White Rabbit Applications and Enhancements

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***Abstract*—This article provides a non-exhaustive overview of applications and enhancements to the White Rabbit (WR) extension of the IEEE 1588 Precision Time Protocol (PTP). Initially developed to serve accelerators at the European Organization for Nuclear Research (CERN), WR has become a widely-used synchronization solution in scientific installations. This article classifies WR applications into five types, briefly explains each and describes example its installations. The article then summarizes WR enhancements that have been triggered by different applications and outlines WR's integration into the PTP standard. Based on the presented variety of WR applications and enhancements, it concludes that WR will continue to proliferate in scientific applications and should soon find its way into industry.**

I. INTRODUCTION

White Rabbit (WR) [1] is an innovative technology that provides sub-nanosecond accuracy and tens of picoseconds precision of synchronization as well as deterministic and reliable data delivery for large distributed systems.

WR is based on well-established networking standards, extending them when needed, to meet the requirements of WR applications. A WR network is a Bridged Local Area Network (IEEE 802.1Q) that uses Ethernet (IEEE 802.3) to interconnect network elements and Precision Time Protocol (PTP, IEEE 1588) to synchronize them. The WR network elements, i.e. 802.1Q bridges and end stations, are called WR switches and WR nodes, respectively, and implement WR enhancements:

1) **Synchronization with sub-nanosecond accuracy and tens of picoseconds precision** among all WR switches/nodes. Such synchronization is provided by the WR extension to PTP (WR-PTP [2]) and its supporting hardware [3][4][5].
2) **Deterministic and low-latency communication** between WR nodes provided by a purposely-made and open design of the WR switch, described in [6].

Studies [6][7][8] have shown that both of the above enhancements can be further extended to operate in a highly reliable manner ensuring at most a single failure per year for a network of 2000 WR nodes.

Since its conception in 2008, the number of WR applications has grown beyond any expectation. The WR Users website [9] attempts to keep track of WR applications and the newsletter in [10] provides a status in June 2018 of some of these applications. Apart from the suitable synchronization performance, the reasons for the proliferation of WR applications are the open nature of the WR project and the fact that the WR technology is based on standards. The former encourages collaboration, reuse of work and adaptations that also prevent vendor lock-in. The latter allows using off-the-shelf solutions with WR networks and catalyzes collaboration with companies. What started as a project to renovate one of the most critical systems at CERN, the General Machine Timing (GMT [11][12]), is now a multilaboratory, multicompany and multinational collaboration developing a technology that is commercially available, used worldwide, and incorporated into the original PTP [13][14].

This article briefly describes in Section II the portfolio of readily available WR network elements. It then explains in Sections III-VIII different types of WR applications, their concept and use examples, summarized in Table I. Application-triggered enhancements are described in Section IX. Finally, in Section X we briefly describe the integration of WR into

