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TOPICAL REVIEW

Enhancing Time Synchronization in Smart Grid With White Rabbit: Theory, Architecture, and Challenges

YU LIU[1], (Graduate Student Member, IEEE), KAZI ISHRAK AHMED[1], NAGA LAKSHMI THOTAKURA[1], JIAHUI YANG[1], YURU WU[1,2], HAOZONG WANG[1], BIAO SUN[1], WEN WANG[1], YONGXIN ZHANG[1], AND YILU LIU[1,2], (Life Fellow, IEEE)
[1]The University of Tennessee at Knoxville, Knoxville, TN 37996, USA
[2]Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA

Corresponding author: Kazi Ishrak Ahmed (kahmed7@vols.utk.edu)

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ABSTRACT The smart grid aims to provide economically efficient and sustainable power to consumers with high quality and security. However, the increasing integration of distributed renewable energy sources presents challenges for smart grid protection and control systems. To enhance smart grid operations, this article introduces White Rabbit (WR) as a more precise and accurate time synchronization technique. To explore White Rabbit's potential applications in the smart grid, this study first explains existing time synchronization techniques and their limitations, followed by an analysis of the role and importance of time synchronization in smart grids. A comprehensive survey is then conducted, covering the theories, principles, implementations, performances, and existing application cases of White Rabbit. The findings suggest that White Rabbit is a promising technique for smart grid deployment. However, several challenges remain on the path to large-scale implementation. These challenges are analyzed in detail, highlighting key areas for future research.

INDEX TERMS Application, challenge, performance, smart grid, time synchronization, white rabbit.

I. INTRODUCTION

The smart grid, as a precise and complex system, relies on a wide range of devices and platforms to ensure secure and reliable operation [1]. These applications, distributed across various locations, are interconnected and require synchronization to enable effective monitoring, protection, and control [2], [3]. A fundamental prerequisite for achieving this functionality is the precise synchronization of time signals across all applications, ensuring seamless coordination and operational efficiency throughout the grid [4].

A time synchronization system continuously distributes time signals to every node in the network. Its performance is evaluated based on two critical factors: reliability and accuracy [5]. The system must meet the stringent time requirements of various applications, which range from millisecond to microsecond precision [6], depending on the specific demands of the smart grid. Additionally, it must remain resilient to interference, maintaining synchronization even under challenging conditions [7].

The time synchronization technologies currently employed in the smart grid face significant limitations, including signal loss, low accuracy, and vulnerability to attacks [8] which can even lead to wide-area outages [9].The 2016 GPS failure, which caused timing signals to be off by 13 microseconds, showed how risky it is to rely only on GPS. [10]. The North American blackout on 14 August 2003 resulted in approximately 63 GW load lost which was due to inconsistent timestamps. With the evolution of the smart grid, driven by advancements such as electronic devices, microgrids,

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and distributed renewable generations, addressing these challenges becomes imperative [11].To meet future demands, the grid must develop advanced capabilities to monitor and forecast conditions, plan strategically, learn from operational data, interpret complex system behaviors, exchange insights across regions, schedule operations effectively, and execute timely, informed decisions [12].

With the evolution of smart grids into increasingly complex and interconnected systems [13], and the development of some emerging timing techniques, such as the pulsar-based timing system [14], the demand for highly accurate and reliable time synchronization technique has increased. White Rabbit, a protocol developed at the European Organization for Nuclear Research (CERN), has emerged as a promising solution for providing sub-nanosecond time accuracy through a combination of precision time protocol (PTP) and Synchronous Ethernet (SyncE) [15]. WR's high accuracy and fixed-latency data transfer make it particularly well-suited for applications requiring precise timing, such as Phasor Measurement Units (PMU), distributed generation, and fault detection within smart grids [16].

However, despite its advantages, implementing WR in smart grid infrastructure presents several theoretical and practical challenges. The protocol's dependence on specialized hardware and fiber optic links limits its flexibility and increases deployment costs [17]. Additionally, the large-scale deployment of WR in geographically dispersed power grids introduces issues related to network segmentation, signal attenuation, and resilience against potential cyber threats [18].

This paper explores the theoretical foundations of WR-based time synchronization in smart grids, examining its unique capabilities and limitations. We also discuss the primary challenges and propose potential directions for future research to enhance WR's applicability in smart grid systems. The main contributions of this paper are:

- A comprehensive summary of key aspects related to time synchronization in smart grid applications, including its role, time requirements, the impact of time inaccuracies, the advantages and limitations of current popular methodologies.
- An in-depth explanation of White Rabbit technology, including its fundamental theories, implementation architecture, and advanced techniques that enhance its performance. This serves as a detailed investigation prior to evaluating its potential application in smart grid systems.
- A broader perspective on the application of WR technology in the smart grid, encompassing the current research status, achievements in application research, and challenges that require further investigation in this field.

The structure of this paper is as follows. Section II reviews the applied time synchronization technology in smart grid. Section III explains the impact of time synchronization error in smart grid. Section IV introduces the WR technology. Section V covers the details of the hardware and software design of white rabbit. Section VI illustrates the factors that will impact synchronization quality. Section VII summarizes the enhancement of WR technology. Section VIII provides the applications and performance of WR in power system. Section IX covers the challenges and future research direction, and Section X is the conclusion.

II. TIME SYNCHRONIZATION TECHNOLOGY REVIEW

Precise and synchronized time signals are essential for a wide range of smart grid applications. It is the backbone to ensure secure and efficient performance within smart grid.

In geographically dispersed power grids, precise time synchronization is critical for aligning local clocks across network nodes. Commonly used methods for achieving this include Global Navigation Satellite Systems (GNSS), Network Time Protocol (NTP), and Precision Time Protocol (PTP). Each of these methods offers specific advantages depending on the requirements for accuracy, reliability, and implementation scale within the grid network.

A. GLOBAL NAVIGATION SATELLITE SYSTEM

GNSS is the most widely used method due to its low cost at the user end and its ability to provide global coverage [19]. As a satellite-based system, GNSS delivers highly accurate time signal continually. A GNSS receiver, connected to an external antenna, determines its three-dimensional position and precise time by processing signals from a minimum of four satellites [10].

GNSS time accuracy can change with different environmental conditions and device sensitivity, but it is typically within 100 nanoseconds [20].

Despite its high accuracy and flexibility, GNSS signals are vulnerable to various disruptions that can compromise their reliability [21]. Signal loss or impairment can occur due to factors such as atmospheric conditions, physical obstructions, or intentional interference like jamming or spoofing [22]. Despite their ease of execution, such attacks can significantly disrupt critical infrastructure [23]. The duration of these interruptions depends on the specific failure mechanism and the resilience of the system in mitigating such issues.

This vulnerability highlights the need for complementary synchronization methods or robust backup systems in critical applications. To safeguard reliability-critical applications amid increasing global positioning system (GPS) dependence, North American Electric Reliability Corporation (NERC) advises organizations to develop a master plan for managing their timing technologies [20].

