Performance Evaluation of a 60 GHz Radio-over-Fiber System Employing MIMO and OFDM Modulation

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***Abstract*—Multiple-input-multiple-output (MIMO) technique for wireless communications is extensively used these days, especially to increase the spectral efficiency of new wireless communication systems like LTE, WiMAX, etc. MIMO in combination with robust modulation techniques like orthogonal frequency division multiplexing (OFDM) provides a good solution for high data rate wireless links. In this paper, the performance of MIMO for a 60 GHz OFDM radio over fiber link is analyzed. System performance of the MIMO system for different antenna spacing is also studied. Using the optimum system parameters, a MIMO OFDM wireless link of up to 51 Gb/s was successfully demonstrated at 60 GHz in a bandwidth of <7 GHz, with a wireless transmission distance of up to 4 m and optical fiber transmission of 1 km. To our knowledge this is the highest data rate demonstrated in the 7 GHz band of 60 GHz.**

***Index Terms*—Millimeter wave communication, optical modulation, radio over fiber, MIMO.**

I. Introduction

DEMAND for wireless data capacity is constantly increasing with the next generation smart mobile devices and new bandwidth-intensive user applications such Facebook, YouTube, Netflix, etc., which have revolutionized the way mobile communications are used. With the recent advances in cloud computing/network storage the requirement for high capacity bandwidth is increasing. Other than in mobile phones, wireless communications are also playing an important role in other consumer electronic devices like TVs, tablets, etc., where very high speed wireless links are required for applications such as HD-video streaming, instant back-up over the air, and other multi-media rich applications. The current wireless systems in the lower frequencies providing wireless services like LTE, and WiFi 802.11n, etc., have a bandwidth of few tens of MHz. Consequently, these wireless systems use the most advanced techniques like multiple input multiple output (MIMO), OFDM, modulation formats of up to 256 QAM in an attempt to offer higher transmission data rates. However, the FCC and other regulatory bodies have freed up to 7 GHz of unlicensed spectrum in the millimeter wave (MMW) band of 60 GHz for wireless access. The huge bandwidth available in this band provides a promising solution for high capacity multi-Gb/s wireless communication, which far exceeds the performance of existing wireless systems.

One of the limitations of such high frequencies like 60 GHz is huge attenuation, which limits the wireless coverage and distribution of these wireless signals pose a challenge. Radio over fiber (RoF) technology with its huge bandwidth is a good solution for the generation and distribution of high bandwidth 60 GHz wireless links [1]–[6]. Until now several techniques were proposed to generate and distribute high capacity wireless links in the 60 GHz band using several advanced modulation formats [2]–[6]. Till now, up to 31 Gb/s wireless links at 60 GHz using OFDM modulation was demonstrated [4]. It is well-known that multiple-input-multiple-output (MIMO) techniques can achieve system capacity that exceeds the Shannon's limit. MIMO is currently used in most of the wireless communication systems like LTE – the 4^{th} generation cellular technology, WiMax, WiFi, etc., for providing increased capacity and robustness. MIMO can provide either increase in the wireless capacity by implementing multiple antennas at the receiver and transmitter sides and employing spatial multiplexing [7]–[9] or it can provide system robustness by employing antenna diversity [10]. Hence implementing MIMO for 60 GHz wireless systems can effectively increase the capacity or robustness of the systems.

MIMO for 60 GHz has attained considerable interest and recent results demonstrate several systems operating in MIMO mode at 60 GHz [11]–[14]. All these systems operate at only a few Gb/s and recent work reported up to 27.15 Gb/s using 60 GHz MIMO with a RoF system employing double sideband single carrier (DSB–SC) signals [6]. To the authors' best knowledge, this paper is the first demonstration of a MIMO RoF system employing OFDM modulation at 60 GHz. The higher spectral efficiency of OFDM and its robustness to multi-path effects make it a highly suitable modulation format to be implemented in combination with MIMO. MIMO

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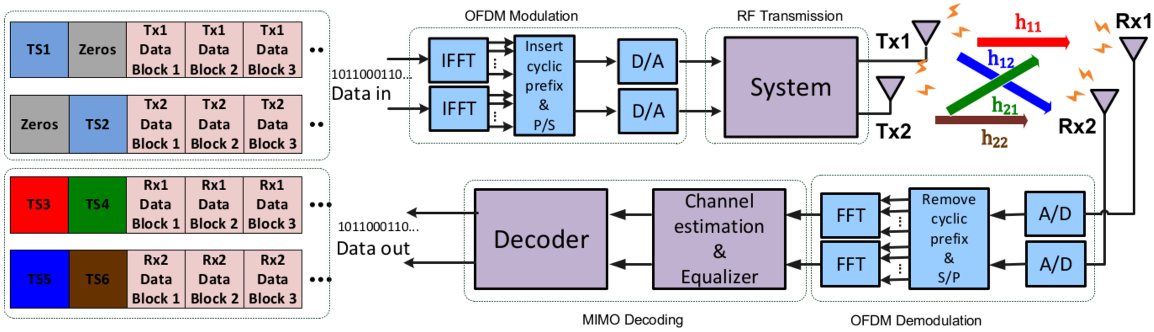


