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Review

Time Synchronization Techniques in the Modern Smart Grid: A Comprehensive Survey

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Abstract: In modern smart grids, accurate and synchronized time signals are essential for effective monitoring, protection, and control. Various time synchronization methods exist, each tailored to specific application needs. Widely adopted solutions, such as GPS, however, are vulnerable to challenges such as signal loss and cyber-attacks, underscoring the need for reliable backup or supplementary solutions. This paper examines the timing requirements across different power grid applications and provides a comprehensive review of available time synchronization mechanisms. Through a comparative analysis of timing methods based on accuracy, flexibility, reliability, and security, this study offers insights to guide the selection of optimal solutions for seamless grid integration.

Keywords: smart grid; time synchronization; time source; time distribution; comparison; mechanism

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1. Introduction

Modern smart grids integrate advanced equipment across a diverse array of devices, from power generation facilities to remote monitoring stations [1,2]. Accurate and synchronized time signals are crucial for ensuring effective monitoring, protection, and control within these grids [3]. Precise timestamps underpin reliable operations and enable coordination across wide geographically dispersed devices. However, local clocks such as crystal oscillators often experience significant time drift due to temperature variations, aging, and other environmental factors that compromise frequency stability [4]. To address these drifts, external time sources like GPS are periodically employed to recalibrate local clocks and correct deviations [5,6].

Time synchronization is fundamental to the correct sequencing of events [7], precise fault detection, and prompt, data-driven decision-making. It forms the backbone of both security and efficiency within smart grids. The critical importance of time synchronization became evident during the North American blackout on 14 August 2003 [8], where approximately 63 GW of load was lost [9]. The blackout investigation faced challenges due to inconsistent timestamps, which delayed root-cause identification. Lessons from this event led the North American Electric Reliability Corporation (NERC) to mandate that internal clocks in disturbance monitoring equipment (DME) be synchronized to within 2 ms of Coordinated Universal Time (UTC) [10].

In the smart grid, time information has evolved from a means of relating historical data post-fault to enabling real-time analysis and immediate remedial action, supporting, eventually, automated operations [11]. The accuracy requirements for time synchronization vary by application, ranging from seconds to microseconds across different grid functions [12]. For instance, the timing precision for phasor measurement units (PMUs) is significantly higher than for supervisory control and data acquisition (SCADA) systems. Beyond accuracy, the availability, backward compatibility, and security of time synchronization systems are also critical considerations, with various standards defining the specific requirements for different grid components and devices [13].

Precise time synchronization is essential for maintaining the stability and reliability of modern smart grids [14]. Accurate synchronization accelerates a broad range of smart grid operations, such as fault detection and network clearing, synchrophasor measurement to monitor network stability, sequence of event time stamping, data acquisition, demand side management (DSM), differential protection, frequency deviation measurements (FDM), and smart metering synchronization.

The importance of time synchronization extends to the security of smart grids. Time synchronization attacks (TSAs) pose a significant threat to the precise functioning of phasor measurement units (PMUs) in the context of smart grids [15]. Many operations in power grids, such as fault detection and event location estimation, depend on precise timing information.

Therefore, precise time synchronization is not only a technical requirement but a cornerstone of the smart grid's ability to deliver reliable, efficient, and secure power. As the grid continues to evolve with the integration of renewable energy sources and advanced technologies, the role of accurate time synchronization becomes increasingly critical.

Time synchronization in power grids is achieved through various methods. While some techniques have been in use for decades, others are recent innovations. The structure of a time synchronization system typically comprises two key components: the time source and the time distribution system. The most widely used time source in power grids is the Global Navigation Satellite System (GNSS) [16], which provides timing accuracy within one microsecond [17], ideal for protection and control applications [18].

The time distribution system, on the other hand, is tasked with aligning the clocks across network nodes to match the time source, thereby ensuring synchronized operations with the required accuracy [19]. The Network Time Protocol (NTP), for example, is widely implemented and provides timing precision within tens of milliseconds [20].

However, the 2016 GPS malfunction, which offset timing signals by 13 microseconds, highlighted the vulnerability of solely relying on GPS, as systems requiring precise timing, such as communication networks and power grids, were significantly disrupted [21,22]. This incident underscored the need for robust backup systems to mitigate future risks and ensure infrastructure reliability.

Emerging techniques for time synchronization are increasingly being developed, yet they lack comprehensive documentation within the existing literature. This survey aims to fill this gap by offering a thorough review of current time synchronization mechanisms. The main contributions of this paper are as follows:

- A comprehensive overview of time requirements across various power grid applications, detailing the specific timing demands of different devices.
- A comparative analysis of time sources and distribution mechanisms, covering both established and emerging approaches with a focus on power grid applications.
- A multi-dimensional assessment of implementing new time synchronization techniques, evaluating performance and feasibility in power grid contexts.

This paper introduces novel perspectives on time synchronization techniques, emphasizing their applicability in smart grids. By addressing current challenges and proposing potential solutions, this work aims to contribute new insights to the field.

For this survey, a comprehensive literature review was conducted using multiple academic databases, including Google Scholar, IEEE Xplore Digital Library, and Web of Science. A targeted search strategy (e.g., (“Time Synchronization” OR “Time Source” OR “Time Distribution”) AND “Smart Grid”) was employed to initially identify 15,500 relevant publications from the year 1990 to 2025, encompassing research articles, review papers, and book chapters. After an initial screening based on relevance and scope, a subset of 391 publications was selected for further evaluation. Following a thorough review of the content, studies less aligned with the focus of this paper were excluded, resulting in a final selection of 112 references that best support the survey’s objectives.

The structure of this paper is as follows: Section 2 introduces time-dependent applications within the power grid and their time requirements. Section 3 covers time sources and their performance. Section 4 discusses the characteristics of various time distribution systems. Section 5 addresses challenges and future research directions, and Section 6 concludes the survey.

2. The Applications in Smart Grid Based on Time Synchronization

Smart grid applications require efficient, real-time communication systems to support continuous monitoring, measurement, and control [3]. However, the dynamics of power system signals are accelerating, driven by the expansion of renewable energy generation and the variability in load demands [23]. This increased reliance on renewable sources and microgrids introduces new temporal challenges, making precise time synchronization essential to ensure stability and efficient control.

2.1. Digital Fault Recorders

Since their introduction in the 1980s, Digital Fault Recorders (DFRs) have become essential tools for monitoring and analyzing the bulk electric power system [24]. By digitizing oscillographic fault data and recording event sequences, DFRs provide crucial insights into system behavior under fault conditions. These devices capture voltage and current waveforms by replicating primary power system signals when triggered by external events. This capability enables utilities to swiftly analyze and restore system operations, offering valuable information on power system protection. Additionally, DFRs display functional system diagrams with analog voltage and current waveforms, facilitating root cause analysis of fault events [25].

To ensure accurate fault analysis, several standards mandate specific time-stamping and synchronization requirements for DFRs. For instance, NERC PRC-002-2 [26] specifies that (1) time stamps must have sufficient resolution to capture circuit breaker changes within 4 ms, and (2) all recorded data must be synchronized within ±2 ms of Coordinated Universal Time (UTC).

2.2. Differential Protection

The fundamental principle of current differential protection is based on Kirchhoff’s Current Law (KCL), which states that the total current entering a junction equals the total current leaving it [27]. During a fault condition, the currents will become unbalanced, resulting in a non-zero sum, which serves as the criterion for tripping [28].

The accurate operation of differential protection relies on precise time synchronization. Insufficient synchronization accuracy can cause phase angle shifts in the phasors, leading to increased differential currents and potential protection malfunctions. For instance, a time error of approximately 100 μs results in a phase error of around 2 degrees [28].

Therefore, to meet these requirements, time synchronization accuracy in the Process Bus must remain within a few microseconds. According to IEC 61850-5 [12], the merging unit must achieve ±4 μs accuracy. IEC 61850-9-2 LE [29] specifies that communication network delays should not exceed 2 μs [30]. Sampled Values are expected to maintain a timing accuracy of better than 1 μs [31].

2.3. Lightning Correlation

A lightning strike on a line or supporting structure can lead to both physical damage and electrical faults. Often, a line will trip following a lightning strike but will reclose several seconds later, remaining energized. However, lightning may still cause damage to insulators or conductors, making it advisable to inspect the area where the strike occurred [32].

The U.S. National Lightning Detection Network (NLDN) supports such assessments by deploying over 100 sensors across the contiguous United States (CONUS) with an average baseline spacing of 300–350 km. The NLDN identifies signals from impulsive lightning events within the very low-frequency/low-frequency range, utilizing time-of-arrival and magnetic direction-finding methods to precisely determine the location of each strike. For each event, the NLDN provides detailed data including the time, location, event type, polarity, peak current estimate, and field waveshape parameters (such as rise time and peak-to-zero time), as well as confidence ellipses for location accuracy [33].

Lightning strikes are timestamped to within one millisecond, allowing utilities to compare strike data with fault inception times obtained from point-on-wave timestamps recorded by DFRs or relays. This comparison helps utilities pinpoint inspection locations and anticipate potential damage based on the strike's intensity. An accuracy of one millisecond relative to absolute time is sufficient for reliable lightning fault correlations [32].

2.4. Traveling Wave Fault Location

Traveling waves are high-frequency electromagnetic pulses that propagate along a transmission line in both directions from the point of the fault. These waves propagate at nearly the speed of light. During a fault, the wavefronts are detected based on their arrival times at each terminal of the transmission line, allowing the fault location to be determined using the total line length and the recorded arrival times of the wavefronts [34].