B. NETWORK TIME PROTOCOL

NTP utilizes user diagram protocol (UDP) to transmit time synchronization messages over data networks [24]. It operates within a hierarchical architecture, where clients periodically exchange messages with NTP servers [25].

By analyzing the timestamps in these messages, clients can estimate both the round-trip delay and the offset of their local clocks [26]. As a software-based, network-dependent synchronization method, NTP is widely accessible and easy to implement.

NTP allows a maximum of 15 stratum levels, as timing accuracy degrades with increasing stratum number. So the node in the lower hierarchy will have lower synchronization precision [26].

Variable factors such as network latency contribute to the degradation of NTP accuracy. While top-tier nodes in the hierarchy can achieve synchronization within a few microseconds, nodes in lower strata may experience accuracy limited to tens of milliseconds [27].

Due to the low accuracy, NTP can only be used to synchronize remote devices to handle noncritical measurements or lower-speed events in power systems, such as weather data or physical security notifications [28].

C. PRECISION TIME PROTOCOL

The IEEE 1588 PTP is an accurate time synchronization approach based on networks as well [29]. PTP time synchronization also operates in a master-slave hierarchy, the master clock receives timing data from a reference source and transmits it to slave clocks via network connections. The slaves synchronize their local clocks using the information contained in these messages [30].

PTP assumes the path delay between two nodes is symmetrical, which is not true in most situations. The asymmetry in propagation time will degrade the accuracy of offset measurements [31]. To improve timing accuracy, hardware timestamping, transparent clocks and boundary clocks are utilized in the topology [31]. With these enhancements, the synchronization accuracy of PTP is typically within 1 microsecond [29].

The performance of PTP can meet the time requirements for most applications in power system, such as protection, control, and monitoring [30]. IEC 61850 standard [32] recommends using PTP for time synchronization at the substation level.

Nonetheless, PTP networks are vulnerable to several types of cyber-attacks, including delay attacks, which can introduce significant timing errors and degrade synchronization precision [33].

With the integration of renewable energy generation and the increasing variability in load demands [34], smart grids are required to manage fast dynamics effectively. This necessitates a higher level of time signal accuracy to ensure efficient control, real-time monitoring, and stable operation of the grid.

III. IMPACTS OF TIME SYNCHRONIZATION INACCURACIES ON SMART GRID

Since the importance of time synchronization has been highlighted, it is worthwhile to examine how time inaccuracies impact the smart grid, particularly their effects on devices and systems that rely on timing signals. Time errors can lead to inaccuracies in monitoring and measurement, potentially affecting the reliability and efficiency of grid operations [35].

Synchronized phasor measurement plays a vital role in the smart grid by enabling effective monitoring, protection, and control [36]. PMUs provide real-time, synchronized measurements of phasors, frequency, and the rate of change of frequency for both voltages and currents [37]. This synchronization is accomplished by simultaneously sampling voltage and current waveforms using precise timing signals [38]. Among the measured quantities, phase data are particularly sensitive to time synchronization accuracy.

The way in which time synchronisation functions are integrated for PMU signal processing and Phasor Data Concentrator data aggregation is shown in Fig. 1.

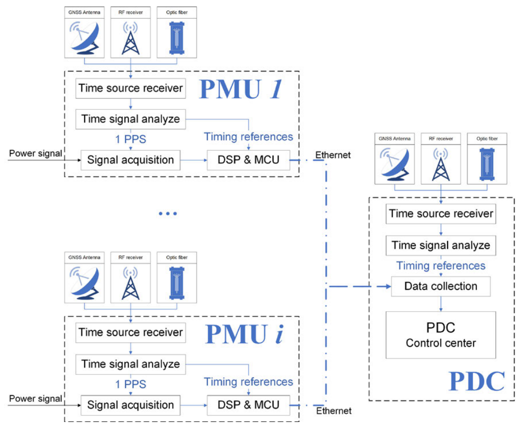

FIGURE 1. Time synchronization functions in PMU application.

The phasor angle error is proportional to time error

$$\epsilon_\theta = 2\pi \times \Delta t \times f \tag{1}$$

where f is the frequency of the system, Δt is the pulse per second (PPS) time signal error. If the PPS time error is 1 μs, the phasor angle error is 3.77 E-4 radians in a 60 Hz system.

Frequency is defined as the derivative of the phase angle in standard frequency measurement algorithms. The frequency error resulting from a timing error is given by:

$$\epsilon_{\text{Freq}} = \frac{d(\epsilon_\theta)}{dt} \tag{2}$$

If the system frequency experiences a significant change, for example in the transient or sub-transient oscillation, leading to a steep slope in the frequency curve, the frequency estimation error will increase [39]. However, such rapid frequency fluctuations are uncommon in power systems. For example, assuming a frequency change rate of 1 Hz/s—highly unusual and unlikely scenario—the frequency measurement error introduced by time synchronization error would be approximately 0.1 μHz. This demonstrates that, even under extreme conditions, the impact of time error on frequency measurements remains minimal.

In contrast to frequency measurement, synchrophasor angle is the most directly affected quantity by time synchronization error [23]. Because the phasor angle differences between grid nodes at the same time are typically very small under normal operating conditions, even a slight error in time synchronization can significantly alter the observed values.

Table 1 presents the variability range of voltage phasor angles at bus nodes in both transmission and distribution systems. For PMUs used in transmission networks, a resolution of a few mrad and an accuracy within ±10 mrad is sufficient for effective monitoring [16].

IEEE C37.118.1-2011 [40] sets a maximum Total Vector Error (TVE) of 1%, which includes both magnitude and phase inaccuracies. To accommodate additional uncertainties, the standard also recommends that timing uncertainty should not exceed 1 μs, corresponding to a phasor angle error of 0.377 mrad.

TABLE 1. Range of variability of the bus voltage phasor angles [16].

System	Grid size	Phasor angles [mrad]
Transmission systems	30 buses	-39.5 ± 47.5
	89 buses (Pegase)	-27 ± 366
	145 buses (IEEE)	-203 ± 901
	1354 bus (Pegase)	-273 ± 508
Distribution systems	37 buses (IEEE)	-2.8 ± 1.6
	69 buses	4.8 ± 11.9
	85 buses	22.0 ± 18.3
	141 buses	-4.2 ± 2.6

For PMUs in distribution systems, the phasor angle accuracy requirements are more stringent because the angle differences between pairs of bus voltage phasors are one to two orders of magnitude smaller than those observed in transmission systems [41]. Consequently, in distribution grids, the resolution and accuracy of synchrophasor angle measurements must exceed 1 mrad and potentially reach the level of 0.1 mrad [16], which requires the time synchronization accuracy to be better than 1 μs.

Similar to PMUs, other devices such as Digital Fault Recorders (DFRs) depend on accurate timing to deliver critical insights into system behavior during fault events. These devices capture voltage and current waveforms by replicating primary power system signals upon detection of external triggers [42]. Any time inaccuracy can lead to errors in voltage and current measurements.

The reliable functioning of differential protection systems relies on precise time synchronization. Insufficient synchronization accuracy can cause phase angle shifts in phasor measurements, potentially leading to elevated differential currents and an increased risk of protection failures [43].

