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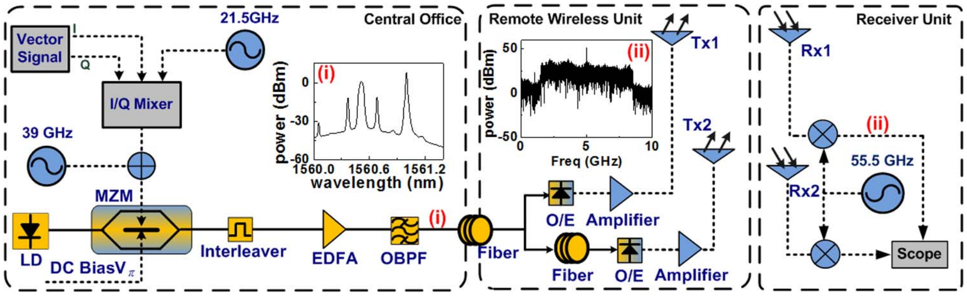

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2×2 MIMO OFDM-RoF System Employing LMS-Based Equalizer With I/Q Imbalance Compensation at 60 GHz

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Abstract: Multiple-input–multiple-output (MIMO) technology is a promising method to increase spectral efficiency in wireless communications. In this paper, a 60-GHz orthogonal frequency-division multiplexing radio over fiber (OFDM-RoF) system employing 2×2 MIMO wireless technology is demonstrated. With the proposed equalizer employing least mean squares (LMS) algorithm, MIMO channel mixing and I/Q-mismatch can be compensated simultaneously. 16-QAM and 32-QAM OFDM signal transmissions under forward error correction (FEC) threshold (1×10^{-3}) are demonstrated. A data rate of 76.3 Gb/s can be achieved with a bit-loading algorithm over 25-km fiber transmission and 3.5-m wireless transmission.

Index Terms: Fiber optics communications, radio-over-fiber, 60 GHz, MIMO, LMS.

1. Introduction

Recently, 60-GHz technology has been recognized as a potential candidate to realize multi-gigabit-per-second wireless applications because of the wideband license-free spectrum (e.g., 7 GHz in USA, and 9 GHz in Europe) [1]–[4]. However, compared with the conventional wireless systems (e.g., WiFi, cellular), 60-GHz wireless communication system has limited signal coverage because of the significantly high propagation loss and attenuation through walls. Accordingly, the coverage of one 60-GHz antenna unit is normally limited within a single room. To extend the coverage of the 60-GHz wireless systems, radio-over-fiber (RoF) technology has been identified as a potential solution [5]. In RoF system, optical fiber network is utilized as the backbone amount the central office and base stations, as shown in Fig. 1. With RoF technology, limitations in the transmission distance at 60 GHz can be overcome. It also viewed as an efficient means to simplify remote units through infrastructural sharing. In recent years, we have investigated the key system performance bottlenecks and demonstrated practical solutions for realizing high data-rate mm-wave-over-fiber systems: We successfully used Orthogonal Frequency Division-Multiplexing (OFDM) with the bit-loading algorithm to minimize the impact of the un-even frequency response on the overall system performance [6]. We have also demonstrated the use of recursive least squares (RLS) and least mean squares (LMS)

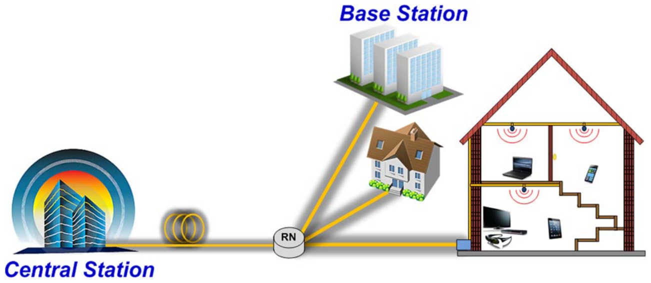

Fig. 1. Depiction of radio-over-fiber system.

