EUROPEAN COMMISSION

Alternative Position, Navigation and Timing (PNT) Services
Technical Report
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TECHNICAL REPORT

1. Introduction

This proposal presents a solution for time transfer using IEEE-1588 timing protocols. The idea is similar to the service already available on Internet based on the NTP protocol but enhanced with better accuracy, resiliency and security. While existing solutions based on IEEE-1588 protocol are not able to distribute timing over Ethernet with deterministic performance and dependability (because timing is degraded along each hop), our solution is based on the deployment of a timing backbone powered by the IEEE-1588-2019 High Accuracy profile links (or equivalently White Rabbit). This guarantees that the distribution of accurate and deterministic timing along the backbone is done with minimum time budget utilization. The requirements are just using optical fibers as already provided by the telecommunication companies and it can be provided without additional EU funding if agencies like GEANT provide the links.

The connection to National Metrology Institutes (NMIs), as national timing labs, guarantees the traceability to UTC scale as well as the higher backup capability in case of GNSS failure. The end user can be directly connected to this backbone network for high accuracy timing recovery or, for more scalable a low-cost solution, by using regular data links running the commodity IEEE-1588-2008 protocol. On this approach, because the IEEE-1588-2008 time server would be located geographically close to the end user (few hops are required from backbone to the end user), the degradation of the time is not critical, making possible to achieve the sub-microsecond accuracy goal in a reliable way without more requirement than installing a PCIe NIC card with IEEE-1588 support.

The following section will elaborate this idea, presenting more deeply the technology background, the company expertise and use cases in order to demonstrate the TRL of the approach and the capability of Seven Solution to provide the solution here indicated. Finally, we will explain the demonstrator proposed to illustrate the experimental feasibility of this concept.

1.1 White Rabbit Precision Time Protocol (WR-PTP) introduction

White Rabbit (WR) protocol is an extension of the IEEE 1588 (PTP), to achieve **ultra-accurate sub-nanosecond synchronization** in general purpose networks based on optical fiber. Since the publication of the new IEEE 1588-2019, White Rabbit is also known as “PTP High Accuracy (HA)” profile.

WR was born with the purpose of improving the IEEE 1588 Precision Time Protocol (PTP) to adapt it to the particle accelerator industry requirements. To achieve this, WR is based on **Synchronous Ethernet** (Standard ITU-T SG15Q13 G.8262) and IEEE 1588-2008**, Precision Time Protocol** (PTP), and interoperable with these ratified standards.

This technology has been used by European Organization for Nuclear Research (**CERN**) for several years since it is a multi-collaborative project led by the CERN with participation of **GSI Helmholtz Centre for Heavy Ion Research** and other partners from universities and industry.

The WR initial goal was to develop a new timing and control system at CERN, and later at the Facility for Antiproton and Ion Research (FAIR) in GSI for reliable data transfer and ultra-accurate time synchronization. Other participants as **University of Granada** ported the WR solution to Astrophysics applications such as arrays of telescopes.

Seven Solutions was the co-designer and original hardware manufacturer of WR technology. In 2010, the technology was transferred by Seven Solutions into commercial solutions for industrial applications within critical infrastructure, with requirements of ultra-accurate and deterministic time transfer, and it has been developed and validated in diverse applications within different sectors since then.

The **enhancements** introduced by WR can be summarized as follows:

- Synchronization and timestamping with **sub-nanosecond accuracy**.
- Clock frequency distribution with a **precision** better than 50 picoseconds.
- Plug&Play distribution through **thousands of nodes and tens of kilometres** over standard optical fiber networks (Larger distances can be achieved with specific network configuration).
- **Dependable, resilient** and **deterministic** global time reference. Timing is not significantly affected by network traffic, weather conditions or number of hops.

The increasing requirements of time synchronization on different markets such as finance and telecom has led to the development of a **new High Accuracy PTP profile**, which is intensively based on White Rabbit technology and has been recently published as the IEEE 1588-2019 HA.

The **default version** of White Rabbit allows **plug-and-play links** up to 10 kilometres with sub-nanosecond accuracy (although we have already extended to links of hundreds and even thousands of Km). Due to that, this technology was adopted by many datacenter-centric applications as **finance**, where clock synchronization accuracy is used for traceability reasons and for enhanced trading strategies. The requirements introduced by other sectors such as telecom has led to the development of different turn-key solutions for extending the timing to a wide area networks and resiliency applications and to deploy inter-datacenter links worldwide.

1.2 About Seven Solutions

Seven Solutions S.L. is a privately held company with high expertise on embedded systems and leading accurate sub-nanosecond time transfer and frequency distribution for reliable industrial and scientific applications. Our company is composed of close to 50 employees, most of them engineers with IT, Telecommunications and electronics profile. With more than ten years of expertise in embedded systems design we have already worked successfully in different cutting-edge projects from different sectors such as avionics, telecommunications, Smart-Grid, space, military and scientific facilities as particle accelerators and radio-telescopes. We are leaders in time and frequency distribution solutions and our mission is to deliver dependable communication as well as Time as a Service to enable the development of the next generation XXI century global society challenges such as autonomous driving of vehicles and UAVs, Cognitive radio systems, ultra-high bandwidth & low latency 5G communications or wide-area safety critical systems.

Since 2010 Seven Solutions has been intensively involved in the development of White-Rabbit Technology (http://whiterabbitsolution.com/) from its very early stage, concretely on the design of the White-Rabbit Switch (WRS) and WR customization for different research facilities. This technology has been adopted by different research institutions such as CERN and GSI for High Energy Physics (Particle Accelerators) and also in distributed astronomy platforms under development such as HISCORE, CTA, SKA, KM3Net, etc. During the last two years, Seven Solutions has been working on the migration on this solution to industrial applications and nowadays this technology is in use on more than 20 projects related with different homeland security projects, MIL/AERO developments, telecommunication companies and stock exchanges. Most of these projects focus on utilization of White-Rabbit solution on the framework of time transfer inside datacenters but on this project we will extend the utilization for wider geographical areas and with the focus on the global solution reliability. Our solution is already used by several hundred of customers worldwide, with more than 400 switches sold worldwide and a larger number of nodes as the ZEN-TP or WR-LEN. Our company already is able to evaluate the scalability of the solution based on the advance instrumentation on the lab able to measure the timing signal quality with a high degree for accuracy. Moreover, we have partnership with key national metrology labs as well as telecommunications companies in order to provide the time transfer solution to the end customers.
Recent publications:

- J. Díaz and E. Ros, “Scalable and Long Distance, Deterministic Time Transfer”, ITSF 2016, Prague, November 2016.
- Sub-nanosecond synchronization accuracy for time-sensitive applications on industrial networks, J.L. Gutierrez-Rivas et al., European Frequency and Time Forum - EFTF, 2016.
- White Rabbit: When Every Second Counts, Xcell Journal, Issue 91, Q2 2015.
- J. Díaz Javier, J.L. Gutiérrez, R. Rodríguez, B. Rat Benoit, “Industrial White-Rabbit Solutions", Poster at “The 2015 Joint Conference of the IEEE Int'l Frequency Control Symposium & European Frequency & Time Forum, IFCS-EFTF, Denver, Colorado USA April 12-16, 2015.

1.2.1 Seven Solutions’ solution ecosystem

The WR technology is supported by all Seven Solutions timing products.
The solution proposed in this document is based on the use of the **WR-Z16** as key device for the implementation of the timing solution which will be presented in the next section. However, Seven Solutions counts with an extensive portfolio of different form factors which conform a **full solution ecosystem** designed to bring WR synchronization to different applications according to the new industrial requirements. Any of these products could be incorporated to the solution based on the specific needs of the deployment.
The **TRL** Level for the Seven Solutions technology is 9. This is fully productized and deployed in Europe and the US.

- **The WR-Z16**

The WR-Z16 is the reliable time precise fan-out clock for White Rabbit distribution on 1G Ethernet-based networks. The WR-Z16 is a standalone device with 16 SFP connectors which easily distributes ultra-accurate time and frequency to all the nodes in the network using a hierarchical architecture. Each SFP port can be configured for providing either WR or PTP over optical fiber. It also includes 1PPS and 10MHz SMA outputs. The WR-Z16 can obtain the external time reference from its 10MHz and 1PPS SMA inputs, from another White Rabbit device through the SFP ports or it can work as a free running device. The WR-Z16 has 2x RJ45 ports for NTP and management and 1x RJ45 serial UART for management. It has a robust design with 1U form factor and is optimized for datacenter environments, including redundant hot swappable power supplies and fans. The WR-Z16 supports SNMP v1/v2/v3, rsyslogd and have an integrated web GUI for remote monitoring and management tasks. Its internal statistics can be exported using JSON, SNMP, rsyslog, the web GUI or command line interface. The WR-Z16 incorporates failover mechanisms which combine redundancy in terms of multiple time sources and holdover capabilities to ensure continued operation in both local and wide area networks.

• Other Seven Solutions products

The following table contains other products which are part of Seven Solutions portfolio. As it was mentioned before, these products are not initially considered for the proposed solution, but they could be incorporated to the final implementation in case it is considered as convenient depending on the requirements of each node/location, for example in terms of the necessary number of ports or interoperability options.

Feature	WR-ZEN TP-FL	WR-ZEN TP-32BNC	WR-ZEN TP	WR LEN	DOWR
Rack units	1U	2U	1U	Compact size	Compact size
Fan configuration	2x embedded	None	2x extractable	None	None
Power location	Front	Front	Rear	Rear	Rear
Power configuration	Dual	Dual	Dual	Single	Single
Management	2x RJ45 Ethernet 1x RJ45 Serial 1x MiniUSB UART	2x RJ45 Ethernet 1x RJ45 Serial 1x MiniUSB UART	2x RJ45 Ethernet 1x MiniUSB UART	1x RJ45 Ethernet 1x MiniUSB UART	1xRJ45 Ethernet 1x MiniUSB UART
Outputs	PPS/10 MHz SMA 4x PPS SMA expansion available on demand	PPS/10 MHz SMA 16x PPS LVTTL BNC C&D 16x 10 MHz/PPS CMOS BNC A&B	PPS/10 MHz SMA 4x 1PPS LVTTL DB9A 4x 10MHz/PPS CMOS DB9B	PPS/10 MHz SMA	PPS/10 MHz SMA
PTP Interoperability	Management Ports	Management Ports	Management Ports	No	Management ports
IRIG-B, NMEA, ToD	No	IRIG-B	IRIG-B, NMEA, ToD	IRIG-B	No
SFP Ports	2	2	2	2	2
1PPS Expansion	4, 8	No	No	No	No
GNSS integrated	No	No	No	No	Yes

Table 1: Main features of other Seven Solutions products

1.2.2 Seven Solutions' successful use cases

For the last 10 years, Seven Solutions has worked successfully in cutting-edge projects from different sectors.

WR has been proved to be a resilient time **backup to GNSS** based sources and it is being used to distribute timing information through optical fibers using already deployed DWDM based networks. In this context, Seven Solutions was awarded in 2019 by the **Department of Transportation of the United States** to perform a demonstration of backup and complementary Positioning, Navigation, and Timing (PNT) Capabilities of Global Positioning System (GPS). The results report showed that Seven Solutions technology was the most accurate timing solution evaluated in the demonstration.

On the other hand, different European funded projects focus on pan-European White Rabbit based clock distribution for scientific and industrial applications such as CLOck NETwork Services (CLONETS - https://www.clonets.eu/) or White Rabbit for Industrial Timing Enhancement (WRITE - http://empir.npl.co.uk/write/).

Seven Solutions also participated in the **Time Over White Rabbit (TOWR), a project of ESA's NAVISP Element 2 programme** in which a **Time as a Service (TaaS**) solution was developed to provide UTC traceability and network resiliency based on multiple time sources to the **Spanish Stock Exchange (BME).** In this use case, Seven Solutions provided ultra-accurate IEEE-1588-2019 (White Rabbit) time transfer over commercial optical fiber networks (using DWDM). This facilitates the regular and accurate cross-validation of a local atomic clock with respect the legal time reference. Furthermore, it provided time resiliency at a local node with holdover better than 1.5 microseconds drift after 24 hours. Additionally, Seven Solutions provided inter-datacenter synchronization between the 2 sites of the stock exchange, situated 44 km (27 miles) away from each other, offering redundant time references and cross-validation on each location as well as failover capabilities.

In **finance** sector, the clock synchronization accuracy is used for traceability reasons and also for enhanced trading strategies. For example, this technology has been adopted by **Deutshe Börse** stock exchange (https://www.eurexchange.com/exchange-en/resources/initiatives/technical-changes/high-precision-time-white-rabbit-pilot) in Frankfurt to synchronize all their network capture and timestamping devices and offers this data to their customers as well as a clock reference aligned to the stock exchange reference. In this sector, several companies already trust in this technology as their main network synchronization mechanism, distributing a time reference between the multiple locations where their trading systems are placed that allows to correlate timestamps, legally trace the events and to enable a back-up reference in case of GPS malfunctioning.

For metro area synchronization, many Tier 1 traders, High Frequency Traders (HFT), and investment banks have deployed Seven Solutions technology (including more than 1000 devices deployed in 2018-2020 for two of the most important HFTs globally).

For the wide area, Seven Solutions has recently deployed in collaboration with Optiver, a financial company, a new WR link of 1350km (the longest WR link up do date) to interconnect Chicago and New Jersey trading locations using commercial telecom networks (https://www.gpsworld.com/white-rabbit-makes-leap-for-time-over-fiber/).

Datacenter companies are also pursuing better synchronization performance in their networks because of the increasing demand of on-the-cloud services which are distributed in servers placed in several locations inside one datacenter or in different datacenters. A Tier 1 datacenter company has deployed a WR link that reach up to 120 kilometers without amplification using bidirectional links. To complete this deployment, internal timing distribution after a long-distance link has been set up using IEEE 1588 (PTP) connections on the last hop and comparing the time difference with the time reference.

In the framework of **telecommunication** networks, packet-based synchronization is used for timing dissemination to reduce the GNSS dependency, the associated costs and to improve timing performance. In example, Fifth Generation (5G) technologies demand more strict synchronization requirements between 110 and 12.5 nanoseconds and, at the same time, require advanced capabilities related to reliability and redundancy. In relation to this, **Deutsche Telekom** has a pilot with five White Rabbit ZEN TP-FL units connected in a chain. The first ZEN is fed with 1PPS and 10 MHz signals as reference. The five White Rabbit ZEN-TP-FL devices are connected between them using several DWDM fiber optic links with 50, 60, 80 and 80 Km, respectively. In this case, a single fiber strand is used where two different wavelengths are used for communication between the different devices. This deployment allows to reach distances longer than 200 km without regenerating or amplifying the signal as a plug-and-play system which is pre-calibrated by Seven Solutions.

Electrical power grids also require accurate time information. New smart grids include synchronophasor where data is time sensitive and requires very accurate synchronization mechanism for event timestamping. Additionally, timing information must be provided to the Power Management Unit (PMU) in a reliable way. These new conditions show that timing synchronization requirements are becoming more demanding for this kind of applications. Several WR-PTP pilots have been driven by this sector.

Metrology institutes all around the world (NPL, PTB, VTT, VSL, etc.) have validated and deployed WR networks to distribute highly precise clocks for their experiments and applications. As well, some of the most exigent scientific facilities as particle accelerators or radio telescopes have also deployed this technology in their infrastructure (https://www.ohwr.org/projects/white-rabbit/wiki/WRUsers).

1.2.3 Industry view on accuracy requirements

Based on the successful stories related to the different industrial sectors which are mentioned in the previous section, and the partnership and collaborations maintained by Seven Solutions with several National Metrology Institutes and other key partners which implement a Time as a Service business model oriented to different users in the industry, we can provide an idea about the requirements in terms of time distribution which are currently present in the market for industrial applications.
One of the sectors which has higher synchronization requirements is the finance sector. Several actors as Stock Exchanges, market makers and traders require the highest accuracy and precision possible (sub-nanosecond level) not only to meet the regulations requirements related to UTC traceability but for improving their network visibility and data quality.
Other industrial sectors such as Telecom or Smart Grids, which may not have the sub-nanosecond requirements for the end user applications, can make a good use of a high accurate

backbone network which allow to distribute the timing in the wide area without impacting the time error budget. This way, it is possible to guarantee that the end-to-end time error will not exceed the microsecond level of accuracy. In fact, some ITU-T architectural concepts such as the cnPRTC are presenting accuracy requirements below 1ns (A class) for interconnecting the core layer nodes with the UTC reference.

The Defense and Aerospace sector also present very strict requirements in terms of time transfer and frequency distribution for several applications which typically involve distributed systems of sensors, telescopes, transmission/reception elements, or RADAR. For example, distributed RADAR systems or phased array antennas require sub-nanosecond accuracy along with very low jitter clock distribution in order to optimize the performance of the system.

In general, all the sectors related to critical infrastructure have a growing interest in counting with alternative solutions for the synchronization which do not rely uniquely in the GNSSS systems and their well know vulnerabilities. For these cases, a solution which can provide, even in wide area networks, better accuracy than the traditional GNSS receivers (limited to a few tens of nanoseconds) and at same time provide network resiliency based on redundant time sources and monitoring capabilities, is very convenient.

2. GNSS back-up based on IEEE 1588-2019 TaaS

The solution proposed by Seven Solutions for the Alternative Position, Navigation and Timing (PNT) Services pre-feasibility study carried out by the European Commission is a **Time-as-a-Service (TaaS)** solution based on the implementation of a wide area **telecommunications backbone** relying on the next generation synchronization protocol IEEE-1588-2019 and concretely on the High Accuracy (HA) profile (widely known as **White Rabbit protocol** and described in section 0). The proposed solution is based only on providing timing, although as it is widely known, the timing information can be used to setup positioning infrastructures based on TDA or TDoA algorithms to fully develop navigation applications as is done on for GSM/LTE/5G technologies.

2.1 Technical description of the solution

The backbone of the mentioned solution consists of a network stratum conformed by a group of several nodes which are directly connected with the time sources of the network. The nodes of the backbone can be situated in remote locations and are synchronized by using WR protocol over the pre-existing optical fiber network. This means that each node can receive multiple time references from different external sources such as local **GNSS servers** or **atomic clocks,** as well as from additional time references which are transferred with sub-ns synchronization accuracy from the distant nodes of the backbone or even from an NMI by using WR protocol. In this solution, GNSS can be used as primary reference and shift to a backup local clocks in case of GNSS failure. Alternatively, as indicated above, time reference can be directly provided by NMIs avoiding completely any dependency on GNSS technologies. For UTC traceability reasons, this is our preferred approach.

Besides, each node can provide timing using WR or PTP to lower levels of the network following a hierarchical topology in order to extend the capillarity of the synchronization network and provide a timing service to the end users, which will be able to access the time references either with high accuracy by connecting directly to the backbone or with sub-microsecond accuracy by using other widely used industrial protocols as IEEE-1588-2008.

One of the main advantages of using WR in the backbone is that the ultra-accuracy and precision of this time protocol allows to transfer the time between the nodes with no impact in the time error budget of the network. This means that time accuracy is not degraded with each hop of the link, as it happens when using exclusively IEEE 1588-2008 for time distribution. The drawback is that it requires a purely optical high accuracy timing backbone but it can be setup just using existing telecommunications networks.

In our proposal, the nodes of the backbone are implemented using a WR-Z16 device (see section 1.2.1). This device includes failover mechanisms with the capability of managing multiple time sources, including holdover. This means that if we suppose that certain node is using a GNSS system as primary time source, the WR-Z16 system is able to detect when this primary time source fails (via jamming/spoofing attack or any malfunctioning) and switch to the next valid time source available in the network, preserving the synchronization of the full system. So, the redundant time references provided to each node will work as a GNSS backup, providing a full resilient synchronization solution to the network (more details on how the failover mechanisms work in section 2.2.1) as well as UTC traceability (see section 2.2.4).

An example of the network topology which can implement the mentioned backbone is shown in the figure below, where a simple scenario with only 2 remote locations is presented.

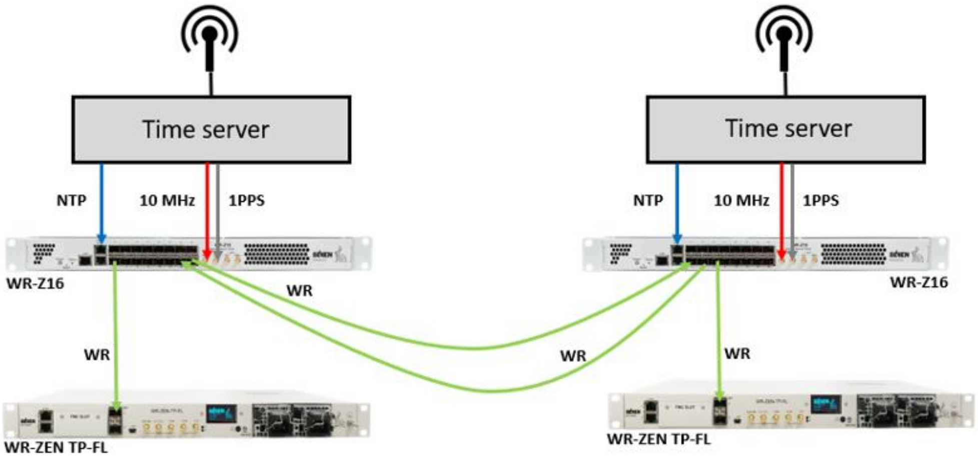


Figure 1: Example of the PNT solution for the backbone: scenario with 2 locations.

