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### 1 Overview

Time transfer is a scheme where multiple sites share a precise reference time. The technique is commonly used for creating and distributing standard time scales such as Universal Coordinated Time (UTC) and International Atomic Time (TAI). White Rabbit Precision Time Protocol (PTP-WR) is one of the best performing time transfer techniques. Outperforming existing capabilities, providing accurate (<200 ps), resilient and secure timing traceable to Universal Time Coordinated (UTC), it is able to exploit telecommunication fibre networks, enabling its use in widespread applications. This project has developed the metrological capacities required to accelerate the industrial adoption of PTP-WR, through improved hardware and calibration techniques, implemented in industrial environments.

<u>WRITE main achievements were:</u> i) developing improved and scalable calibration techniques for PTP-WR, that have been proved to be reliable, and that ensures now the capability to have a complete dissemination chain with an accuracy better than 200 ps; ii) developing architectures and methods for redundant and resilient time transfer to industrial end users; iii) developing a new generation of PTP-WR hardware, offering the accuracy below 200 ps and an unprecedented frequency instability of <6x10<sup>-15</sup> over an observation time of 100 s. (Allan deviation); iv) disseminating Universal Time Coordinated UTC(k) time scales using PTP-WR from NMIs to industrial users (telecommunication, aerospace, electronics manufacturers) and v) contributing to the revision of the IEEE-1588 standard for PTP, that was in 2020 updated in the IEEE-1588-2019 revision, including White Rabbit as "High Accuracy option".

# 2 Need

There is an increasing demand for synchronisation networks that provide precise time and frequency: e.g. telecommunication operators building 5G mobile communication networks, the power-grid sector utilising smart grids, the financial sector needing to comply with EU regulations, and scientific users. International recommendations are driving improvements to current timing and UTC traceability. For example, in finance the European 'Markets in Financial Instruments Directive' (MiFID II), issued by the European Securities and Markets Authority, required improved accuracy and traceability on time stamping of financial transactions from January 2018. In addition, industrial needs required solutions that were easily standardised.

PTP-WR is a technique suited for dissemination of Universal Coordinated Time UTC(k) time scales and frequency. However, whilst the calibration techniques required for PTP WR were well developed in specific, dedicated fibre links where the parameters are well known, there was still a need to develop improved scalable calibration techniques that would match different telecommunication networks.

Currently, time and frequency dissemination for most industrial applications is realised through radio signals and satellite time broadcasting, such as the widely used Global Navigation Satellite System (GNSS). However, GNSS broadcasting suffers from integrity and resilience weaknesses, since the weak power received from the satellites on Earth make spoofing, hacking and disturbance due to space weather a real threat. Techniques with higher resilience and with built in redundancy are therefore required.

The current best achievable time transfer accuracy is 2 ns - 5 ns using high quality GNSS receivers, which corresponds to a frequency resolution of  $10^{-14}$  over one day measurement time, but this requires specific receivers and competences only available in national metrology institutes and very specialised scientific laboratories. Industry generally relies on less highly-performing GNSS timing equipment that is usually limited to an accuracy of 10 ns - 100 ns.

WRITE demonstrated that PTP-WR offers a reliable solution for time dissemination, offering much better performances (200 ps accuracy, resolution at 6x10<sup>-15</sup> over 100 s measurement time). Moreover, PTP-WR over fibre is more resilient to attacks, since it is not affected by jamming or spoofing. WRITE definitely demonstrated that PTP-WR strongly outperforms the commonly used techniques.

At the beginning of the project, in-field dissemination of Universal Coordinated Time UTC(k) time scales and frequency over optical fibres was still to be reliably demonstrated. WRITE implemented several dissemination PTP-WR links over fibre suited for industrial needs, with a solid UTC dissemination. WRITE demonstrated real tests in production or industrial environments, that are fundamental to boost the uptake by industry and other sectors.



# 3 Objectives

The overall goal of the project was to demonstrate all the metrological steps necessary for the industrial adoption of PTP-WR, including improvement of the devices and the study of an effective implementation in ordinary industrial IT infrastructures without degradation of the performance of the technique compared to the results achieved in controlled research laboratories or using dedicated fibre infrastructures.

The specific objectives of the project were:

- To develop improved and scalable calibration techniques for Precision Time Protocol White Rabbit (PTP-WR) fibre links that are applicable to both existing telecommunication configurations with either a single fibre or with duplex fibres, and enabling the delay asymmetry of the propagation time to be accurately known for a time service competitive with GNSS systems. The target uncertainty for device calibrations is 200 ps, and the target uncertainty for propagation-calibration is 1 ns for fibre link lengths up to 1000 km.
- 2. To develop validated techniques for redundant and resilient time transfer to industrial end users that meet the recommendations for the timing characteristics of primary reference clocks (ITU-T Primary Reference Time Clock (G.8272)) and enhanced Primary Reference Clocks in Telecommunications Networks (PRTC) performance levels during a switch of PTP-WR GrandMasters and in hold-over situations. Redundancy within the industrial time-service will be ensured by the use of multiple time-links from source to user, and resilience by providing alternative clock-sources, e.g. time-links, local clocks, and GNSS signals.
- 3. To develop a next generation of PTP-WR devices with improved performance and that interface better with existing industrial protocols and standards such as IEC61850 for Smart Grids. The target frequency instability characterised by an Allan deviation (ADEV) is <1x10<sup>-13</sup> over an observation time of 100 s.
- 4. To demonstrate the use of PTP-WR to deliver Universal Time Coordinated UTC(k) time scales and frequency in the radio frequency (RF) domain from NMIs to industrial users within a specified market segment, and to evaluate the end-to-end uncertainty of the established time transfer.
- 5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, calibration laboratories, standards developing organisations (in particular, IEEE PNCS Precise Networked Clock Synchronization Working Group and ITU) and end users, in particular the telecommunication industry and the National Research and Education Networks.