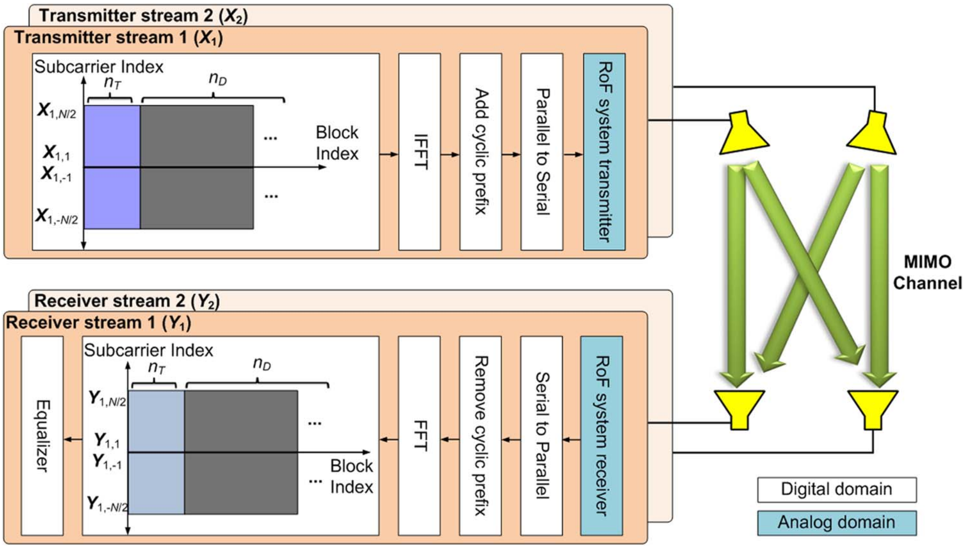

Fig. 2. Conceptual diagram of the proposed TS arrangement.

algorithms to compensate for the I/Q imbalance (which is mainly induced by the electrical I/Q mixer) in Single Input Single Output (SISO) antenna systems [7].

Besides, multiple-input and multiple-output (MIMO) technology is regarded as an attractive method for increasing the wireless channel capacity or the reliability of wireless transmission systems [8]. In this article, MIMO technology applied to a 60-GHz radio-over-fiber (RoF) system to increase the total transmission data rate within a 7-GHz bandwidth. Moreover, a single equalizer based on the least mean square (LMS) algorithm is employed to simultaneously estimate the MIMO channel coefficients and compensate for the I/Q imbalance. A further advantage of the proposed equalizer is that it allows for the flexible arrangement of the training symbols (TSs). By combining the proposed equalizer and the bit-loading algorithm, an extremely high spectral efficiency of 10.92 bit/sec/Hz can be achieved in a 2×2 MIMO 60-GHz RoF system, resulting in an ultra-high data-rate of 76.3 Gb/s over 25-km fiber and 3.5-m wireless transmission.

2. Concept

To generate 60-GHz signals, either an electrical up-conversion [9] or an optical up-conversion [10] is needed. Due to a very wide signal bandwidth of 7 GHz, significant penalty is caused by the I/Q mismatch of electrical or optical up-conversion. Fig. 2 shows the conceptual diagram of the TS arrangement for the proposed OFDM equalization technique with MIMO channel estimation as well as the I/Q imbalance compensation. $\boldsymbol{X}_1$ and $\boldsymbol{X}_2$ denote stream 1 and 2 of transmitted signals,

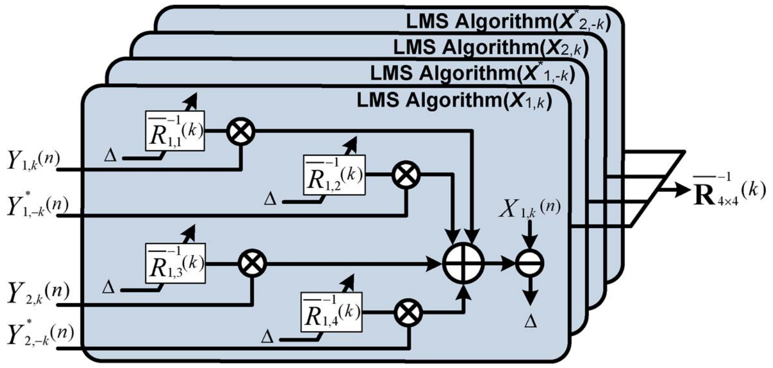

Fig. 3. Conceptual diagram of LMS-based equalizer.

respectively. $\boldsymbol{Y}_1$ and $\boldsymbol{Y}_2$ are the stream 1 and 2 of received signals, respectively. The parameters n_T and n_D represent the number of TSs and data blocks (frames), respectively. N is the number of occupied subcarriers in OFDM symbols.

