuracy level
UE with PTP support	Yes	6G OAS[1], PTP	<1us
UE with GPIO[2]	Yes	6G OAS	<1us
UE with software application	Yes	6G OAS	<10us
Low-cost, low-power device	No	Uncompensated 6G OAS	<10us

[1]Over the Air Synchronization (i.e., RTI); [2]General-Purpose Input/Output.

B. PTP AND gPTP SUPPORT

In release 16, 3GPP introduced new mechanisms for the 5GS to interwork with IEEE TSN networks. IEEE TSN networks use common time synchronization to achieve determinism. As shown in Fig. 2 scenario 2, 5GS acts as a bridge and "time-aware system" when it is integrated with IEEE TSN networks [11], [12]. As a TSN domain uses its own clock domain, gPTP is used to distribute the time information from a grandmaster (GM), the main source of time, to all the time receivers. gPTP is a profile of PTP that defines the essential features and restricts some options of PTP. For other use cases, PTP is widely used to synchronize clocks through a network [13] and its support by 5GS was introduced in 3GPP release 17. As a result, the 5GS can be integrated in a PTP network as another PTP node that disseminates either the 5GS clock or an external clock, see Fig. 2 scenario 3.

While supporting external time domains, the 5GS still uses its own time (typically UTC) as its essential also for wide area network operators and co-existence between networks in adjacent frequency bands. Thus, a translation between the 5GS clock and the (g)PTP domain needs to take place. To leverage IEEE specifications in 3GPP, the support of (g)PTP is done at the edges of the 5GS with introduction of two new functional entities: Device-Side TSN Translator (DS-TT) on the UE side and the Network-Side TSN Translator (NW-TT) on the 5G network side, as illustrated in Fig. 2 scenarios 2 and 3. It is up to implementation how the DS-TT is integrated at the UE side or how the NW-TT is integrated at the User Plane Function (UPF) side. The TTs are responsible of PTP operation (e.g., timestamping, PTP messages correction, PTP path or link delay measurements, residence time in 5GS determination, etc.) and the 5GS is used to transport the time information through the system up to the PTP time receivers. The 5GS can be configured to operate in different modes:

- As a time-aware system following gPTP operation [9].
- As a PTP Boundary Clock. The 5GS is used as the source of time. That is, the 5GS maintains the timescale used in the PTP domain and synchronizes the connected PTP time receivers.

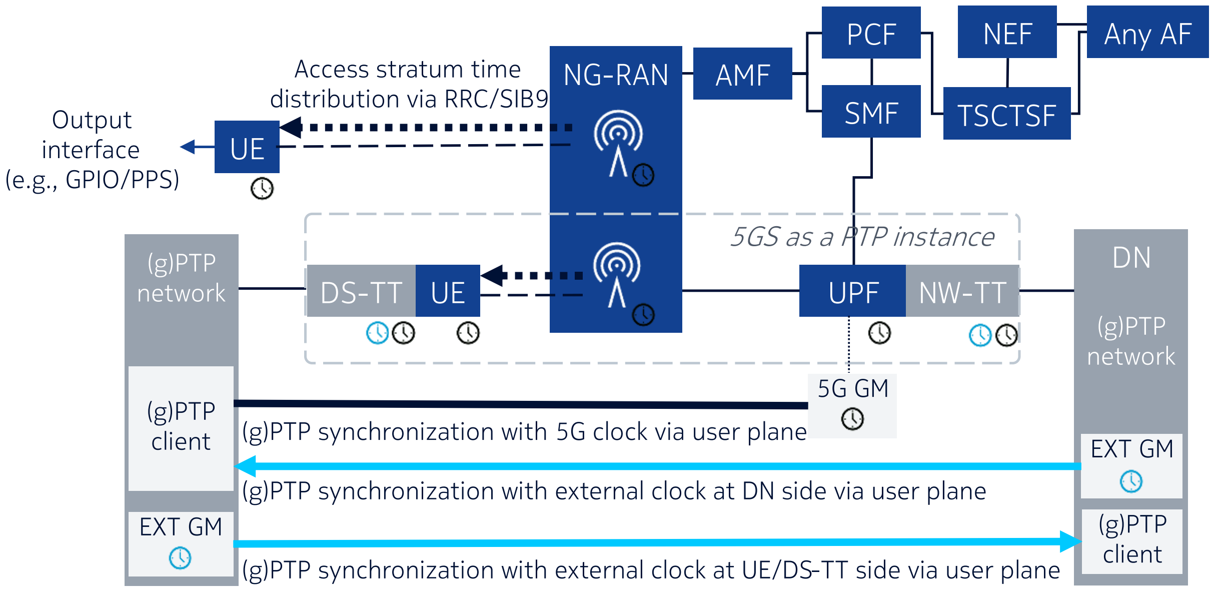

FIGURE 3. Methods for time synchronization as a service in 5G/5G-A. Dark blue boxes are within 3GPP scope. Gray boxes are defined in 3GPP but most of the functionality follows IEEE/non-3GPP specifications. Light blue colored clocks indicate external clock. Black colored clocks indicate 5GS clock.