TABLE I
NON-EXHAUSTIVE LIST OF WHITE RABBIT APPLICATIONS

Facility	Location	Type	Link len.	Network Size 2018 N/S/L	Network Size >2020 N/S/L	Reference
Accelerators, synchrotrons and spallation sources						
CERN	Switzerland	TF	10 km	0/2/1	0/2/1	
CERN	Switzerland	FL	1 km	6/2/1	20/8/1	[15][16][17][18][19]
CERN	Switzerland	TD	10 km	8/2/1	65/31/2	[20][21][22]
CERN	Switzerland	RF	10 km	-/-/-	13/1/1	[20]
CERN	Switzerland	TC	10 km	-/-/	500/40/4	
GSI	Germany	TC	1 km	35/4/4	2000/300/4	[23]
JINR	Russia	TS,TD	1 km	50/15/3	250/30/3	[24]
ESRF	France	RF,TS	1 km	7/1/1	40/5/2	[25]
CSNS	China	TF,TS,TD	1 km	50/4/2	50/4/2	[26]
Neutrino Detectors						
CERN	Switzerland	TS	10 km	10/4/2		[27]
KM3Net	France	TF,TS	40 km	18/1/1	4140/270/3	[28][29][30]
KM3Net	Spain	TF,TS	100 km	18/1/1	2070/130/2	[28][29][30]
DUNE	Switz/USA	TS,TD	1 km	14/5/2	36/5/2	
SBN	USA	TS,TD	1 km	6/1/1	6/1/1	
GVD	Russia	TS,TD	1 km	3/1/1	15/2/1	[31]
Cosmic Ray Detectors						
LHAASO	China	TF,TS	1 km	40/4/4	6734/564/4	[32][33][34][35]
TAIGA	Russia	TS,TD	1 km	20/4/2	1100/90/3	[36][37][38]
CTA	Spain/Chile	TF,TS	10 km	32/3/2	220/10/2	[39]
HAWC	Mexico	TF,TS,TD	1 km	6/1/1	6/1/1	[40]
National Time Laboratories						
MIKES	Finland	TF	950 km	10/few/2	10/few/2	[41][42]
LNE-SYRTE	France	TF	125 km	4/2/4	4/2/4	[43][44]
VLS	Netherlands	TF	137 km	4/2/1	4/2/1	[42]
NIST	USA	TF	10 km	2/-/1	expanding	[45]
NLP	UK	TF	80 km	2/3/2	expanding	[46]
INRIM	Italy	TF,TS	400 km	8/1/1	expanding	[47][48]
Other Applications						
SKA	Australia/Africa	TF	80 km	2/1/1	233/15/3	[49]
DLR	Germany	TD	1 km	1/1/1	1/1/1	[50]
ELI-ALPS	Hungry	TS	1 km			[51]
ELI-BEAMS	Czech Republic	TF,TS,TD,TC	1 km	70/16/2	70/16/2	[50]
EPFL	Switzerland	TS	1 km	2/1/1	2/1/1	[52]
Deutsche Börse	Germany	TS	1 km			[53]
Total number of WR network elements in the applications listed above						
WR nodes (few thousand sold till 2018):				**464**	**17592**	
WR switches (few hundred sold till 2018):				**82**	**1532**	

TF= time and frequency transfer, TC= time-triggered control, TS= timestamping, TD= trigger distribution, FL= Fixed-latency data transfer, RF= Radio-Freq. transfer
N= number of WR nodes, S= number of WR switches, L= number of layers

the IEEE 1588 standard and we conclude in Section XI.

II. WR Network Elements

WR network elements, WR nodes and WR switches, are openly available on the Open Hardware Repository (OHWR) [54] and can be purchased from companies [55]. While all of the WR networks use the same design of the WR switch [56], the design of WR nodes depends on the application. Therefore the WR node design is made available as an open-source intellectual property (IP) core [57] that can be easily used in one of the supported boards or integrated into a custom design. WR-compatible boards are available on OHWR in various form factors, including PCIe [58], VME [59], AMC [60][61], FMC [62], cRIO [63] and PXI [64]. All of these boards are open and commercially available [55]. More and more companies also integrate WR into their proprietary products, [65][66][67]. Such a variety of WR nodes facilitates realization of WR applications described in the following sections.

III. Time and Frequency Transfer (TF)

A. Basic Concept

The most basic application of WR is the transfer of time and frequency from the Grandmaster WR switch/node (Grandmaster) to all other WR switches/nodes in the WR network. WR ensures that the Pulse Per Second (PPS) outputs of all the WR switches/nodes in the WR network are aligned to the PPS output of the Grandmaster with a sub-nanosecond accuracy and tens of picoseconds precision. The accuracy is the mean of the offset between the PPS outputs, while the precision is the standard deviation of this offset. WR switches and nodes use and can output a clock signal (e.g. 10MHz, 125MHz) that is traceable to that of the Grandmaster.

In most applications the Grandmaster is connected to a clock reference. This typically is a Cesium or a Rubidium oscillator disciplined by a global navigation satellite system (GNSS) [68][69][70]. In such cases, the time and frequency transferred by WR are traceable to the International Atomic Time (TAI) and the Coordinated Universal Time (UTC).

