# 60-GHz optical/wireless MIMO system integrated with optical subcarrier multiplexing and 2x2 wireless communication

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**Abstract:** This paper proposes a 2x2 MIMO OFDM Radio-over-Fiber scheme based on optical subcarrier multiplexing and 60-GHz MIMO wireless transmission. We also schematically investigated the principle of optical subcarrier multiplexing, which is based on a dual-parallel Mach-Zehnder modulator (DP-MZM). In our simulation result, combining two MIMO OFDM signals to drive DP-MZM gives rise to the PAPR augmentation of less than 0.4 dB, which mitigates nonlinear distortion. Moreover, we applied a Levin-Campello bit-loading algorithm to compensate for the uneven frequency responses in the V-band. The resulting system achieves OFDM signal rates of 61.5-Gbits/s with BER of $10^{-3}$ over 25-km SMF transmission followed by 3-m wireless transmission.

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## 1. Introduction

Increasing demand for high-definition video and interactive on-line services has made it necessary to provide broadband wireless at the multi-Gbits/s rate. Greater wireless capacity can be achieved by increasing the carrier frequency through the expansion of bandwidth and the introduction of a modulation format with higher spectral efficiency. The license-free V-band (57-64 GHz) can provide considerably more bandwidth than WLAN (2.4 GHz and 5

GHz [1]. However, V-band wireless transmission is limited by high propagation loss in air. The need to remedy this situation led to the development of radio-over-fiber (RoF) technology, combining the advantages of fiber and wireless as a means of expanding the coverage of millimeter-wave (MMW) wireless signals. A higher modulation format can also improve spectral efficiency, such that data rates can be increased even within the same useable bandwidth. Moreover, multi-input multi-output (MIMO) technology can improve spectral efficiency by transmitting multiple signals within the same bandwidth. This has led to the widespread adoption of modulation formats with high spectral efficiency and MIMO technology in communication systems. Recently, several systems combining polarization division multiplexing (PDM) and MIMO with coherent heterodyne have been proposed [2–4]. In [2], a direct-detection (DD) RoF system with PDM was presented; however, polarizing variations of the optical carrier can induce signal fading after the polarization beam splitter (PBS) and photodetector (PD). This necessitates controlling the state of polarization (SoP) using a polarization controller within the DD-PDM RoF system prior to PBS. In [3,4], a coherent-detection (CO) PDM RoF system was proposed to solve issues related to the SoP in DD RoF systems. Nonetheless, a narrow bandwidth laser and additional digital signal process (DSP) algorithms are required to avoid or compensate phase noise.

This paper proposes a V-band 2x2 MIMO OFDM RoF system employing optical subcarrier multiplexing (SCM). This paper systematically outlines the concept on which the proposed system is based and evaluates wireless performance at 60 GHz. Using bit-loading technology, the proposed system achieved OFDM signals as high as 61.5-Gbits/s with a bit error rate (BER) below the forward error correction (FEC) threshold of $10^{-3}$ over 25-km single-mode fiber (SMF) followed by 3-m wireless transmission.
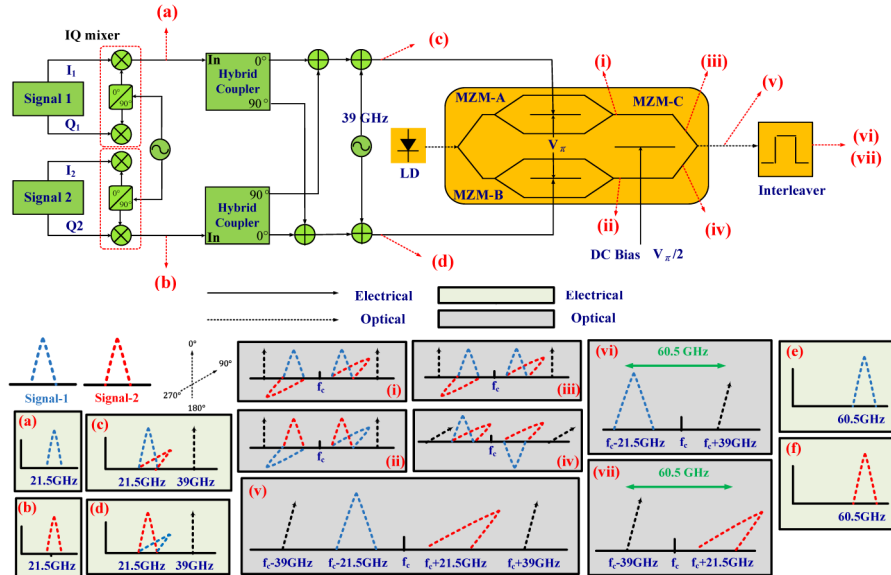


