5G time service

White paper

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Executive summary

For nearly 100 years, "time-of-day" telephony or dedicated radio station services have helped humans set their clocks. Soon, applications and devices will use 5G networks to automatically set and keep their time to microsecond accuracy enabling new private, public and industrial use cases and experiences.

In this white paper, we explore some of the many possible use cases that can benefit from 5G time synchronization services either if the consumers of time require precise time or the devices are located outdoors or deep indoors. We explain how time-of-day services provided by 5G will facilitate a simple way for users and different types of devices to obtain accurate time.

Introduction

Since its introduction in 1933, humans have been able to adjust their clocks using telephone time-of-day or "talking clock" services, where a live or recorded human voice gives the correct local time. Today, time-of-day services are often accessed by computers over the internet to Internet Time Servers running Network Time Protocol (NTP). For cases where the internet is not available, GPS receivers have often been used, but their operation is challenging indoors. Other methods to obtain time-of-day services are considered in Figure 1.

In Release-16 of the 5G standard, 3GPP introduces time synchronization support for 5G over the air, which provides very high accuracy in the microsecond range and with deep indoor penetration. The initial focus for the 5G design has been to meet the strict demands of Industrial IoT (IIoT) and time-sensitive Ethernet networks, but with the next envisioned steps, 5G time-of-day services with microsecond accuracy can empower low-cost and low-power timing devices and clocks. In this white paper, we explain the envisioned functionalities and use cases behind the modern 5G version of "talking clock".

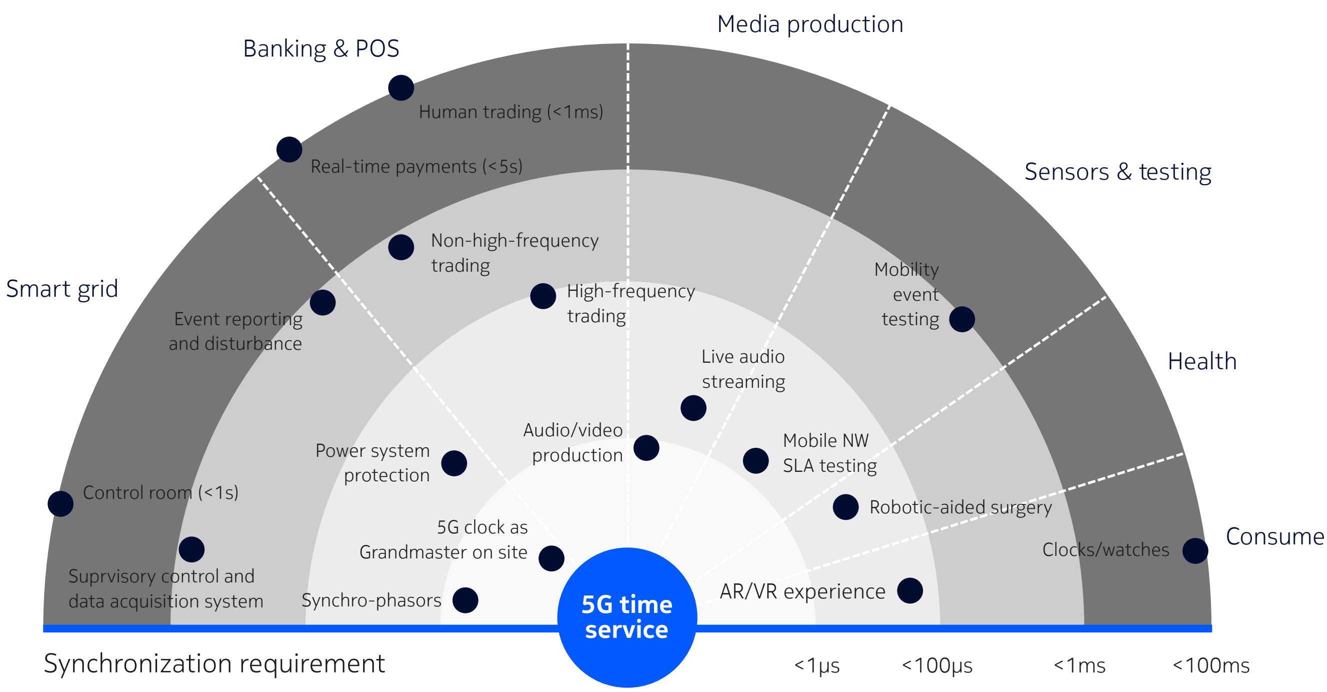
Figure 1. Illustration of the evolution of different methods available to acquire time-of-day synchronization and typical end-user accuracies achieved (inspired by [1])