B. Example Applications

Time and frequency transfer is used by National Time Laboratories to disseminate the official UTC time and to compare clocks. Laboratories in Finland (VTT MIKES), Netherlands (VSL), France (LNE-SYRTE), UK (NLP), USA (NIST) and Italy (INRIM) have WR installations, see Table II. MIKES and INRIM use WR to provide their realization of UTC to clients, e.g. UTC(MIKE) over a 50 km link to the Metshovi Observatory [41] for applications in geodesy and UTC(INRIM) over 400 km to the financial district of Milano. NIST and LNE-SYRTE use WR to distribute within their campus UTC(NIST) and UTC(OP), respectively. The National Time Laboratories are studying WR with different types and lengths of fiber links and attempt to increase its performance, see Table II. These studies have shown that the stability (at $\tau = 1s$) of the off-the-shelf WR switch is 1e-11 and can be improved to 1e-12 without any modifications to the WR-PTP Protocol, see Section IX-A and [41][44][74]. Many of the National Time Laboratories are now working together with other WR users and companies within the EU-funded project WRITE [75] to prepare WR for industrial applications.

TABLE II
WHITE RABBIT INSTALLATIONS IN NATIONAL TIME LABORATORIES

Time Lab	Link Length	Link Type	Time Error	Time Stability	Ref
VTT MIKES	950 km	unidir. in DWDM	±2ns	20ps@1000s	[42]
	50 km	bidir. on adjacent ITU DWDM channels	<1ns	≈2ps@1s (*)	[41]
VSL	2x137 km	bidir. on CWDM (1470&1490nm)(#)	<8ns	10ps@1000s	[42]
LNE-SYRTE	25 km	unidir. at 1541nm	150ps	1-2ps@1000s	[43]
	25 km	bidir. at 1310&1490nm	150ps	1-2ps@1000s	[43]
	125 km	unidir. in the C-band or close OSC channel	2.5ns	1ps@1s (**)	[44]
	4x125 km	unidir. in the C-band or close OSC channel	2.5ns	5.5ps@1s (**)	[44]
NIST	<10 km	bidir. standard WR (1310&1490nm [71])	below 200ps	20ps@1s	[45]
NPL	2x80 km	unidir. in DWDM	<1ns	≈1.7ps@1000s	[46]
	<10 km	bidir. standard WR	<1ns	1.5ps@1000s	
INRIM	50 km	bidir. in WDM	800ps ±56ps		[47]
	70 km	bidir. in WDM	610ps ±47ps		[47]
	400 km	unidir. in DWDM			[48]

(D/C)WDM = (Dense/Coarse) Wavelength Division Multiplexing
Dedicated and commercial quasi-bidirectional optical amplifiers are used [72]
* Low Jitter Daughterboard was used to enhance performance [73]
** Input stage of the Grandmaster was improved, the bandwidth of WR switches/node was increased to 70Hz, PTP message rate was increased

At CERN, the WR-based time and frequency transfer is used to synchronize the operation of different accelerators. The controller of the Antiproton Decelerator is synchronized over a few kilometer long WR link to a similar controller of the LHC Injection Chain that provides proton beam to both, LHC and AD.

IV. Time-Triggered Control (TC)

A. Basic Concept

Many accelerators, synchrotrons and spallation sources are controlled by triggering events in a pre-configured sequence of actions. In fact, it is a very convenient way to control beams of particles that move at very high speeds – often close to the speed of light – faster than the propagation of control signals.

In the time-triggered control schema, a sequence of actions is determined by a controller and distributed to controlled devices in advance. These actions are scheduled to be executed by spatially-distributed devices at a particular time. The responsiveness of such systems greatly depends on the latency of delivering the control-information from the controller to the accelerator devices. The precision of such systems depends on the synchronization quality between these devices and the controller. WR provides precise and accurate synchronization and guarantees an upper-bound in latency through the network to enable the implementation of a time-triggered control for accelerators.

