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A Hybrid System for High-Accuracy Timekeeping Using Millisecond Pulsars

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***Abstract*— Millisecond pulsars exhibit rotational stability rivaling atomic clocks, making them ideal for high-accuracy timekeeping. This paper presents a hybrid pulse-per-second (PPS) generation system that fuses pulsar-derived timing with phase alignment to Global Positioning System (GPS) timing. Logic-gate arrays produce real-time PPS outputs that are continuously calibrated against the pulsar signal to correct oscillator drift, yielding a reliable timing reference independent of GPS. A fully integrated experimental platform for signal generation and distribution achieves an alignment error within 20 nanoseconds in generation and latency under 2 nanoseconds in distribution. These results demonstrate that the architecture satisfies the stringent synchronization requirements of modern energy infrastructures.**

Keywords—Timing; millisecond pulsar; pulse per second; FPGA; signal processing

I. Introduction

The millisecond pulsar, formed from a neutron star, is a cosmic object renowned for its extraordinary stability in rotational period [1], rivaling the precision of atomic clocks [2]. For example, PSR J1939+2134 has an exceptionally short rotational period of 1.5578 milliseconds [3]. Over time, this period exhibits an almost imperceptible slowing, with the rotation lengthening by one microsecond over approximately 2×10^{15} years. Fig. 1 illustrates the classical profile characteristics of a pulsar signal. The stable rotational period ensures a consistent timing of the received signal [4], even though the intensity of the signal varies due to changes in the relative positions of the pulsar and the observer.

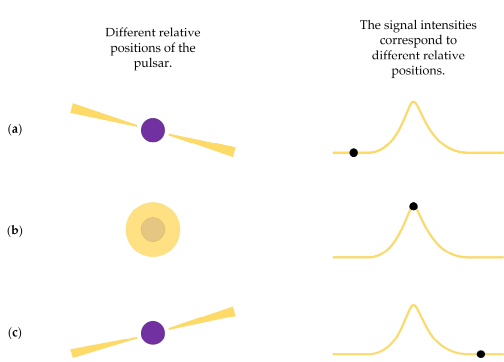

Fig. 1. Demonstration of the pulsar signal intensity.

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Consequently, millisecond pulsars provide a continuously reliable timing clock, immune to terrestrial disruptions, ensuring uninterrupted functionality [5]. Many critical industries depend on GPS for high-precision timing, but GPS signals are vulnerable to jamming, spoofing, and signal degradation. For instance, in power system control, phasor measurement units (PMUs) heavily rely on GPS signals as a precise timing reference to enable synchronized and accurate wide-area measurements [6]. Invulnerable to GPS outages, pulsar-based timing could enhance the reliability of industry applications by offering a high-accuracy alternative timekeeping solution, including distributed energy systems; PMUs and protective relays in smart grids; telecommunications networks; data-center clocking for distributed databases and computing; financial trading platforms; and more [7].

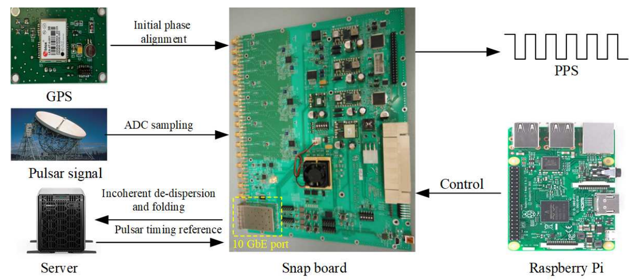

Fig.2. Hardware platform of hybrid timing system.

To implement this concept, a hybrid timing system is proposed that exploits the inherent stability of pulsar signals to achieve high-accuracy timekeeping. In this architecture, the PPS output is driven primarily by the pulsar reference, while GPS serves only for initial phase calibration and occasional validation. Should GPS signals become unavailable, the system continues to generate uninterrupted PPS outputs. The resulting PPS signal is then distributed across the network via the White Rabbit timing-distribution protocol. Experimental validation on an integrated test platform confirms the system's capability for precise PPS generation and reliable distribution.

