Resilient 5G-Advanced timing service

A land-based, resilient and reliable alternative timing system to GPS

White paper

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The global positioning system (GPS) is the preferred positioning, navigation and timing (PNT) system for a vast number of sectors. Its vulnerabilities, however, haven't reduced in the last years, exposing critical sectors that rely on timing for their operation. 5G-Advanced networks are well placed to provide wide area resilient time synchronization and positioning services and serve as a complement or, even, alternative to GPS for critical sectors.

In this white paper, we describe the requirements for a resilient PNT system and the timing resiliency solution supported by future 5G-Advanced networks.

Contents

Introduction

Timing services are crucial to a variety of social and economic activities. They are intrinsic and essential tools in everyday life and have many impacts on our economy. Many services rely on radio signals, the internet and wired connections to obtain “time of the day”. Some of these have significant dependencies on precise timing, including telecommunications, energy, precision agriculture, financial services, transportation systems, critical manufacturing and emergency services. Vulnerabilities in global navigation satellite systems (GNSS) thus expose these economically significant sectors. The existence of alternative GNSS systems such as GPS, GLONASS (GLObalnaya NAvigatsionnaya Sputnikovaya Sistema [Russian]), BeiDou (Chinese for the Big Dipper), or Galileo (EU) are crucial for precise timing and positioning information in our society, but all GNSS suffer from similar vulnerabilities.

Principally, GNSS vulnerability stems from the relative weakness of GNSS signals. The delivery of GNSS timing information is impacted by environmental phenomena, malicious interference and spoofing, incidental interference, adjacent band interference, poor antenna installations, and rare GNSS segment errors [1]. It is estimated that the economic consequences of a 30-day GPS outage could be as high as $45 billion on the US economy alone [2]. The International Air Transport Association shows in their safety and security incident data management program a total of 586 GNSS/GPS jamming or suspected interference reports from the Middle East, North Africa and adjacent states reported during 2021 [3]. The US Department of Transportation (DOT) identified 196 potential GPS interference events from January 2020 through May 2022 [4]. The report also highlighted that the DOT’s efforts to identify GPS interference incidents needed to improve to include all available user reports and eliminate inaccurate information, suggesting that this number might be higher.

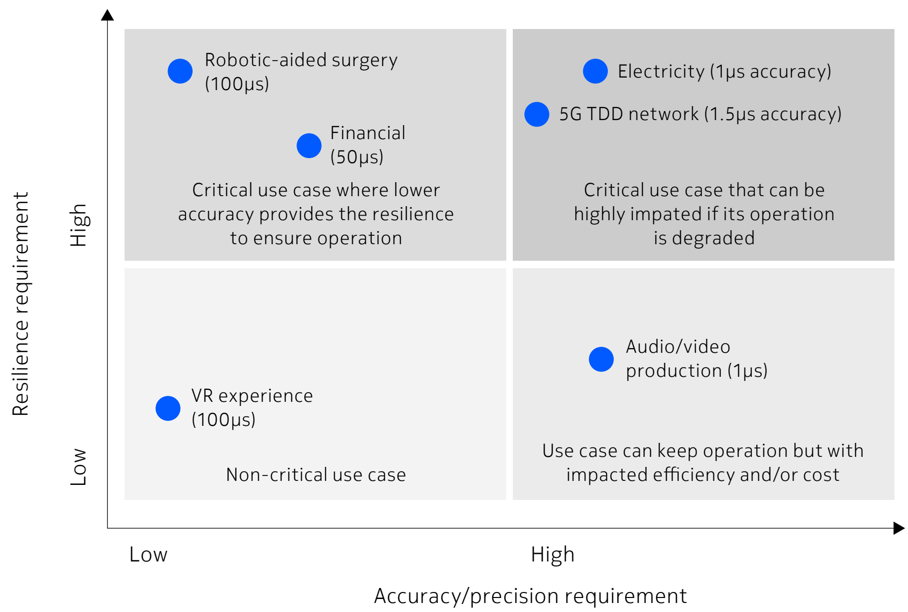
Recent efforts to improve the resiliency of PNT systems that currently rely on data provided by GPS and other GNSS include conducting impact assessments, developing mitigation actions and a conformance framework, exploring complementary timing technologies, and other initiatives to achieve the responsible use of PNT in critical infrastructure (see [5] for more information on these initiatives).

