A High-Precision Assisted Timing Support Mechanism for Edge Access Points

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Abstract— **This paper presents a standards-compliant Edge Access Point (EAP) architecture that delivers precise synchronization for emerging time-sensitive wireless applications in Industrial IoT, autonomous systems, and 5G networks. To overcome the sub-microsecond accuracy limitations of existing wireless protocols, the proposed EAP is the first architecture that integrates the ITU-T Assisted Partial Timing Support (APTS) model with two innovations: (i) hardware-assisted Precision Time Protocol (PTP) time-stamping via an extended Timing Synchronization Function (TSF) counter, and (ii) wireless emulation of Synchronous Ethernet (SyncE). The design supports Telecom Grandmaster clock requirements through dual timing references, Global Navigation Satellite System (GNSS) input and a PTP stream, ensuring Coordinated Universal Time (UTC) traceability within ±100 ns. Simulation results demonstrate dynamic performance well within ±100 ns, with Oven-Controlled Crystal Oscillator (OCXO)–based holdover stability better than 100 ns for up to four hours. Furthermore, client-side evaluations incorporating 10 ns transmit time-stamping error highlight substantial phase error reduction, while the wireless-recovered SyncE clock eliminates the need for high-stability (better than 1 ppm) local oscillators. These results establish the proposed EAP as a practical and robust solution for high-precision synchronization in next-generation wireless networks.**

Keywords—Synchronization, Precision Time Protocol, IEEE1588, Synchronous Ethernet, Wireless Access Points.

I. INTRODUCTION

The proliferation of real-time, distributed wireless applications ranging from data center networks, Industrial IoT autonomous systems, next-generation cellular networks, and smart grids has elevated precise time synchronization from a backhaul function to a critical enabler at the wireless edge. These applications rely on tightly coordinated sensing, actuation, and communication, often requiring synchronization accuracy at the sub-microsecond or even nanosecond level. For example, advanced manufacturing depends on precise timing for the safe coordination of robotic systems, autonomous vehicles require it for accurate sensor fusion, and cellular networks leverage it to support features such as Coordinated Multi-Point (CoMP). Delivering such stringent synchronization over wireless links, however, is fundamentally challenging due to variable delays, interference, and oscillator instability. The need for precision timing necessitates a rethinking of the timing infrastructure within edge access points (EAPs).

Existing synchronization mechanisms fall short of these requirements due to factors such as unpredictable delays, interference, and oscillator drift [1]. The native IEEE 802.11 Timing Synchronization Function (TSF) provides only tens of microseconds of accuracy and is confined to single-access-point operation. Broadcast-based methods such as Reference Broadcast Synchronization (RBS) offer only relative time and are impractical in standards-compliant infrastructure networks. Direct application of Precision Time Protocol (PTP) over Wi-Fi, particularly with software-based time-stamping, results in poor performance due to packet delay variation. Recent advances exploiting TSF counters for hardware-assisted PTP improve accuracy but remain insufficient to address systemic issues, such as oscillator drift, in low-cost clients. Consequently, a holistic architecture that integrates time distribution, frequency transfer, and resilience mechanisms is needed.

To address this challenge, this paper proposes a standards-compliant EAP architecture that synthesizes distinct synchronization principles into a robust, high-performance wireless system. The EAP framework uniquely converges three technological pillars: (i) a Global Navigation Satellite System (GNSS) module serving as the master reference, providing Coordinated Universal Time (UTC) traceability with high-quality holdover; (ii) a Wi-Fi–based PTP implementation with hardware-assisted time-stamping to distribute phase and time-of-day while compensating for packet delay variation; and (iii) a wireless physical-layer frequency dissemination mechanism that delivers a stable frequency reference to clients. Together, these elements establish the EAP as a precise and resilient timing source at the wireless edge, capable of supporting the stringent requirements of emerging time-sensitive applications.

