Bi-Directional 5G NR Fiber-Wireless Systems with Single-Carrier Optical Modulation and Phase Modulation Scheme

Yu-Shen Lin[1], Wei-Cheng Fan[1], Cheng-Jun Lin[1], Chung-Yi Li[2], and Hai-Han Lu[1,*]

[1]Institute of Electro-Optical Engineering, National Taipei University of Technology, Taipei, 106 Taiwan
[2]Department of Communication Engineering, National Taipei University, New Taipei City, 237 Taiwan
**Corresponding author: hhlu@ntut.edu.tw*

Abstract: 5G MMW/sub-THz signals through a bi-directional fiber-wireless system with single-carrier optical modulation for downstream and PM scheme for upstream are implemented. It shows promise for performing 5G NR communication towards MMW and sub-THz bands.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2605) Free-space optical communication; (350.4010) Microwaves.

1. Introduction

As the fifth-generation (5G) market continues to grow, researchers are advancing 5G applications into higher frequency bands above sub-6 GHz, primarily MMW and sub-THz bands ranging from 24 to 300 GHz [1], [2]. For the transmission of MMW and sub-THz signals over fiber-wireless systems, several 5G NR fiber-wireless systems with multi-carrier optical modulation and intensity modulation (IM) scheme have been demonstrated. With multi-carrier optical modulation, however, RF power fading due to fiber dispersion and interference caused by optical beating from multiple carriers degrade the system's performance. In addition, with the IM scheme, the robustness to noise and distortion is low, resulting in degraded system performance. We thereby offered and built a bi-directional 5G NR fiber-wireless system with single-carrier optical modulation for downstream, and phase modulation (PM) scheme with remotely injection-locked DFB LD for upstream through 40-km SMF, 500-m optical wireless, and 2-m/1-m/0.5-m (downstream)/4-m (upstream) RF wireless transmissions. For downstream with single-carrier optical modulation, 20-Gb/s/50-GHz, 20-Gb/s/100-GHz, and 20-Gb/s/150-GHz 16-QAM-OFDM signals transmission over a 5G NR fiber-wireless system is successfully constructed. For upstream with PM scheme, 10-Gb/s/24-GHz and 10-Gb/s/28-GHz 16-QAM-OFDM signals transmission over a 5G NR wireless-fiber system is built in practice. This newly-established bi-directional 5G NR fiber-wireless system has great potential for MMW and sub-THz communications, which significantly impacts the fiber-wireless integration.

2. Experimental Setup

Fig. 1(a) depicts the configuration of a bi-directional fiber-wireless system with single-carrier optical modulation to transmit downstream 20-Gb/s/50-GHz, 20-Gb/s/100-GHz, and 20-Gb/s/150-GHz 16-QAM-OFDM signals, and PM scheme to transport upstream 10-Gb/s/24-GHz and 10-Gb/s/28-GHz 16-QAM-OFDM signals (referred as system I). For downstream, DFB LD1 supplies an optical carrier to an MZM. After driving by a modulator driver, a 20-Gb/s 16-QAM-OFDM signal produced from an OFDM transmitter is sent to the MZM. Over 40-km SMF transport, the optical carrier is supplied in a 50-GHz optical frequency comb (OFC) to produce four optical carriers. These four optical carriers with 50 GHz separation are distributed by OC2 and transmitted through a 500-m optical wireless link via doublet lenses mounted on two buildings' rooftops [see Fig. 1(b)]. The four optical carriers are then circulated by OC3 and detected by a 50-GHz high-speed PD, a 100-GHz ultra-fast PD, and a 150-GHz UTC-PD. The optical signals are then boosted by three separate PAs, and wirelessly delivered by three separate V-band HAs spaced 2 m apart, W-band HAs spaced 1 m apart, and D-band HAs spaced 0.5 m apart. After down-conversion by a mixer with an electrical LO and a frequency multiplier as well as boost by an LNA, an OFDM receiver is used to evaluate the BERs and their associated constellations.