Fig. 1. Schematic principle of proposed SCM RoF system. Insets (a)-(f) and (i)-(vii) show the electrical spectrums and optical spectrums.

## 2. Principle of optical subcarrier multiplexing

Figure 1 illustrates the principle underlying the proposed 2x2 MIMO SCM RoF system. A dual-parallel Mach-Zehnder modulator (DP-MZM) comprising three single-electrode sub-MZMs plays a key role in generating optical 2x2 MIMO signals [5]. The electrical driving DP-MZM signals comprise two OFDM signals at the center frequency of 21.5 GHz and an electrical 39-GHz carrier. For the electrical 39-GHz carrier signal, when two sub-MZMs

(MZM-A and MZM-B) are biased at the null point, the generated optical spectrum comprises an upper sideband (USB) and a lower sideband (LSB) with carrier suppression, as shown in insets (i) and (ii) of Fig. 1. When MZM-C is biased at the quadrature point, a $90^{o}$ optical phase shift can be induced between MZM-A and MZM-B, as shown in insets (iii) and (iv) of Fig. 1. Since there is no phase difference between 39-GHz electrical carriers to drive the MZM-A and MZM-B, both USB and LSB of the generated optical carriers will be retained at the output of DP-MZM.

Both MZM-A and MZM-B driving signals consist of two MIMO OFDM signals, Signal-1 and Signal-2. However, Signal-1 and Signal-2 have different relative phase to drive the MZM-A and MZM-B. Electrical Signal-1 for MZM-B has a + 90° electrical phase shift relative to that for MZM-A, as shown in insets (c) and (d) of Fig. 1. Thus, the USB of generated optical Signal-1 at the output of MZM-B has a relative + 90°phase shift to that at the output of MZM-A, as shown in insets (i) and (ii) of Fig. 1. With MZM-C biased at the quadrature point, the USBs of generated optical Signal-1 from MZM-A and MZM-B will have + 180° phase shift to each other and be countervailed. Hence, only the LSBs of the generated optical Signal-1 will be retained at the output of DP-MZM. Conversely, dealing with driving Siganl-2, the electrical phase for MZM-B has a −90° electrical phase shift relative to that for MZM-A. Therefore, only the USBs of the generated optical Signal-2 will be retained at the output of DP-MZM. At the base station, an optical interleaver is used to separate two optical signals, as shown in insets (vi) and (vii) of Fig. 1. For each output signal of interleaver, there is a 60.5-GHz frequency difference between optical OFDM-modulated signal and optical carrier. After photo detection, two electrical 60.5-GHz OFDM-modulated signals are generated for 2x2 MIMO wireless transmissions.

