52.58-Gbps Fiber-Wireless 60-GHz 2×2 MIMO System Integrating Optical Mode Division Multiplexing and Wireless MIMO

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Abstract: Optical LP_{01} and LP_{11} mode are utilized to carry 2×2 MIMO signals for 60-GHz wireless signals. The proposed system can achieve data rate of 52.58-Gbps for fiber-wireless system with 5-km FMF and 3-m air link.

1. Introduction

To meet the data capacity demand for the next generation of broadband wireless networks, the implementation of fronthaul technology that can efficiently transmit data from a base station (BS) to remote antenna units (RAUs) presents several challenges [1-3]. Multiple-input Multiple-output (MIMO) technology is also proposed to enhance the spectral efficiency in limited bandwidth scenarios. However, MIMO technology will increase the required capacity of optical links between BS and RAUs as shown in Fig. 1. Wavelength division multiplexing (WDM) technology using different Lasers has been developed and utilized in current wireless networks. To increase optical link capacity, optical MIMO technologies using polarization division multiplexing (PDM) and mode division multiplexing (MDM) have attracted lots of attentions. However, the PDM technology can only provide two orthogonal polarization states to double the capacity. In principle, the MDM technology has more orthogonal spatial modes to provide more capacity, which depends on core-size design and mode delay of few-mode fiber [4, 5].

In this paper, we propose an optical/wireless MIMO system using optical MDM. Optical LP_{01} and LP_{11} mode are utilized to carry 2×2 MIMO signals for 60-GHz wireless signals. MDM MIMO and wireless MIMO channel response can be simultaneously recovered by zero-forcing equalizer.

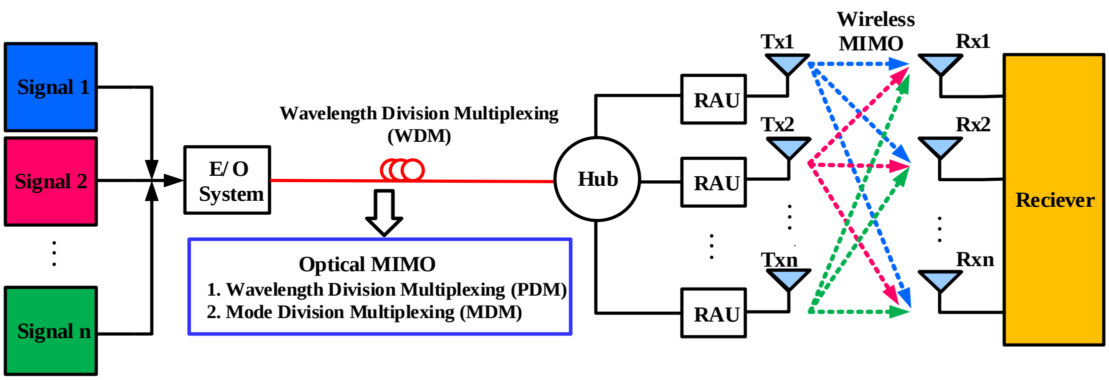


Fig. 1. Architecture of the fiber-wireless MIMO system with different optical multiplexing and de-multiplexing.

2. Experiment Concept and Setup

The optical spatial modes are solutions to the light propagation of few-mode fiber and orthogonal to each other in space. Hence, different signals can be transmitted with different fiber modes in the same fiber and demodulated independently due to orthogonal characteristic. The signals propagated in different modes can enhance the capacity. Compared with optical PDM, optical MDM has more orthogonal modes in principle, which potentially have more capacity. In this paper, we propose the MDM system as an optical MIMO system. In the case of the MDM system with mode coupling in few-mode fibers (FMF), optical spatial mode mixing occurs during transmission. The 2×2 MIMO signals can be expressed as

$$\mathbf{Y}=\begin{bmatrix} y_{\mathrm{LP}_{01}} \\ y_{\mathrm{LP}_{11}} \end{bmatrix}=\begin{bmatrix} W_{11} & W_{21} \\ W_{12} & W_{22} \end{bmatrix}\begin{bmatrix} C_{11} & 0 \\ 0 & C_{22} \end{bmatrix}\begin{bmatrix} \alpha & \beta \\ \gamma & \delta \end{bmatrix}\begin{bmatrix} E_{11} & 0 \\ 0 & E_{22} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}=\mathbf{HX} \tag{1}$$

where x_1 and x_2 are the input signals; y_1 and y_2 are the received signals; E_{11} and E_{22} are the channel response before the FMF; α, β, γ, δ are the LP_{01} and LP_{11} mode coupling effects (CE) which contain strength and the phase rotation; C_{11}

and C_{22} are the ratio of the optical carrier which beats with the corresponding optical signal; W_{11}, W_{12}, W_{21} and W_{22} are the channel response of 2×2 wireless system. After optical and wireless MIMO transmission in the MDM system, the signals can be recovered by the equalizer from (1), and it can be written as

$$\mathbf{X} = \mathbf{H}^{-1}\mathbf{Y} \tag{2}$$

Note that we demodulate optical and wireless channel response simultaneously.