Among the critical infrastructure sectors, telecommunication has one of the highest dependencies on GNSS [1]. This is largely due to cellular networks. For instance, both 5G and 5G-Advanced rely on GNSS receivers for their operations. In this white paper, we explain why resilient timing is important for 5G networks and why the 5G System (5GS) can be seen as a trusted and reliable time source for time-critical use cases.

Timing resiliency requirements and various initiatives

Critical infrastructure depends on accurate time synchronization. Without it, the performance and security of critical systems, facilities and networks may be compromised. In terms of timing accuracy, 5G-Advanced networks can fulfill the needs for time-of-day services to many critical infrastructure use cases. However, their demand for timing requirements also extend to additional dimensions such as, coverage, service availability and uniformity, long-term accuracy and stability of time transfer, as summarized in Figure 1.

Figure 1. Various use cases with different timing resiliency aspects (adapted from [4]).



GPS has become the de facto time source due to its low cost and ubiquity. It is so widespread that there are many consumer use cases where we are not even aware that the provided services depend on GPS. To achieve resilient timing systems, we need to understand the ways in which a use case depends on timing sources in order to evaluate the risks it may experience. The criteria for evaluation include identifying the primary time source for the use case or application, documenting timing dependencies, and identifying the level of timing performance required for its operation.

Resiliency is a requirement that cannot be achieved by individual components (e.g., a time device or a clock) within the use case. Achieving resilience requires a combination of solutions or mechanisms deployed for the use case as a whole. Using a holistic approach means assessing resilience by considering the end user devices used, the applications or systems that require time, the time sources available, etc. As illustrated previously, resiliency can be considered in terms of levels such as high or low. This can be mapped to a more formal definition with the different levels of resiliency defined in the resilient PNT conformance framework, summarized in Table 1.

In the PNT conformance framework, resiliency levels (0 through 4) provide guidance for defining expected behaviors in a resilient PNT system. The levels are cumulative, requiring additional resiliency and architecture impacts for the devices or infrastructure that comprises the PNT system as level numbers increase. For example, level 1 requires minimal architecture depth (e.g., PNT source information is verified with basic consistency checks), while level 4 requires multiple independent and integrated PNT sources to perform processing of the information to ensure there is no degradation in the use case due to any compromise (merely adding more sources of information is not enough; intelligent system of systems management is needed).

Table 1. Minimum requirements per resiliency level (defined in resilient PNT conformance framework [7]).

Level	Minimum requirements
0	Non-resilient system or source
1	Ensures recoverability after removal of the threat 1. Verify stored data 2. Support full system recovery by manual means 3. Securely reload/update firmware
2	Provides a solution (possibly with unbounded [1] degradation) during threat Level 1 plus: 4. Identify compromised PNT source and prevention 5. Automatic recovery of PNT sources and system without disrupting PNT output
3	Provides a solution (with bounded degradation) during threat Level 1 and 2 plus: 6. PNT source corrupted data do not corrupt other PNT sources 7. Cross-verify between PNT solutions from all PNT sources
4	Provides a solution without degradation during threat level 1, 2 and 3 plus: 8. Diversity of PNT source technology to mitigate common mode threats

Recognizing the challenges and the potential impact on national economies, governments and regulators in several countries have acted. Focusing on the time dissemination infrastructure, timing laboratories across the world have initiatives to realize resilient timing. For example, the National Physical Laboratory (NPL) in the UK has a National Timing Centre program to develop the UK's first nationally distributed time infrastructure, reducing the reliance on GNSS [8]. In the US, the National Institute of Standards and Technology (NIST) has developed PNT profiles as a guidance for organizations for the use of PNT services and will offer a time service over optical fiber lines as an alternate source of precision time [9].

All this helps to achieve a land-based, resilient and reliable alternative timing system to GPS. From the US governmental initiative [10], some of the requirements for a resilient PNT system would be:

- Wireless
- Terrestrial
- Wide-area coverage
- Synchronized with coordinated universal time (UTC)
- Able to penetrate underground and inside buildings
- Capable of deployment to remote locations
- Can be adapted and expanded to provide position and navigation capabilities.

A 5G system can match most of the requirements listed, making it an attractive complement or alternative due to its global footprint and the many diverse use cases supported by its infrastructure.