## 3. Experimental setup

Figure 2 presents the experimental setup. The 2x2 MIMO driving signals comprise two 21.5-GHz OFDM signals and one 39-GHz sinusoidal signal. The electrical baseband OFDM signals are generated using an arbitrary waveform generator (AWG) at a sampling rate of 12
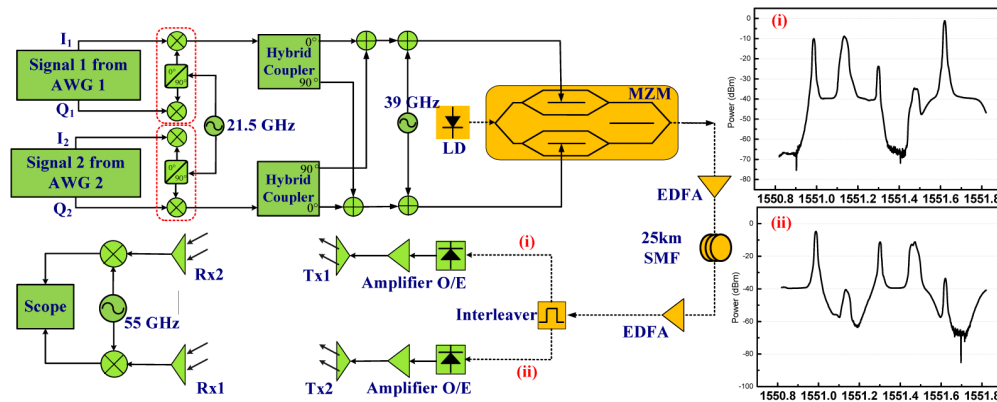


Fig. 2. Experimental setup of 2x2 MIMO SCM RoF system at 60GHz. Optical spectrum (i), and (ii) are obtained at the outputs of interleaver.

GSample/s and then up-converted to 21.5 GHz via two different electrical mixers, as shown in insets (a) and (b) of Fig. 1. Other parameters include an FFT length of 512, a cyclic prefix (CP) of 1/32 symbol time, and 298 subcarriers. After passing through the DP-MZM and erbium-doped fiber amplifier (EDFA), the optical signals are launched into a 25-km SMF, whereupon optical MIMO signals are divided using a 33/66 optical interleaver (*Optoplex Corporation*) to be detected by high-speed PDs for wireless transmission. Insets (e) and (f) in Fig. 1 present the electrical frequency spectrum. Two pairs of rectangular horn antennas with

24-dBi gain are used for 3-m wireless transmission. Then, two MIMO signals are down-converted to 5.5 GHz by using a 55-GHz local oscillator and two balanced mixers and then received by an oscilloscope at a sampling rate of 40 Gsample/s.
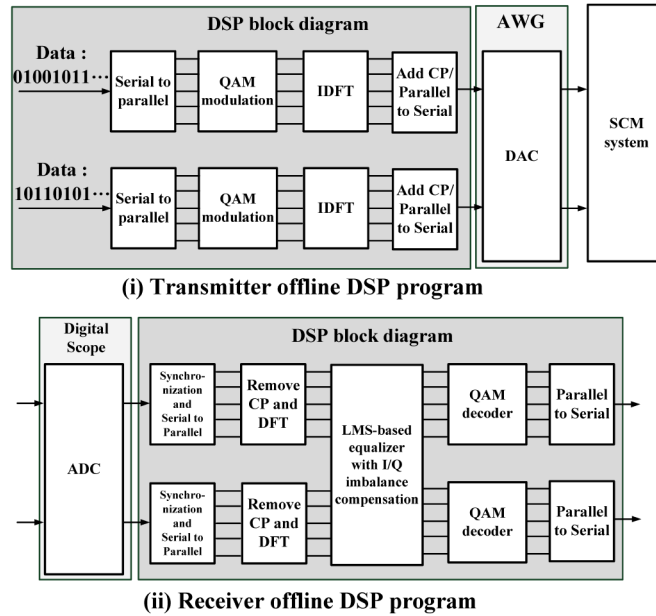


**(i) Transmitter offline DSP program**



**(ii) Receiver offline DSP program**

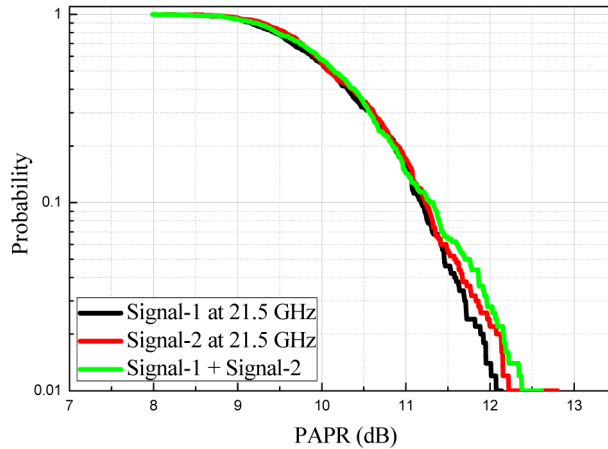Fig. 3. (i) Transmitter and (ii) Receiver offline DSP program.