The traveling wave fault location (TWFL) method requires high sampling rates to have good resolution and accuracy [35]. The performance of TWFL depends on the accurate detection of wavefront arrival times, the sampling frequency, and precise time synchronization [36]. To accurately locate a fault within hundreds of feet, TWFL demands synchronization accuracy about hundreds of nanoseconds [23], translating to clock synchronization within approximately one microsecond.

2.5. Synchrophasor Measurements

Various devices are strategically deployed to enhance the security, reliability, and efficiency of the power system. One such critical device, the Phasor Measurement Unit (PMU), monitors essential situations, including supply interruptions, load variations, contingencies, and faults [37]. A PMU produces synchronized estimates of phasors, frequency, and rate-of-change derived from voltage and/or current signals, accompanied by a time-synchronizing signal. A synchrophasor represents the magnitude and instantaneous phase angle of a signal relative to a cosine function at the nominal system frequency, synchronized with UTC [38].

PMUs are increasingly utilized to deliver synchronized measurements for system situational awareness and dynamic monitoring. Synchrophasor data, being time-sensitive, must be accurately time-stamped and promptly transmitted [39]. To align synchrophasor data from multiple PMUs, a Phasor Data Concentrator (PDC) uses the timestamps associated with each measurement [40].

Synchrophasor applications demand the highest precision in timing requirements across the power system due to frequent reporting, phasor precision needs, and the wide geographic distribution of PMUs [32]. IEEE C37.118.1-2011 [41] specifies a maximum 1% Total Vector Error (TVE), encompassing both magnitude and phase errors. TVE is the total uncertainty in the measurement result due to both magnitude error and phase error. For a 60 Hz system, a 1% phase error corresponds to a timing error of approximately 26.5 µs, while for a 50 Hz system, it corresponds to around 31.8 µs. However, to accommodate other sources of uncertainty, the standard suggests a maximum timing uncertainty of 1 µs instead of 26.5 µs.

2.6. Summary of Applications

It should be noted that each application has connections with others. They can not be separated directly. The detailed time information requirements depend on a specific case; for example, the fault location detection may use a traveling wave, or DFRs data, or PMUs measurements. Different methods can give different location errors, and the corresponding time accuracy requirements should be considered differently. In general, the time information requirements are shown in Table 1 [32].

Table 1. Time requirements in power system [32].

Application	Time Requirements
SCADA	Every 4–6 s reporting rate
Digital Fault Recorder	2 ms
Sequence of events recorder	50 µs to 2 ms
Protective relays	1 ms
Lightning correlation	1 ms
Traveling wave fault location	100 ns to 1 µs
Synchrophasors	1 µs
Communication protocols	
Substation local area network communication protocols	100 µs to 1 ms
Substation LANs	1 µs

The IEC Standard 61850-5 [12] classifies time synchronization requirements for various applications and services, similar to Table 1. It defines six synchronization accuracy classes, ranging from Class A (accuracy within ±1 µs) to Class F (exceeding 1 s) [42].

3. The Time Source Techniques

With an understanding of the various applications in smart grids that rely on precise time synchronization, it becomes essential to investigate the time source techniques that underpin these applications. Selecting an appropriate time source requires a thorough evaluation of factors such as accuracy, resilience, reliability, security, flexibility, and cost. The following section will explore these time source techniques in detail, highlighting both established methods and emerging advancements.

3.1. Global Navigation Satellite Systems

Global Navigation Satellite Systems (GNSSs) provide services for positioning, navigation, and timing. GNSSs include GPS, GLONASS, Galileo, and Beidou, all of which have similar functions [5]. In this paper, GPS is used as a representative example.

3.1.1. Timing Mechanism

GPS is a satellite-based network comprising 24 satellites that provide worldwide coverage. These satellites orbit in Medium Earth Orbit (MEO) with the altitude of about 20,200 km (12,550 miles), each completing two orbits around Earth daily. The GPS constellation is organized into six equally spaced orbital planes, with four satellites in each plane, ensuring that users can view at least four satellites from almost any location on Earth.

GPS satellites continually transmit their spatial coordinates and time information in two frequency bands. A GPS receiver, connected to an antenna, uses signals from at least four satellites to calculate its 3D position and precise time.

Each GPS satellite is equipped with atomic clocks, typically cesium-based, which provide highly accurate timing. This time information is embedded in the broadcast signals, enabling receivers to determine the exact time of transmission. By solving time-of-arrival equations from four or more satellites, receivers can determine their positions and correct any internal clock offsets.

A timing and synchronization module equipped with a GPS receiver can leverage this global time reference to precisely correlate, trigger, and timestamp measurement data. GPS time is maintained by multiple atomic clocks on each satellite and is referenced to the Master Clock (MC) at the United States Naval Observatory (USNO), known as UTC (USNO). This global synchronization allows users to access accurate time without maintaining atomic clocks, as all GPS receivers worldwide are synchronized to the same time signal [43].

3.1.2. Accuracy

The accuracy of GPS, or the potential error in its measurements, is influenced by various environmental factors [11]:

- Satellite Orbit Error: Inaccuracies in a satellite's reported location can impact the GPS receiver's position and time calculations.
- Satellite Clock: Although GPS satellites use atomic clocks, these clocks are still subject to drift and noise. While some of this error is corrected within the signal message, residual errors may persist.
- Ionosphere and Troposphere Delay: GPS signals experience delays due to free electrons in the ionosphere, which vary based on the satellite's position relative to the horizon. Closer to Earth, signal delay is affected by temperature and humidity changes in the troposphere. While receivers partially compensate for these delays, some variation remains uncorrected.
- Multipath: GPS signals can reflect off buildings or other obstacles, leading to delays in the signal.
- Receiver Noise Error: Receiver noise can cause jitter in the signal, resulting in timing errors.

Depending on environmental conditions and device sensitivity, GPS time accuracy can vary, though it is typically within 100 ns [43].

3.1.3. Flexibility

GPS timing synchronization is widely used in different sectors because of its accuracy and flexibility. To receive a GPS time signal, the only things needed are an antenna and a receiver, which makes it easy to access globally. Also, the output time signal of GPS has multiple formats, which means it can be adopted in different applications. Due to its ease of application, the cost of adopting GPS timing is relatively low, with the primary investment being the cost of the antenna and receiver hardware.

3.1.4. Reliability and Security

Due to the wide applications of GPS in the power grid, its reliability is essential. GPS signals can be lost or impaired in several ways, with interruptions varying in duration depending on the failure mechanism and system resilience. These interruptions fall into two main categories [43]:

- Natural: Space weather can disrupt GPS service for extended periods, potentially lasting days, or even cause permanent damage to satellite equipment. Additionally, collisions with other objects in orbit pose a significant risk to the satellites.
- Man-made: Interference can unintentionally disrupt GPS signals, such as radio frequencies near the GPS bandwidth causing signal interference. Additionally, intentional actions like jamming or spoofing of space-based positioning, navigation, and timing (PNT) communications can disrupt single or multiple GPS receivers, whether from stationary or mobile sources.

While the probability of natural GPS interruptions is low, when they do occur, they can last for extended periods. However, jamming and spoofing present more pressing concerns [44]. Jamming aims to disrupt GPS signal reception by introducing sufficient noise at the same frequency to overpower the satellite signal, exploiting its inherently weak nature. Spoofing, on the other hand, involves transmitting a malicious or duplicate GPS signal to deceive the receiver [45]. These types of attacks are relatively easy to execute but can have profound impacts on critical systems.

The power grid relies on accurate time signals for a range of applications, and disruptions to GPS threaten the availability and functionality of these systems, potentially compromising grid operations [18]. As reported in [46], approximately 70% of PMUs have encountered issues related to GPS signal loss.

3.1.5. Application

Due to its flexibility, convenience, and low cost, GPS timing is widely used across various sectors, including power grids. Utilities rely on precise GPS-based timing to accurately timestamp data and measurements for all applications listed in Section 2, such as disturbance analysis, PMUs, and protection devices.

NERC recommends that organizations develop a master plan for their timing technologies to ensure that as GPS usage increases, reliability-critical applications remain unaffected by potential GPS disruptions [43]. One approach to enhance resilience is the addition of redundant or backup clocks.

3.2. Low Earth Orbit

Low Earth Orbit (LEO) satellites offer an alternative option for timing applications, providing unique advantages due to their proximity to Earth.

3.2.1. Timing Mechanism

LEO generally refers to satellites at altitudes ranging from approximately 80–100 km up to about 2000 km [47], with orbital periods of 128 min or less. Most artificial objects in space are located in LEO. The first Low Earth Orbit (LEO) satellites were launched more than 50 years ago, but it was not until the 1980s that the Iridium constellation was introduced, offering global low-latency narrowband communications. More recently, LEO-based broadband constellations, such as OneWeb, Starlink, and Kuiper, have been developed to provide high-capacity wireless connectivity worldwide, focusing on remote areas that are difficult to reach with traditional terrestrial infrastructure [48].

Although broadband megaconstellations were not originally designed for Positioning, Navigation, and Timing (PNT) applications, they are engineered with rapid technological refresh capabilities, allowing adaptability for PNT through software or hardware updates [49]. Currently, one operational LEO timing service exists: the Satellite Time and Location (STL) service, provided by Satelles. The STL service delivers secure, GPS-independent time and location signals from LEO satellites [50]. These signals are transmitted via the Iridium constellation, which became operational in 1998 and consists of 66 satellites arranged in six orbital planes (11 satellites per plane) to ensure global coverage, as illustrated in Figure 1. Like GPS, STL signals are broadcast, though at slightly higher frequencies.

