Transparent Delivery of 100-GHz Radio Signal to Indoor Using Broadband Phase-Modulated RoF System

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Abstract *We demonstrate a broadband RoF system for transparent delivery of 100-GHz radio signal from outdoor to indoor using a low-loss optical phase modulator. We successfully transmitted 32-/64-QAM OFDM with a line rate of approximately 29 Gb/s over the converged system consisting of two RoF links and two radio links in the 100-GHz band. ©2022 The Author(s).*

Introduction

The frequency of radio access networks (RANs) is expected to extend to 114 GHz and above in beyond 5G and 6G networks [1]. Experimental demonstration of RANs in exceeding 100-GHz band was recently conducted [2]. However, the free-space loss is extremely high and the pass-through is very weak in high-frequency bands, making it extremely challenging to communicate with users residing indoors. To extend the communications to indoors, reflecting radio signals on intelligent metasurfaces is proposed as a potential solution. Nevertheless, the control is relatively complicated, and the extending coverage is limited. Radio repeater is another solution; however, only solutions at low-frequency bands are available [3]. To facilitate the deployment of RANs in high-frequency bands, a new coverage extension technology to indoor environments is highly demanded. Optical technologies, especially analog radio-over-fiber (RoF), can play a vital role in facilitating new RANs. As shown in Fig. 1, RoF systems can transparently relay millimeter-wave (mmW) radio signals to indoors. In this system, radio signal from remote radio heads (RRH) is received at relay nodes (RN) and transparently converted to optical signal and transmitted to access points (APs) at which the signal is converted back to the mmW signal to communicate with indoor users. The APs can be flexibly placed, and the control node can manage the signal delivery to maximize the communications capacity, coverage, and energy efficiency. The RoF system should be able to support broadband radio signals in high-frequency bands without adding additional transmission impairments such that a standard receiver can be used by users residing both indoor and outdoor. Nevertheless, the operating frequency and transmission capacity in the previously reported RoF relaying systems were limited [4, 5]; thus, cannot meet requirements for RANs in B5G/6G. Recently, a broadband RoF system was demonstrated using a direct conversion of radio signal to optical signal [6]; however, the optical signal in the second fiber link was down-converted to an intermediate frequency (IF) band; therefore, cannot realize transparent relaying of mmW radio signals.

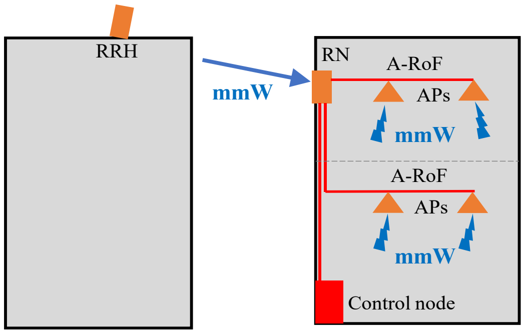

Fig. 1: RoF system for relaying mmW radio signal.

In this paper, we propose and demonstrate a new RoF relaying system in the 100-GHz band using a newly fabricated broadband optical phase modulator (OPM). The use of the OPM without a bias control at the RN significantly simplifies the system as well as the operation and management. The relaying system is completely transparent without any frequency conversion and added digital signal processing (DSP), allowing the same receiver to be used by both indoor and outdoor users. Using the proposed system, we successfully transmitted approximately 29 Gb/s OFDM signal over a converged system cascading two RoF links and two wireless links in the 100-GHz band. To the best of our knowledge, the achieved data rate and operating frequency are the highest ever reported over a relaying system to date.

Experimental Demonstration

The experimental setup for the proof-of-concept demonstration of the proposed system is shown in Fig. 2, including the central station (CS), RRH, RN, AP, and user end (UE). The CS performs signal generation and modulation, whereas the UE receives and demodulates the signal. The optical-to-radio conversion is performed at the RRH, whereas the RN converts radio signal to optical signal for further transmission to the AP