In this example, a link between two different sites located in the wide area is considered. On each location, a local time server is used to provide the GNSS time reference, which is used as main time source for each node.

This GNSS reference is provided to the WR-Z16 via 1PPS, 10 MHz and Time of Day (NTP) signals. The WR-Z16 will be locked to this external reference with sub-ns accuracy.

On the other hand, additional time reference is provided on each location via WR link from the other location. So, in location A (left side), the main time reference is provided by the primary Time server (GNSS), and the secondary reference (GNSS backup) is provided by the WR link which transfers the reference of the backup Time server in location B (right side) with sub-ns accuracy.

The system works in the following way: When the primary Time Server is available, the WR-Z16 in the right side is synchronized through the fiber link to the primary time reference using WR. When the primary time reference is lost, the WR-Z16 in the right side switches its reference to the backup Time Server and the WR-Z16 in the left side is synchronized through the fiber link to the backup time reference using WR.
The WR ZEN TP FL devices are included only as an example of the different intermediate or end nodes which can be obtaining the timing from the system (in this case via WR).
In the configuration presented in this case, two links are being used to interconnect both locations. This means that two lambdas (DWDM channels) are required to implement the connectivity between the sites. However, this is just a recommendation, as a single link using single lambda can also work for this scenario. We just recommend using two for improving the monitoring of the system and reducing the asymmetry.

Another possible configuration is shown in the figure below, where single links are used to transfer the time reference using WR from two locations to a third one, which have no direct access to a time server.

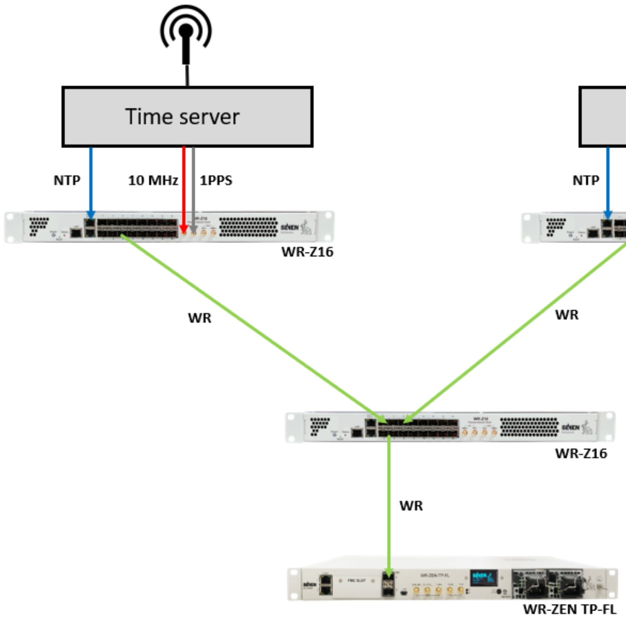


Figure 2: Example of the PNT solution for the backbone: scenario with 3 locations.

In this case, 3 different locations are considered, conforming a ring topology. Two WR-Z16 devices are connected to external time references provided by the Time Severs. A third WR-Z16 device is situated in a lower level of the network hierarchy, receiving two time references via WR from the higher level nodes. This WR-Z16 can switch from the primary reference to the backup reference in case that one of them is lost. It is important to remark that If both references are lost, the WR-Z16 can jump to its internal holdover clock which ensures a time drift lower than 1.5 µs after 24 hours.

In both examples, the use of time source redundancy is focused on avoiding single points of failure on the time reference, which is distributed using White Rabbit all over the network. The negative effects of GNSS jamming and spoofing attacks or time server failures can be avoided by

using with this type of topologies in case GNSS reference is still wanted to be used as primary time reference.
The scalability of WR technology make possible to increase the number of nodes of the topology following the same idea, without impacting the performance. In relation to this, the implementation of this PNT solution based on WR technology over pre-existing optical fiber networks could be extended to cover the entire European territory, as explained in the implementation report.

2.2 Key Features

In this section the most relevant features of the proposed solution will be described. Note that these features are not provided (or not completely) by any other available WR solution in the markets because they are beyond the specifications of the timing protocols but, obviously, a critical feature to provide fully dependable solutions based on the presented approach.

2.2.1 Network resiliency independent from GNSS

The solution proposed based on WR timing distribution provides **dependable and deterministic global time reference**. WR does not depend on local GNSS as time source and its performance is not affected by network traffic as other IEEE-1588 profiles making them ideal for the timing backbone deployment.

To ensure continued operation over possible failures, the WR-Z16 incorporates a system that handles multiple timing sources. It also synthesizes these timing sources into a simplified state (a.k.a Virtual Clock State) to ease the monitoring of the device and distributes a common timing information to the downstream layers. This system uses the multiple timing sources to discipline the local oscillator of the device. These timing sources can be of different types: External Reference (provided via 1PPS and 10 MHz inputs), White Rabbit (High-Accuracy IEEE-1588-2019), NTP (Survey mode only), Holdover (Always used as last timing source if available).

The **FOCA** (**Failover Clock Algorithm**) has been designed for the purpose of automatically switching from one timing source to another in case of a failure in the active timing source has been detected. This algorithm is based on the "Best Master Clock Algorithm (BMCA)" detailed in the IEEE 1588-2019 standard but acts only in case of failure and not when the "best" source appears in the network. It also enforces the evaluation of the timing sources in a rank order configured by the user.

FOCA algorithm has been designed to provide a "safer" approach than BMCA or even ABMCA (Alternate BMCA) to handle switching between multi-references. Its main characteristics are: provides a deterministic behaviour, does not allow a new (rogue) node to become the active reference, recovers back to normal state must be done under the supervision of an operator and allows switching between cross WR/PTP profiles and multiple external timing sources.

As an example, the following figure depicts a configuration where the first two timing sources are employing WR protocol, followed by an external GNSS receiver connected to the front panel reference (GM) and finally ending with the holdover to slowly drift until corrective maintenance. It also illustrates how the two strategies of the FOCA algorithm behave (only fall-down or re-evaluate).

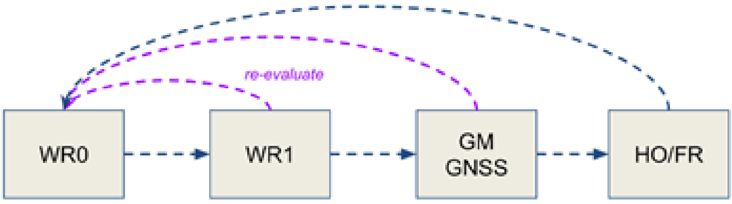


Figure 3: The Failover Clock Algorithm

The concept of “Virtual Clock” has been introduced to ease the monitorization of the global timing status of the device. It allows to abstract the way the timing sources discipline the local oscillator and summarizes how the device will announce its own clock information through the outputs.

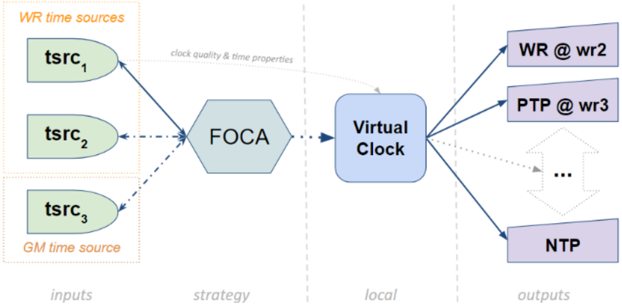


Figure 4: Virtual Clock diagram

When using the FOCA policy, the virtual clock will be fed by the active timing source (e.g., $tsrc_1$), then this information (clock quality & time properties) will be forwarded by all the outputs.

- **Zero-time recovery (ZTR):** A future improvement on the failover algorithm, named the ZTR, has been already designed and validated. It is capable to perform the seamless switchover between time references provided by WR links. This process will be transparent to the user and it will preserve the sub-ns synchronization during the switching so a failure in the active time reference will have no impact in the synchronization performance of the full system.

2.2.2 Scalability and long distance

The WR networks are designed to be highly scalable supporting the extension to **thousands of nodes and long-distance links** including multiple hops within the range of **metro area** or **wide area** deployments, without impacting the synchronization performance. These features allow to ensure the zero impact in the timing error budget in the backbone of the solution proposed (section 2.1).

The typical implementation of wide area networks uses bi-fiber links where WR devices are connected to an optical multiplexer/demultiplexer that receives multiple signals and sends a multiplexed signal. This device allows to multiplex and demultiplex different signals in just one link.

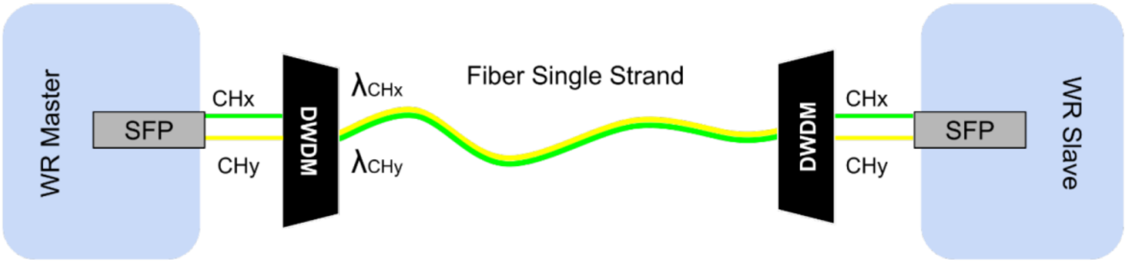


Figure 5: DWDM solution for wide area synchronization

This topology leads to an asymmetry issue because of different latencies in the fiber paths. This asymmetry can be removed combining pre-calibration of the used optical components and specific link calibration. There are different calibration methods which may be suitable depending on the characteristics on the network. Seven Solutions offers a calibration service which includes the certification of the sub-ns level of accuracy in the long distance links.

2.2.3 Interoperability

Seven Solutions products support a wide range of interoperability options with different interfaces and timing protocols and third-party equipment. These options are relevant for allowing the possibility of extending the capillarity of the network by providing PTP downstream to a lower network stratum, as proposed in the implementation report.

- **IEEE 1588-2008 (PTPv2):** The WR-Z16 supports a highly configurable Layer 3 IEEE-1588 on the 16 SFP interfaces. The expected synchronization accuracy when using standard PTP for one hop can be better than ±25 nanoseconds from the reference. If a IEEE-1588-2008 compatible switch is also connected to further fan-out the number of PTP connections, the approximate accuracy is degraded ±50 nanoseconds from the reference in normal operation circumstances. These values are indicative and depend on the accuracy of the third-party hardware and network architecture.

- **NTP:** WR-Z16 provides NTP synchronization on the RJ45 interfaces. In this scenario a high level of accuracy is not expected, however, it allows the device to provide Time of Day information to slave devices.

- **PPS/10MHz**: White Rabbit devices output a 1PPS and 10MHz legacy signals via the output ports. WR ZEN family devices offer the best interoperability with these signals, as they incorporate several options for the configuration of multiple 1PPS/10MHz outputs. The expected accuracy of a PPS slave in comparison to the reference varies depending on the slave characteristics. The synchronization results can be below 1 nanosecond or up to 100 nanoseconds depending on the slave clocking circuitry.

- **White Rabbit integration**: A new High Accuracy Timing IP (HATI) core is available for integration with third party FPGA based devices. When integrated within Seven

Solutions devices the expected accuracy is always below the nanosecond level, however HATI core integration depends on different factors including FPGA vendor and family and internal architecture.

- **Additional interoperability protocols:** Additional mechanisms as IRIG-B or NMEA are also supported in WR ZEN family devices.

2.2.4 UTC traceability

The solution proposed is based on the timing distribution of the primary time references using WR technology. Different time servers can be considered to provide these references to the WR devices, such as **GNSS receivers**, local **atomic clocks** or WR links with the direct connection to NMIs, making as consequence possible to trace the timing solution to the national legal time scale of the user's country. The national NMI can provide a direct **UTC traceability,** which is preserved in the network thanks to WR deterministic and ultra-accurate time transfer. In the case of considering an **atomic clock** as primary time reference instead of a NMI, the UTC traceability can also be achieved by using **Common View** and GNSS receiver at the commissioning stage to provide time transfer between the isolated node and the UTC(k) laboratory.

2.2.5 Monitoring and Management capabilities

Seven Solutions technology incorporate mechanisms for monitoring the status of the different time references existing in the network as well as the status of the synchronization of the different slave nodes in the network.

For monitoring the status of the time reference, the WR-Z16 incorporates a software tool called “**time manager**” which is continuously monitoring the status of the time references which is receiving from different sources (WR link or direct connection with the time server).

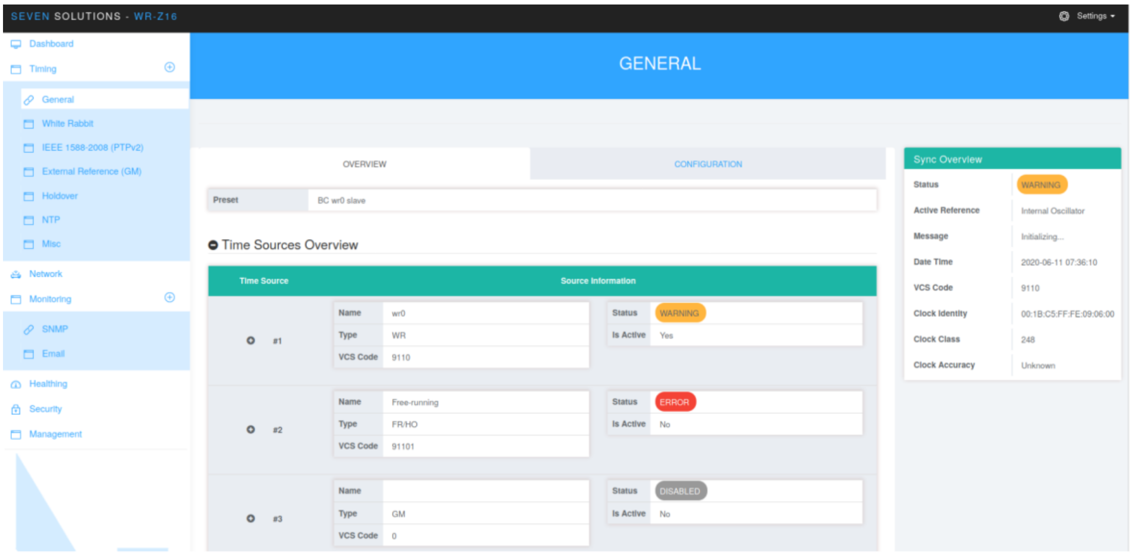
For monitoring the status of the synchronization of all the slave nodes, the WR-Z16 supports **SNMP v2/v3**, **rsyslog** and have an integrated **web GUI**. Its internal statistics can be exported using JSON, SNMP, rsyslog, the web GUI or command line to allow for a complete flexibility of monitoring solutions. **Smart alerts** and **traps** can be configured on the system.
Seven Solutions also offers specific templates which facilitates the integration of the monitoring of WR devices via SNMP in the most used external tools for monitoring and management of networks, such as **InfluxDB, Zabbix, Graphana, Cronograph**, etc. The figure above includes, as an example, a screenshot of the graphical interface of the monitoring solution using Zabbix.

Time	Recovery time	Status	Info	Host	Problem • Severity	Duration	Ack	Actions	Tags
18:18:05		PROBLEM		net.cisco.c2911	Interface Gi0/1(): Link down	1m 49s	No		Environment: Production Teams: Networking
18:18:05		PROBLEM		net.cisco.c2911	Interface Gi0/0(): Link down	1m 49s	No		Environment: Production Teams: Networking
18:15:46		PROBLEM		Switch HP 2530-48g	Interface 11(): Ethernet has changed to lower speed than it was before	4m 8s	No		Environment: DEV
18:11:32	18:17:32	RESOLVED		server.hp.proliant-g9	System-0.17: Temperature is above warning threshold: >50	6m	No		
18:11:32	18:17:32	RESOLVED		server.hp.proliant-g9	Memory-0.4: Temperature is above warning threshold: >50	6m	No		

Figure 6: graphical interface for monitoring using Zabbix

The **Link Layer Discovery Protocol (LLDP**), which functions at the link layer (Layer 2 of OSI model), is supported to discover neighboring devices and their capabilities, and monitor the status of the lower-level nodes of the network.

Speaking about the management of the device, the WR-Z16 provides SSH connectivity and it has an integrated web GUI (see figure 7) for intuitive remote management and enhanced command line tools for advanced users.



Preset: BC wr0 slave

Time Source	Source Information			
#1	Name	wr0	Status	WARNING
	Type	WR	Is Active	Yes
	VCS Code	9110		
#2	Name	Free-running	Status	ERROR
	Type	FR/HO	Is Active	No
	VCS Code	91101		
#3	Name		Status	DISABLED
	Type	GM	Is Active	No
	VCS Code	0		

Sync Overview

Status	WARNING
Active Reference	Internal Oscillator
Message	Initializing...
Date Time	2020-06-11 07:36:10
VCS Code	9110
Clock Identity	00:1B:C5:FF:FE:09:06:00
Clock Class	248
Clock Accuracy	Unknown

Figure 7: Example of management menu of Web GUI on WR-Z16.

2.2.6 Cybersecurity

The WR-Z16 incorporates several mechanisms to provide enhanced security to the system for protection against cybersecurity threads like man in the middle attacks, intentional or accidental spoofing, etc… The proposed solution should be prepared for the worst scenario. As approach to mitigate any security risk, Seven Solutions ecosystem is development based on best security practices and including secure protocols such as SFTP, HTTPS, SNMPv3 and configurability protocols as TACACS+ and RADIUS to guarantee the flexible security policies, from most strict ones to the ones more open and functionality rich as shown on the next table.

	Strict	**Recommended**	**Extended management**
Users/groups	Multiples	Multiples	Single admin
SSH	pubkey only (no root)	pubkey only	pubkey/password
SNMP		v3 (authPriv)	v3 + v2/Traps
Authentication		TACACS+	RADIUS/TACACS+
Logging	/var/log/ + scp	*TLS Rsyslog*	Rsyslog
Web GUI			HTTPS

The above table illustrates the Minimal attack surface ⇔ usability trade-off and how our devices can be configured according to the user need to properly balance the security and usability capabilities of the timing network.

As a brief summary, the key ingredients of our ecosystem for security considerations are:

- Procedures to detect malware or back doors on manufacturer firmware based on utilization of latest OS and tools versions, periodic security patches and third-party equipment security audits.
- Firmware signature for integrity and authenticity as well as Chain of Trust during boot procedure to avoid any unauthorized firmware modification or software installation during commissioning or maintenance operations.
- Flexible configuration to match IT policies including regular password update (PAM/TACACS+/RADIUS), multiple users using group permission, upload public key certificates, customization of firewall (IPTABLES), account “lock-out”(Fail2ban), etc…
- Timing protocol security features. We integrate the new IEEE-1588-2019 security features such as TLV authentication to avoid grandmaster spoofing, Man in the middle attacks or replay attacks. In addition, the utilization of the high accuracy timing protocol imposes specific HW constraints that make easy and fast to detect any timing modification, making unviable phishing attacks. Furthermore, the support of redundant topologies and/or diverse time references integration with different secure protocols (NTP/NTS) and technologies (GNSS) allow time sources cross-validation, removing threads by utilization of advance voting schemes. Finally, (D)DoS attacks with non-timing packets are feasible attacks and for this reason we integrate rules and filters on our devices to mitigate such cases.

- For the firmware integrity, it is verified using md5 checksum (sha-256) and authenticated using PGP (RSA-4K) signature, as described in the figure below:

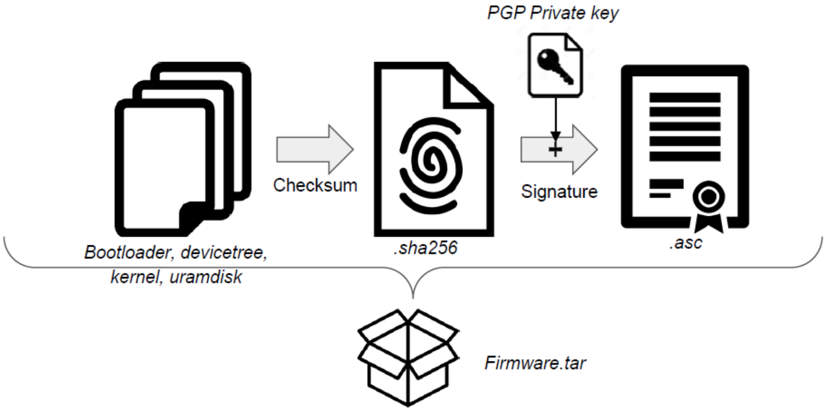


Figure 8: WR-Z16 firmware integrity and authentication processes.