Fig. 4. Simulation results of CCDF.

Figure 3 presents the offline Matlab® DSP program. At the transmitter, two quadrature amplitude modulation (QAM) OFDM signals are mapped through two independent binary data streams based on Gray code. After the OFDM signals are transferred to the time domain via inverse discrete Fourier transform (IDFT) and a CP is added, digital OFDM signals are sent to AWG for analog to digital conversion (ADC), as shown in the inset (i) of Fig. 3. After receiving signals down-converted to baseband, they are synchronized and removed CP. Following the transfer from serial to parallel and discrete Fourier transform (DFT), a frequency domain equalizer LMS-based equalizer with IQ imbalance compensation is used to

represent two MIMO signals [6]. The QAM signals are de-mapped to binary data streams and the BERs are measured according to error count, as shown in the inset (ii) of Fig. 3.

## 4. Experimental results

One of important parameters in OFDM RoF systems is the peak-to-average power ratio (PAPR), which is largely dominated by the number of OFDM subcarriers. The driving signals of MZM-A and MZM-B comprise two OFDM signals (Signal-1 and Signal-2), which can lead to an increase in the PAPR, resulting in nonlinear distortion. Figure 4 presents the simulation results of the complementary cumulative distribution function (CCDF). The CCDF of the PAPR denotes the probability that the PAPR of a data block will exceed a given threshold. With OFDM signals performing IDFT, PAPR is calculated according to the maximum peak power of one data block in the time domain to the average power of one data block [7]. Simulation parameters include a FFT length of 512, a CP of 1/32 symbol time, 298 subcarriers, 1000 blocks, an AWG sampling rate of 12 GSample/s, center frequency of 21.5 GHz, and channel sampling rate of 120 GSample/s. After combining the two signals, no discernable increase in PAPR was observed for a CCDF probability of 0.1. A probability of 0.01 resulted in a PAPR increase of less than 0.4 dB.

Figure 5 presents the BER curves for 55.875-Gbits/s 16-QAM OFDM signals with 3-m wireless transmission. In the back-to-back (BTB) case, OFDM signals are shown to meet the FEC BER limit of $10^{-3}$. Following SMF transmission over a distance of 25 km, the MIMO OFDM signals maintained a BER of $10^{-3}$ with no power penalty. The constellations for the BTB and 25-km transmission cases with PD received power of $-2$ dBm, which is the optimal situation, are also presented in the Fig. 5. Constellations of Signal-1 and Signal-2 can be clearly differentiated in both case of BTB and 25-km transmission.
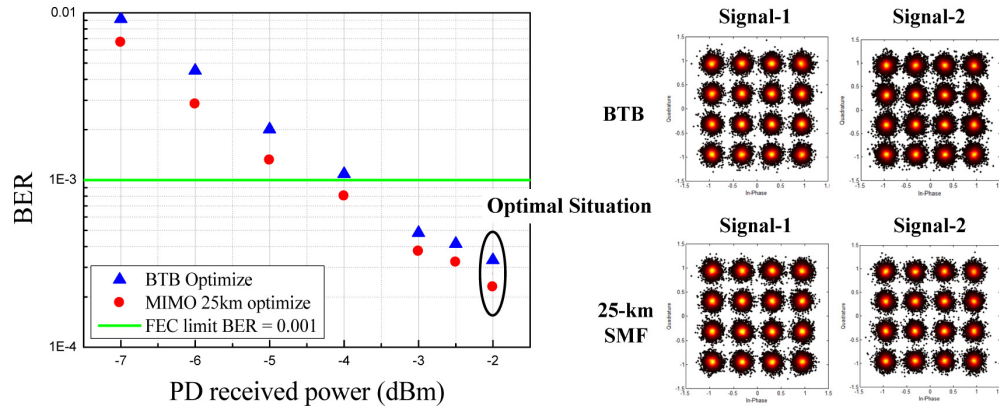


Fig. 5. BER curves for 55.875-Gbits/s 16-QAM OFDM signals.

