Publishable Summary for 17IND14 WRITE
Precision Time for Industry

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.

WRITE main achievements were: 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 $<6\times10^{-15}$ 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”.

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 6×10^{-15} 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.

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:

1. 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 $<1\text{x}10^{-13}$ 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.

Progress beyond the state of the art

This project advanced the state of the art in PTP-WR by establishing the metrological capacities required to accelerate the industrial adoption of PTP-WR for time transfer. Cost effective solutions have been proposed, which can be integrated with existing fibre networks devoted to internet communication, allowing industry to receive a time reference signal traceable to UTC without extra costs related to new infrastructures and with the resilience and reliability typical of telecommunication services.

Improved and scalable calibration techniques for PTP-WR optical fibre links have been developed, including the calibration and characterisation of the internal delays within devices and their dependence on external factors (e.g. temperature), and differential propagation delays through the optical fibre. The work within WRITE demonstrated that PTP-WR surpasses state-of-the-art Two way Satellite Time and Frequency Transfer time transfer, compared with the current state-of-the-art uncertainty in industrial applications of around 100 ns. WRITE demonstrated reliable PTP-WR dissemination at sub-nanosecond level, down to 200 ps accuracy.

Many industrial applications require high reliability and resilience. This project developed redundant and resilient features for time transfer for industrial use, such as redundant links from multiple time sources to one user, and improved resilience by providing alternative clock sources (e.g. time link, local clock, and GNSS signals) and enhanced performance levels. Although similar redundancy and resilience measures have been implemented with classical PTP, the PTP-WR implementation by this project has, for the first time, enabled reliable and standardised time distribution with better performance than GNSS methods.

Two important interfaces for PTP-WR are the time and frequency outputs, and in addition low phase noise, low timing jitter and fast rise time are highly desirable features. WRITE investigated the use of low-noise local oscillators and improved circuitry to obtain sharply defined waveforms, allowing a frequency instability of ADEV $<6\times10^{-15}$ at 100 s integration time. A third essential interface with industrial applications is formed by the PTP-WR optical outputs themselves, which are backward compatible with PTP (IEEE 1588-2008-2019). The project pursued the development of devices that are broadly backwardly compatible with existing industrial protocols and standards.

WRITE enabled uptake of WR UTC services, proving their viability by connecting four NMIs to industrial users active in the space industry and telecommunications through (redundant) fibre-optic links that also carry regular transport data, in order to demonstrate a durable and robust time and frequency transfer process, to test the real Technology Readiness Level, to accelerate the uptake of the IEEE1588-2018 High Accuracy profile to be published, and to demonstrate the routine use of PTP-WR by a high-level European industry.

Results

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

Fibre propagation asymmetry measurement techniques in the laboratory on testbeds were developed. Low-asymmetry links were tested in laboratory. Both fixed-wavelength transceivers and tuneable-transceivers have been tested. Data from laboratory tests on spools were collected, and we collected large amount of data on the in-field link deployed within WP4. Single fibre calibration techniques were developed using fixed-wavelength or tuneable-wavelength transceivers. Calibration techniques were documented.

Work is documented on the open hardware website https://www.ohwr.org/project/wr-calibration/wikis/home.

Field-tests for single-fibre propagation asymmetry calibration techniques were performed on the VTT Otaniemi-Metsähovi testbed (50km) and on the INRIM-LEONARDO connection. The documentation of calibration techniques was produced And links have been built and are operational.

The calibration techniques developed in WRITE achieved a reliable and unprecedented level of better than 200 ps accuracy.

Even though the COVID-19 pandemic outbreak has slowed down field and also laboratory activities, the consortium set up calibration test for the electro-optic components of the time dissemination devices, assessing a metrological validation of the WRITE methods at the interlaboratory level.

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).

Two reliability mechanisms for WR-PTP network solutions were identified: holdover and switchover. For switchover of the WR-PTP switch, two possible mechanisms have been identified: (i) Best Master Clock Algorithm (BMCA): not seamless (20 seconds recovery), and (ii) Seamless switchover: hot-swap between several references. From these two options, only the BMCA was developed in this project, because this approach was 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 beyond this project (more info at http://www.ohwr.org/documents/103).

Holdover mechanisms in case of loss of the link to the WR grandmaster were identified using either an oven-controlled 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.

Redundant WR links have been implemented into new firmware releases of WR switches. In particular, concerning the resilience targets, 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, , responding to different requirements, i.e. the tolerable level of accuracy after few hours-one day. That level spans from 100 ns-1 microsecond (finance, aerospace, telecommunications) to even hundreds of microseconds (electronic manufacturers)

For the first time, a systematic analysis for PTP-WR redundancy and resilience have been made targeting the needs of industrial users.

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 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 the consortium.

New low jitter circuitry has been realised. The data and designs from all the activities are accessible via the WR open hardware repository (www.ohwr.org). 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, a Low-Jitter WR switched has been developed.

All the new developed hardware made a step beyond previous state of the art and for the first time a stability of 6×10^{-15} in terms of fractional frequency Allan deviation has been achieved, together with an accuracy at 200 ps level.

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)

The architecture of four test-beds has been developed, and four test-beds are now established and assessed in Italy, the Netherlands, France, and Sweden.

COVID-19 pandemic outbreak had severely impacted field activities, however the partners have managed to recover the project from the delays.

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.

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, and it will be kept under operation also after the end of the project.

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).

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

This objective was successfully achieved.

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 high-performance, 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^{-16} 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.

List of publications

1. Xie, Yan; Dierikx, Erik; van Veghel, Marijn (2021): Design of “Universal Module” Based Time and Frequency System using White Rabbit Technology. TechRxiv. Preprint. https://doi.org/10.36227/techrxiv.17122154.v1
2. Dierikx, Erik; Xie, Yan; Savencu, Adrian; Lopez, José; Gutiérrez, José Luis (2021): White Rabbit Multi-Point Time Distribution Network. TechRxiv. Preprint. https://doi.org/10.36227/techrxiv.17069279.v1
3. 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: https://doi.org/10.1109/TII.2021.3054365
4. M. Pizzocaro, et al. "Intercontinental comparison of optical atomic clocks through very long baseline interferometry", Nature Physics, 17, pages223–227 (2021) https://doi.org/10.1038/s41567-020-01038-6. http://hdl.handle.net/11696/64130

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

Project start date and duration:		1 June 2018, 42 months
Coordinator: Dr Davide Calonico, INRIM Tel: +39 011 391 9230 E-mail: d.calonico@inrim.it Project website address: http://empir.npl.co.uk/write/		
Internal Funded Partners: 1 INRIM, Italy 2 NPL, United Kingdom 3 OBSPARIS, France 4 RISE, Sweden 5 VSL, Netherlands 6 VTT, Finland	External Funded Partners: 7 LEONARDO, Italy 8 NWO-I, Netherlands 9 OPNT, Netherlands 10 Sevensols, Spain 11 Thales AVS, France	Unfunded Partners:
Linked Third Parties: 12 CNRS, France (linked to OBSPARIS)		
RMG1: IMBIH, Bosnia and Herzegovina, (Employing organisation); INRIM, Italy (Guestworking organisation) RMG2: ME, Montenegro (Employing organisation); INRIM, Italy (Guestworking org.) – withdrawn for pandemic RMG3: ME, Montenegro (Employing organisation); INRIM, Italy (Guestworking org.) - withdrawn for pandemic		