- As a PTP Transparent Clock. The 5GS measures the time taken for the PTP event messages to travel within the 5GS, referred to as the residence time, is used to correct PTP messages. Two different PTP Transparent Clock operations are supported: i) End-to-end Transparent Clock, where the delay measurement is end to end between the PTP transmitter and receiver and the sum of the residence time along the path is reported to the PTP time receiver, and ii) Peer-to-peer Transparent Clock, where all link delays are measured on a peer to peer basis and the sum of residence time and link delay along the path is reported to the PTP time receiver.

For controlling PTP operation within the 5GS and at the same time only involving the 5G network elements involved with PTP operation, containers with the (g)PTP attributes are exchanged (e.g., messages intervals, GM capabilities, port status, etc). There are two type of containers, Port Management Information Container (PMIC) and User Plane Node Management Information Container (UMIC), as illustrated in Fig. 2 scenarios 2 and 3. The PMIC controls the operation of a port at the DS-TT or the NW-TT. The UMIC controls the operation of the 5GS as a PTP instance at the NW-TT. These containers are transparently forwarded within the 5GS up to either:

- TSN Application Function (TSN AF). For TSN scenarios, the TSN AF is responsible to manage the integration of the 5GS with the TSN network. The TSN AF is part of the 5G core and provides interaction with the Central Network Controller (CNC) that is responsible for controlling the TSN bridges in the network. Therefore, the TSN AF is operated by the administrator of the TSN network. Thus, the TSN AF exchanges PMIC/UMIC to configure gPTP operation.
- Time Sensitive Communication and Time Synchronization Function (TSCTSF). A new network function introduced in 5G release 17 to support the TSC toolbox (e.g., time synchronization, periodic deterministic communications). For time synchronization, the TSCTSF is responsible to manage time synchronization services and control DS-TT and NW-TT operation via exchange of PMIC and UMIC to configure gPTP or PTP operation. For gPTP, TSN AF supports integration with IEEE TSN system thus also supports interworking with CNC.

C. TIME SYNCHRONIZATION AS A SERVICE

Offering time synchronization as a service in 5G/5G-A means there is a consolidated Application Programming Interface (API) that represents a unified access to the time synchronization for 3rd parties. Enabling the request of time synchronization as a service in 5G/5G-A is key to create solutions that adapt to the end user application timing requirements. Using the exposure framework, an application server from a 3rd party can communicate with the 5GS via the AF using the time synchronization APIs introduced in release 17 and request the service it needs for a UE or a group of UEs. Then, it is up to the 5GS to configure the 5G system (e.g., the NG-RAN nodes) to satisfy the service request the AF provided.

Two new capabilities were introduced within the exposure framework: i) any AF can request time synchronization as a service, and ii) an AF can learn 5GS and/or UE availability and capabilities for time synchronization service [4]. Using Fig. 3 as a reference, when an AF requests time synchronization as a service, the TSCTSF is in charge of receiving the AF request and setup the service following the corresponding conditions and requirements. The AF can include two conditions: i) temporal validity condition, it describes the time period the service should be active, and ii) requested coverage area (under discussion in 3GPP release 18), it describes the spatial validity condition where the service should be active. Optionally, the AF can provide a time synchronization error budget. This error budget describes the end-to-end time uncertainty that the service can tolerate in the time distribution chain. From the error budget provided by the AF, the TSCTSF derives the Uu time synchronization error budget that defines the specific time error for the radio interface between the UE and the NG-RAN node. If the AF does not include a time synchronization error budget, the TSCTSF may still derive a Uu time synchronization error budget for the UE based on preconfigured values.

