

Toward Practical Photonic THz Links: Field Demonstration of Beam Alignment for Real-Time Wireless Fronthaul at 300 GHz

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Abstract: We report a field demonstration of THz beam alignment enabling a real-time photonic-based 300-GHz wireless fronthaul link, achieving 25-GbE eCPRI NRZ transmission over a 200-m wireless distance with a BER of 1.5×10^{-4} .

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1. Introduction

As mobile networks evolve toward higher capacity and functional disaggregation for 6G and beyond [1], the fronthaul link increasingly demands fiber-like throughput with very low latency. While millimeter-wave wireless systems are constrained by limited bandwidth, the terahertz (THz) spectrum can provide multi-tens-of-gigabit data rates over short distances, providing a practical alternative to fiber deployment [2, 3]. Therefore, THz wireless fronthaul has emerged as a promising solution to achieve high-capacity and flexible connectivity in future mobile networks. However, due to the highly directional nature of THz waves and significant propagation loss, precise beam alignment is essential for stable transmission. Most previously reported photonics-based THz experiments have relied on manual antenna adjustments [4–6], which are labor-intensive and impractical for real-world deployment. The implementation of a beam-alignment mechanism is thus a crucial step toward commercialization of THz wireless fronthaul systems.

To address this challenge, we have developed and, to the best of our knowledge, for the first time field-demonstrated a real-time photonic 300-GHz wireless fronthaul link incorporating a closed-loop THz beam-alignment function. The system concept assumes GPS-assisted coarse positioning to provide an initial pointing direction, after which fine beam alignment is autonomously performed through a raster-scanning routine and subsequently maintained in a feedback loop under real-world field conditions. It achieves stable 25-GbE enhanced common public radio interface (eCPRI) fronthaul transmission, representing an important step toward practical THz wireless deployment.

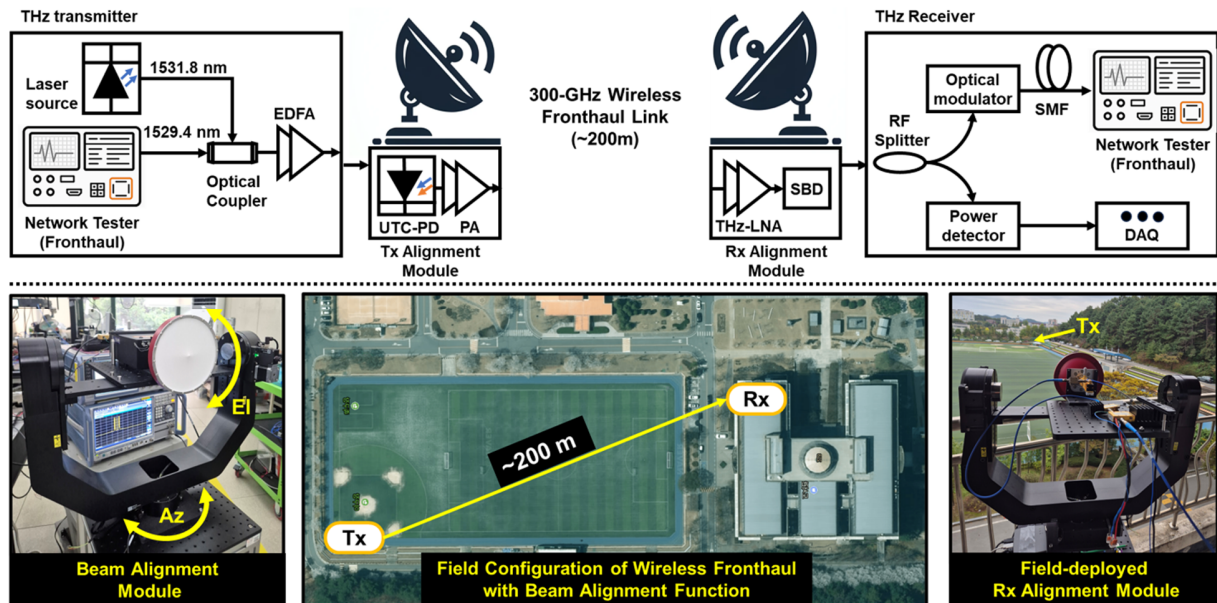


Fig. 1. Field configuration of photonic 300-GHz wireless fronthaul link with beam-alignment function. EDFA: erbium-doped fiber amplifier; PA: power amplifier operating in the 300-GHz band; SBD: Schottky barrier diode detector; DAQ: data acquisition unit.

