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RESEARCH ARTICLE

WILEY

Real-time demonstration of photonics-based THz wireless fronthaul integrated with fiber-optic mobile fronthaul

Sang-Rok Moon | **Sooyeon Kim** | **Eon-Sang Kim** | **Minkyu Sung** | **Seung-Hyun Cho**

Optical Network Research Section, Electronics and Telecommunications Research Institute, Daejeon, Korea

Correspondence
Sang-Rok Moon, Optical Network Research Section, Electronics and Telecommunications Research Institute, Daejeon, Korea.
Email: srmoon@etri.re.kr

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Abstract

A photonics-based terahertz (THz) wireless fronthaul is proposed, and its feasibility is investigated by real-time demonstration. The proposed wireless fronthaul can be simply integrated into existing fiber-optic fronthaul, to serve as a complementary or emergency network. An optical signal can be converted into a THz wireless signal by photonics-based THz-signal generation technology, utilizing a unitraveling carrier photo-diode. Following wireless transmission, the THz wireless signal is reconverted to an optical signal by using a Schottky-barrier diode and an optical transmitter. To investigate the feasibility of our proposed concept, real-time transmission over a 100 m-equivalent configuration is demonstrated with 24.33 Gb/s common public radio interface option 10 signals, at a carrier frequency of 275 GHz. The latency added by the proposed wireless fronthaul was measured to be few 100 ns, which is negligibly lower than the wireless transmission latency required by 6G key performance indicator.

KEYWORDS

mobile fronthaul, optical communication, THz communication, wireless fronthaul

1 | INTRODUCTION

Mobile fronthaul generally refers to the connection between baseband units (BBUs) and remote radio units (RRUs). Fiber-optic links are widely utilized for the implementation of transmission links for mobile fronthaul, because they provide wide bandwidth, low loss, and high reliability.[1,2] However, fiber optic links have high deployment costs and limited flexibility. These limitations have become more noticeable with the evolution of mobile communication technology, as the coverage area of each mobile cell tends to decrease because of increasing carrier frequency. Wireless fronthaul can compensate for these limitations by offering connection flexibility and lower deployment costs. Hence, wireless fronthaul has attracted significant interest in recent years.[3–8] One of the promising applications of wireless fronthaul is the complementary (or ad hoc) network of the fiber-optic fronthaul.

Figure 1 illustrates the concept of mobile fronthauling with a wireless fronthaul. As shown in Figure 1, it covers shaded areas where optical fiber deployment is not

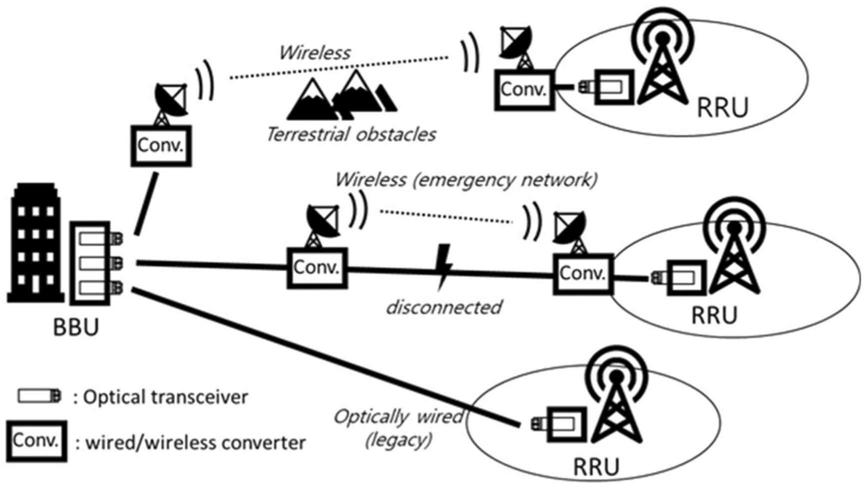

FIGURE 1 Concept of mobile fronthauling with the wireless fronthaul. BBU, baseband unit; RRU, remote radio unit.

affordable, and it can also be used as an emergency network when fiber-optic links are disconnected. The requirements of the wireless fronthaul are as follows. First, it should be compatible and seamlessly integrate with the existing legacy fiber-optic fronthaul. Second, it should offer a transmission capacity ranging from tens of gigabits of transmission to potentially hundreds of gigabits. In function split option 7.2, the data rate is expected to increase to ~100 Gb/s.[9] Additionally, the network should be transparent to support centralized control at BBUs without any protocol changes. Finally, the latency of the wireless network should be sufficiently low.