Fig. 2. presents the experimental setup of the 2×2 fiber-wireless MIMO system. The signals are orthogonal frequency-division multiplexing (OFDM) signals with a 7-GHz bandwidth. The OFDM signals are generated by using an arbitrary waveform generator (AWG) with 12-GHz sampling rate. The FFT size is 512, the number of subcarriers is 298, the format of the training symbol is 4 quadrature amplitude modulation (QAM), the format of the data symbol is 16 QAM, and the cyclic-prefix (CP) ratio is 1/16. After AWG, the two OFDM signals are up-converted to 20 GHz by I/Q mixers, combined with an additional 39.5-GHz tone, and then sent to a single-electrode Mach–Zehnder modulator (SD-MZM) biased at the null point. After SD-MZM and optical interleaver, the optical signals consist of one un-modulated signal and one OFDM-modulated signal with a frequency distance of 60 GHz. After optical mode multiplexing, few mode transmission with LP_{01} and LP_{11} mode, and optical mode de-multiplexing, two mixed signals are sent to two photodiodes for 2×2 3-m wireless transmission.

Fig. 3 presents optical mode division multiplexing (MUX) and mode division de-multiplexing (DEMUX) based on half-wavelength phase plate. One of two optical OFDM signals after SD-MZM and optical interleaver is directly coupled into FMF, and the other is converted from LP_{01} into LP_{11} mode before FMF coupling. After FMF transmission, optical mode de-multiplexing can be done by reverse process. Then, the optical signals are then converted to electrical 60-GHz signals by the PD. After 3-m wireless transmission, the signal waveforms are then captured by using the oscilloscope.

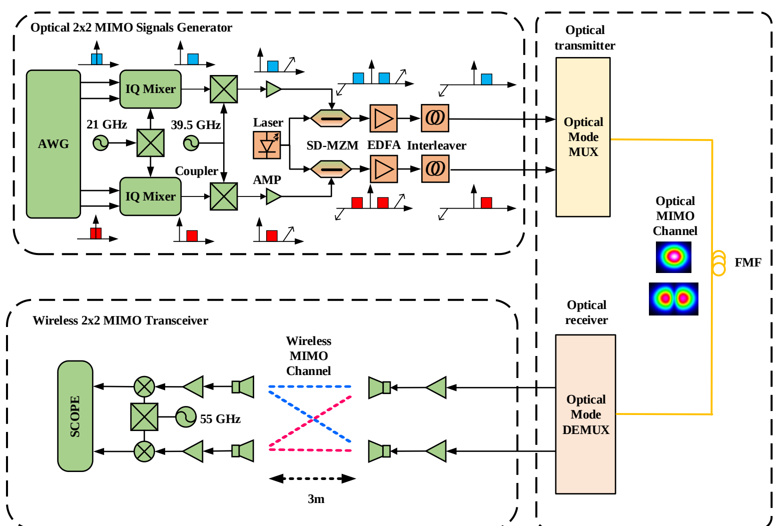


Fig. 2. Schematic diagram of the 2×2 fiber-wireless MIMO system.