Fig. 1. Block diagram of the 2×2 MIMO system, and the schematics of the training symbol design of 2×2 MIMO-OFDM signals.

typically requires multi-path environment for providing the capacity gain, but recent studies [15]–[17] have proved that for optimum antenna spacing, MIMO performance in LOS can surpass a typical Rayleigh faded channels. In previous work we have demonstrated both OFDM and single carrier modulation formats based RoF systems, and we observed that OFDM is robust to the non-flat frequency response of the RoF link [6].

In this paper, we study the performance of a 2×2 spatially multiplexed MIMO-OFDM system employing a 60 GHz RoF system. Based on the optimum system parameters record wireless data speeds of up to 51 Gb/s (2×25.5 Gb/s) were achieved using 16 QAM modulation within 6.375 GHz bandwidth. This result represents a very high spectral efficiency of 8 b/s/Hz.

II. Operating Principle of 2×2 MIMO for OFDM

In MIMO communication systems, multiple antennas are located at either side of the link; where an $M \times N$ MIMO system consists of M transmit antennas and N receive antennas. The M transmitted signals are received by the N receivers, where after MIMO decoding the transmitted signals can be recovered. Uncorrelated wireless paths between the transmitters and the receivers are required for distinguishing the received signals and hence for proper operation of MIMO systems. When MIMO is implemented with spatial multiplexing, space-time codes provide increase in capacity for fixed power and bandwidth, and the maximum capacity increase is determined by the minimum number of antennas ($min(M, N)$) in the MIMO system [7]–[9].

Fig. 1 shows the block diagram of an $M \times N$ MIMO communication system using OFDM modulation with training symbols for wireless channel estimation. The transmitter and receiver are divided into two blocks, namely: the OFDM modulation/demodulation part and the MIMO decoding part. The blocks performing OFDM modulation and demodulation are similar to any OFDM based communication system [18], [19]. For the $M \times N$ MIMO-OFDM signal generation, M independent data streams were generated and each data stream mapped to a digital modulation format. These M serial data streams were converted to parallel followed by inverse fast Fourier transformation (IFFT), which was applied to generate multiple complex time domain streams, and form the OFDM carriers. In OFDM modulation, the cyclic prefix is inserted between each OFDM block to overcome inter symbol interference. After the insertion of the cyclic prefix and subsequent digital to analogue conversion, M independent RF streams each containing independent data are generated, representing H spatially multiplexed MIMO channels.

At the receiver, N antennas receive the combination of the M transmitted RF signals after transmission over the air and down converted to the desired IF (intermediate frequency) for digital signal processing, which involve MIMO decoding and OFDM demodulation. MIMO decoding includes FFT and Zero-Forcing (ZF) algorithm. In the $M \times N$ MIMO system, the OFDM signal for the i^{th} transmit antenna at the k^{th} sub-carrier is denoted by $x_i[k]$, while $\mathbf{H}$ denotes a channel matrix with $(i,j)^{th}$ entry $\mathbf{h}_{ij}$ for channel coefficients between the i^{th} transmit antenna and j^{th} receiver antenna, where $i = 1, 2 \ldots M$ and $j = 1, 2 \ldots N$. The signal at the receiver antenna can be mathematically expressed as:

$$y_i = \mathbf{H}_{ij}[k]x_i[k] + w_i[k] \tag{1}$$

Where $y_j[k]$ represent received signal for the j^{th} receiver antenna at the k^{th} sub-carrier. $w_j[k]$ denote the additive complex Gaussian noise for the j^{th} receiver antenna. Using the Zero-Forcing (ZF) algorithm [7], the transmitted data can be recovered by inversing the estimated channel matrix as:

$$\tilde{x}[k] = \mathbf{H}[k]^{-1}y[k] = x[k] + \mathbf{H}[k]^{-1}w[k] \tag{2}$$