II. Hybrid Timing System

The hybrid timing system incorporates multiple hardware components and is primarily controlled by a field-programmable gate array (FPGA)-based hardware processor that implements the designed timing-track methodology. The

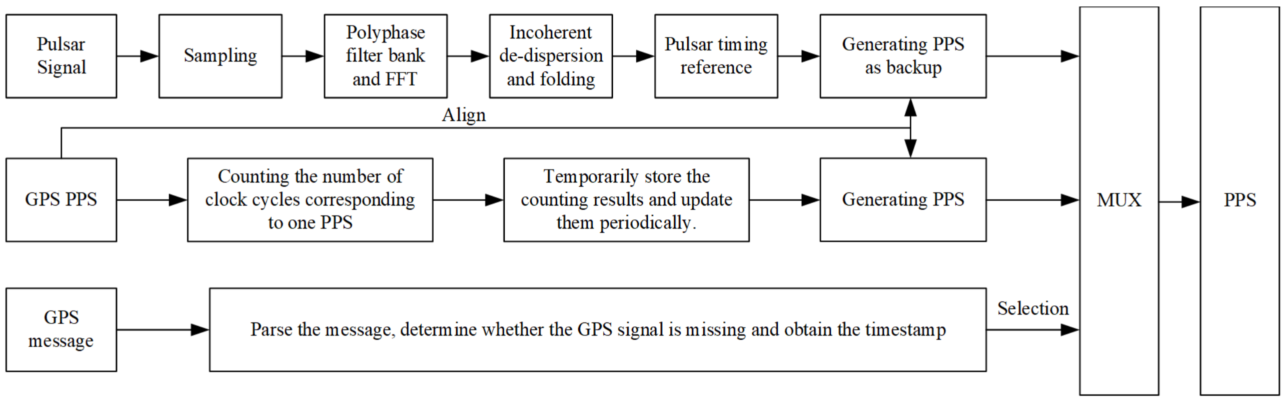

Fig.3. Workflow of Hybrid timing system for PPS Generation.

hardware platform is shown in Fig. 2, and the timing-track methodology is illustrated in Fig. 3.

A. Hardware Platform

Millisecond pulsars emit continuous, wideband radio-frequency (RF) signals spanning the MHz to GHz range. To capture these signals without aliasing or information loss, multichannel ADCs are used to sample RF inputs in accordance with radio telescope requirements [8]. Consequently, high sampling rates and low-latency digital processing are essential to maintain signal fidelity and support real-time analysis.

As shown in Fig.2, The SNAP (Smart Network ADC Processor) board is employed as the primary data - acquisition and preprocessing platform due to its integrated Xilinx Kintex-7 FPGA, with hundreds of digital signal processing (DSP) slices for highly parallel, pipelined signal processing [9]. The board supports up to 1 GS/s per channel in single-channel mode across twelve ADC channels, enabling simultaneous digitization of multiple receiver paths. Its FPGA-centric architecture simplifies hardware control and permits on-the-fly implementation of digital downconversion, filtering, and channelization, thereby fulfilling the demanding real-time requirements of millisecond pulsar observations.

High-speed data transmission to a backend server is achieved via the SNAP board's 10 GbE interface, where pulsar signal processing is performed. Configuration flexibility is provided by a Raspberry Pi, which manages SNAP parameters over a control link. GPS time referencing is obtained from a u-blox LEA-6T GPS module, whose output delivers sub-microsecond timing accuracy for phase alignment.

B. Methodology

As shown in Fig. 3, a hybrid workflow integrates GPS and pulsar references to produce a continuous, high-accuracy PPS output. The PPS generation logic is as follows: the FPGA on the SNAP board is driven by an external oscillator with an original clock frequency of 10 MHz, which is multiplied to 100 MHz to support FPGA operations. First, the pulsar signal is digitized by multichannel ADCs and processed through a polyphase filter bank and FFT, followed by frequency-domain filtering. Incoherent de-dispersion mitigates propagation-induced noise, while an adaptive folding technique enhances signal clarity and quality, generating a high-fidelity pulsar timing reference.

Concurrently, incoming GPS messages are parsed in real time to verify satellite lock and extract precise timestamps; during periods of valid GPS reception, on-board counters accumulate clock cycles between time tags to produce a GPS-derived PPS signal, which is periodically recalibrated to maintain accuracy. Upon loss or degradation of GPS signal, a hardware multiplexer automatically switches to the pulsar timing reference, ensuring uninterrupted PPS output.

Once the pulsar timing reference is obtained and the GPS timing reference is phase-aligned, the SNAP board uses multiple FPGA clock cycles to generate the PPS signal. A comparator compares the timing reference with the counter value, while a constant block adjusts the duty cycle, ensuring accurate and consistent pulse generation. This seamless failover mechanism guarantees uninterrupted, high-accuracy timekeeping even in GPS-denied environments.

C. Illustration of pulsar timing reference

Fig. 4 illustrates the utilization of the pulsar timing reference for precise timestamp tracking. The top panel depicts the pulsar timing reference obtained from PSR J1939+2134 at a carrier frequency of 610 MHz. Each clearly resolved pulse corresponds to the known pulsar period of $P_s = 1.5578$ms. For clarity, each period is represented by $N_{ps} = 1000$ sampling points, the pulsar peaks are labeled as n_{peak}.

