Simple 2x2 MIMO 60-GHz OFDM RoF System with Single-Electrode MZMs Employing Beating Interference Mitigation and IQ Imbalance Compensation

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Abstract: We propose simple 2x2 MIMO 60-GHz RoF systems using single-electrode MZMs. Employing signal-signal beating interference mitigation, IQ imbalance compensation, and bit-loading technique, >40-Gbps OFDM signals over 12-km fiber and 3.5-m wireless transmission are achieved.

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1. Introduction
As the demands for wireless multi-Gbps video-based interactive services increase, 60-GHz unlicensed band (i.e. 57-64 GHz) has been viewed as a promising candidate to provide multi-Gbps wireless communication [1]. However, the higher carrier frequency of 60 GHz (a mm-wave) leads to the significantly higher loss across existing building walls, resulting in essentially in-room radio cells, with a typical cell radius of less than 10 m. To extend the coverage, the radio-over-fiber (RoF) system approach, which distributes RF signals from a central station (CS) to multiple base station (BS) over an optical fiber, is a promising means of reducing the overall cost of 60-GHz wireless access networks owing to its nearly unlimited bandwidth and extremely low propagation loss. Moreover, it is imperative that the employed RoF links are as simple as possible to reduce cost, while providing the needed performance. Recently, we proposed simple 60-GHz OFDM RoF systems with one single-electrode Mach-Zehnder modulator (SD-MZM) [2]. Compared with conventional optical double sideband RoF systems using 60-GHz MZM or electro absorption modulator [3], the proposed RoF system can support longer fiber transmission distance (4 km vs. 500 m) and has less bandwidth requirement of optical OFDM transmitter (35.5 GHz vs. 64 GHz). Furthermore, by properly choosing the carrier frequencies of two driving signals, we can mitigate dispersion-induced penalty and further improve the fiber transmission distance from 4 km to 12 km [4], and signal-signal beating interference (SSBI) mitigation algorithm is proposed to improve signal-to-noise ratio (SNR) [5].

On the wireless side, with increasing the numbers of antennas at the transmitter and/or receiver, the multiple-input multiple-output (MIMO) technology can not only increase the data rate but also improve the system reliability through spatial diversity. In this paper, we utilize 2x2 MIMO technologies in the proposed simple 60-GHz RoF system using SD-MZMs with properly choosing the carrier frequencies of two driving signals. Since the 60-GHz unlicensed band has 7 GHz wide, the OFDM image interference from IQ imbalance caused by electrical IQ mixer cannot be avoided, which generates more SSBI. Hence, SSBI mitigation algorithm with IQ imbalance
compensation for the 2x2 MIMO system is proposed. Applying the bit-loading scheme, >40-Gbps OFDM signals with 12-km fiber and 3.5-m wireless transmission are achieved.

2. Principle of 2x2 MIMO SSBI Mitigation

Figure 1 shows the proposed simple 2x2 MIMO RoF system employing SD-MZMs biased at \( V\pi \). The MZM driving signal consists of two signals: an OFDM-modulated signal at a center frequency of \( f_1 \) and a sinusoidal signal at a frequency of \( f_2 \). The allocation of the frequencies of \( f_1 \) and \( f_2 \) plays an important role on the RF power fading and SSBI [2]. To consider the full 7GHz bandwidth at 60 GHz, an OFDM driving signal is up-converted to a center frequency of \( f_1 \).

To re-construct and mitigate SSBI, we design training symbols for 2x2 MIMO channel estimation as following:

\[
T(\xi) = \sum_{n=-N_a/2}^{N_a/2} \exp \left( j \frac{2\pi n}{N} \right)
\]

where \( N \) is the IFFT size, \( N_a \) is the number of the non-null subcarriers, \( n \) and \( \xi \) are the discrete-time index and the subcarrier index, respectively, \( d_\xi \) is the data symbol modulated on the \( \xi \)-th subcarrier. The channel response of odd OFDM subcarriers can be estimated from training symbols without SSBI, and that of even OFDM subcarriers can be calculated by using interpolation of adjacent channel responses [5]. Hence, the received MIMO wireless signals can be recovered and expressed as:

\[
\begin{bmatrix}
Y_{1,\xi} \\
Y_{2,\xi}
\end{bmatrix}
= \begin{bmatrix}
H_{11,\xi} & H_{12,\xi} \\
H_{21,\xi} & H_{22,\xi}
\end{bmatrix}
\begin{bmatrix}
G_{1,\xi} & G_{1,\xi}^* & 0 & 0 \\
0 & G_{2,\xi} & 0 & G_{2,\xi}^*
\end{bmatrix}
\begin{bmatrix}
X_{1,\xi} \\
X_{2,\xi} \\
X_{1,\xi}^* \\
X_{2,\xi}^*
\end{bmatrix}
+ \begin{bmatrix}
W_{1,\xi} \\
W_{2,\xi}
\end{bmatrix}, \quad \xi = \pm 1, \pm 2, ..., \pm \frac{N_a}{2}
\]

where \( X_{1=1,2,\xi} \) and \( Y_{j=1,2,\xi} \) are the signals of \( \xi \)-th subcarriers for MIMO transmitters and receivers, respectively, \( H_{ij,\xi}, G_{ij,\xi}, \text{and} \ W_{ij,\xi} \) are the wireless channel response, IQ imbalance coefficients, and noise, respectively. Note that we can calculate the IQ-imbalance coefficient from the mixed matrix of wireless channel and IQ-imbalance via the relationship: \( G_{1,\xi} + G_{1,\xi}^* = 1 \) [6]. Hence, we can re-construct the SSBI with IQ imbalance compensation, and the operating concept of the SSBI cancellation is shown in Fig. 2.

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Fig. 2. Schematic diagram of iterative SSBI mitigation.

Fig. 3. SNR versus CSPR
3. Experimental parameters and results
The OFDM signal is generated by an arbitrary waveform generator. The sampling rate is 12 GSample/s. The inverse fast Fourier transform (IFFT) length is 512, resulting in a subcarrier symbol rate of 23.4375 MSymbol/s. 298 subcarriers of OFDM signals with cyclic prefix (CP) length of 16 are adopted. After 3.5-m wireless transmission and down-converting, the OFDM signal at 5 GHz is captured by a digital oscilloscope with a 80-GSample/s sampling rate and a 3-dB bandwidth of 16 GHz.

When the generated 60-GHz OFDM signals have SSBI, the carrier-to-signal power ratio (CSPR) will play an important role on the performance. Figure 3 shows the SNR of 8-QAM 41.9-Gbps OFDM signal versus various CSPRs. The optimal CSPR with the highest SNR is 11 dB. As the CSPR is less than 11 dB, the SSBI dominates the performance. Hence, as the iteration number of SSBI mitigation increases, the performance can be further improved. As the CSPR reaches more than the optimal value, the noise dominates the performance and iteration of more than 2 times cannot give further SNR improvements. Figure 4 shows the BER curves of 8-QAM 41.9-Gbps OFDM signals with the optimal CSPR. Notable, after 9-km fiber transmission distance, the OFDM signals can still meet the FEC limit of $3.8 \times 10^{-3}$.

Since the dispersion-induced RF fading would degrade the SNR of some subcarriers [4], those subcarriers with worse SNR will dominate the performance of the 60-GHz OFDM signal. Consequently, the Levin-Campello rate-adaptive bit-loading algorithm is employed to maximize the data capacity with a given target BER, and the modulation order (i.e. number of bits) of each subcarrier is adaptively allocated according to the measured SNR of subcarriers [7]. Figure 5 shows the achievable data rate with bit-loading technique at the target BER of $3.8 \times 10^{-3}$ versus different fiber transmission distance. The data rate can reach more than 50 Gbps and 40 Gbps even after 8-km and 12-km fiber transmission, respectively. After 12-km transmission, the corresponding constellations of QPSK, 8-QAM, and 16-QAM formats are shown in inset of Fig. 5.

4. Conclusion
In this paper, we propose the simple 2x2 MIMO 60-GHz RoF system using two SD-MZMs with properly choosing the carrier frequencies of two driving signals. Applying the algorithms of SSBI mitigation, IQ imbalance compensation, and bit-loading technique, >40-Gbps bit-loading OFDM signal over 12-km fiber and 3.5-m wireless transmission are achieved.

5. References