# 4 Results

#### Development of improved and scalable calibration techniques for PTP-WR fibre links (Objective 1)

PTP-WR time transfer links work by estimating a one-way delay from master to slave based on measurement of a two-day delay (round-trip-time, RTT) master-slave-master. To deliver time with potentially subnanosecond accuracy PTP White Rabbit equipment needs calibration. The starting point for WRITE was a link including transmission and reception delays in the WR-equipment on both master and slave side, bit-slide values that are variable but available from the WR software, and propagation delays in the fibre ( $\delta_{MS}$ , $\delta_{SM}$ ). CERN developed a calibration procedure that allows determining the fixed master and slave delays as well as the fibre-asymmetry parameter  $\alpha$  that accounts for the difference in propagation delay from master to slave (MS) and from slave to master (SM). The asymmetry parameter (unitless) is defined as

$$\alpha = \frac{\delta_{MS} - \delta_{SM}}{\delta_{SM}}$$

A typical value for  $\alpha$  is around 260 PPM (parts-per-million) for a single-fibre link using 1000BASE-BX10-D and -U optical transceivers operating on 1490 nm and 1310 nm. On single fibre links the asymmetry is caused by chromatic dispersion in the fibre, i.e. the refractive index of the fibre differs for the wavelengths used in the MS and SM directions.

WRITE introduced a new link model for absolute calibration, shown in Figure 1. Compared to the old link model new electrical and optical reference planes are introduced, and the fixed delay is divided into an electrical delay inside the PTP-WR device (TXcal and RXcal) and an electro-optical delay in the transceiver (TXsfp and RXsfp). There are no changes to the propagation link model. With these new definitions the task of end-to-end absolute calibration can be divided into three separate tasks:



•Electrical-Electrical (EE) calibration, where the TXcal and RXcal delays are determined for a certain PTP-WR device. This task relates the external PPS reference plane to the Electrical reference plane of the SFP transceiver.

•Electro-Optical (EO) calibration, where the internal delays of the SFP transceiver TXsfp and RXsfp are determined. These delays represent the delay between the electrical SFP reference plane and the optical reference plane.

•Propagation calibration, where the asymmetry coefficient  $\alpha$  is determined. The asymmetry coefficient quantifies the propagation asymmetry arising between the optical reference planes.



Fig.1 Scheme of the new link model for absolute calibration introduced by WRITE.

Since the optical propagation delay is directly proportional to the effective group refractive index  $N_{e}$ , we can re-state the definition of the asymmetry parameter as

$$\alpha(\lambda_{MS}, \lambda_{SM}) = \frac{N_e(\lambda_{MS}) - N_e(\lambda_{SM})}{N_e(\lambda_{SM})}$$
(Eq. 2)

VTT compared measured values to the predicted asymmetry parameter using Eq. 2: the overall behaviour is captured very well, and predicted asymmetry parameters from Eq.2 agree with laboratory measurements to within 10 %. A subset of results is reported in Table 1.

SFP standard/description	ТХ	RX	Asymmetry coefficient 'alpha' / PPM	Equation7 / PPM
1000BASE-BX10-D/U	1490 nm 1000BASEBX10-D	1310 nm 1000BASEBX10-U	250	255
	1550 nm	1490 nm	192	186
L-band BiDir optics from ADVA	1605 nm	1615 nm	37	41
10GBASE-BX, SFP+	1330 nm	1270 nm	14	16
L-band DWDM optics, spacing 100 GHz	1611.8 nm	1610.93 nm	3.9	3.6
C-band DWDM channels at 100 GHz spacing, 1000BASE-DWDM	ITU channels CH17-61 on Wavelength 1528.77-1563.86 nm	adjacent channel	~3	
ʻbelow' C-band DWDM optics, spacing 100 GHz	1511.8 nm	1511.05 nm	2.2	2.3

Table 1: Typical asymmetry coefficients determined in laboratory or field-tests for bidirectional WR-PTP links. The predicted asymmetry parameters were computed from Equation 7 and 6 using parameters S0 = 0.092 ps /nm2 km and a zero-dispersion wavelength of 1311 nm.



WRITE used a new method to calibrate the asymmetry coefficient, a swapping technique that can be used on either a single-fibre or a dual-fibre link in a case where the asymmetry can be swapped/reversed. On single fiber-links this involves either swapping the SFP-modules physically, thereby exchanging wavelengths at master and slave, or if tuneable SFPs are used, exchanging the wavelengths at master and slave. On dual-fibre links the swapping of asymmetry can be achieved by physically swapping the TX and RX fibres. The swapping technique and associated measurements are illustrated in Fig. 2.



Fig. 2: Technique for asymmetry calibration by reversal of asymmetry. Link in forward configuration with long uplink and short downlink, measurement result  $PPS_F$  (top left). Link in reverse configuration with short uplink and long downlink, measurement result  $PPS_R$  (top right). The average of  $PPS_F$  and  $PPS_R$  measurements against a stable slave clock (S CLK) yield a virtual symmetry point (red) from which the PPS-skew in either forward or reverse configuration can be evaluated.

To perform asymmetry calibration by swapping, WR-devices are initialised with zero asymmetry and known hardware-delays (if available). Time-interval counter measurements between the slave 1PPS signal and a local reference clock are then performed at the slave node. Measurements are performed in two configurations "forward" and "reverse". Note that the slave clock used as the reference for measurement needs to be external to the WR-link being calibrated, but the reference clock does not need to be synchronised with the master node. The 1PPS time-interval between the WR slave and the slave reference clock is recorded as  $PPS_F$  and  $PPS_R$  and the round-trip time  $\Delta$  is recorded from the WR-equipment. The 1PPS correction is given by half the difference between the measured values. The asymmetry parameter is solved as:

$$\alpha = \frac{2PPS_{skew}}{\frac{\Lambda}{2} - PPS_{skew}}$$
 (Eq. 3)

Results from swapping calibration are shown in Fig. 3 from NWO-I data, and in Fig. 4, from NPL tests.



Fig. 3: 1PPS offsets measured at slave WR-switch, against a stable local reference clock, when the TX-wavelengths at Slave and Master were changed so that the channel-separation (on the X-axis) was -500 GHz, -300 GHz, -100 GHz, +100 GHz, +300 GHz, +500 GHz, and +900 GHz.