Time of Day service	Telephone time of day including automated computer time		Radio station time service	GPS time transfer	Internet time service	5G time service
Access method by user	Landline	VoIP, cell phone	Wireless receiver	Wireless receiver	Internet access, ex. PC or time device	Wireless receiver
Typical synchronization accuracy	<30 ms	<150 ms	<50 ms	<100 ns	<100 ms	< 1µs
Years of public operation	1933 - today		1945 - today	1973 - today	1990 - today	2021 onwards

5G time service use cases

In an earlier white paper, time synchronization in combination with advanced Ethernet applications such as IEEE Time Sensitive Networking was described in detail [2]. In this section we focus on different use cases suitable for time synchronization over wide area 5G networks. The example use cases considered in this section have been compared in the radar chart in Figure 2, which shows required synchronization accuracy for each use case. In the following sub-sections, these use cases are discussed in more detail.

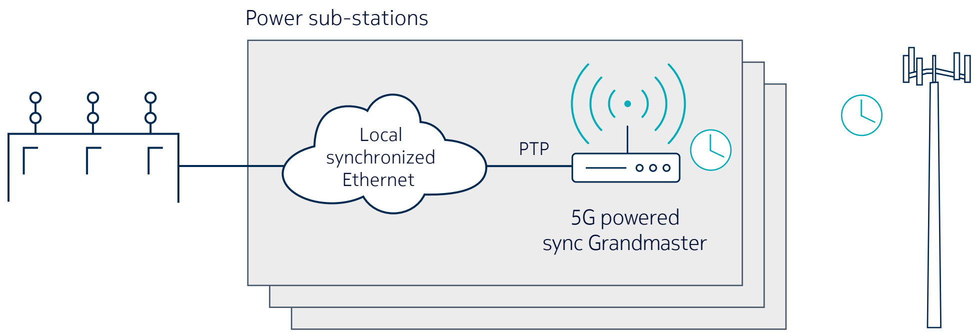
Figure 2. Illustration of various use cases that can be served by 5G time services in terms of synchronization requirements



Smart grid

The smart grid industry relies on timestamping of events for efficient management and operations as well as adjusting power sub-systems. Global Navigation Satellite System (GNSS) is commonly used for time synchronization, for example, in power sub-stations, which often requires the installation of an external antenna for good satellite coverage indoors. In many countries, however, there is already good coverage of cellular networks inside power systems and time synchronization via 5G will offer a convenient alternative or backup to GNSS for better reliability. An example use case is shown in Figure 3 where 5G directly provides time to an indoor located timing device. Depending on the use case, synchronization accuracies in the range of 1 microsecond to a millisecond can be served by 5G, including adaptation to the Precision Time Protocol (PTP) profiles used in the smart grid industry.

Figure 3. Illustration of the use of 5G time synchronization in power sub-stations