With the proposed equalization technique, Information about The MIMO wireless channel and the I/Q imbalance can be obtained to recover the received signal. Considering the wireless MIMO channel and I/Q imbalance on the kth subcarrier of the OFDM positive frequency part $(k > 0)$, the received TS signals can be expressed as

$$\begin{bmatrix} \boldsymbol{Y}_{1,k} \\ \boldsymbol{Y}_{2,k} \end{bmatrix} = \begin{bmatrix} H_{1,1}(k) & H_{2,1}(k) \\ H_{1,2}(k) & H_{2,2}(k) \end{bmatrix} \begin{bmatrix} G_1(k) & G_1(k) & 0 & 0 \\ 0 & 0 & G_2(k) & G_2(k) \end{bmatrix} \times \begin{bmatrix} \boldsymbol{X}_{1,k} \\ \boldsymbol{X}^*_{1,-k} \\ \boldsymbol{X}_{2,k} \\ \boldsymbol{X}^*_{2,-k} \end{bmatrix} + \begin{bmatrix} W_{1,k} \\ W_{2,k} \end{bmatrix} \tag{1}$$

where $\boldsymbol{X}_{m,n}$, $\boldsymbol{Y}_{m,n}$, and $\boldsymbol{W}_{m,n}$ are the transmitted signals, received signals, and additive noise vectors, respectively. All of them are $1 \times n_T$ vectors. m is stream index which equals 1 or 2. n is the subcarrier index which is from $-k$ to k. The symbol, $(.)^*$, denotes complex conjugate operation. G_m are the IQ-imbalance factors [11]. $H_{o,p}$ are the elements of MIMO channel matrix with the total system frequency response, where o and p denote the indices of transmitter and receiver antennas. On the other hand, the negative frequency part of the received OFDM signals, $[\boldsymbol{Y}^*_{1,-k}\boldsymbol{Y}^*_{2,-k}]^T$, also can be expressed as $[\boldsymbol{X}_{1,k}\boldsymbol{X}^*_{1,k}\boldsymbol{X}_{2,k}\boldsymbol{X}^*_{2,-k}]^T$. Thus, $[\boldsymbol{Y}_{1,k}\boldsymbol{Y}_{2,k}]^T$ and $[\boldsymbol{Y}^*_{1,-k}\boldsymbol{Y}^*_{2,-k}]^T$ can be combined as

$$\begin{bmatrix} \boldsymbol{Y}_{1,k} \\ \boldsymbol{Y}^*_{1,-k} \\ \boldsymbol{Y}_{2,k} \\ \boldsymbol{Y}^*_{2,-k} \end{bmatrix} = \boldsymbol{R}(k) \times \begin{bmatrix} \boldsymbol{X}_{1,k} \\ \boldsymbol{X}^*_{1,-k} \\ \boldsymbol{X}_{2,k} \\ \boldsymbol{X}^*_{2,-k} \end{bmatrix} + \boldsymbol{W} \tag{2}$$

where $\boldsymbol{R}$ is a 4×4 channel matrix and $\boldsymbol{W}$ is a $4 \times n_T$ noise vector.

From equation (2), the inverse of the channel matrix can be estimated as $\overline{\boldsymbol{R}}^{-1}$ by retrieving the TSs

$$\begin{bmatrix} \boldsymbol{X}_{1,k} \\ \boldsymbol{X}^*_{1,-k} \\ \boldsymbol{X}_{2,k} \\ \boldsymbol{X}^*_{2,-k} \end{bmatrix} = \overline{\boldsymbol{R}}^{-1}(k) \times \begin{bmatrix} \boldsymbol{Y}_{1,k} \\ \boldsymbol{Y}^*_{1,-k} \\ \boldsymbol{Y}_{2,k} \\ \boldsymbol{Y}^*_{2,-k} \end{bmatrix} \tag{3}$$

where, $\boldsymbol{X}_{1,k}$ is a $1 \times n_T$ vector of kth subcarrier of TS. Then, $\overline{\boldsymbol{R}}^{-1}$ is estimated in the LMS sense as shown in Fig. 3, where Δ is the error vector to adjust channel factors in the LMS algorithm. The LMS-based equalizer, accordingly, can be utilized to recover from the MIMO channel and compensate for the I/Q imbalance simultaneously.