Fig. 4: PPS skew for SFPs operating on different ITU channels, from different manufacturers. Red: Edge, Green: Skylane, yellow: Smartoptics. The approximate wavelength in nanometres is indicated in blue on the x-axis.

WRITE used also another procedure that can be used on single-fibre links following a tuning method, either manual or automated, where one wavelength, e.g.  $\lambda_s$ , is kept constant, and in the other direction the wavelength is tuned to two values  $\lambda_1$  and  $\lambda_2$ . In this method the asymmetry parameter can be determined from measurements of Roundtrip Time which are available from the WR-software. No 1PPS measurements or slave reference clock is required.

The following discussion considers a case where the SM-wavelength is constant, and the MS-wavelength is tuned. Two measurements of the RTT using the two MS-wavelengths, denoted  $\Delta(\lambda_1)$  and  $\Delta(\lambda_2)$  are used to estimate the RTT for an ideal (but not practically accessible) configuration where SM and MS wavelengths are equal,  $\Delta(\lambda_s)$ . The estimation can be done using linear interpolation/extrapolation if  $\lambda_1$  and  $\lambda_2$  are chosen appropriately close to  $\lambda_s$ .

$$\alpha(\lambda_1, \lambda_S) = 2 \frac{\left[\Delta(\lambda_2) - \Delta(\lambda_1)\right] \left[\lambda_S - \lambda_1\right]}{\left[\lambda_2 - \lambda_1\right] \Delta(\lambda_1) + \left[\Delta(\lambda_2) - \Delta(\lambda_1)\right] \left[\lambda_S - \lambda_1\right]} (Eq. 4)$$

Electrical absolute calibration of PTP-WR devices is achieved by measuring the time relationship between the internal timestamps ( $t_1$ ,  $t_{4p}$  and  $t_{2p}$ ,  $t_3$ ) and the external electrical time reference planes of each individual PTP-WR device (see figure 2). The calibration constants  $\Delta_{TXcal}$ ,  $\Delta_{RXcal}$  include propagation delays due to hardware and gateware implementation.

The electrical time reference planes consist of the connector that conveys the PPS inter-second boundary marker signal and the electrical interface to the electrical-optical/optical-electrical (EO/OE) converter (SFP module) that conveys the serial bits that encode the message timestamp point (MTP, defined in IEEE 1588-2019 paragraph 7.3.4.1). In most cases an SFP module is used as EO/OE converter in which case its electrical time reference plane is the electrical SFP connector that is made accessible for measurements by using a SFP timing calibration module.

NWO-I previously developed a method for calibration of the Electro-Optic (EO) delay of a reference photoreceiver. In WRITE, a twin EO-calibration setup was built at VTT, and measurements of EO-delays for two different reference receivers using both the NWO-I and VTT setups were performed.

EE and EO calibrations have been performed at NWO-I and VTT following the developed methods to test also the reproducibility of the new calibration procedure. Results are reported in Table 2 and Table 3.

Work on definition of reference planes was documented on the open hardware website. <u>https://www.ohwr.org/project/wr-calibration/wikis/home</u>

grand-master -> slave	PPS residual (ps) (□)	n	Expected accumulated uncertainty   (ps)
SPEC7 <sub>Sn01_NWO-I</sub> -> SPEC7 <sub>Sn07_NWO-I</sub>	43 (4)	80	45

EURAMET

	SPEC7 <sub>Sn07_NWO-I</sub> -> SPEC7 <sub>Sn01_NWO-I</sub>	-64 (3)	77	45
A	μ, Δ (ps)	54, 21		
	SPEC7 <sub>Sn07_NWO-I</sub> -> SPEC7 <sub>Sn10_NPL</sub>	536 (22)	3	45
В	SPEC7 <sub>Sn10_NPL</sub> -> SPEC7 <sub>Sn07_NWO-I</sub>	-524 (20)	4	45
	μ, Δ (ps)	530, 12		
	SPECNWO-I -> SPECVTT	96 (38)	80	93
С	SPEC <sub>VTT</sub> -> SPEC <sub>NWO-I</sub>	-119 (38)	80	93
	μ, Δ (ps)	107, 23		
	SPEC7 <sub>Sn01_NWO-I</sub> -> SPEC_NWO-I	162 (32)	80	75
D	SPECNWO-I -> SPEC7Sn01_NWO-I	-112 (29)	80	75
	μ, Δ (ps)	137, 50		
	SPEC7 <sub>Sn01_NWO-I</sub> -> SPEC <sub>VTT</sub>	241 (24)	77	75
Е	SPECVTT -> SPEC7 <sub>Sn01_NWO-I</sub>	-208 (19)	78	75
	μ, Δ (ps)	224, 33		

Table 2: EE absolute calibrations inter-comparison results for different combinations of PTP-WR devices.

	Calibration at NWO-I	Calibration at VTT	
	Delay and uncertainty (ps)	Delay and uncertainty (ps)	Difference (ps)
TIA-1200	2934.6 ± 2.0	2998.9 ± 10	64.3 ± 10.2
DET08CFC/M	2980.0 ± 2.0	3042.3 ± 6	62.3 ± 6.3
Difference	45.4 ± 2.8	43.3 ± 11.7	

Table 3: Results of the OE absolute calibration comparison for the two detectors at VTT and NWO-I.

Key outputs and conclusions of Objective 1:

- Improved model for PTP-WR asymmetry evaluation.
- New technique for channel asymmetry calibration.
- Calibration of Electrical to Electrical Interface, with accuracy contribution <75 ps.
- Calibration of Optical to Electrical Interfaces, with accuracy contribution <65 ps.

This objective was successfully achieved.



Development of validated techniques for redundant and resilient PTP-WR time transfer to industrial end users (Objective 2)

WRITE identified topologies for redundant WR networks. Parallel and ring topologies are acceptable solutions. The scalability was evaluated for WR-PTP in parallel networks using WR-PTP switches in different configurations: boundary clock, transparent clock and hybrid clock. The requirements for system hold-over have been identified for several industrial domains (power grid, electrical substations, synchro phasor, etc).