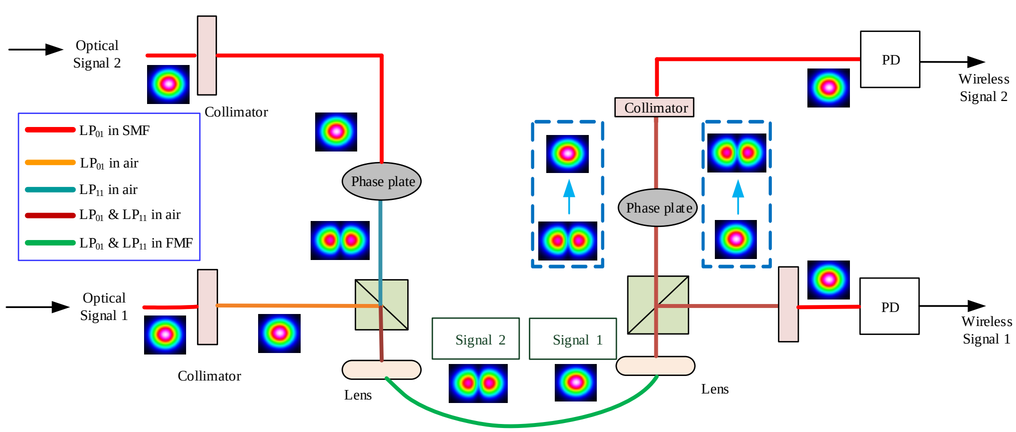
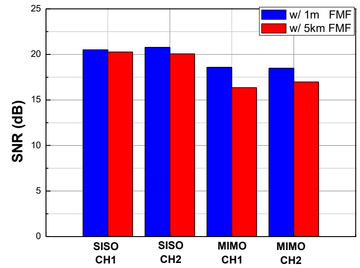


Fig. 3. Schematic diagram of the mode division multiplexing architecture.

3. Experimental Result and Discussion



	SISO: LP_{01} Signal 1	SISO: LP_{11} Signal 2	MIMO Signal 1	MIMO Signal 2
1-m FMF	20.5141	20.7795	18.5984	18.4916
5-km FMF	20.2591	20.0615	16.3538	16.9758

Fig. 4. Comparison of SISO and 2×2 MIMO fiber-wireless systems with different FMF transmission distances.

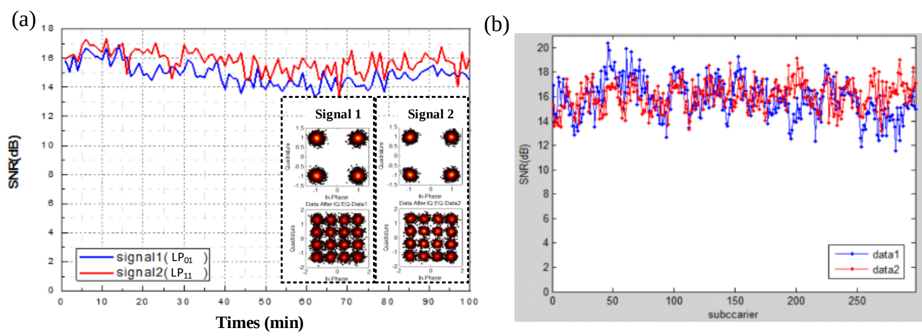


Fig. 5. Performance of the 2×2 optical/wireless MIMO system with 5-km FMF link. (a) The average SNRs versus time (b) SNR of each OFDM subcarrier from 57 GHz to 64 GHz.

To test the performance of different optical modes, signal 1 and signal 2 are independently transmitted over LP_{01} and LP_{11} mode, respectively. Fig. 4. shows signal-to-noise ratios (SNR) of the single-input single-output (SISO) optical/wireless system. There is no difference between signal 1 and signal 2 by using different optical mode transmission over 1-m FMF link. The penalty of less than 1 dB can be observed over 5-km FMF link. In 2×2 optical/wireless MIMO system, there is 2-dB SNR penalty due to optical mode coupling and wireless MIMO channel. The penalty will increase to 4 dB as the FMF length is 5 km. This result reveals the fiber mode coupling become more serious with increased FMF transmission length. In the case of 5-km FMF link, our proposed system can achieve 2×2 52.58-Gbps optical/wireless transmission, and bit error rate (BER) is 3.7542×10^{-3}.

To observer the stability of the optical/wireless MIMO system, we measure averaged SNR of signal 1 and signal 2 for each minute. Fig. 5. (a) shows the system SNR is stable in 100 minutes. Fig. 5. (b) shows that the SNR of each subcarriers from 57 GHz to 64GHz is flat without any frequency-selective fading.

4. Conclusions

We successfully demonstrate the optical/wireless system integrating optical mode multiplexing and wireless MIMO transmission. Optical LP_{01} and LP_{11} mode are utilized to carry 2×2 MIMO signals for 60-GHz wireless signals. MDM MIMO and Wireless MIMO channel response can be simultaneously recovered by zero-forcing equalizer. The maximum date rate of 52.58 Gbps can be achieved under forward error correction (FEC) limit of 3.8×10^{-3} BER.

5. References

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