From the eqn. 2, the estimation of the channel matrix is the most important part of the MIMO-OFDM demodulation process. The channel estimation is performed by using training symbols. Considering an example of a 2×2 MIMO system, a special arrangement of training symbol is implemented by switching between the on-off positions as shown in Fig. 1 (left) [20]. The received signals then corresponding to either the first or the second training symbol time, which can be expressed as eqn. 3:

$$\begin{bmatrix} TS_3[k] \\ TS_4[k] \end{bmatrix} = \begin{bmatrix} \mathbf{h}_{11}[k] & \mathbf{h}_{21}[k] \\ \mathbf{h}_{21}[k] & \mathbf{h}_{22}[k] \end{bmatrix} \begin{bmatrix} TS_1[k] \\ 0 \end{bmatrix} + w[k]$$
$$\begin{bmatrix} TS_5[k] \\ TS_6[k] \end{bmatrix} = \begin{bmatrix} \mathbf{h}_{11}[k] & \mathbf{h}_{21}[k] \\ \mathbf{h}_{21}[k] & \mathbf{h}_{22}[k] \end{bmatrix} \begin{bmatrix} 0 \\ TS_2[k] \end{bmatrix} + w[k] \tag{3}$$

Form the above matrices in eqn. 3, the channel coefficients can be estimated by appropriate training symbols and the transmitted data can be recovered by using the ZF algorithm. The estimated channel matrix can be expressed as:

$$\tilde{\mathbf{H}} = \begin{bmatrix} TS_3/TS_1 & TS_4/TS_1 \\ TS_5/TS_2 & TS_6/TS_2 \end{bmatrix} \tag{4}$$

From the MIMO demodulation process described previously, it can be noted that the channel matrix plays a crucial role in the MIMO system performance, and for a better performance, the channel matrix should be well conditioned, which means significant de-correlation between the transmitted signals is required. The condition of the channel can be quantified using the parameter channel Condition Number (CN), which can be defined as the ratio between the maximum and minimum singular values (using singular value decomposition SVD) of the channel matrix [21].

$$CN = \frac{max(\lambda_i)}{min(\lambda_i)} \quad (5)$$

Whereλ_i is singular value of channel matrix. $\mathbf{H}$ is said to be well-conditioned if the CN is close to 1 and ill-conditioned if the CN is close to infinite. The CN impacts the MIMO performance, and for higher CN channels, the required SNR to achieve the same capacity increases, causing significant reduction in the performance of the MIMO system.

III. Experimental Set-up

Fig. 2 schematically depicts the experimental setup of the implemented 60 GHz RoF system [22] for generation and transmission of a 2×2 MIMO OFDM signal. Using an arbitrary waveform generator with a sampling rate of 12 GS/s the in-phase and quadrature-phase components of an OFDM signal were generated, with a maximum RF bandwidth of 3.5 GHz each. The OFDM QAM signal consists of 74 subcarriers within the 7 GHz bandwidth, and 1/8 cyclic prefix to mitigate inter symbol inference induced by the system.

The OFDM signals were then up-converted to 25 GHz using an electrical I/Q mixer as shown in inset (i) of Fig. 2. In order to generate a 60 GHz OFDM signal from optical heterodyne in the photo detector, the 25 GHz OFDM signal was combined with another 35.5 GHz carrier signal as shown in inset (ii) and (iii) of Fig. 2. The RF signals were then used to modulate an optical carrier at 1550 nm generated using a Distributed Feedback (DFB) laser, in a Mach-Zehnder modulator with a 3-dB bandwidth of ∼50 GHz. To achieve the 60 GHz RF signal, the Mach-Zehnder modulator (MZM) was biased at its minimum point to generate a carrier suppressed optical signal, as shown in Fig. 3(a). The optical signal at the output of the MZM was amplified using an Erbium Doped Fiber Amplifier (EDFA) with a nominal gain of 20 dB. To generate two independent signals for a 2×2 MIMO system, the optical signal was split equally using a 3 dB coupler, and the two resulting signals de-correlated by delaying one of the signals using a 1 km optical fiber. The now de-correlated optical signals were individually photo-detected using a 60 GHz photo-detector to generate a 2×2 MIMO-OFDM signal at a carrier frequency of 60.5 GHz. The 60 GHz signals were radiated using standard horn antennas with a gain of ∼24 dBi.

To compensate for the uneven gain of the two RF paths, and to maintain the same RF output power at the two antennas, the optical power into the photo detectors for channel 1 and channel 2 were set to −2 dBm and −3.5 dBm respectively. At the receiver two horn antennas were used to receive the 2×2 MIMO signals, and later amplified using a low-noise amplifier. The two received signals were down-converted to two separate

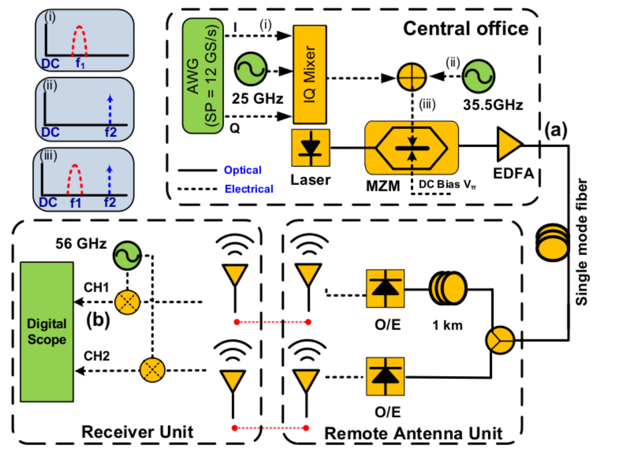


Fig. 2. Schematic of the experimental set-up depicting a central office, remote wireless unit and a receiver unit.

