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White Rabbit project: a brief survey of time and clock synchronization

Proyecto White Rabbit: Un breve estudio sobre la sincronización de tiempo y reloj

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ABSTRACT

This paper provides an overview of the White Rabbit (WR) project, a high-precision, Ethernet-based time and clock synchronization system. Initially developed collaboratively involving various academic and research institutions, WR demonstrates exceptional synchronization accuracy, as evidenced by simulations and experimental results. Notable advancements include the WR Precision Time Protocol (WRPTP), which achieves sub-nanosecond precision, and innovative synchronization techniques utilizing single-wavelength light in single-mode fibers. The protocol finds application in diverse fields, including particle detection, scientific instrumentation, and telecommunications. This review examines the principal technological improvements, FPGA-based implementations, and a broad range of applications enabled by WR technology, highlighting its significance in advancing synchronization precision across various technological sectors.

Keywords: IEEE 1588, fiber optics, synchronization.

RESUMEN

Este artículo presenta un resumen del proyecto White Rabbit (WR), un sistema de sincronización de tiempo y reloj de alta precisión basado en Ethernet. Desarrollado inicialmente mediante un esfuerzo de colaboración que involucró a varias instituciones académicas y de investigación, WR ha logrado una notable precisión de sincronización, demostrada a través de simulaciones y experimentos. Los avances clave incluyen el protocolo de tiempo de precisión WR (WRPTP) con una precisión de sub-nanosegundo y nuevos métodos de sincronización que utilizan luz de una sola longitud de onda en fibras monomodo. Las aplicaciones del protocolo abarcan múltiples campos, incluyendo la detección de partículas, la instrumentación científica y las telecomunicaciones. Este estudio revisa las principales mejoras, implementaciones basadas en FPGA y diversas aplicaciones posibilitadas por la tecnología WR, enfatizando su importancia en la mejora de la precisión de sincronización en diferentes dominios tecnológicos.

Palabras clave: IEEE 1588, fibra óptica, sincronización.

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INTRODUCTION

The White Rabbit (WR) project [1] began as a collaborative initiative among universities, research centers, laboratories, and companies to enhance synchronization over Ethernet using the IEEE 1588 Precision Time Protocol (PTP).

Initial simulations in Omnet++ and FPGA-based experiments showed synchronization accuracy within 380 ps over a 10 km optical Ethernet link [2]. The WRPTP [3] later achieved precision below 10 ps over 5 km, compatible with existing PTP equipment.

WR was first used in the CERN Neutrino to Gran Sasso (CNGS) project [4] to transmit UTC from a GPS receiver to underground detection points. It now serves various applications, including cosmic particle detectors and time distribution systems.

Comparisons between PTP Transparent Clocks (TC) [5] and Boundary Clocks (BC) within WR highlight their roles: BCs adjust and retransmit synchronization to slave clocks. In contrast, TCs adjust in-transit synchronization messages for network delays. Both use Digital Dual Mixer Time Difference (DDMTD) [6] for high-precision phase offset measurements.

Enhancements in synchronization precision through the L1 physical layer [7] are crucial for PTP networks, as L1 clock and local PTP clock signal offsets can cause synchronization errors. The interaction between L1 and PTP synchronization in WR devices is explored in [8], which details the Phase-Locked Loop (PLL) architecture that maintains the phase offset between the local PTP and the recovered L1 rx clock signals.

A novel synchronization method using single-wavelength light in a single-mode fiber achieves sub-nanosecond synchronization over 50 km without asymmetry calibration [9]. Over 5 km, it showed an average synchronization error of 50 ps (std. dev. 30 ps) versus 172 ps (std. dev. 32 ps) for the conventional method; over 50 km, it maintained 132 ps (std. dev. 28 ps).

In [10], absolute calibration methods for WR components are described, allowing component exchange without complete network recalibration and improving precision through in situ calibration of the fiber delay coefficient. In [11], it was demonstrated that WR's sub-nanosecond accuracy, crucial for OFDM systems, is resistant to temperature changes, although it exhibits higher phase noise than coaxial cables. In [12], WR's temperature sensitivity was further investigated, noting significant time drift errors between nodes with 25 ºC variations, though optical fibers showed minimal impact due to PTP compensation.

WR applications are diverse, including time and frequency transfer, time-triggered control, precise timestamping, trigger distribution, fixed-latency data transfer, and radio-frequency transfer [13].

This article discusses WR's clock and time synchronization, recent protocol improvements, and their applications in scientific and technological fields.

MATERIALS AND METHODS

This work is structured as a narrative survey focused on White Rabbit (WR) time and clock synchronization and its main applications. No new experimental measurements are reported; instead, we synthesize and compare results from the existing literature.

Study design

The goal of this survey is to consolidate reported performance figures, implementation details, and application scenarios of WR-based systems, and to relate them to broader time and frequency synchronization practices. The emphasis is on quantitative results (accuracy, stability, jitter) and on architectural or implementation aspects relevant for reproducible WR deployments. The main thematic axes considered in this work –protocol and performance, FPGA implementation, and real-world applications– are summarized in Figure 1.

Database search

Major scientific databases were surveyed between 2010 and early 2025, including IEEE Xplore, Scopus, and Web of Science. The main search strings combined terms such as:

– "White Rabbit", "WR-PTP", "precision time protocol", "sub-nanosecond synchronization", "time and frequency transfer", "FPGA", "synchronous Ethernet", "PTP over fibre", "UTC dissemination".