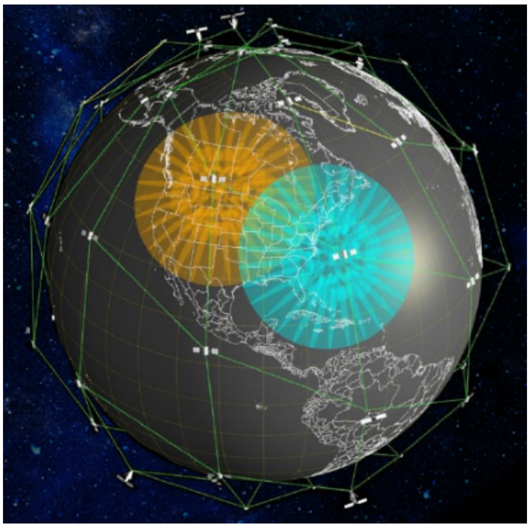

Figure 1. Iridium constellation orbits [51].

The LEO satellites in the Iridium constellation orbit at an altitude of just 781 km, which is over 25 times closer to Earth than GPS satellites. At the poles, between six and eight satellites are typically visible at once, whereas only one satellite is usually visible from the equator. With an orbital period of approximately 100 min, these satellites complete about 14 orbits around Earth each day [50].

LEO can provide a Stratum 0 UTC source of timing. A Stratum 0 source of timing refers to reference clock devices that provide UTC with minimal delay. High-precision timekeeping devices such as atomic clocks, GPS are Stratum 0 sources of timing, serving as the foundational elements in time synchronization protocols like the Network Time Protocol (NTP).

3.2.2. Accuracy

Due to the shorter distance from LEO satellites to Earth, signal power is stronger, resulting in highly accurate timing. According to [50], a receiver can achieve sub-microsecond accuracy from a single signal burst. Reference [52] reports a positioning accuracy of 20 m indoors with timing accuracy within 1 µs. Studies in [53,54] measured and quantified the accuracy and stability of pulse-per-second (PPS) timing outputs from STL receivers by comparing them to UTC (NIST) and GPS. Results show that an uncalibrated STL receiver can provide sub-microsecond accuracy, with accuracy under 100 ns achievable through delay calibration. While the STL receiver offers superior short-term stability compared to the GPS Disciplined Clock (GPSDC), its stability decreases over longer periods, ranging from several hours to days. In general, LEO timing accuracy can reach 1 µs, or even 100 ns with calibration.

3.2.3. Flexibility

Like GPS, LEO timing is easy to deploy and connect. The LEO signal has higher strength compared to GPS; with a small antenna and a receiver, the LEO signal can be accessed globally, and the receiver handles signal interception, performs error correction, and computes PNT data.

The cost of implementing LEO-based timing can be similar to that of GPS timing, with the primary investment being hardware costs. However, since GPS is a mature technology with an already deployed satellite network, there are no additional service fees. In contrast, LEO-based timing operates in an open market, with services provided by different companies. Depending on their pricing strategies, users may incur service fees in addition to hardware costs. This makes LEO timing slightly more expensive than GPS, but the overall cost remains relatively low.

3.2.4. Reliability and Security

PNT service by LEO is designed to be immune to certain GPS vulnerabilities [50]. Efforts are underway to address robustness and enhance services.

LEO satellites are designed with a focus on precision, with plans to introduce signal encryption to enhance resilience against malicious attacks like spoofing. Additionally, overlapping beam patterns formed by signals from multiple satellites reduce the risk of signal loss due to spoofing, as these patterns are challenging to replicate [55].

The raw signal power received from LEO satellites on Earth is approximately 300 to 2400 times stronger than GPS signals, which makes LEO less susceptible to jamming and interference. In contrast, GPS signals suffer significant attenuation due to distance-related path losses during their transmission from satellites to the ground [52]. This increased signal strength also allows LEO signals to be received indoors, making them suitable for use with indoor antennas.

3.2.5. Application

As of the time of writing, no literature has documented the application of LEO-based timing in the electrical grid. However, cases in other sectors are provided here to offer insights into its potential applications.

For nearly three decades, satellite operators have pursued the goal of deploying LEO constellations for global broadband services. The initial LEO satellites were designed primarily for communications, and recently, several companies have submitted petitions to the Federal Communications Commission (FCC) to deploy extensive constellations in both LEO and MEO [56]. The global reach, low latency, and broad bandwidth of these services position them to revolutionize broadband communications [49].

In addition to communications, Positioning, Navigation, and Timing (PNT) has emerged as a viable service offered by LEO satellites, with applications across sectors like 5G networks, data centers, and financial services.

Given that LEO offers timing accuracy, performance, and receiver characteristics comparable to GPS, it could potentially be used for time synchronization in all the applications listed in Section 2 that currently rely on GPS.

3.3. Pulsar Star

A pulsar is a rotating neutron star with strong magnetic fields that emit beams of electromagnetic radiation from its magnetic poles, which can be detected when these beams are directed toward Earth, as shown in Figure 2. The electromagnetic radiation from these rotating neutron stars spans the entire spectrum, making them remarkable celestial objects detectable across every observational window of the cosmos [57]. Since the discovery of the first pulsar in 1967, the number of known pulsars has rapidly grown. Today, over 3000 neutron stars have been detected across wavelengths ranging from radio to high-energy bands [58].

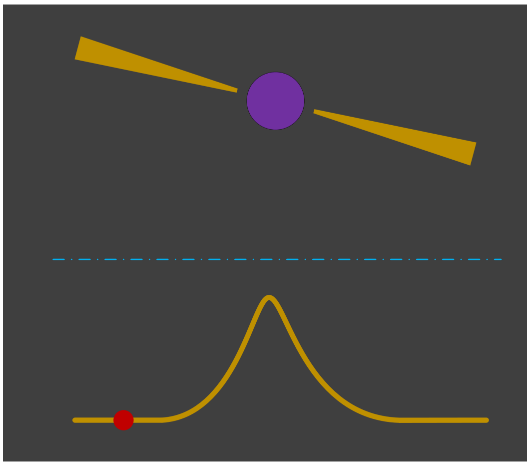

Figure 2. Pulsar beams.

3.3.1. Timing Mechanism

Pulsar emission is modulated by the star's rotational frequency, $\nu = \frac{\Omega}{2\pi}$ (where Ω is the angular velocity), which is exceptionally stable and enables microsecond-level precision in measuring the pulsed signal [58]. There is one type of pulsar called millisecond pulsar (MSP), which rotates extremely rapidly with periods of less than 10 milliseconds. MSP is even more stable. For example, the period drift rates of the millisecond pulsars PSR B1937+214 can reach $6.74 \times 10^{-17}\ \mathrm{s}^{-1}$ [59]. Additionally, pulsars exhibit long-term stability that extends over millions of years, significantly surpassing the stability of terrestrial atomic clocks [60], as shown in Figure 3.

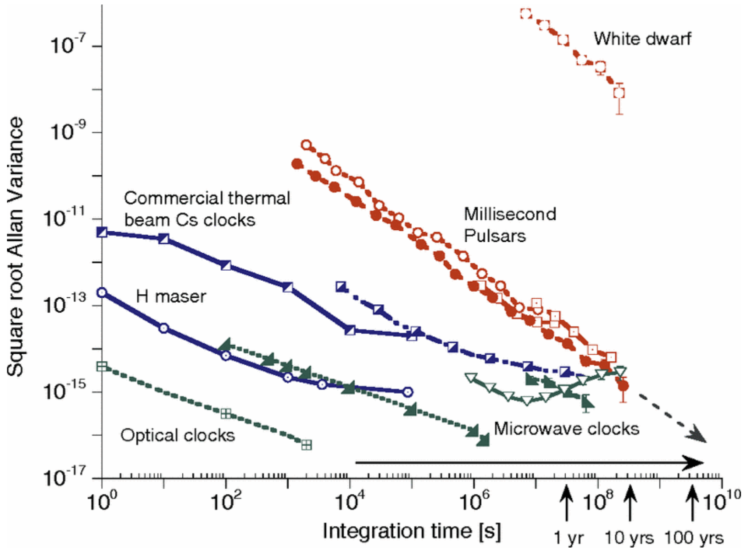

Figure 3. Derived frequency stability for a range of different frequency sources [59].

Observations can uncover the rotational evolution of pulsars using a technique called pulsar timing, which monitors the neutron star's rotation on a turn-by-turn basis [58]. Pulsar timing is a technique that involves comparing the observed pulse arrival times with the predicted arrival times, which are calculated using a physical model of the pulsar's signal and its propagation to the observatory [61]. This technique enables the pulsar to be used as a time source, especially for MSP.

The periodic pulse signals that the pulsars emit can be observed by radio telescopes. However, pulsars are weak radio sources, and their flux densities are relatively low and fluctuating with time [62]. It makes the pulses indiscernible with noise and interference; as shown in Figure 4, the timing signal with the waveform is highlighted [63]. In addition, during the transmission, the pulse signals are affected by the frequency-dependent transmission speed in the interstellar medium [64], which results in dispersion in the received observation data and degrades the time resolution of the pulse signal, as shown in Figure 5. As a result, it is impossible to use the pulse signals for timing directly. Signal processing is necessary to detect and recover the pulse signals from distortion, noise, and interference [62].