2.2.7 Zero touch provisioning

Seven solutions technology avoids expensive costs related to calibration and complex deployments with high requirements of maintenance, allowing **plug-and-play links** in both local and wide area networks. The devices which are provided are already pre-calibrated for the optical equipment which will be used, and no extra configuration is required on user side in order to perform the commissioning and deployment of the WR network. For the specific use cases that require ad-hoc calibration, due to the fact that the network includes additional elements or equipment which cannot be pre-calibrated, Seven Solutions provide a specific service for this purpose. This calibration service can be performed in different ways depending on the scenario, including the possibility of counting with local smart hands and Seven Solutions providing remote assistant and technical support for the case when on-site link calibration is required.

Plus, WR is a cost-effective solution. This technology is **very easy to integrate in the existing network infrastructure, as it is** based on existing protocols and **standards** such as PTP and Ethernet.

The Zero touch provisioning is a very interesting feature from the point of view of the TaaS model proposed for this solution, as it will make easy the deployment on customer side, minimizing the dedicated resources and facilitating the service implementation.

2.3 Comparison with other technologies

Since GNSS technology is used for critical infrastructures, a failure can compromise business and safety. For this reason, it is crucial to complement the timing services that GNSS provides. Thus**,** **backup systems** should step in when GNSS signals become abnormal, unreliable or corrupted.

Despite the efforts to improve its resilience, GNSS signals are vulnerable to failure, disruption and interference. To mitigate these problems, the GNSS user community utilizes **different techniques** (most of them focus on spoofing detection). Examples can be found in the latest GNSS User Technical Report that provides expert analysis on the GNSS trends and it points out to **authentication methods** in order to avoid false signals irruption. In the case of jamming, the same report proposes different solutions for jamming attenuation: **Filtering** spurious signals at the receiver RF front ends; avoid their **reception at antenna level** (using patterns designed to receive only predetermined signals); **switching to complementary solutions** as existing radio infrastructure (e.g. eLORAN, ALS162), other existing networks (e.g. SDH/SONET), clock network services (e.g. CLONETS), or atomic clocks (e.g. caesium), or **Inertial Navigation Systems** based on motion sensors. In the case of **complementary atomic clocks,** but although rather stable as a holdover mechanism, during their use traceable synchronization to a global reference is lost (it is also a rather expensive choice). Another worldwide alternative for time sources is to use internet to distribute clocks, but in this case the accuracy achievable is not good enough for many applications, e.g. using **Network Time Protocol (NTP)** over long distance does not provide anything better than tens of milliseconds, and it suffers from dependencies on the network traffic load. On the other hand, solutions based on IEEE 1588 **Precision Time Protocol (PTP)** version 2 use free-running oscillators in each node which leads to drifts caused by asymmetries and miscalibration (due to temperature changes and other factors) between master and slave nodes. Thus, the synchronization accuracy achievable depends very much on the specific characteristics of the links and usually degrades with distance, data traffic and number of hops.

Under these circumstances, GNSS-dependent industries could benefit from accurate time distribution with negligible degradation and bandwidth consumption. The solution, based on the new High Accuracy profile in IEEE-1588-2019 HA standard, usually known as **White Rabbit PTP** (WR-PTP), is much more scalable and accurate than other alternatives. By using an **infrastructure of redundant GNSS time receivers** distributed and connected through redundant WR-PTP links with references scattered across hundreds of Km, the infrastructure can get the time references available from safe locations. In addition, the scheme fits the critical infrastructures most specific needs and augments the time synchronization accuracy and frequency distribution precision that is currently achievable by traditional GNSS-based systems.

3. Demonstration proposal

The target of this demonstrator is to show how the proposed backbone can be deployed, what performance figures are achievable as well as to illustrate the resilience capabilities and tools for development of a monitoring control centre for this ground-segment facility. The next subsections will provide better details on these goals and better illustrate the proposed demonstrator.

3.1 Goal of the demonstration

It is Seven Solutions **objective** to demonstrate the capability to transfer an inference of time across many tens of kilometres (the links length is limited by the JRC proposed setup area distance but it is not a limitation of the technology capability) allowing the interconnection of disparately located GNSS receiver or reference clock sites so that an algorithm could compare several instances of time with such high precision that any location can determine if its active time reference is correct, guaranteeing a switching to a provided high precision alternative in case it is necessary. This technique would avoid the effects derived from local jamming and spoofing. Initially, the objective of the demo does not imply the test to be held outside of the

JRC site, but the available network infrastructure on JRC site will determine the link length which can be considered for the tests (alternatively Seven Solutions will provide the optical fiber equipment in case it is not available in JRC site).

The physical infrastructure of this time transport mechanism is hack proof since the transfer mechanism is a physical clock signal embedded within a chosen lambda. By using an infrastructure of redundant GNSS time receivers or time sources distributed and connected through redundant WR-PTP links with references scattered across hundreds of Km, the infrastructure can get the time references available from safe locations meeting, this way, the critical infrastructures most specific requirements. The WR system work not only as a back for the GNSS, but also for complementing this solution by providing monitoring capabilities and enhancing the synchronization accuracy which is possible to achieve using only GNSS-based systems.

3.2 Technical description of the demo proposal

In order to demonstrate the viability of the solution presented in the section 2, Seven Solutions offer the implementation in the test laboratory of a simple version of the backbone described in the mentioned section and the realization of the proper tests to show the key timing performance parameters described in section 4, as well as the system capabilities in terms of network resiliency provision and monitoring capabilities.
This version of the backbone for testing purpose will be based on the use of four WR-Z16 devices, connected as shown in the diagram below:

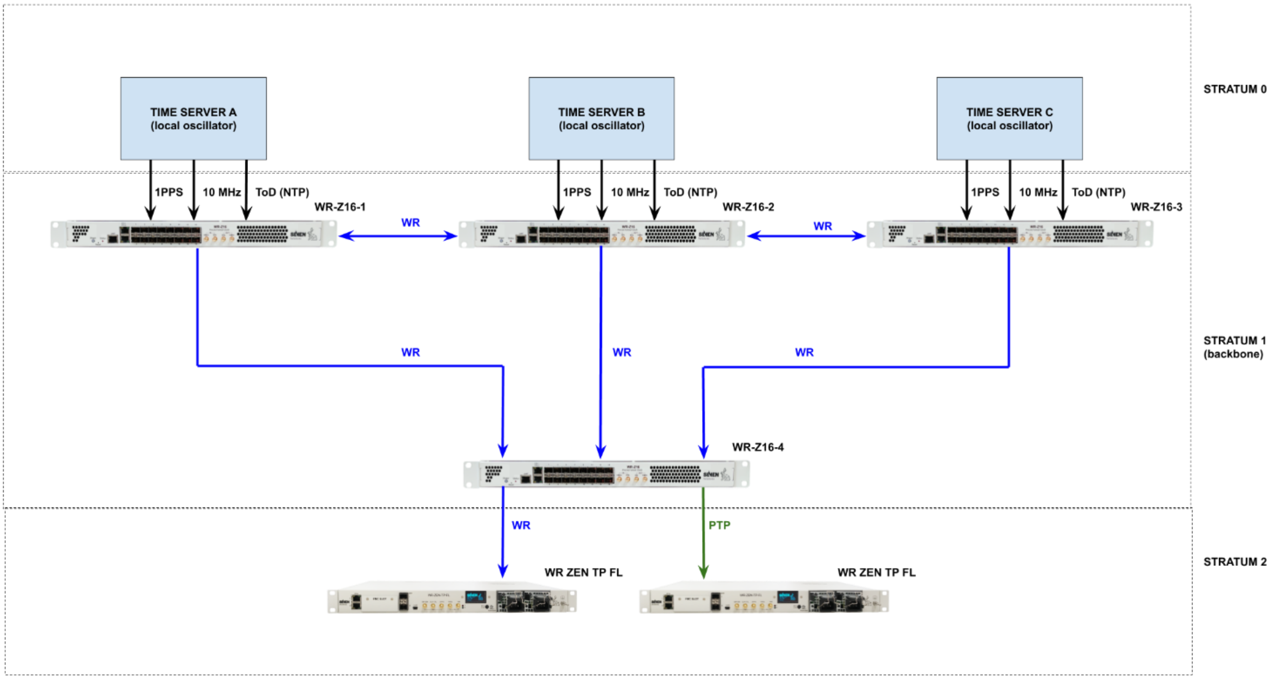


Figure 9: Network topology of the demo proposal.

The **Stratum 0** is conformed by the time servers which provide the primary time references to the network. These devices can be any third-party time server (local oscillator, GPSDO, etc.) available in the JRC installations for testing purpose (if they are not available, Seven Solutions will provide these devices for the demonstration, as indicated in the test plan (section 5)).

The **Stratum 1**, which correspond to the backbone, is conformed by four WR-Z16 devices which are interconnected in a ring topology. The device in the lower level receives the time references via WR link for the three WR-Z16 devices which are connected directly to the time server via 1PPS, 10MHz y ToD signals.

The **Stratum 2** is conformed by WR ZEN TP FL devices, which can act as WR slave device, or as an IEEE-1588-2008 slave for showing the interoperability performance of the technology with this protocol. This illustrates how to deploy a network architecture which includes a lower level of IEEE-1588 slaves devices. In this case the WR-Z16 behaves as IEEE-1588-2008 grandmaster node.
Note that this WR ZEN TP FL working as IEEE-1588-2008 slave auxiliary device can be any third party PTP compliant device available in JRC installations for testing purpose (if they are not available, Seven Solutions will provide the WR ZEN TP FL in the test plan (section 5)) for this test too thanks of the interoperability capabilities of the ZEN family products.

Different configurations using the same equipment will be considered in order to perform the plan test described in section 5.3.

3.3 KPIs

The following list of KPIs is considered:

- KPI #1: Average monthly service availability (target: 99.7%).
- KPI #2: Continuity per hour (target: 99.9%)
- KPI #3: Integrity per hour (target: 99%)
- KPI #4: Maximum Time to Alarm (target: 1s)
- KPI #5: Time Accuracy versus UTC reference at backbone nodes (target: 1us for 1,14,100 days*).

  **Real time error of the solution is below 1ns, but the precision on results may be limited by the clock reference specifications and measuring equipment and/or because of asymmetry errors*
- KPI #6: Time Accuracy versus clock reference provided to WR Grand Master device (target: 1ns)
- KPI #7: Time distribution stability (Allan Deviation)
- KPI #8: Frequency distribution stability (Allan Deviation)
- KPI #9: First time to provide services upon cold start-up (target: 1min**)

  *****The time may vary depending on the network topology, as each WR-Z16 node requires this time to evaluate the multiple time references received.*

3.4 Extension to service model

The demonstration of the solution explained in this section is intended to be implemented for production networks following a Time as a Service model, as detailed in the implementation plan document, provided along with the present document.

4. Performance parameters

In this section, the most relevant performance parameters about the WR time and frequency distribution will be shown.

It is necessary to remark that the performance parameters presented in this section are related to the capabilities of WR synchronization protocol over fiber with respect to a given external time reference, which can be any time server capable of providing a valid UTC reference, but not to the time server itself. This means that these parameters will show the performance of WR for timing distribution whose accuracy with respect to the reference will depend on the time stability the time server can provide.

There are specific parameters related to the time server which are not considered in the section, as the WR protocol can work as timing distribution technology independently from the external time source which is considered in each case. Note that because our solution will propose to be connected to NMI clocks, traceability is already granted by those national institutions.

4.1 Time accuracy to clock reference

The time error which is possible to achieve using WR technology for timing distribution both local and wide area deployments is below 1 ns. As an example, the results for a long-distance link (120km end to end with 2 hops) are shown in the figure below. The time error was measured by comparing the 1PPS outputs from the WR GM device and the end node.

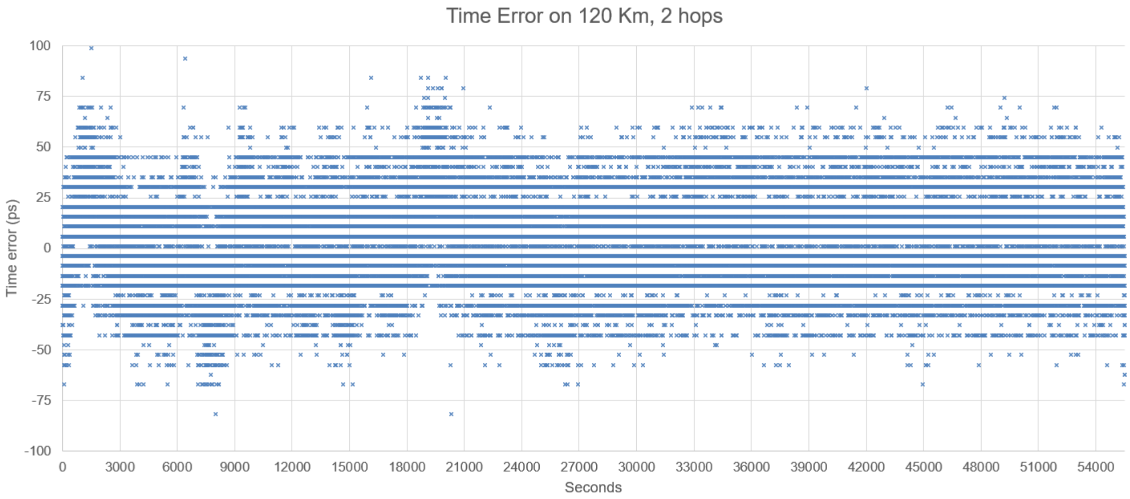


Figure 10: Time accuracy to time reference

4.2 Availability

The service availability which is typically achieved by the solution proposed is above 99.7%. This value corresponds to 2 hours of unavailability per month.
Given the high MTBF of Seven Solutions products, this factor is not relevant for the calculation of the availability, so the main two factors are the time dedicated to maintenance tasks in the timing equipment itself and the availability presented by the optical fiber service provider. The specific values provided are based on the calculations performed by Seven Solution for the NAVISP EL2-033 TOWR project (a project of ESA's NAVISP Element 2 programme).
The 99.7% value can be extended to more than 99.9% just by using protected optical fiber links and introducing redundant time sources on the network topology. Thanks to this, the system would be able to switch to another time reference available during maintenance tasks on the primary time reference, maximizing the time availability of the service.
The provision of specific services related to the technical support can also contribute to increase the availability, for example by providing spare devices and improving the Time to Repair for any incidence which may arise.

4.3 Continuity

The service continuity of the solution proposed for a continuity time interval of 1 hour is above 99.9%, based on the MTBF of the WRZ products which are involved in the solution (MTB>300k hours).

4.4 Integrity

The high values of integrity of the solution are based on the capability of implementing a wide area network based on timing distribution over optical fiber (which is not affected by the well known vulnerabilities of the GNSS-based systems), the use of multiple and redundant time references of different nature in the network, and the built-in monitoring and failover mechanisms which allow to identify a faulty time reference by checking the integrity of the data in comparison with the rest of the time references of the network.

4.5 Timing stability (Allan Deviation)

The Allan deviation of the frequency output for a second hop slave* is shown in the table and figure below:

0.1 s	1 s	10 s	100 s	1000s	10000 s	80000s
2.64E-11	3.13E-12	3.27E-13	3.65E-14	3.91E-15	4.50E-16	8.53E-17

ENBW 5Hz

Table 2: Allan Deviation values with Morion clock as reference

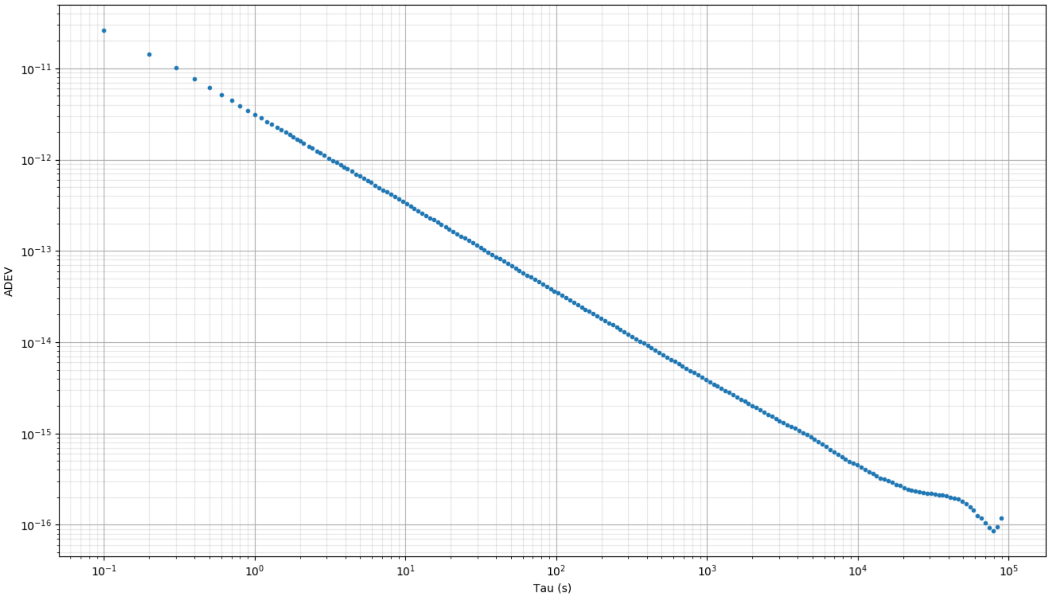


Figure 11: Timing stability (Allan deviation) with Morion as reference

*The values of the ADEV for slave nodes are strongly dependant of the stability of the time reference provided to the WR Grandmaster device. In the example shown in this section, a Morion BTULN Oscillator was used as a time reference.

As an additional reference, the figure below include the ADEV measurements for 1PPS and 10MHz long distance distribution, using a Muclock as time reference.

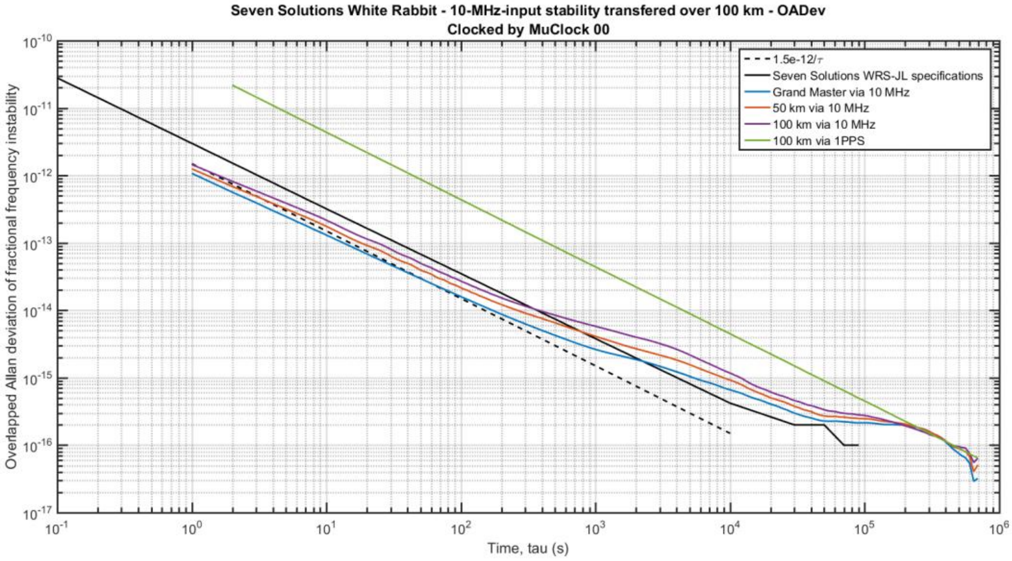


Figure 12: Timing stability for long distance (Allan deviation) with Muclock as reference

4.6 Frequency stability (Phase noise)

The phase noise (DBc/Hz) is shown in the table below for each mode of operation of the WR device.

	1 Hz	10 Hz	100 Hz	1 KHz	10 KHz	100 KHz
GM	-97.1	-105.2	-117.7	-140,00	-145.7	-145.2
1st hop slave	-92	-100.5	-119.8	-138.9	-145.3	-140.9
2nd hop slave	-90.2	-98.6	-117.6	-138.6	-143.9	-138.9

Table 3: Phase Noise values

The figure below shows the graphic of the phase noise for the GM mode:

Figure 13: Phase Noise for the GM mode

4.7 Holdover performance

The following figure shows the time drift measured in holdover mode (with no time reference provided via WR or any external time server) for different learning time periods. Multiple iterations (N) were considered on each case in order to obtain reliable statistics.

The holdover mode was triggered on each iteration after losing the synchronization from a WR link.

As it can be seen, when the learning time is long enough (typically >24h) the measured time drift is lower than 1.5us after 24h of elapsed time with the holdover activated.