The main contributions of this work are as follows:

- **Standards-Compliant Hybrid Design:** A novel integration of ITU-T Assisted Partial Timing Support (APTS) with dual timing references (GNSS and PTP), enabling delivery of both time and frequency references traceable to UTC and resilient to reference outages.
- **High-Precision Performance:** Demonstration of compliance with ITU-T G.8272 Primary Reference Time Clock (PRTC-A) requirements (±100 ns accuracy), with four-hour holdover stability using compensated Oven-Controlled Crystal Oscillators (OCXOs), validated through detailed error budget and holdover analysis.
- **Wireless Timing Innovations:** Introduction of an extended TSF mechanism for hardware-assisted PTP time-stamping and the first emulation of Synchronous Ethernet (SyncE) over wireless, significantly improving client-side phase and frequency stability without requiring sub-ppm local oscillators.

By consolidating these mechanisms into a single standards-based architecture, this work advances the state of the art in wireless synchronization. It provides a practical solution for Industrial IoT, autonomous systems, and 5G time-sensitive services.

The rest of the paper is organized as follows: Section II discusses the evolution of wireless network synchronization techniques. Section III presents an overview of the proposed system architecture, followed by wireless-specific synchronization enhancements in Section IV. Section V details the simulation results, and Section VI concludes the paper with a summary and future work.

II. RELATED WORK

Accurate time synchronization has long been recognized as a fundamental requirement in communication systems. Conventional wired synchronization methods, such as Global Navigation Satellite System (GNSS) timing and Synchronous

Ethernet (SyncE) [2], provide sub-100 ns accuracy and have been widely deployed in backhaul and transport networks. However, these approaches assume direct physical connectivity and high-stability oscillators, making them unsuitable for wireless edge environments characterized by multipath fading, packet delay variation, and resource-constrained clients.

Precision Time Protocol (PTP, IEEE 1588) [3] has emerged as the de facto standard for distributing precise time over packet-switched networks. While hardware-assisted PTP implementations can achieve sub-microsecond accuracy in wired deployments, performance over wireless links is degraded due to asymmetric propagation delays, interference, and time-varying medium access delays [4]. Software-based time-stamping introduces additional jitter on the order of microseconds, further limiting PTP's applicability in wireless systems.

Native synchronization mechanisms in IEEE 802.11 networks, such as the Timing Synchronization Function (TSF), provide only tens of microseconds of accuracy [5], which is inadequate for time-sensitive applications. Reference Broadcast Synchronization (RBS) [6] introduced a relative time framework by exploiting broadcast packet reception; however, it requires specialized message exchanges and lacks compatibility with infrastructure-based Wi-Fi deployments. More recent work has explored extending the TSF counter for hardware-assisted PTP implementations, showing improved precision. Still, these methods do not account for oscillator instability at low-cost clients and typically lack robustness under mobility and interference.

Direct GNSS synchronization provides absolute UTC traceability and remains the baseline for telecom-grade systems. However, GNSS is vulnerable to coverage gaps (e.g., indoors and in urban canyons) and spoofing/jamming attacks. To maintain timing during outages, high-stability oscillators such as OCXOs or atomic clocks are often employed, but these are cost-prohibitive for mass-market wireless devices. Consequently, GNSS-based solutions are not viable as the sole synchronization method at the wireless edge.

SyncE has proven highly effective for frequency synchronization in wired Ethernet environments, offering ppm-level stability. Nonetheless, it requires continuous physical-layer connectivity and cannot be directly extended to wireless links. Wireless emulation of SyncE remains largely unexplored, with existing solutions relying instead on software-based phase-locked loops that suffer from significant drift and instability under dynamic channel conditions.

Summary of Limitations: Collectively, these approaches highlight a gap in achieving sub-100-ns synchronisation over wireless networks. PTP suffers from variable packet delays; TSF and RBS lack the required accuracy and compliance with standards; GNSS is unreliable in many deployment scenarios; and SyncE is inherently wired. Moreover, most existing techniques address either time transfer or frequency transfer in isolation, whereas next-generation Industrial IoT, autonomous systems, and 5G services demand both. These limitations underscore the need for a unified, standards-compliant synchronization framework at the wireless edge that integrates time distribution, frequency recovery, and resilience to reference outages.

