

Cell-Free Coherent Joint Transmission for 6G ISAC Enabled by Microwave Photonic Synchronization

Zhijian Zhang, Haoran Wu[✉], *Graduate Student Member, IEEE*, Lihan Wang[✉], *Member, IEEE*, Jiangtao Zhang, Xudong Wen, Peidong Feng[✉], *Student Member, IEEE*, Jianbo Sun[✉], Xiaowei Ma[✉], *Student Member, IEEE*, Mingyu Liu[✉], Wancheng Yang[✉], *Senior Member, IEEE*, Xiangchuan Wang[✉], *Member, IEEE*, and Shilong Pan[✉], *Fellow, IEEE*

Abstract—Distributed cell-free communication networks can synthesize ultralarge virtual apertures and provide substantial distributed gains for 6G communication systems. However, multinode spatial coherence remains limited by the complexity of conventional fiber-based synchronization networks. In this article, a scalable and architecturally streamlined microwave photonic synchronization scheme capable of the concurrent distribution of time-triggered, local oscillator (LO), and clock signals over optical fiber is proposed. By exploiting the inherent properties of these signals for real-time delay metrology and active link compensation, the proposed approach circumvents the need for auxiliary optical wavelengths or additional hardware overhead in the fronthaul network. The experiments show a delay measurement deviation of ± 1.5 ps, and phase stabilization within $\pm 2.5^\circ$ @ 10 GHz is achieved over a 2-km fronthaul link. We further present, to the best of the authors' knowledge, the first distributed coherent integrated sensing and communication (ISAC) cell-free network enabled by microwave photonic synchronization. With two remote nodes (RNs), the cell-free networks yield an over 5.3 dB improvement in error vector magnitude (EVM) and sensing signal-to-noise ratio (SNR) based on the coherent gain. The proposed architecture provides a practical route toward scalable coherent ISAC networks with enhanced coverage and capacity.

Index Terms—Cell-free network, integrated sensing and communication (ISAC), microwave photonics, time-frequency synchronization.

I. INTRODUCTION

INTEGRATED sensing and communication (ISAC) is increasingly recognized as a cornerstone capability of 6G and beyond, driven by the growing demand for perception-enabled services in intelligent transportation, low altitude platforms, industrial automation, and immersive human-machine

interfaces [1], [2], [3], [4], [5], [6]. Unlike legacy infrastructures, future wireless communication networks are expected to support not only high-throughput data transmission but also high-fidelity sensing services, such as localization [7], tracking [8], and environment mapping [9], through the shared use of spectrum, hardware, and deployment resources [10]. This convergence is driven by the dual demand for higher communication capacity and higher sensing precision. From a physical-layer perspective, both objectives critically depend on increasing the effective signal-to-noise ratio (SNR) and exploiting higher effective spatial degrees of freedom (DoFs) [11], [12].

To enhance the SNR and DoFs, cell-free ISAC has recently garnered significant attention [13], [14], [15], [16], [17], and a typical scenario is shown in Fig. 1. Compared with co-located massive MIMO, the geographically distributed remote nodes (RNs) in a cell-free architecture provide macrodiversity and more uniform spatial coverage, particularly for users far from a single base station. Most existing architectures rely on cooperation at the information-level or feature level, where each node performs localized sensing and communication processing and then forwards the resulting information to a central unit (CU) for fusion. The corresponding fronthaul can be implemented in wired or wireless forms. Wired fronthaul, typically supported by high-capacity optical fibers [18], enables large-volume data delivery, whereas wireless fronthaul [19] provides higher deployment flexibility but suffers from stricter capacity, latency, and synchronization limitations. Under these practical constraints, cooperative cell-free ISAC architectures have been extensively explored to jointly serve users and sense targets through coordinated access point (AP) mode selection and power control, demonstrating notable performance improvements [19], [20], [21]. For example, a noncoherent cell-free ISAC framework is proposed [17], demonstrating that joint TOA/AOA measurements can achieve localization without phase-level synchronization. A symbol-level fusion method is developed [23], which extracts phase features from demodulated orthogonal frequency division multiplexing (OFDM) symbols, requiring only standard symbol-timing synchronization. However, both methods inherently discard the raw carrier-phase information across distributed nodes, fundamentally limiting the spatial resolution and coherent processing gain.

An even more attractive architecture is coherent joint transmission (CJT), which achieves waveform-level coherent synthesis of signals from N nodes, thereby yielding a

Received 26 May 2026; revised 31 July 2026; accepted 31 July 2026. Date of publication 12 August 2026; date of current version 11 September 2026. This work was supported in part by the National Natural Science Foundation of China under Grant 62271249; and in part by the Fundamental Research Funds for the Central Universities under Grant NE2025004, Grant NC2025006, and Grant NC2024004. (Zhijian Zhang and Haoran Wu contributed equally to this work.) (Corresponding authors: Lihan Wang; Xiangchuan Wang.)

Zhijian Zhang, Haoran Wu, Lihan Wang, Jiangtao Zhang, Peidong Feng, Jianbo Sun, Xiaowei Ma, Mingyu Liu, Wancheng Yang, Xiangchuan Wang, and Shilong Pan are with the National Key Laboratory of Microwave Photonics, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China (e-mail: andwwlh@nuaa.edu.cn; wangxch@nuaa.edu.cn).

Xudong Wen is with Jiuquan Satellite Launch Center, Jiuquan 732750, China.

Digital Object Identifier 10.1109/TMTT.2026.3720258

0018-9480 © 2026 IEEE. All rights reserved, including rights for text and data mining, and training of artificial intelligence and similar technologies. Personal use is permitted, but republication/redistribution requires IEEE permission.

See <https://www.ieee.org/publications/rights/index.html> for more information.

theoretical N^2 -fold SNR gain at the user equipment (UE) side or sensing target. Existing studies have shown that coherent processing can further exploit the phase information embedded in waveforms, achieving higher gains for joint communications and sensing performance [24], [25], [26], [27], [28]. For example, a coherent architecture with collaborative transmission among multiple APs is adopted [24]. Under this architecture, in the single-stream downlink, doubling the number of cooperating AP ports increased the received SNR by approximately 5 dB. However, realizing such performance gains critically relies on high-precision synchronization in time, frequency, and phase across each AP. Meanwhile, the synchronization capability also needs to remain stable over the long term and be practically maintainable.