Time transfer dissemination based on packet-based networks can suffer from their operation being altered due to, among others: failure of a link between two devices, or failure of a device that is part of the network (an end-user node, or a bridging/switching) device.

Since the moment that a fault has been detected and notified, the time of grace begins. This time of grace is the interval in which the system that relies on the time synchronisation network can operate before it needs to stop or suffer damage. Depending on the time that takes to recover a functional service the techniques and protocols can be grouped in non-zero time recovery and zero time recovery.

In particular, two reliability mechanisms for WR-PTP network solutions were identified by VSL and Sevensols: holdover and switchover. For switchover of the WR-PTP switch, two possible protocols have been addressed: (i) Best Master Clock Algorithm (BMCA): not seamless (20 seconds recovery), and (ii) Seamless switchover: hot-swap between several references. It was decided that, from these two options, only the BMCA is developed in this project, because this approach is in line with the existing IEEE 1588 standard. A prototype version of a BMCA was tested, and will be included in the next formal release of the WR firmware (more info at <a href="http://www.ohwr.org/documents/103">http://www.ohwr.org/documents/103</a>).



Fig. 5. Switchover concept for redundant time distribution in ring topologies. Each node receives two copies of the same time information, one is considered the primary time reference (blue) and the other is used as the backup one (red).

The hierarchy of the PTP protocol is determined by the Best Master Clock Algorithm (BMCA), which dynamically determines which clock should be considered as the reference clock based on a constant evaluation to choose the best one.

The principle of operation of this mechanism and the problems that it solves are similar to the packet-switching network issues that rise when more than one path between nodes exists in complex network topologies. When this happens, if no mechanism is put in place, switching loops may occur and the network would cease functioning. Broadcast and multicast messages (which are essential during normal operation of the network for protocols such as ARP) will be indefinitely circulated and multiplied across the network, often hijacking all the available bandwidth and resources of the network equipment.

In the same manner, while simple PTP networks can have a tree network topology, this generates a challenging situation at the GrandMaster site: a malfunctioning or compromised grandmaster reference can render the whole network inoperable. For that reason, networks can be designed with redundancy in mind by having more than one grandmaster-capable timing source, and by avoiding single points of failure across the network topology. Yet, in any given moment a PTP network must reach a collective understanding of what device is the GrandMaster that provides a common time notion.

The principle that lies behind PRP is the establishment of two parallel networks, with completely independent elements. The nodes are doubly attached to both networks, and all the traffic that is sent by the nodes is



duplicated and physically sent through both networks. The nodes feature a so-called Link Redundancy Entity (LRE) that handles the duplication of frames, and the detection of duplicates. The receiving node will expect two copies of each frame, discarding the second. Using this approach, not only is the system tolerant to faults in the operation of one of the independent networks without frame losses, but also faults become apparent from the first moment that a duplicate frame is expected and never arrives. The handling of frames by the LRE is assisted by the inclusion of a PRP trailer at the end of each Ethernet frame.

Parameter	Description
clockAccuracy	Determines the accuracy of the clock. Its possible values are expressed in table 6 of the IEEE 1588-2008 standard.
clockClass	Determines the stability of the Grandmaster distributed clock (GM) of the PTP network.
priority 1	This parameter is used by the BMCA to establish priorities regarding the selection of the best available master. Ranges from 0 to 255. Lowest values indicate a higher priority.
priority 2	Same functionality as priority1.
offsetScaledLogVariance	This represents the variations in the PTP clock when, configured as a free running master, it is compared to an external reference source (such as a GNSS receiver or an atomic clock).

Table 4. PTP parameters that are relevant to the decision of the BMCA.

For the experimental setup at VSL and Sevensols there are four devices to be highlighted:

- 3x WR Switches
- A Linksys LGS116 16-Port Gigabit Enterprise Desktop Switch for Business.

The three WRSs are connected to the switch via Ethernet network cables with RJ45 connectors. The connection to the switch allows to jointly access the management of the three WRS to prepare and change the configuration of the devices. To connect the WRSs together, two pairs of SFPs are required. In this way the device that will act as Slave will have in its first two ports the "typically reserved for slave role" SFPs that will be connected each one with one of the WRS Masters, which have in port 5 connected the "typically reserved for master role" SFP.

Holdover mechanisms in case of loss of the link to the WR grandmaster were identified using either an ovencontrolled crystal oscillator (OCXO) in the WR main loop or using an internal expansion board with a suitable oscillator or using 1PPS/10MHz reference signals from an external reference clock. An evaluation of an OCXO in the WR main loop was made with and without hold-over capabilities implemented in the software.

A hold-over oscillator solution has been developed together with an update of the WR switch firmware for supporting different types of hold-over oscillators, depending on the requirements. Fig. 6 shows the hardware realised by Sevensols in WRITE for holdover purposes.





Fig. 6. Hardware developed by Sevensols to test hold-over mechanism. Up: WRITE Holdover expansion board. An Abracon AOCJY-10.000 OCXO is surface-mounted. Medium: WR Switch-LowJitter hardware with the WRITE Holdover expansion board mounted on top.

In order to maximise the holdover time of a WR implementation, the following factors must be taken into consideration:

- The stability of the oscillator: the current main oscillator in the White Rabbit Switches is a voltagecontrolled temperature-compensated crystal oscillator (VCTXCO). This kind of oscillator is not stable enough for a holdover implementation. Other kinds of oscillators, such as the oven-controlled crystal oscillators (OCXO), show the lowest frequency instability in the short term. However, the OCXO longterm stability is worse than what could be achieved by using other frequency sources such as a cesium or rubidium frequency standard.
- The environmental conditions: the oscillators and other electronics are affected by changes in temperature and air flows. It has been observed that the stability of certain oscillators is considerably impacted by the air currents generated by the WRS fans.
- The stability of the power supplies and electric signals: the stability of an oscillator is directly impacted by the stability of the electric source that powers it. In addition, since the local oscillator is steered by the use of a digital-to-analog converter, the linearity and relative accuracy of these devices are also potential causes of frequency instability



The holdover hardware was coupled to a White Rabbit Switch with improved performances (WRS Low Jitter), and the extension board for holdover has been tested with the set-up shown in Fig.7.



