Transparent Radio–Fiber–Radio–Fiber System in 100-GHz Band for Indoor Uplink Signal Transmission in Beyond 5G

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Abstract: We demonstrate the first radio–fiber–radio–fiber system for transparent delivery of 100-GHz radio signals from indoor to a central station. We successfully transmitted 16-QAM single-carrier and OFDM signals with line rates of approximately 30 and 40 Gb/s over the system consisting of two cascaded wireless–RoF links in the 100-GHz band.
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1. Introduction

In beyond 5G and 6G networks, radio access networks (RANs) are expected to continue to 95 GHz and beyond for extreme communications [1]. However, high free-space loss and weak penetration of radio signals in the high-frequency bands are the largest bottleneck for the deployment of new RANs. Transparent coverage extensions between outdoors and indoors will be the key to facilitate the deployment of the RANs in the high-frequency bands. Analog radio-over-fiber (RoF) systems can play a vital role in relaying radio signals between outdoors and indoors to avoid high penetration loss [2–3]. However, previous studies only focused on transmission of radio signals in low-frequency bands, such as below 60 GHz. Recently, broadband RoF systems using the direct conversion of radio signals to optical signals have been demonstrated [4–7]. Nevertheless, the systems can only be applicable for fixed wireless bridge applications owing to the signal down-conversion in the second fiber link. A broadband RoF system that can relay radio signals in the 100-GHz band from outdoors to indoors was recently demonstrated for the downlink direction [8]. However, to the best of our knowledge, the transmission of radio signals in beyond 90 GHz from an indoor environment to a central station (CS) has never been reported for the uplink direction.

In this paper, we proposed and demonstrated a novel system capable of transparently transporting radio signals in the high-frequency band from an indoor resident to a CS using broadband RoF systems. The key technologies include newly fabricated optical modulators for the direct conversion of millimeter-wave (mmW) radio signals to optical signals and a simple photonic down-conversion technology. Using the proposed system, we successfully transmitted single-carrier (SC) and orthogonal frequency-division multiplexing (OFDM) signals with the line rates of 30 and 40 Gb/s, respectively, over two cascaded wireless–RoF links in the 100-GHz band. To our best knowledge, the attained data rate and operating frequency are the highest ever reported over an uplink system.

2. System concept and key technologies

The proposed system for a transparent transmission of high-frequency radio signals from an indoor user end (UE) to a CS is shown in Fig. 1(a). The system consists of four sections: (1) radio access links between UEs and access points (APs); (2) RoF relay links between APs and relay nodes (RNs); (3) RANs between RNs and remote radio heads (RRHs); (4) RoF mobile fronthaul links between RRHs and CSs. To assure signal transparency between indoors and outdoors such that same terminals can be used to communicate with the RRHs from both environments,

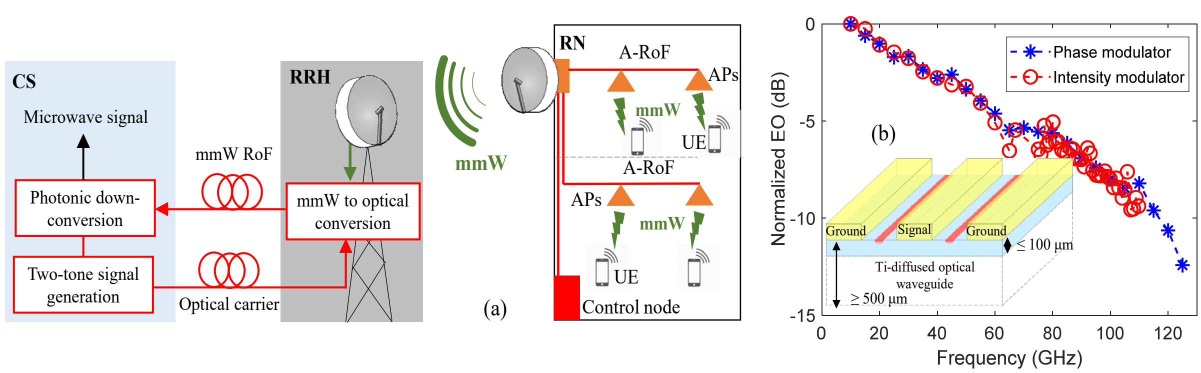

Fig. 1. (a) Proposed system concept; (b) thin substrate optical modulators and electro-optic responses.