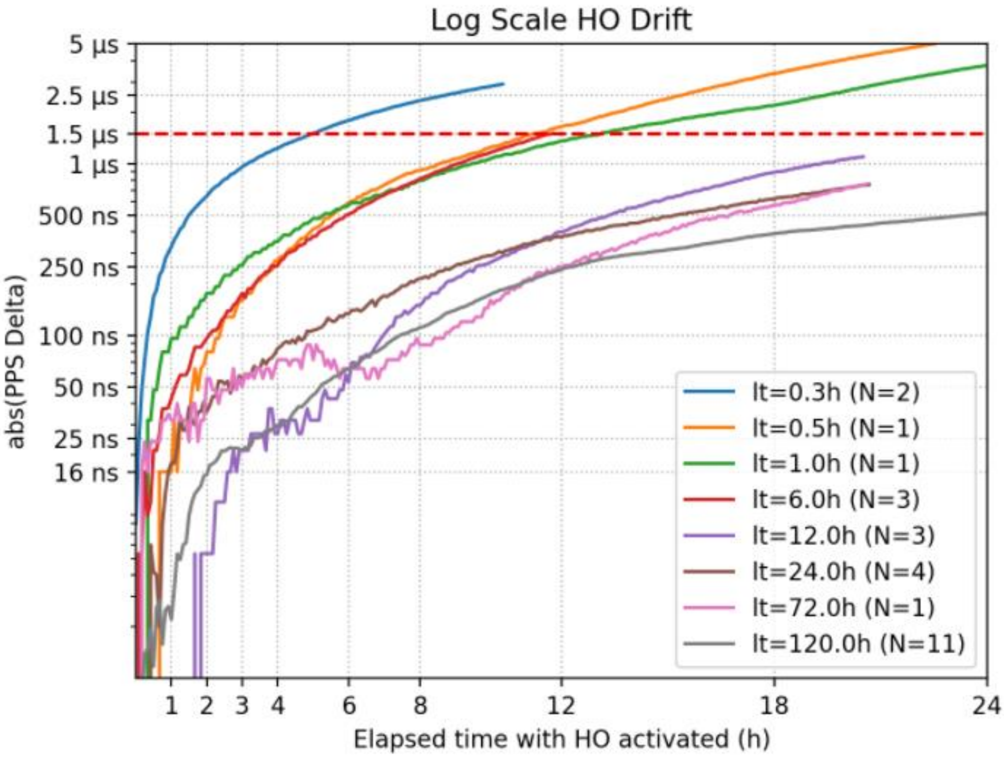


Table 4: Holdover performance

4.8 Downtime during failover

The maximum downtime during failover (defined as the time the system takes to switch from the active time reference to a secondary one) is 1.5 minutes.

4.9 Other parameters and summary of performance

The following table summarizes the key performance parameters of the solution, which has been presented in this section:

Performance Parameter	Value						
Availability	>99.7%						
Continuity	>99.9%						
Integrity	>99%						
Time to alarm	<1s*						
First time to provide services upon cold start-up	<1 min**						
TIme accuracy to UTC	1us***						
Time accuracy to clock ref.	<1ns						
Holdover performance	<1.5 us/24h						
Max. downtime during failover	1.5 min						
Max time error during failover	25ns						
Phase noise (DBc/Hz)		1 Hz	10 Hz	100 Hz	1 KHz	10 KHz	100 KHz
	GM	-97.1	-105.2	-117.7	-140	-145.7	-145.2
	1st hop slave	-92	-100.5	-119.8	-138.9	-145.3	-140.9
	2nd hop slave	-90.2	-98.6	-117.6	-138.6	-143.9	-138.9
Allan Deviation	0.1 s	1 s	10 s	100 s	1000s	10000 s	80000s
	2.64E-11	3.13E-12	3.27E-13	3.65E-14	3.91E-15	4.50E-16	8.53E-17

Table 5: Summary of key performance parameters of the solution

* *It is the time the system needs to detect the faulty reference and raise an alarm or/and perform the failover to the next reference available.*

** *The time may vary depending on the network topology, as each WR-Z16 node requires this time to evaluate the multiple time references received.*

*** *Real error is below 1ns, but the precision on results may be limited by the time server specifications and measuring equipment and/or because of asymmetry errors.*

Please note that data related to a certain number of days of working after GNSS outage has not been considered, as the proposed solution operates independently form a local GNSS outage. This is achieved thanks to the use of multiple time references on each location (including non-GNSS references such as an atomic clock or NMI).
Thanks to this, the specified performance can be applied from 1 to 100 days.

5. Demo test plan

In this section, the details about the demo proposal are explained, including the topologies and configurations proposed and the material involved.

This section has been updated as agreed in the kick-off meeting and next discussions between Seven Solutions and JRC teams, according to the timeline and milestones defined in the project documentation.

5.1 Description of demonstration test plan

In order to show the Seven Solutions technology synchronization capabilities in the Alternative Position, Navigation and Timing (PNT) Services tender and technological demonstration, Seven Solutions will be willing to provide the material (hardware and user equipment when applicable), technical support (technology deployment, configuration, and data collection support) and logistical support during the preparation and execution phases of the demonstration.

For the sake of the demonstration, Seven Solutions has already allocated the necessary devices and auxiliary equipment that will be used to demonstrate the capabilities of the technology. The demonstration does not intend to cover all the possible scenarios due to the high integrability of this technology with third-party equipment, but it will show different reference scenarios to illustrate its most relevant features.

Seven Solutions is open to evaluate and propose different topologies and share its integration know-how in any step of the demonstration. Apart from that, Seven Solutions also have timing dedicated measurement equipment and diverse optical equipment to deploy proof of concept scenarios in its lab, which could be used for this demonstration if it is necessary.

As explained before, White Rabbit deployment procedure is not complex as all the devices are industrial appliances and the required fiber network infrastructure does not need any specific customization. For this reason, the on-site period for installation and setup should be meet.

Regarding personnel, Seven Solutions count with several highly qualified engineers that could perform any of the requested activities. Additionally, some backup staff will be warned in case of unexpected situations, both remotely and available to travel to the demonstration location. Besides that, Seven Solutions also offer a general technical support service that could join the demonstration effort if needed.

In total, 6 engineers are already assigned to cover the different phases of the project. For the the on-site demonstration we will involve one on-site senior engineer, one on-site junior engineer and one off-site senior engineer. A maximum of 2 persons will need to be authorized to access the demonstration site during the demonstration tasks.

The post-demonstration tasks will be performed remotely, but our personnel will be available to join any online meeting or answer any question. Additionally, Seven Solutions support service will be available during the whole execution timeframe, offering its service 12 hours per day, 7 days per week.

5.2 Needed infrastructure and support

Seven Solutions is willing to provide the following list of loan material for the demo realization:

- **Required Equipment provided by Seven Solutions**

  - 4 x WR-Z16 (one of them with holdover expansion)
  - 1 x WR ZEN TP FL
  - 3 x AXCEN SFP pairs for links length lower than 10 km
  - 2 x Fiberstore DWDM SFP pairs for links up to 80 km
  - 4 x optical filters
  - Power cables
  - Optical fiber cables (2x25km, 3x5m)

- **Auxiliary equipment provided by Seven Solutions**

  - Optional: 1 x WR ZEN TP FL (extra) for acting as PTP slave (in case no third party PTP slave is available in JRC installations)
  - Orolias's SecureSync for acting as time server.
  - NI's Optical Splitter for replicating 1PPS/10MHz signals and facilitate measurements.
  - Auxiliary cables for management/measuring purposes

- **Equipment/support to be provided by JRC**

  - **Power supply:** The devices will require standard AC 100-240 V 60 Hz power supply.
  - **PC connected to LAN:** for remote management and monitoring of the Seven Solutions equipment.
  - **Space:** The White Rabbit equipment has a size of 4U 19-inch enclosure. Additionally, 2U will be recommended to be reserved for the auxiliary equipment. The fiber, measuring equipment and rest of the components will need enough room. As it is a static deployment, space is not expected to be an issue at any point.
  - **Third party time servers (optional):** If a time server is available in the testing environment, it can be used in the proposed demo topologies as explained previously. Despite this fact, we are intended to provide our own time sources for the tests.
  - **Third party PTP slave (optional).** A Meinberg M100 has been proposed to be used as PTP slave node. This device supports the telecom profiles (G.8275.1) which are planning to be included in the demo.

- **Measurement equipment:** The most accurate way to measure the time synchronization capabilities on each of the scenarios is comparing the Pulse per Second (PPS) outputs offset between the time source and the synchronized node. In order to measure these outputs, a counter or an oscilloscope is suggested as testing equipment. Additional measuring equipment can be considered in order to measure frequency stability (Allan deviation, phase noise) if it is considered as convenient.

5.3 Tests description

The different tests and configurations which are proposed for the demo are described in this section. All the test scenarios are based on the test topology described on section 3.2, with the proper changes based on the objective of each test.

The WR-Z16 devices are capable to synchronize with very high accuracy to an external source which provides analog signals 1PPS and 10 MHz and an optional NTP link for Time of Day information. This capability allows to use different time sources as atomic clocks, masers or GNSS receivers to provide information to the WR time distribution chain. As mentioned before, the possibility of using different time sources is considered in this test proposal.

We propose a specific configuration based on bidirectional DWDM links without amplification to implement the long distance links (>10km). This configuration allows to deploy plug-and-play long-distance WR links using pre-calibrated values up to 100 km without amplification. Using the WR-Z16 as nodes, the 25 km fiber spool, optical filters and the Fiberstore SFPs, DWDM long distance links can be tested in conjunction to short distance links.
The network infrastructure required for the proposed tests is purely based on optical fiber. However, alternative mediums such as copper or OTA links has been tested and validated in controlled environments, but they are considered to be out of the scope of this test. If it were necessary, we could share specific information about the results of this proof of concept for the reference of the commission.

Using the infrastructure specified, Seven Solutions plans to perform the tests which are summarized in the following table during the demo period:

Test ID	Test name	Duration	Measurements	Metrics	Objective	Location
T1	System verification	<2h (estimated)	-	Fail/pass	Setup the DUTs and verify correct operation	JRC
T2M	Short term sync stability vs clock reference	24h	1PPS, 10MHz	TE, ADEV, MTIE vs clock ref.	Showing short-term time and frequency distribution performance tracking the reference of a clock provided by 7S	JRC
T2N (optional)	Short term sync stability in HO vs UTC reference	24h	1PPS, 10 MHz	TE vs UTC ref.	Showing short-term frequency distribution performance in Holdover based on UTC reference	JRC
T3	Medium term time stability	14 days	1PPS	TE, ADEV, MTIE vs UTC ref.	Showing medium-term time transfer performance based on UTC reference	7S
T4M	Network monitoring	<2h (estimated)	descriptive	descriptive	Showing monitoring capabilities of the solution	JRC
T4N	Failover scenario A	<2h (estimated)	descriptive	descriptive	Showing resiliency capabilities of the solution for failover scenario A: loss of GNSS reference	JRC
T4O	Failover scenario B	<2h (estimated)	descriptive	descriptive	Showing resiliency capabilities of the solution for failover scenario B: failure in optical fiber link	JRC
T4P	Failover scenario C	<4h (estimated)	descriptive	descriptive	Showing resiliency capabilities of the solution for failover scenario C: slow frequency drift	7S
T4Q	Interoperability	<2h (estimated)	descriptive	descriptive	Showing interoperability with other timing protocols capabilities of the solution	JRC

Table 6: Summary of test description table

5.3.1 Test 1 (T1): System verification

The objective of this test is preparing the setup for the DUTs and verify that it is operating properly. The setup, which will be used for T2M, will be configured, including long distance links and multiple hops to simulate a network with 3 stratum levels, as well as the measuring equipment.

The network topology which will be built is included in the figure below:

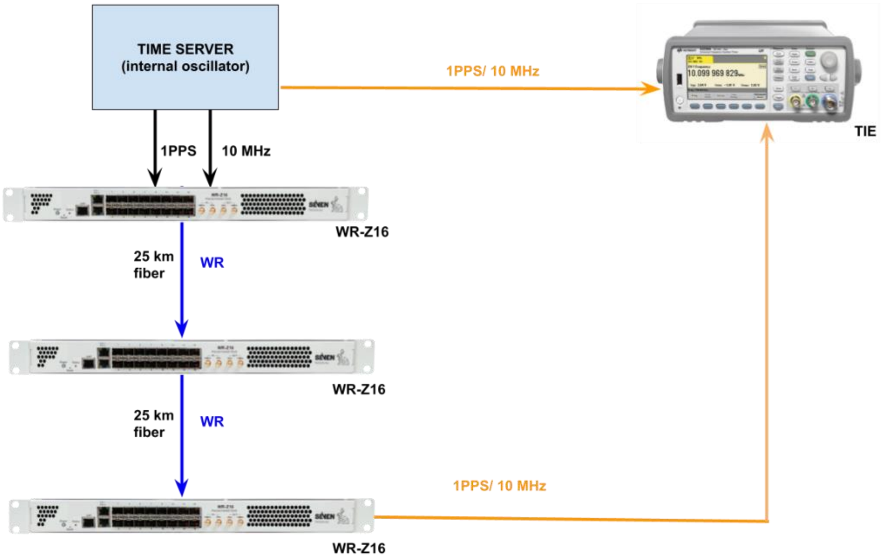


Figure 14: Test topology for T1 and T2M

During this test, the provided time server will be initialized with GNSS reference and prepared to enter in holdover mode.
Plus, we will verify that the data is logged properly in the measuring device which will be a time interval counter (TIE).

As a result of this test, the full system will be checked to ensure that it is fully operational, and we will confirm that the setup is ready for the following tests.

The description table of T1 is shown below:

Test ID	Test name	Duration	Measurements	Metrics	Objective	Location
T1	System verification	<2h (estimated)	-	Fail/pass	Setup the DUTs and verify correct operation	JRC

5.3.2 Test 2 (T2): Short-term sync stability

The objective of this test will be characterizing the short-term stability of the time and frequency distribution performed by the WR solution. For this, we will measure the 10 MHz and 1PPS outputs from the DUT located in the stratum 3, using the 10 MHz and 1PPS signals provided by the time server a reference for the measurement (the GM node could also be used as reference in order to measure the performance of pure WR distribution).
Depending on the time server used as a reference, there are two possible sub-tests (named as T2M and T2N) which will be described in the following subsections.

As it can be seen in the previous figure, 25 km fiber links are used to connect the devices from different stratum levels in order to show the synchronization performance in the long-distance scenario.

The duration of this test will be 24h, so the data related of the 1PPS/10MHz outputs will be collected for this period, for its later processing, calculation of AVAR and MTIE and evaluation.

5.3.2.1 Test T2M: Short-term sync stability vs clock ref.

In this test, the short-term synchronization stability of the stratum 3 node will be measured using a time server provided by Seven Solutions as a clock reference (SecureSync).
This time server will be working in free running (holdover mode). In order to optimize the performance, we recommend keeping the SecureSync locked to the GNSS reference for initialization and holdover learning for a 24h period. After this, the holdover can be launched by disconnecting the GNSS antenna and the measuring process can start.
With this test, we intend to show how good the technology can follow and distribute the external reference provided by any clock reference, independently from how stable it is.

The same topology presented in the section 5.3.1 will be used for this test. In this case, the signals provided from the time server and DUT to the TIE for the data to be logged will be 10 MHz and 1PPS outputs.
The description table of T2M is shown below:

Test ID	Test name	Duration	Measurements	Metrics	Objective	Location
T2M	Short-term sync stability vs clock reference	24h	1PPS, 10MHz	TE, ADEV, MTIE vs clock ref.	Showing short-term time and frequency distribution performance tracking the reference of a clock provided by 7S	JRC

5.3.2.2 Test T2N: Short-term sync stability in HO vs UTC ref.

In this test, considered as optional, the time reference used to measure the short-term synchronization stability is a JRC clock which provides UTC reference. With this, we intend show how good is the performance of the WR-Z16 in holdover mode, when no external time references are available.

The WR-Z16 of the Stratum 1 is initialized by providing the reference from Seven Solutions provided Time Server (SecureSync). We recommend keeping the holdover learning for a period of 24h prior to launching it, in order to provide an optimal performance. The action of disconnecting the 10MHz and 1PPS inputs from the WR-Z16 will trigger the holdover mode. Once the device is in holdover mode, the 1PPS measuring process can start, using the JRC clock as UTC reference for the measurements. The TE measures will represent the Holdover drift vs time).
The following figure shows the topology considered for this test:

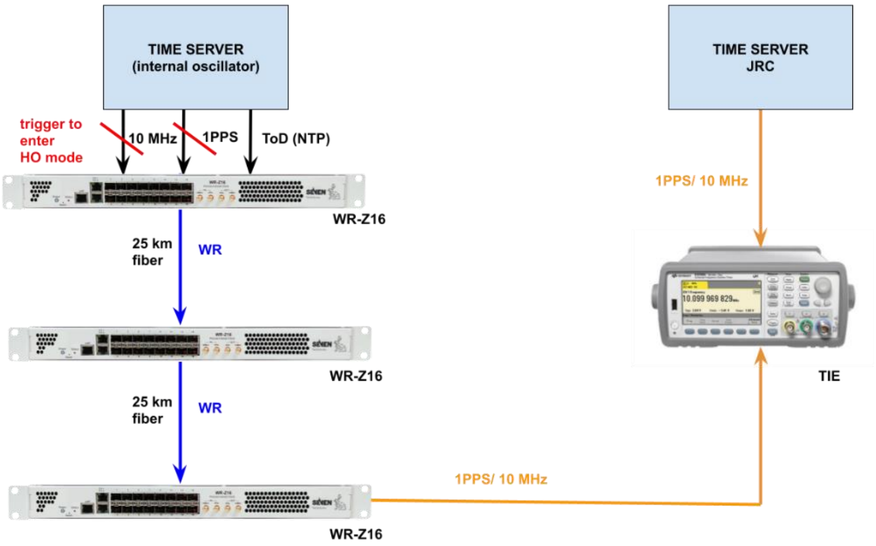


Figure 15: Test topology for T2N

The signals provided from the time server and DUT to the TIE for the data to be logged will be 1PPS/10MHz outputs.
The description table of T2N is shown below:

Test ID	Test name	Duration	Measurements	Metrics	Objective	Location
T2N (optional)	Short term clock stability in HO vs UTC reference	24h	1PPS, 10 MHz	TE vs UTC ref.	Showing short-term frequency distribution performance in Holdover based on UTC reference	JRC

5.3.3 Test 3 (T3): Medium-term clock stability

In this third test, the performance in terms of stability in the short-term of the time transfer using WR for the timing distribution in the backbone will be characterized.
In order to characterize the stability of the time transfer, the AVAR and MTIE of the 1PPS output from the DUT located in the third stratum level (WR ZEN TP FL) of the network can be obtained, using the 1PPS output from the time server as reference.

As agreed, this test will be performed in Seven Solutions' installation in order to simulate the scenario proposed in the implementation report, where high performance time references from National Metrology Institutes are used for the timing distribution.

In relation to this, a Maser will be used in this test as time reference for the WR Grandmaster node of Stratum 1, and a time reference from the Spanish Metrology Institute (Real Observatorio de la Armada, ROA) will be used to provide an UTC reference for the measurements for this test.

Once the Maser is disconnected from the ROA reference, which provides UTC reference based on Common View and it is disciplining the Maser, it will start working in free running mode, so we will start the test and measure the time error between the WR node of stratum 3 and the ROA reference. This test is intended to show the time transfer performance of the solution when using high performance time servers which do not rely on GNSS receivers.

In this case, the signals provided from the ROA UTC reference and DUT to the TIE for the data to be logged will be 1PPS outputs. This raw data from the time error will be used to calculate the MTIE and ADEV.

The figure below shows the high-level topology which will be considered for this test.

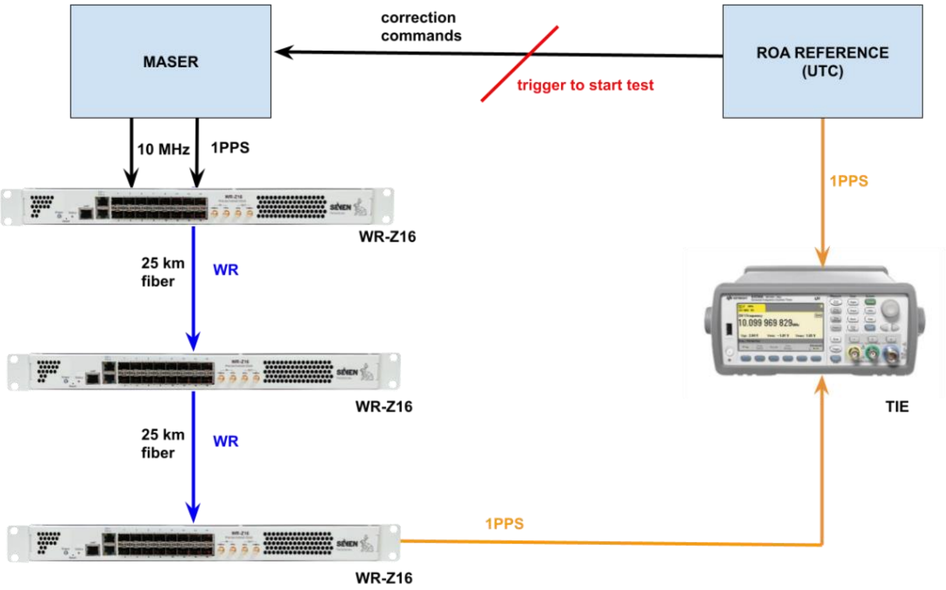


Figure 16: Test topology for T3

The duration of this test will be 14 days, so the data related to the time error will be collected for this period and used to calculate the MTIE and ADEV.