Fig 7. Schematic diagram of the evaluation set-up with the WRS-LJ with hold-over extension board connected to an SRS PRS10 Rubidium frequency standard

Results are reported in Fig. 8, showing that the holdover hardware smoothly manages to keep the timing within 20 ns even after more than one hour without network synchronisation. One hour of network loss is equivalent to a sever fault of internet and White Rabbit synchronisation broadcasting.



Figure 46. Phase drift of the WRS-LJ with PRS10 oscillator in four experiments of holdover operation during more than

Fig 8. Phase drift of the WRS-LJ with hold-over extension board connected to an SRS PRS10 Rubidium frequency standard, during more than 1 hour operations.

Key outputs and conclusions of Objective 2:

- Development of a protocol for the switchover of the WR-PTP switch, based on Best Master Clock Algorithm (BMCA), in line with the existing IEEE 1588 standard.
- Holdover architecture based on different Local Oscillators, experimentally tested to keep the timing within 20 ns even after more than one hour without network synchronisation.

This objective was successfully achieved.

# Development of a next generation of PTP-WR devices with improved performance and high-compatibility interfacing with industrial applications (Objective 3)

The goals that were set for the WRITE with respect to PTP-WR devices with improved performances were reached. The main objective of demonstrating an ADEV better than 1e-13 was reached in all implementations. The novelties developed in the WRITE are mainly: the development of ultra-high performance WR user board (SPEC7) and GM/BC/End-user board (HPSEC) by NWO-I, the industrial version of the low-jitter WRS developed by CERN as a product on the Shelf by Sevensols, and the external filtering of the WR 10 MHz



output with external low noise oscillators by OBSPARIS and INRIM. The High Performance SEC sets a new state-of-the-art performance level, with a noise floor that even compete with the ELSTAB technology developed by AGH. The WRS-LJ is now a commercially available product.

Three completely new boards were produced, that were not existing before the project. A deep review of external local oscillator was performed, and various implementations were tested. A local oscillator filtering approach was proven as cost effective for people interested in accurate signals and low phase noise at short term.

With such level of performances, the performance of a WR link is no more limited by the noise floor of the electronics, but set by the detail of the implementation in field (network architecture) and asymmetry of the delay of the link, chromatic dispersion, and residuals of periodic perturbation due to temperature.

In term of time accuracy, that was mainly addressed in WP1, valuable knowledge has been gained during the design process and validation of SPEC7 and HPSEC. This knowledge leads to new points of attention (like "Lock-sweep", for HPSEC) and will find its way into future projects that are developing PTP-WR hardware. Examples of such developments are the timing systems for Gravitational Wave detectors that set extreme limits on phase noise (Virgo and future Einstein Telescope).

The Cubic Kilometre Neutrino Telescope (KM3NeT) in the Mediterranean Sea also uses WR technology. Although timing specifications for this application are less stringent, the knowledge gained in the WRITE helped to elevate the level of performance for the KM3NeT timing network.

The consortium completed the analysis of single components to be improved to increase the overall performances of WR-PTP devices. In particular, WRITE tested alternative Local Oscillators and now the new design of the board is well advanced.

Different WR platforms have been compared, completing the design and realisation of a new SPEC 7 board (KINTEX). Tests on the board by different partners ensured repeatability and reproducibility, thanks to a strong collaborative attitude in the consortium.

New low jitter circuitry has been realised. The data and designs are accessible via the WR open hardware repository (<u>www.ohwr.org</u>). The Local Oscillator (LO) in existing hardware has been improved, with a full review and a complete laboratory test of alternative LOs for PTP-WR hardware. An external servo loop circuit for the improved LO has been designed, realised and optimised, and the new LO is available for the hardware technology SPEC 7. In addition, a low noise power supply as well as a new 4x output distribution unit have been developed and realised.

Twelve SPEC7 boards (Zynq-7000) were produced, and they have been assessed at CERN, INRIM, VTT, NPL and NWO-I. SPEC7 sources are now merged into the main branch of the WR open hardware repository. This is a fruitful collaboration among partners of the consortium but also relevant stakeholders such as CERN.

A High Precision Oscillator (HPSEC) was designed and tested. With this oscillator the SPEC7 performance can be significantly upgraded.

Fig.9 and 10 shows a picture of the SPEC7 hardware and the Phase noise at 10 MHz of its 10 MHz output.



Fig. 9 SPEC7 V2 electronics board.





Fig. 10 Phase noise of the 10 MHz output for SPEC7. The phase noise is 22 dB lower than in Fig. 5, as expected from the division ratio between the two carrier frequency

Fig. 11 shows a picture of the HPSEC realised in WRITE.



Fig. 11 Pictures of the HPSEC, front side and perspective view.

The White Rabbit Switch Low Jitter (WRS-LJ) is a revision of the standard White Rabbit Switch (WRS) that is focused on improving the clocking resources of the device. The WRS-LJ integrates the low jitter circuitry within the switch core board (SCB), shown in Fig. 12. The new design also reduces the power consumption and improves the thermal dissipation with respect to its predecessor.

The design of the clock circuitry is based on previous work published in OHWR [#wrlowjitter] that initially materialised in the development of the WRS Low Jitter Daughterboard [#ljdaughterboard]. With the development of the WRS-LJ, the improvements in clocking provided by the Low Jitter Daughterboard are directly integrated into the SCB. That is, the previous TCXO that serves as local oscillator of the WRS has been replaced by a more stable VCXO (Connor-Winfield DOT050), and there is a dedicated PLL for the

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synthesis of the grandmaster clock signal. In previous revisions, this process was performed in two cascaded FPGA Mixed-Mode Clock Managers (MMCM) that would firstly multiply the 10 MHz external clock up to 100 MHz, and then reduce to 62.5 MHz in a second stage. Using an external, dedicated PLL dramatically improves the noise of the grandmaster clock for frequency distribution, and the behaviour of the WRS-LJ as a boundary clock is also improved by the more stable VCXO. Regarding the output circuitry, the clocks and 1-PPS signals are now cleaner and more accurate.



