4-channel Beamformer Enhanced 9-Gb/s MMW 5G-FWA over 25-km Transmission with Bit-loading OFDM

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Abstract: An MMW 5G-FWA system is experimentally demonstrated with bit-loading OFDM and a 4-channel beamforming receiver. 9 Gb/s data rate is achieved after 25-km transmission with similar BER performance of 0º and 60º incident angles.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation;

1. Introduction

The demand for high-speed data transmission is ever-growing for future applications, such as high-definition television (HDTV), wireless augmented reality (AR) and virtual reality (VR). Fiber-to-the-home (FTTH) [1] provides broadband, reliable and Gigabit-class network connectivity and well suits for such rapid growing demand. However, as a last mile data solution, delivering fiber to the end-user sometimes is too expensive to the construction cost or geographically difficult. On the other hand, fixed-wireless access (FWA) [2] via 5G new radio (NR) [3] exhibits a fiber-like broadband transmission and a rapid deployment, becoming an alternative approach to achieve a ubiquitous-connective network, as shown in Fig. 1. However, due to operation at millimeter-wave (MMW) band, 5G-FWA signal is susceptible to atmospheric gases attenuation, such as water vapor and oxygen. To enhance the link power budget, phased array is necessitated to mitigate signal loss but the resulting narrow beamwidth makes the transceiver alignment difficult. Phased array with self-steering beamforming ability is desired to eliminate manual or mechanical antenna alignment. In our previous work [4], an all-passive phased array beamformer covering from -90º to 90º incident angles with continuous beam-steering ability was demonstrated with 2-GHz operation bandwidth via continuous waveform testing. However, its broadband modulation ability has not been studied in a 5G-FWA.

In this paper, we propose and experimentally demonstrate a 4-channel beamforming enhanced MMW 5G-FWA with intensity-modulation and direct-detection orthogonal frequency division multiplexing (OFDM) signal over 25-km fiber transmission. To maximize the achievable data capacity, bit loading technique [5] is applied via employing adaptive quadrature amplitude modulation (QAM) level according to the received signal-to-noise ratio (SNR) among the OFDM subcarrier. For testing the most critical scenario of a 120º covered 3-sector antenna cell [6], the performance of enabling 4-channel beamforming with 0° and maximum 60° incident angles are evaluated via their received bit-error rate (BER). A significant SNR enhancement due to the employed beamformer results a 2-order BER performance improvement. The achievable data rate of the proposed scheme is investigated in back-to-back (BtB), 5-, 10-, 15-, 20- and 25-km fiber transmission. 10.08 Gb/s and 9 Gb/s data capacity are achieved under the forward error correction (FEC) requirement in BtB and after 25-km transmission for ubiquitous-connective and Gigabit-class MMW 5G-FWA.

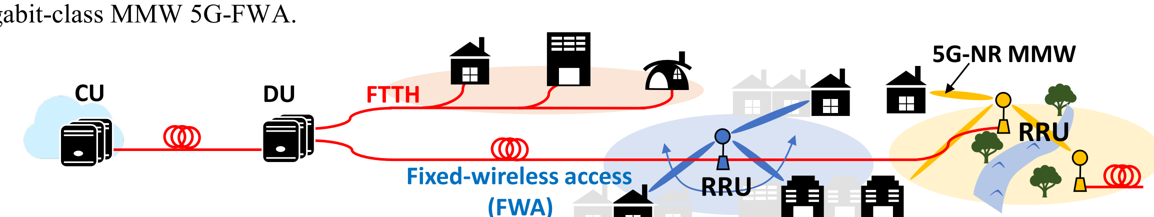

Fig. 1 Beamforming enhanced ubiquitous-connective MMW 5G-FWA network. CU: central unit. DU: distributed units, RRU: remote radio units, FTTH: fiber-to-the-home, FWA: fixed-wireless access, 5G-NR: 5G new radio, MMW: millimeter wave.

2. Concept of the MMW 5G-FWA system with autonomous beamforming and bit loading

Schematic diagram of the MMW beamforming enhanced 5G-FWA incorporated with the bit loading technique is shown in Fig. 2. A far-field MMW signal can be considered as a plane wave. As it injects into the N-element beamforming array with an incident angle of θ_{in}, it would generate progressive phase shifts of $\pi n \sin\theta_{in}$ among each channel, where $n=0, 1, 2, \ldots, N-1$. While, to flexibly support the 5G-NR frequency bands, the beamformer array [4] is implemented with wideband low noise amplifiers and down-conversion mixers in conjunction with all-passive phase detector and feedback phase compensator. The phase detector can convert the phase difference of θ_{diff} between the middle channels to the corresponding control voltage. After that, the subsequently voltage-controlled phase compensator feedbacks the relevant negative phase to mitigate the phase difference. This autonomous phase feedback loop without foreknowledge of the arrival signal information greatly reduce the complexity and alignment difficulty of the phased array transceiver at remote radio units (RRUs). The output signals are then in phase added up with *10logN* SNR enhancement and directly modulated via an optical transmitter for delivering the signals to DU and CU. The received signal of the MMW 5G-FWA can be expressed as:

$$Y = H_{total} \cdot X; \quad H_{total} = H_{wireless} \cdot H_{beamformer} \cdot H_T \cdot H_{fiber} \cdot H_R \tag{1}$$

where X is the delivered signal from the transmitter and H_{total} is the overall channel response, which could be further divided into wireless path, beamforming array, optical transmitter and receiver, and fiber path. Those un-ideal channels would result a non-uniform SNR distribution among OFDM subcarriers and limit the received performance at the lower SNR regions. Fortunately, the transmission channel of FWA is relatively static, and thus an adaptive OFDM, applying different QAM to fit in the SNR, is an effective solution to enhance the received performance and enlarge the data capacity. As indicated in Fig. 2, by evaluating the channel information at the receiver, we can feedback a suggested QAM assignment to transmitter. Afterwards, different QAM levels are reallocated to each subcarrier to maximize the overall data rate while concurrently guarantee all the subcarrier can be demodulated under the FEC criteria.

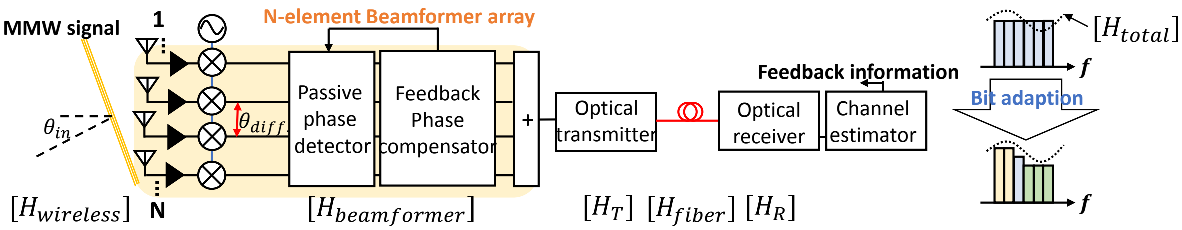

Fig. 2 Schematic diagram of the MMW 5G-FWA incorporated with bit loading.

3. Experiment Demonstrations and Results

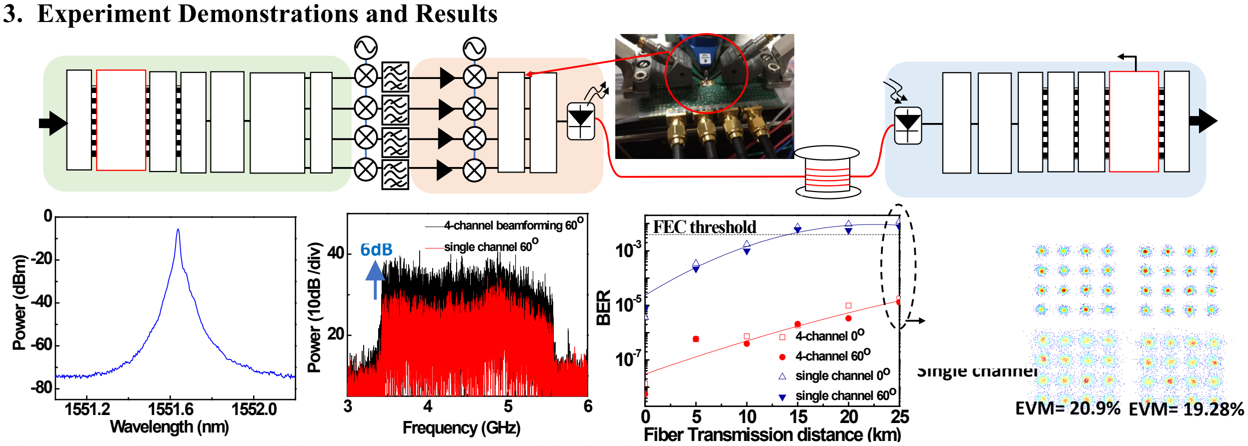

Fig. 3 (a) Experimental set up of the MMW FWA system and the flowchart of the bit loading OFDM processing. (b) The optical spectrum after 25-km fiber transmission. (c) Electrical spectra of 60º incident angle after 25-km fiber transmission with 4-channel and single-channel receiver. (d) BER performance versus different transmission distance. (e) The corresponding constellation diagrams of 4-channel and single-channel schemes after 25-km transmission with 0° and 60° incident angles. D/A: digital-to-analog convertor.

Figure 3(a) shows the experimental setup of the proposed MMW 5G-FWA system and the flowchart of the offline bit loading OFDM processing. To evaluate the uneven frequency response of the overall transmission system, 16-QAM signal is firstly employed. After the inverse fast Fourier transform (IFFT) and the parallel-to-serial (P/S) conversion, a 2-GHz bandwidth OFDM signal is up-converted to 5 GHz intermediate frequency for directly modulating the complex-value of OFDM signals. Each OFDM frame is composed of 137 subcarriers over 1024 FFT size and generated by a 4-channel arbitrary waveform generator (AWG) running at 16 GSa/s. To perform the different incident angle investigation, progressive phase shifts are inserted before 4-channel AWG output. 4 mixers driven by 21 GHz local oscillator (LO) cascaded with 4 bandpass filters are applied to up-convert the OFDM signal to 26 GHz, which is a promising band for 5G deployment in China for MMW transmission [7].