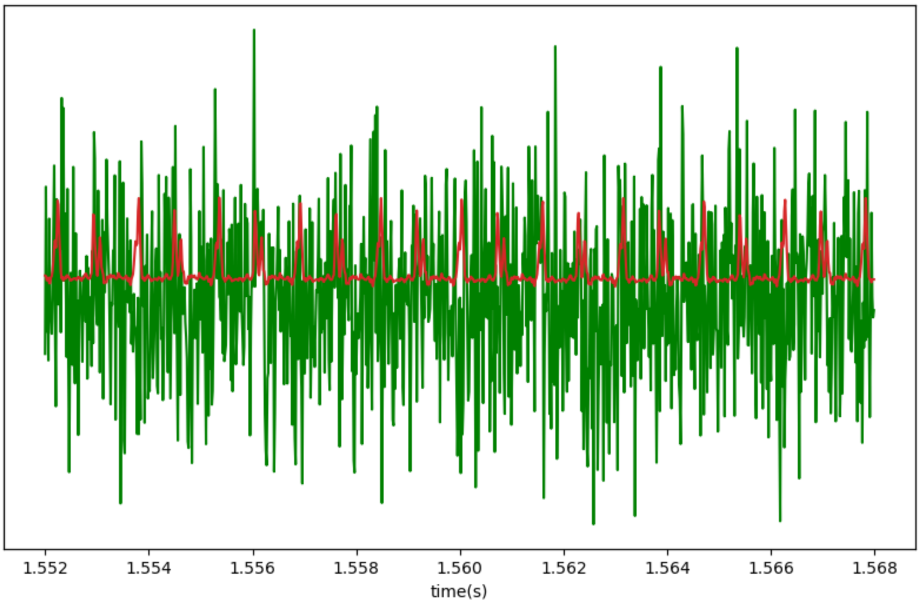

Figure 4. MSP J1939+2134 received waveform and pulse profile.

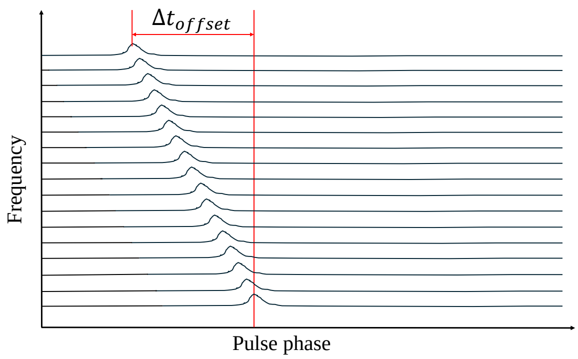

Figure 5. Pulses at different frequencies with effect of dispersion.

The entire processing procedure, shown in Figure 6, starts from the output of the Analog-to-Digital Converter (ADC) in the radio telescope and ends with the Pulse-Per-Second (PPS) signal generation [62].

Although pulsar timing signals exhibit high long-term stability, the short-term stability is less precise due to multiple sources, such as noise and interference from outer space, the atmosphere, the antenna, and signal processing errors. To address this, a local clock with good short-term stability is used, combined with a locking and control module, to ensure accurate pulse signal generation as referenced in [63].

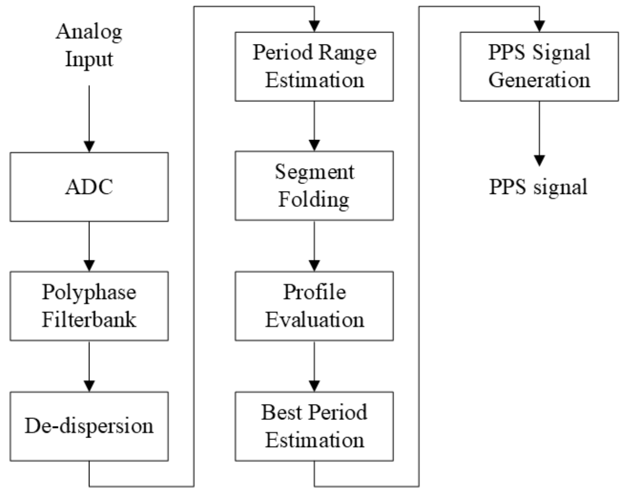

Figure 6. Block diagram of pulsar data processing.

3.3.2. Accuracy

Since a pulsar is a star far away from Earth, many factors in the propagation path, data processing, and hardware implementation can have an impact on the timing accuracy.

Through long-term observations of MSPs, pulse arrival times can be measured with a precision better than 1 µs [61].

In the case study of reference [62], MSP J1939+2134 with period 1.557 ms, the total process time is 599.5 s, and the sampling period after PFB is 16 µs; the theoretically minimum achievable error in PPS signal is 26.69 ns.

Reference [65] describes the pulsar-based positioning system. Using more than three pulsars, a timing error of 1 µs is sufficient to meet the requirements for a pulsar-based positioning system.

The timing drift of the tested pulsar-calibrated timing source is 1 µs over 91 min, as reported in reference [66]. Higher accuracy can be achieved by observing stable pulsars and integrating longer-term pulse data.

In general, with stable MSPs and enough observation time, the timing accuracy of a pulsar can achieve 1 µs or better.

3.3.3. Flexibility

Most pulsars are detected and monitored at radio wavelengths, typically utilizing either single large parabolic antennas with diameters of 30 m or more, or arrays of smaller antennas [58], for observing extremely bright pulsars, the antennae size can decrease, but it is still large compared to GPS or LEO antennae, which makes pulsar timing not very flexible. However, deploying a radio telescope at each location is unnecessary, as the accurate timing signal can be distributed using time distribution protocols.

The implementation of pulsar timing is the most expensive option, requiring a significant investment in telescope receivers and a complex signal back-end processing system.

3.3.4. Reliability and Security

Compared to the GPS timing system, the pulsar-based timing system offers enhanced resilience against system failures, space weather, and cyberattacks [67].

- System Failures: The likelihood of system failures is significantly reduced since radio telescopes are typically installed in open, unobstructed environments.
- Resilience to Space Weather: The working frequency of a radio telescope receiver is generally broader than that of a GPS receiver. This wider frequency range allows some signals to penetrate the atmosphere, even under adverse weather conditions.

- Protection Against Spoofing: GPS spoofing can be avoided because radio telescopes can observe multiple pulsars simultaneously. Unlike GPS receivers, which lock onto the strongest signal, radio telescopes identify specific pulsar signals, adding an extra layer of security.

3.3.5. Application

By the time of writing this paper, no known literature shows any application of a pulsar clock in the electrical grid or other industry sectors. But there are some lab experiments and a real pulsar clock for research.

The world's first pulsar clock was installed in St. Catherine's Church, Poland, in 2011. It was the first clock to measure time using a signal source beyond the solar system and the second type of clock to use a signal source outside Earth. The roof of the church houses a panel with 16 antennas that receive signals from six pulsars, with the pulsar signals processed digitally using an FPGA device.

Reference [63] designed a pulsar-based timing instrument (PBTI), which uses 3 h MSP J1713+0747 data recorded from the radio telescope, NRAO20. The generated PPS signal can be directly utilized for monitoring local power system devices. It also discusses potential applications of PBTI, including accurate sampling interval control, back up of GPS, and a power system controller.

Reference [66] introduces a pulsar-calibrated timing source to serve as the alternative timing solution when the GPS signal is unreliable. By estimating the actual frequency of the crystal oscillator used in the pulsar sampling equipment, a precise timing signal can be generated.

Reference [68] analyzes the possibility of deploying a 20 m radio telescope within an electrical substation to receive pulsar signal.

A hardware and software framework is developed in reference [69] to facilitate real-time high-density pulsar data transmission and processing, which can promote the application of pulsars in grid synchronization.

In general, with microsecond-level timing accuracy, pulsar timing can be applied to Digital Fault Recorders, event recorders, protective relays, lightning correlation, and other applications.

3.4. WWVB

WWVB is a time signal radio station located near Fort Collins, Colorado, operated by the National Institute of Standards and Technology (NIST). It continuously transmits digital time codes on a 60 kHz carrier frequency, providing a stable frequency reference traceable to the national standard maintained by NIST [70]. These time signals are broadcast every minute without interruption.

WWVB utilizes its own clock system, comprising a group of cesium beam clocks, which are steered to align with UTC (NIST) in Boulder. Although the UTC-synchronization accuracy at the WWVB time source can reach up to 35 ns, receivers located at various distances from the WWVB transmitter in Fort Collins, Colorado, experience differing levels of path delays. These delays, determined by the receiver's distance, limit WWVB synchronization accuracy to between 1 and 15 ms [71]. This limitation arises because the system operates in a one-way mode without compensating for path delay, resulting in signal delays of up to 15 ms at some locations within the continental United States [72]. However, if path delays are corrected, WWVB can deliver UTC with an uncertainty of approximately 100 µs [70].

Similar to GPS, due to its ease of application, the cost of adopting WWVB timing is relatively low.

The WWVB radio time service operates at a short wavelength, allowing its signals to penetrate indoors [73]. However, the 60 kHz radio time signal is highly susceptible to interference from sources such as screens, fluorescent lamps, nearby power lines, and transformers. The signal coverage area can be different in the day and night affected by noise ratio.

As a result, in terms of time accuracy, the uncertainty level of WWVB time dissemination is insufficient for applications requiring high precision, such as determining phasor angle separation. WWVB is more suitable for remote devices with lower precision and reliability requirements, such as SCADA monitoring or timestamp non critical information.

3.5. Summary of Time Sources

Among the four time sources discussed, all except pulsars utilize radio broadcast signals; pulsars emit natural electromagnetic radiation. While these sources share certain timing characteristics, their timing mechanisms and processes differ significantly.

GPS and LEO are satellite-based sources, while pulsars are neutron stars. Signals from GPS, LEO, and pulsars travel through space to reach Earth, covering varying distances. GPS, LEO, and WWVB provide controlled, man-made signals, while pulsars emit naturally consistent signals with long-term stability.

GPS, LEO, and WWVB broadcast time signals directly in formats such as timestamps or PPS (Pulse-Per-Second). In contrast, pulsar signals are natural pulses mixed with significant noise, requiring advanced signal processing and an initial timestamp from another source to generate usable time signals.