Fig. 12. SCB of the WRS-LJ. The new SCB is backwards compatible with the casing of the standard WRS.

The final result of the integration among the hardware developed in WRITE, hence the Spec7 with the HPSEC and the WRS-LJ, is shown in Figure 13 and 14, in terms of Phase Noise and Allan deviation, showing a performance of an instability already at the level of 5e-15 (fractional frequency Allan Deviation) after only 100 s of measurement.



Fig. 13 Phase noise of the 10 MHz clock output of the HPSEC when it is locked to a "standard" White Rabbit Switch (Orange: WRS-3/18) and a Low Jitter White Rabbit Switch (Blue: WRS-3-LJ/18), compared to the OCXO Noise floor when free running (Yellow).





Fig. 14 Modified Allan Deviation measurement result on SPEC7+HPSEC connected to a low jitter White Rabbit Switch (WRS-3-LJ/18).

Key outputs and conclusions of Objective 3:

- Development of ultra-high performance WR user board (SPEC7) hardware, development of new hardware GM/BC/End-user board (HPSEC).
- Development of new hardware switch with low jitter (WRSLJ).
- Instability of the PTP-WR dissemination with new hardware is 5.6e-13 at 100 s in terms of fractional frequency Allan deviation. Accuracy contribution <200 ps.

This objective was successfully achieved.

Demonstration of the use of PTP-WR to deliver UTC(k) time scales and frequency in the RF domain from NMIs to industrial users and evaluation of the end-to-end uncertainty of the established time transfer (Objective 4)

WRITE testbeds were proposed to provide a testing- and implementation environment for the different technical challenges identified for improved industrial use of PTP/WR. Before WRITE, there were not existing White Rabbit links disseminating UTC to industries.

Moreover, the realised testbed demonstrated excellent performances in terms of accuracy and instability, and also in terms of reliability and long term operations.

Typical industrial requirements may still be moderate today, but evolving applications and new regulations will demand high TRL level solutions such as those investigated by WRITE. Existing, and presumable future, public regulations require metrological traceability to sources of common reference time and frequency, such as provided by UTC.

On the other hand, new solutions for industry must clearly show resilience and reliability, and this was the case of WRITE demonstrations.

The architecture of four testbeds has been developed, and four testbeds are now established and assessed in France, Italy, the Netherlands, and Sweden, as shown in Fig. 15





Fig 15. Geographical location of the 4 testbeds developed in WRITE all bringing a realisation of Universal Time Coordinated (UTC) to different industrial adopters.

UTC itself is not directly accessible but approximated by different UTC(k) realisations, which in turn provide traceability to the definition of UTC and the estimates of discrete epochs of UTC. The NMIs involved in WRITE all operate high quality UTC(k) timescales with typical uncertainties in the low nanosecond range that are limited by the GNSS or TWSTFT methods used. Statistical properties of such timescales allow to interpolate the discreate estimated points of UTC and make a continuous traceability possible. Because of the technologies used to link UTC(k)s to UTC the traced UTC uncertainty of the White Rabbit demonstrators is limited by the UTC(k) calibrations.

The applications for demonstrating WRITE were chosen from the more demanding applications requiring high performance traceable time and/or frequency transfer. Two testbeds (OBSPARIS, INRIM) target space industry manufacturing atomic clocks requiring reference signals for the characterising oscillators to support production and quality systems. Both testbeds are representing the WRITE improved state of the art White Rabbit performance. The other two testbeds (VSL, RISE) were focusing on topology, connectivity, and redundancy. Robust distribution is an important aspect of a time service. Operators need thus to address the increasing demand of high availability and possibly uninterrupted time and frequency services and need to mitigate service interruptions.

In France, OBSPARIS and Thales AVS established the link over a distance in the order of 50 km. WR is implemented on a dark fibre, even if DWDM architecture is present, resulting in a valuable flexibility of this link for future testing. The main novelties and remarkable results are:

- The established link is 50 km long, already one of the longest existing links using White Rabbit.

- The results can be compared with the state of the art of atomic clocks according to their public specifications, with respect to the requirements of industry Thales AVS, but even the most demanding space and geodesy requirements.

- The instability of the link is 8e-12 at 1 second, 8e-14 at 100 s, <1e-15 at 1e5 s in terms of fractional frequency Allan deviation, as shown in Fig. 16.

- The link achieves the Hydrogen masers (HMs) stability level after only 100 second integration time; hence the link can be used to calibrate any commercially available clock or be used as reference.





Fig. 16. Frequency instability in terms of fractional frequency Allan deviation for the UTC (OP) dissemination using WR from OBSPARIS to Thales AVS. The data reports also as reference the instability of different commercial clocks and the requirements of different user communities.

In Italy, INRIM and LEONARDO completed the link (230 km) disseminating UTC (IT). The link is realised by DWDM multiplexing, and a coherent time and frequency transfer is also present on the same fibre. LEONARDO used the link to evaluate the performance and the absolute frequency of their local commercial clocks (Hydrogen Masers), part of their production line. The link is under continuous operation. The main novelty and remarkable results are:

- The link is established between INRIM and LEONARDO premises at 140 km, using 230 km fibre, and it is the longest WR link under operation (recently surpassed by its extension).

- The architecture is unique since it couples the coherent ultrastable laser frequency dissemination with WR time transfer on the same fibre as shown in Fig. 17.

- The link instability achieves 1e-11 at 1 second, 1e-13 at 100 s, 5e-15 at 1e5 s terms of fractional frequency Allan deviation, using Hydrogen Masers as reference at LEONARDO, as shown in Fig. 18.

- The accuracy is assessed using an independent technique based on geodetic GNSS receivers, and no offset is observed at the accuracy level of 2.5 ns, limited by the GNSS technique (WR expected to be <1 ns).