Any AF can request one of the two types of time synchronization services supported in the 5GS for a UE:

- (g)PTP time distribution method: It uses (g)PTP messages forwarded via user plane, as illustrated in Fig. 3 with solid arrows between a GM and a PTP time receiver. This service can be configured to disseminate an external clock (blue clock in Fig. 3) or 5GS clock (black clock in Fig. 3). The GM of the (g)PTP domain, i.e., the source of time, can be located at the UE/DS-TT side, at the data network (DN), or at the UPF/NW-TT (only for 5GS clock dissemination). This service can be configured for UEs with a Protocol Data Unit (PDU) Session for IP or Ethernet scenarios.
- Access stratum time distribution (ASTI) method: It uses RTI delivered from the NG-RAN node to the UE via control plane at the radio interface, as illustrated in Fig. 3 with dotted arrows between the NG-RAN node and the UE. This service introduced in 3GPP release 17 allows the AF to request RTI delivery for a UE compared to previous releases where only the UE was able to indicate its preference to RTI provision to the NG-RAN node using UE assistance information. ASTI can be only used to disseminate 5GS clock and does not require the UE to have an active PDU Session, as it only relies on control plane signaling. To control access stratum time distribution at the radio interface, existing control plane exchanges in the specification are reused adding two new attributes (i.e., indication to enable/disable RTI delivery and Uu time synchronization error budget). To forward these attributes from the TSCTSF to the NG-RAN node, there is no direct control plane interface between both elements, as shown in Fig. 3. Thus, the TSCTSF uses the Policy Control Function (PCF) to reach the Access and Mobility Management Function (AMF) that will forward the attributes to the corresponding NG-RAN node.

Both methods cannot be requested by the AF for the same UE but (g)PTP operation relies on the DS-TT being synchronized to the 5GS clock (as can be seen in Fig. 3) with black clocks at DS-TT and NW-TT associated with the 5GS as a PTP instance). Therefore, access stratum time distribution is required to provide the 5GS clock to the UE/DS-TT.

To be able to cover use cases where the AF may not be available to request time synchronization, further enhancements for time synchronization service are under study in 3GPP release 18 to enable the activation of time synchronization service ((g)PTP method or ASTI method) based on the UE subscription. With this, UE subscription data types include time synchronization data that enable the 5GS to activate the service as soon as the UE registers with the 5G network (for ASTI) or establishes a PDU Session (for (g)PTP).

D. TIMING RESILIENCY

As 5G time-of-day service may be used in critical infrastructure, and with the mindset that 5G can be used as a land-based backup for GNSS, 5G itself has to be less dependent on GNSS. To this end, 3GPP is studying the support for 5G-A timing resiliency requirements under the ongoing 5G release 18 [14]. As an evolution for time synchronization as a service, this resiliency dimension exploits the monitoring of the time synchronization status of the network elements involved in the time distribution chain (e.g., the serving NG-RAN node or the UPF/NW-TT). The enablers for 5G-A time synchronization status monitoring solution are illustrated in Fig. 4 and Fig. 5.

Following the steps shown in Fig. 4, in step 1 the NG-RAN node (for ASTI or (g)PTP based service) or the UPF/NW-TT (if applicable for (g)PTP based service) detect timing synchronization degradation, failure, or improvement. If a status change is detected, in step 2a the RAN node notifies the UEs subscribed to this service regarding the RAN timing synchronization status. This sub-procedure is further illustrated in Fig. 5, where the reporting to the UE can be at a high level indicating if the service is acceptable or not (based on acceptance criteria available in the UE subscription or provided by the AF) or the detailed clock quality metrics (i.e., RAN clock quality information such as clock accuracy, traceability to UTC, time source, synchronization state, frequency stability). Additionally, in step 2b, the TSCTSF may receive the RAN or UPF/NW-TT timing synchronization status updates via Operations, Administration and Maintenance (OAM) or using control plane signaling at node level. Based on the received reports, in step 3 the TSCTSF is responsible for determining if the time synchronization service provided to a UE can still be fulfilled or not following the service acceptance criteria. To determine the impacted set of UE, in addition to the status reports, the TSCTSF needs to subscribe to UE location services at the access and mobility management function (AMF). If the TSCTSF determines there is a status change for a time synchronization service provided to UEs for which an AF originally requested the service, the TSCTSF may inform the AF about the timing synchronization status for those UEs (step 4).