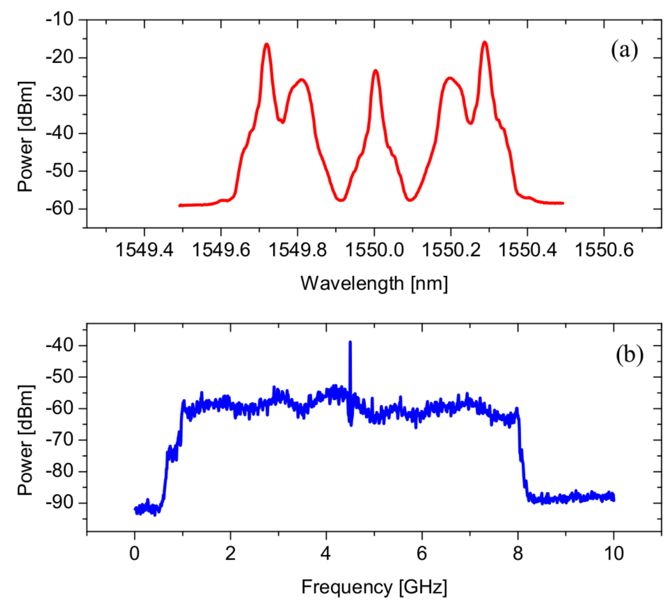
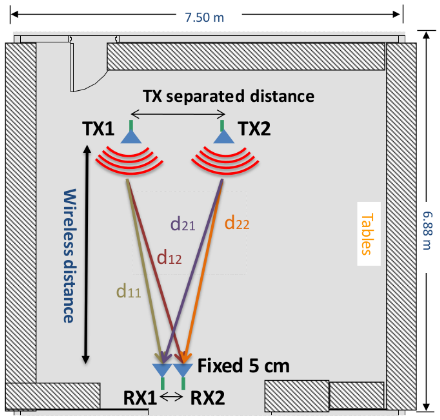


Fig. 3. Optical spectrum for double-sideband carrier suppression scheme after EDFA (a). Electrical spectrum of MIMO-OFDM signal at 4.5 GHz carrier frequency after down-conversion at received unit (b).

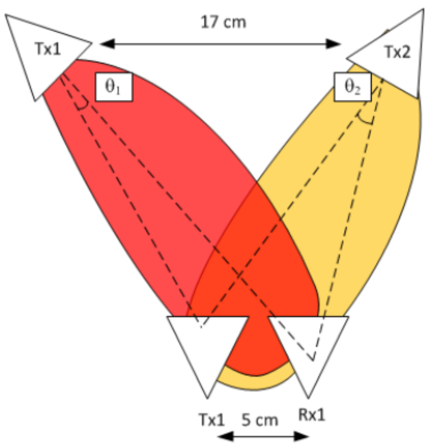
IF signals at 4.5 GHz as shown in Fig. 2. The 4.5 GHz IF signals were later sampled at a rate of 40 GS/s using a digital sampling scope, and demodulated using a PC based offline digital signal processor.

IV. Experimental Results and Discussions

Over the air wireless transmission measurements of 60 GHz 2×2 MIMO system were performed in a typical laboratory (dimensions: 7.5 × 6.88 m). The floor plan of the laboratory and the possible signal radiation paths for a 2×2 MIMO system are shown in Fig. 4(a). The transmitters and receivers were placed on two tripods, at a height of 1.3 m above the floor. At the receiver side, the two antennas were separated by a fixed distance of ∼5 cm, which was the minimum separation distance allowed by the bulk horn antennas employed, and which was sufficient to avoid coupling-induced correlation between the antennas [13]. From the geometrical calculations (for Tx antenna separation of 17 cm and Rx separation



(a)



(b)

Fig. 4. Spatial arrangements for 2×2 MIMO RoF systems (a), and the corresponding geometrical interpretation of the radiated signal's beamwidth (b).