B. Example Applications

WR is used at GSI (Darmstadt, Germany) as the basis for a time-triggered control system of accelerators, called General Machine Timing (GMT) [76]. WR-based GMT has replaced the previously used system for the existing GSI accelerators and will control GSI's new Facility for Antiproton and Ion Research (FAIR) [77]. Control of the GSI and FAIR accelerators requires that the control-information is delivered from a common controller to any of the controlled subsystems in any of the accelerators within 500 μs. The most demanding of these subsystems requires an accuracy of 1-5 ns. The controller, called Data Master, is a WR node. The subsystems are either WR nodes or have a direct interface with WR nodes. All these WR nodes are connected to a common WR network that provides synchronization, delivers control-information from the Data Master to all subsystems as well as between subsystems, and allows diagnostics.

The WR-based GMT has been operational at GSI since 2015. First, it was used to control a small CRYRING accelerator built purposely to test the WR-based GMT [78] and consisting of 30 WR nodes in three layers of WR switches. Then, the GMT system that had been used so far was replaced with a WR-based GMT that consists of 35 WR switches and it is commissioned for operation, with a first beam in June 2018. When FAIR is completed in 2025, the WR network at GSI and FAIR will include 2000-3000 WR nodes connected to 300 WR switches in five layers.

V. Precise Timestamping (TS)

A. Basic Concept

In a great number of applications, time and frequency are transferred in order to timestamp accurately and/or precisely incoming signals. Such incoming signals can be either discrete pulses that are timestamped with time-to-digital converters or analogue signals that are sampled (digitized) with the distributed frequency and associated with the distributed time. Timestamps are usually produced to measure the time of flight (ToF) or to correlate events between distributed systems. Precise timestamping is one of the most widely-used applications of WR. The ability to timestamp input signals and send these timestamps over a WR network to a standard PC for analysis proves to be an extermely convenient solution to many otherwise challenging distributed measurements.

B. Example Applications

The first application of WR was in the second run of the CERN Neutrinos to Gran Sasso (CNGS) experiment [27] and required timestamping of events at the extraction and detection of neutrinos. This allowed ToF detection. Two WR networks were installed in parallel with the initial timing system: one at CERN and one in Gran Sasso. Each WR network consisted of a Grandmaster WR switch connected to the time reference [68][69], a WR switch in the underground cavern and WR nodes timestamping input signals. The measured timestamping performance of the deployed system over 1 month of operation was 0.517 ns accuracy and 0.119 ns precision.

The most demanding WR applications in terms of timestamping are cosmic ray and neutrino detectors that record the time of arrival of particles in individual detector units distributed over distances up to several kilometers. Based on the difference in the times of arrival of the same particles detected by different units, the trajectories of these particles are calculated. For these applications, a high precision and accuracy is required in harsh environmental conditions due to their locations [38].

The Large High Altitude Air Shower Observatory (LHAASO), located at 4410 m above sea level in China (Tibetan Plateau), requires a 500 ps RMS [32] alignment of timestamps produced by 7000 WR nodes distributed over 1 km^2 and exposed to day-night variation of -10 to +55 degrees Celsius. To meet such requirements, active compensation of temperature-related hardware delays has been implemented [33] and each of the WR nodes will be individually calibrated using a portable calibrator [34]. These methods have proved to work in a prototype installation that has been running since 2014 (50 WR nodes, 4 WR switches in 4 layers, [35]).

The Cubic Kilometre Neutrino Telescope (KM3NeT [28]) is a research infrastructure housing the next generation neutrino telescopes located at the bottom of the Mediterranean Sea. The needed angular resolution of 0.1 degree means that the submerged Digital Optical Modules (DOMs), which constitute KM3NeT, must be synchronized with 1 ns accuracy and a few 100 ps precision. 4140 DOMs at 3500 m depth 100 km off-shore of Italy and 2070 DOMs at 2475 m depth 40 km off-shore of France will be synchronized with an on-shore reference using a WR network [29][30]. Initial tests have been successfully performed with 18 DOMs to validate the system.