GPS and LEO offer global coverage, and while pulsar signals can also cover the globe, this requires observing multiple pulsars from different directions and switching between them as Earth rotates. WWVB primarily serves the U.S., though coverage may vary with distance from the broadcast station. Similar time signal services exist globally, such as JJY in Japan and BPC in China.

All four sources require receivers, but pulsar timing relies on large telescopes, making it less practical. This limitation highlights the need for robust time distribution systems in pulsar timing. GPS and pulsar receivers require outdoor installation, while LEO and WWVB receivers can function indoors, though WWVB may face reception challenges based on signal strength and location.

In power grid applications, GPS is widely used for time synchronization but is susceptible to signal loss and interference. LEO, offering similar mechanisms, flexibility, and accuracy, is emerging as a strong candidate for time synchronization in these applications. Pulsar signals, while naturally emitted and stable over the long term, are less flexible and less accurate than GPS, though sufficient for certain applications. WWVB is easy to deploy but limited in both accuracy and geographic reach.

A brief summary of the four time sources is shown in Table 2.

Table 2. Comparison of four different time sources.

Time Source	GPS	LEO	Pulsar	WWVB
Accuracy	Within 100 ns	100 ns$\sim$1 µs	$\sim$1 µs	1$\sim$15 ms
Flexibility	Flexible	Flexible	Not flexible (telescope is needed)	Flexible
Cost	Low	Low	High	Low
Reliability and security	Vulnerable	More resilient	More secure in terms of attacks	Vulnerable
Application	Most popular	Used in other sectors not in power system	Limited in lab experiment for now	Popular

4. Characteristics of Different Time Distribution Systems

In the U.S. power grid, where each interconnection spans vast geographical areas, achieving accurate timing presents significant challenges. Time errors among devices can potentially be misinterpreted as power system disturbances [23]. To ensure safe grid operation, a reliable and accurate time distribution system is essential. Building on our understanding of time-synchronized applications and the specific clock sources that support them, the following section will examine the characteristics of various time distribution systems, assessing their effectiveness in delivering precise and resilient time signals across the power grid infrastructure.

4.1. Network Time Protocol

The Network Time Protocol (NTP), as defined in RFC 5905 [74], is a widely used standard for transferring time over data networks, utilizing the User Datagram Protocol (UDP) to send timed messages.

4.1.1. Time Distribution Mechanism

At the network level, NTP operates within a hierarchical structure of participating servers [75]. The client, acting as the initial sender, periodically exchanges messages with the NTP server using a poll interval that gradually increases. Each NTP message includes the three most recent timestamps from exchanges between the two nodes. Once the message returns to the sender, a fourth timestamp is added, enabling the calculation of the round trip time and clock offset [19]. The synchronization algorithm is employed regularly and multiple times in quick succession for enhanced accuracy and reliability.

The measured offset is utilized to smoothly adjust the client clock through a control loop. Additionally, the client verifies the first timestamp in each incoming response, which should correspond to the transmission timestamp from the previous request, allowing it to detect packet loss or out-of-order delivery [19].

Each NTP daemon can be configured to utilize multiple independent reference time sources. It periodically polls these sources to evaluate and classify them as reliable or unreliable. This process enables the daemon to select a new system peer if the current peer becomes unavailable [18].

4.1.2. Accuracy

Each level in the NTP hierarchy is referred to as a Stratum. At the highest level, Stratum 1 servers synchronize directly with precise external time sources, such as atomic clocks or GPS devices (Stratum 0) [19]. NTP supports up to 15 strata, with synchronization accuracy decreasing as the stratum number increases. This means that the further a client is from a Stratum 0 time source, the lower the achievable synchronization precision.

In NTP, only the smallest observed round-trip times are considered to minimize the impact of network queuing delays. However, path delay asymmetry is not accounted for. Additionally, NTP networks experience extra latency because they rely on software-based processing, requiring timestamp requests to wait for the local operating system. In real-world environments, NTP is subject to various factors that cause asymmetrical runtimes in the round trip, leading to errors in time synchronization [76].

Variable network latency causes the precision of NTP to degrade, from a few microseconds at the top nodes, as achieved by NTPv4 in a local area network (LAN), to tens of milliseconds in the lower hierarchies, such as in wide area networks (WANs) [19].

4.1.3. Flexibility

NTP is a network-based and software-based time synchronization standard, which makes it easy and flexible to access. It allows computers across a network to synchronize their clocks with each other conveniently.

NTP requires only an Internet connection for time synchronization. Since the Internet is widely available today, the implementation cost is very low.

4.1.4. Reliability and Security

NTP is vulnerable to security issues, including the potential spoofing of NTP packets, which can lead to incorrect clock settings. There have been cases of NTP misuse and abuse, where servers have fallen victim to Denial-of-Service (DoS) attacks [77].

NTP is highly susceptible to attacks from malicious servers, which can occur in two primary ways: (1) the attacker gains control over existing timeservers within the NTP server pool, and (2) the attacker introduces rogue timeservers into the server pool to manipulate time synchronization [78].

4.1.5. Application

NTP is widely used by millions of hosts on the Internet to synchronize their clocks, ensuring accurate timekeeping essential for the proper functioning of many network applications [79] inside the substations and control centers.

When data connections are available and synchronization precision on the order of a few milliseconds is sufficient, NTP can be used to synchronize remote devices. In power systems, these devices typically handle noncritical measurements (e.g., weather data) or lower-speed events (e.g., market pricing signals or physical security notifications) [80].

Due to the accuracy, reliability, and security demands, Precision Time Protocol is usually adopted for time synchronization in modern power system applications listed in Section 2 [81].

4.2. Precision Time Protocol

The IEEE 1588 Precision Time Protocol (PTP) facilitates accurate synchronization of clocks in packet-based networked systems, accommodating heterogeneous systems with clocks of varying precision, resolution, and stability [82].

4.2.1. Time Distribution Mechanism

The protocol is suitable for systems where devices communicate over networks, including Ethernet [82].

PTP organizes clocks in a master–slave hierarchy, with the master clock serving as the time reference for the entire system, as illustrated in Figure 7. The protocol employs the Best Master Clock Algorithm to select the master clock, arranging the PTP network into a logical tree structure. The grandmaster clock acts as the tree's root, while slave clocks receive time synchronization messages over network links. Slaves adjust their clocks based on the time information exchanged in these messages [18]. Typically, the PTP grandmaster obtains its time information through a GPS receiver. PTP uses the request–response mechanism shown in Figure 8 to compute path delays within the network.

The PTP master clock initiates synchronization by sending a **Sync** message, marked with a departure timestamp t_1, which is timestamped upon arrival at the slave clock as t_2. The slave then responds with a **DelayReq** message, departing at t_3 and arriving back at the master clock at t_4 [83]. These timestamps define the trip times: t_{ms} for the master-to-slave journey and t_{sm} for the slave-to-master journey.

The slave calculates the round-trip path delay using the timestamps according to Equation (1). This delay is then used to compute the clock offset using Equation (2). By applying this offset, the slave adjusts its clock. Upon completing this process, the slave clock is synchronized with the master clock.

$$\text{Path\_Delay} = \frac{t_{ms} + t_{sm}}{2} = \frac{(t_4 - t_3) + (t_2 - t_1)}{2} \tag{1}$$

$$\text{Clock\_Offset} = (t_2 - t_1) - \text{Path\_Delay} \tag{2}$$

The computation of the clock offset and propagation time relies on the assumption that the master-to-slave and slave-to-master propagation times are equal and remain constant throughout the synchronization process [82].

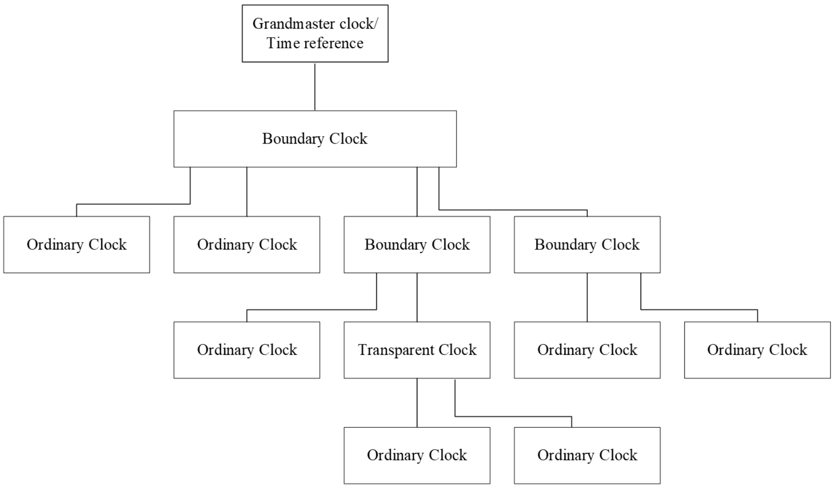

Figure 7. Hierarchy topology of PTP.

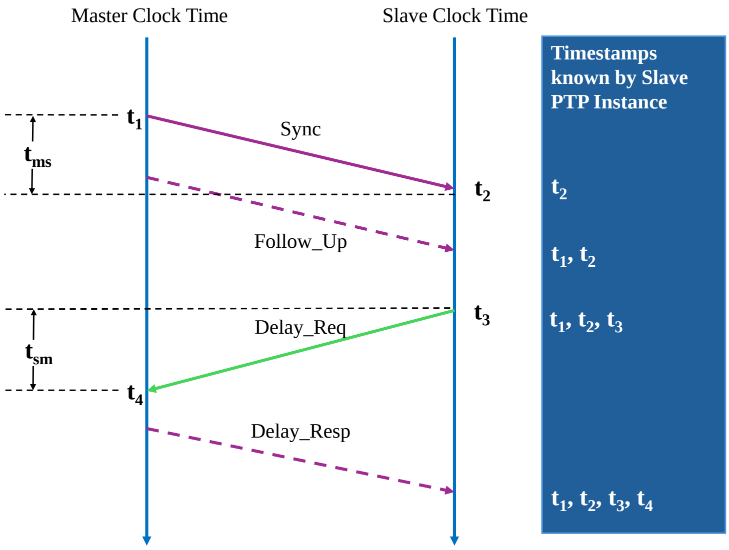

Figure 8. Basic PTP timing message exchange [80].