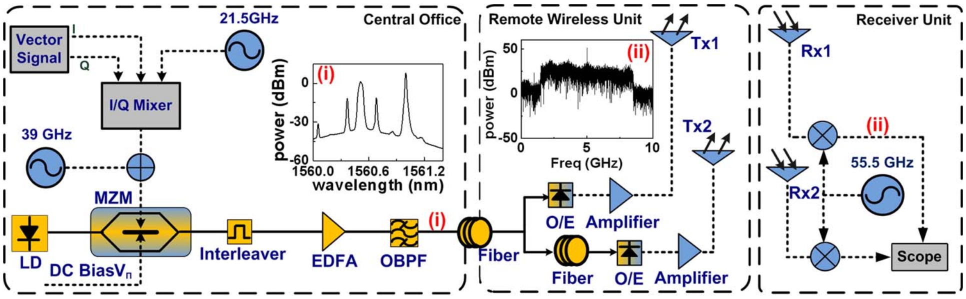

Fig. 4. Experimental setup of the 60-GHz 2X2MIMO RoF system.

3. Experimental Setup

Fig. 4 schematically depicts the experimental setup of the 60-GHz 2 × 2 MIMO RoF system employing one single-electrode MZM (40Gb/s Intensity modulator) [12]. The OFDM I/Q signals were generated by an arbitrary waveform generator (AWG) with a sampling rate of 12 GS/s at baseband. The length of inverse fast Fourier transform (IFFT) was 512. The subcarrier number of the OFDM signals was 296, so the signal bandwidth was 6.9375-GHz. Each subcarrier was modulated with the m-QAM format. Then, the baseband OFDM I/Q signals were up-converted with an electrical I/Q mixer (RF: 20-31GHz, LO: 20-31GHz, IF: DC-4.5GHz). Hence, an OFDM signal occupying 7-GHz bandwidth at a center frequency of 21.5 GHz was obtained. The OFDM signal was combined with a 39-GHz sinusoidal signal before being sent into the MZM. The MZM was biased at the null point to achieve optical double sideband with carrier suppression modulation. The laser source was a commercial DFB laser (1550.92 nm, 20 mW).

With this modulation architecture, two optical double sideband signals were generated after the optical modulator, and fiber dispersion induced power fading became an issue [13]. In order to overcome this issue, a 33/66-GHz optical interleaver (Insertion loss of pass band is less than 3 dB) was utilized to remove one OFDM-modulated optical sidebands and one un-modulated optical sideband. After the amplification of an EDFA (42-dB gain, 4.3-dB noise figure), the signal was filtered by a tunable optical band-pass filter (0.8-nm bandwidth @ 1550 nm) to remove amplified spontaneous emission (ASE) noise as shown in inset (i) of Fig. 4. After fiber transmission of 25 km, the optical signal was evenly split by a 50:50 optical coupler. One of the optical signals was delayed by 2-km single-mode fiber to imitate two de-correlated OFDM signals for MIMO operation.

After photo-diode detection and amplification, two 60-GHz OFDM signals were fed into two standard gain horn antennas with 24-dBi gain. After wireless transmission, two mixed OFDM signals from the 2 × 2 MIMO channel at 60.5-GHz were down-converted to two separate IF frequencies at 5-GHz and captured by a real-time scope with a sampling rate of 80 GS/s and bandwidth of 16 GHz. The inset (ii) of Fig. 4 shows one of the down-converted electrical spectra of the received signals. An off-line Matlab program was employed to demodulate the MIMO signals. Error counting of the demodulated data was utilized for bit error rate (BER) measurement.

4. Result and Discussion

To study the performance of TS-aided equalization, the SNR trend of 16-QAM OFDM signals with different TS block numbers is shown in Fig. 5. With training symbols less than 20 blocks, performance deceased rapidly because the LMS-based equalizer need enough training symbol length to calculate the channel coefficients by iterative method. Considering the required performance of system and the computing complexity, we chose 32 as the number of the training symbol blocks for the subsequent experiments.