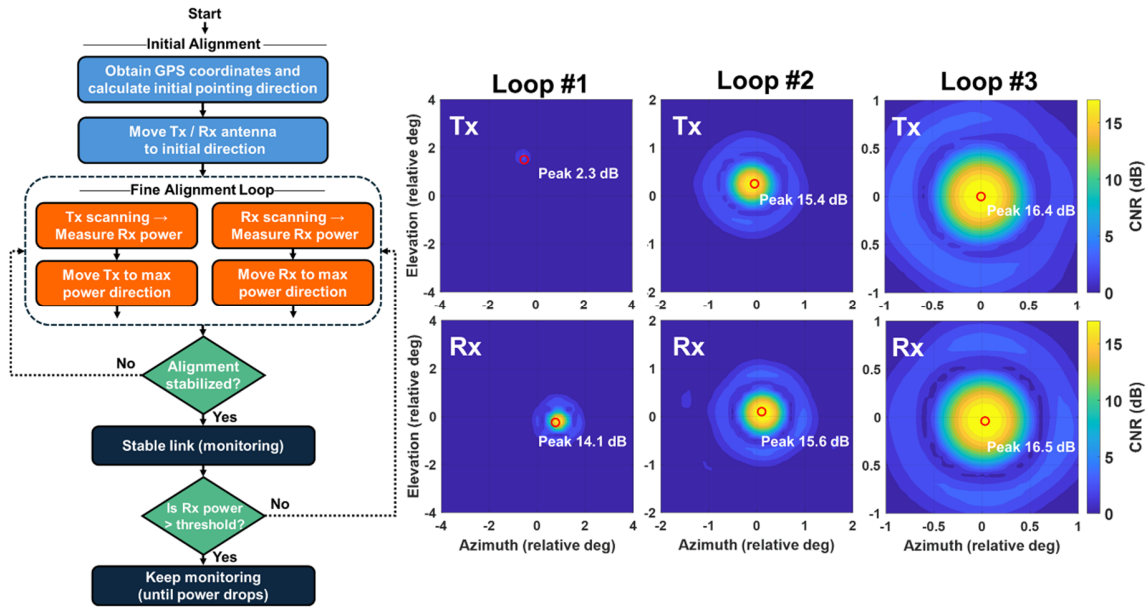


Fig. 2. Automatic beam-alignment process and experimental evolution of received CNR distribution for the photonic 300-GHz wireless fronthaul link.

2. Field demonstration of photonic 300-GHz wireless fronthaul link with THz beam alignment

Figure 1 illustrates the field configuration of the photonic 300-GHz wireless fronthaul link incorporating an automatic beam-alignment function. In the transmitter (Tx) section, two optical carriers are generated, one of which carries a 25-GbE NRZ signal generated by a VIAVI network tester, emulating a real-time eCPRI fronthaul link. The two optical carriers are combined and amplified before being delivered to the Tx-alignment module. In this module, a UTC-PD-based photomixer generates a 300-GHz wave through optical heterodyning. The generated THz wave is then amplified by a power amplifier operating in the 300-GHz band and radiated through a Cassegrain antenna toward the receiver (Rx). Both the Tx and Rx include a beam-alignment unit equipped with motorized mechanical stages that steer the antennas in the azimuth (Az) and elevation (El) directions, providing precise angular control for automatic alignment. At the Rx, the incoming THz signal is first amplified and then envelope-detected by a Schottky barrier diode (SBD), yielding an electrical baseband signal. The detected baseband signal is split into two paths: one is directed to an optical modulator to reconstruct the optical fronthaul signal for end-to-end performance evaluation, and the other is connected to a power detector for received-power monitoring. The modulated optical signal is fed to the Rx-side VIAVI tester to assess the end-to-end fronthaul performance, while the power-detector output provides the received-power distribution. Using a data-acquisition unit, the received-power information is continuously monitored and utilized for automatic beam-alignment control.