In addition to these, three critical applications directly influenced by timing accuracy are transmission line fault detection and location, disturbance event location, and voltage stability monitoring [44]. In transmission line fault detection and location, the lack of precise timing signals at both ends of a faulty line can impair the system's performance and reduce its accuracy in pinpointing fault locations. Timing inaccuracies also raise the risk of false alarms triggered by fault indicators. In voltage stability monitoring, such errors can delay or suppress voltage instability alarms by overestimating the available power margin, potentially leading to physical damage to generation and distribution equipment [30].

IV. WHITE RABBIT TECHNOLOGY

The WR project was initiated by CERN in 2008 to address the limitations of the General Machine Timing system, with the objective of achieving sub-nanosecond synchronization and deterministic data transmission over Ethernet. Designed to support more than 1,000 nodes and spanning distances of up to 10 km, WR ensures minimal and well-controlled latency in data transfer. The project is a collaborative effort that promotes open-source software and hardware designs, allowing compatibility with components from various manufacturers [45].

The WR Network is built on established IEEE standards [46], incorporating enhancements while maintaining backward compatibility to meet CERN's stringent timing requirements. It functions as a bridged LAN, utilizing Virtual Local Area Networks (VLAN) [47] and leveraging Ethernet-based interconnections between switches and nodes. Time synchronization is achieved through the IEEE 1588-2019 PTP [48].

A typical WR Network architecture consists of WR Nodes and White Rabbit Switch (WRS), interconnected via fiber optic or copper cables, as depicted in Figure 2.

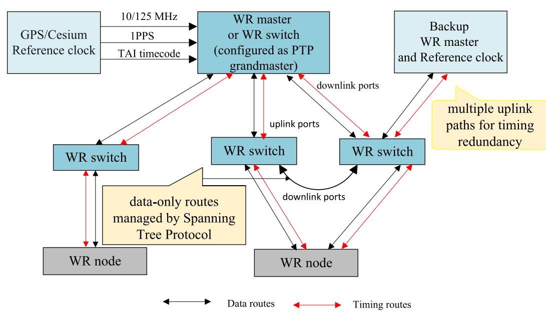

FIGURE 2. The white rabbit network architecture [49].

The system follows a hierarchical synchronization model, ensuring high-precision time distribution. At the top of the hierarchy, the grandmaster switch synchronizes with an absolute reference clock (such as a GPS receiver or a cesium clock), acquiring both a pulse per second (PPS) signal and a 10 MHz frequency reference. Even in the absence of the reference clock, all WR nodes remain synchronized, drifting at the same angular speed, thus maintaining identical relative phases [50].

The WRS plays a crucial role in time synchronization within the WR Network. Initially, it derives the absolute co-ordinated universal time (UTC) using the received time code and PPS signal. Once synchronization is established, the switch transitions to computing time based solely on the 10 MHz signal, rendering the time code and PPS unnecessary. This allows the grandmaster switch to detach from its reference sources, reducing dependency on external synchronization. The accuracy of round-trip time measurements primarily depends on the 10 MHz reference signal. Once synchronized, the grandmaster disseminates timing information across all WR nodes through the WRS. To ensure network stability, restarting the grandmaster switch is recommended only when absolutely necessary and should occur infrequently over the network's operational lifespan [17].

WR can be designed for environmental resilience, ensuring that timing deviations remain below 1 ns, even in the presence of temperature fluctuations and long fiber connections [51]. These characteristics position WR as one of the most precise implementations of IEEE 1588 PTP, making it a critical technology for scientific research, industrial automation, and other time-sensitive applications.

WR timing distribution relies on three core components, each contributing to its sub-nanosecond synchronization capabilities.

A. PRECISION TIME PROTOCOL

White Rabbit's implementation of the Precision Time Protocol (WR-PTP) enhances the IEEE 1588-2008 standard by integrating additional calibration procedures and protocol refinements to achieve sub-nanosecond precision [49]. As illustrated in Figure 3, the synchronization process in standard PTPv2 follows a two-step exchange: the master node transmits a *Sync* message at local time t_1, followed by a *Follow_Up* message carrying the precise timestamp t_1. Upon receiving the Sync message, the slave records the reception time t_2 and subsequently sends a *Delay_Req* at t_3. The master responds with a *Delay_Resp*, including its timestamp t_4. These four timestamps facilitate path-delay and offset calculations, while additional messages provide clock hierarchy details and link calibration data [52].

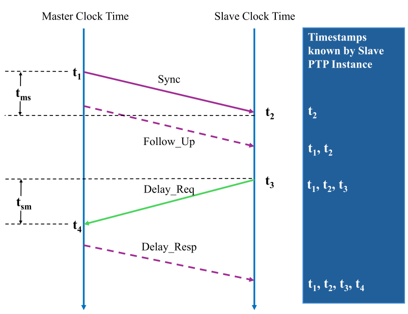

FIGURE 3. Basic PTP timing message exchange [53].

Timestamps taken in a master's local clock domain (t_1) make an ordinary PTP Sync message ambiguous. When the slave subtracts its own receive time, the raw offset is confounded by civil-time discrepancies (different time-zone offsets) and daylight-saving shifts, so two nodes can believe they are synchronized while drifting by whole hours or minutes [49]. WR-PTP resolves this ambiguity in two steps. First, the WR grandmaster locks to an absolute, zone-free Coordinated Universal Time (UTC) / International Atomic Time (TAI) epoch and distributes that epoch (along with PPS + 10 MHz) — so every switch and slave works in the same global time base, isolating the presentation of local time from the measurement of network time [54]. Second, WR-PTP adds Type-Length-Value (TLV) records to PTPv2 management messages, where Type denotes the data (e.g., link-delay calibration), Length specifies its size, and Value contains real-time metrics such as one-way delay and link-asymmetry corrections [55]. Those TLVs allow each slave to correct asymmetric propagation delays in real time before applying its zone offset for display [49].As a result, time zones now only affect the final, human-readable clock face; they no longer interfere with the underlying synchronization, which remains aligned to sub-nanosecond precision across a geographically distributed network.

B. LAYER-1 (L1) SYNTONIZATION

SyncE, as standardized by the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) [56], ensures frequency synchronization, referred to as syntonization, between master and slave devices at the physical layer with minimal overhead [57]. As shown in Fig. 4, the grandmaster node, connected to a high-accuracy reference clock (typically GPS-disciplined), transmits this frequency reference to its network interface timing code, which adjusts the line code frequencies accordingly. Unlike traditional Ethernet, where nodes operate with independent oscillators prone to frequency drift, SyncE continuously broadcasts a stable clock signal through Ethernet line codes [58]. The slave device's clock data recovery (CDR) unit then extracts this reference frequency and synchronizes its local oscillator to it.

By eliminating frequency drift at the physical layer, SyncE ensures that higher level synchronization protocols—such as PTP—only need to compensate for timing offsets rather than frequency variations. This approach establishes the fundamental framework for achieving the sub-nanosecond synchronization accuracy characteristic of WR networks [59].