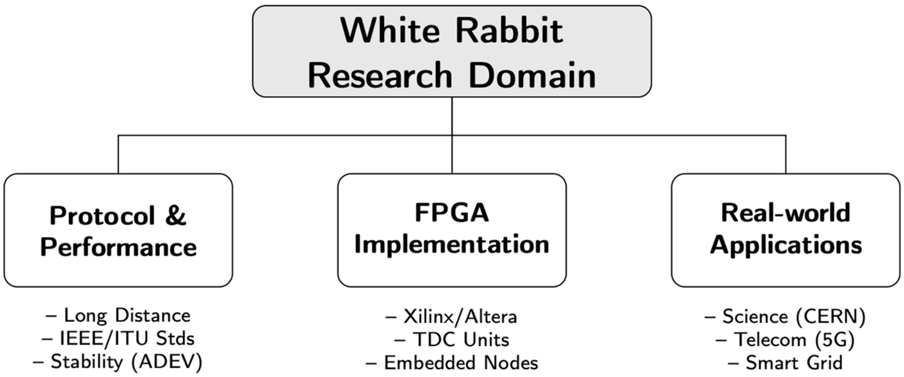

Figure 1. Thematic classification of the White Rabbit research domain into protocol and performance, FPGA implementation, and real-world applications.

Additional references were identified through backward and forward citation tracking of key WR publications and documents produced by major experimental facilities and metrology institutes. The overall identification, screening, eligibility, and inclusion workflow used for the literature search is depicted in Figure 2.

Inclusion and exclusion criteria

Works that met at least one of the following conditions were included:

(i) present original performance measurements (accuracy, stability, or jitter) of WR-based systems;

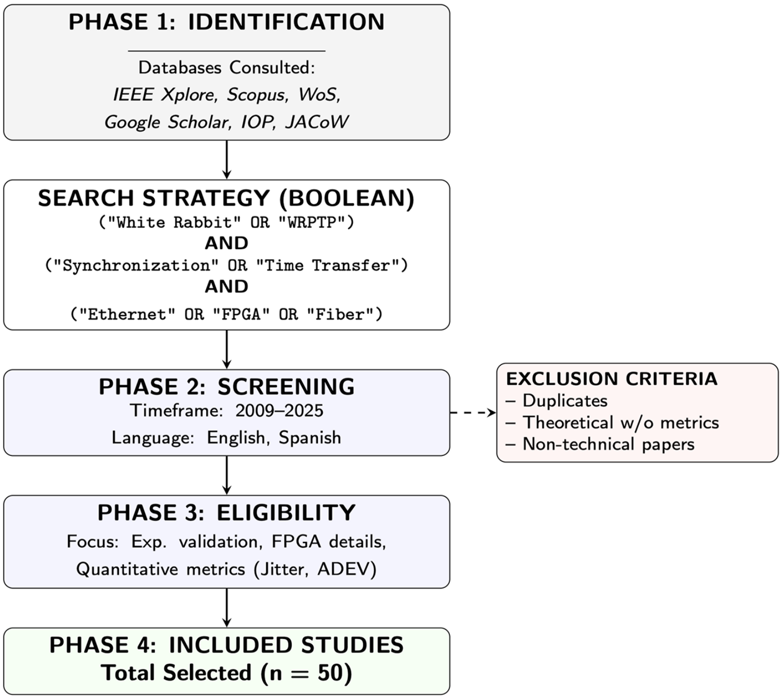

Figure 2. Survey methodology and study selection workflow for the White Rabbit literature, including databases consulted, screening criteria and final number of included studies.

(ii) describe FPGA-based WR implementations or hardware platforms;
(iii) analyze applications of WR in scientific or industrial domains (e.g., particle physics, smart grids, radar, 5G); or
(iv) provide architectural or algorithmic enhancements to WR, such as improved clock recovery, delay compensation, or monitoring.

Those papers that only mentioned WR tangentially without reporting quantitative results were excluded, as were non-peer-reviewed materials lacking sufficient technical detail for meaningful comparison.

Data extraction and normalization

For each selected paper, we extracted: (i) link distance, (ii) main performance metrics (e.g., RMS accuracy, MTIE, TDEV, ADEV, phase error), (iii) hardware platform (e.g., specific FPGA family, oscillators), and (iv) key experimental conditions when available (such as fibre type, temperature range, and traffic configuration).

These data were then organized into summary tables to enable a qualitative comparison of performance across different use cases and hardware implementations. When the original authors did not explicitly report a given parameter, it is either left blank or qualitatively described in the corresponding table entry.

This methodology aims to provide a comprehensive and technically consistent view of the state of the art in WR-based synchronization, while making explicit the limitations imposed by heterogeneous reporting practices across the literature.

WHITE RABBIT PROJECT

The WR project employs DDMTD [6], which converts a high-frequency phase shift into a low-frequency domain, providing a time-multiplication effect. When implemented correctly, the time multiplication system enables the measurement of short-period frequency stability for two synchronous or quasi-synchronous oscillators with ultra-low background noise. This technique is commonly used to measure phase differences between two clock signals with very similar frequencies. It enables the cancellation of common phase noise. The DDMTD proposed in [6] is illustrated in Figure 3.

The system has two D-type flip-flops that act as multipliers. The input of one flip-flop is connected to the timing signal, clk_1, while the second flip-flop is connected to the second timing signal, clk_2. The clock for both flip-flop inputs is connected to a common clock source. This source's frequency is offset by a few Hz from the clk_1 and clk_2 clocks to provide two beat-note frequencies. This flip-flop clock signal is called clk_{dmtd}. The absolute frequency difference between clk_1 and clk_{dmtd} represents the system's beat frequency, clk_{beat}, which governs the overall performance of the DMTD.