Synchronization techniques for wireless communication and sensing mainly follow two technical routes. One route is based on over-the-air (OTA) synchronization, while the other relies on optical-link-based synchronization. OTA synchronization and calibration methods primarily achieve phase-level synchronization through offset estimation, phase tracking, and dynamic compensation [29], [30]. For example, OTA synchronization among distributed nodes is realized by enabling direct exchange of synchronization signals among APs, performing beamforming along the dominant channel direction, and combining phase-offset and carrier-frequency-offset estimation [30]. Nevertheless, when oscillator drift is taken into account, this method requires recalibration from time to time in order to effectively maintain the beamforming gain at the UE side. Moreover, since OTA synchronization depends on the wireless channel, its performance is inherently sensitive to interference, blockage, multipath fading, and channel fluctuations.

In contrast, optical-link-based synchronization schemes mainly include active, passive, and two-way time-frequency transfer [31], [32], [33], [34]. Active synchronization approaches compensate phase and delay variations along the fiber through closed-loop control. An active feedback loop was implemented to correct round-trip phase errors in real time, achieving ps-level stability in transfer delay over a 2-km link [31]. For example, an optical linearly frequency-modulated (LFM) waveform was employed for fiber link delay measurement, and the measured delay variation was compensated via a digital delay line, successfully reducing the transmission delay mismatch between two distributed radar nodes to less than 20 ps [34]. In contrast, passive synchronization schemes suppress fiber-induced phase fluctuations through phase conjugation without explicitly measuring the link delay. For example, a bidirectional passive stabilization scheme was proposed in [35], enabling the transmission of a 6-GHz signal over a 20-km optical fiber and reducing the phase jitter from 41 to 1.17 ps. Another widely adopted approach is two-way time-frequency transfer, where clock offset between two nodes is estimated through bidirectional signal exchange. The estimated timing and frequency deviations are then compensated through feedback adjustment of the clock parameters, enabling high-precision synchronization between distributed nodes. Real-time, femtosecond-level clock synchronization across a low-lying, strongly turbulent, 12-km horizontal air path by OFC-based synchronization is realized in [36].

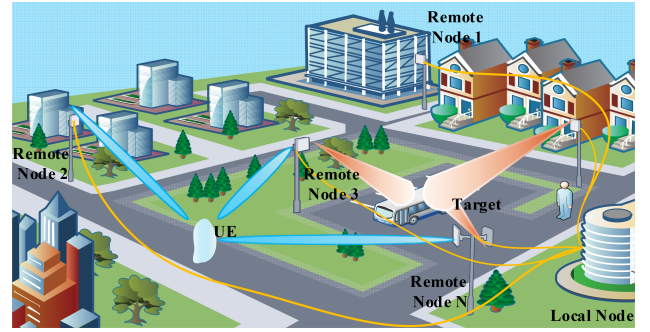


Fig. 1. Typical cell-free ISAC scenario.

Compared with conventional network-protocol-based synchronization approaches, these methods improve the synchronization accuracy by several orders of magnitude [37], [38]. However, they often require additional delay measurement units, extra optical wavelength resources, or even ultrastable OFCs, thereby increasing system complexity and cost. This greatly limits scalability for practical large-scale deployment.

This article presents a cell-free CJT ISAC system consisting of one central node and N RNs, achieving microwave photonic time-frequency synchronization with ps-level accuracy. Considering the requirements of ISAC cell-free architecture, synchronization references, including the time-triggered signal (TTS), 10-MHz clock, and local oscillator (LO), are distributed from the central node to the RNs using distinct optical carrier wavelengths. This configuration obviates the need for additional LO signal generation at the RNs, thereby simplifying RN implementation. By exploiting the backpropagated signals from the RNs, the system performs both coarse and fine measurements of fronthaul-link delays. Enabling real-time, unambiguous calculation and active compensation of link delay jitter without additional wavelength or hardware overhead. Moreover, the integrated waveform is reused for ISAC functions, thereby simplifying the transceiver architecture and reducing the hardware complexity of the RNs. The experimental results validate the feasibility of the proposed cell-free CJT ISAC system. In coherent mode, the communication error vector magnitude (EVM) is improved from 12.49% to 6.75%, and the sensing echo SNR is increased by 5.6 dB.

The remainder of this article is organized as follows. Section II describes the architecture of the proposed cell-free CJT ISAC system and the principle of microwave photonic time-frequency synchronization, and analyzes the SNR gains for communication and sensing using OFDM waveforms. Section III presents the experimental setup, verification results, and corresponding analysis. Finally, Section IV concludes this article.

II. PRINCIPLE

A. Microwave Photonic Time-Frequency Synchronization

The proposed cell-free CJT ISAC architecture is illustrated in Fig. 2. A total of N RNs with identical hardware configurations are connected to a central node through fronthaul optical fiber links. At the central node, a laser array generates three optical carriers at wavelengths λ_1 , λ_2 , and λ_3 , which are injected into three Mach-Zehnder modulators (MZMs). In the MZMs, the three carriers are modulated by a TTS, a

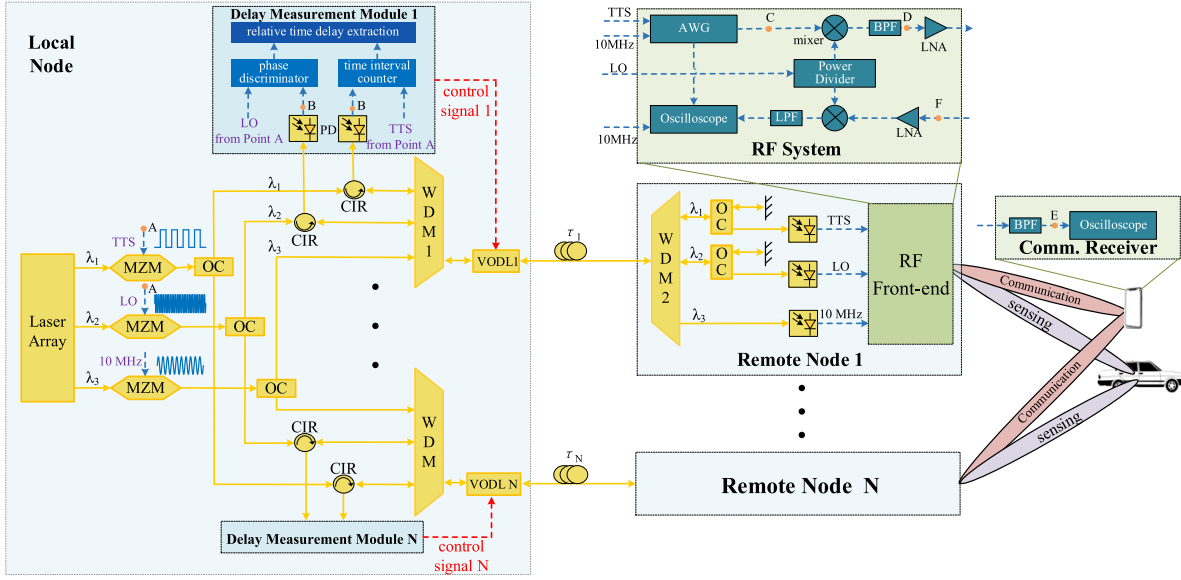


Fig. 2. Schematic of the proposed cell-free CJT ISAC architecture. MZM: Mach-Zehnder modulator; OC: optical coupler; CIR: circulator; WDM: wavelength-division multiplexer; PD: photodetector; VODL: variable optical delay line; LNA: low-noise amplifier; BPF: bandpass filter; LPF: lowpass filter; AWG: arbitrary waveform generator; and TIC: time-interval counter.