A terahertz (THz) wireless link with photonics-based THz signal generation can satisfy the above requirements because it provides seamless wireless signal generation, supports a high data rate, and is inherently transparent. There have been several demonstrations applying a photonics-based approach and integrating it with fiber-optic links.[10–13] These demonstrations showed ~100 Gb/s transmission using coherent signal formats over a few meters of links. These results imply that the photonics-based THz wireless link has significant potential for high-speed wireless communication. However, the short-reach high-speed links in the previous demonstrations were not appropriate for THz wireless fronthaul applications.

In this paper, we propose a THz wireless fronthaul that can serve as a complementary network to legacy fiber-optic networks. Because most existing fiber-optic fronthaul systems employ a nonreturn-to-zero (NRZ) signal format, the proposed THz wireless fronthaul also adopts the NRZ signal format for seamless integration with a previously installed fiber-optic mobile fronthaul. To investigate the feasibility, real-time transmission was demonstrated over a 100 m-equivalent wireless link (10 m wireless setup with 20 dB attenuator) using an off-the-shelf network tester and optical transceivers. NRZ common public radio interface (CPRI) option 10 signals of 24.33 Gb/s were transmitted over a wireless link, and the measured bit error rate (BER) satisfied the KP4 (RS 544,514) threshold BER (2.2×10^{-4}). Furthermore, the latency added by the proposed wireless fronthaul was confirmed to be considerably lower than that of a 6G key performance indicator (KPI). To the best of our knowledge, this is the first real-time demonstration of THz wireless fronthaul.

2 | EXPERIMENTAL SETUP

Figure 2 shows the experimental setup used to demonstrate the proposed THz wireless fronthaul. For real-time BER measurements, a network tester (VIAVI MTS-5800) was used. Using the network tester, 24.33 Gb/s of NRZ data were generated following the CPRI option 10. The signal was converted into an optical signal using electro-absorption modulated laser (EML)-based off-the-shelf optical transceiver 1 (Lightron SFP28 C-band transceiver). The wavelength of the data-carrying light was 1529.55 nm (196 THz). It was then amplified using erbium-doped fiber amplifier 1 (EDFA 1). A constant-wave (CW) light with a wavelength of 1531.7 nm (195.725 THz) was generated by a tunable laser diode (TLD, Pure-photonics PPCL550). The polarization of the data-carrying and CW light were aligned using polarization controller 1 (PC 1). The two wavelength-separated lights were combined using a 50:50 optical coupler and amplified using EDFA 2. The combined light was then injected into a unitraveling photodiode (UTC-PD) after polarization alignment and optical power adjustment by PC 2 and a variable optical attenuator (VOA), respectively. In the UTC-PD, a beat signal was generated by via an optical heterodyne mixing procedure between the two wavelength-separated lights. The center frequency of the beat signal was 275 GHz because the frequency difference of the lights was already