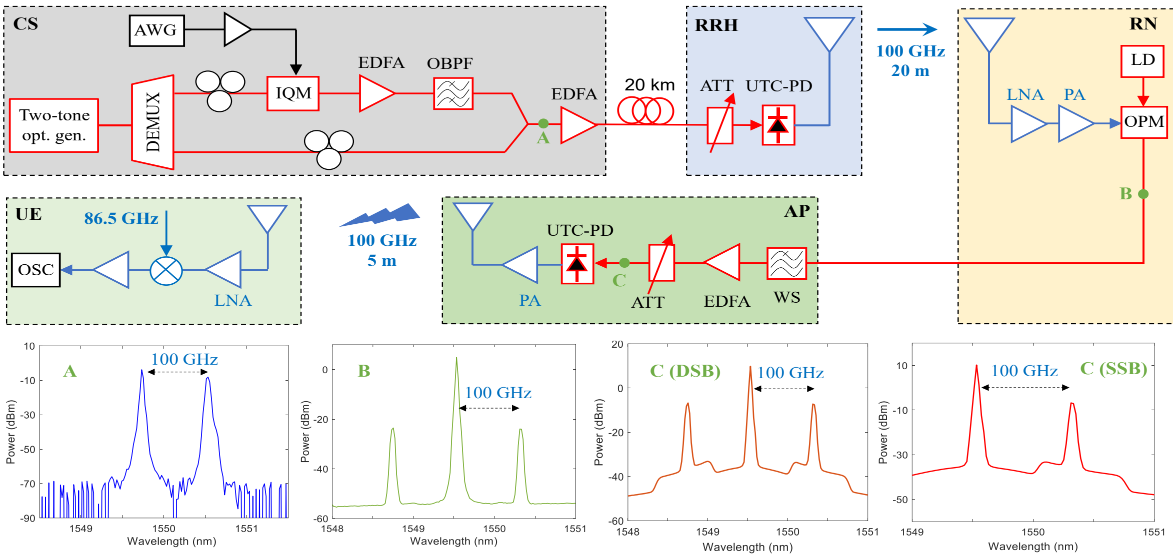

Fig. 2: Experimental setup for transparently relaying 100-GHz radio signal to indoor using phase-modulated RoF system.

where the radio signal is regenerated and transmitted to the UE. In the system, the RN consists of only an OPM and radio front-end, significantly simplifying the operation. At the CS, a two-tone optical signal with a frequency separation of 92 GHz was generated using a dual-parallel MZM [7]. The two optical sidebands were separated, and the upper sideband was modulated by OFDM signal at 8 GHz using an optical IQ modulator. The bias voltage to the modulator was controlled to generate only upper modulation sideband. The modulated signal was amplified and re-combined with the unmodulated sideband. The combined signal was amplified and transmitted to the RRH using a 20-km single-mode fiber (SMF). At the RRH, the signal was input to a uni-travelling-carrier photodiode (UTC-PD) to convert to an mmW signal at 100 GHz. The mmW signal was transmitted into the air using a 42-dBi antenna. After transmission over approximately 20 m in free space, the signal was received using a 35-dBi antenna at the RN. The signal was amplified using a low-noise amplifier (LNA) and a power amplifier (PA) before being converted to an optical signal using the newly fabricated OPM. For direct detection of the phase-modulated optical signal, a single-sideband (SSB) signal [8] and a double-sideband (DSB) signal with the optical carrier rotated by 90 degrees [9] were generated using a WaveShaper (WS). It should be noted that an optical filter can also be used to generate an optical SSB signal. In addition, the optical carrier-to-sideband ratio (CSR) was optimized to generate an optimal radio signal. The signal was amplified and input to another UTC-PD for converting to a radio signal at 100 GHz. An optical attenuator was used to adjust the received optical power. The generated radio signal was amplified and

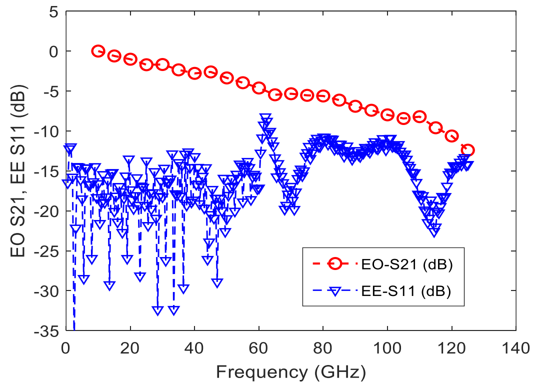

Fig. 3: S21 and S11 response of the OPM.

transmitted to free space using a 23-dBi horn antenna. After transmission over approximately 5 m in fee space, the signal was received using another horn antenna, amplified, and down-converted to 13.5 GHz using an electrical mixer. Finally, the signal was amplified, sent to a real-time oscilloscope, and demodulated. The optical spectra at different points along the system are also shown in the figure.

For transparent relaying of high-frequency radio signal, a broadband optical modulator is of critical importance. In this work, we fabricated and employed a broadband OPM to simplify the system and RN. The use of an OPM without a bias control at the RN can significantly simplify the operation and prevent the performance from degradation due to bias drift. The modulator was fabricated on the x-cut thin-film lithium niobate in the low dielectric constant layer for ripple-free operation and maximized electro-optic responsivity [6]. The electro-optic S21 response and the electrical reflection S11 of the modulator are shown in Fig. 2, showing a broadband operation up to 120 GHz, which is sufficient for converting radio signals in future RANs.