System II shows a 5G NR fiber-wireless system with multi-carrier optical modulation. In system I, the 50 GHz OFC is located behind the 40 km SMF. A single optical carrier is transmitted over 40-km SMF transmission, and four optical carriers are transmitted over 500-m optical wireless and 2-m/1-m/0.5-m RF wireless transmissions. In system II, the 50 GHz OFC is located before the 40 km SMF [inset (i) of Fig. 1(a)]. Four optical carriers are transmitted over 40-km SMF, 500-m optical wireless, and 2-m/1-m/0.5-m RF wireless transmissions.

For upstream, DFB LD2 (with 1541.71 nm central wavelength) supplies an optical carrier to a phase modulator. After passing through a modulator driver, two combined 10 Gb/s 16-QAM-OFDM signals in the 24 and 28 GHz MMW band are sent to the phase modulator. Through 500-m optical wireless link, an OC2 circulates the optical signal and feeds it into a 40-km SMF. Over 40-km SMF transmission, the optical signal is injected into the DFB LD3/LD4 (with 1541.93/1541.59 nm central wavelength) to enable a PM-to-IM conversion and an optical detection. The 10-Gb/s/24-GHz and 10-Gb/s/28-GHz MMW signals are then amplified by two separate PAs, and wirelessly transmitted by two separate Ka-band and K-band HAs spaced 4 m apart. After LNA enhancement, an OFDM receiver analyzes the link performance in terms of BERs and their corresponding constellations.