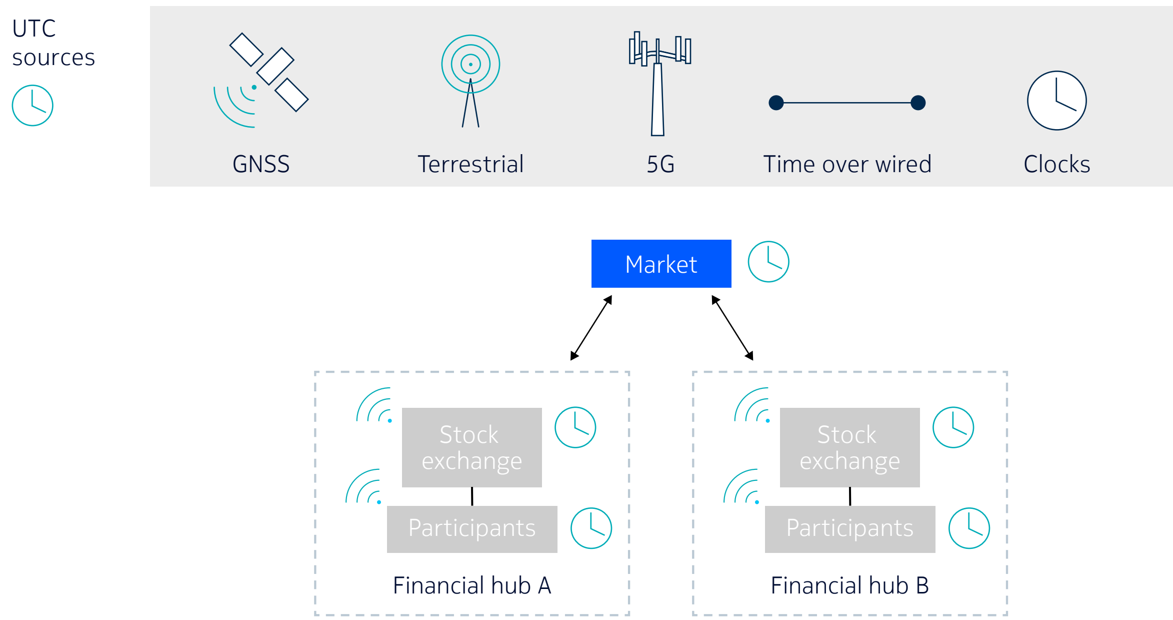
Banking and points of sale

Business activities and financial transactions, such as purchases between a buyer and a seller, rely on timing. Timing is necessary to record activities, execute rules and identify conflict, economic crime, etc. For instance, the points of sale (POS) for a retail or service business can be widely distributed. There may be thousands of independent machines running concurrently that need to be synchronized to a common time source on a real-time basis to ensure the data of all transactions are synchronized together (e.g., between online shopping and physical stores). Coordinated Universal Time (UTC) is the reference for all POS and is used to timestamp any events that take place.

Timestamping accuracy requirements for POS is easily met with 5G. Furthermore, time synchronization is also a key aspect in proof-of-stake blockchain-based approaches that seek to significantly improve the energy and transaction efficiency compared to approaches such as Bitcoin. Here, accurate time synchronization based on GNSS or NTP is associated with some risks such as poor indoor coverage, poor configuration and spoofed sources. These risks can be mitigated using 5G-based methods in parallel or as alternative.

For financial services and high-frequency trading (HFT) where prices change rapidly, the time window for trades is microseconds. Figure 4 shows an illustration of time synchronization in a banking use case with 5G providing a traceable UTC time to the financial hubs. Depending on the trading activity, financial regulations have imposed different requirements in terms of maximum divergence from UTC (ranging from 100 microseconds to 1 second) or granularity of the timestamp (ranging from 1 microsecond to 1 second) [3]. 5G can immediately meet regulation requirements for distributed financial systems as an alternative source to provide traceable UTC.

Figure 4. Illustration of time synchronization in trading and 5G providing traceable UTC



Media production and events

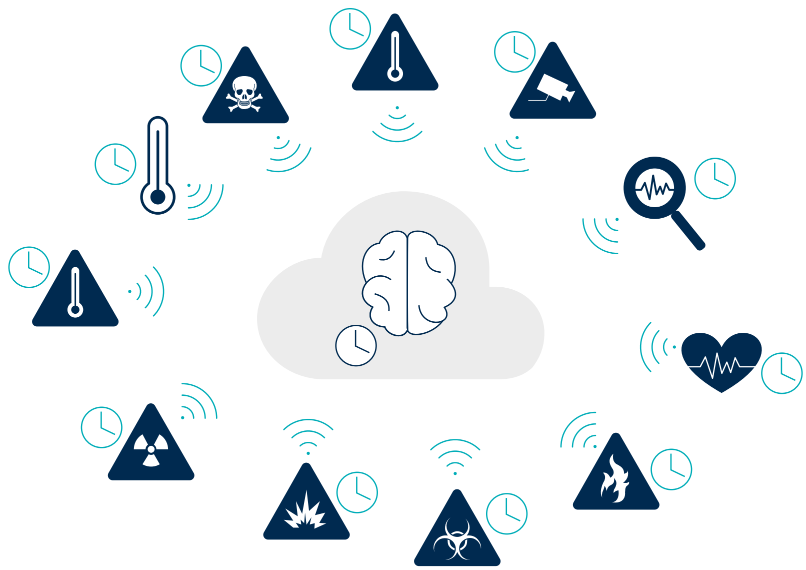
When audio and video are multiplexed for live events, time synchronization is essential to perfectly align different media sources. Media production or streaming devices (microphones, earbuds, instruments, video recorders including drones) rely more and more on wireless communications to generate new experiences and make production more efficient. 5G plays a key role enabling these new use cases [4]. Mixed reality live shows based on 5G are already happening, for example, fashion runway shows, art shows and concerts. In such shows, fast connectivity and low latency are essential. As well, different components, such as headsets, event screens, or live effects, must be accurately synchronized.