III. SYSTEM ARCHITECTURE FOR THE EDGE ACCESS POINT

The central innovation of this work is the introduction of the EAP as a high-stability, localized synchronization hub, transforming the traditional role of wireless access points into authoritative timing masters. Unlike existing approaches that depend on distant, core-network timing sources with significant latency and vulnerability to network dynamics, the proposed architecture establishes a hierarchical timing domain in which the EAP functions as a PTP Grandmaster (GM) for a cluster of wireless devices (Fig. 1). This design enables a two-layer access point hierarchy that delivers end-to-end synchronization within 1 µs, addressing the stringent requirements of industrial IoT, autonomous systems, and 5G/6G edge applications.

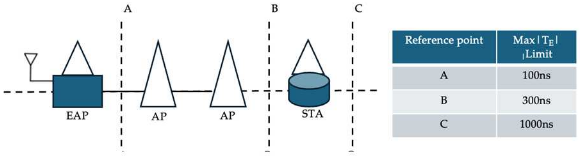

Fig. 1. Proposed reference model for synchronization framework

A key novelty lies in the dual-reference timing strategy. The EAP integrates a high-precision GNSS receiver for UTC-traceable synchronization with a continuously monitored network-delivered PTP feed. During GNSS disruptions (e.g., jamming, obstruction, or antenna failure), an assisted holdover mechanism dynamically calibrates the PTP feed using the last-known-good timing error measurement. This approach departs from conventional holdover schemes that rely solely on the local oscillator [7], significantly improving resilience. By combining calibrated PTP with high-stability oscillators, the EAP achieves sub-microsecond accuracy even under adverse conditions. In scenarios where both GNSS and PTP are unavailable, the system seamlessly falls back to oscillator-only holdover while preserving standards-compliant performance through the ITU-T APTS framework.

Another novel aspect is the explicit time-error budgeting methodology (Table I). This architecture decomposes the synchronization error across each network segment, offering verifiable compliance with ITU-T G.8272 PRTC-A requirements. This rigorous allocation not only validates feasibility but also provides a blueprint for deployment in real-world edge networks.

TABLE I. END-TO-END TIME ERROR BUDGET

Network Element	**Time Error Analysis**			
	ITU-T Standard	***Device Class***	***max|T_E|***	***Cumulative Time Error (ns)***
PRTC at Source (EAP)	G.8272	PRTC-A	100	100
Intermediate T-BC 1	G.8273.2	T-BC Class A	100	200
Intermediate T-BC 2	G.8273.2	T-BC Class A	100	300
Wireless Link (AP to Client)	N/A	N/A	700	1000

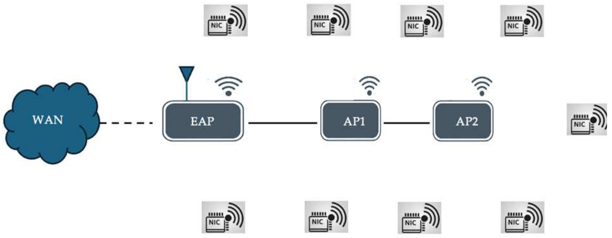

Fig. 2. System architecture with EAP, APs, and end clients on NICs

Figure 2 shows the complete system architecture, where client devices, equipped with standard Network Interface Cards (NICs), are synchronized via the EAP and intermediate APs. By consolidating GNSS-traceable timing, PTP calibration, and wireless frequency dissemination into a single standards-aligned framework, the proposed EAP represents a novel architectural advance toward reliable, scalable, and ultra-precise synchronization at the wireless edge.

IV. WIRELESS SYNCHRONIZATION ENHANCEMENTS

A. *PTP with Hardware-Assisted Time-stamping*

A significant limitation of implementing PTP over Wi-Fi arises when time-stamping is done in software at the application or kernel level. Such implementations are subject to non-deterministic delays introduced by the host operating system and the network stack, leading to synchronization errors on the order of hundreds of microseconds to milliseconds. In practice, this performance offers slight improvement over the simpler Network Time Protocol (NTP) [8].