The description table of T3 is shown below:

Test ID	Test name	Duration	Measurements	Metrics	Objective	Location
T3	Medium-term time stability	14 days	1PPS	TE, AVAR, MTIE vs UTC ref.	Showing medium-term time transfer performance based on UTC reference	7S

5.3.4 Test 4 (T4): Network monitoring, failover, and interoperability test

The objective of this test is characterizing the monitoring, interoperability and resiliency capabilities of the DUTs which implement the WR network.

The configuration which will be used for this test is shown in the figure below:

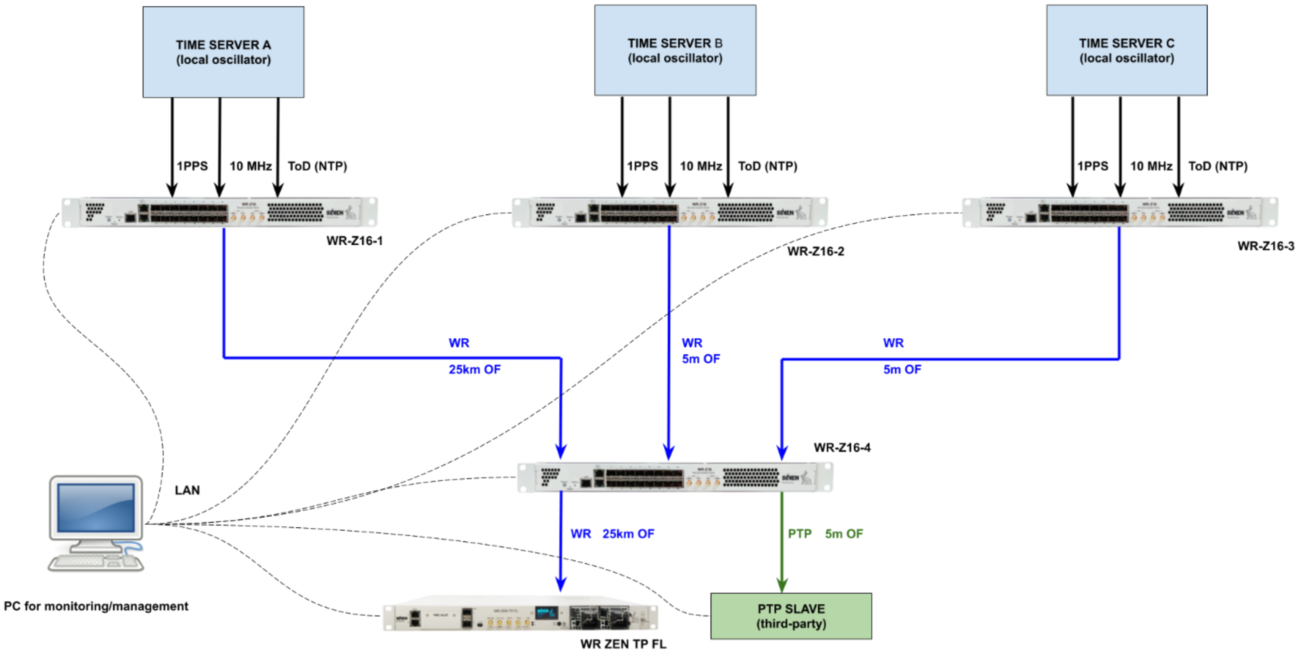


Figure 17: Test topology for T4

The different tests performed in this period are detailed in the following subsections.

5.3.4.1 T4M: Network monitoring test

This test will demonstrate the monitoring capabilities of the solution, both for knowing the status of each time reference used in the network, and the synchronization status of all the nodes located in each stratum level. This experiment is very relevant to explain how this EU infrastructure can be later integrated as any other ground segment control system used for instance for Galileo. The hold backbone of the facility can be remotely monitored. Moreover, the time-error, asymmetries skew can be minimized globally thanks to redundant links utilization. All these capabilities can be controlled from a centralized location in order to monitor the status of the infrastructure.

A PC is required for this test to show the monitoring capabilities of the WR-Z16. The web interface will be used for this purpose. The possibilities that SNMP and LLDP protocols can provide in terms of monitoring will be shown as well, including the integration with external tools such as Grafana and Kibana for improved visualization. Note that the utilization of LLDP allows to implement the previously known as “Reverse PTP” protocol (now defined as part of the IEEE-1588-2019 stack). This makes possible in-band monitoring of the time offset existing at the end user location with total security and without requiring any additional links. This allows determining the time error of the end nodes and therefore, to determine the Quality of Service offered to the customers. In a very similar way than the Galileo High Accuracy Service (HAS) idea, this opens the door to the development of Commercial Services mimic the Galileo offering to customers.

The description table of T4M is shown below:

Test ID	Test name	Duration	Measurements	Metrics	Objective	Location
T4M	Network monitoring	<2h (estimated)	descriptive	descriptive	Showing monitoring capabilities of the solution	JRC

5.3.4.2 T4N: Failover scenario A

The capabilities in terms of network resiliency will be tested by providing multiple and redundant time references to the WR-Z16 and showing the behaviour of the system after the failure detection on each time source. The failures in the time sources will be intentionally originated during the test. In relation to this, the test will show how failover mechanisms based on automatic switchover between different time sources is implemented in order to provide reliable timing to end user and maintain sub-us accuracy according to the KPI related to time accuracy with respect to UTC, even in case of multiple failures in the time sources.

Besides the metrics of this test are purely qualitative and descriptive, the downtime between switching may be shown as well as the time drift based on convenience. The monitoring interface will allow to visualize all the relevant information regarding the failover action and its effects on the synchronization.

In this first scenario, we will simulate the loss of the time reference provided by time server A by removing input signals (10 MHz, 1PPS) of the WR-Z16-1 (stratum 1). This can be easily done by removing physically the corresponding cables.
As a result of this failover trigger action, the WR-Z16-4, which is configured with reference related to the time server A as primary reference, will detect the failure in the active time reference and perform the failover to the secondary time reference which is the one related to the time server B.

The description table of T4N is shown below:

Test ID	Test name	Duration	Measurements	Metrics	Objective	Location
T4N	Failover scenario A	<2h (estimated)	descriptive	descriptive	Showing resiliency capabilities of the solution for failover scenario A: loss of GNSS reference	JRC

5.3.4.3 T4O: Failover scenario B

In this second failover scenario, we will simulate a failure in the optical fiber link which transfers the time reference provided by time server using WR over fiber. This can be easily done by removing physically the optical fiber link between WR-Z16-1 and WR-Z16-4.

As a result of this failover trigger action, the WR-Z16-4, which is configured with reference related to the time server A as primary reference, will detect that this time reference is not available anymore and perform the failover to the secondary time reference which is the one related to the time server B.

The description table of T4O is shown below:

Test ID	Test name	Duration	Measurements	Metrics	Objective	Location
T4O	Failover scenario B	<2h (estimated)	descriptive	descriptive	Showing resiliency capabilities of the solution for failover scenario B: optical fiber link failure	JRC

5.3.4.4 T4P: Failover scenario C

In this third failover scenario, we will simulate a slow frequency drift in the 10MHz input provided to one of the WR-Z16 devices of the stratum 1. This is the typical situation we face when a spoofing attack is occurring over the GNSS receiver.

The monitoring capability of the WR-Z16 devices will allow to identify the faulty reference by using the voting scheme which continuously compares a minimum of three independent time references to detect any disturbance which may appear on them. Once the faulty reference is detected, the system will discard it so it will not be available anymore to be selected as active reference by the FOCA policy. Due to the higher complexity of this scenario, Seven Solutions team proposes to perform this test in their installations.

The description table of T4P is shown below:

Test ID	Test name	Duration	Measurements	Metrics	Objective	Location
T4P	Failover scenario B	<4h (estimated)	descriptive	descriptive	Showing resiliency capabilities of the solution for failover scenario C: slow frequency drift	7S

5.3.4.5 T4Q: PTP Interoperability test

In this test we will show the interoperability with PTP that WR-Z16 provides. For this, a PTP link will be stablish between the WR-Z16 of second level stratum and the third level stratum nodes. A third-party device is planned to be used as PTP slave. Seven Solutions proposes to use a Meinberg M1000 as PTP slave, which supports the PTP telecom profile G.8275.1.

The description table of T4Q is shown below:

Test ID	Test name	Duration	Measurements	Metrics	Objective	Location
T4Q	PTP Interoperability	<2h (estimated)	descriptive	descriptive	Showing interoperability with other timing protocols capabilities of the solution	JRC

6. Demo test results

In this section we present the results of the demonstration activities corresponding to the plan which was described in the previous section.

6.1 Test results: T1 (System verification)

The setup represented in the following figure was built in JRC installations. This test topology is based on the figure 14, which was presented in section 5.3.1. Additional details have been added in order to fully specify the final connections and equipment used in the JRC scenario.

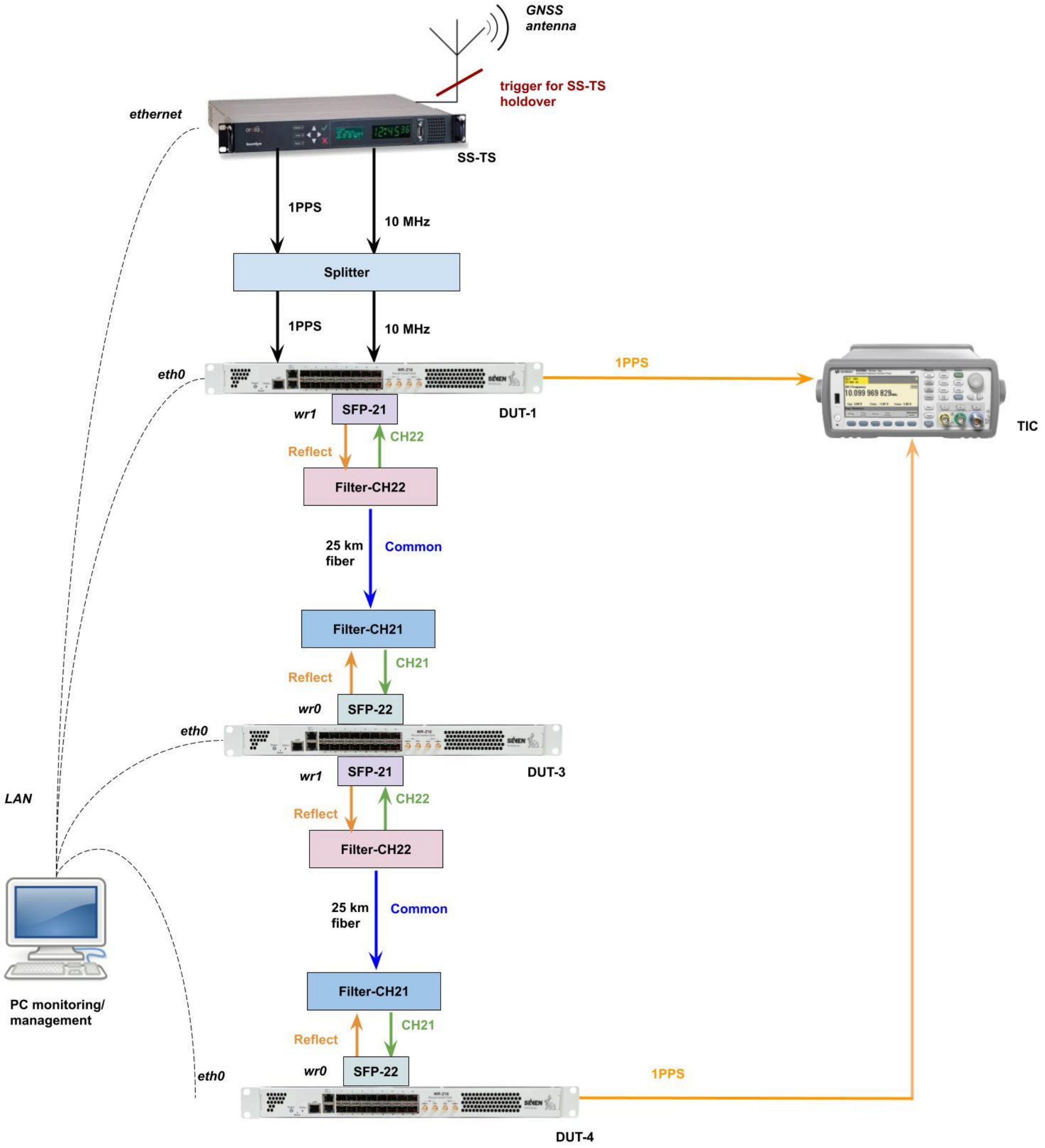


Figure 18: Full details on Test topology for T1

The topology was built by JRC team, with remote support from the Seven Solutions team. The devices were preconfigured for the specific topology, which is described in the figure above, so no additional configuration actions were required.

The correct operation of the system was checked in order to ensure that the system was ready for starting the measurements corresponding to T2 test.
During this test, the correct status of each device of the network, as well as the synchronization between all the WR nodes. Was checked by Seven Solutions team via remote management tools.
The following table shows the basic configuration of the devices and the status parameters which were checked in this test.

Tag	Operating mode	Port configuration	Network configuration	Comments	Status Parameters to be checked
SS-TS	GNSS synced	-	DHCP	The time server was initialized using the GNSS reference	In System Status panel: System GNSS reference is sync
DUT-1	GM	Master on all ports	DHCP	The GM receives the time reference from the Time Server	In Sync Overview panel: Active Reference GM:Front-Panel Message: Locked
DUT-3	BC	Slave on wr0 Master on wr1	DHCP	Intermediate node	In Sync Overview panel: Active Reference BC:WR @ wr0 Message: Locked (TRACK_PHASE)
DUT-4	OC/BC	Slave on wr0	DHCP	End node	In Sync Overview panel: Active Reference BC:WR @ wr0 Message: Locked (TRACK_PHASE)

Table 7: Pre-configuration of devices for T2

6.2 Test results: T2M (Short-term sync stability vs clock ref).

This test uses the topology prepared in T1.

The steps followed for starting this test were:

- Initializing the SecureSync using GNSS reference. The only action required for this is connecting the GNSS antenna to the device.
- A learning period of 24h locked to GNSS reference is recommended to optimize the performance of free-running mode in the SecureSync.
- The GNSS reference is disconnected. This trigger will launch the free-running/ holdover mode in the SecureSync.
- Start the 24h measurement: 1PPS signals from DUT-1 and DUT-4 are used as outputs to measure the time error in this scenario.

The following figures present the short-term 1PPS performance measured during this test:

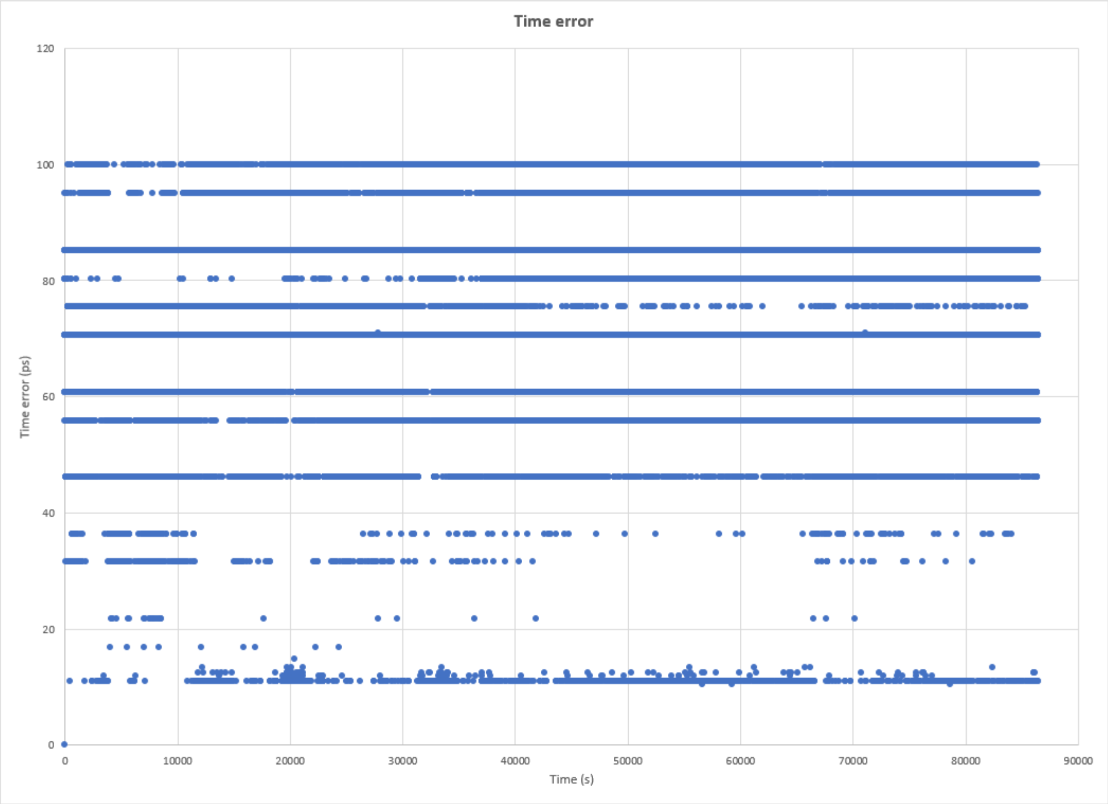


Figure 19: T2M results: TE

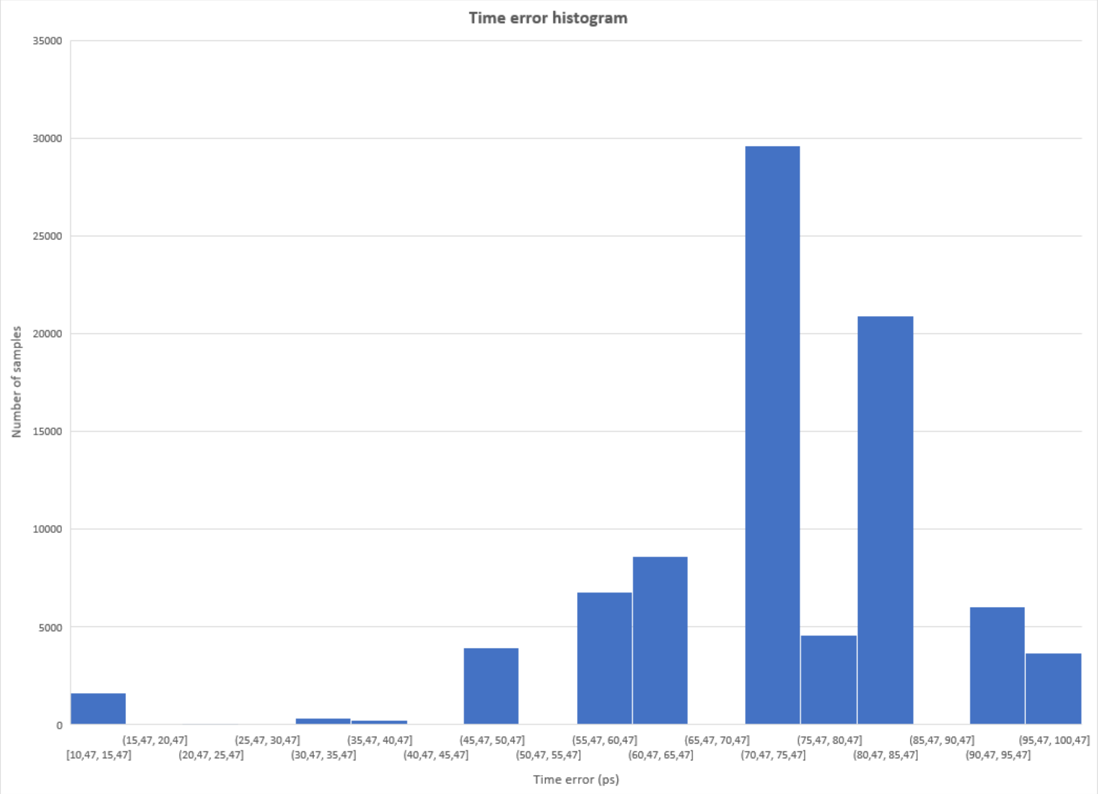


Figure 20: T2M results: histogram of TE

The corresponding Allan Deviation and MTIE graphs are included below:

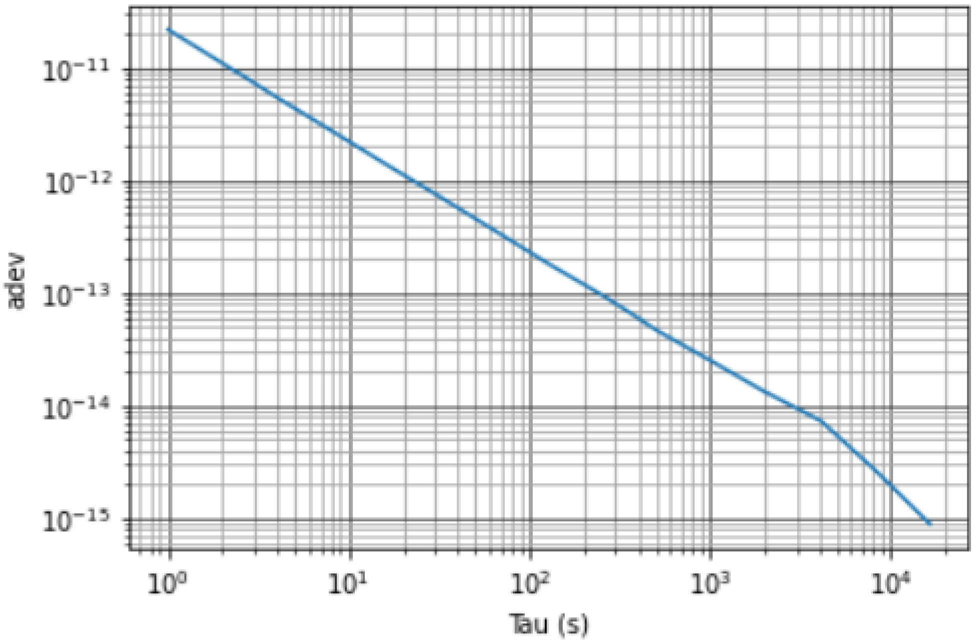


Figure 21: T2M results: ADEV

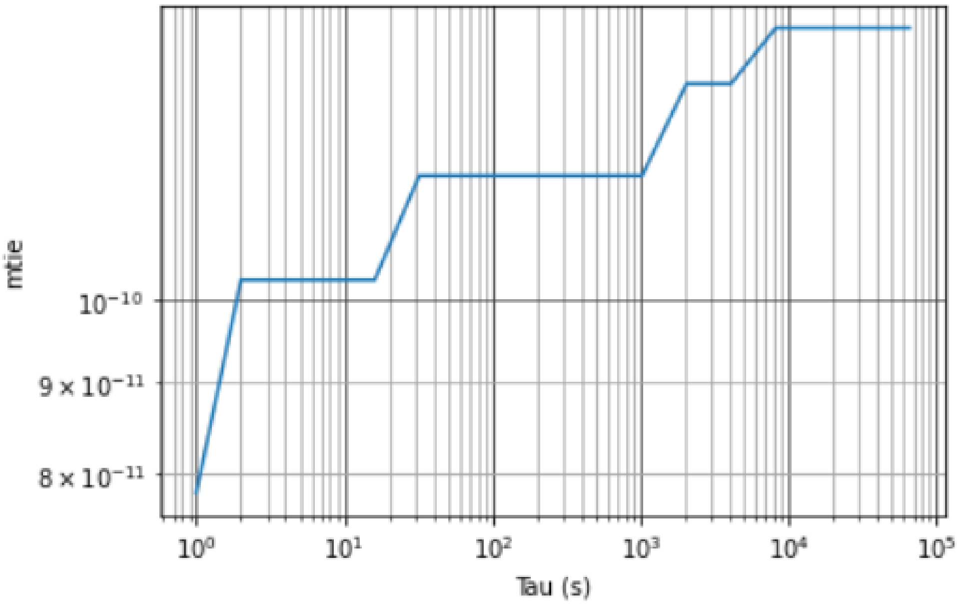


Figure 22: T2M results: MTIE

Some relevant statistical parameters are included in the table below:

Accuracy (average)	73.25 ps
Jitter (standard deviation)	16.12 ps
Peak to peak error	89.39 ps

The results shown in the table below corresponds to the expected results for the scenario proposed. However, the distribution of values which can be seen in the figures does not show the expected Gaussian distribution of the time error, evidencing some kind of resolution issue in the measuring equipment. This issue is still pending to be identified.

As an example, for the sake of comparison, the figures below show equivalent measurements using a Keysight 53230A in Seven Solutions installations (*):

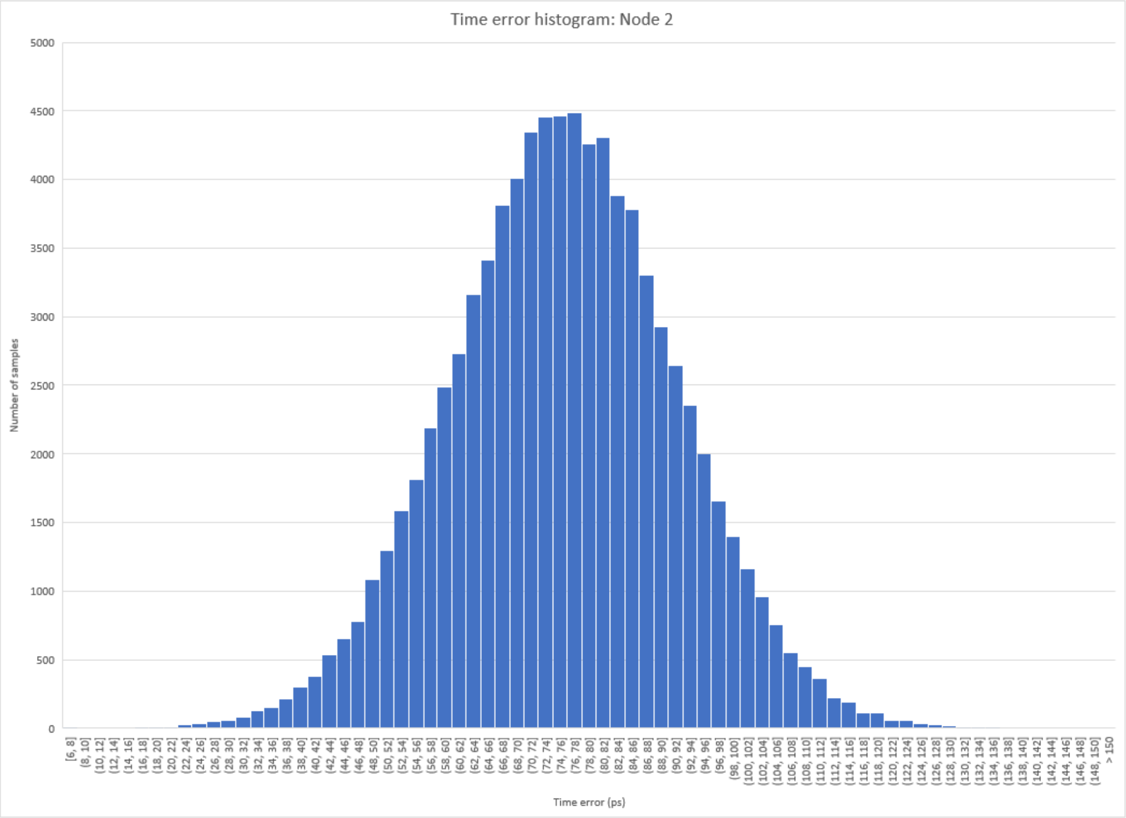


Figure 23: Reference results: TE

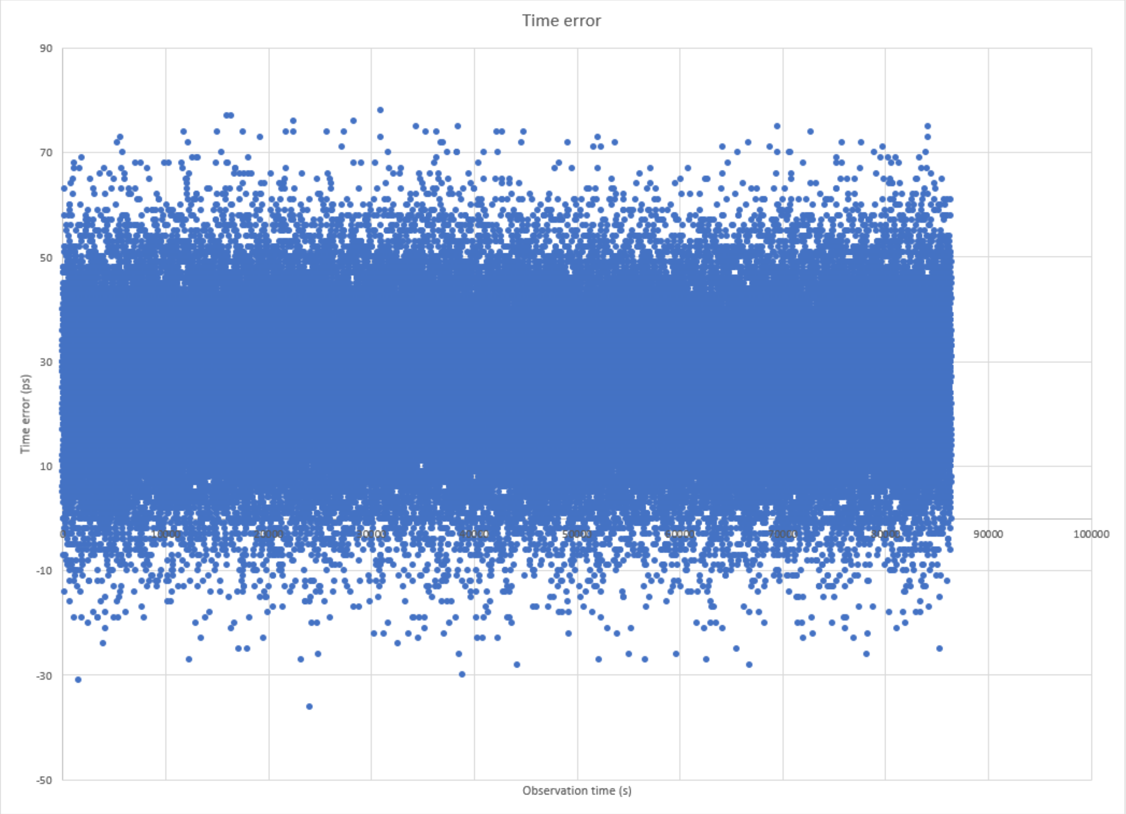


Figure 24: Reference results: Histogram of TE

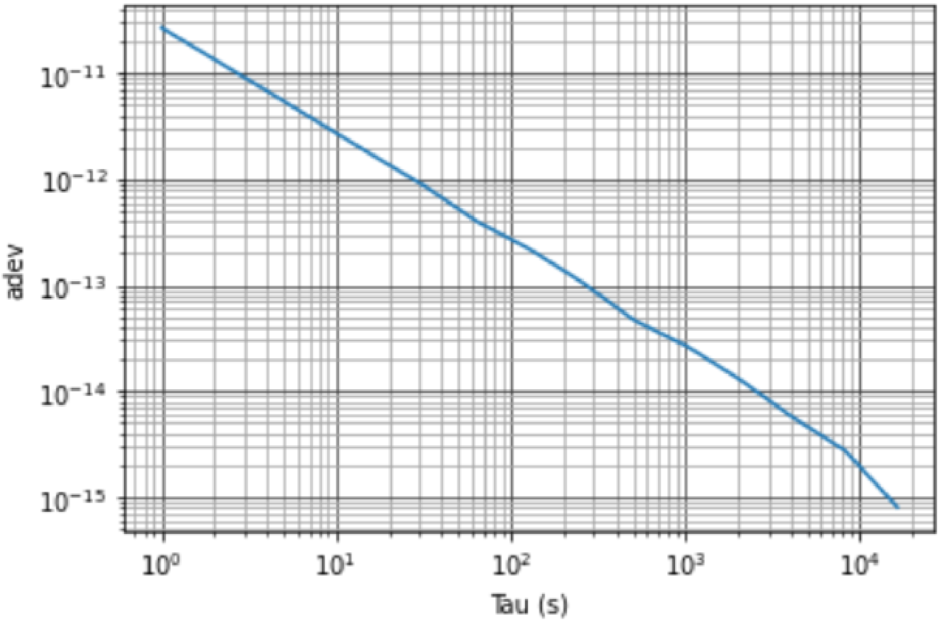


Figure 25: Reference results: ADEV

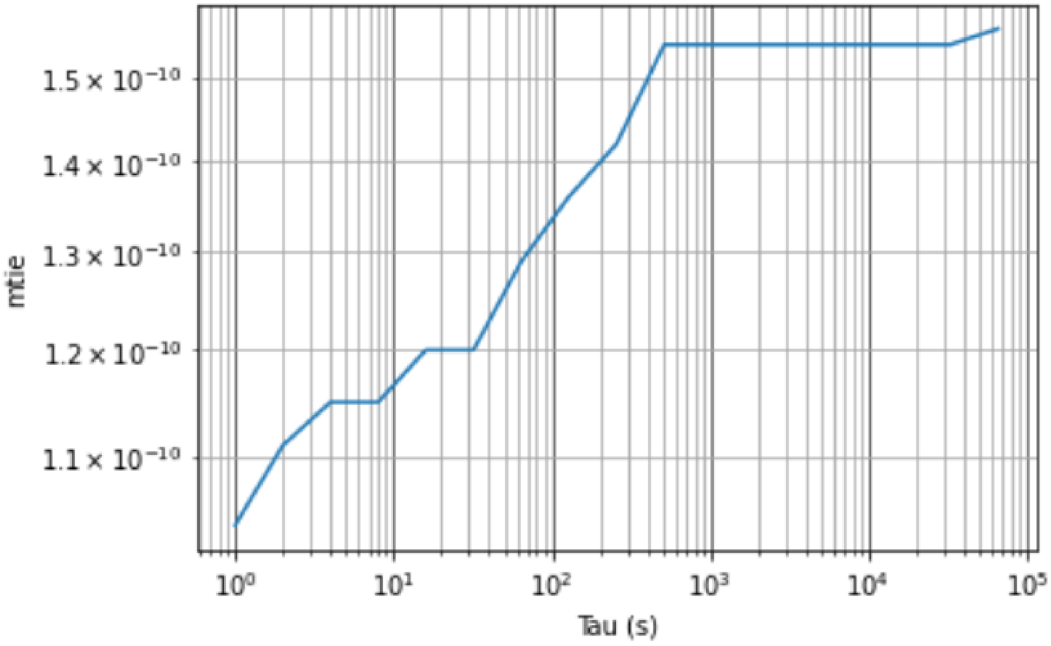


Figure 26: Reference results: MTIE

(*) Raw data of this test, as well as the data from the long distance link deployed for fintech application and referred in section 1.2.2 is provided along with this documentation for reference purpose.

6.3 Test results: T2N (Short-term sync stability in HO vs UTC ref).

The steps followed to perform this test are detailed below, along with the used topology (which required minor changes with respect to the topology used for T2M).

- The following modifications in the test topology were done:
  - Connecting GNSS Antenna for the SecureSync Time Server as in the initial step of T1 (this will start the learning mode for the Holdover in the WR-Z16).
  - Use the 1PPS output from the SecureSync as reference for the time error measurement.

    The resultant topology is the following:

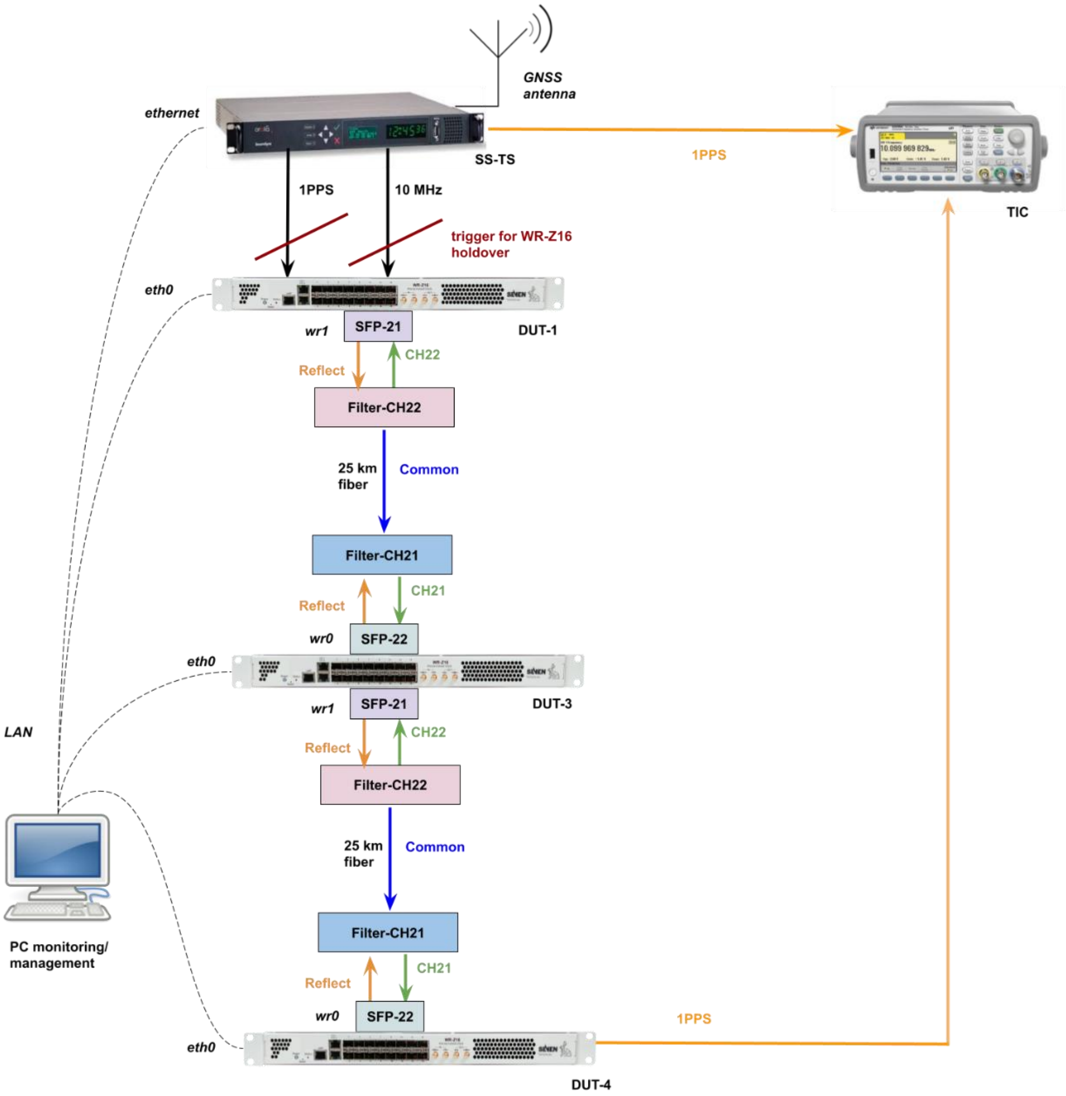


Figure 27: Full details on Test topology for T2N

- Keeping this configuration for 24h (it is the minimum recommended learning time for the WR-Z16 holdover).
- Checking status parameters of table 3 and ensure holdover is ready (this was done by Seven Solutions team remotely).
- Remove the 10MHz input of the DUT-1 to trigger the holdover.
- Start measuring the time error by using the 1PPS signals from the SecureSync and DUT-4.

The following figure shows the holdover performance measured in 3 different iterations:

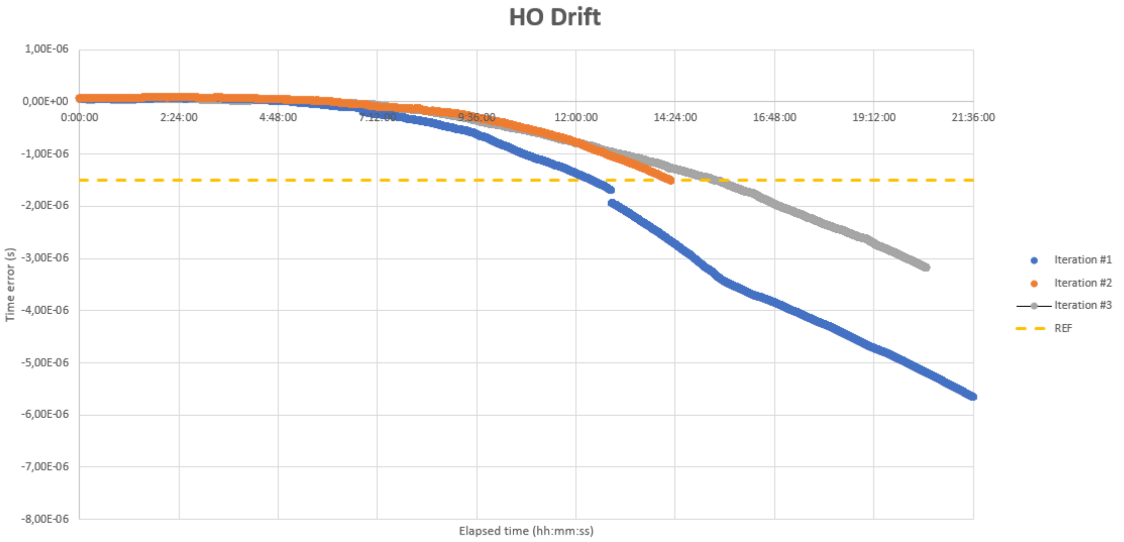


Figure 28: T2N results: TE in Holdover mode (WR-Z16) for 3 iterations

We can see in the results that the performance is worse than expected (<1.5 us/24h).
There are several factors related to the measuring process which could have affected the results, as the environmental conditions or the learning time of each case (it should have been 24h in all cases but maybe some unexpected circumstances affected this). We also must consider that normally many iterations must be done to obtain reliable results and characterize the holdover performance. The section 4.7 can be checked in order to compare with the expected results , as a figure was included indicating the performance which was measured using the same equipment in Seven Solutions installations (another figure has been added in this section in order to provide more specific information to compare, as this figure shows iterations using the same 24h learning time as well).
Plus, one of the lines corresponding to one of the iterations present unexpected time drift jumps, which may be related to some issue in the measuring process.
We can also see that we do not have enough measurements in holdover activated mode for all the iterations (it should have been 24h in each case). The causes of this are unclear at this point.