4.2.2. Accuracy

Any asymmetry in propagation time and variations in transmission delay can degrade the accuracy of offset measurements between two clocks [84]. In practice, the path delay between a master and slave clock is rarely symmetrical.

PTP clock synchronization accuracy relies on the precision of recorded timestamps. To enhance this accuracy, three key elements have been introduced: hardware timestamping, transparent clocks, and boundary clocks [84].

PTP employs hardware timestamping instead of software timestamping, allowing devices dedicated to synchronization to achieve higher time resolution. Unlike NTP, PTP devices timestamp the time spent by synchronization messages within each device, accounting for device latency.

Transparent clocks refer to network devices, such as switches, that facilitate compensation for variable packet delays. These devices provide "residence time correction" by adding the time spent within each transparent clock to the correction field of PTP messages, thereby improving delay measurement accuracy across the network [84].

Boundary clocks are used to segment large networks, reducing the load on each PTP master by handling fewer clients. A boundary clock synchronizes its local clock to a PTP master using information from "Sync" messages and can act as a surrogate PTP master for downstream clients, as illustrated in Figure 8 [84].

With these design enhancements, PTP achieves synchronization accuracy and precision within the sub-microsecond range, requiring minimal network and computing resources [82]. In well-designed networks, sub-nanosecond time transfer accuracy is attainable.

4.2.3. Flexibility

Like NTP, PTP is a network-based time synchronization standard, which makes it easy and flexible to access, with no need to install and maintain dedicated timing cables. But in order to improve synchronization quality, PTP is typically used in conjunction with hardware support with regard to the generation of timestamps [80], which is different from the software-based NTP.

With the hardware-based Ethernet time synchronization method, the cost of PTP can be higher than NTP due to the need for dedicated hardware. However, it remains relatively inexpensive.

4.2.4. Reliability and Security

PTP networks are vulnerable to various cyber-attacks, including delay attacks, packet modification attacks, transparent clock attacks, and time reference attacks. These attacks can significantly degrade the protocol's accuracy, rendering it unsuitable for some or all clocks in the network, potentially leading to severe consequences [85].

The delay attack is the most critical vulnerability in PTP networks. PTP assumes symmetry in the master-to-slave and slave-to-master path delays when calculating the propagation delay. A delay attack exploits this assumption by introducing asymmetrical delays, which are hard to distinguish from regular network congestion or delays. This makes the attack difficult to detect and effective in disrupting the synchronization of PTP slave clocks [18].

4.2.5. Application

The PTP power profile enables the use of PTP for power system protection, control, and automation applications [18]. It is recommended for time synchronization at the substation level by the IEC 61850 standard [86]. Due to its high accuracy, it can be implemented in all the applications listed in Section 2. However, considering the cost, critical applications such as PMUs, fault recorders, and protection relays typically adopt PTP.

Most deployed PMU devices rely on GPS for a synchronizing clock, with the GPS signal typically communicated to power system measurement and control devices using the IRIG-B protocol. However, due to the need for specialized cabling, additional timing requirements, and the increasing number of devices requiring precise time in power system substations, this traditional approach is gradually being replaced by PTP [80].

As power system applications increasingly depend on measurements from PMUs and faster devices, alternative clock synchronization methods beyond GPS are being explored. Proper deployment of PTP is being considered as a means to integrate GPS and other trusted, precise clock sources into a unified timing architecture. This approach offers backup timing sources and enhances the overall robustness of precision time synchronization, which is essential for accurately measuring power system conditions [80].

4.3. White Rabbit

The White Rabbit (WR) Project is a collaborative project conceived and developed by the European Organization for Nuclear Research (CERN), as well as parties from academia and industry. Its main purpose is to develop a method capable of fully deterministic, sub-nanosecond clock synchronization within distributed, Ethernet-based computer networks [87].

CERN, home to the Large Hadron Collider (LHC), which accelerates particles around a 27 km ring, relies on a large Ethernet network for time synchronization, with performance requirements at the subnanosecond level. To meet these stringent requirements, CERN developed a PTP Profile known as White Rabbit [80].

White Rabbit introduces several innovative techniques, including enhancements for utilizing Ethernet hardware clocks and calibrating asymmetry in fiber-optic cabling. These innovations have been incorporated into a new PTP Profile, known as the High-Accuracy Delay Request–Response Default PTP Profile, specified in the IEEE 1588-2019 standard. By formalizing White Rabbit within the IEEE 1588 framework, this profile extends best-in-class performance to a variety of applications, including nonscientific fields such as electric power grid measurement and control [80].

4.3.1. Time Distribution Mechanism

WR is built upon the Ethernet (IEEE 802.3) [88], Synchronous Ethernet (SyncE) [89], and PTP standards. It also incorporates a technique called Precise Phase Measurement. The integration of these technologies allows WR to achieve sub-nanosecond accuracy.

A typical White Rabbit (WR) network, as illustrated in Figure 9, consists of WR nodes and WR switches connected by fiber links. From a data perspective, it functions as a standard Ethernet switched network with no hierarchy, allowing any node to communicate with any other node. However, in terms of time synchronization, a hierarchical structure exists, beginning with the WR master at the top, cascading down to other WR switches and subsequently to the nodes [90].

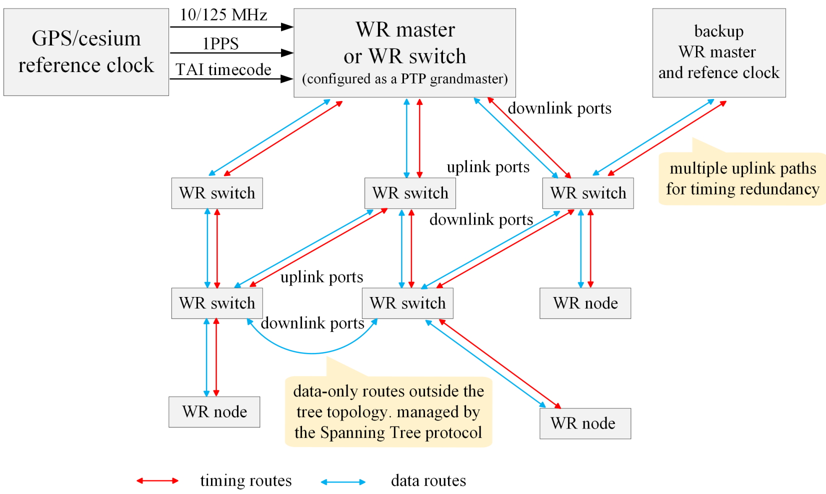

Figure 9. The WR network architecture [91].

The top-level switch in the hierarchy, referred to as the grandmaster, receives absolute time along with the PPS signal and a 10 MHz reference from an external source, typically a Cesium or Rubidium oscillator disciplined by GPS [92]. During startup, the WR switch uses the timecode and PPS to establish the absolute UTC time and then relies solely on the 10 MHz signal for time calculations. Once the reboot process is complete, usually within a few minutes of powering on, the timecode service and PPS signal are no longer required, and the grandmaster switch can potentially disconnect from these sources. The accuracy of the round-trip time measurement is primarily determined by the precision of the 10 MHz reference. The grandmaster switch distributes the time information to additional WR nodes through intermediate WR switches [90].

Typical PTP implementations use free-running oscillators at each node, leading to increasing time drifts between the master and slaves. This issue is addressed by the SyncE protocol, which transfers frequency over the Ethernet physical layer to ensure that all network nodes operate at precisely the same rate. Each WR switch utilizes the clock recovered from the data link to sample incoming data. For transmission, it employs an embedded PLL-based oscillator locked to the recovered clock, ensuring synchronized frequency across the network.

As shown in Figure 10, on a link directly connecting two WR nodes, A and B, the L1 tx clock signal transmitted by node A at its port, which is in the master state, is synchronized to its local PTP clock. WR node B, with its port in the slave state, synchronizes its local PTP clock to the L1 rx clock signal received from node A. Consequently, the local PTP clocks of both WR nodes are frequency-traceable to the same source, the grandmaster, without relying on the PTP protocol. The PTP protocol is used solely to measure the link delay and offset from the master, enabling WR node B to adjust the time counter and phase of its local PTP clock [93].

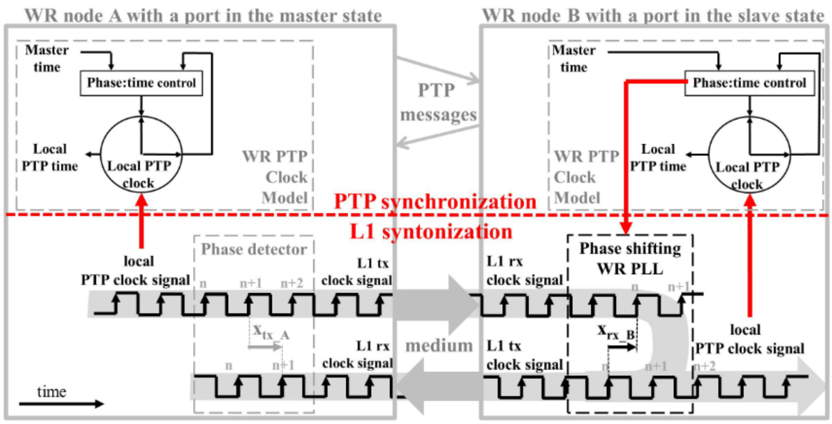

Figure 10. WR synchronization and syntonization scheme [93].