1 The output can deviate within a manufacturer-defined envelope.

Resilient timing over 5G-Advanced

From a 5G consumer perspective, 5G/5G-Advanced networks provide time-of-day services with microsecond level accuracy for any type of device connected to 5G [11]. The customer has limited access, however, to information about the synchronization status the 5G system is experiencing, a requirement for critical time-dependent use cases. For the 5G system to be a resilient time source that can be used as a land-based complement or alternative to GNSS across multiple sectors, two main challenges need to be addressed:

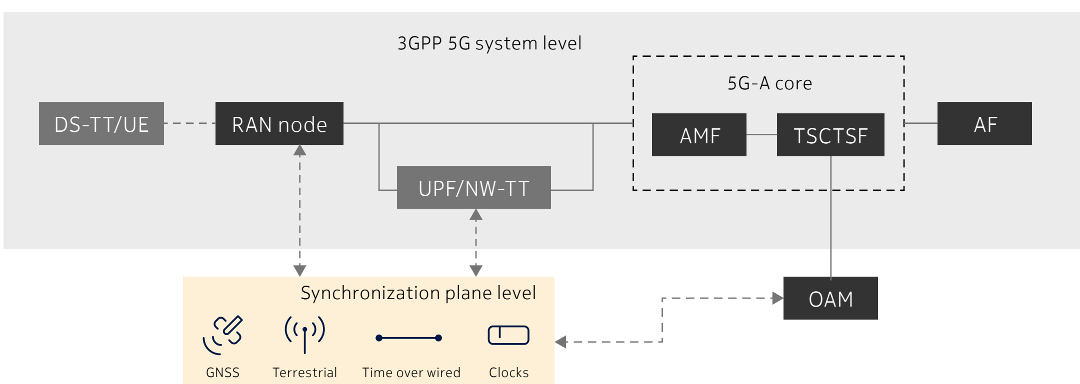
1. How to reduce the dependency to GNSS in 5G deployments
2. How to build a trusted 5G time-of-day service for critical infrastructure sectors and their end customers.

The first challenge relies on the specific timing solutions the operator has in place in the 5G/5G-Advanced deployment. These include:

- Integration with other timing reference systems (e.g., fiber-based global terrestrial timing services)
- Tightened holdover capabilities for network equipment (i.e., the time period the equipment can hold accurate timing as per requirements after losing its reference)
- Robustness against jamming, spoofing, coverage degradation, etc.

These mechanisms are in the synchronization plane of the 5G deployment, as illustrated in Figure 2, which is beyond 3GPP scope and not covered in this white paper.

Figure 2. View of 5G synchronization plane links to 5G system operation



To mitigate the second challenge, recent 3GPP standardization efforts in the Release 18 Timing Resiliency System (TRS) study have introduced enablers to support timing resiliency, which are an evolution of the time synchronization service in 5G. As the 5G system has unique assets to supervise its own time source health, 3GPP work in Release 18 assists in exploiting these capabilities and enabling a bridge between synchronization plane solutions and the time synchronization services the 5G system offers to end users. In the following sub-sections, we discuss in more detail the TRS enablers for time source status monitoring and reporting within 5G-Advanced.

Timing resiliency use cases

In addition to the critical infrastructure sectors listed earlier, any time-based service can benefit from resilient timing (e.g., information technology for smart devices, cloud operation). Nonetheless, among the critical infrastructure sectors, 3GPP started its timing resiliency study analyzing telecommunications, energy and financial services to derive potential new service requirements for the 5G system [12].