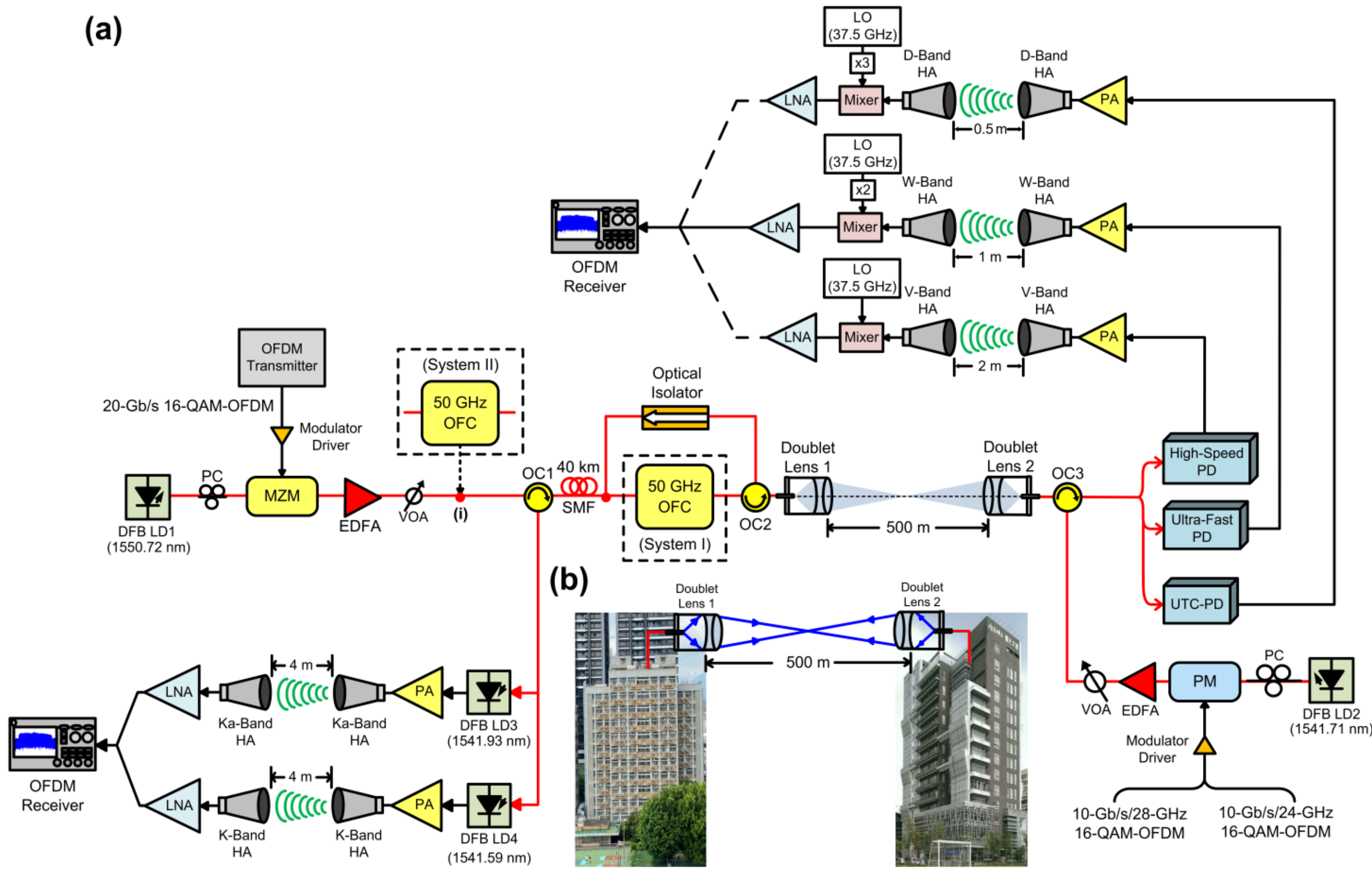

Fig. 1. (a) Configuration of bi-directional fiber-wireless system with single-carrier optical modulation to transmit downstream 20-Gb/s/50-GHz, 20-Gb/s/100-GHz, and 20-Gb/s/150-GHz 16-QAM-OFDM signals, and PM scheme to transport upstream 10-Gb/s/24-GHz and 10-Gb/s/28-GHz 16-QAM-OFDM signals. **(b)** A 500-m optical wireless link via doublet lenses mounted on two buildings' rooftops.

3. Results and Discussions

Fig. 2(a) shows the measured downstream BERs as a function of received MMW/sub-THz power over cross-media of 40-km SMF, 500-m optical wireless, and 2-m/1-m/0.5-m RF wireless, for system I (single-carrier optical modulation) and system II (multi-carrier optical modulation), respectively. In system I, a BER of 4.8×10^{-5} (< 3.8×10^{-3} FEC limit) is attained at received MMW/sub-THz power of -26.6 (20-Gb/s/50-GHz), -25.5 (20-Gb/s/100-GHz) and -24.3 (20-Gb/s/150-GHz) dBm. In system II, a degraded BER performance of 1.2×10^{-2} (> 3.8×10^{-3} FEC limit) is obtained at received MMW/sub-THz power of -17 (20-Gb/s/50-GHz), -15.5 (20-Gb/s/100-GHz), and -14.8 (20-Gb/s/150-GHz) dBm. This degradation in BER performance occurs mainly due to fiber dispersion-induced power fading because of the 40 km SMF transmission and interference due to optical beating from multiple optical carriers. Figs. 2(b), 2(c), and 2(d) present the associated constellations of 20-Gb/s/50-GHz, 20-Gb/s/100-GHz, and 20-Gb/s/150-GHz 16-QAM-OFDM signals of system I with a BER of 4.8×10^{-5}. Clearly, each 16-QAM-OFDM signal has a clear constellation. Figs. 2(e), 2(f), and 2(g) present the related constellations of 20-Gb/s/50-GHz, 20-Gb/s/100-GHz, and 20-Gb/s/150-GHz 16-QAM-OFDM signals of system II with a BER of 1.2×10^{-2}. One can see that each 16-QAM-OFDM signal has a blurred constellation.