At the RRU side, the incoming RF signals are firstly amplified and down-converted to 4.5-GHz intermediate frequency to fit into the operation bandwidth of the applied beamformer [4]. The photo of the employed 4-channel beamformer is also inserted in Fig. 3(a). After the beamforming, the 4 channel outputs are combined via a 4-by-1 power combiner and then directly sent into a direct modulated laser (DML) with a central wavelength of 1551.65 nm and 5.5 dBm output power. After fiber transmission, a commercial 10-GHz photo detector (PD) is applied to optical-to-electrical convert the OFDM signal. The electrical signal is then captured by real time oscilloscope (RTS) running at 20 GSa/s and processed offline in Matlab, including down-conversion, FFT, one-step zero-forcing equalization and QAM de-mapping. To optimize the data capacity, the SNR among each subcarrier are estimated and the adaptive QAM level is fed back to the transmitter. The optical spectrum after 25-km fiber link is shown in Fig. 3(b).

To cope with the 3-sector antenna cell scenario, the performance of 0° and 60° incident angles are investigated. As shown in Fig. 3(c), in contrast to the single channel receiver scheme, a 6-dB SNR enhancement is measured due to the in-phase sum-up at the output of the 4-channel phased array beamformer. Fig. 3(d) depicts the BER performance of the 4-channel beamforming enhanced MMW 5G-FWA system as a function of transmission distance. The single channel scheme could achieve 2-GHz bandwidth 16-QAM OFDM signal delivery under the FEC threshold within only 10-km transmission. While, with the help of the 4-channel beamformer, the BER performance is enhanced and consistently outperform the single channel scheme over 2 order. The similar performance among different incident angles of 0° and 60° reveals the feasibility of the proposed ubiquitous-connective 5G-FWA. The constellation diagrams after 25-km transmission are inset in Fig. 3(e). The single channel constellations are ruined with EVM around 20% and thus cannot be demodulated under the FEC threshold, while the 4-channel beamforming enhanced 5G-FWA scheme achieves a more concentrated constellation with EVM around 11%.

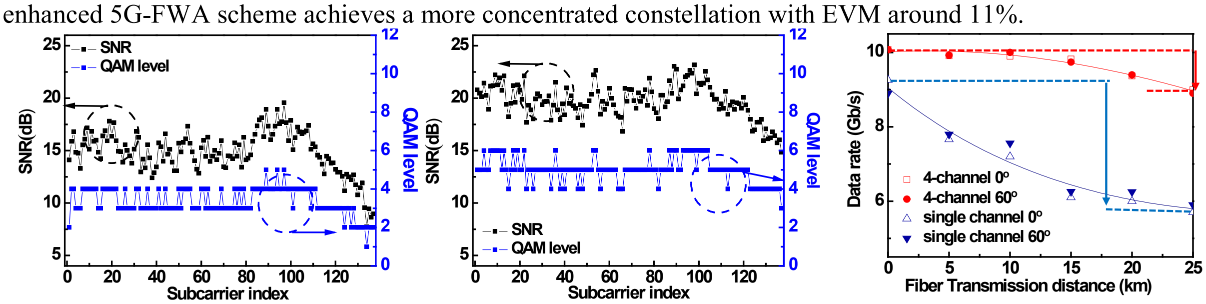

Fig. 4 (a-b) SNR and the corresponding available QAM level of single channel and 4-channel receiving with 60° incident angle versus the subcarrier index after 25-km fiber transmission. (c) The overall data capacity versus fiber transmission distance.

Figure 4(a) exhibits the subcarrier SNR and the applied QAM level of the single channel bit-loading OFDM receiving with 60° incident angle after 25-km fiber transmission. The un-flat channel response results a QAM level variation among subcarriers and the highest available data format is 32 QAM as well as the overall data capacity is 5.9 Gb/s. On the other hand, in contrast to single channel scheme, a 6-dB SNR enhancement via the proposed 4-channel beamformer pushes the highest QAM level to 64 QAM and maintains the lowest format of 8 QAM, as indicated in Fig. 4(b). The optimized data capacity versus fiber transmission distance is shown in Fig. 4(c). The available data rate gradually reduces with the increase of the fiber transmission distance. With the help of the 4-channel beamformer, we can achieve raw data rates of 10.08 Gb/s and 9 Gb/s in BtB scheme and 25-km fiber link, respectively. While, without the 4-channel beamformer, a significant data rate declination of 38.4% drop between BtB and 25-km transmission is measured.

4. Conclusions

A 4-channel beamformer enhanced MMW 5G-FWA with bit-loading OFDM has been experimentally demonstrated. The BER performance of beamforming with 0° and 60° incident angles are similar and improved significantly comparing with the single channel receiving scheme. 9 Gb/s channel capacity is achieved after 25-km transmission for future Gigabit-class networking with ubiquitous connectivity.

5. References

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