Accurate time synchronization via 5G opens new flexibility and reduces the need for local dedicated distribution networks and timeservers to achieve media synchronization. One example is multi-cam editing where external timecoding from a master timecode generator is used to ensure alignment of recordings and an improved workflow. 5G provides excellent indoor timecoding support, and devices can be built using standard output and signaling formats for use in professional or prosumer camcorders (e.g., BNC interface and SMPTE 2xx).

Sensors and testing

Timestamping capabilities in general are essential when troubleshooting complex events where exact timing and order of events is a key aspect. For instance, timing support in distributed sensors and test devices is illustrated in Figure 5. This is especially useful when cloud-based AI/ML frameworks are used to find correlations among a large variety of events observed in different places. Accurate timestamping can be used to automate storage into databases across a large set of inputs for generating sensor fusion as well as advanced correlations, which can lead to new insights in a large range of fields, including medicine, law enforcement, agriculture and autonomous driving.

Figure 5. How events with accurate and common timestamps help AI/ML based learning



Another use case includes drive testing in cellular networks where customized 5G devices are used to test the performance of deployments, including handover failures, data rates and coverage. Despite having GPS receivers and access to the internet, today's commercial test devices can timestamp events with an accuracy in the order of 100 ms only. This means that events cannot be accurately correlated with other events within the operator's network, or across devices when multiple devices are used for testing in parallel. Having access to microsecond level timing within the 5G device enables very accurate timestamping of radio events, thus enabling much deeper testing of network performance as well as advanced device capabilities (e.g., hybrid access devices). Accurate timestamping of both the device and the network also allows for one-way delay analysis compared to today's round-trip-time-based (RTT) methods. For instance, it can be used to test the network's capability to satisfy latency-based service level agreements (SLAs) in each direction and to make advanced troubleshooting of deployment issues.

Consumer

For consumer devices not connected to the Internet, GNSS or radio-station time service is sometimes an in-built option that is used to provide the time. This can include watches, metering and augmented and virtual reality devices (AR/VR). In the latter case, time synchronization becomes an essential service for multi-party AR/VR experiences. For many of these cases, a low-cost 5G based solution can offer benefits for the device and improve the quality of experience (QoE).

Health and medicine

In the health segment, timestamping can be useful for coordinated medicinal treatments. Synchronization is a prerequisite for advanced use cases such as remote robotic surgery.

Achieving timing services over 5G

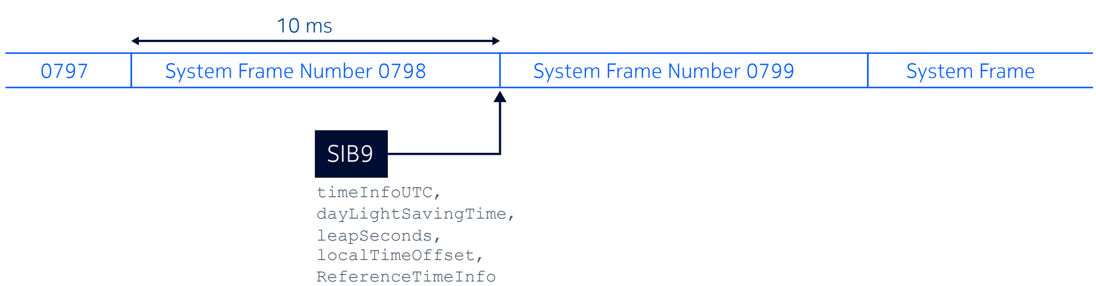
For cellular connectivity, the user equipment (UE) needs to know on which frequency and at what time it can exchange traffic with the base station, thus the UE and base station are synchronized to each other (although the UE does not know the absolute time of the synchronization). With Releases 16 and 17 of 5G, which create support for IIoT and time sensitive communications (TSC) beyond the scope of IIoT, the need for accurate 5G absolute time synchronization (i.e., synchronization to a physical time like UTC) has become much more critical. In the following sub-sections, we discuss the different methods to enable this accurate time synchronization in more detail.