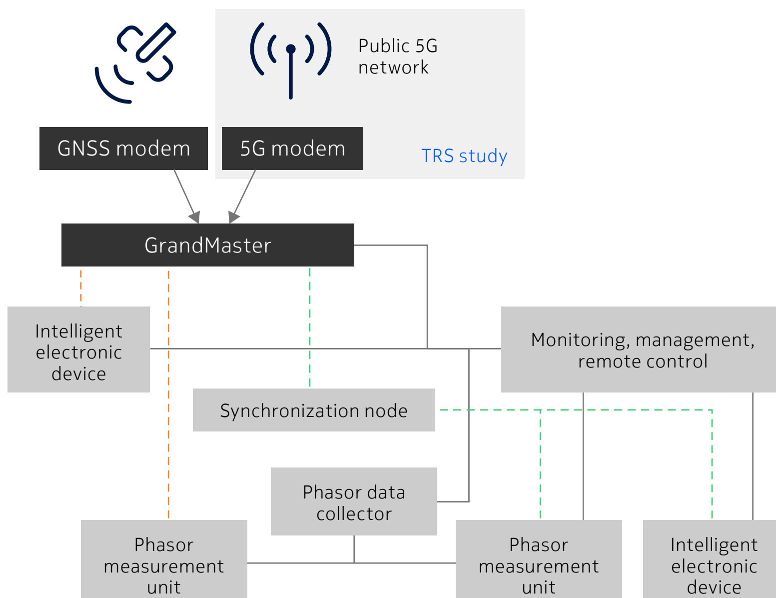
TRS needs in telecommunications

This use case focused on how the 5G systems can maintain time synchronization in the event of a loss or degradation of GNSS reference timing. The network operator is the stakeholder that decides how to manage and operate timing resiliency within their network.

TRS needs in smart grids

Power grids utilize a wide area network to operate critical infrastructure and smart devices deployed in the field communicate with centralized data facilities running intelligent analytics. Timing integrity is crucial for multiple operations such as fault-detection, monitoring network stability, data acquisition, etc. In this case, the smart grid operator is the third party that requests the 5G system to be used as a supplement to current GNSS receivers (integrated as an alternative radio in the grandmaster, as illustrated in Figure 3), or an alternative to GNSS (to avoid the need for GNSS receivers).

Figure 3. Example of synchronization in smart grid



TRS needs in the financial sector

Timekeeping is crucial for trading activities operations. A reliable common time reference is required to audit or to detect wrongdoing in transactions between markets and market participants. For instance, timestamping transactions enables regulators to know exactly who made what trade and precisely when. In this use case, the market participants need to follow rules for clock synchronization that include not only accuracy requirements for different types of trading activities, but also traceability to the time reference that is being used [13][14][15]. In order to demonstrate the time information is legit, the timestamping must be mapped back to UTC. To achieve this traceability, each link involved in the time dissemination chain from the reference time scale (UTC) up to the point of timestamp must be documented. The market participants, as a third party, can request the 5G system to provide additional timing synchronization status information to document the time dissemination chain.

Overview of 5G-Advanced time synchronization as a service

TRS functionality is built on top of timing synchronization-as-a-service, which is defined in 3GPP [11]. 5G/5G-Advanced offers a consolidated API that provides unified access to the time synchronization service for third parties. Any customer can request time synchronization as a service using the API or configure the time synchronization service in the user subscription.

When requesting the service it can optionally include a time synchronization error budget (the end-to-end time uncertainty the service can tolerate), a temporal validity condition (the time period the service should be active), and a spatial validity condition (the area the service should be active) [16][11]. There are two types of time synchronization services supported in the 5G system, as illustrated in Figure 4:

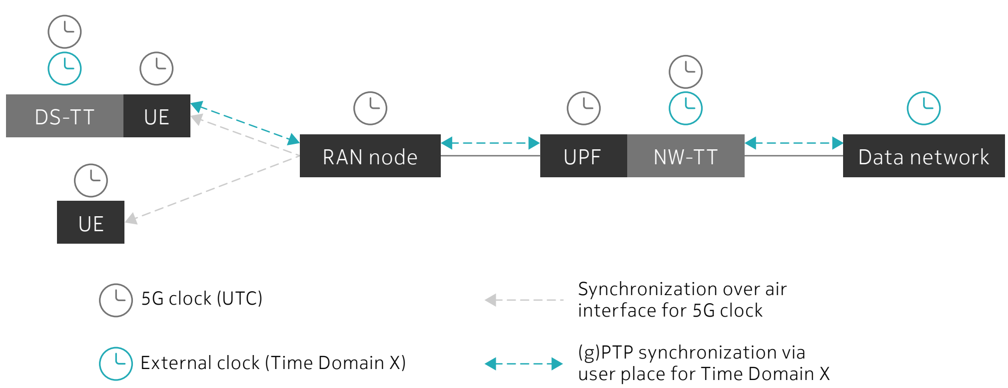
1. **Time synchronization based on over-the-air synchronization**

   This method uses control plane signaling (broadcast and/or unicast signaling) at the radio interface to provide the 5G clock to the user equipment (UE), represented by the dotted gray lines in Figure 4.