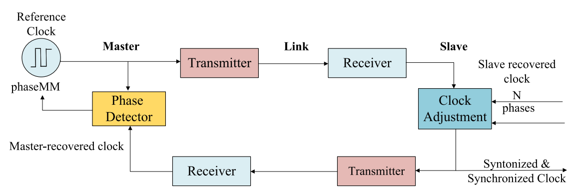

FIGURE 4. WR link connection [60].

C. PRECISE PHASE MEASUREMENT

To maintain sub-nanosecond synchronization, WR continuously monitors and corrects phase offsets between master and slave clocks using Digital Dual Mixer Time Difference (DDMTD) technology [61]. In SyncE, the slave extracts the master's reference frequency from the received line codes and

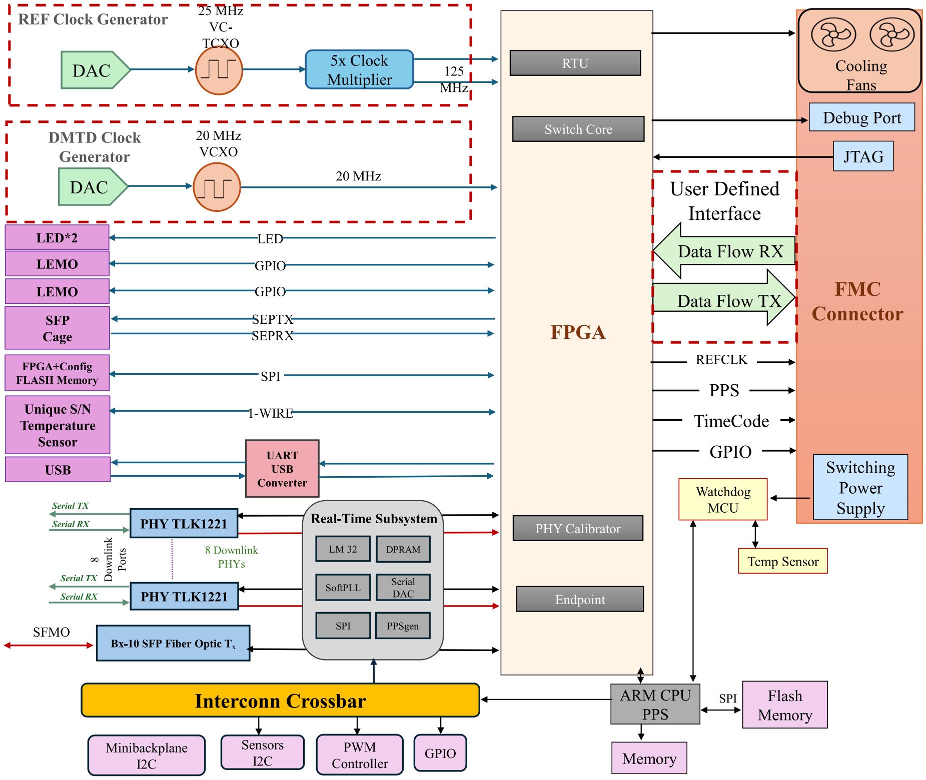

FIGURE 5. WRS hardware scheme.

synchronizes its local oscillator using a phase-locked loop (PLL). This PLL filter eliminates the jitter introduced during clock extraction, achieving an impressive jitter reduction to as low as 2.5 ps [62].

To ensure precise phase alignment, WR implements a closed-loop correction system where the synchronized clock is returned to the master via a feedback path. The DDMTD unit at the master node compares the phase difference between its outgoing reference clock and the clock recovered from the slave. Any detected phase discrepancy is then conveyed to the slave through the correction field in a PTP message, enabling real-time phase adjustments. This dynamic feedback mechanism compensates for latency variations caused by fiber temperature fluctuations and other environmental factors [61].

By continuously measuring and adjusting phase differences, WR ensures high-precision synchronization throughout the network, maintaining offset variations within the sub-nanosecond range. The digital implementation of DDMTD allows for fine-grained phase control while mitigating the drift and inconsistencies typically associated with purely analog systems [63].

As a result, WR-based networks can reliably deliver highly stable and precise time signals, making them ideal for applications that demand stringent timing accuracy, even across large-scale or complex network topologies. A comparison of WR to existing time synchronization technologies is summarized in TABLE 2.

TABLE 2. Comparison of WR to existing time synchronization technologies.

Technology	NTP	PTP	WR
Accuracy	ms	Within 1 μs	sub-ns
Cost	Low	Low	High
Reliability	Vulnerable	More resilient	Most secure

V. HARDWARE AND SOFTWARE ARCHITECTURE OF WHITE RABBIT

The WR technology exemplifies the seamless integration of advanced hardware and software techniques, designed to achieve unparalleled synchronization accuracy in distributed data acquisition systems. WR makes sure there is a single clock domain with sub-nanosecond accuracy by using SyncE, PTP extensions, and DDMTD algorithms.

A. HARDWARE TECHNIQUES

WRS is built on a sophisticated Field Programmable Gate Array (FPGA)-based hardware architecture, ensuring accurate time synchronization and deterministic data switching across a scalable, fault-tolerant network. The primary hardware components include:

1) WHITE RABBIT HARDWARE ARCHITECTURE

The WRS serves as the backbone of WR networks, providing precise time and frequency distribution using SFP fiber-optic transceivers and Gigabit Serial PHY (TLK124) for low-latency, deterministic communication. A physical layer (PHY) calibrator corrects transmission asymmetries, ensuring that all nodes remain in precise synchronization.

The core of WR's synchronization system is an FPGA-based real-time processing unit, which is responsible for timestamping, delay compensation, and clock adjustments [64]. The LM32 soft processor executes time-sensitive calculations, while the Software Phase-Locked Loop (SoftPLL) dynamically compensates for clock drift.

2) REFERENCE CLOCK GENERATION & SYNCHRONIZATION MECHANISMS

WR achieves high-precision synchronization through a closed-loop feedback system, which continuously monitors and corrects phase discrepancies. SoftPLL, combined with SyncE, first ensures frequency stability, allowing higher-level synchronization processes to function efficiently. As illustrated in Figure 5, key components include the Reference Clock Generation module, which generates a stable master clock signal, ensuring synchronization across all network nodes. A CDR unit extracts the reference frequency from received signals, aligning the slave clock with the master clock [65]. DDMTD technology provides highly accurate phase measurements, enabling real-time adjustments to subordinate clocks.

3) DELAY COMPENSATION & REAL-TIME TIMESTAMPING

To mitigate delays caused by fiber-optic transmission, WR utilizes DDMTD for precise fine delay measurement, continuously tracking phase deviations with picosecond-level accuracy. This method facilitates immediate adjustment for discrepancies resulting from fiber length, ambient factors, and temperature variations. WR uses hardware timestamping directly at the PHY layer instead of software timestamping like most PTP-based synchronization does. This cuts down on software-related latency and improves the accuracy of synchronization.