To overcome this limitation, we propose hardware-assisted PTP time-stamping using an extended IEEE 802.11 TSF counter. TSF is a mandatory 64-bit counter implemented in all Wi-Fi Network Interface Cards (NICs) that increments in units of microseconds [9]. By repurposing the TSF as an emulated PTP Hardware Clock (PHC) and extending its resolution to the nanosecond domain, the Enhanced Access Point (EAP) can achieve sub-microsecond synchronization accuracy across the network. This approach aligns with recent advances in IEEE 802.11mc Fine Timing Measurement (FTM) and hardware time-stamping methods, which have demonstrated nanosecond-level precision between wireless nodes [10], [11]. By incorporating these capabilities into the EAP, the proposed framework addresses the fundamental bottleneck in Wi-Fi-based PTP synchronization and enables Grandmaster-grade accuracy at the wireless edge. For simulations in this work, a 10 ns hardware time-stamping accuracy is assumed.

B. *Wireless SyncE emulation*

Synchronous Ethernet (SyncE) distributes a common frequency reference in wired networks, typically disciplined by GNSS, to all nodes. We propose a novel Wireless SyncE emulation mechanism that extends this principle to the wireless domain by embedding the GNSS-disciplined frequency in the RF carrier transmitted from the EAP [12].

The EAP, stabilized by a high-quality DOCXO locked to GNSS, transmits packets with minimal frequency drift. Wireless clients recover this frequency using a digital Clock and Data Recovery (CDR) loop (implemented as a PI controller), which filters high-frequency packet delay variation (PDV) introduced by CSMA/CA, interference, and multipath. The recovered clock, traceable to the GNSS reference, disciplines the client oscillator, providing a highly stable frequency baseline.

By anchoring the client's oscillator to this wireless SyncE reference, the PTP servo loop converges faster, maintains tighter phase lock, and significantly improves holdover performance during temporary synchronization outages [13]. In effect, the proposed Wireless SyncE delivers the precision of wired SyncE in a fully wireless context, a capability not addressed by existing Wi-Fi synchronization techniques.

C. *Holdover and Synchronization Resiliency*

Maintaining synchronization during the loss of all external timing references is essential for network resiliency. We propose to equip the EAP with a high-stability Oven-Controlled Crystal Oscillator (OCXO) enhanced with ageing compensation, enabling holdover performance of up to 4 hours with ±100 ns phase-error drift.

In the absence of GNSS and PTP references, the system enters a free-run state where the oscillator's frequency stability dictates timing accuracy. Standard oscillators are inadequate for high-precision holdover due to their sensitivity to temperature variations and ageing effects. The proposed solution incorporates an OCXO with adaptive compensation, leveraging a Kalman filter to model oscillator behavior over a 16-hour learning window. This method robustly compensates for diurnal temperature fluctuations of up to 8 °C, where polynomial-based methods fail, and consistently maintains 100 ns accuracy during outages.

This approach represents a novel integration of advanced holdover compensation with wireless synchronization, ensuring that the EAP continues to support time-sensitive applications through extended disruptions in GNSS or backhaul connectivity.

V. PERFORMANCE ANALYSIS

The simulations in this paper are done using MATLAB. The following assumptions are made in the simulations:

- The GNSS module has a PRTC-A-like performance, with ±100 ns of diurnal variation.
- The local OCXOs are assumed to perform like commercial OCXOs used in edge equipment, with 10ppb to 0.2ppb frequency-versus-temperature performance across -40 °C to +85 °C and an ageing rate of 0.2ppb/day. The loop bandwidth of the servo system is at 1mHz.
- A time-stamping engine with an error of 1µS and 10nS is simulated on the transmitter side, and the client-side performance is evaluated. Symmetrical path delays are assumed in this case.

The primary performance metric for the EAP's time output is its accuracy relative to UTC. The accuracy requirement is formally specified by the PRTC classes defined in ITU-T Recommendation G.8272 [9]. The EAP's time output must not exceed ±100nS relative to UTC under dynamic conditions when the system is locked to GNSS. In holdover, the maximum phase-error drift is also assumed to be within ±100 nS over 4 hours.

The client-side performance target for $\max|T_E|$ is 700ns. For the wireless frequency filtering at 0.1Hz, a TCXO with 1 ppm frequency-versus-temperature performance over -40 °C to +85 °C is assumed.

A. Dynamic performance of EAP

Figure 3 shows the system's GNSS-locked mode performance level, simulated with a GNSS output signal filtered at 1 mHz and 1 PPS, in a constant-temperature scenario. The masks correspond to the limits specified in the G.8272 specification for PRTC-A clocks [14].