2. **Time synchronization based on generic Precision Time Protocol (gPTP) or Precision Time Protocol (PTP)**

   This method uses (g)PTP messages forwarded via the user plane within the 5GS (dotted blue lines in Figure 4). The service can be configured to disseminate an external clock (blue clock in Figure 4) or 5GS clock (gray clock in Figure 4). The source of the (g)PTP domain, i.e., the grandmaster (GM), can be located at the UE/device-side time-sensitive networking (TSN) translator (DS-TT) side, at the data network, or at the user plane function/network-side TSN translator (UPF/NW-TT) (only for 5GS clock dissemination). Note, over-the-air time synchronization is required for this method to provision the 5G clock to the DS-TT.

Figure 4. 5G Time-of-day synchronization service



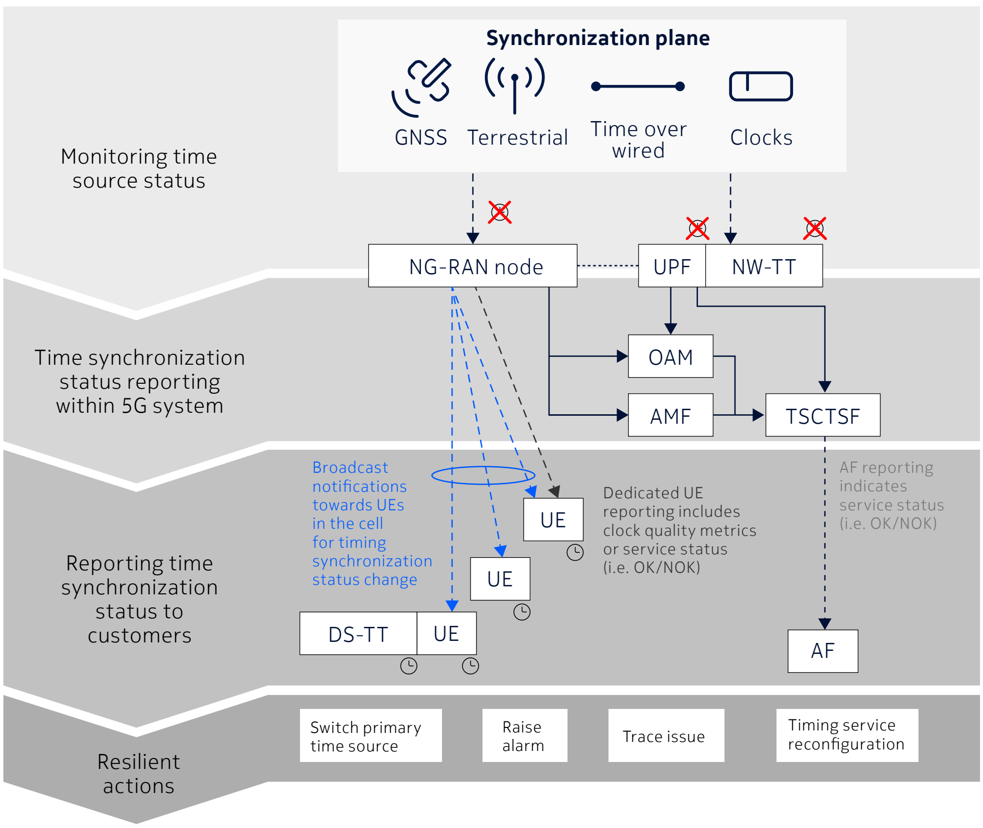
Timing resiliency extensions to 5G-Advanced time synchronization service

As a result of the analysis of the use cases, 3GPP identified four main areas to be supported in the Release 18 5G-Advanced specification, as illustrated in Figure 5.

1. Mechanisms for a third party to request timing resiliency in the 5G system
2. Monitoring the timing source the 5G system is using to detect degradation, failure and recovery
3. Reporting by the 5G system on the status of the time synchronization service it is providing based on the knowledge of the reference time source it is consuming
4. Based on this reporting, the consumers of the information may reconfigure the service requested from the 5G system, switch the reference time source used, or keep logs of the events, etc.

Note, the TRS functionality listed above does not require additional hardware to be available in the network elements. It relies on additional internal logic, provisioning of attributes within the 5G system already available in the network elements that are part of the time distribution chain, and additional signaling extensions to current procedures between the network elements. In the following sub-sections, the listed areas are discussed in more detail.