The hardware timestamping approach in WR utilizes a combination of Gigabit Ethernet PHY transceivers and FPGA-based computation. Accurate timestamps are added to the data stream by the PHY transceivers to ensure low-jitter transmission. The FPGA's timestamping engine then processes and improves these signals. Furthermore, the PPS generator integrated into the FPGA offers a remarkably robust timing reference, synchronized across all network nodes. These components collaborate to facilitate real-time monitoring of propagation delays, enabling the network to modify synchronization parameters with sub-nanosecond precision perpetually [66].

4) FAULT-TOLERANT & REDUNDANT HARDWARE ARCHITECTURES

To maintain high availability, WR incorporates redundant clock sources and automatic failover mechanisms. If the primary master clock fails, the system automatically transitions to a backup reference, minimizing disruptions. High-availability seamless Redundancy and the Parallel Redundancy Protocol also make networks more resilient by making sure that they stay in sync even if a link fails [67].

5) EXTERNAL INTERFACES & TIMING SIGNAL DISTRIBUTION

WR's clock distribution system delivers 10 MHz reference signals, PPS, and serial time codes for external synchronization support. Depending on the needs of the application, timing signals are sent through certain FPGA output ports, like the FMC (FPGA Mezzanine Card) connector, SMA coaxial connectors, and GPIO pins. The 10 MHz reference signal and PPS output are generally supplied through SMA connectors, guaranteeing compatibility with external synchronization apparatus such as oscillators, frequency counters, and industrial timing devices. Simultaneously, serial time codes are conveyed using SPI and UART interfaces, enabling integration with Remote Terminal Units (RTUs), industrial sensors, and measurement instruments. Furthermore, Dual-Port RAM (DPRAM) with Direct Memory Access (DMA) facilitates rapid data transfers between the FPGA and external processors, minimizing software-induced latency. This guarantees that external devices obtain synchronized timing signals in real-time with minimal processing cost. By using a mix of SMA, FMC, SPI, and UART ports, WR sends timing signals to all linked systems quickly and accurately, down to the nanosecond level.

B. SOFTWARE METHODOLOGIES

The software framework of the WRS plays a crucial role in enhancing its hardware capabilities, providing essential functionalities for network synchronization, management, and fault recovery. Operating on a real-time Linux platform, it ensures seamless integration with FPGA-based hardware, optimizing both performance and reliability. The key software methodologies include:

1) WHITE RABBIT PROTOCOL IMPLEMENTATION (PPSI)

The PPSi daemon extends the IEEE 1588 PTP with WR-specific enhancements, enabling synchronization at the sub-nanosecond level. It directly interfaces with FPGA components, including the PPS generator and timestamping modules, to maintain highly accurate timing across the entire network.

2) HARDWARE ABSTRACTION AND DRIVER SUPPORT

To streamline interaction between software applications and hardware components, the wrsw_hal daemon functions as an abstraction layer, bridging user space applications with modules such as PHY calibration and routing logic. Additionally, custom drivers like WR-NIC optimize kernel-level operations, ensuring low-latency and efficient communication between the software and network hardware.

3) MONITORING AND MANAGEMENT TOOLS

For remote monitoring and system management, the WRS employs a single network management protocol (SNMP)

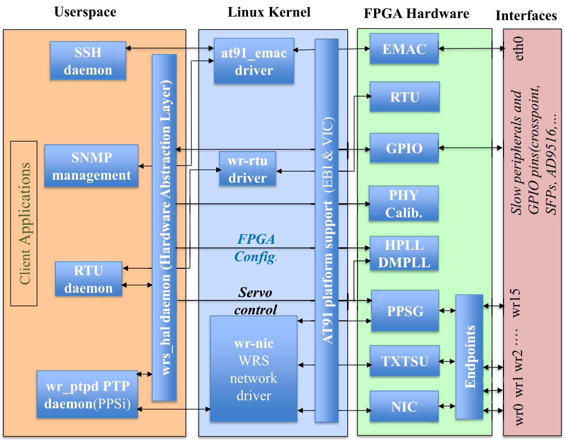

FIGURE 6. **WRS software architecture.**

daemon alongside a web-based interface, allowing administrators to assess synchronization accuracy, jitter levels, and network parameters in real-time. Secure access to the management interface is enforced through SSH-based authentication, enhancing system security.

4) DYNAMIC TOPOLOGY MANAGEMENT AND FAULT TOLERANCE

The WRS software dynamically adapts to network topology changes through Fast Switchover Units, which facilitate smooth transitions between primary and backup clock sources. This ensures continuous synchronization, particularly in mission-critical applications where precise timing is essential.

5) INTEGRATION WITH SOFTWARE-DEFINED NETWORKING

Recent advancements incorporate Software-Defined Networking (SDN) to improve synchronization traffic management and centralize network administration. By dynamically reconfiguring routing paths in response to real-time network conditions, SDN controllers optimize synchronization accuracy and enhance overall system efficiency.

VI. INFLUENTIAL FACTORS ON THE QUALITY OF TIME SYNCHRONIZATION

When evaluating time synchronization quality, several key aspects are considered—namely, precision, accuracy, and stability. Although WR offers high performance, its synchronization quality can be affected by various factors, including environmental conditions and system design parameters.

A. ERROR ACCUMULATION IN MULTI-HOP DEVICE CASCADES

WR could experience performance degradation in multi-hop cascades due to synchronization error accumulation. Reference [45] constructed an experimental system by cascading four WR switches, where an error accumulation trend was demonstrated by the results. Reference [68] further confirmed this through experiments with more cascaded devices. The experiments show that in the traditional WR architecture, when exceeding 10 hops, the offset accuracy surpasses 1 ns, as shown in Fig. 7, and the PPS jitter increases significantly. This indicates that the scalability of the traditional WR system is limited, which presents challenges for its application in large-scale distributed systems such as smart grids.

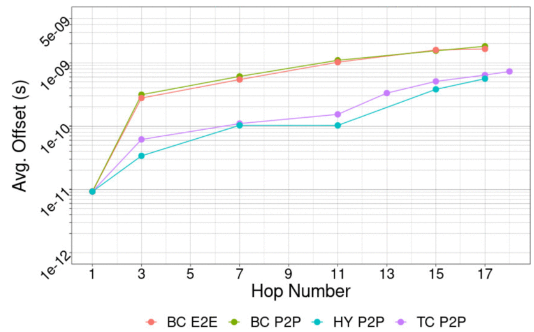

FIGURE 7. **Averaged PPS offset measurements for different clock settings [68].**

B. TEMPERATURE

As a sub-nanosecond-level synchronization solution, the impact of temperature on the WR system must be carefully considered. This influence manifests primarily in two aspects: 1) fixed hardware delay, and 2) variation of the fiber asymmetry coefficient [69]. Although WR systems calibrate and compensate for both factors, these compensations are typically constant (usually based on room temperature conditions). Therefore, during significant temperature fluctuations, errors of tens of picoseconds or even greater may occur [70], affecting synchronization accuracy. Fortunately, experimental results indicate that the impact of temperature changes is linear [71], which provides the possibility for developing online real-time compensation algorithms.