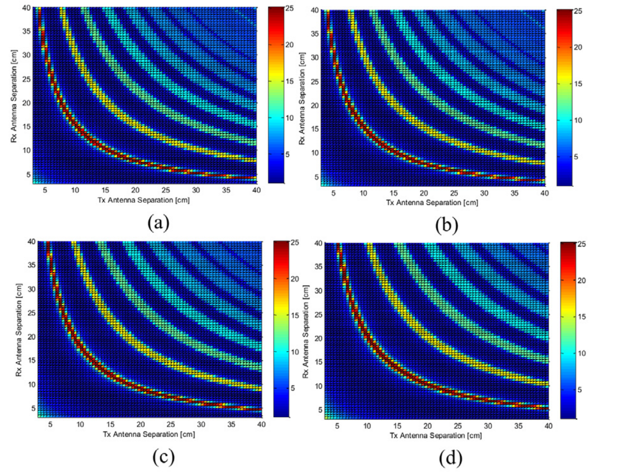
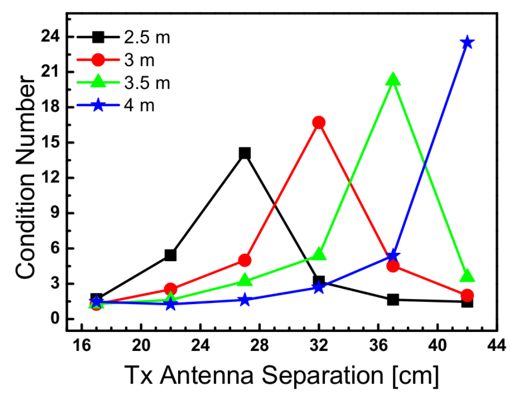
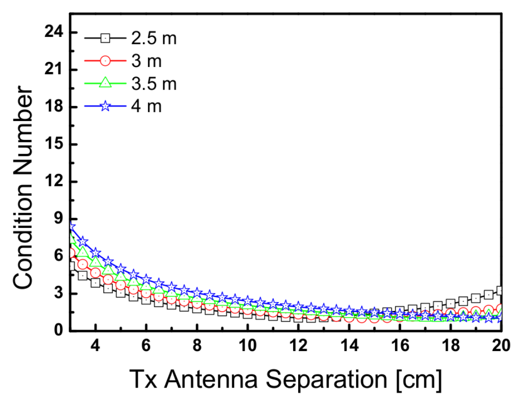


Fig. 5. Simulated condition number values for varying receiver and transmitter antenna separation for different wireless transmission distances. 2.5 m (a), 3 m (b), 3.5 m (c), and 4 m (d).



(a)



(b)

Fig. 6. The channel condition number for different transmitter antenna separations in a 2×2 MIMO 60 GHz wireless link at different receiver to transmitter distance evaluated experimentally (a) and using simulations (b).

of 5 cm) we found that the minimum beam width (θ_1, θ_2) as shown in Fig. 4(b), required for radiating on both the receiver antennas is far less than the 3-dB beam width of the antennas used, which is around 30 degrees. To ensure MIMO is correctly implemented, the transmit antennas were angled in such a way to receive strong 60 GHz signals at both the RF antennas from each transmitter antenna as depicted in Fig. 4(b).

During the whole experiment, both transmit antennas were angled such that they always faced towards the center of the two receive antennas. We investigated the impact of transmit antenna separation, the wireless transmission distance and optical fiber transmission on the performance of the MIMO system.

The effect of receiver antenna separation was modeled by calculating the condition number for different receiver and transmitter antenna spacing. From the simulation results shown in Fig. 5, it can be observed that the impact of the receiver and transmitter antenna separation can be interchanged resulting in the same condition number. However, it should be noted that in practical implementations of 60 GHz wireless access systems, transmitter antennas will be integrated inside the user equipment, providing for fixed and close antenna spacing. On the other hand, there may be more room in the 60 GHz access point to spread the transceiver antennas further apart as desired.

First, the optimum antenna separation between the transmit antennas was investigated. Fig. 6(a) shows the measured condition number of the 2×2 MIMO signal plotted against the

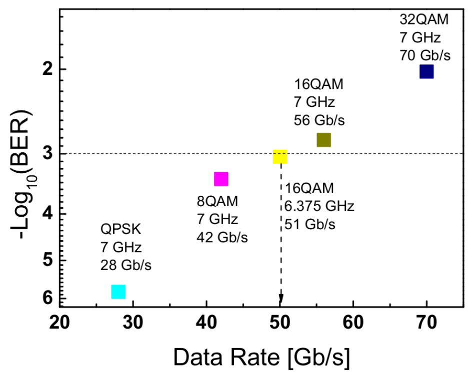


Fig. 7. BER performance versus with data rate by QPSK, 8 QAM, 32 QAM in 7 GHz bandwidth and 16 QAM in 6.375 GHz.