- The link is permanently established and will be used in the future for further experiments and characterisation. Building on WRITE architecture design and results, INRIM has extended the link to Middle Italy with a 1000 km WR link for aerospace and Galileo uses.





Fig. 17 Scheme of the WR link architecture between INRIM and LEONARDO. On the same fibre, WR time transfer coexists with ultrastable laser coherent frequency transfer.



Fig. 18. Frequency instability in terms of fractional frequency Allan deviation for the UTC(IT) dissemination using WR from INRIM to LEONARDO.

In the Netherlands, VSL and OPNT installed a link from VSL to Amsterdam, close to potential customers. The link is currently under operation, disseminating UTC (VSL). The link collected further amount of data in extended operations and results have been published. The link is established between VSL and an Internet Exchange in Amsterdam, with a loop configuration VSL-Delft-Amsterdam-Delft-VSL, covering about 200 km.

The main novelty and remarkable results are:

- The accuracy is assessed directly comparing the impinged signal with the signal coming back from the loop, as shown in the scheme of the link in Fig. 19.

- The accuracy was assessed in three different campaigns, achieving 1 ns, 1.5 ns, and 1.6 ns, with a good reproducibility. The overall campaigns spanned 2 years, as shown in Fig. 20.

- Long term stability was assessed, reporting continuous operations over more than two months.
- Stability is 3e-16 at 1e5 seconds and <1e-17 for measurements time above 1e5 s, as illustrated in Fig. 21

Time deviation was always less than 400 ps over any measurement time.





Fig. 19. Scheme of the UTC (NL) time dissemination using WR from VSL to an Internet Exchange in Amsterdam, establishing a loop configuration (Delft-Amsterdam-Delft).



Fig. 20. Data results for accuracy evaluation taken over a 2-year period on the VSL/OPNT link in the Netherlands.



Fig. 21. Frequency instability in terms of fractional frequency Allan deviation (on the left) and Time Deviation (on the right) for the UTC (NL) dissemination using WR in the Netherlands.

Last, the two established WR links to NETNOD AB in the Stockholm area have been operated and characterised, UTC (SP) is disseminated.

The characterisation and operation of the test bed collected larger amount of data and novelties and remarkable results are summarised here as follows:

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- The link is established between RISE and NETNOD AB, a Swedish non-profit independent Internet infrastructure organisation, on 10 km, following the architecture illustrated in Fig. 22.

- The accuracy is assessed using an independent comparison with GNSS techniques and achieved 7 ns, limited by the GNSS equipment calibration.

- Long term stability was assessed, reporting continuous operations over more than six months.
- Stability achieved a time deviation of <100 ps for every measurement time, as illustrated in in Fig. 23.

A functional test of the BCMA was carried to test the switchover between two time sources. The used algorithm took several seconds to complete during which the timing of the WR is in weak holdover – this could be a limit for most demanding uses.







Fig. 23. Time deviation over 175 days for the RISE-NETNOD AB WR link, showing less than 100 ps time deviation (left); phase over 30 days, showing a peak to peak over the period of only 1.6 ns.

Key outputs and conclusions of Objective 4:

- In France, UTC (OP) is disseminated to Thales AVS via a PTP-WR link of 50 km. Instability of the link is 8e-12 at 1 second, 8e-14 at 100 s, <1e-15 at 1e5 s in terms of fractional frequency Allan deviation.
- In Italy, UTC (IT) is disseminated to Leonardo via a PTP-WR link of 230 km. Instability of the link is 1e-11 at 1 second, 1e-13 at 100 s, 5e-15 at 1e5 s in terms of fractional frequency Allan deviation.
- In the Netherlands, UTC (VSL) is disseminated to an Internet Exchange in Amsterdam, via a PTP-WR link of in a loop configuration VSL-Delft-Amsterdam-Delft-VSL, covering about 200 km. Instability is 3e-16 at 1e5 seconds and <1e-17 for measurements time above 1e5 s.</li>
- In Sweden, UTC (SP) is disseminated to NETNOD AB with two PTP-WR links, in the Stockholm area, both tens of km long. Accuracy is 7 ns, limited by the GNSS equipment calibration. Instability achieved a time deviation of <100 ps for every measurement time.</li>

This objective was successfully achieved.



# 5 Impact

WRITE has presented its activities and results through 5 paper submissions to international peer-reviewed journals (out of which 4 are now published), and 16 contributions at international conferences, such as the 2018 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS 2018, Geneva, Switzerland) or the Joint Conference of the IEEE International Frequency Control Symposium & European Frequency and Time Forum (IFCS-EFTF 2019, Orlando, Florida).

The WRITE stakeholder workshop communicated the project results to 100 participants from science, industry, NMIs and European National Research and Education Networks (NRENs). Active workshop discussions facilitated the exchange of ideas between the consortium, stakeholders and users of PTP-WR, many of them experts in this field. The workshop was promoted at international conferences and on the project website, with the slides made available on the CERN repository ohwr.org.

WRITE has presented the consortium activities to standardisation bodies, namely at EURAMET TC-TF and at BIPM, in the working group focused on Advanced Time and Frequency Transfer.

#### Impact on industrial and other user communities

WRITE realised new complete PTP-WR solutions (improved devices and performance, commercial network architecture compatibility, calibration procedures), addressing the needs of industrial manufacturers, service providers and end users. Improved reliability of secure time dissemination services is enabled as developments in the project tackle the distortion of GPS signals due to electromagnetic interference, and the vulnerability to spoofing or space weather. The project's devices and methods offer reliable and high performing time transfer to users with performance and traceability beyond the current state-of the-art for stability and accuracy, but with the unique feature of being resilient and continuously calibrated with traceability to UTC.

The industrial partners collaborated in the knowledge transfer activity, regarding both - methods and devices, and together with the NMIs were involved in the field realisations and the design of the fibre links.