C. TRANSMISSION DISTANCE

Although WR was initially designed as a synchronization solution for distances within 10 km, its application in smart grids often requires a transmission distance far beyond this range. Therefore, some researchers have conducted studies on WR's performance over long distances [72], [73]. In general, ultra-long distances amplify all the aforementioned influencing factors, making temperature variations, chromatic dispersion, and physical link asymmetry more pronounced. When the transmission distance reaches several hundred kilometers, the synchronization accuracy of WR may degrade to the nanosecond level.

D. COMMUNICATION MEDIUM

When applying different communication media, the mechanisms of asymmetry vary, leading to differences in the performance of WR.

For a single-fiber channel, the asymmetry primarily arises from chromatic dispersion, as the uplink and downlink signals use optical beams of different wavelengths. In general, WR can compensate for this asymmetry using the asymmetry parameter α sufficiently. However, when using a dual-fiber channel, the physical lengths and connection points of the two fibers may differ, introducing additional asymmetry [72].

WR can also be applied in wireless communication, where asymmetry is even more pronounced. Unlike optical fibers, wireless communication channels do not inherently possess physical symmetry [74]. Furthermore, if the wireless communication relies on an existing network infrastructure, factors such as routers, switches, and network congestion may introduce asymmetric packet delays, further impacting time synchronization accuracy [75]. Additionally, wireless communication is more susceptible to packet loss, weather conditions, and environmental influences, making the impact of asymmetry more severe [76]. When these issues become significant, additional time source calibration may be required to ensure the precision of WR synchronization.

VII. ENHANCEMENT STRATEGIES FOR WHITE RABBIT

As this technology continues to develop and evolve, numerous studies have focused on addressing the limitations of traditional WR and enhancing its performance across various applications, including hardware improvements and methodological advancements.

A. P2P CLOCKS AND SCALABILITY IMPROVEMENTS

Reference [68] addresses the scalability and stability limitations of WR synchronization in large cascaded networks. As described in Section VI, the end-to-end (E2E) delay model treats the network as a single logical link, neglecting intermediate node delays, which leads to increased jitter and higher processing overhead. To mitigate these issues, the authors propose transitioning WR to a P2P delay model and incorporating transparent clocks (TCs) and hybrid clocks (HYs). TCs forward synchronization messages without adjusting their local clocks, thereby reducing processing overhead, as shown in Fig. 8, while HYs combine message forwarding with limited oscillator adjustments to enhance stability, as shown in Fig. 9. Experimental results demonstrated that P2P-based TCs maintained sub-nanosecond accuracy across 18 nodes, while HYs achieved comparable performance up to 17 nodes—significantly outperforming the E2E-based WR model. These enhancements improve WR's scalability and stability, making it more suitable for large-scale deployments in telecommunications, smart grids, and scientific infrastructures.

B. TEMPERATURE COMPENSATION

Reference [69] solves the challenge of maintaining high synchronization precision in WR networks under significant temperature variations, as required by the Large High-Altitude Air Shower Observatory. Temperature changes affect fixed delays in circuit boards, optical fibers, and transceivers, as well as the fiber asymmetry coefficient, causing synchronization errors beyond the acceptable range. To address these

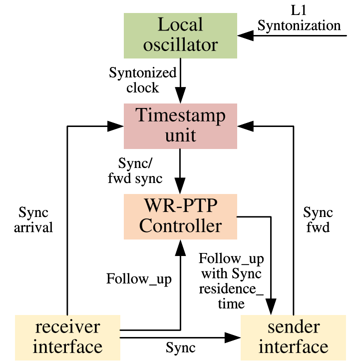

FIGURE 8. The pipeline of transparent clock [68].

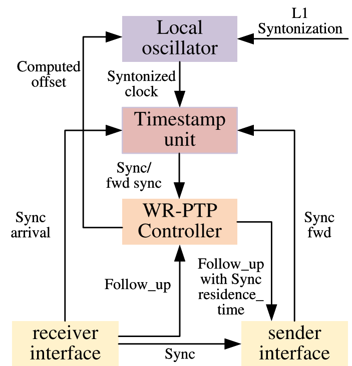

FIGURE 9. The pipeline of hybrid clock [68].

issues, the authors proposed real-time correction methods by modeling the temperature dependence of fixed delays and the fiber asymmetry coefficient. Experimental results showed that dynamically adjusting fixed delays based on onboard temperature measurements reduced PPS offset variations from 700 ps to less than 150 ps, with a standard deviation below 50 ps. These enhancements significantly improved synchronization precision, allowing WR to meet stringent timing requirements in extreme environments.

C. LONG-DISTANCE SYNCHRONIZATION

Reference [72] addresses the challenge of extending the WR-PTP for time and frequency transfer over long-distance fiber links, particularly up to 1000 km, where the original WR design faced limitations. The main issues include delay asymmetry caused by unequal fiber lengths and chromatic dispersion, as well as environmental factors like temperature fluctuations affecting synchronization accuracy. To mitigate these, the authors implemented two long-distance WR links: a 950 km dual fiber link using density wavelength division multiplexing, as shown in Fig. 10, and a 2 × 137-km bidirectional single-fiber link with custom optical amplifiers. Both sets of controls employed GPS precise point positioning and calibration techniques to address delay asymmetry. The results demonstrated a time transfer accuracy within ±2 ns over four months for the dual-fiber link, while the bidirectional link achieved a time offset uncertainty of approximately 8 ns. These enhancements highlight the ability of WR for precise synchronization in long-haul networks with proper calibration and infrastructure improvements.

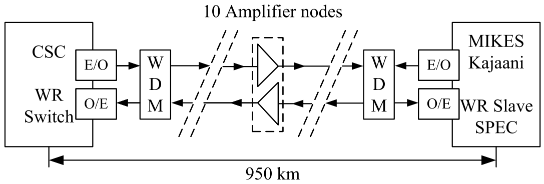

FIGURE 10. **Diagram of the 950-km Espoo–Kajaani WR link [72].**

D. FPGA NOISE REDUCTION

Reference [64] involves the performance limitations of WR clock synchronization, particularly in achieving short-term stability and reducing close-in phase noise for applications requiring high precision, such as national timekeeping and deep-space navigation. The primary issues stem from the noise introduced by FPGA-based components, including the DDMTD phase detector and gigabit transceivers, which contribute to jitter and flicker noise. To mitigate these issues, the authors developed a low-jitter daughterboard to replace noisy components such as internal PLLs and oscillators in the WR switch. The low-jitter daughterboard incorporates high-stability oscillators and optimized clock synthesis, achieving a tenfold improvement in short-term stability with a modified Allan deviation of 4×10^{-13} at $\tau = 1$ second. This enhancement demonstrates the feasibility of overcoming FPGA-based noise limitations, making WR suitable for ultra-precise applications.