The additional figure is included below showing the HO performance for several iterations measured in Seven Solutions installations for a learning time of 24 with the same equipment and setup used in JRC test.

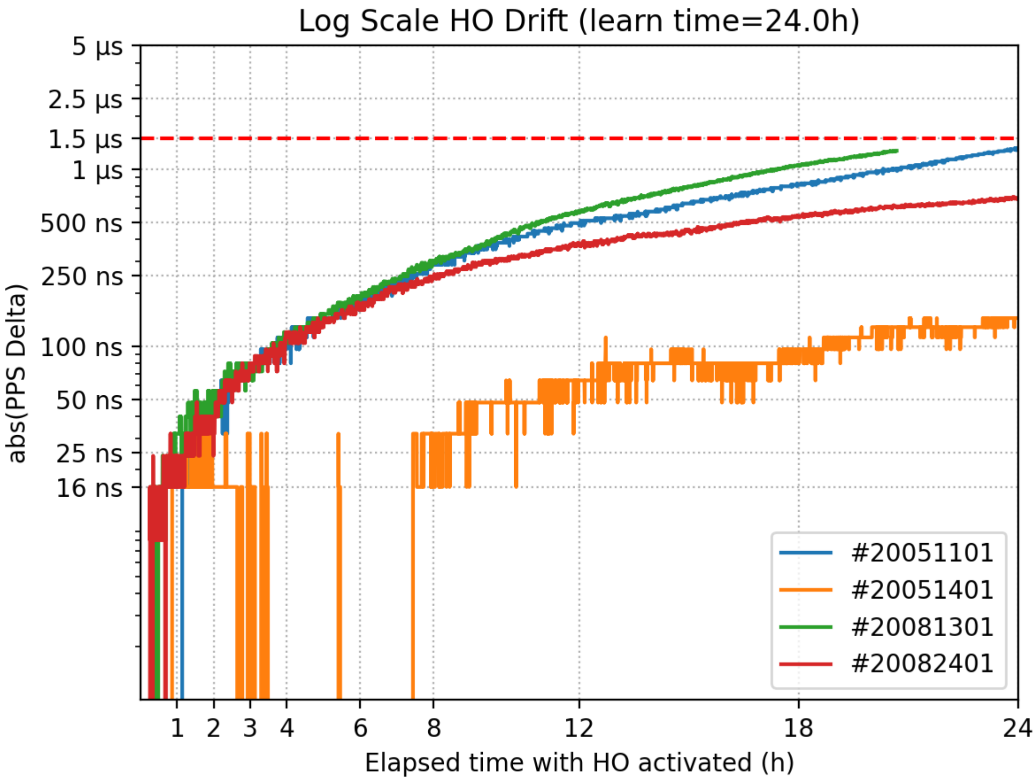


Figure 29: Reference results: TE in Holdover mode (WR-Z16) for 24h learning time

We also have to remark that the indicated performance is what the manufacturer of the Holdover oscillator we are using in the WR-Z16 specifies in the datasheet of this component. In relation to this, the test performed had the only purpose of confirming the data provided by the manufacturer, which it was successfully done in Seven Solutions installations.

It is also worth to mention that the Holdover performance is not one of the main capabilities to be shown in this demonstration because, as we discussed with European Commission team, this is a feature which will normally be considered in the end nodes located on user side, and it is not so relevant in the backbone network we proposed, where the multiple time references transferred from remote locations will provide the required network resiliency.

6.4 Test results: T3 (Medium-term time stability)

This test was performed in Seven Solutions installations, due to the logistics issues associated with the shipment of a Maser.

The setup used for this test (located in University of Granada installations) is shown in the diagram below. The GNSS receiver (PolaRx5x) is using an external clock (the maser itself) and common view data provided by the National Metrology Institute of Spain (ROA) to correct the data obtained from the GPS information. This way, the UTC traceable time error related to the maser is obtained in the GNSS receiver by using the corrected GPS data (UTC) as a reference.

In the original setup, the ROA reference is also used to discipline the maser by applying the proper corrections on daily basis. For this test, the corrections (done by the Frequency and Phase Offset Generator) were stopped at the test starting time, although the ROA reference was still used as time reference for the measurement as explained before.

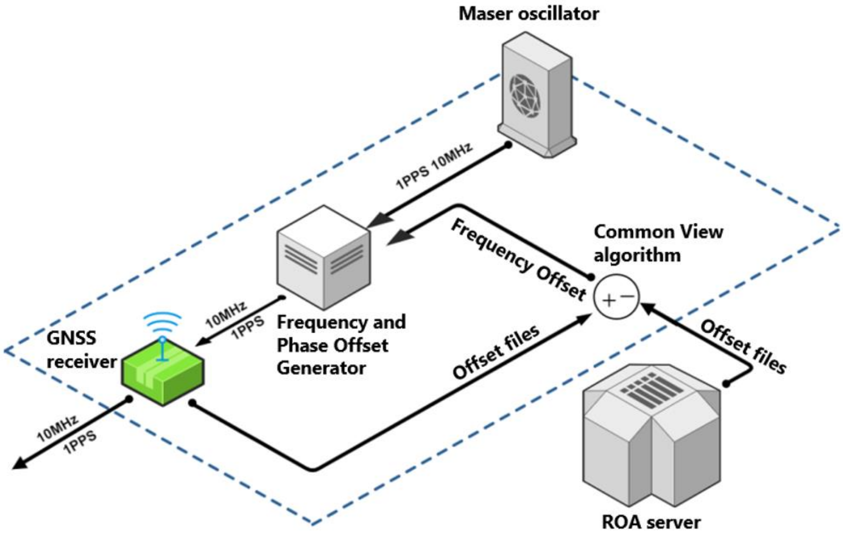


Figure 30: Setup for T3

In relation to this, the following figure shows the time error performance of the maser in free-running mode, using the Common view data from ROA as UTC traceable reference for the measurement.

The raw data and a video of the setup corresponding to this test is provided along with this document.

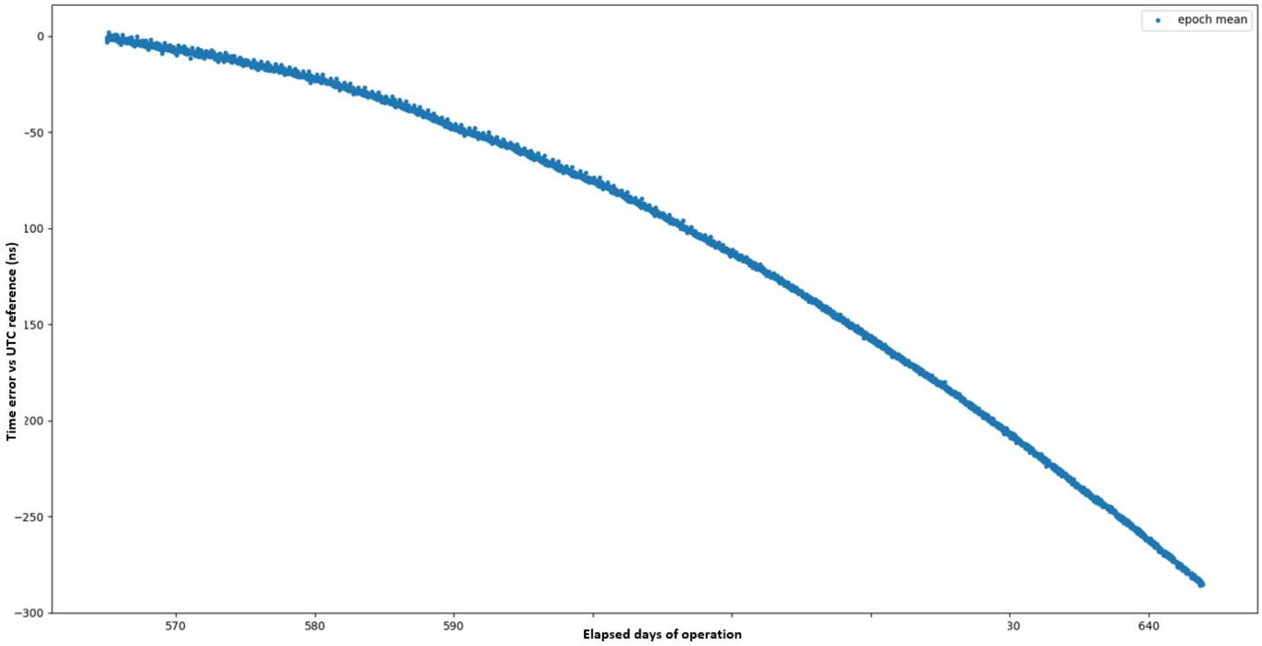


Figure 31: T3 results: TE of a Maser in free-running operation.

The measurements shown in this figure correspond to the raw data measured for 80 days of operation. In this period, the maximum time error measured was lower than 280ns. This shows a time drift average of 3.5 ns/day.

This result allows us to confirm that the requirement of less than 1us of synchronization error in wide area networks during 100 days of operation without GNSS reference is possible when using high performance time sources (like from NMIs) and WR distribution (which allows sub-ns time transfer performance without impacting the time error budget in the distribution network).

6.5 Test results: T4M (Monitoring)

The monitoring system was installed by Seven Solutions in the management PC which connected to the same LAN as the DUTs in JRC installations.

The topology which will be used for all the tests related to T4 is the following:

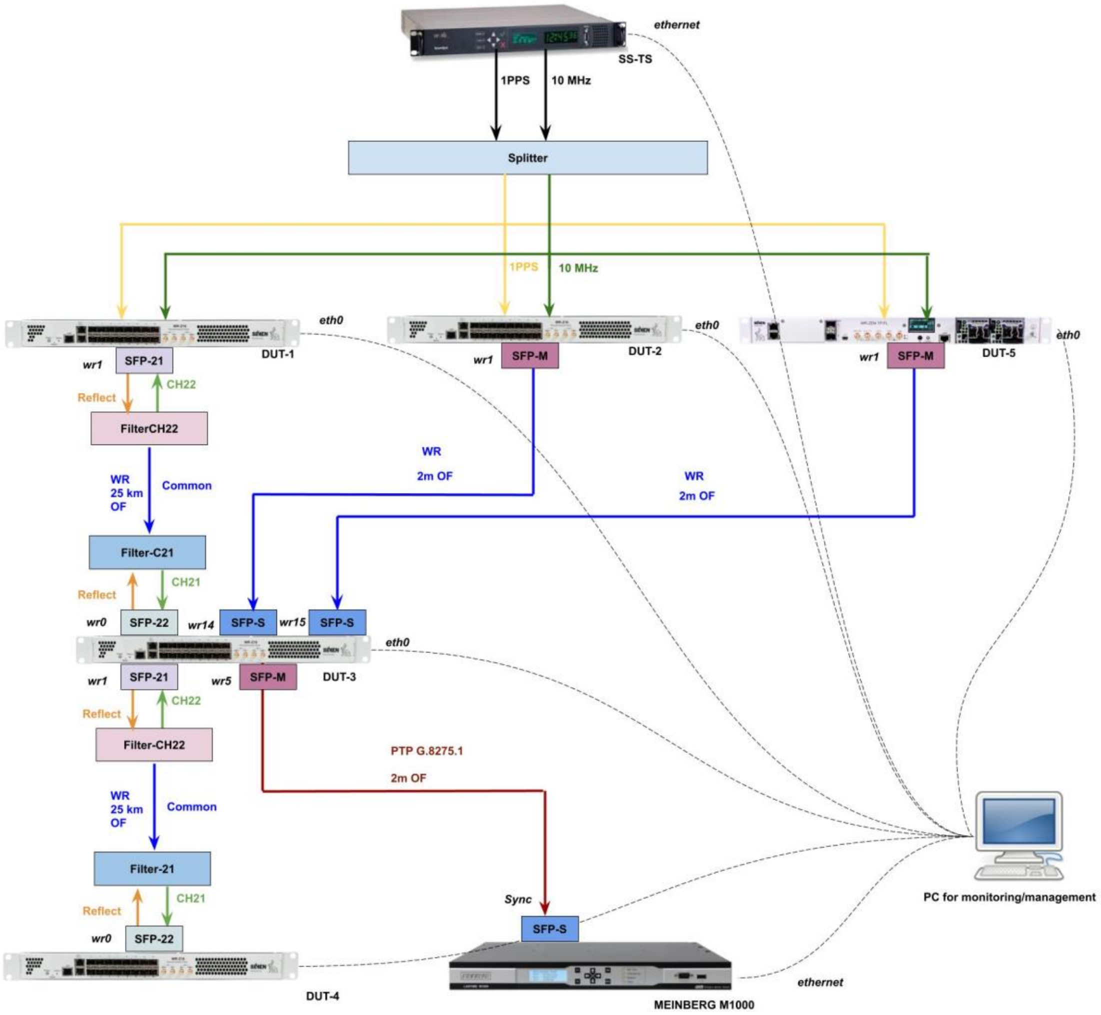


Figure 31: Full details on Test topology for T4M

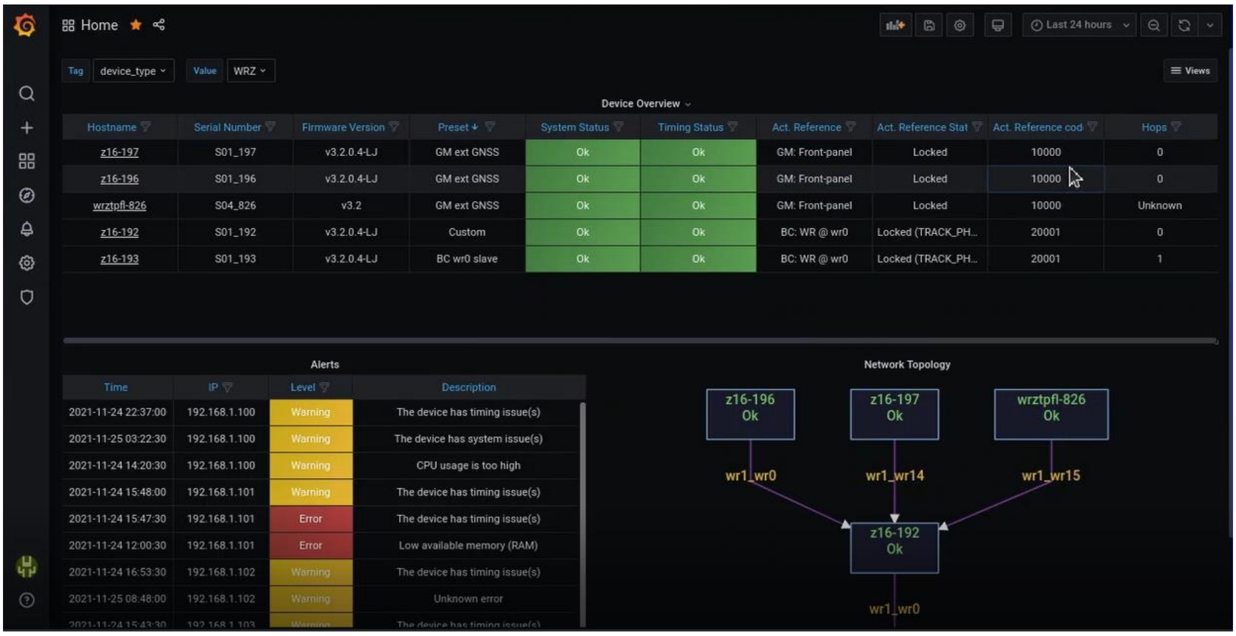
The full is of devices used in this topology and their pre-configuration is shown in the table below:

Tag	Operating mode	Port configuration	Network configuration	Comments	Status Parameters to be checked
SS-TS	Free running	-	DHCP	The time server will be working in free running mode (GNSS is disabled)	In System Status panel: System GNSS reference is HO/free running
DUT-4	GM	Master on all ports	DHCP	The GM receives the time reference from the Time Server	In Sync Overview panel: Active Reference GM:Front-Panel Message: Locked
DUT-3	BC	Slave on wr0 Slave on wr14 Slave on wr15 Master on wr1	DHCP	Intermediate node	In Sync Overview panel: Active Reference BC:WR @ wr0 Message: Locked (TRACK_PHASE) In time src tab: wr14 referece is ok (passive) wr15 referece is ok (passive)
DUT-2	GM	Master on all ports	DHCP	The GM receives the time reference from the Time Server	In Sync Overview panel: Active Reference GM:Front-Panel Message: Locked
DUT-1	GM	Master on all ports	DHCP	The GM receives the time reference from the Time Server	In Sync Overview panel: Active Reference GM:Front-Panel Message: Locked
DUT-5	OC/BC	Slave on wr0	DHCP	End node	In Sync Overview panel: Active Reference BC:WR @ wr0 Message: Locked (TRACK_PHASE)
MEINBERG M1000	OC/BC	PTP G.8275.1 Slave	DHCP	PTP End Node	In PTP tab of web GUI- Global submenu: Port state: slave

Table 8: Pre-configuration of devices of T4

During this test (approx. 2h duration), the capabilities of the monitoring interfaces were shown. First, the web interface of each device was shown, including all the monitoring and management options available. Later, the test was focused on the centralized monitoring interface which was installed in the management PC in order to show how the specific templates provided by Seven Solutions can be used for integrating the monitoring capabilities of the products with external tools.

Some screenshots of the interface (based on Grafana) which was installed in the management PC, and was deeply reviewed during this demo test, are included below:



Tag: device_type · Value: WRZ

Device Overview

Hostname	Serial Number	Firmware Version	Preset	System Status	Timing Status	Act. Reference	Act. Reference Stat	Act. Reference cod	Hops
z16-197	S01_197	v3.2.0.4-LJ	GM ext GNSS	Ok	Ok	GM: Front-panel	Locked	10000	0
z16-196	S01_196	v3.2.0.4-LJ	GM ext GNSS	Ok	Ok	GM: Front-panel	Locked	10000	0
wrztpfl-826	S04_826	v3.2	GM ext GNSS	Ok	Ok	GM: Front-panel	Locked	10000	Unknown
z16-192	S01_192	v3.2.0.4-LJ	Custom	Ok	Ok	BC: WR @ wr0	Locked (TRACK_PH...	20001	0
z16-193	S01_193	v3.2.0.4-LJ	BC wr0 slave	Ok	Ok	BC: WR @ wr0	Locked (TRACK_PH...	20001	1

Alerts

Time	IP	Level	Description
2021-11-24 22:37:00	192.168.1.100	Warning	The device has timing issue(s)
2021-11-25 03:22:30	192.168.1.100	Warning	The device has system issue(s)
2021-11-24 14:20:30	192.168.1.100	Warning	CPU usage is too high
2021-11-24 15:48:00	192.168.1.101	Warning	The device has timing issue(s)
2021-11-24 15:47:30	192.168.1.101	Error	The device has timing issue(s)
2021-11-24 12:00:30	192.168.1.101	Error	Low available memory (RAM)
2021-11-24 16:53:30	192.168.1.102	Warning	The device has timing issue(s)
2021-11-25 08:48:00	192.168.1.102	Warning	Unknown error
2021-11-24 15:43:30	192.168.1.103	Warning	The device has timing issue(s)

Figure 32: T4M results: screenshot of monitoring interface- dashboard

Statistics

Hostname	Last	Mean	Maximum	Minimum	Peak to peak
z16-192	0 s	0 s	0 s	0 s	0 s
z16-193	0 s	0 s	0 s	0 s	0 s
z16-196	55 µs	112 µs	3.02 ms	-143 µs	3.16 ms
z16-197	56 µs	105 µs	1.60 ms	-1.6 ms	3.23 ms

Statistics

Hostname	Interface	Metric	Last	Mean	Maximum	Minimum	Peak to peak	mode_ppsi

Figure 33: T4M results: screenshot of monitoring interface- time sources

Hostname	System Status	FPGA Temperature	CPU Usage	RAM Usage	Disk1 (/boot) Usage	Disk2 (/media) Usage
wrztpfl-826	Ok	53 °C	7.01%	57.6%	8.14%	5.67%
z16-192	Ok	70 °C	85.7%	64.3%	11.5%	5.74%
z16-193	Ok	70 °C	34.1%	63.2%	11.5%	5.74%
z16-196	Ok	70 °C	22.0%	65.7%	11.5%	5.74%
z16-197	Ok	70 °C	15.5%	60.5%	11.5%	5.74%

CPU Usage

	Mean	Max	Min	Last
wrztpfl-826	23.0%	64.3%	0.952%	7.01%
z16-192	41.5%	117%	5.64%	85.7%
z16-193	28.4%	112%	5.76%	34.1%
z16-196	29.1%	104%	5.96%	22.0%
z16-197	30.2%	77.9%	4.37%	15.5%

RAM Usage

	Mean	Max	Min	Last
wrztpfl-826	294 MB	295 MB	294 MB	294 MB

Figure 34: T4M results: screenshot of monitoring interface- healthing

6.6 Test results: T4N (Failover scenario A)

The topology and configuration used is the same as in T4M. Once the setup of T4M is ready, the failover was triggered as described in each scenario

In this scenario, the trigger of the failover is removing physically the 10MHz input of DUT-4. The active reference switches from wr0 to wr14 in DUT-3.