The WR system is illustrated in Figure 4. The DDMTD is part of the WR ecosystem [6], where

Source: Based on [6].

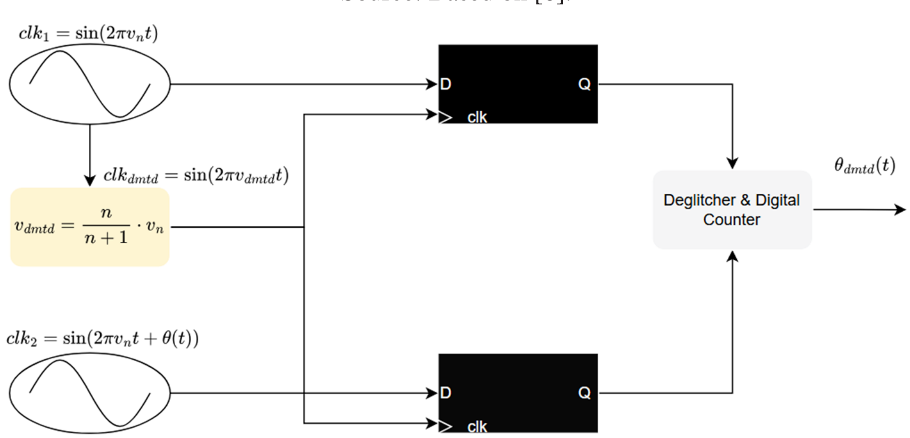

Figure 3. DDMTD in the WR System.

Source: Based on [6].

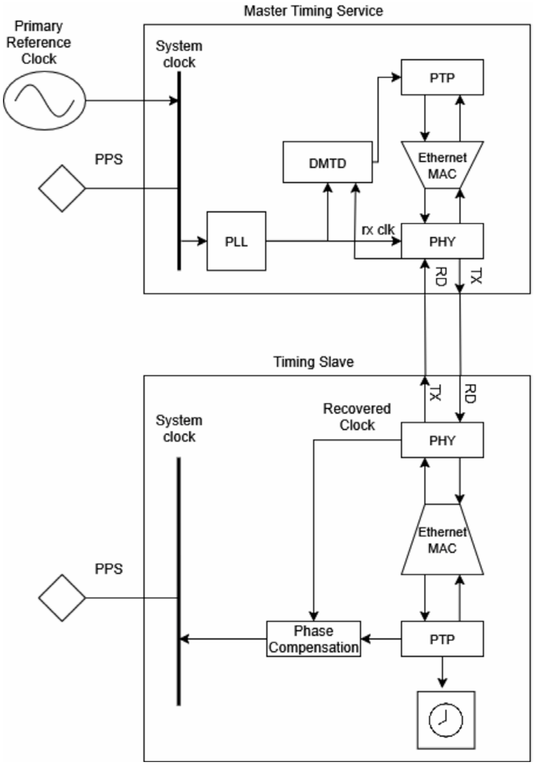

Figure 4. WR System with DDMTD Implemented.

it measures the phase difference between the recovered clock and the transmitter's clock. It then applies compensation in one of two ways: either it directly adjusts the phase of the transmitter's clock, or it informs the IEEE 1588 stack of the correction applied to that clock. The result is a clock with sub-nanosecond accuracy and minimal accumulated phase error between nodes.

ADVANCES IN SYNCHRONIZATION

The following section highlights recent research findings and technological developments that demonstrate the effectiveness and improvements achieved with WR-based synchronization systems.

The implementation of the WR-PTP protocol in long-distance fiber-optic links is analyzed [14], achieving a precision of ±2 ns over a 950 km link in Finland and ±5 ns with an eight ns uncertainty over a 274 km bidirectional link in the Netherlands. These results compare favorably with GPS-PPP, as they mitigate the challenges posed by delay asymmetry due to chromatic dispersion through precise calibration.

Additionally, the use of WR for precise time and frequency dissemination in long-distance telecommunications networks is explored [15]. Two configurations were compared: one using a single fiber with two wavelengths and the other using two fibers with a single wavelength. Both configurations achieved a minimum time deviation of 1 ps over 1000 seconds and an Allan deviation of 10^{-15} over 10,000 seconds.

A study on time and frequency transfer using WR technology over a cascaded 500 km optical fiber link is presented [16]. The experiment utilized a unidirectional link with commercial WR equipment and enhanced software parameters. The results demonstrated frequency transfer stability of 2×10^{-15} over an integration time of 200,000 s, and time transfer stability reaching a minimum of 1.2 ps at 20 s of integration.

Moreover, the implementation of a Kalman filter algorithm to improve time synchronization in WR networks is described [17]. Simulations show that the Kalman filter reduces the master-slave clock offset from 330.62 ns to 13.93 ns and the frequency deviation from 1.84×10^{-7} to 2.25×10^{-9}, thus enhancing precision and accelerating synchronization convergence.

Furthermore, time and frequency transfer using WR over 71-76 GHz millimeter-wave carriers is explored [18]. This study demonstrates that WR can achieve an Allan deviation (ADEV) of 7.1×10^{-12} at 1 second and a Time Deviation (TDEV) of less than 10 ps at 10,000 seconds. After 4 seconds of averaging, the precision is sufficient to transfer a cesium atomic frequency standard.