Over-the-air time synchronization to UTC

The process of synchronizing a 5G device to the absolute 5G network time, typically UTC, is done by direct messaging over the air interface. 5G uses a simple but accurate method to communicate time of day to the device. The device (UE) identifies so-called system frames by monitoring the air interface, each with a system frame number (SFN). Contained within the 5G system information block 9 (SIB9) is the information related to GPS time and UTC. SIB9 messages are broadcast to inform devices of the exact time at the boundary between two SFNs. Hence, when the device has locked its internal clock to the system frame pacing, it can use this message to set its absolute time.

SIB9 contains the time information as well as flags to assist the device to understand the local time as shown in Figure 6. Reading the SIB9 and acquiring the time-of-day alignment can be performed by any device even if not subscribed to the 5G service. It only requires a 5G-capable receiver in the device as SIB9 can be broadcast in the cell. For fully subscribed devices, the network may also provide the timing information to each device by means of dedicated signaling (using Radio Resource Control (RRC) messages). More details are available in [5].

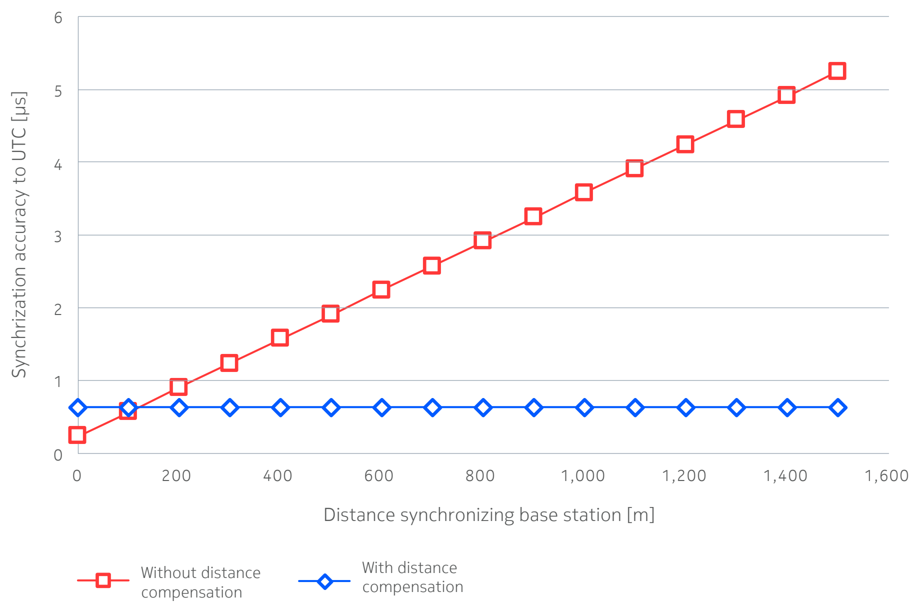
Figure 6. Communication of time-of-day over air interface in SIB9 message



The distance the radio messages travels between the base station and the device causes a time difference between the time when the system frame was sent by the base station and the time when it was received at the device. This time difference is referred to as the radio signal propagation delay. As the propagation delay between the device and the base station delivering the timing information increases, the achieved synchronization accuracy degrades, unless the delivered time information is compensated. Even without compensation, however, good synchronization accuracy can be achieved for very large cells in the kilometer range as shown in Figure 7.

For a connected device, which requires subscription to the 5G operator, the propagation delay can be estimated based on the timing advance procedure, and compensation can be applied to mitigate the error caused by distance. While any connected UE can do compensation on their own, standardized and controlled compensation methods are introduced in 5G Release-17. The performance difference with and without compensation is shown in Figure 7. For small distances less than 100 meters, compensation should typically be avoided, as propagation delay estimation has a certain error bound.