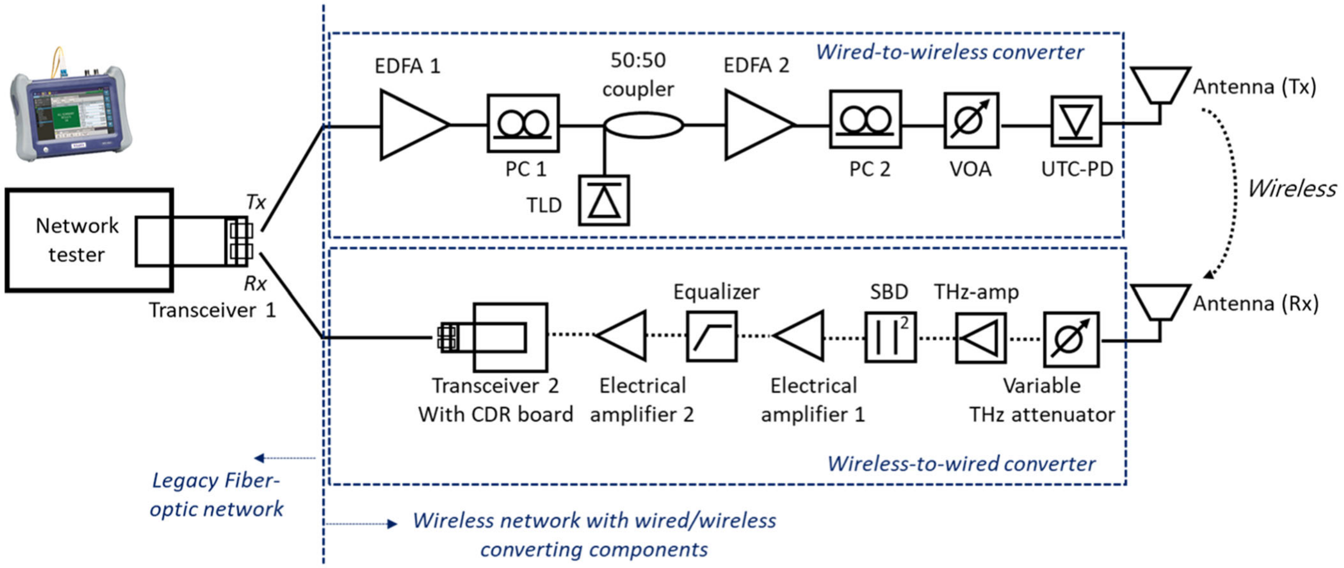

FIGURE 2 Experimental setup for real-time demonstration of wireless fronthaul. CDR, clock data recovery; EDFA, erbium-doped fiber amplifier; PC, polarization controller; SBD, Schottky barrier diode; TLD, tunable laser diode; UTC-PD: unitraveling carrier photo-diode; VOA, variable optical attenuator.

set to 275 GHz. A frequency of 275 GHz was intentionally selected by experimental optimization to obtain the best transmission performance. A wireless link was established using two antennas, with antenna gains of 48 dB each. After the wireless transmission, the received power was adjusted using a variable THz attenuator (RPG, WTA 220-330) and THz-band amplifier. The signal was then down-converted to a baseband using a Schottky barrier diode (SBD, VDI WR3.4ZBD-F). The baseband signal was amplified using two amplifiers. An equalizer (SHF EQ. 16 A) was used between the amplifiers to enhance the high-frequency components. The signal was then transferred to the clock data recovery board and converted to an optical signal by Transceiver 2. Finally, the optical signal is received using Transceiver 1.

Figure 3 illustrates the frequency characteristics of the key THz components, THz amplifier, and UTC-PD. The graph with square symbols shows the THz amplifier gain as a function of the frequency. The graph with circular symbols on the auxiliary axis depicts the UTC-PD output power as a function of frequency at a driving current of 6 mA. At 275 GHz, the gain of the amplifier was ~17.1 dB, and the THz output power was −9.1 dBm.

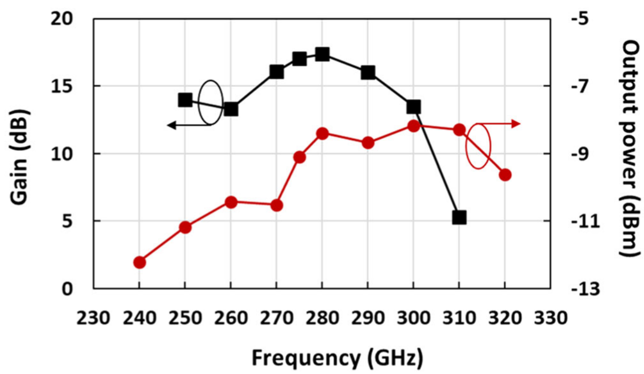

FIGURE 3 Frequency characteristics of sub-THz band components. Square symbols: THz amplifier gain and circle symbols: UTC-PD output power.

3 | DEMONSTRATION OF WIRELESS TRANSMISSION

Figure 4A shows a photograph of the established 10 m wireless transmission setup. An additional transmission distance was simulated by adjusting the attenuation value of the variable THz attenuator. For instance, a 100 m transmission was emulated by a transmission distance of 10 m and attenuation of 20 dB. The BER values were measured for various configurations, such as back-to-back (i.e., two antennas were closely placed), 10 m + 2 dB, 10 m + 8 dB, 10 m + 15 dB, and 10 m + 20 dB. For all configurations, BER values below the KP4 forward error correction (FEC) threshold (2.2×10^{-4}) were achieved at the optimal operating point. Two types of performance limitations were observed in the experiments. Initially, the BER deteriorated as the UTC-PD current increased to a certain level, which is attributed to the saturation of the THz amplifier, thereby limiting the allowable range of the UTC-PD current. Additionally, the BER degraded when