Other applications of WR that use timestamping include the Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy (TAIGA) in Siberia [36][37][38], Cherenkov Telescope Array (CTA) to be built in Chile and Spain [39], the Extreme Light Infrastructures (ELI) in Hungary [51] and Czech Republic [50], Satellite Laser Ranging at German Aerospace Center (DLR), High Precision Timestamps Daily File Service at German Stock Exchange (Deutsche Börse) [53] or Phasor Measurement Units synchronization for the power industry and smart grid applications studied at Swiss Federal Institute of Technology Lausanne (EPFL) [52].

VI. Trigger Distribution (TD)

A. Basic Concept

Trigger distribution combines, to some extent, the time-triggered control and precise timestamping described before. In this application, an input trigger signal is timestamped by a WR node and sent over the WR network to many WR nodes that act upon the received message simultaneously, at a precise delay with respect to the input signal. The input trigger can be either a pulse or an analogue signal exceeding a treshold. Once the trigger occurs, the information about the trigger (e.g. ID), along with the timestamp, is sent over the WR network to other WR nodes, usually as a broadcast. The deterministic characteristics of the WR network allows the calculation of the upper-bound latency for the message to reach all the WR nodes. In order to make sure that all the "interested" WR nodes act upon the trigger simultaneously, the delay between the input trigger and the time of execution is set to be greater than the upper-bound latency.

B. Example Applications

The trigger distribution schema has been used at CERN since 2015 in the WR Trigger Distribution (WRTD) system for instability diagnostics of the LHC [20][21]. In the WRTD, there are a number of instruments capable of detecting LHC instabilities and continuously acquiring data in circular buffers. Upon detection of instabilities, such a device generates a pulse that is timestamped by a Time-to-Digital Converter (TDC) integrated in a WR node [79], as depicted in Figure 1. The timestamp produced by the TDC is broadcast over the WR network, with a user-assigned identifier, allowing the unique identification of the source of the trigger. WR nodes interested in this trigger take its timestamp, add a fixed latency (300 μs) and produce a pulse at the calculated moment. This pulse is an input to a device that continuously acquires beam monitoring data in a circular buffer. These buffers are deep enough to accommodate the introduced fixed latency so that they can be rolled back to provide diagnostic data of the beam at the time the instability was detected by the source device. In such a way, the onset of instabilities can be coherently recreated. It is worth noting that the diagnostic instruments used in WRTD do not implement WR. They are integrated with WR through timestamping of their trigger outputs and generation of inputs that trigger their actions.

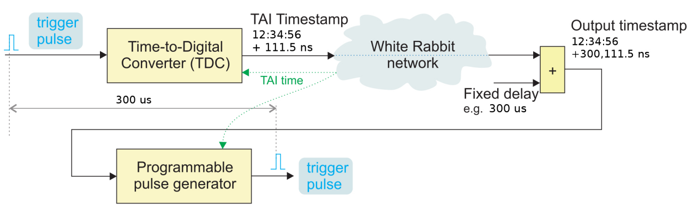

Fig. 1. White Rabbit Trigger Distribution.

The concept that has been proven to work in WRTD is now being generalized to provide trigger distribution for CERN's Open Analog Signals Information System (OASIS) [80]. OASIS is a gigantic distributed oscilloscope that provides over 6000 input channels and spans all CERN's accelerators except LHC. Triggers in this system are currently distributed via coax cables that may be one kilometer long without delay compensation and multiplexed using analogue multiplexers. In order to use OASIS to diagnose LHC and to improve its performance, the distribution of triggers is being upgraded to use WR. The WR-based trigger distribution in OASIS is meant to be generic and reusable. It is developed within the White Rabbit eXtensions for Instrumentation (WRXI) project [22] that is based on the existing LAN eXtensions for Instrumentation (LXI) standard. The WRXI for OASIS is meant to be operational in 2019.