Figure 5. Timing resiliency system overview in 5G-Advanced



Timing synchronization status request

For 5G-Advanced to be a land-based complement or alternative to GNSS, it needs to be able to offer resilient timing synchronization as a service. There are two mechanisms supported in Release 18 that facilitate a broader range of configuration cases:

- A third party (e.g., a smart grid operator or a market participant) can request time synchronization as a service via the API, mentioned above, including demanding timing resiliency for a specific UE or a group of UEs.
- An end-user subscription can include a demand for timing resiliency for the UE.

Depending on the mechanism, different network functions of the 5G-Advanced core network (i.e., time-sensitive communication and time synchronization function (TSCTSF), access and mobility management function (AMF), or operations, administration and maintenance (OAM)) will be responsible for triggering and controlling the internal timing synchronization status monitoring and reporting status updates.

Timing synchronization status monitoring

5G deployments already have timing synchronization monitoring mechanisms for their operations. The TRS study uses two internal network elements for this monitoring, as illustrated in Figure 5:

- The gNB provides 5G time information (typically UTC) to the UE using control plane signaling making it a key entity to enable time source status awareness in 5G-Advanced networks.
- The UPF with NW-TT can be a source of monitoring when the time synchronization service is based on (g)PTP and the UPF/NW-TT is configured to send (g)PTP messages within the 5G system acting as a PTP instance.

When the timing synchronization status (TSS) changes in these network elements, a report is generated and provided to the consumers of this information. The reports contain a set of attributes as listed in Table 2.

Table. 2 Timing synchronization status information specified in Release 18

Attribute	Description	How attributes help to achieve resilient timing
Synchronization state	Indicates the state of the node synchronization	The status describes the mode in which the clock is operating when providing an output signal. This way, the consumer can determine the expected performance of the clock in a short or long period. Three main modes of operation are defined for a clock, as defined in [17]: • If the output signal is controlled by an external reference and the performance between the reference (input) and the output is bounded, this mode is referred as “locked mode” • If the output signal has lost its controlling reference but is still able to reproduce the locked condition (with some limitations), it is referred to as “holdover mode” • If the output signal has never had a controlling reference or it lost it and it cannot reflect the influence of its external reference, this is referred to as “free run mode”
Traceable to GNSS	Indicates whether the current time source is traceable to the GNSS	For use cases where traceability to a time reference is required (e.g., in a financial use case for compliance with the timestamp or in smart grid use cases to ensure devices can interoperate and handle timing discontinuities). These Booleans notify that the provisioned 5G clock has been monitored and audited in each link within the time distribution chain of the 5G system (e.g., knowledge of the uncertainty of the time signal provisioned to the UE)
Traceable to UTC	Indicates whether the current time source is traceable to the UTC	
Frequency stability	Estimate of the variation[2] of the local clock when it is not synchronized to an-other source	Frequency stability is a description of how good the oscillator is when there is no reference. There may be multiple factors that will influence this value such as the oscillator aging. For time critical use cases, this helps to understand how the time signal provided by the 5G system will degrade when there is a time reference degradation or failure
Clock accuracy	Describes the mean in nanoseconds over an ensemble of measurements of the time between the clock under test and a reference clock	This attribute helps describe quantitatively how uncertain is the time information the 5G system provides compared to the reference; an essential attribute for any resilient use case to monitor the performance the timing signal from the time source to the UE
Parent time source	Describes the primary source the node is currently using	For any resilient use case, this attribute assist documentation of the performance of the primary reference time source the 5G system is consuming and the identification of a time source that may be also accessible to connected devices but it is experiencing a degradation or failure (e.g., GNSS)

2 Variability is in offset scaled logarithm to the base 2 of the variance in units of seconds squared

Timing synchronization status reporting

Once there is a timing synchronization status update available at the gNB and/or UPF/NW-TT, the next step is to report the update to the entities interested in the updates to perform further actions, as illustrated in Figure 5. There are three different entities that may receive updates in 5G-Advanced:

UE

The UE can receive the gNB's timing synchronization status as a direct receptor of the 5G clock, which the gNB provides via the air interface. The reporting to the UE can be at a high level indicating if the time synchronization service is acceptable or not (based on acceptance criteria). Or the reporting can be the detailed timing synchronization status information described in Table 2 and illustrated in Figure 6. These status updates may influence the UE's decision to switch to another reference time source upon a degradation/failure/recovery of the 5G clock. For UE(s) in radio resource control (RRC) IDLE mode, the gNB broadcasts a report ID in order to indicate a change in time synchronization status so the UE can re-connect to receive the gNB's current timing synchronization status.