The detailed path delay, frequency detector, and phase align sequence is shown in Figure 11.

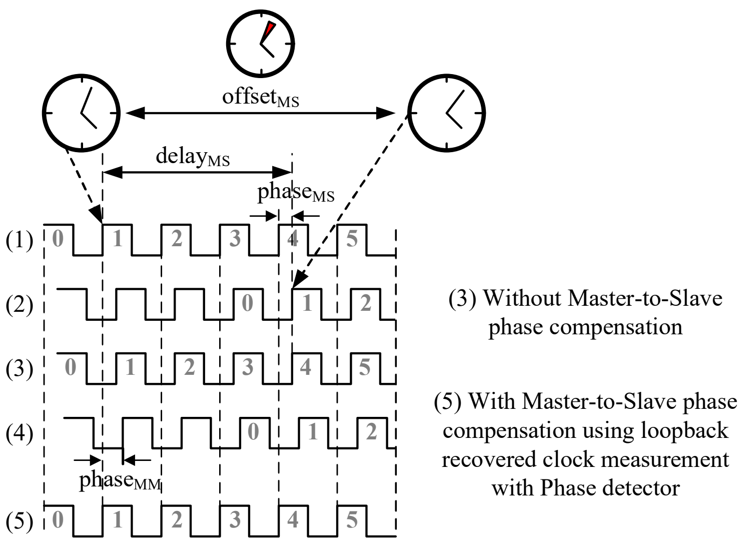

Figure 11. WR time synchronization scheme [91].

Synchronization in WR is achieved through phase adjustment (phase-steering) rather than directly altering the time counter value. The WR PLL not only synchronizes the local PTP clock to the recovered L1 rx clock signal but also maintains a specified phase offset between these two clock signals [93]. Each WR switch is equipped with a phase measurement module that uses phase/frequency detectors to periodically measure the phase difference between the recovered clock and the master clock [94].

This procedure ensures a high level of jitter elimination. Since it operates at the physical layer, its accuracy is unaffected by data transmission issues, such as packet delays or traffic load. The technology has demonstrated the capability to transfer highly accurate timing over long distances [91].

Same as PTP, WR calculates the path delay, but the difference is that WR considers the asymmetry in propagation time. In a WR network, PTP messages are handled not only by the grandmaster clock but also by the WR switches. This approach minimizes the exchange of PTP messages over long links between the master and far-side slaves, thereby reducing the jitter that each switch inherently introduces. Additionally, it decreases the number of messages exchanged between the master and slaves, lowering PTP-related throughput requirements and freeing up more bandwidth for mission-critical data exchange [90].

4.3.2. Accuracy

There are two key elements that distinguish the implementation of WR PTP from other PTP implementations: (1) tight cooperation between the PTP synchronization and the Layer 1 (L1) syntonization, L1 syntonization means a matching frequency of physical clocks at the hardware layer; (2) enhanced timestamping precision through phase detection. The implementation of L1 syntonization is evaluated using SyncE metrics and phase noise transfer analysis [93]. These techniques enable WR to achieve sub-nanosecond accuracy, provided the network employs only fiber interconnections and dedicated telecom switches.

The frequency distribution can achieve a precision better than 50 ps [95].

The National Time Laboratories in different countries including NIST are studying WR with different types and lengths of fiber links. The time error is within 8 ns. The stability (at τ = 1 s) is 1×10^{-11} and can be improved to 1×10^{-12} without any modifications to the WR-PTP Protocol [92].

4.3.3. Flexibility

Higher accuracy means lower flexibility compared to NTP and PTP. WR requires hardware investment including fiber and switches. Although fiber is the preferred physical layer for WR, copper can be utilized as well in parts of the network where timing requirements are less stringent [96].

But if the electrical grid is already equipped with fiber-optic cables, it can facilitate the application of WR; for example, differential protection will use optical fiber for communication. PMU-based monitoring or control application depends on telecom infrastructures to transmit PMU data; the same physical layer can be utilized for time dissemination [90].

With the requirement for dedicated hardware and optical fiber, WR is the most expensive method to implement. However, this cost is justified by its high-accuracy performance.

4.3.4. Reliability and Security

The protocol ensures reliable and deterministic data delivery, enabling the synchronization of thousands of devices across a network that extends over several kilometers [97].

But it is still a relatively new technology. Many improvements have been made in terms of WR research and application.

Reference [98] studies the hardware reliability of the WR switch. It shows good performance in extreme environments.

Reference [95] exposes five adoption issues and the corresponding solutions.

4.3.5. Application

At the time of writing, no literature has documented real-world applications of WR in power grids. However, extensive experiments and research on WR can be found in the literature. Additionally, WR has been implemented in real-world applications in other sectors to enhance time synchronization accuracy.

With growing demands for precise time synchronization in sectors such as science, finance, and telecommunications, WR is being increasingly adopted for various applications. The technology is currently under evaluation by the United States Department of Transportation as a potential GPS backup, and several telecom companies have presented preliminary findings at international conferences and professional societies [95].

An overview of White Rabbit (WR) applications is provided in [92]. WR is used at GSI (Darmstadt, Germany) as the foundation of the General Machine Timing (GMT) system for accelerator control, operational since 2015. It is also deployed in the Cubic Kilometre Neutrino Telescope, located on the Mediterranean seabed, for precise timestamping. At CERN, WR facilitates fixed-latency data transfer, enabling real-time distribution of magnetic field values in accelerator operations.

WR's application in long-distance optical fiber links was demonstrated in [99], which realized a 950-km WR link across existing communication fiber networks between Espoo and Kajaani, Finland.

WR is also increasingly explored in power grid applications. Reference [90] discusses WR's use in synchrophasor networks, comparing the accuracy of WR-based PMUs with other technologies such as GPS and PTP, and highlighting WR's suitability for PMU sensing networks. In distribution PMUs, WR meets the high accuracy requirements essential for these networks, with total vector error (TVE) standards at least two orders of magnitude stricter than those for transmission PMUs (TVE below 0.01%) [100].

A case study in [101] illustrates WR's use in distributing precise timing in substation automation systems. Because WR provides both accurate time and frequency transfer, it is particularly suited for applications in high-precision sampling.

In general, due to its strong performance, WR can be implemented in all the applications listed in Section 2. The primary factor to consider is the cost.

4.4. 5G

For cellular networks, 5G is the fifth-generation technology standard with high reliability and supporting determinism in terms of latency up to 1 ms, and synchronism with jitter below 1 µs, as required by Third Generation Partnership Project (3GPP) [102].

4.4.1. Time Distribution Mechanism

Synchronization is one of the most important issues for telecommunications. Reliable and low-latency deterministic communications require accurate timing information [103].

Multiple standards related to 5G have very strict time error requirement. In fact, 5G radios use Time Division Duplex technology, where the uplink and downlink, respectively, use the same frequency band. There is a space between transmission time intervals called a guard band, which is a period of silence. Guard bands are implemented to ensure that there is no overlap in the timeslots transmitting and receiving information, otherwise the frequency overlaps and causes interference between adjacent timeslot channels. To increase the data transmission rate, guard bands should be as small as possible but also consider interference mitigation. This is the reason why accurate time information is essential in 5G.

Carrier Aggregation (CA) is a key technology in 5G, enabling the simultaneous use of multiple carriers across the same or different frequency bands to enhance mobile data throughput [104]. The time alignment error (TAE) requirement for CA is specified in 3GPP TS 36.104, not exceeding 130 ns or 260 ns [105]. This is the alignment requirement between links, which is the relative time error. For absolute time error, within ±1.5 µs drift to UTC is required [105].

Since 5G already has an accurate time information network for communication purposes, this time information can be used in any applications that need time synchronization. In this sense, the 5G network can be treated as a time distribution network.

Why can the 5G network achieve a high time accuracy? This is determined by PTP. In terms of time synchronization, 5G can be explained as an extension of PTP. The time synchronization needs in 5G are defined in separate PTP Profile standards. The International Telecommunication Union Telecommunication Standardization Sector (ITU-T) has defined two important telecom profiles for PTP: G.8275.1 and G.8275.2. Among these, G.8275.1 offers the highest level of accuracy [106]. Additionally, IEEE provides key PTP standards relevant to mobile networks. One of these is IEEE 802.1AS, which specifies a "generalized" PTP (gPTP) profile and forms part of the Ethernet Time-Sensitive Networking (TSN) standards, as shown in Figure 12.

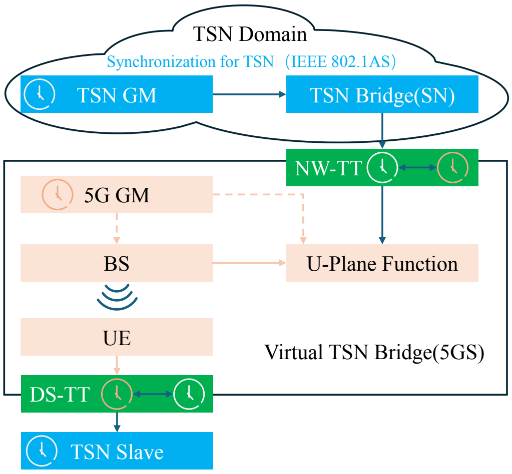

Figure 12. Time synchronization message transportation in 5G-TSN network.