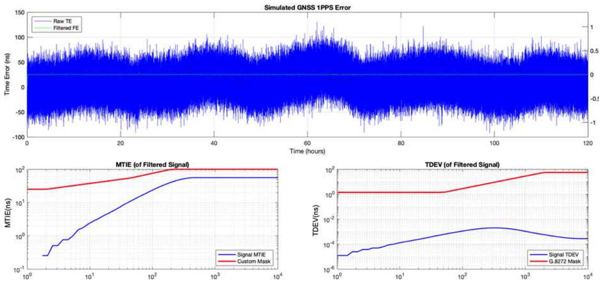

Fig. 3. MTIE and TDEV performance across multiple days of operation

Figure 2 illustrates the system's performance under the influence of temperature. The servo is operated with a 1 mHz filter, and the system filters the incoming GNSS signals. However, the low filter value requires a high-stability oscillator, as the oscillator's high-frequency components will appear at the system output. This simulation considers a 10 ppb frequency-stability oscillator that operates over the temperature range of -40 °C to +85 °C. The temperature variation mimics a diurnal change of about 5°C with some ambient temperature variation.

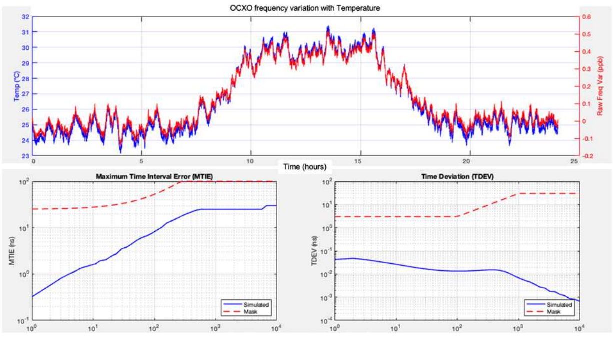

Fig. 4. Performance under a 5°C temperature variation

Supporting a 30°C temperature variation requires a much better oscillator; therefore, Figure 5 simulates a 0.5 ppb OCXO. The overall MTIE and TDEV results are within the specification's limits.

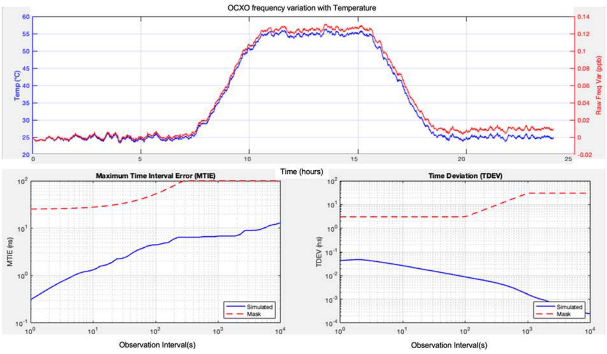

Fig. 5. Temperature performance with 30°C variation

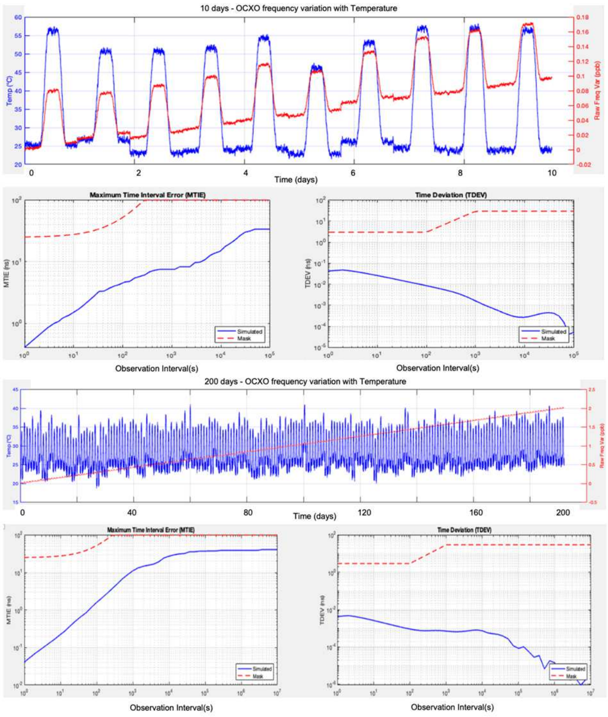

Fig. 6. Simulation over 10 and 200 days of operation

Figure 6 shows the simulation results across 10 and 200 days, covering the 10M observation points on the MTIE plots as in the G.8272 specifications. The performance is within the specification masks.