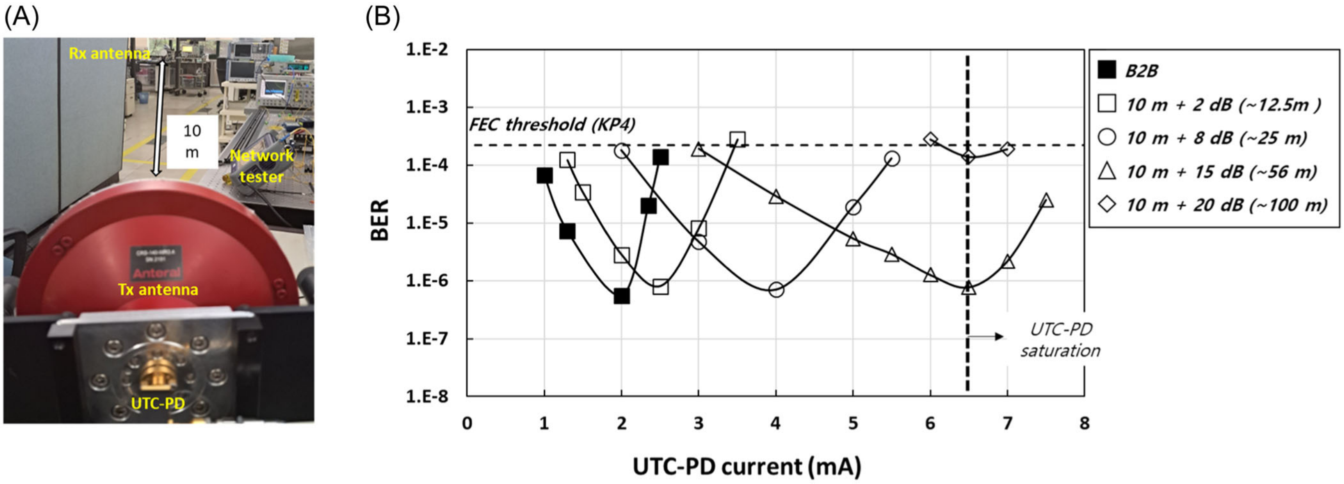

FIGURE 4 Demonstration of the proposed THz wireless fronthaul. (A) Photograph of a 10 m wireless transmission setup and (B) bit error rate measurement results.

TABLE 1 measured round-trip time.

Configuration	Round-trip time (ns)
Loop-back[a]	12
B2B	435
10 m wireless transmission	572 ns

[a]The Tx and Rx of the transceiver at the network tester were directly connected by a 1 m patch-cord.

the UTC-PD current reached 6.5 mA owing to UTC-PD saturation. As a result of this saturation, the BER of the 100 m equivalent configuration was considerably worse than that of the other configurations. These limitations can be overcome by improving the saturation power of the components.

In addition, we measured the round-trip time to determine the latency added by the wireless fronthaul. The results are displayed in Table 1. In the loop-back measurement, which directly connects the Tx and Rx of the optical transceiver at the network tester directly by 1 m patch-cord, the measured round-trip time was 12 ns. With the wireless fronthaul, the measured round times in the B2B configuration and 10 m wireless transmission were 435 and 572 ns, respectively. These round time values are low compared to the 100 μs wireless transmission latency observed for the 6G KPI.[14] The round-trip time was mainly attributed to the propagation time of the optical patch cords and tens of meters of erbium-doped fibers in the EDFA. Notably, the propagation time through a 1 m optical fiber was ~5 ns. If the optical components are compactly integrated and the number of employed EDFA is reduced, the latency can be further reduced.

4 | CONCLUSION

In this paper, we present a real-time demonstration of a THz wireless fronthaul, which is the first such demonstration, to our knowledge. The THz wireless fronthaul adopts photonics-aided THz signal generation technology, which enables seamless and transparent integration with the legacy fiber-optic mobile fronthaul. This high compatibility can make it a complementary or an emergency network to the existing mobile fronthaul. Through real-time BER measurements, the transmission of a 24.33 Gb/s NRZ signal, following CPRI data option 10, was experimentally demonstrated over 100 m-equivalent wireless links. The measured round-trip time caused by the insertion of the THz wireless fronthaul was a few 100 ns, which is considerably lower than the wireless transmission latency required by the 6G KPI.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Sang-Rok Moon http://orcid.org/0000-0003-4230-0960
Sooyeon Kim http://orcid.org/0000-0002-5826-2287

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