INRIM extended the architecture developed in WRITE from LEONARDO to Fucino (central Italy), to transfer UTC (IT) to the premises of Telespazio, a company in charge of the operations for the ground segment of the Galileo Global Navigation Satellite System. In the future, the technologies and the methods developed within WRITE could be exploited by the European project Galileo. In Rome, a connection to another aerospace company, Thales Alenia Space Italia, was completed and Thales Alenia Space Italia is now receiving a timing signal traced to UTC (IT) by PTP-WR dissemination. This dissemination is the extension from 230 km to 1000 km of the testbed developed in WRITE: a demonstration of the scalability of the techniques developed and implemented during the project.

INRIM has also started a collaboration for testing WR on the fibre infrastructure of the Italian National Research and Education Network, Consortium GARR. An experimental set-up was implemented in Rome.

VSL started a collaboration with the European Space Agency (ESA) to test PTP-WR on 50 km for space applications.

OBSPARIS started to implement the PTP-WR technique on a French large infrastructure for Time and Frequency dissemination over fibre, T-REFIMEVE, promoted in December 2020 by the Ministry of Higher Education, Research and Innovation (MESRI) and the General Secretariat for the Investment Plan (SGPI).

#### Impact on the metrology and scientific communities

The project's outputs facilitated more accurate and efficient dissemination of the SI second, by enabling a traceable signal to be brought to the time and frequency users with unprecedented accuracy through the optical fibre network. Since fibre based PTP-WR time transfer to industries has been successfully demonstrated, complementary time links can be implemented enabling uninterrupted time transfer from all participating laboratories, even in cases when satellite signals are disturbed. In the long run, countries that do not possess primary frequency standards (optical or microwave) will be able to obtain easy access to accurate time and frequency signals available from the best clocks in Europe via the optical fibre networks. The collection of data for the realisation of International Atomic Time and the international reference timescale Coordinated Universal Time (UTC) would also benefit and indeed, PTP-WR will offer an outstanding method for clock comparisons, at least matching the performance of caesium clocks, as it outperforms satellites techniques and relies on common traffic infrastructures. Many scientific users, for example atomic and molecular spectroscopy, very long baseline radio astronomy (VLBI), and the realisation of all other SI units, have more stringent requirements



on timing stability and accuracy than most industrial users, and even scientific laboratories and academia that do not require the best-performing T/F solutions, would nonetheless benefit from improved solutions offered at a reasonable cost. WRITE provided all users with improved devices and techniques, highly reliable solutions and lower calibration uncertainties.

#### Impact on relevant standards

WRITE work has contributed to the new release of the IEEE 1588 standard that defines PTP, in particular VTT and NWO-I contributed to the revised IEEE 1588-2019 standard, published in 2020. The partners also actively participated in the activities of the Storage Networking Industry Association (SNIA). The new high-performance time transfer technique developed by the project is beneficial for the activities of the BIPM, in particular the Working Group on Coordination of the Development of Advanced Time and Frequency Transfer Techniques (WG-ATFT). The EURAMET Technical Committee for Time and Frequency (TC-TF) was regularly updated with reports on the project activities. The radio astronomical community maintains its own technical standards concerning time transfer issues, and will also benefit from the project.

#### Longer-term economic, social and environmental impacts

From both the economic and the social point of view, WRITE demonstrated in industrial environment a highperformance, scalable, cost-effective PTP-WR technique that will be greatly beneficial for the implementation of smart grids, and a broad range of applications described collectively as Internet of Things. The opportunity for synchronisation at the 10<sup>-16</sup> level at two distant stations, such as the PTF (Precise Timing Facilities) of the GALILEO ground segment, will enable a test of the accuracy and stability of the GPS or GALILEO systems to be performed with significantly higher precision than with previously available techniques.

As for the telecommunications industry, the partners foresee an impact on wireless 5G telecommunications. All of these services will have a significant social impact, allowing new types of access to medical aid, information management and economic transactions. The opportunity for tight synchronisation of sensors will in turn generate a precise and distributed knowledge of control parameters on a variety of socially relevant infrastructures, such as car traffic in large urban areas, power distribution, geological and seismic surveys, and water distribution.

The wide adoption of PTP-WR on existing fibre networks will be beneficial to the environment for a number of reasons. Firstly, smart power grids will benefit from better timing of power distribution devices and their synchronisation will make power distribution more efficient, with a relevant impact on environment. Secondly, sensing for air pollution needs synchronisation and precise timing to reconstruct airflow modelling, hence PTP-WR solutions developed in the project will help to generate an improved understanding of the environment, and to identify and act on pollution sources. Thirdly, a more long-term impact relates to water distribution, where new technologies, such as the smart water meters, Internet-of-Things devices and various sensors measuring hydraulic and quality parameters, will help monitoring and control in water distribution networks, including identification of leaks.

# 6 List of publications

- Xie, Yan; Dierikx, Erik; van Veghel, Marijn (2021): Design of "Universal Module" Based Time and Frequency System using White Rabbit Technology. TechRxiv. Preprint. <u>https://doi.org/10.36227/techrxiv.17122154.v1</u>
- 2. Dierikx, Erik; Xie, Yan; Savencu, Adrian; Lopez, José; Gutiérrez, José Luis (2021): White Rabbit Multi-Point Time Distribution Network. TechRxiv. Preprint. <u>https://doi.org/10.36227/techrxiv.17069279.v1</u>
- J. L. Gutiérrez-Rivas, F. Torres-González, E. Ros and J. Díaz, "Enhancing White Rabbit Synchronization Stability and Scalability Using P2P Transparent and Hybrid Clocks," in IEEE Transactions on Industrial Informatics, vol. 17, no. 11, pp. 7316-7324, Nov. 2021, doi: <u>https://doi.org/10.1109/TII.2021.3054365</u>
- M. Pizzocaro, et al. "Intercontinental comparison of optical atomic clocks through very long baseline interferometry", Nature Physics, 17, pages223–227 (2021) <u>https://doi.org/10.1038/s41567-020-01038-6</u>. <u>http://hdl.handle.net/11696/64130</u>

This list is also available here: <u>https://www.euramet.org/repository/research-publications-repository-link</u>