10-MHz reference clock, and a LO signal, respectively. The modulated optical signals are equally split into N branches by three $1 \times N$ optical couplers (OCs) to distribute through the respective fronthaul links. Before being transmitted through the fronthaul links, the carriers at λ_1 and λ_2 pass through two optical circulators (CIRs) and, together with the carrier at λ_3 , are multiplexed by a wavelength-division multiplexer (WDM). The multiplexed signal is subsequently routed through a variable optical delay line (VODL) and transmitted to the RNs over a fronthaul fiber link. At the RN, the multiplexed signal is demultiplexed into three wavelength components by a WDM. The optical carriers at λ_1 and λ_2 are each divided into two paths. One branch of each signal is detected by a photodetector (PD) and then delivered to the radio frequency (RF) front end. The other branches, at wavelengths λ_1 and λ_2 , are reflected by optical mirrors and transmitted back to the central node through the fronthaul fiber link. At the central node, the reflected signals of different wavelengths are demultiplexed by a WDM, and after passing through the CIR, they are converted into electrical signals by two PDs.

Assume that the TTS and the LO signal at point A can be expressed as

$$s_{\text{TTS},A}(t) = \sum_{k=-\infty}^{+\infty} \text{rect}\left(\frac{t - kT}{t_p}\right) \quad (1)$$

$$s_{\text{LO},A}(t) = \cos(2\pi ft + \phi_0) \quad (2)$$

where T and t_p are the period and pulsewidth of the TTS, respectively, and f and ϕ_0 are the frequency and initial phase of the LO signal. Accordingly, after round-trip propagation through the fronthaul fiber link and neglecting the fixed system transfer delay, the signals at point B can be written as, respectively,

$$s_{\text{TTS},B}(t) = s_{\text{TTS},A}(t - 2\tau) = \sum_{k=-\infty}^{+\infty} \text{rect}\left(\frac{t - 2\tau - kT}{t_p}\right) \quad (3)$$

$$s_{\text{LO},B}(t) = \cos(2\pi ft - 4\pi f\tau + \phi_0) \quad (4)$$

where τ denotes the one-way propagation delay in the fronthaul fiber link. After photodetection, the TTS from points A and B are fed into a time-interval counter (TIC).

By measuring the time interval between the rising edges of the two TTS, the TIC obtains the round-trip transfer delay τ_{TIC} , which is given by

$$\tau_{\text{TIC}} = 2\tau \pm \Delta\tau \quad (5)$$

where $\Delta\tau$ denotes the measurement error of the TIC. Meanwhile, the LO signals from points A and B are fed into a digital phase detector to obtain the phase difference $\Delta\varphi$. The relationship between the phase difference and the propagation delay can be expressed as

$$\tau = \frac{1}{2} \left(NT_{\text{LO}} + \frac{\Delta\varphi}{2\pi} T_{\text{LO}} \right) \quad (6)$$

where N denotes the integer-cycle ambiguity introduced by phase wrapping, and $T_{\text{LO}} = 1/f$ represents the period of the LO signal. By combining (5) and (6), N can be determined as

$$N = \frac{2\tau}{T_{\text{LO}}} - \frac{\Delta\varphi}{2\pi} = \left(\frac{\tau_{\text{TIC}}}{T_{\text{LO}}} - \frac{\Delta\varphi}{2\pi} \right) \pm \frac{\Delta\tau}{T_{\text{LO}}} \quad (7)$$

Since N is an integer, it can be uniquely determined by nearest-integer rounding, provided that $\Delta\tau/T_{\text{LO}} < 1/2$

$$N = \text{round}\left(\frac{\tau_{\text{TIC}}}{T_{\text{LO}}} - \frac{\Delta\varphi}{2\pi}\right) \quad (8)$$

where $\text{round}(\cdot)$ denotes the nearest-integer operation. According to (6) and (7), the fronthaul link transfer delay jitter can be measured in real time without requiring additional signals or extra wavelength resources. The fixed differential group delay between the two wavelength channels caused by chromatic dispersion can be calibrated during system initialization. Based on the measured results, a control signal is generated to drive the VODL, enabling real-time delay compensation and ensuring identical propagation delays for the synchronization signals delivered to each RN.

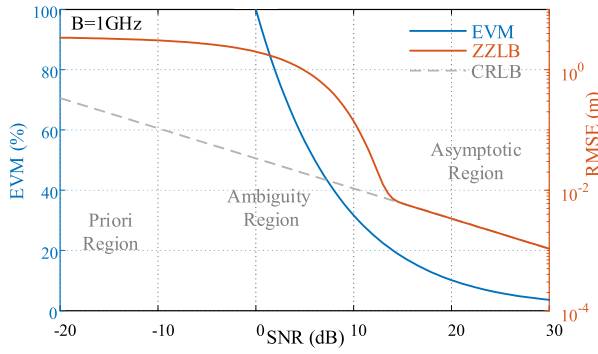


Fig. 3. Communication EVM and ranging accuracy versus SNR.

B. Cell-Free CJT ISAC

In ISAC scenarios, SNR is a critical metric for both the communication capacity and sensing accuracy. The relationships between SNR and EVM, and between SNR and the Cramér–Rao lower bound (CRLB), can be expressed as follows, respectively,

$$\text{EVM} = \frac{1}{\sqrt{\text{SNR}}} \quad (9)$$

$$\text{CRLB} \approx \frac{c}{2\pi B \sqrt{2 \cdot \text{SNR}}} \quad (10)$$

where c is the light speed, and B is the bandwidth of ISAC signal. As shown in Fig. 3, both the EVM and the root-mean-square error (RMSE) decrease monotonically with increasing SNR. The ranging RMSE exhibits three distinct regions dependent on SNR. Specifically, at low SNRs, it falls into the prior region, where the error is bounded by prior spatial knowledge. As SNR increases, it enters the ambiguity region, experiencing a sharp drop in RMSE. At high SNRs, it ultimately reaches the asymptotic region, where the accuracy tightly converges to the CRLB.