As shown in Fig. 2, an automatic beam-alignment routine is implemented, consisting of GPS-assisted coarse pointing followed by alternating fine alignment of the Tx and Rx antennas. In each iteration, the Tx (then the Rx) performs a raster scan while the received power is measured at the Rx, and the antenna is steered toward the direction yielding the maximum received power. The scan window is adaptively narrowed in each iteration to refine the alignment. The link is considered stabilized once the angular scan range ($\Delta\theta$), relative power variation $|\Delta P|/P$, and received power P_{rx} satisfy predefined thresholds ($\Delta\theta_{th}$, ϵ , P_{align} , respectively). After convergence, the link enters a monitoring mode; if the received power drops below a monitoring threshold (P_{mon}), the process re-enters the fine-alignment loop. The right panels in Fig. 2 present the measured carrier-to-noise ratio (CNR) distributions for the Tx and Rx antennas over three consecutive iterations of the fine-alignment process. In the first iteration, with a $\pm 4^\circ$ scan range, both antennas exhibited weak received power, with peak CNRs of 2.3 dB on the Tx side. Once the Tx beam was properly aligned, the Rx antenna was able to acquire a significantly stronger signal with a peak CNR of about 14.1 dB. In the second iteration, the scan range was reduced to $\pm 2^\circ$, and the beams began to converge, yielding peak CNRs of approximately 15.4 dB (Tx) and 15.6 dB (Rx). In the final iteration, with a $\pm 1^\circ$ scan range, both antennas achieved stable alignment, reaching peak CNRs of 16.4 dB and 16.5 dB, respectively. These results clearly demonstrate the convergence and effectiveness of the proposed automatic beam-alignment process, where adaptive narrowing of the scan window enables precise direction tracking and stable link establishment.

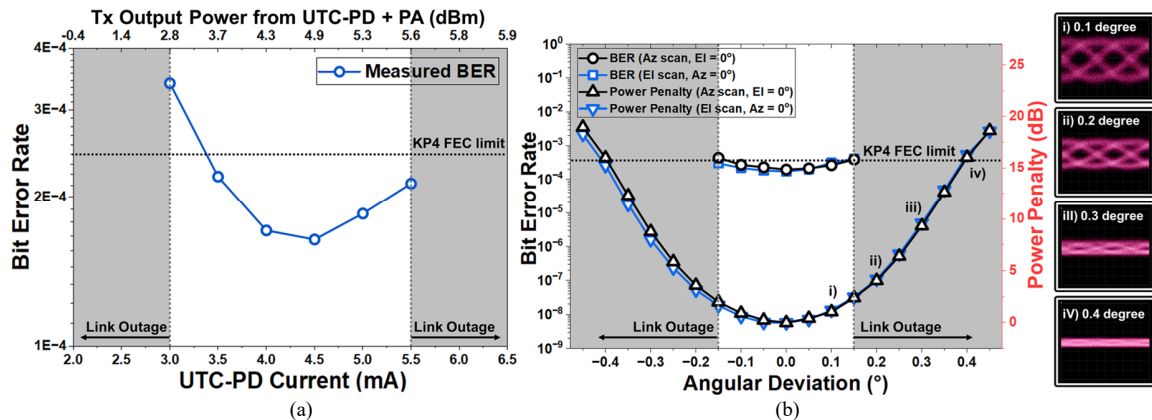


Fig. 3. BER performance of wireless fronthaul with beam-alignment functionality at 300 GHz. (a) Measured BER as a function of UTC-PD current (b) Measured BER and power penalty as functions of beam misalignment angle. The inset eye diagrams corresponding to (i) 0.1°, (ii) 0.2°, (iii) 0.3°, and (iv) 0.4° azimuth misalignment angles are shown on the right.