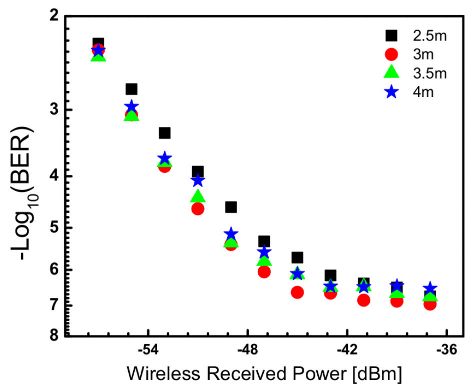


Fig. 8. BER performance of 60 GHz 2×2 MIMO-OFDM QPSK signal as function of wireless received power with wireless distance from 2.5 m to 4 m.

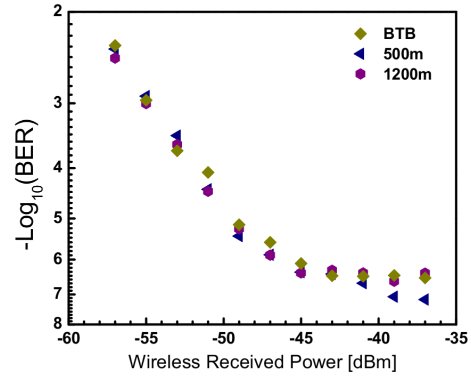


Fig. 9. BER performance as function of wireless received power through 4 m wireless transmission with BTB, 500 m and 1200 m fiber transmission with QPSK signal.

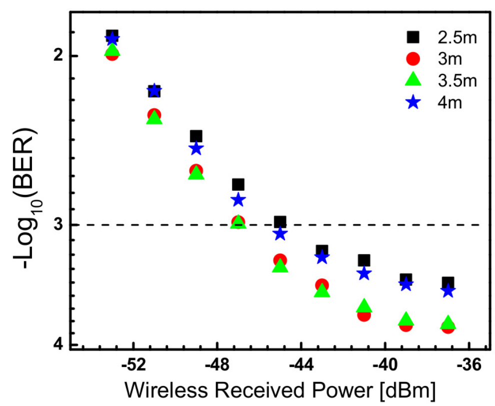


Fig. 10. BER performance as function of wireless received power through 4 m wireless transmission and 1200 m fiber transmission with 16 QAM signal.

separation between the transmit antennas for different wireless transmission distances. The CN obtained was the average of all the 74 sub-carriers and was calculated from the estimated parameters of the 2×2 MIMO channel matrix.

The effect of transmitter antenna separation was simulated for various wireless transmission distances and plotted as shown in Fig. 6(b). It can be observed that the lowest condition number was obtained anywhere between 12 cm to 18 cm of antenna separation, and variation in condition number over the 6 cm range was minimal. From these results we chose 17 cm to be the optimal antenna separation for most of the wireless transmission distances. Due to physical limitations of the experimental set-up transmitter antenna separation below 17 cm were not implemented.

With the transmit antenna separation fixed at 17 cm, wireless transmission experiments using the 60 GHz 2×2 MIMO OFDM system were performed with different modulation formats like QPSK, 8 QAM, 16 QAM and 32 QAM over the whole 7 GHz of available bandwidth. Fig. 7 summarizes the bit-rates possible for the MIMO system with different modulation formats and their corresponding calculated bit error ratios. From Fig. 7 it can be seen that for 7 GHz bandwidth, 28 Gb/s using QPSK modulation and 42 Gb/s using 8 QAM modulation were achieved with the BER complying with the FEC thresholds, whereas the higher modulation formats like 16 QAM (56 Gb/s) and 32 QAM (70 Gb/s) failed to meet the BER requirements. To overcome the distortion limitations faced by the 7 GHz wide spectrum, the bandwidth of the OFDM signal was reduced to 6.375 GHz. This allowed the OFDM-MIMO system with 16 QAM modulation to meet the minimum FEC BER performance requirement of $< 10^{-3}$ with a higher data-rate of 51 Gb/s. This record wireless data transmission speed corresponds to a high spectral efficiency of 8 b/s/Hz.

To further understand the performance limitations of the proposed MIMO system, several experiments were performed for varying wireless transmission distances as well as different optical fibre transmission distances.

The wireless transmission distance was varied from 2.5 m to 4 m, whereas the fiber transmission distances of 500 m and 1200 m were considered. Fig. 8 shows the BER plots of the 60 GHz 2×2 MIMO-OFDM QPSK signal, plotted against the received RF power at different wireless transmission distances. The separation between transmit antennas was fixed at 17 cm from Fig. 6. From 2.5 m to 4 m of transmission distance, only 1 dB of received power penalty was recorded for a BER of 10^{-3}. This result, in combination with the results shown in Fig. 5 indicates that the transmitter antenna separation had more impact on the performance of the MIMO system than the wireless transmission.