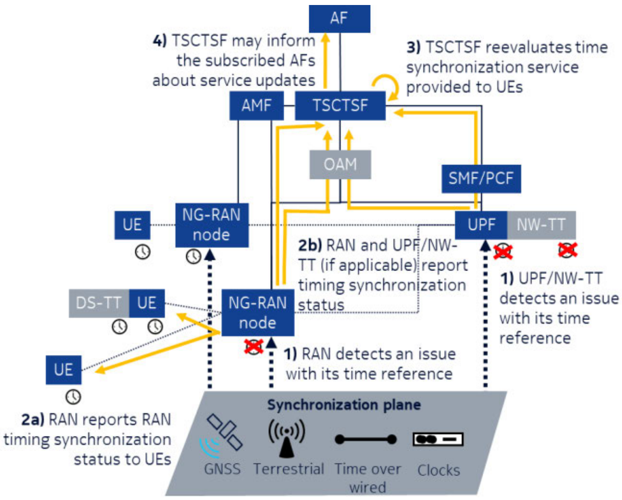

FIGURE 4. 5G-A time synchronization status monitoring signaling flow. Dark blue boxes are within 3GPP scope. Gray boxes are defined in 3GPP but most of the functionality follows IEEE/non-3GPP specifications.

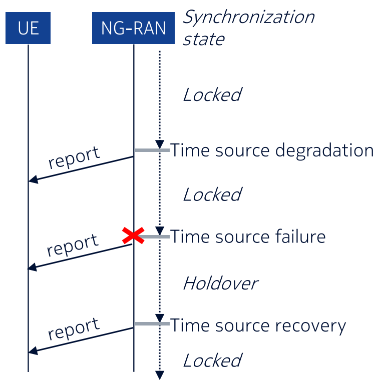

FIGURE 5. 5G-A time synchronization status reporting towards the UE.

IV. TECNOLOGY ENABLERS AND OUTLOOK FOR 6G

While time synchronization and timing resiliency capabilities in 5G have come a long way, community research and development activities are needed to improve the scope of applicability of time services in 6G. Especially as many of the use-cases listed in Section II will gain increasing importance in the time period where 6G will be active. One example is the use of XR to enable digital twins, i.e., replicating the real world in real time. This virtual replica can be used for monitoring operations, enable additional AI use cases with data-driven decision making, predict maintenance needs, etc. To unlock this precise mirroring, time synchronization will be essential. In the following some of the main gaps, research challenges, and opportunities are listed.

A. ARCHITECTURAL INTEGRATION OF TIMING SERVICES

There is a significant shift where 5G-A and 6G networks will provide many add-on services to end-users besides basic data transport services, as illustrated in Fig. 6. Aside from the discussed time synchronization service, this includes also other domains such as sensing, positioning, context, security, etc. A revised architectural framework is needed for managing these services in a manner that allows for dynamically configuring them, both in terms of their scope but also their service quality. As examples, this requires a fresh look at how services based on e.g., control plane delivery are handled in a more flexible and scalable QoS/QoE framework not only focused on user plane performance as in previous cellular generations, or how different services may have feature interactions such as timing and positioning or sensing. As time synchronization services improve in accuracy, related services like positioning will improve in performance. For sensing, the introduction of radar alike techniques into the network will require to coordinate the transmissions, if multiple emitter nodes are involved, to reduce interference. This can also benefit positioning services. It is still open if sensing requirements will derive into additional relative synchronization requirements between the 6G network nodes or the already present requirements for 5G are sufficient.

Additionally, a consideration of new options for improving timing by combining both 6G non-terrestrial and terrestrial layers is needed. Non-terrestrial networks have the potential to enable connectivity everywhere. However, they raise major challenges for achieving accurate time synchronization. For example, from a UE perspective the fast movement of the serving satellite (e.g., getting closer or away) generates time drift (i.e., the clock the satellite provides gradually deviates from accurate or "true" time the 6G provisions). 5G overcomes this challenge using pre-compensation at the UE side based on the information the satellite provides (i.e., ephemeris of the satellite and feeder link delay) in addition to its own location from GNSS. 6G presents a research opportunity to further improve the time synchronization performance for non-terrestrial network scenarios and reduce their dependency to GNSS.