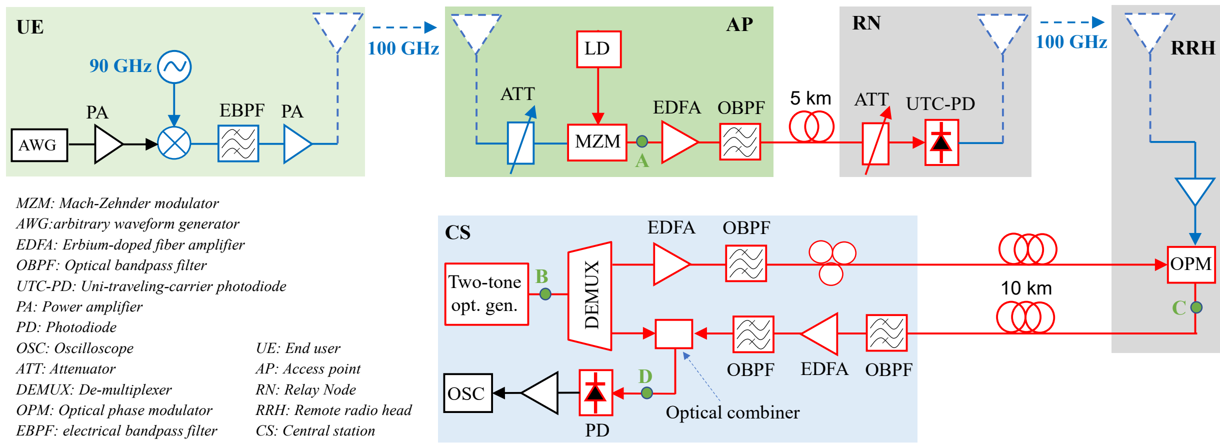

Fig. 2. Experimental setup for 100-GHz signal transmission over a transparent radio–fiber–radio–fiber system.

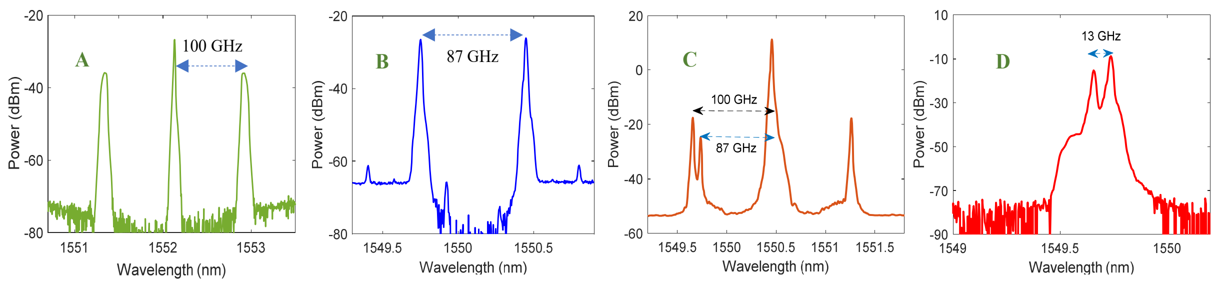

Fig. 3. Optical spectra at point A, B, C, and D in the experimental setup.

indoor radio signals should be transparently transported. In this study, we proposed a RoF relay system using a broadband optical intensity modulator for the direct conversion of mmW signals in the 100-GHz band to optical signals. For the mobile fronthaul links, we employed a broadband RoF system using an optical phase modulator for conversion of mmW signals to optical signals and photonic down-conversion technology for simultaneously detecting and down-converting the signal to the microwave band. To realize a direct conversion of mmW signals in the 100-GHz band to optical signals, we fabricated and employed broadband optical modulators using x-cut thin-film lithium niobate [4, 8]. The electro-optic responses of the fabricated modulators are shown in Fig. 1(b), indicating a good frequency response up to 110 GHz. The photonic down-conversion was identical to the previous work [4]. However, in this study, we employed an optical phase modulator for the signal conversion to simplify the RRH and avoid the performance degradation due to bias voltage drift.

3. Experimental setup and results

The experimental setup for the proof-of-concept demonstration of the proposed system is shown in Fig. 2, including five parts at the UE, AP, RN, RRH and CS. The UE performed signal generation and modulation, whereas the CS received and demodulated the signal. The radio-to-optical conversion was performed at the AP and RRH, whereas the RN converted optical signals back to radio signals for outdoor RAN transmission. Notably, in the proof-of-concept demonstration, radio signals were connected directly from the UE to AP and from the RN to RRH without transmission in free space to simplify the setup. Nevertheless, this simplification does not alter the system concept and its applicability. In a practical system, high-gain antennas can be used to compensate for the losses and attenuations in the free-space transmission. At the UE, intermediate frequency signals at 10 GHz generated from an arbitrary waveform generator were upconverted to the 100-GHz band using an electrical mixer. The signals were filtered and amplified before being input into a broadband optical intensity modulator for converting transparently to an optical signal at the AP. The bias voltage to the modulator was set at the quadrature point for a linear signal modulation, as shown in Fig. 3(a). The signal was amplified using an EDFA, filtered, and transmitted to the RN using a 5-km SMF. At the RN, the signal was input to a uni-travelling-carrier photodiode to convert it to an mmW at 100 GHz. The signal was amplified using a power amplifier before being fed into an optical phase modulator for conversion to an optical signal for further transmission to the CS. The optical carrier signal for the signal modulation at the RRH was generated remotely at the CS. In this study, to simplify the receiver and DSP at the CS, we employed a simple photonic down-conversion technology for detecting and down-converting the signal to the