The behavior of the system was checked using the web interface of the devices involved and the monitoring system configured in the management PC in T4M.

Additionally, a TIC was used to measure the time error between the SecureSync time server (locked to GNSS reference) and DUT-3 and DUT-4 nodes.

The results are included in the figures 28 and 29.

6.7 Test results: T4O (Failover scenario B)

The topology and configuration used is the same as in T4M.

In this scenario, the trigger of the failover will be removing physically the fiber cable between DUT-2 and DUT-3. The active reference will switch from wr14 to wr15 in WR-DUT-3.

The behavior of the system was checked using the web interface of the devices involved and the monitoring system configured in the management PC in T4M.

The results corresponding to scenario A and B of this failover test, are included in the figures below. Two different iterations were done in order to check the behavior in DUT-3 and DUT-4:

Figure 35: T4N and T4O result: time error in DUT-3 with SS as reference

We proposed to measure in the DUT-3 as it is the node receiving multiple time references. By our design, based on the fintech industrial requirements, the failover to the backup reference must happen only when a failure is detected in the active time reference. As detailed explained in the section 2.2.1, this is a safer approach than the BMC algorithm. This behavior implies that a node will not automatically re-evaluate the time sources (for example to relock to the first priority time source once it is available again). This action must be done manually under the supervision of the network administrator. Based on this design, the behavior of the DUT-4, which only receives a single time reference (from DUT-3) would be losing the synchronization after its unique time reference is not available and keep this status unless a manual actual is taken.

Given that the performance of DUT-4 under failover scenario was identified as a interesting point to show, specific re-configuration was done by Seven Solutions in order to allow the automatic re-evaluation of the time source in the slave, allowing it to maintain the synchronization during the failover test.

The performance measured in DUT-4 is shown in the figure below:

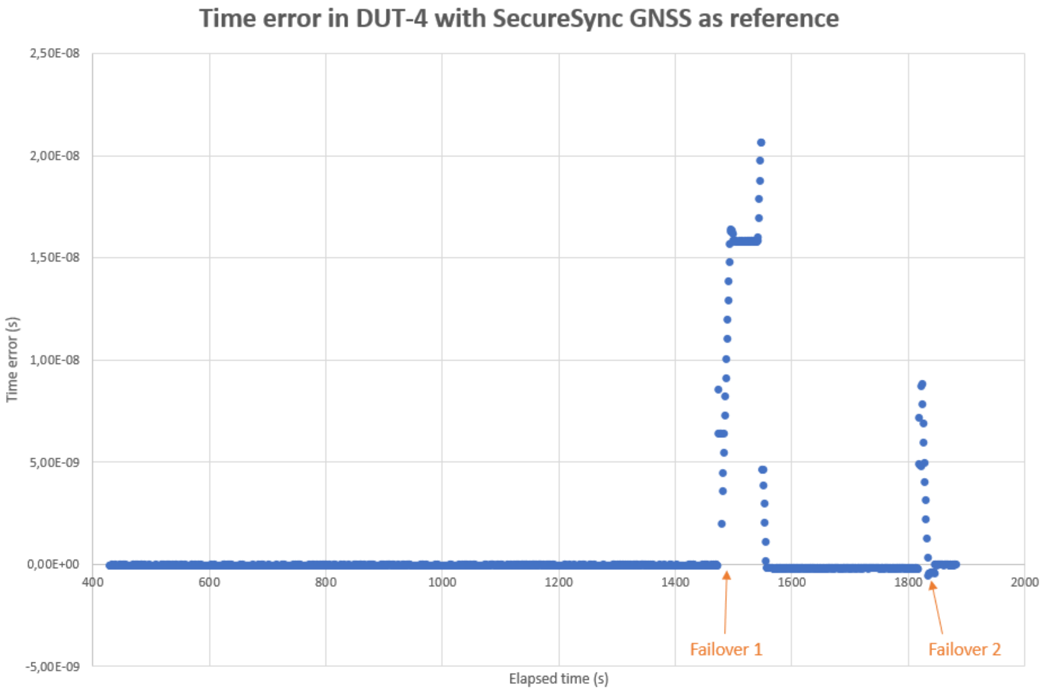


Figure 36: T4N and T4O result: time error in DUT-4 with SS as reference

As it can be seen, automatic failover was always successful after the two different trigger actions considered, and the maximum time error measured in the downtime (during the switchover between time sources) was lower than 25 ns in each case.

It is necessary to remark that the failover mechanism is design to be flexible and capable to work with multiple time sources of different nature which can be located in the wide area. If we consider only WR links and a unique time reference for all the GMs devices, an improved performance can be achieved by optimizing the algorithm for this specific scenario. However, we consider this is not a realistic scenario, so the current implementation was decided to be the most interesting capability to show in the demonstration. In fact, in T4P was shown how this failover implementation also works in a scenario based on 3 independent GNSS-based references which typically provide a 1PPS instability of a few tens of ns (in this scenario a mechanism with ps level sensitivity would not be operative).

6.8 Test results: T4P (Failover scenario C)

This test was in Seven Solutions installations, due to its complexity.

It is basically a failover scenario in which the detection of a frequency drift in the external reference based on a voting system is used as a trigger for a smooth switchover to a backup reference.
The topology used in this scenario is equivalent to T4M, but using 3 independent time sources (GNSS based time servers) to provide a time reference to each device of the Stratum 1. This modification in the topology was done as it is considered a more interesting an realistic scenario.

The behaviour of the system was measured by using a Swabian Time Tagger device which measures the 1PPS output from all the nodes of the system in comparison with a provided reference.

In the graph below the time error over time of all the WR nodes in the system can be seen, using the 1PPS output from the SecureSync as reference for all the measurements:

- The orange line shows the first GM (DUT-1), which is the active reference in the initial time for the switchover node (DUT-3). This reference starts drifting when we disconnect the GNSS antenna (t=150s) from the time server 1.
- The blue line shows the secondary GM (DUT-2), which is the backup reference for the switchover node, and it is retrieving the time from the time server 2.
- The third GM (DUT-5) is used as a reference (so it is not shown as a line in the graph).
- The grey line is the switchover node which is receiving 3 time references (from DUT-1, DUT-3 and DUT-5, which are connected to independent time servers (GNSS receivers).
- The yellow line is the slave node (DUT-4) of the switchover node (DUT-3), which is following its master and not losing sync during the switchover.

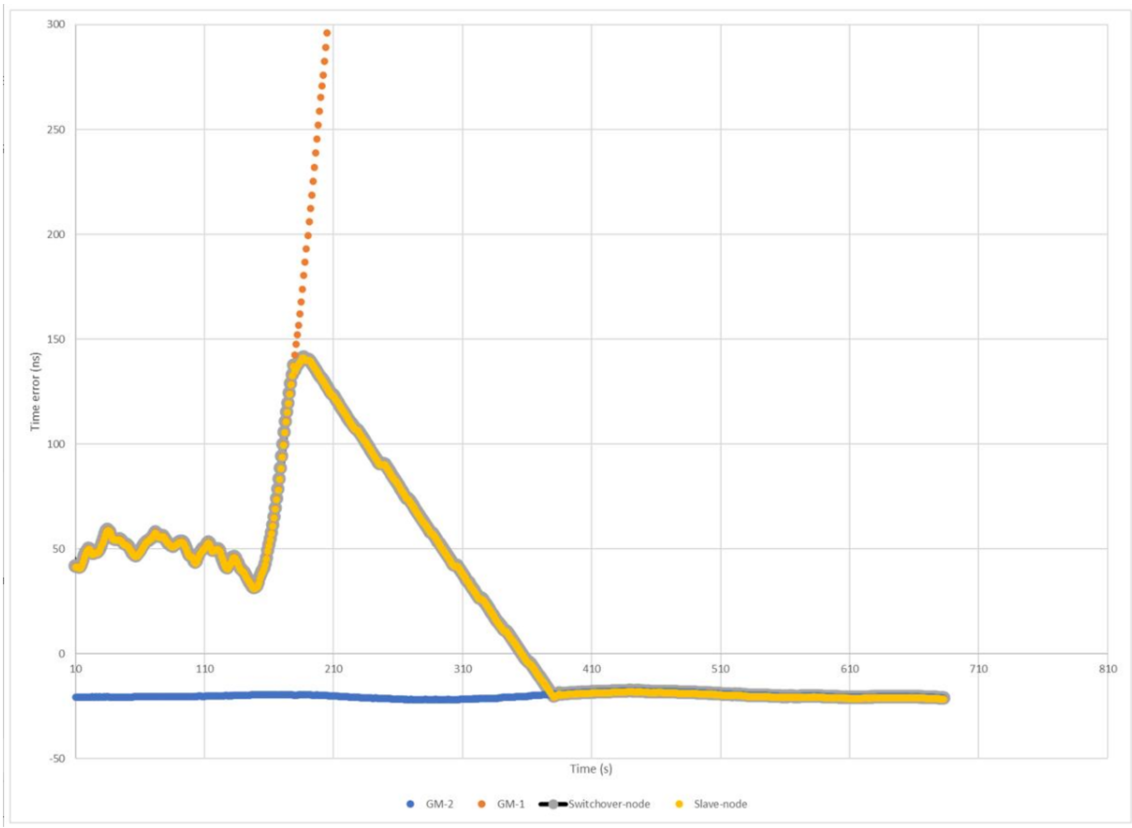


Figure 37: T4P result: Time error in all WR nodes based on GNSS reference

The DUT-3 performs the switchover to this reference when it detects a 100ns drift in the active reference with respect to the second GM (DUT-2) and third GM (which is the node locked to the SS (time server C) and used as reference for the measurements).

6.9 Test results: T4Q (PTP Interoperability test)

Same topology as in T4M was used in this test.
To perform this test, a Meinberg M1000 was used as a third-party PTP slave in order to show the PTP interoperability capabilities of the Seven Solutions WR products. In this case the telecom profile of PTP (8275.1) was configured in both PTP master and slave roles.
The monitoring of PTP communication was done directly in the M1000. The relevant statistics are shown in the screenshots below (obtained directly from Meinberg web interface).

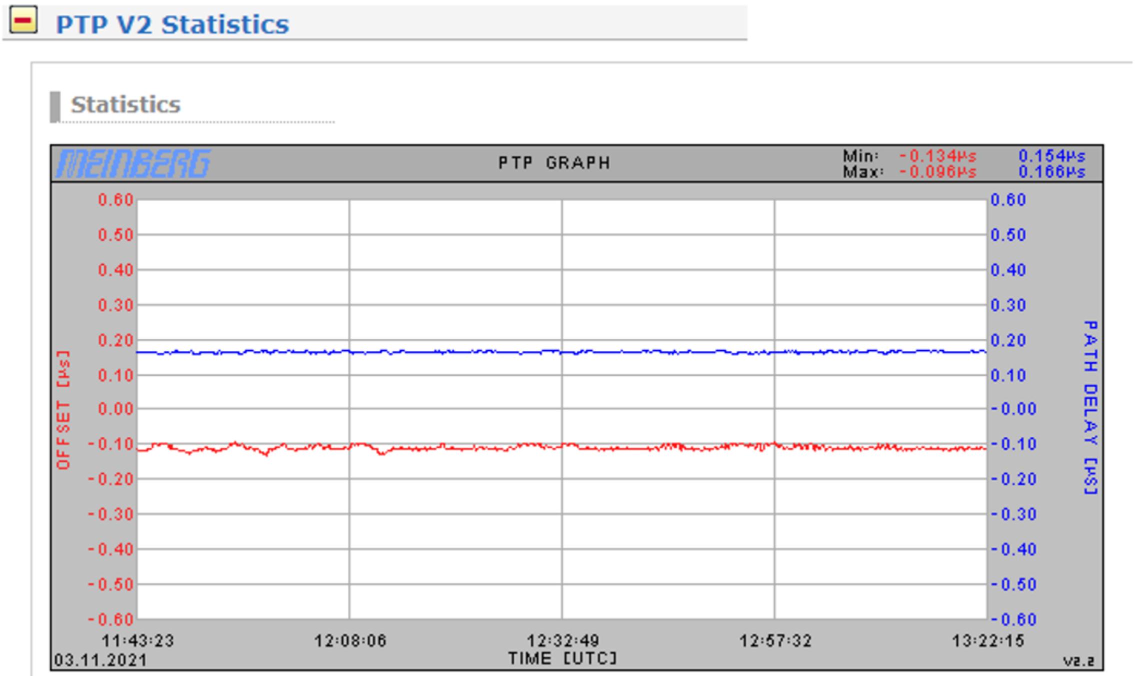
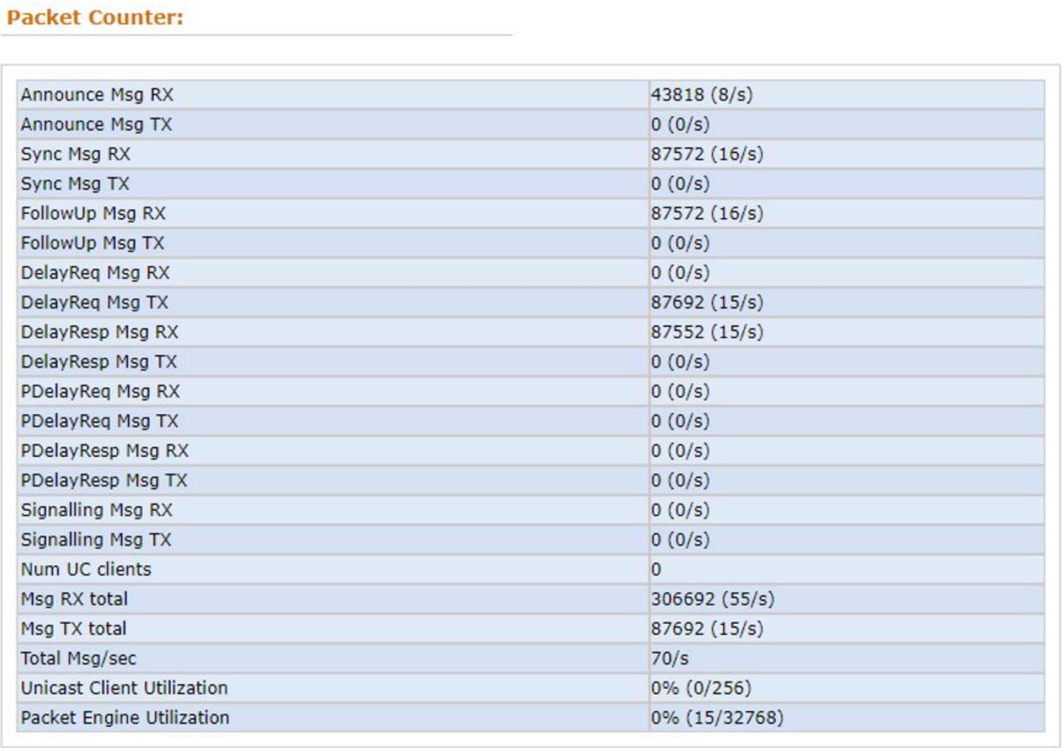


Figure 38: T4Q result: Offset and path delay reported in Meinberg M1000 working as PTP slave of the WR device.



Packet Counter:

Announce Msg RX	43818 (8/s)
Announce Msg TX	0 (0/s)
Sync Msg RX	87572 (16/s)
Sync Msg TX	0 (0/s)
FollowUp Msg RX	87572 (16/s)
FollowUp Msg TX	0 (0/s)
DelayReq Msg RX	0 (0/s)
DelayReq Msg TX	87692 (15/s)
DelayResp Msg RX	87552 (15/s)
DelayResp Msg TX	0 (0/s)
PDelayReq Msg RX	0 (0/s)
PDelayReq Msg TX	0 (0/s)
PDelayResp Msg RX	0 (0/s)
PDelayResp Msg TX	0 (0/s)
Signalling Msg RX	0 (0/s)
Signalling Msg TX	0 (0/s)
Num UC clients	0
Msg RX total	306692 (55/s)
Msg TX total	87692 (15/s)
Total Msg/sec	70/s
Unicast Client Utilization	0% (0/256)
Packet Engine Utilization	0% (15/32768)

Figure 39: T4Q result: PTP Packets statistics in Meinberg M1000 working as PTP slave of the WR device.

7. Summary

The following table, included in the next page, presents a summary of the results of the demonstration.

As a conclusion, the solution and demonstration described in this document allow to show the feasibility of developing a solution based on IEEE 1588-2019 HA Time as a Service (TaaS) which is independent from GNSS, and provides UTC traceability, high availability, and network resiliency. Furthermore, the model of service presented follows a similar idea as the Galileo solutions in terms of architecture and model of service. These characteristics makes the service very easy to implement and use on customer side, both if they want to use a PTP connection via NIC card, or subscribe to a premium WR service via direct connection to the backbone, as detailed in the implementation report.

Test ID	Test name	Duration	Measurements	Metrics	Objective	Location	Results summary
T1	System verification	<2h	-	Fail/pass	Setup the DUTs and verify correct and normal operation the White Rabbit network	JRC	System was properly verified by Seven Solutions team by accesing the equipment remotely.
T2M	Short term sync stability vs clock reference	24h	1PPS	TE, ADEV, MTIE	Showing short-term timing distribution performance tracking the reference of a clock provided by 7S	JRC	The tests results show sub-ns accuracy time transfer in 2hops with 50km end to end link length: - peak-to-peak time error<90ps - jitter <17ps - ADEV: 2e-11@1s, 2e-12@10s, 2e-13@100s, 2e-14@1000s, 1e-15@10000 - MTIE: 7,8e-11@1s, 1,02e-10@10s, 1,17e-10@100s, 1,17e-10@1000s, 1,41e-10@10000
T2N	Short term sync stability in HO vs UTC reference	24h	1PPS	TE vs UTC ref.	Showing short-term timing distribution performance in Holdover mode based on UTC reference	JRC	The test results shown a holdover performance lower than 1.5us/24h after 24h of learning time locked to a GNSS. * due to reasons pending to investigate, the performance measured in JRC was worse than in 7Sols installations using same equipment.
T3	Medium term time stability	>30 days	1PPS	TE vs UTC ref.	Showing medium-term time transfer performance based on UTC reference	7S	The test results shown a time error below 280ns after 80 days of operation of a maser time reference working in free running mode.
T4M	Network monitoring	<2h	descriptive	descriptive	Showing monitoring capabilities of the 7Sols WR system	JRC	The demo was succesfully completed by showing the monitoring and management capabilities of the solution, based on both the web interface and the centralized monitoring system installed on JRC management PC.
T4N	Failover scenario A	<2h	descriptive	descriptive	Showing resiliency capabilities of the 7Sols WR system for failover scenario A: loss of GNSS reference	JRC	The automatic failover was succesfully completed showing a maximum time error during the switching lower than 25ns on each iteration, for both stratum 2 and 3 devices.
T4O	Failover scenario B	<2h	descriptive	descriptive	Showing resiliency capabilities of the 7Sols WR system for failover scenario B: failure in optical fiber link	JRC	The automatic failover was succesfully completed showing a maximum time error during the switching lower than 25ns on each iteration, for both stratum 2 and 3 devices.
T4P	Failover scenario C	<4h	descriptive	descriptive	Showing resiliency capabilities of the 7Sols WR system for failover scenario C: slow frequency drift	7S	The automatic failover was succesfully completed after detection of a faulty time source due to a frequency drift (>100ns) using a voting system based on 3 independent time sources.
T4Q	Interoperability	<2h	descriptive	descriptive	Showing interoperability with other timing protocols capabilities of the 7Sols WR system	JRC	The inteoperability of the devices was demostrated by showing the correct PTP G.8275.1 synchronization between 7Sols devices and a Meinberg M1000.