A new WR architecture for implementation in 10 Gigabit Ethernet (GbE) networks is presented [19]. Experimental results showed that the proposed solution maintains synchronization precision similar to 1 GbE WR devices, with improved frequency stability of 4.0×10^{-12} for the master and 4.7×10^{-12} for the slave in the 10 GbE design, compared to 4.9×10^{-12} and 6.4×10^{-12}, respectively, in the 1 GbE design. Additionally, synchronization accuracy of less than 103 ps was achieved according to the

MTIE metric. Regarding data bandwidth, the 10 GbE implementation reached 91.2% of the total link capacity, with a latency of 198-205 ns and a deviation of 2.59 ns, regardless of data utilization.

An experimental study investigated the precise and accurate transfer of time over a fiber optic link using white rabbit (WR) technology [20]. The findings indicated that time transfer accuracy remained within 50 ps of the primary clock over an extend period, and the link stability achieved a value of 10^{-16} with a 2,000-second integration time.

The implementation of the White Rabbit (WR) system for precise time and frequency transfer within the CESNET infrastructure in the Czech Republic is explored [21]. The WR technology, which combines bidirectional communication over a single fiber, SyncE, and PTP, enables accuracy better than 1 ns. Laboratory tests showed that the Maximum Time Interval Error (MTIE) was below 1 ns in all configurations, and the TDEV remained within expected values.

The improvement in stability and scalability of WR synchronization using P2P transparent clocks and hybrid clocks is analyzed [22] in daisy-chain configurations of up to 19 nodes, were both P2P transparent clocks and P2P hybrid clocks maintained synchronization accuracy below 1 ns.

A scalable network using WRPTP over a 200 km DWDM optical fiber network is described [23]. The setup included five WR switches: one grandmaster (GM), three boundary clocks (BC), and one slave node (SL). They achieved nanosecond-level accuracy, with an initial round-trip offset of less than 0.5 ns, and maintained it within 2 ns over a year. Redundant link tests ensured synchronization within specified limits. Using a rubidium oscillator, the hold-over function showed a clock drift of less than 50 ns over one hour.

The precise and secure transfer of time and frequency signals using WR technology over a 30 km optical fiber link at the CSIR-National Physical Laboratory in India was investigated [24]. Using WRLite nodes and an optical feedback loop, they maintained time synchronization uncertainty within 150 ps, even under temperature variations of up to 35 ºC. The frequency stability of the time transfer link reached a value of 10^{-15} over several hours of integration, highlighting WR's capability to provide precise, stable time transfer under variable environmental conditions.

The WR protocol was implemented in a time-division multiplexing passive optical network (TDM-PON) system [25]. The study addresses two main technical challenges: rapid clock and data recovery (CDR) at the receiver and precise time slots alignments in a high-bandwidth network environment. Experimental results show that the CDR time is reduced to 38.6 ns, and time synchronization accuracy is achieved with an average of 341 ps, with a best recorded accuracy being 143 ps.

Time transmission in free space using WR is presented [26]. In this research, a new transceiver-type optical module was designed to improve the transmission power. Tests were conducted at 50 meters, yielding a result of 20.5 ps over 24-hours. The TDEV, which measures stability, was 14.3 ps at 1 second and dropped to 3.9 ps at 20,000 seconds [26].

In Switzerland, an unoccupied network –known as dark channels– in the L-band of a telecommunications fiber optic network, spanning approximately 500 km, was used [27]. The results indicated an accuracy of +28 ± 289 ps for the first loop and +84 ± 415 ps for the second loop [27].

A summary of this section is presented in Table 1. This table displays the main results from the consulted references, along with the test distance (if available), the level of precision, stability, and a brief description.

WHITE RABBIT SYSTEMS BASED ON FPGA

The following section provides an overview of various implementations of WR systems utilizing FPGA technology, highlighting key hardware components, measured synchronization times, distances, and application areas.

The creation of a compact and autonomous WR node based on the FPGA Mezzanine Card (FMC) standard is presented [28]. This node is an efficient solution for sub-nanosecond time distribution and control in distributed real-time applications. Test results show synchronization of 65 ps (RMS) and data throughput of over 0.3 Gbps. The WR technology

Table 1. Summary of WR studies results.