E. SIMPLIFIED CALIBRATION

Traditional WR synchronization requires fiber asymmetry calibration due to the use of different wavelengths for uplink and downlink transmission, which introduces chromatic dispersion and propagation delay asymmetry. This dependency on pre-calibrated auxiliary fiber links makes WR deployments complex and less scalable. Reference [77] proposes a novel synchronization method that eliminates the need for asymmetry calibration by using a single-wavelength bidirectional transmission with optical circulator. This approach ensures identical propagation delays for both directions, simplifying WR network calibration. Experimental results demonstrate a significant reduction in synchronization error, achieving 50 ps over 5 km and 132 ps over 50 km, compared to 172 ps and 1574 ps, respectively, using the conventional method. By removing the requirement for continuous fiber calibration, this enhancement makes WR more practical for large-scale and long-distance synchronization applications.

In addition, traditional WR synchronization relies on relative calibration, where hardware delays are measured against a golden calibrator. Although effective, this method requires all WR devices in a network to be calibrated using the same reference, making it impractical for large-scale or evolving deployments. To address this limitation, [78] proposes an absolute calibration method that directly measures hardware delays without relying on a fixed reference. This approach eliminates the need for recalibrating all devices when new components, such as small form-factor pluggable transceivers, are introduced. By adopting absolute calibration, WR systems achieve greater flexibility, improved scalability, and reduced calibration overhead, significantly enhancing deployment efficiency for long-haul and complex networks.

VIII. APPLICATIONS AND PERFORMANCES IN SMART GRID

Originally developed for the nuclear physics domain, WR has since been adopted across a wide range of sectors, including telecommunications, industrial automation, finance, and more. Inspired by its success in these fields, several studies—lbeit limited in number—have begun to explore WR's application and performance within smart grid environments. These initial investigations, summarized in Table 3, provide a valuable foundation for further research and practical implementation in future smart grid systems.

A. APPLICATIONS OF WHITE RABBIT IN SMART GRID

1) PMUs AND SYNCHROPHASOR NETWORKS

WR technology enhances the accuracy of synchrophasor measurements by providing deterministic phase synchronization. Unlike traditional GPS-based PMUs, WR-enabled PMUs employ hardware time-stamping and disciplined internal clocks, ensuring precise phase-angle measurements while eliminating synchronization drift. This capability is particularly beneficial for higher-order harmonic analysis and real-time grid monitoring [50].

2) FAULT DETECTION AND LOCALIZATION

Accurate fault detection requires precise timestamping of voltage and current waveforms across multiple substations. WR reduces synchronization uncertainty, leading to improved fault localization accuracy and faster protection system response. Enhanced timing precision helps minimize fault impact and improves overall grid reliability [79].

3) WIDE-AREA MONITORING AND CONTROL

WR enables synchronized data acquisition across geographically dispersed nodes, supporting real-time grid control and stability analysis. The sub-nanosecond synchronization accuracy of WR facilitates better coordination of grid operations, including automated load balancing and frequency regulation, thus improving dynamic stability [80].

4) SMART GRID AUTOMATION AND DISTRIBUTED ENERGY RESOURCES

The integration of renewable energy sources and microgrids requires precise time coordination to manage distributed energy resources effectively. WR enables seamless communication between control centers and field devices, improving synchronization for energy dispatch, voltage regulation, and demand response optimization [81].

B. PERFORMANCE EVALUATION OF WHITE RABBIT IN SMART GRID APPLICATIONS

1) SYNCHRONIZATION ACCURACY AND STABILITY

WR achieves sub-nanosecond synchronization accuracy, outperforming conventional synchronization methods such as PTP and inter-range instrumentation group (IRIG-B). Experimental evaluations report synchronization errors as low as 21 ps between WR switches and 111 ps for extended nodes, ensuring high stability under varying network conditions [82].

2) RELIABILITY IN HARSH ENVIRONMENTS

Unlike GPS-based systems, WR maintains stable performance in environments where satellite signals are unreliable, such as underground substations or urban areas with signal obstructions. The use of hardware-based timestamping minimizes phase drift, making WR a reliable synchronization method for smart grids [17].

3) NETWORK REDUNDANCY AND FAILOVER MECHANISMS

WR supports High-availability Seamless Redundancy and Parallel Redundancy Protocol, ensuring continuous synchronization even in the event of hardware or link failures. Timing frames are duplicated, allowing seamless switching to backup timing sources within microseconds, thus enhancing network reliability [81].

4) SCALABILITY FOR LARGE-SCALE DEPLOYMENTS

In ring and cascade topologies of the power grid, WR has demonstrated its capability to maintain sub-nanosecond accuracy across up to 13 nodes. This scalability makes it suitable for large-scale smart grid deployments, where synchronized data exchange between thousands of devices is required for real-time monitoring and control [80].

5) RESILIENCE AGAINST ATTACKS

GPS-dependent synchronization methods are vulnerable to spoofing and jamming, which can lead to incorrect grid state estimations. WR provides an alternative by utilizing fiber-optic infrastructure, reducing susceptibility to cyber threats [30].

IX. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

According to the European Regulators Group for Electricity and Gas, a smart grid is an electricity network capable of cost-effectively integrating the behavior and actions of all connected users—including generators, consumers, and prosumers—to deliver a power system that is economically efficient, sustainable, low in losses, high in quality, secure, and safe [83], [84].

Despite its many advantages, the smart grid faces several challenges, particularly in integrating renewable energy resources. Recently, numerous renewable energy generators, such as solar, tidal, biomass, and wind generators—spanning capacities from a few kilowatts to several megawatts—have become increasingly widespread worldwide. The entire electrical power system integrates these geographically distributed sub-systems [85]. However, the variability, unpredictability, and weather dependence of renewable energy sources present significant challenges for their integration into the smart grid [86]. Additionally, the digital integration complexity of these dispersed components poses further challenges for smart grid operation, protection, and control systems.

To manage the fast dynamics and system complexity introduced by distributed renewable energy, the smart grid requires enhanced-performance time synchronization techniques. For a time synchronization method to be suitable for smart grid applications, several key factors must be considered, including accuracy, flexibility, cost, reliability, security, and scalability.

For WR, its most important feature is its high accuracy, which fully meets the requirements of smart grid applications. This high accuracy is also the primary motivation for implementing this technique in power systems. Based on the literature we reviewed, other aspects of WR can be further improved to better suit smart grid applications. Future research should focus on addressing these challenges to enhance the effectiveness.

1) **Flexibility and cost**: The cost of achieving high accuracy performance with WR comes from the investment in dedicated hardware and optical fiber, making it significantly more expensive than PTP. Additionally, the reliance on optical fiber infrastructure reduces WR's flexibility. To address this, efforts have been made to explore alternative approaches, such as using wireless media for signal transmission. However, further research is needed to improve wireless communication performance, particularly in mitigating issues related to asymmetry and congestion. Furthermore, alternative methods, such as delivering time signals via Layer 2 instead of Layer 1, also merit investigation, as congestion in this approach may be less severe than in wireless communication, and asymmetry is more controllable.
2) **Reliability**: Since WR relies on dedicated optical fiber and the physical layer for time signal transmission, its reliability is significantly improved compared to PTP. However, optical fiber is susceptible to physical damage, and its performance is sensitive to environmental changes, such as temperature variations. Reliability is the most critical factor to consider in smart grid applications. Based on the literature reviewed, there has been limited focus on reliability studies, highlighting the need for further research in this area.
3) **Security**: One of the drawbacks of PTP is its vulnerability to several types of attacks—such as

TABLE 3. Review of White Rabbit applications in smart grid.