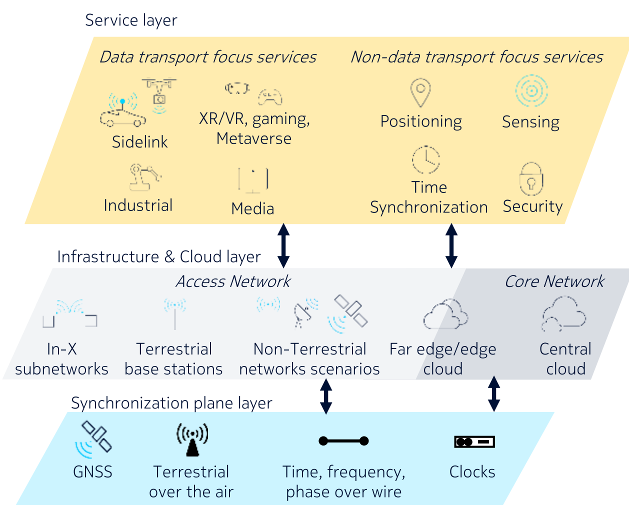

FIGURE 6. 6G synchronization functional architecture and example 6G add-on services.

B. TIMING ACCURACY TO NANOSECOND LEVEL IN WIDE AREA

As discussed in Section II, an accuracy better than 1-10 microseconds allows for many use cases to be supported. However, there are further use cases that require a better accuracy, e.g., similar to a few tens of nanoseconds that can be supported by high-end GNSS equipment today. Timing accuracy goes hand in hand with positioning accuracy, where a desire to bridge the gap between terrestrial and GNSS performance is desired for resiliency as well as stand-alone purposes. Potential improvements come natural with larger sub-carrier spacings introduced as 5G-A and 6G moves into the millimeter and sub-THz frequency domains, but a key challenge is to extend these benefits to wide area coverage. Further radio research is needed to improve not only fundamental performance limitations including accurate propagation path compensation, but also to do it in a way that allows cost-efficient hardware implementation and deployments. Utilization of parallel information available from e.g., sensing mechanisms at the base station to improve accuracies also needs to be considered.

C. RE-DISTRIBUTION OF TIME

6G is expected to enable life-critical subnetworks and advanced side-link applications among devices [15]. Many of these small networks host applications as discussed in Section II and will rely on accurate time-synchronization of all sub-components. For these use cases, including their co-existence if leveraging same spectrum, an effective synchronization plane architecture is needed to ensure efficient and lossless timing re-distribution and calibration including high resiliency towards loss of connection to a common synchronization overlay. For example, for the envisioned short-range, low power 6G ''in-X'' subnetwork, open challenges are how to optimize the end-to-end time distribution chain decision in the subnetwork to reduce the accumulated error at the remote UEs or the behavior per hop to compensate the error at the time distribution chain.

D. BUILDING EXTREME TIMING RESILIENCE

Time synchronization will be a baseline requirement for several sophisticated use cases in 6G where not only accurate time synchronization is needed, but the insurance also that the service can be trusted is essential too. Beyond passive monitoring and reporting as discussed for 5G-A networks, 6G may explore further ways of interaction between the timing services provided to the UE(s), frequency and phase synchronization services assisting or complementing time synchronization, and the synchronization plane the deployment has, building common interoperation enablers on top of proprietary solutions, or involving more the UE(s) into the service performance evaluation. For example, frequency and phase synchronization will be already present in the context of how the access network and the UE communicates over the radio interface. One step further is to consider 6G network as a stable frequency/phase synchronization interface to an end consumer. Thus, this frequency/phase synchronization service can be exploited in two different ways: i) it can be offered to 3rd parties to enable assisting other reference sources the end consumer may have available in their deployment, as a way to increase resilience, and ii) it enables more flexibility when requesting a synchronization method with the 6G as it allows indicating the type of synchronization the end consumer needs (i.e., time, frequency, phase).

V. CONCLUSION

Recent 5G/5G-A standardization efforts are settling the path towards flexibly supporting a wide range of timing synchronization use cases, deployments, and devices. Time synchronization is an essential component of a communication system, not only for the internal operation of 5G/5G-A networks, but also for 5G/5G-A to be part of critical infrastructure use cases in society, integrated 5G-TSN industrial networks, smart grid, media delivery and productions, etc. In this paper we presented the latest 5G/5G-A architecture enablers for the support of time synchronization use cases.

Looking ahead, the evolution of time distribution systems will continue and 6G will need to inherit time synchronization capabilities already in place in 5G/5G-A to become a key part of society and industry. Envisioned future use case scenarios for 6G like Metaverse, network sensing, or connected intelligent machines will increase the need for native and flexible timing synchronization for accurate timekeeping support through the network of connected devices.

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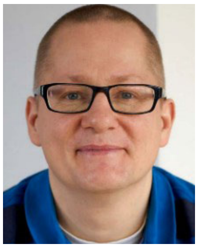

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