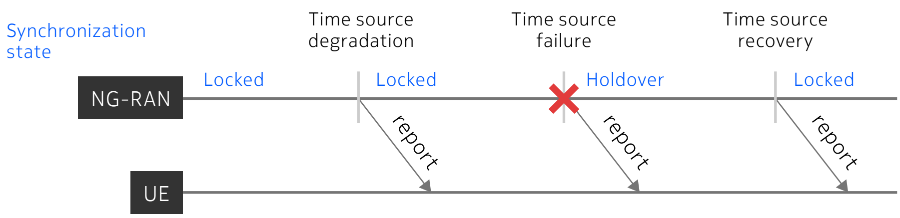
TSCTSF

As the network function managing time synchronization as a service within the 5G system, the TSCTSF can use the reports to evaluate if the service provided via the (g)PTP synchronization method can still satisfy the required demands (e.g., the tolerable error), or if it should be modified, for example, deactivating UEs from the PTP instance or updating the clock quality information the UEs receive.

Application function (AF)

As requester of time synchronization as a service, the AF may receive notifications of the service status from the TSCTSF (if the service is acceptable or not based on a criteria). Using the updates, the AF may modify the service configured for a UE or a group of UEs.

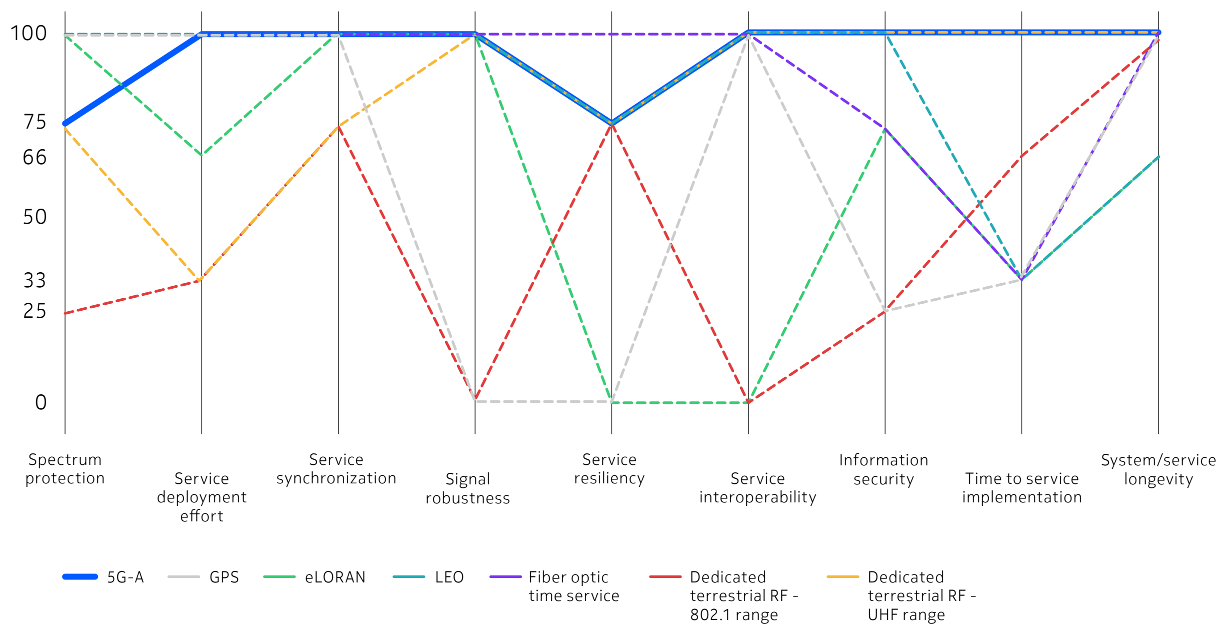
Figure 6. 5G-Advanced time synchronization status reporting towards the UE



Comparison to other resilient timing solutions

Timing resiliency progress in the 3GPP specification positions 5G-Advanced networks as a viable resilient timing alternative or complement to GPS. Figure 7 summarizes the key qualitative metrics to help assess the strong and weak points of 5G-Advanced as a time offering solution. The evaluation is extracted from the demonstration done in [18] to evaluate candidate PNT systems, extending the comparison to include 5G-Advanced.