After the beam alignment was stabilized, the photonic 300-GHz wireless fronthaul link successfully transmitted a 25-GbE fronthaul signal over a 200-m line-of-sight (LoS) distance under outdoor conditions. The recovered optical signal was fed to the VIAVI network tester for real-time performance evaluation. Figure 3(a) presents the measured BER as a function of the UTC-PD current. The available fade margin was limited to approximately 2 dB due to propagation loss and system impairments such as bandwidth limitations and timing jitter. This resulted in link outages at both low currents (due to insufficient received power) and high currents (due to nonlinear distortion from saturation). The optimal performance was achieved at a bias current of approximately 4.5 mA, yielding a minimum BER of 1.5×10^{-4} , which is below the KP4 FEC limit of 2.4×10^{-4} . Figure 3(b) illustrates the high sensitivity of the link to beam misalignment. The link remained stable only within a narrow alignment tolerance of $\pm 0.15^\circ$; deviations beyond this range caused a rapid BER increase and link failure. This sensitivity is attributed to the limited system power margin and the inherently narrow beamwidth of the 300-GHz link. The inset eye diagrams visually confirm this, showing a progressive closure of the eye as angular deviation increases.

While the present implementation employs a 2-D raster scan for fine alignment, which is inherently time-consuming, our goal in this work is not to compare tracking algorithms but to realize a robust, automatically aligned 300-GHz wireless fronthaul link and to verify its stability in the field. Faster alignment and tracking could be achieved by replacing the raster scan with simple local search strategies (e.g., gradient or hill-climbing using local power measurements), state-estimation algorithms (e.g., Kalman-filter-based pointing-error tracking), or sparse-sampling schemes (e.g., compressed-sensing-style beam probing with multi-resolution patterns) [7]. Such accelerations are orthogonal to the system concept and are left for future optimization of the tracking module.

3. Conclusion

In this work, we successfully demonstrated a real-time photonic 300-GHz wireless fronthaul link integrating an automatic beam-alignment function. The system autonomously established and maintained antenna pointing through received-power feedback, achieving stable 25-GbE wireless fronthaul link over a 200-m LoS path in an outdoor environment. These results validate the viability of high-capacity photonic THz wireless links for practical fronthaul applications and showcase a robust solution to the critical challenge of precise, automated alignment.

Acknowledgement

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References

- [1] K. B. Letaief *et al.*, "The roadmap to 6G: AI empowered wireless networks," *IEEE Commun. Mag.* **57**, 84–90, (2019).
- [2] Z. Zhang *et al.*, "Beyond 100-Gb/s optoelectronic terahertz communications: Key technologies and directions," *IEEE Commun. Mag.* **58**, 88–94 (2020).
- [3] P. T. Dat *et al.*, "Photonics-enabled millimeter-/terahertz-wave signal processing and applications," *J. Lightw. Technol.* **43**, 6071–6085 (2025).
- [4] M. Sung *et al.*, "Photonic THz communications based on radio-over-fiber technology for 6G mobile network: Design and opportunity," *IEEE J. Sel. Top. Quantum Electron.* **29**, 1–11 (2023).
- [5] W. Li *et al.*, "Photonic terahertz wireless communication: Towards the goal of high-speed kilometer-level transmission," *J. Lightw. Technol.* **42**, 1159–1172 (2024).
- [6] Y. Wei *et al.*, "Demonstration of a photonics-aided 4600-m wireless transmission system in the sub-THz band," *J. Lightw. Technol.* **42**, 8564–8576 (2024).
- [7] Q. Xue *et al.*, "A survey of beam management for mmWave and THz communications towards 6G," *IEEE Commun. Surv. Tut.* **26**, 1520–1559 (2024)