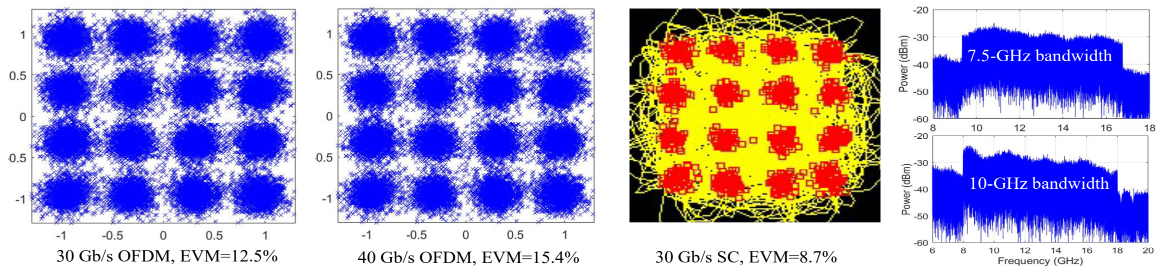

Fig. 4. Constellations of received OFDM and single-carrier signals and spectrums of OFDM signals.

microwave band simultaneously [4]. At the CS, a two-tone optical signal with a frequency separation of 87 GHz (as shown in Fig. 3(b)) was generated using a dual-parallel Mach–Zehnder modulator [9]. The upper sideband was amplified and transmitted to the RRH for signal modulation. The phase-modulated signal (with the optical spectrum shown in Fig. 3(c)) was transmitted to the CS using a 10-km SMF. At the CS, the lower sideband of the modulated signal was selected using an optical filter. The filtered signal was amplified, filtered, and combined with the lower sideband of the generated two-tone optical signal. The combined signal with the spectrum as shown in Fig. 3(d) was input to a low-speed photodiode for being converted to a radio signal at 13 GHz. Finally, the signal was amplified, sent to a real-time oscilloscope, and demodulated.

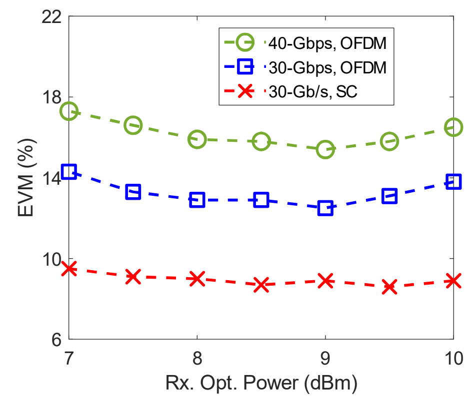

Fig. 5. Signal performance versus received optical power at RN.

We transmitted both OFDM and SC signals over the system. An OFDM signal consisting of 4096 subcarriers, of which 20% at the band edges were inactive, was generated and transmitted. The OFDM signal generation and demodulation relied on a classical DSP method using a one-tap equalizer per subcarrier. A SC signal with a roll-off factor of 0.15 was generated, and a pre-compensation technique was applied to the transmitted signal to overcome the non-flat frequency response. The constellations of the 30 and 40 Gb/s OFDM signals and 30 Gb/s SC signal are shown in Fig. 4. For the 40 Gb/s OFDM signal, an error vector magnitude (EVM) of 15.4 % was received, satisfying the 7 % FEC overhead BER of 3.8×10^{-3} for 16-QAM signals [10]. The 30 Gb/s SC signal was successfully transmitted with an EVM of 8.7 %. The performance of the SC signal was better than that of the OFDM signals because the non-flat frequency response was compensated. As shown by the signal spectrums in Fig. 4, the cascaded channel response of the system was frequency selective, thus, the total EVM of the OFDM signals was increased. However, this effect can be resolved using a pre-compensation and/or a bit/power loading technique. The EVM performances for the 30 and 40 Gb/s OFDM signals and 30 Gb/s SC signal for different received optical powers at the RN are depicted in Fig. 5. For the 40 Gb/s OFDM signal, satisfactory performance was attained when a power of approximately 8 dBm was received, corresponding to a radio transmit power of –10 dBm. It is noteworthy that free-space radio links were omitted in the experiment; however, by increasing the transmit power to 10 dBm using a power amplifier and including a pair of 50-dBi antennas, a wireless link of up to 300 m between the RRH and RN can be expected. The wireless link distance can be further increased using a low-noise amplifier at the RRH. The radio link between the UE and APs is typically less than 10 m and can be easily realized using standard antennas.

4. Conclusion

We demonstrated the first transparent radio–fiber–radio–fiber system in the 100-GHz band using novel RoF systems. The system employed newly fabricated optical modulators for direct conversion of mmW signals to optical signals and photonic down-conversion technology, significantly simplifying the antenna sites and receiver. We transmitted 16-QAM SC and OFDM signals with line rates of 30 and 40 Gb/s over the system. The system is promising for extension of coverages to indoor areas and facilitating the deployment of new RANs in B5G/6G networks.

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