Reference	Key Objective	Main Findings
Razzaghi et al. (2017) [50]	Implement WR-PMU for precise phase measurements.	Achieved deterministic phase synchronization.
Fring et al. (2024) [79]	Improve fault localization using WR synchronization.	Reduced synchronization uncertainty, enhancing accuracy.
Cao et al. (2022) [80]	Develop WR-based real-time synchronization for WAMC.	Achieved sub-nanosecond accuracy, enabling fast response.
Gutiérrez et al. (2019) [82]	Evaluate WR synchronization performance.	Reported 21 ps accuracy between WR switches.
Derviş et al. (2020) [17]	Compare WR with PTP in smart grids.	WR exhibited lower phase variability and improved reliability.
Ramos et al. (2018) [81]	Assess redundancy mechanisms for WR synchronization.	HSR and PRP ensured seamless failover with microsecond recovery.
Moussa et al. (2016) [30]	Analyze cybersecurity vulnerabilities of time protocols.	Identified risks in GNSS and PTP; WR mitigated spoofing threats.

delay, packet modification, transparent clock, and time reference attacks—which can severely compromise its synchronization accuracy. To address these vulnerabilities, extensive research has been dedicated to threat modeling and mitigation strategies. Reference [87] demonstrates three threat models: temporal vortex errors, a novel man-in-the-middle packet injection, and time transmitter offsets with clock frequency manipulation, along with corresponding mitigation techniques. Reference [88] proposes multiple methods for implementing realistic delay attacks and verifies their feasibility on a hardware testbed. Reference [89] proposes detection and mitigation mechanisms against the known PTP delay attack.

To make WR a promising technique for smart grid applications, it should be capable of addressing these security challenges. However, based on the literature reviewed, there has been limited research on attack defense mechanisms for WR, with even less focus on security measures specifically tailored for smart grid applications.

4) **Scalability**: The smart grid is geographically distributed, especially with the integration of distributed renewable energy sources. To implement WR in the smart grid, it must be capable of distributing time synchronization signals over a large-scale area. Some efforts have already been made to investigate WR's scalability and performance over long distances. However, with a focus on smart grid applications, considering the unique characteristics of grid topology, the scalability challenge warrants further in-depth investigation.
5) **Integration with existing approach**: Most smart-grid devices already utilize the IEEE 1588 PTP, so the most practical upgrade is to add WR only to links that require sub-nanosecond accuracy. For systems with high reliability demands, WR can also be integrated with existing PTP setups to provide a seamless backup option, enhancing overall system robustness. Integration is not plug-and-play. WR requires bidirectional, fixed-wavelength fibre and often custom optical filters; every fibre span must be pre-calibrated for delay asymmetry before service; and, for the time being, WR relies on specialist FPGA-based switches and interface cards that cost more than a standard PTP clock.

X. CONCLUSION

With the development of smart grid technology, the grid faces increasing challenges in fast monitoring, control, and protection. Accurate time signals are a prerequisite for the operation of all devices and systems, ensuring precise electrical measurements and effective emergency control. Given the growing demand for highly accurate and secure time synchronization techniques in the smart grid, WR emerges as a promising solution.

This article provides a comprehensive guide to the application of WR in the smart grid. To ensure completeness and practical value, it summarizes the principles and limitations of existing time synchronization techniques, highlighting the advantages of WR. The investigation covers all critical aspects that must be considered before deployment, including the theories, principles, implementations, performances, and existing application cases of WR.

After a thorough review of these aspects, WR emerges as a promising technique for smart grid deployment. It delivers deterministic, sub-nanosecond time alignment ($\leq$ 1 ns) over fibre links while supporting hierarchical networks with hundreds of downstream nodes. Beyond accuracy, WR also demonstrates superior reliability and security compared to traditional time synchronization techniques.

Based on the literature reviewed, this article provides insights into future research directions. Several challenges remain on the path to large-scale implementation, including cost-effective approaches, practical deployment methods, and enhanced techniques for reliability and security.

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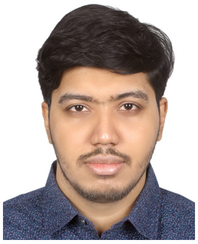
YU LIU (Graduate Student Member, IEEE) received the B.S. and M.S. degrees in electrical engineering, and high voltage and insulation technology from Wuhan University, China, in 2014 and 2017, respectively. She is currently pursuing the Ph.D. degree with The University of Tennessee at Knoxville, Knoxville, TN, USA.

Her research interests include time synchronization system in power grid, grid strength, and grid modeling.



KAZI ISHRAK AHMED received the B.Sc. degree in electrical and electronic engineering from Bangladesh University of Engineering and Technology, in 2024. He is currently pursuing the Ph.D. degree with The University of Tennessee at Knoxville, Knoxville, TN, USA.

His research interests include power system dynamics, transient analysis, and machine learning applications.

NAGA LAKSHMI THOTAKURA, photograph and biography not available at the time of publication.

JIAHUI YANG, photograph and biography not available at the time of publication.

YURU WU, photograph and biography not available at the time of publication.

HAOZONG WANG received the B.S. and Ph.D. degrees in electrical engineering from Tsinghua University, Beijing, China, in 2017 and 2023, respectively. He is currently a Postdoctoral Researcher with The University of Tennessee at Knoxville, Knoxville, TN, USA. His research interests include power system protection, fault location, and oscillation damping control.

BIAO SUN, photograph and biography not available at the time of publication.

WEN WANG received the B.S. degree in engineering management from Northeast Forestry University, China, in 2011, and the M.S. degree in world economics from Wuhan University, China, in 2017. He is currently pursuing the Ph.D. degree with The University of Tennessee at Knoxville, Knoxville, TN, USA.

His research interests include electricity market and virtual inertia.

YONGXIN ZHANG received the Ph.D. degree in electrical engineering from Tsinghua University. He is currently a Postdoctoral Researcher with the Department of Electrical Engineering and Computer Science, Tickle College of Engineering, The University of Tennessee at Knoxville. His research interests include power systems, data sciences, and timing sources.

YILU LIU (Life Fellow, IEEE) received the B.S. degree from Xi'an Jiaotong University, China, and the M.S. and Ph.D. degrees from The Ohio State University, Columbus, OH, USA, in 1986 and 1989, respectively.

She was a Professor with Virginia Tech. She led the effort to create North American Power Grid Frequency Monitoring Network (FNET), Virginia Tech, which is currently operated with UTK and Oak Ridge National Laboratory (ORNL), as a GridEye. She was elected as a member of the National Academy of Engineering, in 2016. She is the Governor's Chair with The University of Tennessee at Knoxville, Knoxville, TN, USA, and ORNL. Her current research interests include power system wide-area monitoring and control, large interconnection-level dynamic simulations, electromagnetic transient analysis, and power transformer modeling and diagnosis.