Figure 7. Achievable synchronization accuracy versus distance to base station providing synchronization

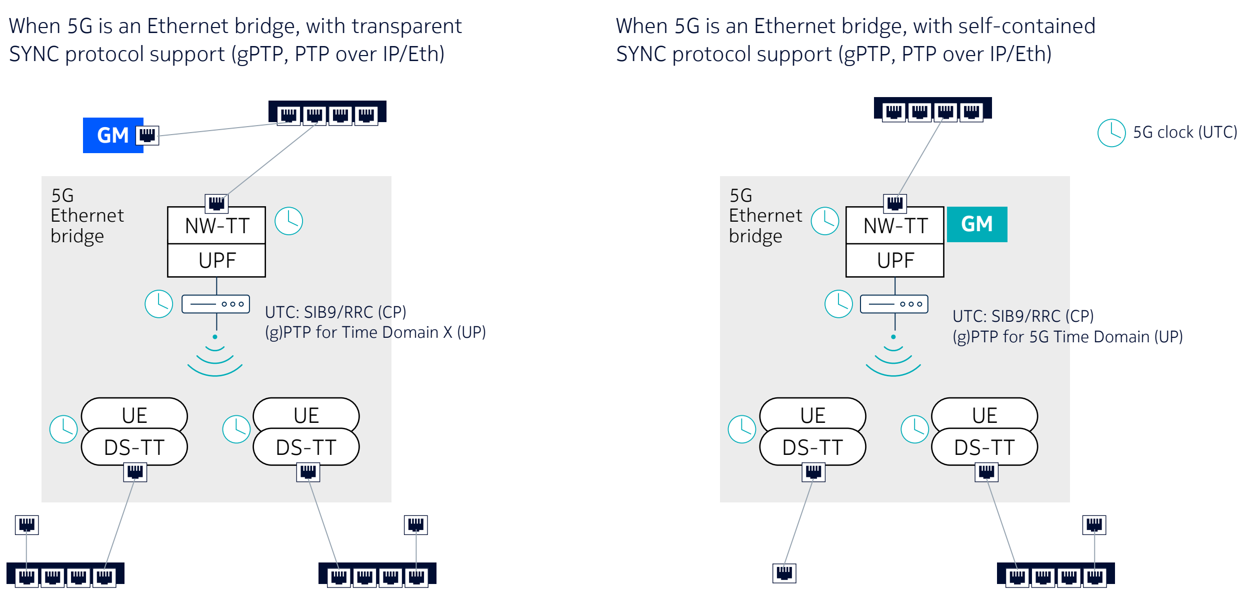


Time synchronization for 5G industrial IoT

In 5G Release-16, full downstream and tight synchronization support was introduced for 5G to serve advanced and time-critical Ethernet services, including IEEE Time Sensitive Networking (TSN) [6]. When used in IIoT, the 5G system can act as an IEEE Std 802.1AS [7] compliant Ethernet bridge, as illustrated in Figure 8. Each device represents one port of such a bridge, and there is one or more ports also in the 5G core network side. The input/output points of the 5G network are the device-side TSN translator (DS-TT) inside the device and the network-side TSN translator (NW-TT) on the 5G network side. The translator functionality implements IEEE Std 802.1AS including compensation for delay and jitter that takes place as individual time synchronization messages traverse the 5G network as user plane traffic. In this way a device can be synchronized to a vertical grand master clock (GM) connected to the 5G network end-point with an accuracy better than 900 ns (without considering additional propagation delay error).

In 5G Release-17, uplink time synchronization support is added so that the GM clock can be located on the device side of the network to synchronize devices that are attached to other 5G devices or sitting behind the 5G network. Additionally, support for best-master clock algorithms (BMCA) is added to support high clock resiliency use cases. Besides IEEE Std 802.1AS support (gPTP), also IEEE Std 1588 PTP [8] support is added in Release-17 to facilitate a broader range of use cases and IP applications.