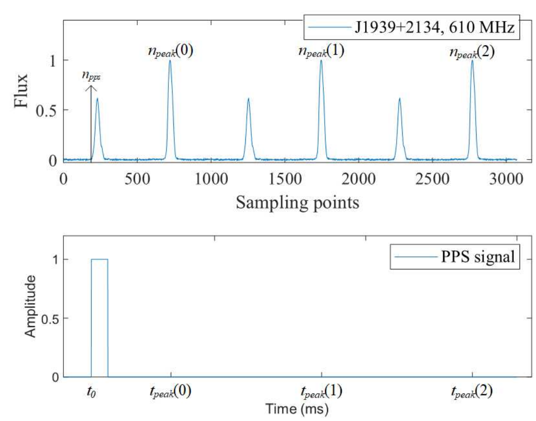

Fig.4. Timestamp tracking of pulsar timing reference with PPS calibration.

The lower panel shows the interaction between the PPS signal and the pulsar timing reference. The rising edge of this PPS trace, occurring at sample index n_{pps}, defines the end of last second and the start of a new second. The timestamps of each pulsar peak are given by:

$$t_{peak}(n) = t_0 + \left(n + \frac{n_{peak}(n) - n_{pps}}{N_{ps}}\right) \times P_s, n = 0,1, \ldots$$

where t_{peak} are the timestamp of pulsar peaks, t_0 is the timestamp of the PPS rising edge, and n is the pulsar count.

Obviously, once the initial timestamp t_0 of one second is calibrated, the timestamps of all subsequent pulsar peaks follow directly. In practice, the sampling points N_{ps} captured within each pulsar period is not constant. Variations in the sampling frequency and slight drift in the local oscillator cause N_{ps} to fluctuate from one period to the next, necessitating continuous calibration to maintain precise timing. Utilizing the fact that the interval between $t_{peak}(n)$ must remain equal to P_s, the value of N_{ps} can be calibrated. Accordingly, the timestamp of the next second t_1 could be estimated by combining the pulsar peaks and the calibrated $\widehat{N}_{ps}$:

$$t_1 = t_0 + \frac{f_s}{\widehat{N}_{ps}} \times P_s$$

where f_s is the rated sampling frequency of the system, set to 100MHz in this implementation.

III. Experiment Platform and Validation

To verify feasibility of the proposed method, an experimental platform comprising multiple components is designed, and tests were conducted to evaluate PPS generation and distribution performance.

A. Hybrid Timing System: A Resilient Timing Source

As introduced in the previous section, the hybrid timing system combines GPS and pulsar references to produce a continuous, high-accuracy PPS output, ensuring precise and reliable time synchronization.

B. White-Rabbit: A Timing Distribution Network

With the timing source established, wide-area application requires a robust timing-signal distribution network. A leading solution is the White Rabbit (WR) network, developed in Europe to deliver timing signals over fiber links up to 10 km [10]. WR's architecture extends standard Ethernet hardware clocks and incorporates calibration procedures to correct fiber-optic link asymmetry, thereby ensuring deterministic latency and high timing accuracy across multi-node topologies [11].

C. Experiment Platform Configuration

Fig. 5 illustrates the experiment platform, which integrates the hybrid timing source with a WR distribution network to validate the proposed architecture. The setup comprises a GPS receiver, a SNAP board, a 10 MHz reference oscillator, and multiple WR Z16 switches [12]. First, the SNAP board acquires the GPS PPS signal via its TTL port and captures the pulsar signal via its ADC channels to synthesize an accurate and consistent PPS output. A common 10 MHz oscillator phase-

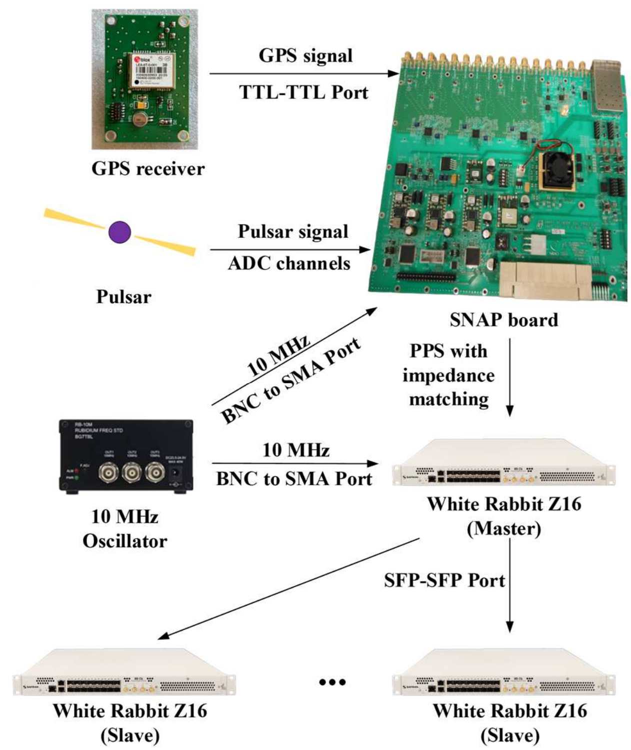

Fig.5. Framework of the pulsar timing distribution system.

locks both the SNAP board and the WR master switch, ensuring synchronous operation. Finally, the impedance-matched PPS output is injected into the WR master switch, which propagates the high-precision timing over optical fiber to the WR slave switches.