Figure 7. Comparison of time offering solutions extended from [18] to include 5G-Advanced (see Table 3 for meaning of metrics and values)



The metrics illustrated in Figure 7 are further detailed in Table 3, focusing on the timing domain. Figure 7 demonstrates that 5G-Advanced is a competitive land-based complement or alternative for GNSS, leveraging its infrastructure, wide coverage, and terminal equipment availability for multiple sectors.

Table 3. Qualitative metrics for time offering solutions comparison used in Figure 7, bolded values represent 5G-Advanced scoring)

Metric	Description of X-axis metrics	Values on Y-axis
Spectrum protection	Regulatory protection of the spectrum used for distribution of timing information (if applicable)	Protected - 100% **Owned - 75%** Leased - 50% Shared - 25%
Service deployment effort	Indication of service deployment effort in the form of the time and resources needed to deploy the technology	**Low - 100%** Medium - 66% High - 33%
Signal robustness	Indication of the observation of the technology from the UE point of view (if stable and successful signal reception)	**Strong -100%** Weak - 0%
Service resilience	Assessment of the technology response to off-nominal or changing conditions, levels defined: Fail-safe: The system monitor (if available and in use) or the user equipment transitions to a secondary source for the timing function and continues service without interruption Fail-over: The system or user equipment, if interrupted, indicates loss of service and a prompt indicates that the timing function should transition to another service Fail-soft: The system or user equipment stopped providing the timing function Fail-hard: The system or user equipment provided an undefined or uninterpretable output timing function	Fail-safe - 100% **Fail-over - 75%** Fail-soft - 40% Fail-hard - 0%
Service interoperability	Indication of the system interoperability with GPS and other timing solutions (e.g. compatibility for transmitters, receivers, cross-monitoring, simultaneous operation, layering of services, etc)	**High - 100%** Low - 0%
Information security	Assessment of the inclusion of security measures in the technology	**High - 100%** Medium - 75% Low - 25%
Time to service implementation	Indication of the range of time needed to implement timing services based on the technology (e.g., considering the maturity of documentation, maturity of operation configurations, availability and fielding of equipment, etc). Levels defined: • Short: <2 years • Medium: 2 to 5 years • Long: >5 years	**Short - 100%** Medium - 66% Long - 33%
System/service longevity	Indication of the potential technology's service outlook, the projected operating life. Levels defined: • Long: >30 years • Medium: 15 to 30 years • Short: <15 years	**Long - 100%** Medium - 66% Short - 33%
Service synchronization	Indication of the immediacy in the technology to a UTC-traceable source	**UTC - 100%** Cascade - 75% Self-synchronizing - 0%

Conclusion

This white paper summarizes the technological innovations in 3GPP Release 18, along with its motivations for, offering timing resiliency services in 5G-Advanced. Time-of-day synchronization over 5G has evolved to the point that 5G-Advanced networks will be a trusted timing complement or alternative to GNSS and provide a stronger ecosystem to exploit the current 5G synchronization infrastructure. Notably, it can simply be deployed with a software upgrade to an existing 5G network.

There are multiple benefits to deploying 5G-based resilient timing service for critical infrastructure and various consumers, such as public network consumers (e.g., smart grid or financial industry) or private network consumers (e.g., manufacturers). For use cases already enjoying high-reliability 5G connectivity, they can leverage this critical timing information capability as well. The solution extends the availability of trusted timing information to locations with limited or costly access to GNSS signals and reduces the dependency of critical infrastructure on GNSS, which mitigates the significant economic risks many sectors face currently with GNSS outages.

Abbreviations

5GS	5G system
AF	Application function
AMF	Access and mobility management function
DS-TT	Device-side TSN translator
GM	Grand master
gNB	Next-generation node B
GNSS	Global navigation satellite system
GPS	Global positioning system
gPTP	Generic precision time protocol
NIST	National Institute of Standards and Technology
NW-TT	Network-side TSN translator
OAM	Operations, administration and maintenance
PNT	Positioning, navigation and timing
PTP	Precision time protocol
RAN	Radio access network
TDD	Time-division duplex
TRS	Timing resiliency system
TSCTSF	Time-sensitive communication and time synchronization function
TSN	Time-sensitive networking
TSS	Timing synchronization status
UE	User equipment
UTC	Coordinated universal time

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