Figure 8. Illustration of synchronization mechanisms when 5G acts as an Ethernet bridge envisioned for IIoT uses. Devices act as ports of the bridge. DS-TT at the device side and NW-TT at the network side are synchronized to the 5G time domain (e.g., UTC)



5G time synchronization for individual devices

In IIoT, devices (comprised of UE and DS-TT) are considered as ports on a bridge in an Ethernet network. Many use cases, however, require time synchronization support for a single device camping in the network with basic access to a public 5G network and not part of an Ethernet bridge construct. In 5G Release-17 and Release-18, several such use cases are envisioned. Figure 9 shows five different methods to access time of day from the 5G network and ways to use that information by an application attached to the device (e.g., connected via Ethernet port, a dedicated sync hardware port or via drivers for the operating system). The actual delivery of time information over the air interface using SIB9 and/or RRC messaging is described in the previous section.

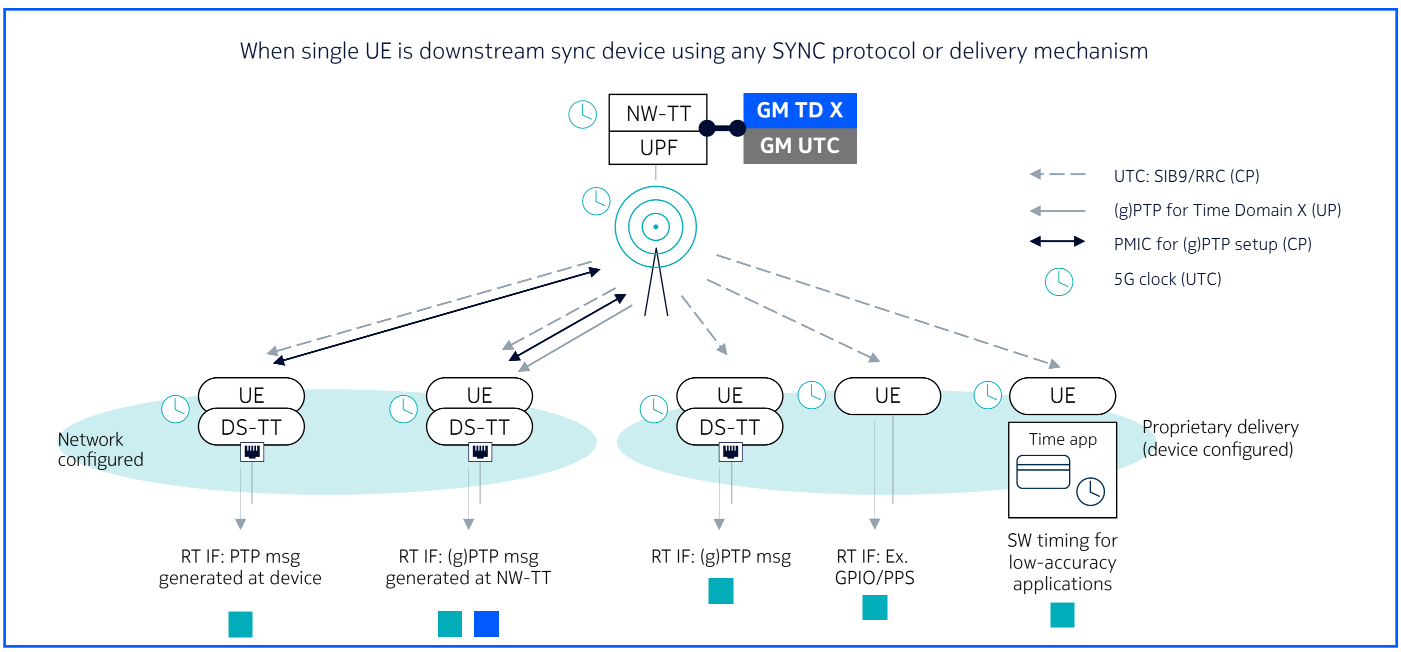
The many different methods offer flexible support for a wide range of use cases as well as device designs. The device range can vary from advanced devices, such as DS-TT and advanced synchronization protocols, to very simple devices only capable of reading the time of the 5G system broadcast channels (i.e., SIB9), not requiring a transmitter module, a 5G subscription or even a SIM card slot. Taking the device type as a starting point, Table 1 presents some of the options and the typical synchronization accuracy.