To show a direct association with SMF length and BERs, we reduce the SMF length to 25 km to investigate the BERs of 20-Gb/s/50-GHz, 20-Gb/s/100-GHz, and 20-Gb/s/150-GHz 16-QAM-OFDM signals of system II. Through 25-km SMF, 500-m optical wireless, and 2-m/1-m/0.5-m RF wireless transmissions, the BER reaches 1.2×10^{-3} (< 3.8×10^{-3} FEC limit) at received MMW/sub-THz power of -21.5 (20-Gb/s/50-GHz), -20.2 (20-Gb/s/100-GHz) and -19.1 (20-Gb/s/150-GHz) dBm. With SMF length reduced from 40 to 25 km, fiber dispersion-induced power fading is suppressed to a certain extent, resulting in an improved BER performance.

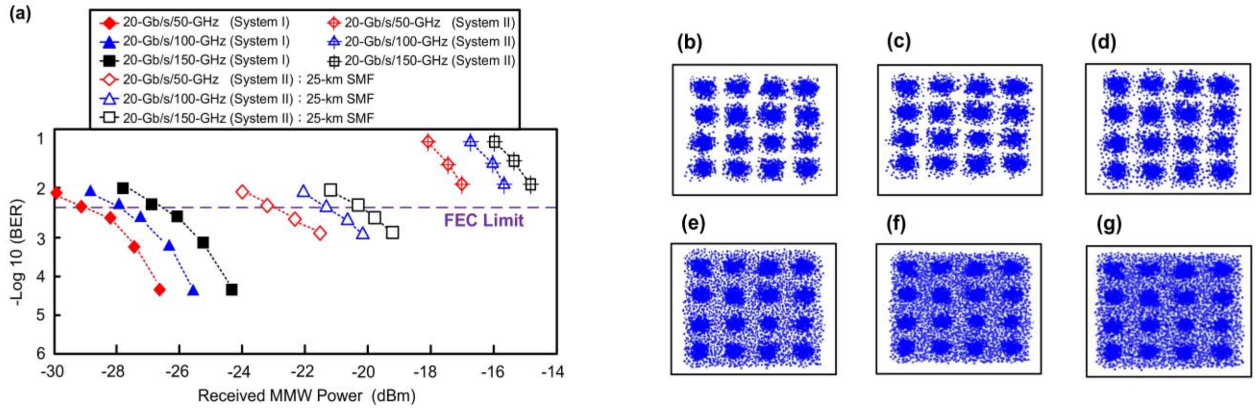

Fig. 2. (a) Measured downstream BERs as a function of received MMW/sub-THz power for system I and system II. The associated constellations of **(b)** 20-Gb/s/50-GHz, **(c)** 20-Gb/s/100-GHz, and **(d)** 20-Gb/s/150-GHz 16-QAM-OFDM signals of system I at 4.8×10^{-5} BER. The related constellations of **(e)** 20-Gb/s/50-GHz, **(f)** 20-Gb/s/100-GHz, and **(g)** 20-Gb/s/150-GHz 16-QAM-OFDM signals of system II at 1.2×10^{-2} BER.