VII. Fixed-Latency Data Transfer (FL)

A. Basic Concept

Fixed-latency data transfer provides a well-known and precise latency of data transmitted between WR nodes in the WR network. It uses very similar principles to the trigger distribution described in Section VI. The time of data transmission is timestamped and this timestamp is sent in the Ethernet frame with the data. When the data is received, a programmable delay is added to the transmission timestamp and the associated data is provided to an application precisely at the delayed time. Such a functionality is implemented by the so-called "WR Streamers" IP core [15] which adds a data transmission layer on top of WR and acts as a fixed-latency FIFO over Ethernet. By providing such functionality to the application, the application does not need to be aware of time but rather processes data as it comes, knowing that all the WR nodes in the WR network will execute the same action at the same time. In order to take advantage of the precise fixed-latency data transfer, the application needs to be integrated with a WR node.

B. Example Applications

The fixed-latency data transfer is used in the BTrain-over-WhiteRabbit (WR-BTrain) [16] system that distributes in real-time the value of the magnetic field in CERN accelerators.

In circular accelerators, the acceleration of the beam by radio-frequency (RF) cavities needs to be synchronized with the increase of magnetic field in the bending magnets. BTrain is the system at CERN that measures and distributes the value of the magnetic field (B-value) in real-time to the RF cavities, power converters and beam instrumentation. While the RF cavities simply follow the ramp of the magnetic field, the power converters adjust the current of the magnets such that the intended B-value is obtained, closing a control loop. BTrain is essential to the operation of most of CERN accelerators, i.e. Booster, PS, SPS, LEIR, AD and ELENA.

The original BTrain system uses coaxial cables to distribute pulses that indicate increase and decrease of the B-value. This method is now being upgraded to a WR-based distribution of the absolute B-value and additional information [17]. In this upgraded system B-values are transmitted at 250 kHz (every 4 μs) from the measurement WR node to all the other WR nodes that are integrated with RF cavities, power converters and beam instrumentation. In the most demanding accelerator, SPS, the data must be delivered over 2 hops (WR switches) with a latency of 10 μs ± 8 ns.

The WR-BTtrain has been successfully evaluated in the PS accelerator where it has been running operationally since 2017 [18]. By 2021, all the CERN accelerators, except LHC, should be running WR-BTrain operationally [19].

Fixed-latency data transfer is also considered for the operation of the Nuclotron-based Ion Collider Facility (NICE) at the Joint Institute for Nuclear Research (JINR) [81] that already uses WR as the main clock and time distribution system [24].

VIII. Radio-Frequency Transfer (RF)

A. Basic Concept

Radio-frequency (RF) transfer over WR network allows the digitization of periodic input signals in a WR master node, the sending of their digital form over a WR network, and the subsequent regeneration of the signal coherently with a fixed delay in many WR slave nodes. Such a digital RF transfer provides a number of advantages over an analogue transmission of RF signals. For example, it is scalable and allows the transmission of multiple RF signals from multiple sources over a single WR network, whereas analogue transmission typically requires a dedicated network per source and signal. It also allows easy and automatic phase-alignment of the output RF signals with compensation for temperature changes of transmission cables, whereas such alignment and compensation in analogue transmission is very challenging.

In the RF transfer over WR Network schema, depicted in Figure 2 and detailed in [20], a digital direct synthesis (DDS)

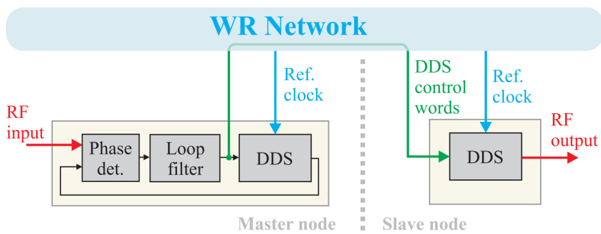

Fig. 2. Radio-frequency transmission over White Rabbit.

based on the WR reference clock signal (125 MHz) is used to generate an RF signal in the WR master node. The generated RF signal is then compared by a phase detector to the input RF signal. The error measured by the phase detector is an input to a loop filter (e.g. Integral-Proportional controller) that steers the DDS to produce a signal identical to the RF input - effectively locking the DDS to the input signal. The tuning words of the DDS are the digital form of the RF input that is sent over the WR network. Each of the receiving WR slave nodes recreates the RF input signal by using the received tuning words to control the local DDS with a fixed delay. In such way, the WR slave nodes produce RF outputs that are syntonized with the RF input, phase-aligned among each other, and delayed with respect to the RF input – all with sub-nanosecond accuracy and tens of picoseconds precision. Such a performance is possible because the noise of the DDS and the reference clock signal provided by WR to digitize/synthesize the RF signal are much lower than the required characteristics of the digital RF signal transmission, thus negligible.