Fig. 6(a) shows the BER curves of 16-QAM and 32-QAM OFDM signals with the proposed equalization technique. Both signals can meet forward error correct (FEC) limit (1×10^{-3}) for

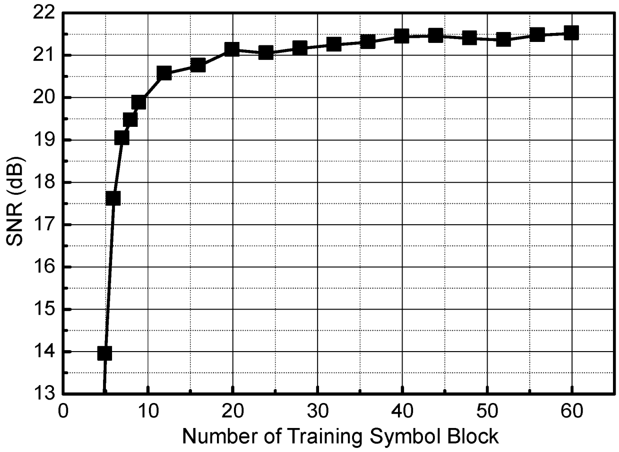

Fig. 5. Corresponding SNR versus different block numbers of TS.

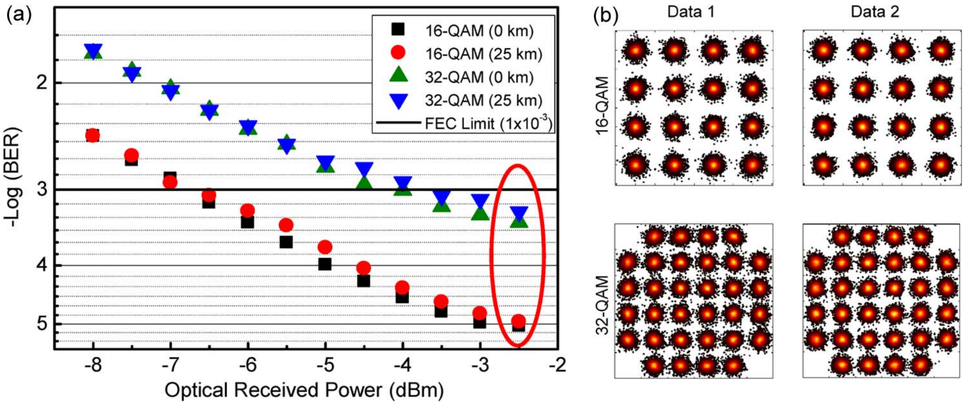

Fig. 6. (a) BER curves of 16-QAM/32-QAM OFDM signals with/without 25-km fiber transmission. (b) Constellation diagrams with 2.5-dBm optical received power over 25-km fiber transmission.

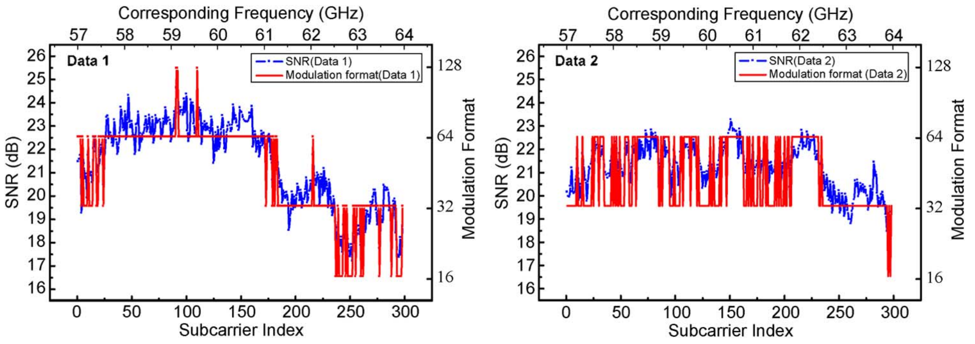

Fig. 7. SNR and corresponding modulation format for each subcarrier with bit-loading algorithm over 25-km fiber transmission, left and right figures represent data stream from transmitter 1 and transmitter 2, respectively.

back-to-back case. After 25-km fiber and 3.5-m wireless transmission, the receiver power penalty of both signals at the FEC limit are less than 0.5 dB. The data rates of the 16-QAM and 32-QAM OFDM signals are 55.5 and 69.375 Gb/s, respectively. Constellation diagrams of the 2 MIMO channel signals with -2.5-dBm optical received powers are shown in Fig. 6(b).