Table II shows the performance in terms of $\max|T_E|$ for various OCXOs, with frequency versus operating temperature (-40°C to +85°C) characteristics ranging from 0.1ppb to 1ppb. Such commercial OCXOs are used in similar GNSS edge grandmaster systems. A temperature variation of 20°C is assumed and is swept across the entire operating range of 125 degrees. As the loop bandwidth decreases, the oscillator variation affects the output time error; as it increases, the error from the reference source starts to appear at the output. A frequency-versus-temperature output of 0.2 ppb with 1 mHz filtering is ideal for the cost-benefit performance.

TABLE II. PHASE ERROR PERFORMANCE OF THE EAP

FvT (ppb)	**Max|T_E| for various Loop Bandwidth Values**						
	0.10 mHz	***0.50 mHz***	***1.00 mHz***	***10 mHz***	***30 mHz***	***50 mHz***	***75 mHz***
0.1	66.4	24	26.4	35.0	46.3	52.5	59.2
0.2	130	24.2	25.8	35.4	45.7	53.4	60
0.5	297	24.3	26.1	35.2	46.9	54.3	60
1	594.1	35	25.5	35.6	45.7	52.9	59.8

B. Holdover Capability Analysis

A critical measure of a timing system's robustness is its holdover performance—the ability to maintain time accuracy after all external synchronization references are lost. The architectural proposal is that the EAP must maintain its time error within ±100 nanoseconds for four hours. This capability ensures service continuity during prolonged GNSS outages or backhaul network failures. This analysis does not consider the first stage of PTP-supported holdover; the primary investigation is scenarios without PTP and GNSS-related failures.

To meet this stringent requirement, a very high-performance oscillator is necessary. Standard Temperature-Compensated Crystal Oscillators (TCXOs) and even many lower-grade Oven-Controlled Crystal Oscillators (OCXOs) are incapable of this level of stability. The holdover performance almost entirely depends on the stability of the EAP's local oscillator. When in holdover, the clock's phase will drift over time due to its initial frequency offset at the start of holdover, its intrinsic ageing rate, and its sensitivity to environmental changes, especially temperature.

At ambient temperature, an OCXO with 0.2ppb frequency-versus-temperature performance and 0.1ppb/day ageing cannot achieve more than 4 hours of holdover, as seen in the figure below. The contribution from the ageing is too high to achieve a 4-hour holdover consistently.

The performance of the compensated system and the holdover performance across various temperature ranges are captured in Table III.

TABLE III. HOLDOVER PERFORMANCE ACROSS THE TEMPERATURE RANGE

Sl. No	**Holdover Performance after compensation**	
	Peak Var. (°C)	***FvT = 0.2 ppb***
1	2	> 8.0 hr
2	4	> 8.0 hr
3	6	5.51 hr
4	8	4.33 hr