To enhance this critical metric, the cell-free CJT ISAC is employed to realize SNR gain through waveform-level coherent synthesis of communication and sensing signals. As illustrated in Fig. 2, at the RF front end of each RN, an OFDM waveform generated by an arbitrary waveform generator (AWG) is used for both communication and sensing. It should be noted that the TTS and 10-MHz frequency reference clock at each RN are synchronized by the synchronization network described in Section II-A. Accordingly, the signal at point C can be expressed as

$$s_{\text{BB-OFDM}}(t) = \sum_{k=0}^{N_{\text{sub}}-1} X_k e^{j2\pi k \Delta f t}, \quad 0 \leq t < T_{\text{sym}} \quad (11)$$

where N_{sub} represents the number of subcarriers, X_k represents the complex data symbol on the k th subcarrier, Δf represents the subcarrier spacing, and T_{sym} represents the effective duration of an OFDM symbol, defined as the reciprocal of the Δf . The signal bandwidth is determined by $N_{\text{sub}} \Delta f$, which is also equal to the effective symbol rate. Subsequently, the OFDM waveform is upconverted via a mixer using a phase-stable LO signal with frequency f_c , which is derived from the central node. After passing through a bandpass filter and being amplified by a low-noise amplifier (LNA), the signal

is transmitted into free space. The signal at point D can be expressed as

$$s_{\text{RF-OFDM}}(t) = \sum_{k=0}^{N_{\text{sub}}-1} X_k e^{j2\pi(k\Delta f + f_c)t}, \quad 0 \leq t < T_{\text{sym}}. \quad (12)$$

It is worth mentioning that, to achieve CJT, the channel characteristics of the wireless link should be estimated, which can be expressed as

$$H_{i,k} = \sum_{l=1}^{L_i} \beta_{i,l} \cdot \exp(-j2\pi(k\Delta f + f_c) \cdot \tau_{i,l}) \quad (13)$$

where L_i represents the number of multipath between the i th RN and the communication receiver; β and τ represent the complex gain and propagation delay. Consequently, time alignment and coherent precoding are conducted to compensate for the RN-to-receiver wireless channel responses [28]. For extreme wireless links in scenarios such as high-mobility, severe shadow fading, advanced techniques can be incorporated to address these extreme wireless conditions [38], [39], [40].

Further expanding to multiuser scenarios [41], after the required complex weights for the distributed RNs are determined by precoding or beamforming techniques such as zero-forcing (ZF) or maximum ratio transmission (MRT) [42], the proposed synchronization architecture maintains sufficiently stable timing and carrier-phase relationships among the RNs, thereby enabling these precoding weights to be accurately realized over the distributed fronthaul.

Therefore, the received signal at point E can be expressed as

$$r_{\text{RF-comm}}(t) = \sum_{i=0}^{N-1} \alpha_i \sum_{k=0}^{N_{\text{sub}}-1} X_k e^{j2\pi(k\Delta f + f_c)t} + n(t) \quad (14)$$

where α denotes the amplitude attenuation mainly induced by the path loss and antenna gain, and $n(t)$ denotes the Gaussian white noise. After bandpass filtering, the received signal is directly acquired by an oscilloscope. After downconversion to zero intermediate frequency, frame synchronization is carried out using the short and long training sequences. The cyclic prefix (CP) is removed, followed by a fast Fourier transform (FFT), yielding the frequency-domain representation of the k th OFDM subcarrier as

$$Y_k = \left(\sum_{i=0}^{N-1} \alpha_i \right) \cdot X_k + W_k \quad (15)$$

where W_k is the Gaussian white noise in the frequency domain. After channel equalization based on the ZF criterion, the estimated signal can be written as

$$\hat{X}_k = Y_k / \sum_{i=0}^{N-1} \alpha_i = X_k + W_k / \sum_{i=0}^{N-1} \alpha_i = X_k + \tilde{W}_k. \quad (16)$$

From the equation above, it is evident that when α_i are approximately identical, the received SNR is proportional to the square of the number of RNs employed

$$\text{SNR}_{\text{comm}} = \frac{E[|X_k|^2]}{E[|\tilde{W}_k|^2]} = \frac{P_s \cdot \left| \sum_{i=0}^{N-1} |H_{i,k}| \right|^2}{\sigma_w^2} \quad (17)$$

where $E[\cdot]$ represents the expectation function, P_s is the transmitting power, and σ_w^2 is the noise variance.

In the sensing scenario, the signal synthesized at the target and received by the j th receiver can be expressed as

$$r_{\text{RF-sen},j}(t) = \sum_{i=0}^{N-1} \alpha_{i,j} \cdot \bar{\xi} \cdot s_{\text{RF-OFDM}}\left(t - \frac{2R_j}{c}\right) + n(t) \quad (18)$$

where R_j represents the propagation distance from the j th transmitter to the target location, $\bar{\xi} = |\bar{\xi}|e^{j\varphi_{\bar{\xi}}}$ is the complex scattering coefficient of the target, and c is the speed of light. After bandpass filtering and downconversion through the other branch of the power divider, the echo signal is sampled by an oscilloscope. The digitized signal is then processed like that of the communication receiver, including downconversion, synchronization, CP removal, and FFT. After removing the modulation payload in the frequency domain, the channel response can be expressed as

$$H_{k,j} = \bar{\xi} \sum_{i=0}^{N-1} \alpha_{i,j} e^{-j2\pi(k\Delta f + f_c)\frac{2R_j}{c}} + \tilde{W}_{k,j}. \quad (19)$$

An inverse FFT (IFFT) is then performed to obtain the ranging results

$$h(t)_j \approx \bar{\xi} \left(\sum_{i=0}^{N-1} \tilde{\alpha}_{i,j} \right) \cdot \text{sinc}\left(B \cdot \left(t - \frac{R_j}{c}\right)\right) + n(t). \quad (20)$$

As shown in (18), the individual signal peaks are coherently superposed in the time domain. Consequently, when each α is equal, the SNR improves by approximately N^2 times in transmit coherent mode, which can be expressed as

$$\text{SNR}_{\text{sen},j} = \left(\sum_{i=0}^{N-1} \bar{\xi} \tilde{\alpha}_{i,j} \right)^2 / \sigma^2. \quad (21)$$

Consequently, further coherent combining of the received signals from N RNs is capable of yielding an approximate N^3 -fold SNR improvement. As can be seen from (17) and (21), this substantial SNR gain enables the optimization of EVM and RMSE for communication and sensing in complex environments.