In V-band communication, the frequency response of components is susceptible to serious fluctuations. The Levin-Campello bit-loading algorithm is employed to deal with the uneven frequency response of the V-band in order to increase the data rate by obtaining weighting factors and bit locations corresponding to OFDM subcarriers at a target BER of $10^{-3}$ [8]. Inset (i) of Fig. 6 presents the bit location of each OFDM subcarrier after assigning formats of 8-QAM, 16-QAM, 32-QAM, and 64-QAM. Following the estimation of weighting factor and bit location, an OFDM signal with bit loading is generated using the offline DSP program in the inset (i) of Fig. 3. Using the bit-loading algorithm with a PD received power of $-2$ dBm, the total data rate of 2x2 OFDM MIMO can be increased from 55.875 Gbits/s to 61.5 Gbits/s following 25-km SMF transmission. The SNRs of two MIMO OFDM signals with bit-loading

are presented in the inset (ii) of Fig. 6. The constellations based on modulation with different QAM formats can be clearly differentiated, as shown in Fig. 7.
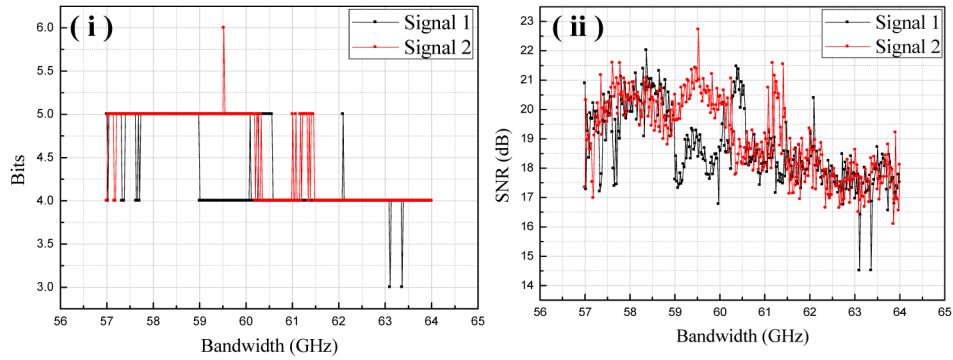


Fig. 6. Results of bit-loading with 7-GHz bandwidth OFDM signals for 61.5Gbits/s transmission over 25-km SMF including (a) bit formats and (b) SNRs.
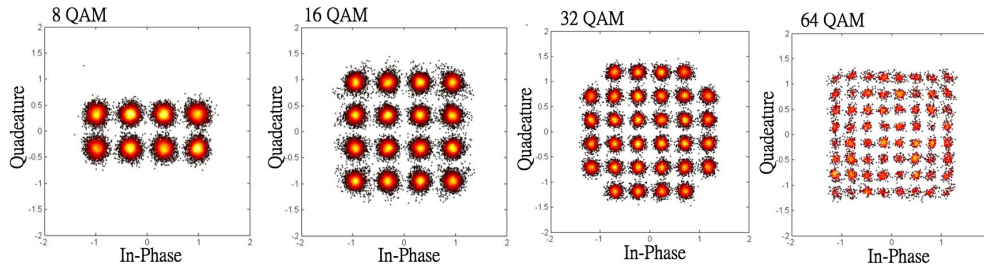


Fig. 7. Constellations with bit-loading algorithm over 25-km SMF transmission.

## 5. Conclusion

This paper presents a 2x2 MIMO SCM RoF system based on DP-MZM for operation at 60 GHz. Experimental results show that the 2x2 MIMO 16-QAM OFDM signals are able to achieve a BER of $10^{-3}$ for BTB and 25-km SMF transmission. Using the bit-loading algorithm to compensate for the uneven wireless channel response at 60 GHz, the data rate can be increased from 55.875 Gbits/s to 61.5 Gbits/s.