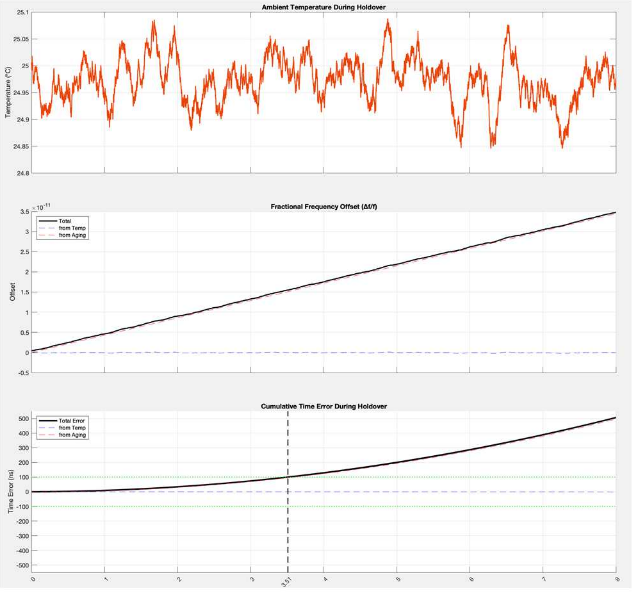

Fig. 7. Holdover behaviour on ambient temperature

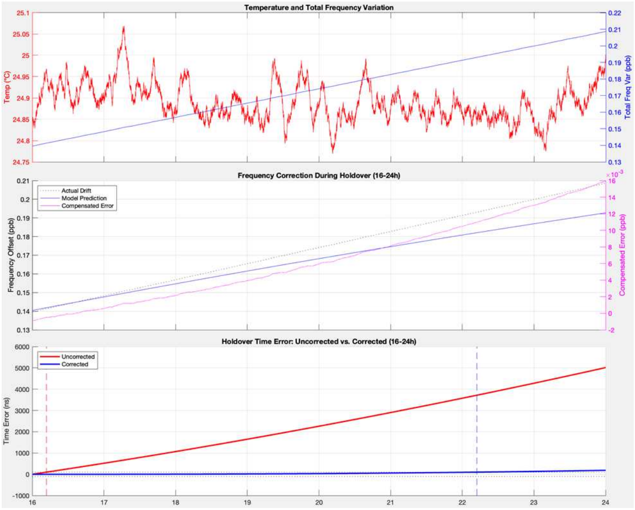

Fig. 8. Compensated Holdover behaviour

VI. CHALLENGES IN REAL-WORLD IMPLEMENTATION

Transitioning this simulated architecture to a physical hardware platform presents several practical challenges. Although the framework utilizes the IEEE 802.11 Timing Synchronization Function (TSF) counter for hardware-assisted time-stamping, achieving nanosecond-level precision remains difficult. Access to TSF is not standardized across Wi-Fi System-on-Chip (SoC) vendors and often requires low-level driver interfaces or custom hardware modifications to achieve the necessary accuracy [15], [16]. To meet the proposed performance, time-stamping accuracy must fall within the nanosecond range, making the choice of a Wi-Fi SoC and driver that supports high-resolution TSF access critical and complex [17]. In simulations, wireless channel impairments were primarily modelled through Packet Delay Variation (PDV) to evaluate the robustness of the PTP servo and frequency recovery loops. However, real-world RF environments are far more complex, introducing multipath fading, signal interference, and packet loss that result in non-Gaussian, unpredictable delays not fully captured by PDV models [18]. These impairments can cause prolonged PTP message outages and significantly impact clock recovery performance, necessitating advanced client-side filtering and possibly Multi-Link Operation (MLO) for redundancy [19], [20]. Furthermore, the architecture's reliance on algorithms, such as Kalman filter-based holdover compensation, adds computational overhead, requiring real-time execution on the embedded processor without disrupting the EAP's core functions, such as data forwarding and time stamping [21]. A practical deployment must therefore carefully balance algorithmic complexity, SoC processing capabilities, and the targeted holdover performance [22].

VII. CONCLUSION AND FUTURE DIRECTIONS

The proposed architecture lays the groundwork for high-precision wireless timing via the EAP and opens avenues for further research to enhance its performance and reliability. Future work should evaluate client-side wireless frequency recovery—particularly using CDR techniques—and the impact of local oscillator stability and filtering on recovered timing accuracy. Assessing the combined performance of Wireless SyncE and the PTP servo under real-world wireless impairments will help define oscillator and filtering requirements. Adapting PTP for Multi-Link Operation (MLO) could significantly improve synchronization accuracy, potentially achieving sub-microsecond precision.

This paper presents a comprehensive architectural framework for an Edge Access Point designed to meet next-generation wireless applications' increasingly stringent synchronization demands. The proposed design moves beyond the limitations of existing wireless timing protocols by creating a synergistic system that is robust, standards-compliant, and capable of achieving performance levels previously associated only with wired telecommunications infrastructure.

In conclusion, the architecture presented herein provides a complete and robust blueprint for a new class of edge access points. By transforming the AP from a simple data conduit into a high-integrity timing source, this framework enables the precise coordination and control required by the intelligent, untethered systems of the future.

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