III. EXPERIMENTS AND RESULTS

A. High-Stability Signal Transmission Through Fronthaul

To investigate the feasibility of the proposed system, an experimental setup with one central node and two RNs was implemented, as shown in Fig. 2. At the central node, three continuous-wave optical carriers at 193.4, 193.6, and 193.8 THz are injected into three MZMs, respectively. The MZMs are driven by a TTS, a 10-MHz reference clock, and an LO signal. The TTS is generated by a pulse generator, the 10-MHz clock is provided by a rubidium clock, and the LO signal is generated by a low-phase-noise microwave signal generator. The modulated optical signals are then split into two distribution paths for each RN by three 50:50 1×2 OCs. In one path, the two optical signals carrying the TTS and LO signals pass through a CIR from ports 1 to 2, and are then multiplexed together with the 10-MHz-modulated optical signal into a single-mode fiber (SMF) through a WDM. After passing through the VODL, the multiplexed signals

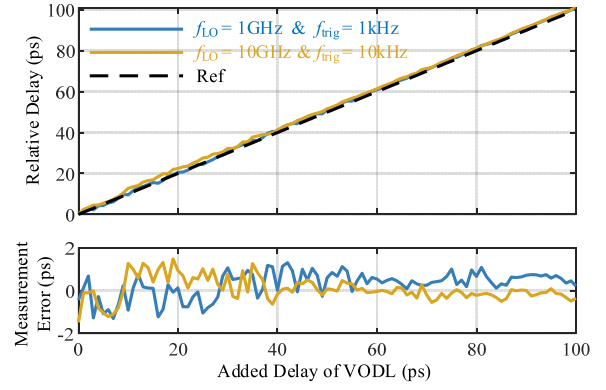


Fig. 4. Linearity of the delay measurement, obtained by comparing the measured delay variations with the delay introduced by VODL.

are transmitted to the RN over a 2-km SMF serving as the fronthaul link, and then demultiplexed into three separate channel by another WDM.

At the RN 1, the optical signal carrying the 10-MHz reference clock is directly converted into an electrical signal by a PD. Meanwhile, the optical signals carrying the TTS and LO signals are each split into two branches via 50:50 1×2 OCs. The lower branch signals are converted into the electrical domain by two PDs, while the upper branch optical signals are reflected by optical mirrors back to the WDM. These reflected signals are then remultiplexed and transmitted back to the central node through the same 2-km SMF and VODL. After returning to the central node, these backpropagated signals are demultiplexed by the WDM, enter port 2 of the corresponding CIRs, and are routed from port 3 to a delay measurement module for precise delay variation estimation. The module comprises a TIC (Keysight 53230A) and a vector network analyzer (VNA, Ceyear 3674H). The TIC is utilized to acquire coarse transfer delay of the fronthaul for resolving the integer phase ambiguity. Due to its 20-ps time-interval resolution, the TIC theoretically enables ambiguity-free transfer delay estimation for LO frequencies up to 25 GHz.

Initially, experiments were conducted to evaluate the accuracy of the proposed delay measurement scheme. To rule out possible frequency-dependent anomalies associated with the synchronization pulse and LO signals, two groups of operating parameters were tested: an LO signal at 1 GHz with a TTS pulse repetition rate of 1 kHz, and an LO signal at 10 GHz with a TTS pulse repetition rate of 10 kHz. During the experiments, the VODL was tuned in 100 increments of 1 ps.

The delay variations were then measured under the two sets of signal parameters, and the corresponding results are shown in Fig. 4. It can be observed that the measured delay variations are in excellent agreement with the preset values, with deviations within ± 1.5 ps.

Furthermore, to verify the fronthaul transfer delay stability of the proposed system, a proportional–integral–derivative (PID) controller was employed to drive the VODL for active compensation based on the measured link jitter. Over a continuous 1-h period, the actual delay drift of the fiber link, together with the rising-edge timing jitter of the transmitted TTS with pulse repetition rates of 1, 10, and 100 kHz were measured. As illustrated in Fig. 5(a), the uncompensated fronthaul link exhibits a significant delay drift exceeding 400 ps over 1 h.

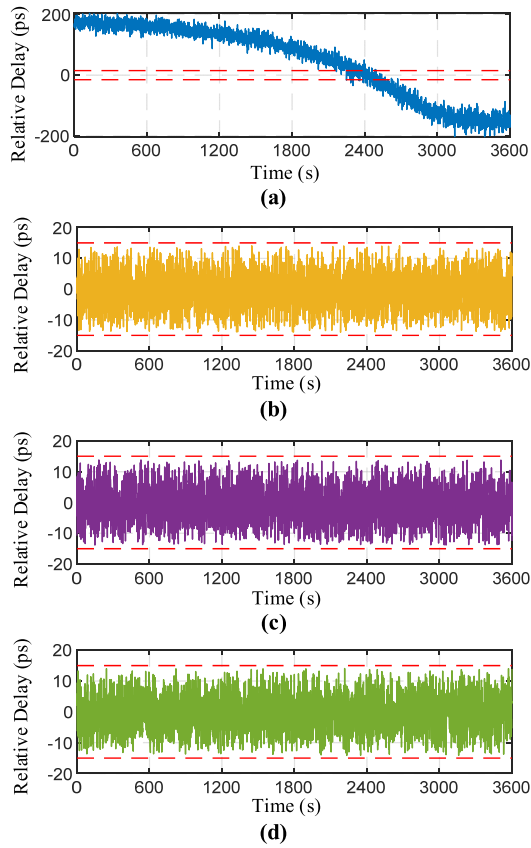


Fig. 5. Comparison of fronthaul transfer delay stability before and after compensation: (a) free-running; (b) with 1-kHz TTS; (c) with 10-kHz TTS; and (d) with 100-kHz TTS.

In contrast, Fig. 5(b)–(d) demonstrates that, with the active compensation, the rising-edge jitter of the 1-, 10-, and 100-kHz TTS remains largely unaffected by thermally induced fiber drift, with standard deviations (STDs) of only 6.04, 5.92, and 5.99 ps, respectively. These residual jitters are mainly attributed to the intrinsic timing jitter of the electrical pulse generator rather than to the optical link itself.

Subsequently, to verify the quality of the signals delivered to the RN through the proposed transmission network, we evaluated the long-term frequency stability of the 10-MHz reference clock and the phase variations of the LO signals at 1, 5, and 10 GHz over a 1-h period. Fig. 6 illustrates the Allan deviation (ADEV) of the delivered 10-MHz signal. At short averaging times (with $\tau < 100$ s), all three curves exhibit a typical downward trend dominated by white phase noise. However, as the averaging time increases, the uncompensated 2-km fronthaul link suffers from severe long-term drift induced by environmental perturbations, causing the ADEV to rise. In contrast, once active delay compensation is enabled, the stability is fully restored and closely follows the back-to-back (B2B) baseline. This indicates that the proposed feedback mechanism effectively suppresses the slow fiber-induced phase variations while preserving the inherent short-term stability.