Reference	Distance [km]	Accuracy / time error (metric, value)	Stability (metric, value)	Experimental conditions / notes
[14]	950	± 2 ns (absolute time error)	– (not reported)	Long-haul fibre link in Finland; WR-PTP time transfer
[14]	2×137	± 5 ns (absolute time error)	8 ns (time-transfer uncertainty)	Bidirectional fibre link in the Netherlands
[15]	25	< 1 ps (minimum time deviation, TDEV)	≈ 1×10^-15 (Allan deviation at 10 000 s)	Two fibre configurations (dual-λ single fibre vs single-λ dual fibre)
[16]	500	1.2 ps (minimum time deviation, TDEV at 20 s)	2×10^{-15} (Allan deviation at 200 000 s)	Cascaded long-haul WR link
[17]	–	13.93 ns (residual master-slave clock offset with Kalman)	2.25×10^{-9} (frequency deviation)	Kalman-filter-based synchronization algorithm
[18]	1	< 10 ps (time deviation, TDEV)	7.1×10^{-12} (Allan deviation at 10 000 s)	WR over 71-76 GHz millimetre-wave link
[19]	120	< 103 ps (MTIE, synchronization accuracy)	≈ 4×10^{-12} (Allan deviation)	10 GbE WR; latency 198-205 ns; jitter 2.59 ns
[20]	0.4	< 50 ps (time error vs primary reference clock)	≈ 1×10^{-16} (Allan deviation at 2 000 s)	400 m fibre link; ultra-stable reference clock
[21]	17	< 1 ns (Maximum Time Interval Error, all setups)	≈ 80 ps (TDEV at 10^4 s)	CESNET infrastructure; SyncE + PTP + WR
[22]	–	< 1 ns (synchronization accuracy)	– (not reported)	Peer-to-peer transparent clocks in daisy-chain topology
[23]	200	< 50 ns (time error; round-trip offset)	≈ 1×10^{-11} (Allan deviation at 4 000 s)	Scalable WRPTP over DWDM fibre; redundancy and hold-over tests
[24]	30	150 ps (time-transfer uncertainty)	≈ 1×10^{-15} (Allan deviation)	WRLite nodes with optical feedback; temperature variation up to 35 °C
[25]	20	341 ps (average time error; best 143 ps)	3.61×10^{-12} (Allan deviation)	WR in TDM-PON; fast CDR and time-slot alignment
[26]	0.05	20.5 ps (time error over 24 h)	3.9 ps (TDEV at 20 000 s)	Free-space WR link of 50 m; high-power optical transceiver
[27]	500	+28/+84 ps (mean time offset vs UTC(CH), loops 1/2)	±289/±415 ps (time uncertainty, loops 1/2)	Dark-channel WR time dissemination over 500 km telecom fibre

combines data transmission and time control over common media, making it particularly useful for projects such as LHAASO and CJPL.

Similarly, the development of a distributed time-to-digital conversion (TDC) system using WR technology and an Altera EP2C35F484C6 FPGA for the LHAASO project is described [29]. This system requires precise synchronization to capture the arrival times of high-energy particles. It uses compact WR nodes (CUTE-WR) that provide a synchronized 125 MHz clock and time references. TDC nodes with 32-channel FPGA-based modules achieve temporal accuracy better than 30 ps. Tests show synchronization with a standard deviation of 20 ps and an accuracy of 50 ps, while phase difference measurements exhibit a standard deviation of 29.2 ps.

The use of WR technology for time synchronization in the Tunka-HiSCORE experiment, a gamma-ray and cosmic-ray detector in Siberia, is described [30]. The system uses WR nodes and Gigabit Ethernet switches to achieve sub-nanosecond synchronization accuracy. The main hardware includes the SPEC card, equipped with a Spartan-6 FPGA, and the FMC-DIO5Ch card for digital inputs and outputs. Laboratory tests demonstrated a clock accuracy better than 0.2 ns and jitter less than 60 ps. Field tests with the HiSCORE-28 array confirmed a synchronization accuracy better than 0.3 ns.

Additionally, the integration of an FPGA-based TDC (Altera EP2C35F484C6) within a WR node is detailed in [31], achieving high-precision time synchronization and measurement. The system uses WR nodes and switches that distribute a low-jitter, synchronized clock from a custom VCXO and PLL. The hardware includes the SPEC card with a Spartan-6 FPGA for data management and synchronization. Tests demonstrated a standard deviation of 50 ps between two distributed TDCs and an RMS accuracy of hundreds of picoseconds. This integrated system facilitates clock distribution, synchronization, TDC calibration, and data transmission through a single fiber connection.

WR technology has been applied in data acquisition (DAQ) systems for scientific infrastructure and power networks [32]. Using hardware like 14-bit 62.5 MHz FMC ADC cards, a WR-ZEN development board equipped with a Xilinx Zynq-7015 SoC, and a WR switch, assessments conducted with 2-meter and 5-kilometer optical fibers achieved sub-nanosecond synchronization precision. The results showed an average error of 1.437 nanoseconds and a standard deviation of 4.575 nanoseconds, indicating high accuracy and stability in GPS-denied environments.

The implementation of multi-channel TDC units on SPEC (Spartan-6 FPGA) and ZEN (Zynq FPGA) platforms is described [33]. These TDC units, with resolutions of 1 ns and 0.25 ns, were developed to ensure the sub-nanosecond time synchronization required in astroparticle experiments, such as the TAIGA project for gamma-ray and cosmic-ray detection. The system uses WR nodes to distribute a high-precision clock from a central master to distributed nodes. Each node can use the DIO-5Ch card to provide up to 5 TDC channels.

In another study, a clock and data recovery (CDR) technique that achieves a lock time of less than 625 ps for 25.6 Gb/s transmissions is described [34]. Using Xilinx VCU108 FPGAs to emulate data center nodes, data transmissions is carried out through via an optical switch and 2 km of optical fiber. The phase-caching technique maintains the lock time below 625 ps even with temperature variations up to 0.11 ºC/s. In six-hour tests, error-free transmissions were achieved, receiving more than 3.4×10^{14} error-free bits.

The performance limits of WR clock synchronization implemented with a Xilinx Virtex-6 (XC6VLX240T) FPGA are analyzed [35]. The study focuses on the digital dual-mixer time difference (DDMTD) phase detector and Gigabit Ethernet transceiver. The DDMTD in the WR Switch (WRS) demonstrate a modified Allan deviation of 4×10^{-13} at τ=1 s. The Gigabit Ethernet transceiver exhibits a flicker phase noise of -100 dBc at 1 Hz.

In contrast, the implementation of WR for precise synchronization in radiofrequency positioning systems is examined [36]. Using the Intel Cyclone 10 GX FPGA hardware platform, the study achieved sub-nanosecond synchronization with timestamping accuracy no worse than 100 ps.