Fig. 3(a) presents the upstream BERs of 10-Gb/s/24-GHz and 10-Gb/s/28-GHz 16-QAM-OFDM signals through hybrid-medium of 500-m optical wireless, 25-km/40-km SMF, and 4-m RF wireless. With IM scheme and 40-km SMF transmission, a poor BER performance of 7.7×10^{-3} (> 3.8×10^{-3} FEC limit) is obtained at -22.1 (10-Gb/s/24-GHz) and -21.2 (10-Gb/s/28-GHz) dBm received MMW power. With PM scheme and 40-km SMF transmission, however, a good BER performance of 8.7×10^{-6} (< 3.8×10^{-3} FEC limit) is obtained at -32.8 (10-Gb/s/24-GHz) and -31.7 (10-Gb/s/28-GHz) dBm received MMW power. By using PM scheme at the transmitter site and remotely injection-locked DFB LD at the receiver site, RF power fading due to fiber dispersion can be significantly suppressed, leading to a considerably improved BER performance. Moreover, with IM scheme and 25-km SMF transmission, the BER reaches 5.1×10^{-4} (< 3.8×10^{-3} FEC limit) at received MMW power of -27.4 (10-Gb/s/24-GHz) and -26.1 (10-Gb/s/28-GHz) dBm. As the SMF length decreases from 40 km to 25 km, fiber dispersion-induced power fading and fiber transmission loss are partially reduced, leading to an improved BER performance. Figs. 3(b) and 3(c)/Figs. 3(d) and 3(e) present the corresponding constellations of 10-Gb/s/24-GHz and 10-Gb/s/28-GHz 16-QAM-OFDM signals at $4.8\times10^{-5}/7.7\times10^{-3}$ BER with PM/IM scheme and 40-km SMF transmission. Clear (PM scheme)/blurry (IM scheme) constellations are achieved for each 16-QAM-OFDM signal. Results reveal that a bi-directional fiber-wireless system with PM for upstream outperforms that with IM for upstream.

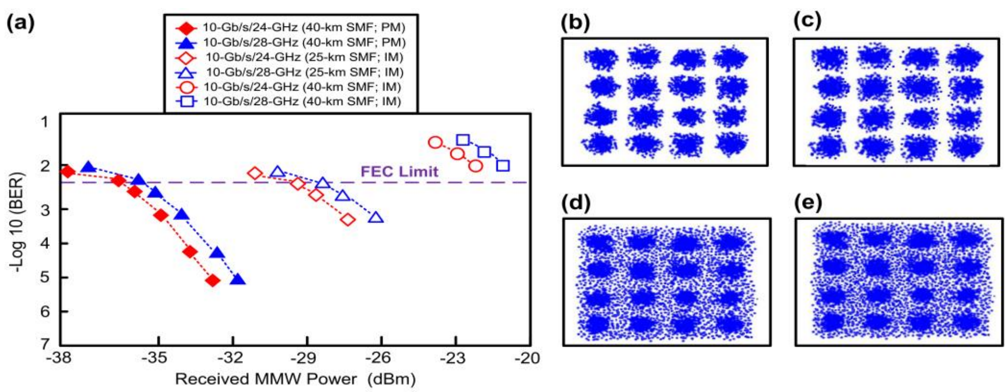

Fig. 3. (a) Measured upstream BERs as a function of received MMW power with PM/IM scheme and 25-km/40-km SMF transmission. The corresponding constellations of 10-Gb/s/24-GHz and 10-Gb/s/28-GHz 16-QAM-OFDM signals at 4.8×10^{-5} (**(b)** and **(c)**)/7.7×10^{-3} BER (**(d)** and **(e)**).

4. Conclusion

5G MMW and sub-THz signals over a bi-directional fiber-wireless system with single-carrier optical modulation for downstream and PM scheme for upstream have been implemented in practice. Over 40-km SMF, 500-m optical wireless, and 2-m/1-m/0.5-m (downstream)/4-m (upstream) RF wireless transmissions, the 5G 16-QAM-OFDM signals are transmitted with low BERs and clear constellations. It shows promise for performing 5G NR communication towards MMW and sub-THz bands, which have significant effects on fiber-wireless integration.

References

[1] H. H. Lu, C. Y. Li, W. S. Tsai, P. S. Chang, Y. T. Chen, C. X. Liu, T. Ko, and Y. Y. Lin, *IEEE/OSA J. Lightw. Technol.* **40**, 2348–2356 (2022).
[2] A. Morales, G. Nazarikov, S. Rommel, C. Okonkwo, and I. T. Monroy, *IEEE Trans. Terahertz Sci. Technol.* **11**, 261–268 (2021).