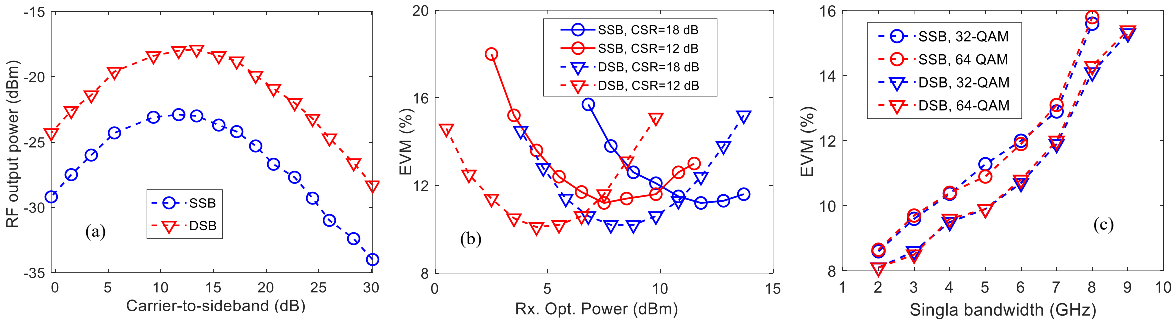

Fig. 4: System performance: (a) output 100-GHz signal; (b) OFDM signal vs rx. opt. power at AP; (c) vs signal bandwidth.

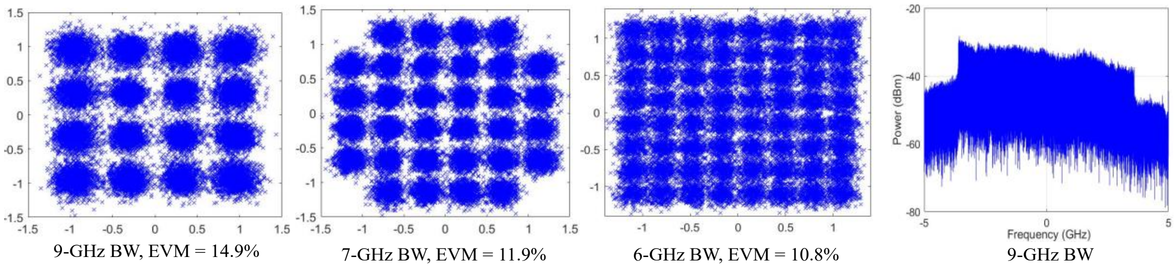

Fig. 5: Examples of constellations and spectrum of received signal.

The CSR of the phase-modulated signal has an impact on the generated signal in the second radio link. To determine the optimal CSR, we measured the output power of the UTC-PD at the AP. For the measurement, a carrier IF signal at 8 GHz was transmitted from the CS and the CSR was adjusted by attenuating the optical carrier. The results for different CSRs are shown in Fig. 3(a) for both SSB and DSB cases. It shows a clear relation between the CSR and the output signal. An optimal CSR of approximately 12 dB was observed when the optical carrier was attenuated by 20 dB. It is also observed that the DSB signal generates a much higher radio signal. Subsequently, an OFDM signal was transmitted over the system and the performance in terms of error vector magnitude (EVM) was evaluated. In the experiment, an OFDM signal consisting of 2048 subcarriers, of which 20% at the band edges were inactive, was generated using an arbitrary waveform generator. The required EVM values to satisfy the 7% and 20% FEC overhead limit for a 32-QAM and 64-QAM signal are 12.1% and 11.2%, respectively [10]. We first measured the signal performance for different received optical powers at the AP. The performances of a 5-GHz bandwidth (BW) 16-QAM signal for two CSR values of 12 and 18 dB are shown in Fig. 3(b). In both cases, the signal performance is maximized at a specific power and degraded when the power is increased beyond the values. This could be attributed to the distortion of the receiver at the UE. It is also observed that the signals with the optimal CSR value of 12 dB requires a power of approximately 3 dB lower than those of the 18-dB CSR signals. The performances of the OFDM signal with different BWs are shown in Fig. 3(c) for both thenSSB and DSB cases. In this measurement, the CSR was set at the optimal value of 12 dB. For the SSB signal, satisfactory performance was confirmed when the BW is increased to 6 GHz and 5 GHz for 32-QAM and 64-QAM signal, respectively. For the DSB signal, satisfactory performance was confirmed for a 9-GHz BW 16-QAM, 7-GHz BW 32-QAM, and 6-GHz BW 64-QAM signal with a line rate of approximately 29 Gb/s. Examples of the constellations of the received signals and the spectrum of a 9-GHz BW signal are shown in Fig. 4. It is noteworthy that only a basic DSP with a single-tap equalizer was employed in the experiment. The radio link distances were limited by the experiment space and can be further extended by adding a PA to the transmitter at the RRH and/or using higher-gain antennas.

Conclusion

We demonstrated the first RoF relaying system in the 100-GHz band. The system employs a newly fabricated optical phase modulator for direct conversion of a 100-GHz signal to an optical signal, significantly simplifying the system. We successfully transmitted OFDM signal with a line rate of approximately 29 Gb/s over the system consisting of two RoF links and two radio links in the 100-GHz band. The proposed system opens a door for the deployment of RANs in high-frequency bands in B5G and 6G networks.

Acknowledgements

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