Furthermore, Fig. 7 presents the phase drift of the LO signals under free-running and actively compensated conditions. Without compensation, the phase error gradually accumulates over time. Notably, for the same temporal drift, higher LO frequencies exhibit more severe phase deviations, with the

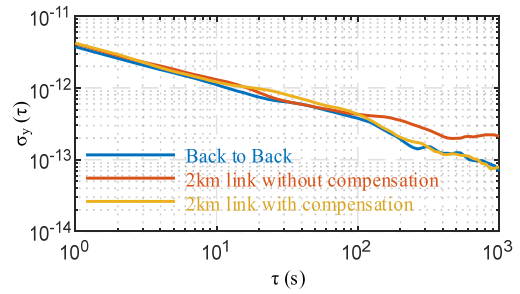


Fig. 6. Frequency stability comparison of the optical link under three different transmission conditions.

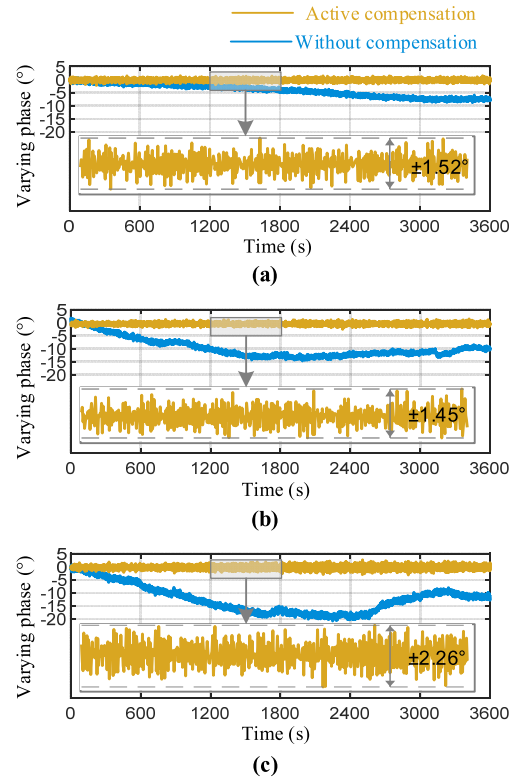


Fig. 7. Comparison of the measured LO phase variation with and without compensation under different LO frequencies: (a) 1, (b) 5, and (c) 10 GHz.

maximum phase error reaching approximately 20° at 10 GHz over 1 h. By contrast, when delay compensation is activated, the phase variations at all tested frequencies are effectively suppressed and strictly confined within $\pm 2.5^\circ$. This high degree of phase coherence provides a solid foundation for the cell-free CJT ISAC system.

B. Cell-Free CJT ISAC Validation

To validate the proposed cell-free CJT ISAC architecture, a proof-of-concept experimental setup was established, comprising two RNs, one sensing target, and dedicated communication receivers. To emulate a flat-fading environment, the two RNs were positioned to be nearly equidistant from the receiver. This symmetrical geometry effectively isolates the impact of phase synchronization errors by minimizing the influence of frequency-selective fading, thereby enabling a rigorous evaluation of the system coherence.

Driven by the centrally distributed and stabilized 10-MHz reference clock and 10-kHz TTS, the transmitter employs a

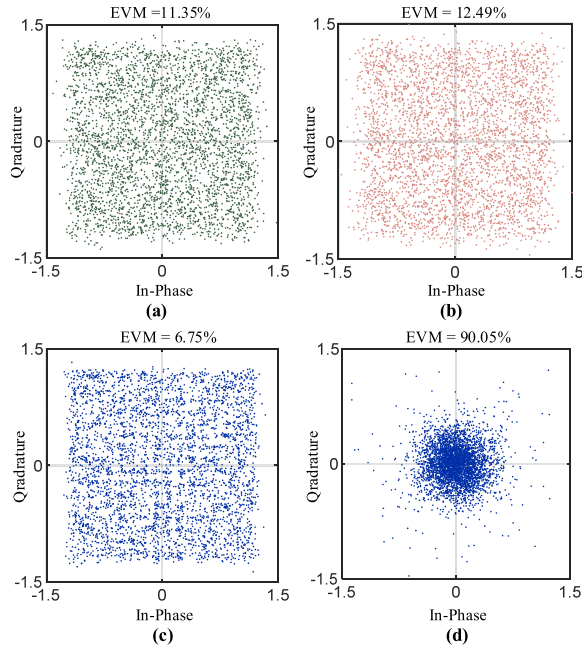


Fig. 8. Constellations of the received OFDM signals under different transmission scenarios. (a) Tx1 only; (b) Tx2 only; (c) with CJT; and (d) without CJT.

64-GSa/s AWG to generate the intermediate-frequency OFDM signal with 409.6-MHz bandwidth and 256-QAM modulation. The signal is then upconverted to 9 GHz via a mixer driven by the distributed LO signal through a power divider. After bandpass filtering (9 GHz center, 500-MHz bandwidth) and 30-dB electrical amplification, the RF signal is radiated into free space via a 15-dBi horn antenna (HA).

In the experiment, the UE was positioned approximately 2.5 m away from the two transmitting HAs, with the two RN-to-UE propagation distances configured to be nearly equal, thus obtaining the greater gain. It is worth noting that the residual difference between the two propagation distances introduces an additional phase offset, which is included in the channel response $H_{i,k}$ and compensated before CJT.

Therefore, after wireless propagation, the superimposed signals are received by the corresponding HAs at the UE side. In the communication link, the received signals are directly filtered and digitized by an oscilloscope operating at 64 GSa/s. In the sensing path, by contrast, the target echoes are first downconverted using the complementary branch of the aforementioned LO signal. Finally, the communication payloads are recovered, and target ranging profiles are extracted simultaneously.

We first characterize the communication performance by evaluating the EVM and the corresponding constellation diagrams under various transmission paradigms. As shown in Fig. 8(a) and (b), during single-RN mode, RN 1 and RN 2 achieve comparable EVM values of 11.35% and 12.49%, respectively. This close performance confirms the successful establishment of nearly symmetric channel conditions, thereby providing a rigorous baseline for the subsequent CJT evaluation. When the proposed synchronization framework is applied, the constellation clusters become significantly more compact, resulting in an improved EVM of 6.75%, as shown in Fig. 8(c). This corresponds to coherent processing gains

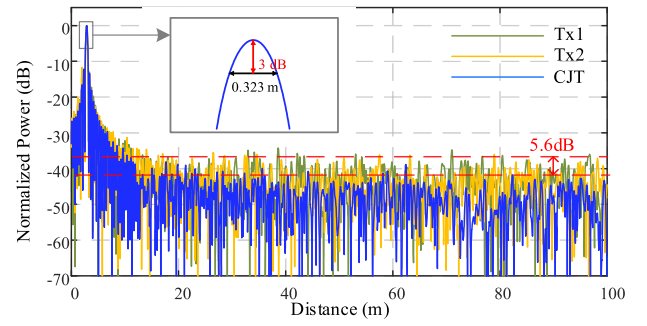


Fig. 9. Range Profile of the OFDM sensing under different transmission scenarios.

of 4.52 and 5.35 dB relative to the two single-RN cases. Conversely, in the absence of CJT for delay measurement and compensation, the differential fronthaul delay introduces a relative timing offset and a carrier-phase offset, resulting in severe SNR degradation and the EVM degrades drastically to 90.05%, as shown in Fig. 8(d).