D. Experiment Result

Fig. 6 presents the GPS PPS signal (yellow trace), the 10 MHz reference oscillator (red trace), and the generated PPS output (green trace). The SNAP board's 100 MHz system clock—derived from the 10 MHz reference—gates the hybrid timing system's PPS output so that its rising edge aligns with that of the GPS PPS. The measured latency between the GPS PPS and the generated PPS is approximately 20 ns, a result of

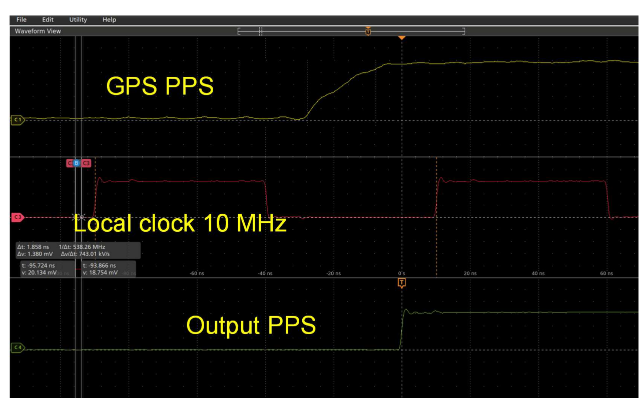

Fig.6. Experiment result from the hybrid timing system.

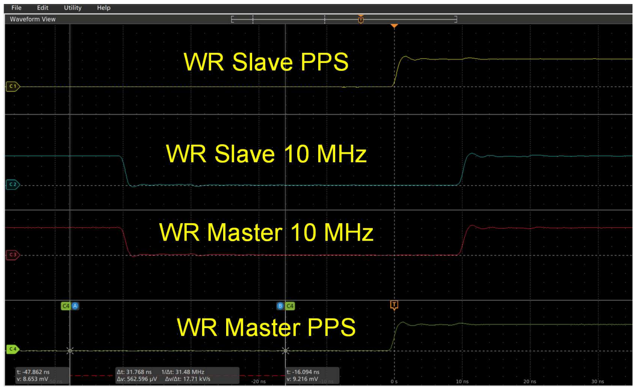

Fig.7. Experiment result from the WR timing distribution network.

the phase-alignment process between the 100 MHz clock and the 1 Hz PPS signal.

Meanwhile, Fig.7 illustrates the WR master and slave switch outputs over a 100 ft single-mode fiber link. Both switches reproduce an identical 10 MHz reference signal—confirmed on a high-bandwidth oscilloscope—demonstrating near-perfect frequency transfer across the network. Analysis of the PPS outputs reveals that the master's and slave's PPS edges differ by just under 2 ns, a fixed latency attributable to optical propagation in the fiber.

These results demonstrate that the experiment platform produces an ultra-stable PPS reference and distributes it reliably across long distances, satisfying the stringent synchronization requirements of modern energy and scientific infrastructures.

IV. Conclusion

Inspired by the exceptional stability of millisecond pulsars, this paper proposes a hybrid PPS generation system that fuses pulsar-derived timing with phase alignment to GPS timing. The SNAP board implements logic-gate arrays to generate real-time PPS outputs, continuously calibrated against the pulsar stream to correct oscillator drift. Leveraging the inherent precision of the pulsar signal, the system delivers high-accuracy timekeeping and serves as a dependable backup when GPS is outage.

To validate the design, a real-world experimental platform incorporating a White Rabbit timing distribution network was deployed. Test results demonstrate alignment within 20 nanoseconds between the generated pulse-per-second and the GPS reference, and under 2 nanoseconds of latency when distributing the timing signal across master–slave nodes. These findings confirm that the proposed architecture satisfies the stringent synchronization requirements of modern energy infrastructures, offering a resilient solution for high-precision timekeeping.

Future long-term trials in representative operational networks will evaluate system stability, drift, and robustness under extended real-world conditions. These studies will further confirm seamless integration with existing industry infrastructures and guide refinements for truly continuous, autonomous timekeeping.

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