4.4.2. Accuracy

As explained, the time accuracy is within ±1.5 µs compared to UTC. More strict time requirements such as several ns can be achieved according to different standards and solutions [107].

4.4.3. Flexibility

If the 5G network is set up for communication in a power grid, we can take advantage of this infrastructure to conduct time synchronization at the same time, which makes it a very flexible time synchronization method.

With existing network infrastructure already in place for communication purposes, 5G timing can be a cost-effective solution, comparable to NTP and PTP.

4.4.4. Reliability and Security

Partly due to the implementation of network slicing, 5G is regarded as a reliable communication method and is generally secure. Network slicing is a paradigm that enables the shared use of the same infrastructure to deliver differentiated 5G services. This differentiation can be observed in terms of functionality (e.g., mobility, security, and control) and performance (e.g., latency, throughput, error rate, reliability, and availability) [108]. This ensures that critical time-sensitive communication is isolated from other traffic, protecting privacy and improving reliability and accuracy.

But, like PTP, there are some attacks targeting the time signal. Much of the literature provides corresponding solutions.

There are other concerns in terms of time synchronization in power grids with 5G technology [109], such as resilience, network congestion, and signal interference. Accurate synchronization could be affected by natural disasters and severe weather. Any downtime in the 5G network could impact real-time grid operations.

4.4.5. Application

In power grid wireless communication, 5G is a popular method. Managing power distribution networks, which face a growing integration of distributed energy resources and increasing demands for reliability, efficiency, and flexibility, requires advanced communication technologies and services. These technologies are essential for functions such as protection, control, and remote monitoring [110]. However, no real-world application of 5G for time distribution in power grids has been reported so far.

Reference [111] designs a high-precision wireless network time synchronization module based on PTP. This module can achieve a time synchronization accuracy of up to approximately 150 ns, with a maximum fluctuation range between the slave clock and the master clock of 400 ns.

Considering its accuracy performance, 5G can be implemented in applications such as fault and event recorders, protection systems, and network communication timing.

4.5. Summary of Time Distribution Systems

All four time distribution systems are network-based and have close interconnections.

NTP is the simplest time distribution method but offers lower accuracy, in the millisecond range, which limits its application in power grids. It is more suited for non-critical applications. The other three methods—PTP, White Rabbit, and 5G—are all based on PTP with different implementations and performance levels. PTP provides higher accuracy than NTP, reaching the microsecond range with dedicated hardware. Furthermore, 5G can be considered an extension of PTP with similar accuracy but operating over a wireless network. White Rabbit combines Synchronous Ethernet and PTP, utilizing dedicated hardware and optical fiber to achieve the highest accuracy in the nanosecond range. However, it is also the most expensive method.

A brief summary of the four time distribution systems is shown in Table 3.

Table 3. Comparison of four different time distribution systems.

Time Distribution Systems	NTP	PTP	WR	5G
Accuracy	ms	Within 1 μs	ns	Within ±1.5 μs
Flexibility	Flexible	Flexible	Not flexible (hardware and fiber investment)	Flexible if it has 5G network
Cost	Low	Low	High	Low
Reliability and security	Vulnerable	More resilient	More secure	Resilience concern
Application	Popular	Popular	Used in other sectors	No application in timing

5. Challenges and Future Research Directions

As power systems become increasingly complex and interdependent, achieving precise synchronization presents several challenges related to distance, accuracy, and reliability.

In wide-area monitoring, time signals must be highly synchronized across vast geographical areas, complicating the extension of time distribution systems' coverage. The capability to capture and analyze local and inter-area oscillations, respond to fluctuating conditions from intermittent renewable energy sources, and manage distributed generation allows the grid to detect transient events and respond dynamically, enhancing operational efficiency and reliability [32]. These requirements demand higher levels of time signal accuracy.

Reliability and security are also paramount. Existing time synchronization methods face challenges from spoofing and cyberattacks, necessitating alternative or backup solutions to a ensure continuous, secure operation.

To address these challenges, future research directions include the following:

1. Integration of Multiple Time Sources: As systems dependent on precision timing, like GPS and synchrophasor networks, are vulnerable to intentional and unintentional failures, incorporating multiple time sources can enhance redundancy and reliability [23]. The integration process must be designed for real-time, seamless switching to maintain uninterrupted synchronization and system stability.
   Reference [112] provides insights into time source integration. In this study, a μPMU was designed and implemented with dual time synchronization signals (GPS and IEEE 1588). Using GPS as the primary time synchronization signal and IEEE Std. 1588 as the backup ensures data integrity by maintaining synchronized electricity information and time.
2. Advancement of Pulsar Timing Signals: Pulsar signals, being naturally resistant to attacks, offer a promising backup for GPS in time synchronization. However, applying pulsar timing in power grids requires developing flexible and reliable solutions beyond laboratory settings. This includes designing systems that can effectively capture and process pulsar signals with sufficient accuracy and compatibility for grid infrastructure.
3. Enhancing GPS and LEO Anti-Attack Measures: While anti-attack strategies have been incorporated into LEO timing designs, there is room for further security enhancement. Continued research on advanced encryption, authentication methods, and signal interference mitigation can improve the resilience of GPS and LEO systems against cyber threats and spoofing attacks, establishing a more secure and reliable time synchronization framework.
4. Developing Cost-Effective White Rabbit Solutions: Although White Rabbit (WR) technology achieves high timing accuracy, its complex structure and implementation cost pose challenges. Future research could focus on cost-effective WR solutions by simplifying system architecture and optimizing components, making WR a more feasible option for widespread deployment in power grids.

6. Conclusions

In this paper, four time sources (GPS, LEO satellites, pulsar signals, and WWVB) and four distribution mechanisms (NTP, PTP, White Rabbit, and 5G) were systematically evaluated, and their characteristics, performance, and suitability for power grid scenarios were compared. While traditional methods like GPS remain widely adopted due to their balance of accuracy and flexibility, emerging technologies such as LEO constellations and 5G are redefining synchronization paradigms with enhanced coverage and scalability.

The analysis underscores that no single method is universally optimal. Instead, the selection hinges on aligning the method's strengths with the application's priorities. For instance,

- High-precision applications: Phasor measurement units (PMUs) and substation automation necessitate sub-microsecond accuracy and deterministic performance, making White Rabbit or PTP with 5G the preferred choices. These methods leverage optical synchronization or ultra-reliable low-latency communication (URLLC) to meet stringent timing requirements.

- Wide-area monitoring and fault detection systems: These prioritize resilience alongside precision. Here, GPS/LEO serves as a viable primary source if augmented with anti-jamming measures, while pulsar signals offer a niche backup for GNSS-denied environments due to their inherent spoofing resistance.
- Cost-sensitive deployments: Applications such as smart metering and demand response favor scalable solutions like 5G network timing or LEO satellites, which minimize per-device costs while achieving millisecond-level accuracy sufficient for non-critical tasks.
- Legacy systems: Systems like SCADA require compatibility with existing infrastructure, positioning PTP with hardware timestamping as a pragmatic upgrade path that balances accuracy with interoperability.

Security emerges as a critical cross-cutting concern. While GPS and NTP are vulnerable to cyberattacks and signal interference, methods like quantum-secured PTP or hybrid architectures combining GNSS with terrestrial PTP mitigate risks through encryption and multi-source validation. Meanwhile, WWVB and pulsar-based systems, though limited in accuracy, provide low-complexity alternatives for non-critical or remote applications.

Looking ahead, the integration of emerging technologies—such as LEO constellations for global coverage, 5G for scalable synchronization, and AI-driven error correction—will enable hybrid frameworks that maximize robustness. However, interoperability standards and cybersecurity protocols must evolve in parallel to address the growing complexity of grid infrastructure. Future research should prioritize harmonizing these technologies while exploring pulsar-based timing and quantum encryption to future-proof power grids against both technical and threat-related disruptions.

In conclusion, the optimal synchronization strategy for power grids lies in a context-aware approach that rigorously evaluates accuracy, security, cost, and coverage against operational needs. By judiciously selecting and combining methods—such as pairing GNSS with terrestrial PTP or deploying 5G for distributed assets—grid operators can achieve a resilient, future-ready synchronization ecosystem that supports the transition to smart, decentralized energy systems.

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Abbreviations

The following abbreviations are used in this manuscript:

NERC	North American Electric Reliability Corporation
UTC	Universal Coordinated Time
PMU	Phasor Measurement Unit
SCADA	Supervisory Control and Data Acquisition
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
DFR	Digital Fault Recorder

KCL	Kirchhoff's Current Law
NLDN	National Lightning Detection Network
TWFL	Traveling Wave Fault Location
PDC	Phasor Data Concentrator
TVE	Total Vector Error
MEO	Medium Earth Orbit
MC	Master Clock
USNO	United States Naval Observatory
PNT	Positioning, Navigation, and Timing
LEO	Low Earth Orbit
STL	Satellite Time and Location
NTP	Network Time Protocol
PPS	Pulse Per Second
NIST	National Institute of Standards and Technology
GPSDC	GPS Disciplined Clock
FCC	Federal Communications Commission
MSP	Millisecond Pulsar
PFB	Polyphase Filter Banks
FPGA	Field-Programmable Gate Array
PBTI	Pulsar-Based Timing Instrument
UDP	User Datagram Protocol
LAN	Local Area Network
WAN	Wide Area Network
PTP	Precision Time Protocol
WR	White Rabbit
CERN	European Organization for Nuclear Research
SyncE	Synchronous Ethernet
PLL	Phase-Locked Loop
L1	Layer 1
GMT	General Machine Timing
3GPP	Third Generation Partnership Project
CA	Carrier Aggregation
TAE	Time Alignment Error
TSN	Time-Sensitive Networking
ADC	Analog-to-Digital Converter

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