To characterize the sensing performance, a target was placed at a stand-off distance of approximately 2 m, while the receivers at RN 1 and RN 2 were used to capture the sensing echoes. As shown in Fig. 9, the extracted range profile accurately identifies the target at the intended position. Notably, the measured 3-dB range resolution is 0.323 m, which agrees well with the theoretical limit determined by the signal bandwidth. In addition to precise target localization, the proposed CJT framework provides substantial SNR enhancement. Compared with both RN 1 and RN 2 that operate in single-RN mode, the coherent scheme achieves processing gains of about 5.6 dB, approaching the theoretical limit of 6.02 dB for transmit coherent mode. These robust coherent integration gains convincingly demonstrate the viability of the proposed architecture for advanced sensing applications.

IV. CONCLUSION

In this article, a scalable and low-complexity cell-free CJT ISAC architecture empowered by microwave photonic synchronization has been proposed and experimentally validated for the first time. By ingeniously multiplexing synchronization reference signals over a shared optical fiber link to extract the delay jitter, the proposed system fundamentally overcomes the hardware complexity and resource bottlenecks of conventional time–frequency distribution networks. In experiments, ps-level signal synchronization accuracy was achieved. Capitalizing on this stringent synchronization, the subsequent ISAC experiment demonstrated substantial coherent processing gains, delivering a 5.35-dB communication performance improvement (a decrease of 5.74% in communication EVM) alongside a 5.6 dB enhancement in sensing SNR. These results compellingly demonstrate that the proposed cell-free CJT ISAC architecture effectively integrates independent APs into a unified virtual aperture, thereby laying a viable technical foundation for large-scale, waveform-level coherent 6G ISAC networks.

REFERENCES

- [1] F. Liu et al., "Integrated sensing and communications: Toward dual-functional wireless networks for 6G and beyond," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1728–1767, Jun. 2022.