Likewise, a sub-nanosecond synchronization technique using a Xilinx Kintex-7 FPGA is presented [37]. It implements the WR protocol directly on the FPGA, achieving tens of picoseconds of accuracy without external clock circuits. Tests showed a synchronization standard deviation of -104.32 ps and a variation of ±26.92 ps over 17 hours. Additionally, across 50 restarts, the synchronization variation ranged from -150 ps to 260 ps.

A timestamping mechanism known as Precise Network Time Monitoring (PNTM) was implemented on an FPGA and combined with the WR protocol [38]. This configuration achieves picosecond-level precision. The hardware used includes WR-compliant devices and a Xilinx Zynq FPGA for PNTM implementation. Measurements demonstrated single-digit picosecond precision, with a standard deviation σts of 5 ps. Experiments conducted over fiber links of up to 50 km confirmed the system's high accuracy and stability.

The stability of clock recovery in distributed power electronics networks using a phase-locked loop (PLL) and the WR protocol is analyzed [39]. They used a customized power electronics building block (PEBB) controller with a Xilinx Zynq-7030 SoC, incorporating a DAC and a voltage-controlled crystal oscillator (VCXO). The study achieved sub-nanosecond synchronization accuracy, with a local clock frequency of 125 MHz and synchronization within ±0.5 ns across a communication network with one primary and one secondary PEBB controller.

The Zynq-embedded node for the Cherenkov Telescope Array (ZEN-CTA) has been developed to integrate WR synchronization, enabling uniform clock and trigger time-stamping for small-sized telescopes [40]. The hardware setup includes a Xilinx Zynq-7015 SoC, 14-bit 62.5 MHz FMC ADC cards, and a WR switch. Using WR-assisted time-to-digital converters (TDCs), the system achieves a time-stamping precision with a standard deviation of 90 ps and supports event rates up to 7.14 MHz.

A WR time-synchronization system was implemented in high-energy physics experimental devices, as described in [41]. Using a ZYNQ 7045 FPGA, the system provides sub-nanosecond clock distribution across a network spanning several kilometers. Experimental results indicate that node synchronization exhibits an average deviation of 250 ps and a standard deviation of 23.12 ps.

A high-precision time-synchronization system based on WR technology is implemented [42]. Employing a Xilinx Kintex-7 FPGA, the system achieves synchronization errors below 1 ns and an accuracy exceeding 100 ps across transmission distances up to 10 km. The delay compensation resolution is finely tuned to 20 ps.

An expansion board designed to implement the WR protocol on an FPGA is described in detailed [43]. The hardware incorporated oscillators at 125 MHz and 124.992 MHz, as well as clock generators powered by 25 MHz oscillators. Simulations results indicate total jitter of 1.56 ps and 1.74 ps. Additional features include EEPROM, a pulse-per-second (PPS) adapter, and a USB UART. Testing ensure a characteristic impedance of 100 Ω for differential lines and 50 Ω for non-differential lines, thereby validating the required sub-nanosecond precision.

Table 2 provides a summary of this section, listing the references, the specific FPGA hardware utilized, the measured values reported in each study, the distance, and the application of WR.

APPLICATIONS

The WR project provides precise time synchronization across various technologies. The following section outlines relevant applications of WR.

Smart grid

Phasor Measurement Units (PMU) facilitate frequency synchronization within electrical grids. The integration of WR in PMUs is studied [44], where a PMU-WR is compared with a GPS-based PMU. The PMU-WR shows a phase-error standard deviation of 8.16 µrad at 50 Hz, compared with 7.94 µrad for GPS. The mean relative phase error is 9.96 µrad with a standard deviation of 7.99 µrad, compared to 11.65 µrad and 8.74 µrad for GPS.

A subsequent study assesses the WR protocol for time synchronization in PMUs [45], demonstrating that WR archieves sub-nanosecond synchronization accuracy, outperforming GPS and the Precision Time Protocol (PTP). The phase error standard, or PMU-WR, is approximately 8 µrad, compared to 11.3 µrad for GPS and 12.3 µrad for PTP. The Allan deviation for WR is lower than that observed for GPS and PTP. Under non-nominal conditions, PMU-WR sustains high accuracy, with a maximum deviation of 13.93 ns and a frequency deviation of 2.25×10^{-9}.

LHAASO project

The LHAASO project aims to detect galactic cosmic ray sources. The system achieves precise synchronization by distributing time and clock signals via synchronous Ethernet and PTP, using the WR protocol. The development of a sub-nanosecond synchronization system for the LHAASO project, utilizing the WR protocol, is described [46]. Testing with 30 cm, 1 km, and 5 km optical fibers showed standard deviations of 105-115 ps and a peak-to-peak deviation of less than 100 ps. This system enables synchronization of up to 10,000 nodes with sub-nanosecond precision, a capability critical for accurate cosmic-ray detection in LHAASO.

Radar network synchronization

The WR protocol was applied in the NeXtRAD project to enhance radar network synchronization [47]. Using 2-meter and 5-kilometer optical fibers, the system achieved sub-nanosecond precision. The hardware included Fine Delay FMC cards and GPSDO modules synchronized via pulses-per-second (PPS) from the WR system. Tests confirmed high precision and stability, making it viable in GPS-denied environments.

The use of WR for synchronizing radars in GPS-denied environments was examined [48]. The study used Fine Delay FMC cards and WRDO oscillators, synchronized by WR-generated PPS. With 2-meter and 10-kilometer optical fibers, they achieved

Table 2. Summary of WR FPGA implementations.