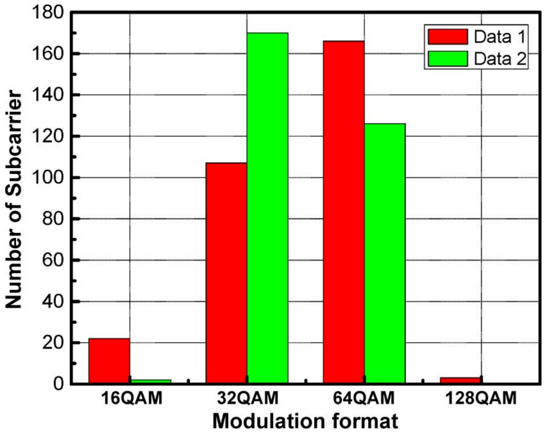

Fig. 8. Number of subcarriers for each modulation format with bit-loading algorithm.

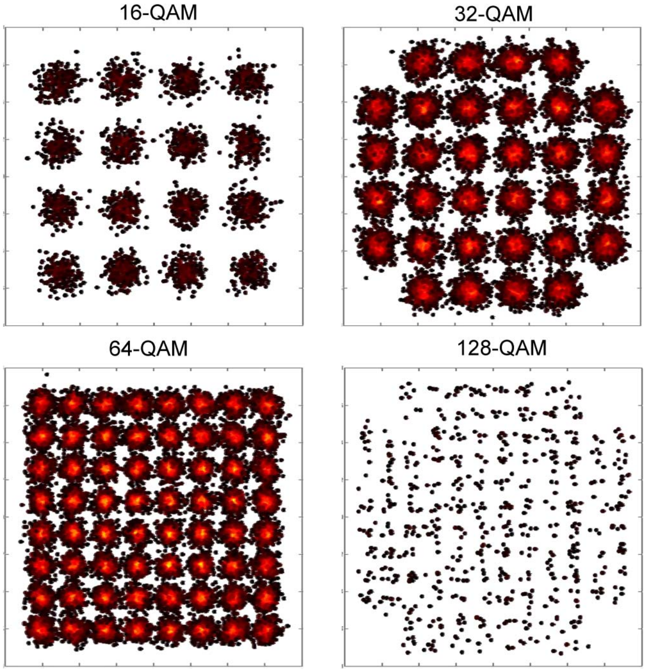

Fig. 9. Constellations with bit-loading algorithm over 25-km fiber transmission.

To pursue higher data rate transmission in the channels with uneven frequency response, bit-loading algorithm is utilized to optimize the power weighting and format allocation of each OFDM subcarriers. 16-QAM, 32-QAM, 64-QAM and 128-QAM formats are assigned depending on the corresponding SNR of each OFDM subcarrier. Figure 7 shows the measured SNR versus sub-carrier numbers and the modulation format allocations of each sub-carrier. Please note that the number of modulated subcarrier was 298, which is different from the transmission with fixed modulation format but the occupied bandwidth of 6.98 GHz still less than 7 GHz. The number of subcarriers with different modulation formats was shown in Fig. 8. As a result, with 25-km fiber and 3.5-m wireless transmission, the total data rate of the 2 × 2 MIMO wireless channel can achieve 76.3 Gb/s at the FEC limit. In comparison, the spectral efficiency can be further improved from 10 to 10.92 bit/s/Hz. Constellation diagrams of different kind of modulation formats of the bit-loading signals are also shown in Fig. 9.

5. Conclusion

In this article, a LMS-based equalizer is proposed and experimentally demonstrated with a 2 × 2 MIMO OFDM-ROF system at 60 GHz. With this equalizer, MIMO channel separation and I/Q imbalance compensation can be performed simultaneously. Data rate of 69.375 Gb/s is achieved with 32-QAM OFDM signals over 3.5-m wireless and 25-km fiber transmission. Bit-loading algorithm is also utilized to improve the spectral efficiency by optimizing the power weightings and modulation format allocations of the OFDM subcarriers. With the bit-loading algorithm, the spectral efficiency of the 60-GHz 2X2 MIMO system was increased from 10 to 10.92 bit/s/Hz with data rate of 76.3 Gb/s within the FEC limit of 1×10^{-3}. To the best of our knowledge, this is the highest spectral efficiency which has ever been reported within the 7-GHz license-free band at 60 GHz.

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