- [2] L. Wang, X. Wang, and S. Pan, "Microwave photonics empowered integrated sensing and communication for 6G," *IEEE Trans. Microw. Theory Techn.*, vol. 73, no. 8, pp. 5295–5315, Aug. 2025.
- [3] J. A. Zhang et al., "Enabling joint communication and radar sensing in mobile networks—A survey," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 1, pp. 306–345, 1st Quart., 2022.
- [4] X. Chen et al., "Deep-learning-based angle-of-arrival estimation using microwave photonic down-conversion without calibration," *Chin. Opt. Lett.*, vol. 24, no. 5, May 2026, Art. no. 053902.
- [5] M. H. Alsamh, A. Hawbani, S. Kumar, and S. H. Alsamhi, "Multisensory metaverse-6G: A new paradigm of commerce and education," *IEEE Access*, vol. 12, pp. 75657–75677, 2024.
- [6] M. Chen and Q. Cheng, "Multimode communication with programmable photonic integrated mesh," *Photonix*, vol. 5, no. 1, p. 28, Oct. 2024.
- [7] X. Peng, X. Hu, J. Gao, R. Jin, X. Chen, and C. Zhong, "Integrated localization and communication for IRS-assisted multi-user mmWave MIMO systems," *IEEE Trans. Commun.*, vol. 72, no. 8, pp. 4725–4740, Aug. 2024.
- [8] B. He, F. Wang, and J. Cheng, "Joint secure transceiver design for integrated sensing and communication," *IEEE Trans. Wireless Commun.*, vol. 23, no. 10, pp. 13377–13393, Oct. 2024.
- [9] H. Que, J. Yang, T. Du, S. Xia, C.-K. Wen, and S. Jin, "Cooperative mapping, localization, and beam management via multi-modal SLAM in ISAC systems," *IEEE Trans. Commun.*, vol. 73, no. 11, pp. 12023–12037, Nov. 2025.
- [10] K. Chen et al., "Integrated radar and communication design with low probability of intercept based on 4-D antenna arrays," *IEEE Trans. Antennas Propag.*, vol. 70, no. 9, pp. 8496–8506, Sep. 2022.
- [11] F. Zhao et al., "A Ka-band 4TX/4RX dual-stream joint radar-communication phased-array CMOS transceiver," *IEEE Trans. Microw. Theory Techn.*, vol. 72, no. 3, pp. 1993–2008, Mar. 2024.
- [12] K. Chen, X. Gong, F. Yang, Y. Chen, S.-W. Qu, and S. Yang, "Joint beamforming and waveform optimization in 4-D antenna arrays for integrated sensing and communication systems," *IEEE Trans. Antennas Propag.*, vol. 73, no. 10, pp. 7787–7799, Oct. 2025.
- [13] F. Ye et al., "Implementation of 6G TKμ extreme connectivity via cell-free massive MIMO system: A theoretical evaluation," *IEEE Trans. Wireless Commun.*, vol. 23, no. 11, pp. 17744–17760, Nov. 2024.
- [14] L. Zhou, J. Dai, W. Xu, and C. Chang, "Joint target detection and channel estimation for distributed massive MIMO ISAC systems," *IEEE Trans. Cognit. Commun. Netw.*, vol. 11, no. 1, pp. 300–315, Feb. 2025.
- [15] X. Lou, W. Xia, S. Jin, and H. Zhu, "Beamforming optimization in distributed ISAC system with integrated active and passive sensing," *IEEE Trans. Commun.*, vol. 73, no. 3, pp. 1607–1620, Mar. 2025.
- [16] R. Thomä and T. Dallmann, "Distributed ISAC systems—multisensor radio access and coordination," in *Proc. 20th Eur. Radar Conf. (EuRAD)*, Berlin, Germany, Sep. 2023, pp. 351–354.
- [17] K. Han, K. Meng, and C. Masouros, "MIMO-OFDM signaling design for noncoherent distributed ISAC systems," *IEEE Trans. Wireless Commun.*, vol. 25, pp. 7792–7808, 2026.
- [18] H. Bao, F. Ponzini, and C. Fager, "Wideband mm-Wave 6×2 distributed MIMO transmitter using sigma-delta-over-fiber," *J. Lightw. Technol.*, vol. 42, no. 9, pp. 3107–3117, May 1, 2024.
- [19] C. Diaz-Vilor, A. Lozano, and H. Jafarkhani, "Cell-free UAV networks with wireless fronthaul: Analysis and optimization," *IEEE Trans. Wireless Commun.*, vol. 23, no. 3, pp. 2054–2069, Mar. 2024.
- [20] M. Elfiatoure, M. Mohammadi, H. Q. Ngo, and M. Matthaiou, "Cell-free massive MIMO for ISAC: Access point operation mode selection and power control," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Kuala Lumpur, Malaysia, Dec. 2023, pp. 104–109.
- [21] S. Liu, R. Liu, Z. Lu, M. Li, and Q. Liu, "Cooperative cell-free ISAC networks: Joint BS mode selection and beamforming design," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Dubai, United Arab Emirates, Apr. 2024, pp. 1–6.
- [22] W. Yan, O. A. Topal, Z. Behdad, Ö. T. Demir, and C. Cavdar, "Communicate or sense? AP mode selection in mmWave cell-free massive MIMO-ISAC," in *Proc. 58th Asilomar Conf. Signals, Syst., Comput.*, Pacific Grove, CA, USA, Oct. 2024, pp. 889–893.
- [23] Z. Wei et al., "Symbol-level integrated sensing and communication enabled multiple base stations cooperative sensing," *IEEE Trans. Veh. Technol.*, vol. 73, no. 1, pp. 724–738, Jan. 2024.
- [24] Q. Jiang et al., "Experimental performance of bidirectional phase coherent transmission and sensing for mmWave cell-free massive MIMO systems with reciprocity calibration," *IEEE J. Sel. Areas Commun.*, vol. 44, pp. 3591–3607, 2026.
- [25] S. Xu, H. Sun, Y. Xu, T. Guo, C. Li, and L. Yang, "Distributed compression method for channel calibration in cell-free MIMO ISAC systems," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 7, pp. 2349–2363, Jul. 2025.
- [26] R. Li, Z. Xiao, and Y. Zeng, "Toward seamless sensing coverage for cellular multi-static integrated sensing and communication," *IEEE Trans. Wireless Commun.*, vol. 23, no. 6, pp. 5363–5376, Jun. 2024.
- [27] X. Sun et al., "Performance analysis and optimization for network-assisted full-duplex cell-free multi-static ISAC systems," *IEEE Trans. Green Commun. Netw.*, vol. 10, pp. 272–288, 2026.
- [28] R. Puerta et al., "Analog mobile fronthaul for 6G and beyond," *J. Lightw. Technol.*, vol. 42, no. 21, pp. 7458–7467, Nov. 1, 2024.
- [29] H. V. Balan, R. Rogalin, A. Michaloliakos, K. Psounis, and G. Caire, "AirSync: Enabling distributed multiuser MIMO with full spatial multiplexing," *IEEE/ACM Trans. Netw.*, vol. 21, no. 6, pp. 1681–1695, Dec. 2013.
- [30] U. Kunnath Ganesan, R. Sarvendranath, and E. G. Larsson, "BeamSync: Over-the-air synchronization for distributed massive MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 23, no. 7, pp. 6824–6837, Jul. 2024.
- [31] X. Liu, J. Wang, Q. Sang, X. Wang, and S. Pan, "High-accuracy active phase stabilization system based on microwave photonic phase-derived ranging," in *AOPC 2024: AI in Optics and Photonics*, vol. 13502. Bellingham, WA, USA: SPIE, Dec. 2024, Art. no. 135020Q.
- [32] C. Huang et al., "Multi-access RF transfer with passive phase correction," in *Proc. 20th Int. Conf. Opt. Commun. Netw. (ICOON)*, Shenzhen, China, Aug. 2022, pp. 1–3.
- [33] J.-D. Deschênes et al., "Synchronization of distant optical clocks at the femtosecond level," *Phys. Rev. X*, vol. 6, no. 2, May 2016, Art. no. 021016.
- [34] H. Wang, S. Li, X. Xue, X. Xiao, and X. Zheng, "Distributed coherent microwave photonic radar with a high-precision fiber-optic time and frequency network," *Opt. Exp.*, vol. 28, no. 21, pp. 31241–31252, Oct. 2020.
- [35] J. Wei, F. Zhang, S. Pan, and L. Yu, "Stable frequency dissemination via optical fiber based on passive phase fluctuation cancellation," in *Proc. Eur. Microw. Conf. (EuMC)*, Paris, France, Sep. 2015, pp. 1276–1278.
- [36] L. C. Sinclair et al., "Synchronization of clocks through 12 km of strongly turbulent air over a city," *Appl. Phys. Lett.*, vol. 109, no. 15, Oct. 2016, Art. no. 151104.
- [37] L. Wang et al., "Single-shot optical transfer delay measurement with sub-picosecond accuracy and sub-millisecond range," *Photon. Res.*, vol. 13, no. 5, pp. 1302–1312, May 2025.
- [38] L. Wang, Y. Yang, Q. Sang, J. Wang, X. Wang, and S. Pan, "Time-domain Vernier effect for ultra-fast and ambiguity-free optical transfer delay measurement," *J. Lightw. Technol.*, vol. 43, no. 10, pp. 4538–4545, May 15, 2025.
- [39] Y. Zhang, X. Zhu, Y. Liu, Y. Jiang, Y. L. Guan, and V. K. N. Lau, "Hierarchical BEM based channel estimation with very low pilot overhead for high mobility MIMO-OFDM systems," *IEEE Trans. Veh. Technol.*, vol. 71, no. 10, pp. 10543–10558, Oct. 2022.
- [40] A. R. L. Paiva, W. C. Freitas, R. P. Antonioli, Y. C. B. Silva, and G. Fodor, "Mitigating the impact of channel aging in cell-free MIMO systems using a channel predictor based on extended Kalman filter," *IEEE Trans. Veh. Technol.*, vol. 74, no. 6, pp. 8544–8560, Jun. 2025.
- [41] F. Liu, W. Yuan, C. Masouros, and J. Yuan, "Radar-assisted predictive beamforming for vehicular links: Communication served by sensing," *IEEE Trans. Wireless Commun.*, vol. 19, no. 11, pp. 7704–7719, Nov. 2020.
- [42] Y. Wu, D. Wang, and X. You, "Cell-free radio access network technology for 6G," *ZTE Technol. J.*, vol. 30, no. 4, pp. 14–25, Aug. 2024.
- [43] Z. Hong, S. Xu, T. Li, C. Li, D. Wang, and X. You, "Robust cascaded team MMSE precoding for cell-free distributed downlink under hierarchical fronthaul," *IEEE Trans. Wireless Commun.*, vol. 23, no. 10, pp. 14515–14529, Oct. 2024.