Fig. 9 shows the BER plots of the 60 GHz MIMO-OFDM QPSK signals with a wireless transmission of 4 m and with variable fibre transmission distances. Comparing no fibre

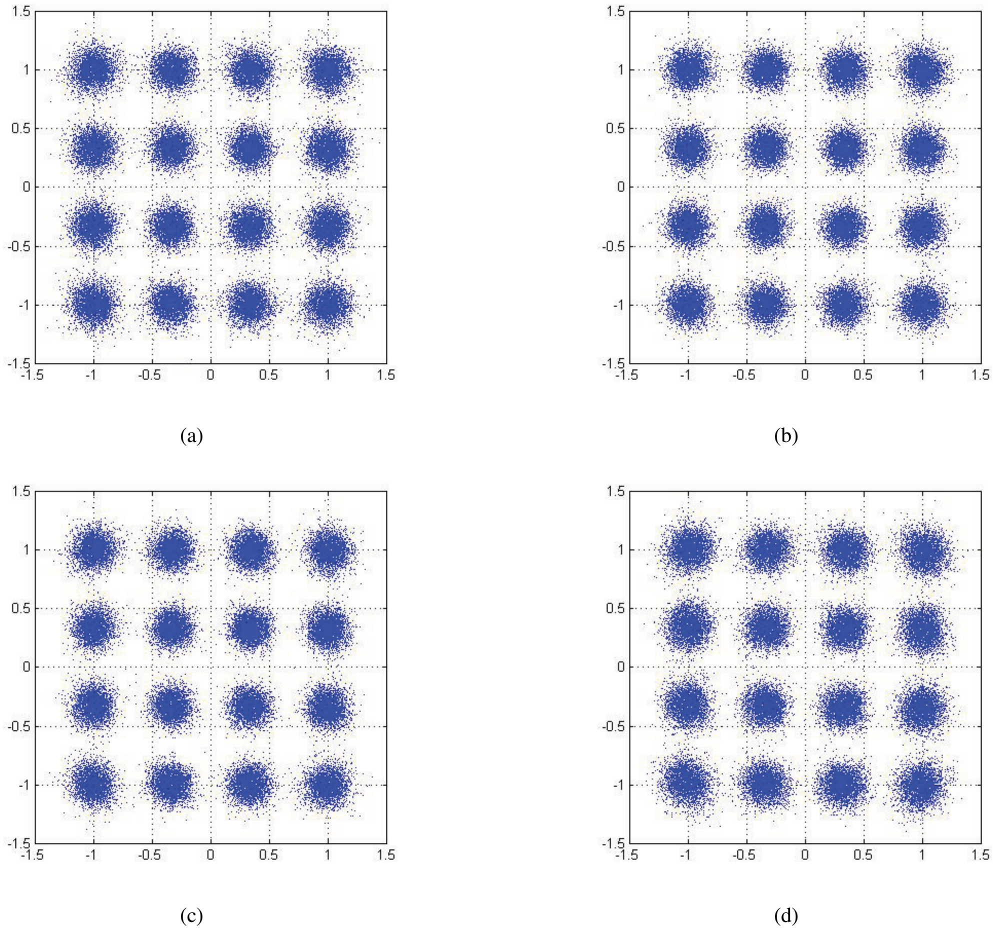


Fig. 11. Constellation diagrams of MIMO-OFDM with 16QAM by transmitting (a) 2.5m (b) 3m (c) 3.5m (d) 4m wireless distance.

transmission case with 500 m and 1200 m fiber transmission as shown in Fig. 9, it can be observed that no significant penalty was induced by fibre transmission up to 1200 m. Fiber transmission of about 1 km is sufficient for typical indoor deployment scenarios. Similar tests were performed with the 51 Gb/s MIMO system, with 6.375 GHz bandwidth and 16 QAM modulation format, and a fiber transmission of 1200 m. Fig. 10 summarizes the BER results plotted against the RF received power. From Fig. 9 and Fig. 10 it can be observed that 16 QAM modulation format required 10 dB more received RF power compared to QPSK to achieve the same BER threshold of 10^{-3} but with almost twice the bit-rate. The received power levels indicate that there was sufficient RF power budget to accommodate longer wireless transmission distances. The slight difference (0.3×10^{-4}) in the BER between 2.5 and 4 m on one hand and 3 and 3.5 m on other hand as observed in Fig. 10 is attributed to the slight variations in the CN of the different wireless transmission distances for the same 17 cm transmitter antenna separation as shown in Fig. 6(b) in addition to the tolerance of the experimental set-up. In any case all wireless transmission distances achieved BER performance well below the FEC limit. The objective of this experimental investigation was not focused on quantifying the performance differences between various wireless transmission distances, but on demonstrating the feasibility of realizing RoF signal generation and distribution of high data-rate 60 GHz MIMO signals.

Fig. 11 shows the constellation diagrams of the MIMO-OFDM 16 QAM system for the wireless transmission distances between 2.5 m to 4 m and BER $< 10{-}3$. As can be seen from the Fig. 11, the constellation diagrams were clear in all cases.