B. Example Applications

The WR-based radio-frequency transfer is being implemented in the European Synchrotron Radiation Facility (ESRF) [82][25]. The operation of the ESRF accelerator facility is controlled by a ”Bunch Clock” system[1] that delivers to accelerator subsystems a ≈352 MHz RF signal and triggers initiating sequential actions synchronous to the RF signal, such as ”gun trigger”, ”injection trigger” or ”extraction trigger”[2]. The jitter of the output RF signal is required to be below 50 ps. The RF signal is continuously trimmed around the 352 MHz value as the tuning parameter in the ”fast orbit feedback” process. Apart from the 352 MHz signal, other frequencies are distributed, such as the 355 kHz Storage Ring revolution frequency or the 10 Hz Injection sequence.

The current ESRF ”Bunch Clock” system is being refurbished to use WR [25]. The solution has passed a 6-months validation test in 2015. In 2016, a prototype system successfully injected bunches in the storage ring providing <10 ps jitter. A system consisting of a WR switch and eight WR nodes is expected to be operational in July 2018. It will be expanded to 41 WR nodes and 4-5 WR switches by 2020. The ESRF ”Bunch Clock” system not only distributes a number of RF frequencies, it also provides timestamps and triggers that can be synchronous with these RF frequencies.

The radio-frequency transfer in CERN’s Super Proton Synchrotron (SPS) accelerator is also being upgraded to use WR. The SPS requires distribution of a 200 MHz RF signal with 0.25 ps RMS jitter (100 Hz to 100 kHz) and an accuracy of ±10 ps. These requirements necessitate enhancements of WR.

[1]A ”Bunch Clock” system generates a clock signal that is synchronous with particle bunches circulating in a synchrotron or an accelerator.

[2]”Gun trigger” initiates generation of an electron bunch at the LINAC input, ”injection trigger” initiates the transfer of the bunch from the LINAC into the Booster, ”extraction trigger” initiates the extraction of the bunch from the Booster into the Storage Ring at the end of acceleration [25].

IX. Performance Enhancements

The growing number of applications catalyzes improvements of WR performance that are summarized in this section.

A. Jitter and Clock Stability

The applications of WR for time and frequency transfer in National Time Laboratories as well as for RF transfer in CERN’s SPS require improvement of jitter and clock stability. The frequency transfer over a WR network was characterized in [83] and its ultimate performance limits were studied in [74]. The studies [41][44][74] have shown that the performance of a WR switch currently commercially available can be improved as follows:

- Allan deviation (ADEV) **from 1e-11 to 1e-12** ($\tau = 1s$),
- Random jitter **from 11 to 1.1 ps RMS** (integration bandwidth from 1 Hz to 100 kHz).

This prompted the development of the Low-Jitter Daughterboard [73], which improves the performance of the WR switch to 1e-12 without any modifications to the WR-PTP Protocol, see [41][44][74]. The improved WR Switches are now commercially available [84]. A high performance low-jitter WR node is developed for the SPS’s RF transmission achieving jitter of sub-100 fs RMS from 100 Hz to 20 MHz [85]. A WR node [86] to achieve stability of 1e-13 over 100 s is designed within the WRITE project [75].

B. Temperature Compensation

Studies [27] have shown that the temperature variation of WR nodes and switches degrades synchronization performance, still maintaining sub-nanosecond accuracy. This degradation and its sources have been carefully characterized [33] showing that its major contributor is the variation of hardware delays, considering links whose lengths are less than 10 km (see next section). These delays are usually calibrated for WR devices [87] at a room temperature and assumed constant throughout operation. Their variation however is linear with temperature and so an online correction can be applied. Such correction was developed for the LHAASO experiment [27], which requires 500 ps RMS synchronization of 7000 WR nodes in a harsh environment. For temperatures between -10 and +50 degrees Celsius, the developed correction reduces the peak-to-peak variation from 700 ps to <150 ps with a standard deviation <50 ps [33].