Table 1. Time-of-day synchronization solutions for standalone devices

Device type	5G subs. needed	Sync domain	Method of syncing device	Method for syncing applications	Accuracy level
Full UE/DS-TT	Yes	5G (UTC) only	5G air interface (Control plane (CP) or User plane (UP))	Ethernet, device PTP GM clock	<1μs
Full UE/DS-TT	Yes	Any, incl. 5G (UTC)	5G air interface and received PTP message (CP/UP)	PTP boundary or transparent clock. Compensates and forwards PTP message	<1μs
UE with GPIO	Yes	5G (UTC) only	5G air interface (CP)	Dedicated IF e.g., GPIO/1PPS	<1μs
UE with SW application	Yes	5G (UTC) only	5G air interface (CP/UP)	Via operating system on device	<10μs
Low-cost, low-power device	No	5G (UTC) only	5G air interface (CP), uncompensated	Dedicated IF e.g., GPIO/1PPS	<10μs

Whenever the most accurate results are needed, the network needs to help measure the propagation delay, which requires an active connection (temporary or regular), thus a subscription to the carrier. If lower accuracy of 5-10 μs is acceptable, compensation is not strictly needed. Another factor is whether the device takes care of its own synchronization delivery to its attached clients or if this functionality should be configured by the network. For network configured scenarios, configuration of the (g)PTP operation at the device side is done by exchanging a port management information container (PMIC) between the DS-TT and the 5G system. This type of scenario can be helpful when a company manages a fleet of devices that require automated deployment and monitoring.

Figure 9. Illustration of how standalone devices can achieve time-of-day synchronization from the 5G network and provide accurate timing to their attached clients (RT IF indicates any real-time interface).



Comparison to GNSS/GPS

As shown in the use cases, 5G is a viable alternative or supplement to GNSS/GPS for providing time synchronization to UTC or any well-defined time domain. The pros and cons of both solutions are illustrated in Table 2. It is worth noting that the telecommunications sector is one of the big consumers today of GNSS-provided timing and in that sense relies on GNSS for its operations. However, in Release-18, 5G will introduce a timing resiliency service that will make the 5G system robust in case of GNSS failure or degradation. This resiliency will benefit users who perform time-of-day synchronization over the 5G air interface.

Table 2. Comparison of 5G and GNSS for getting time-of-day

Comparison metric	5G	GNSS
Accuracy (UTC)	<900 ns with subscription, <5-10 µs without subscription	<100ns
Indoor support	Yes	Limited, may require external antenna and wiring
Populated area coverage	Yes	Yes
Remote area coverage	Limited, later available via 5G non-terrestrial networks	Yes
Service subscription required	Only for most accurate use cases	No
Service resiliency	High with 5G timing resiliency system	Medium, many GNSS risk factors
Power consumption	Medium-high for most accurate timing Very low for <10µs accuracy use cases	Medium

Summary and conclusions

Precise time-of-day synchronization over 5G is one of the first examples of wireless networks becoming an essential part of critical infrastructure nationally and globally, serving societies and industries in areas beyond mobile broadband and IoT applications. This white paper has introduced the technological options including possibilities for low-cost device types that can be integrated into a large range of critical applications within industrial, public and consumer segments.

Abbreviations

1PPS	One Pulse Per Second
5GS	5G System
AI	Artificial Intelligence
AR	Augmented Reality
BMCA	Best Master Clock Algorithm
CP	Control Plane
DS-TT	Device-side TSN translator
GM	Grand Master
GNSS	Global Navigation Satellite System
GPIO	General Purpose Input/Output
GPS	Global Positioning System
gPTP	Generic Precision Time Protocol
HFT	High-Frequency Trading
IIoT	Industrial Internet of Things
ML	Machine Learning
NTP	Network Time Protocol
NW-TT	Network-side TSN translator
PMIC	Port Management Information Container
POS	Point of Sale
PTP	Precision Time Protocol
QoE	Quality of Experience
RRC	Radio Resource Control
RTT	Round-Trip-Time
SFN	System Frame Number
SIB	System Information Block
SLA	Service Level Agreement
SMPTE	Society of Motion Picture and Television Engineers
SW	Software
TA	Timing Advance
TD	Time Domain
TSC	Time Sensitive Communication
TSN	Time Sensitive Networking
UE	User Equipment
UP	User Plane
UTC	Coordinated Universal Time
VR	Virtual Reality

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