Reference	FPGA Hardware	Timing performance (metric, value)	Distance [km]	Application/notes
[28]	FMC	65 ps (RMS synchronization error)	1	LHAASO, CJPL - compact autonomous WR node
[29]	Altera EP2C35F484C6	20 ps (TDC bin size), 50 ps (time resolution), 29.2 ps (std dev of time-difference measurements)	1.2	LHAASO - distributed TDC with WR-based timing
[30]	Spartan-6	0.2 ns (mean synchronization error), 60 ps (jitter), 0.3 ns (upper bound of synchronization error)	0.1-0.2	Tunka-HiSCORE - WR-based time sync for Cherenkov array
[31]	Altera EP2C35F484C6	< 50 ps (time-stamping accuracy)	1	Cosmic rays and neutrino experiments – WR TDC integration
[32]	Xilinx Zynq-7015	1.437 ns (mean offset), 4.575 ns (standard deviation)	2–5	Scientific infrastructure – WR-based DAQ in GPS-denied environments
[33]	Spartan-6, Zynq	0.25 ns (synchronization accuracy between nodes)	1	TAIGA - multi-channel TDC on SPEC + DIO-5Ch
[34]	Xilinx VCU108	< 625 ps (timestamping accuracy after CDR)	2	Data centers - WR with high-speed optical CDR; >3.4×10^14 error-free bits
[35]	Xilinx Virtex-6	4×10^-13 (Allan deviation at 1 s), -100 dBc/Hz @ 1 Hz (flicker phase noise of Ethernet transceiver)	10	Performance limits of WR clock synchronization
[36]	Intel Cyclone 10 GX	100 ps (timestamping accuracy, no worse than this)	–	Radio-frequency positioning - precise WR time synchronization
[37]	Xilinx Kintex-7	-104.32 ps (mean offset), ±26.92 ps (standard deviation), -150 to 260 ps (synchronization variation after restarts)	–	Sub-nanosecond synchronization in WR-based systems
[38]	Xilinx Zynq	< 10 ps (time error), 5 ps (standard deviation of time-difference measurements)	50	Fintech and industrial automation - Precise Network Time Monitoring (PNTM) over WR
[39]	Xilinx Zynq-7030	±0.5 ns (maximum time-synchronization error between PEBB controllers)	–	Power electronics - distributed clock recovery in power conversion network
[40]	Xilinx Zynq-7015	90 ps (standard deviation of timestamp differences)	–	Cherenkov Telescope Array - Zynq-embedded WR node for high-rate events
[41]	Zynq-7045	250 ps (average deviation), 23.12 ps (standard deviation)	< 10	Particle physics - WR time synchronization in high-energy experiments
[42]	Xilinx Kintex-7	< 1 ns (overall time error), < 300 ps (jitter), 20 ps (delay-compensation resolution)	10	5G and astronomy - WR synchronization with fine delay tuning
[43]	–	1.56 ps (RMS time-difference), 1.74 ps (standard deviation)	–	Expansion board for WR on FMC - sub-nanosecond validation on differential lines

sub-nanosecond precision, a standard deviation of 0.119 ns, and an Allan deviation of 1.96×10^{-13} at 1 second for a 100 MHz input.

RF systems and 5G networks

A fully digital low-level RF system synchronized with the WR for the IFMIF accelerator prototype was developed [49]. Using Xilinx Virtex-6 FPGA-based hardware, ADC and DAC cards, and WR switches, tests achieved sub-nanosecond synchronization precision, with an RMS phase variation of 0.08, and an RMS amplitude variation of 0.0051%.

WR was investigated for precise time synchronization in 5G URLLC networks for factory automation [50]. Using an FPGA, combining PTP, Synchronous Ethernet (SyncE), and DDMTD, sub-nanosecond synchronization precision was achieved in line-of-sight (LOS) conditions.

DISCUSSION

This study provides a comprehensive overview of the White Rabbit (WR) project, emphasizing its evolution, architecture, and substantial contributions to high-precision time and clock synchronization. A systematic literature review identifies key advances in protocol configurations, synchronization performance, FPGA-based hardware implementations, and applications in various scientific and technological fields.

One of WR's major strengths is its exceptional accuracy and stability, which clearly differentiate it from conventional IEEE 1588 PTP solutions. Recent research has shown that WR can achieve picosecond- and nanosecond-level accuracy over long-distance fibre links. For instance, a precision of ±2 ns was reported over a 950 km optical fibre link in Finland, and ±5 ns over a 274 km bidirectional link in the Netherlands [14]. Additionally, WR has demonstrated time-transfer stability of 10^{-16} with an integration time of 2,000 seconds [20], making it suitable for demanding synchronisation scenarios. Even in field conditions, such as the Tunka-HiSCORE experiment, sub-nanosecond synchronization accuracy better than 0.3 ns has been confirmed [30].

WR's versatility is reflected in its wide range of applications. Within smart grids, WR has been successfully integrated into Phasor Measurement Units (PMUs), outperforming GPS and PTP in synchronization accuracy. The PMU-WR system achieved a phase-error standard deviation of approximately 8 μrad, compared to 11.3 μrad for GPS and 12.3 μrad for PTP [44], [45]. In high-energy physics, projects such as LHAASO and TAIGA rely on WR's sub-nanosecond precision to synchronize thousands of nodes for accurate particle and cosmic-ray detection [29], [33], [46]. Additionally, WR has proven reliable in GPS-denied environments such as radar networks, where standard deviations as low as 0.119 ns have been reported [48]. WR has also been applied in radio-frequency systems for particle accelerators [49] and in 5G networks suppporting factory automation [50].