C. Long-haul Link

Experiments have shown that WR can successfully provide sub-nanosecond accuracy on bidirectional links up to 80 km [41][43][47][49], taking care for the effects described in the next section. Links longer than 80 km require active amplifiers and/or unidirectional fibers. This deteriorates accuracy due to an unknown asymmetry. On the 137 km bidirectional link in the Netherlands [42], dedicated optical amplifiers that work with bidirectional fibers are used in an attempt to overcome these limitation. The tests so far have shown <8 ns accuracy while a new "in-site" calibration under development at VLS is expected to calibrate out this asymmetry (over a 2x137 km link) to a few hundred picoseconds [88]. On the 950 km unidirectional link in Finland [42], GPS precise point positioning was used to calibrate asymmetry and achieve ± 2 ns accuracy. This method requires re-calibration after any disruption of the network. Laboratory tests of a 500 km WR connection using five cascaded WR devicies and four 125 km unidirectional links showed a 2.5 ns peak-to-peak time error [44].

D. Link Asymmetry

WR estimates and compensates asymmetry of bidirectional links knowing the relation between the wavelengths in the two directions. This relation, characterized by the *alpha* parameter, is calibrated at room temperature and assumed constant. However, the variation of fiber temperature results in changes of the actual *alpha* (e.g -0.12 ps/km/K for 1310/1490 nm) while the variation of WR nodes/switches temperature result in laser wavelength variation (e.g. 17 ps/nm km for 1550 nm). These and other effects analyzed in [49] are significant on long links and can amount to over 3 ns inaccuracy for 80 km bidirectional links using 1490/1550 nm and exposed to a 50 degrees Celsius temperature variation. The Square Kilometre Array (SKA) [89] radio telescope mitigates these effects to achieve <1 ns accuracy on 80 km links by using a DWDM SFP on ITU channels C21/C22 (1560.61/1558.98 nm) and combining them on a single fiber via a simple DWDM channel filter, as described in [49].

E. Absolute Calibration

The accuracy of WR depends greatly on the calibration of hardware delays. WR has been using procedures for relative calibration of these delays [87]. With relative calibration, sub-nanosecond accuracy can be achieved provided that the synchronized WR devices are calibrated against the same "golden calibrator".

The recently completed work on absolute calibration [90][91][92] allows the precise measurement of the actual value of hardware delays and their different contributors. With such calibration, a "golden calibrator" will not be required and adding a new type of component (e.g. SFP) to a WR network will not necessitate a time-consuming calibration of all devices with this component.

X. WR Standardization in IEEE 1588 (PTP)

The P1588 Working Group [13] is revising the IEEE 1588 standard, due to be finished in 2019. This group has been studying WR in order to incorporate its generalized version into the standard [14]. This resulted in a third Default PTP Profile, High Accuracy, that mandates a number of IEEE 1588's new optional features. All together, these additions are functionally equivalent to WR and allow the support of WR hardware. Along with the new features, informative annexes are added with a "standardized" description of the WR calibration procedures [87] and an example implementation of the High Accuracy profile, a.k.a White Rabbit, that achieves sub-nanosecond synchronization. The mapping between WR and High Accuracy is described in [93].

XI. Conclusions

WR is an innovative solution to provide sub-nanosecond accuracy and tens of picoseconds precision of synchronization over large distances. The number of WR applications and their specifications have exceeded the original expectations of the project. This proliferation can be attributed to the fact that WR is standard, open and commercially available. The open nature of WR allows its users to contribute to the project with their specific expertise and new developments. WR has become a *de facto* standard for synchronization in scientific installations and it is now becoming an industry standard within IEEE 1588. With its wide adaptation in science, commercial support, upcoming standardization and EU-funded projects to catalyze applications in industry, WR will continue to proliferate in scientific applications and should soon find its way into industry.

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