FPGA-based implementations have been essential to WR's success. Hardware platforms such as Xilinx Zynq, Kintex-7, Virtex-6, and Spartan-6 are frequently used to manage protocol logic and ensure precise timing [30], [31], [35], [37], [42]. The development of Time-to-Digital Converter (TDC) units based on FPGAs has enabled timing precision better than 30 ps [29], [33]. Likewise, advanced techniques such as the Digital Dual Mixer Time Difference (DDMTD) phase detector [6], Kalman-filter-based algorithms to improve synchronization convergence [17], and monitoring mechanisms such as Precise Network Time Monitoring (PNTM), which enable picosecond-level packet timestamping [38], have been explored and implemented.

Comparison with industrial synchronization standards

Beyond conventional IEEE 1588 PTP, several industrial standards define profiles and performance targets for time transfer in telecom and automation systems. Examples include IEEE 802.1AS for Time-Sensitive Networking (TSN) [51], ITU-T G.827x time and phase profiles for mobile networks [52], and IEC 61850-9-3 time distribution in electrical substations [53]. These frameworks generally target synchronization accuracy at sub-microsecond to low-microsecond under optimal engineered conditions, using boundary and transparent clocks to mitigate jitter and asymmetry.

In contrast, the reviewed WR deployments routinely achieve sub-nanosecond time transfer over tens to hundreds of kilometers, with Allan deviations in the 10^{-15}–10^{-16} range for frequency transfer [14]-[16], [20], [24]. WR can therefore be viewed as a complementary technology: it is most valuable in scenarios where IEEE 802.1AS-, ITU-T G.827x- or IEC 61850-based solutions are not sufficient, such as large-scale physics experiments, metrology links, or demanding smart-grid and radar applications. Nevertheless, the coexistence and interoperability of WR with these standards in hybrid networks remains an open topic and a relevant direction for future work.

Although WR has achieved significant advancements, it continues to face challenges that remain the focus of ongoing research . Temperature sensitivity has been identified as a critical concern. Nevertheless, Neelam, Olaniya, Kushwah, and Panja [24] demonstrated that WR can maintain synchronization uncertainty within 150 ps even under 35 ºC fluctuations, due to PTP compensation and the use of single-mode optical fibres. Implementation in complex networks, such as long-distance Dense Wavelength Division Multiplexing (DWDM) links, presents an additional challenge, as these configurations require precise calibration to mitigate delay asymmetry [23].

Resilience and security considerations

Most of the reviewed WR deployments are assessed under controlled or quasi-ideal conditions. However, real-world infrastructures must address failures, cascaded topologies and intentional attacks. From a resilience perspective, WR networks must consider scenarios including grandmaster clock failures, extended chains of boundary or transparent clocks, traffic congestion and fiber impairments. Although several studies demonstrate stable operation over hundreds of kilometers and multi-hop links [16], [21], [23], a systematic analysis of failover strategies, hold-over performance and re-synchronization transients in large-scale WR networks remains limited in the literature.

Security is another critical aspect. Since WR builds on PTP, it inherits PTP's known vulnerabilities, including delay attacks, spoofed synchronization messages, and replay attacks on Sync and Follow_Up packets. For safety-critical applications, including smart grids, 5G fronthaul or radar networks, future WR deployments should incorporate cryptographic protection, access control, and anomaly-detection mechanisms specifically design for timing traffic. Integrating WR's sub-nanosecond performance with robust security and fault-tolerance measures remains an open research challenge and a fundamental requirement for widespread industrial adoption.

In summary, White Rabbit is a robust, scalable solution for systems requiring ultra-high-precision synchronization. White Rabbit's adaptability across hardware platforms, demonstrated performance under varied conditions, and integration with emerging technologies position WR as a next-generation reference for time and frequency distribution in critical infrastructures.

Future research should address enhanced delay-compensation optimization, the development of more compact and power-efficient systems, integration with established industrial standards, and the definition of harmonised reporting practices for performance metrics (e.g., time error, TDEV, ADEV, MTIE). These measures would facilitate direct cross-comparison between WR deployments.

CONCLUSION

The WR project has proven to be a versatile and powerful tool for achieving sub-nanosecond accuracy in time and clock synchronization across a varied range of applications, including scientific research, telecommunications, and industrial automation. Continuous advancements, such as improvements in the WRPTP and novel synchronization methods, highlight its importance in modern synchronization technologies. WR's integration with FPGA and other digital systems, along with its resilience to environmental conditions, reinforces its status as a leading solution for time and frequency distribution. In summary, White Rabbit significantly enhances synchronization accuracy and opens new possibilities for advanced synchronization systems in multiple technological domains.

Regarding future work, several research and development directions remain open. First, further optimization and experimental validation of delay-compensation techniques are needed under more challenging conditions, including dense DWDM networks, extreme temperature variations, and highly loaded links. Second, there is growing interest in more compact, power-efficient, and cost-effective WR nodes that can be embedded in edge and industrial devices while preserving sub-nanosecond performance. Third, integrating WR with security and resilience mechanisms –such as cryptographic protection, access control, and timing traffic anomaly detection– will be essential for safety-critical deployments in smart grids, 5G fronthaul, and radar networks. Finally, defining harmonised benchmarking and reporting practices for performance metrics (e.g., time error, TDEV, ADEV, MTIE) and sharing open datasets would greatly facilitate cross-comparison between WR deployments and accelerate its adoption in new application domains.

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