V. CONCLUSION

We experimentally investigated the performance of a 2×2 spatially multiplexed MIMO radio-over-fiber system operating at 60 GHz. The results show that the performance of the 60 GHz MIMO system depends on the antenna separation distance at the transmitter. A record wireless data transmission speed of 51 Gb/s over 4m wireless distance was successfully demonstrated by using an optimal antenna separation of 17 cm at the transmitter. A high spectral efficiency of 8 b/s/Hz was achieved. Data-rates higher than 51 Gb/s were also tested, but their performance was found to be above the FEC coding threshold We investigated different fiber transmission distances and observed that there was no penalty for fiber transmission distances of up-to 1.2 km, which are sufficient for typical indoor deployments. The received power levels and their corresponding BER plots indicate that there was sufficient power budget to further increase the wireless transmission distance beyond 4 m.

REFERENCES

[1] J. Capmany and D. Novak, "Microwave photonics combines two worlds," *Nat. Photonics*, vol. 1, pp. 319–330, 2007.

[2] C. T. Lin, E. Z. Wong, W. J. Jiang, P. T. Shih, J. Chen, and S. Chi, "28-Gb/s 16-QAM OFDM radio-over-fiber system within 7-GHz license-free band at 60 GHz employing all-optical up-conversion," in *Proc. Conf. Lasers Electro-Optics (CLEO)*, May 2009.

[3] M. Weiss, A. Stohr, F. Lecoche, and B. Charbonnier, "27 Gbit/s photonic wireless 60 GHz transmission system using 16-QAM OFDM," in *Proc. Int. Topical Meeting Microw. Photonics (MWP)*, Oct. 2009, pp. 1–3.

[4] A. Ng'oma, C. T. Lin, W. L. Y. Wang He, W. J. Jiang, F. Annunziata, J. Chen, P. T. Shih, J. George, and S. Chi, "31 Gbps RoF system employing adaptive bit-loading OFDM modulation at 60 GHz," in *Proc. Optical Fiber Commun. Conf. (OFC)*, 2011.

[5] C. T. Lin, A. Ng'oma, W. Y. Li, C. Y. Wang, T. S. Lu, C. H. Ho, C. C. Wei, J. Chen, and S. Chi, "MIMO-enhanced radio-over-fiber system at 60 GHz," in *Proc. European Conf. Optical Commun. (ECOC)*, 2011.

[6] C. T. Lin, A. Ng'oma, W.-Y. Lee, C. C. Wei, C-Y. Wang, T.-H. Lu, J. Chen, W. Jiang, and C.-H. Ho, "2×2 MIMO radio-over-fiber system at 60 GHz employing frequency domain equalization," *Opt. Exp.*, vol. 20, no. 1, pp. 562–567, 2012.

[7] Q. H. Spencer, A. L. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multiuser MIMO channels," *IEEE Trans. Signal Process.*, vol. 52, no. 2, pp. 461–471, 2004.

[8] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Pers. Commun.*, vol. 6, pp. 311–335, 1998.

[9] G. G. Raleigh and J. M. Cioffi, "Spatio-temporal coding for wireless communication," in *IEEE Trans. Commun.*, vol. 46, no. 3, pp. 357–366, 1998.

[10] J. Salz "Digital transmission over cross-coupled linear channels," *AT&T Technol. J.*, vol. 64, no. 6, pp. 1147–1159, 1985.

[11] C. Sheldon, E. Torkildson, M. Seo, C. P. Yue, U. Madhow, and M. Rodwell, "A 60 GHz line-of-sight 2×2 MIMO link operating at 1.2 Gbps," in *Proc. IEEE Int. Symp. Antennas Propag. Soc. (APSURSI)*, July 2008, pp. 1–4.

[12] S. Geng, S, Ranvier, M. Kyro, and P. Vainikainen, "Performance and capacity analysis of 60 GHz MIMO channel for WPANs," in *Proc. IEEE Int. Symp. Antennas Propag. Soc. (APSURSI)*, June 2009, pp. 1–4.

[13] M. Jiang, G. Yue, and S. Rangarajan, "MIMO transmission with rank adaptation for multi-gigabit 60 GHz wireless," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Dec. 2010, pp. 1–5.

[14] W. Keusgen, A. Kortke, L. Koschel, M. Peter, R. Weiler, H. Zirath, M. Gavell, and Z. He, "An NLOS-capable 60 GHz MIMO demonstrator: System concept & performance," in *Proc. IEEE 9th Int. New Circuits Syst. Conf. (NEWCAS)*, June 2011, pp. 265–268.

[15] F. Bøhagen, P. Orten, and G. E. Øien, "Design of optimal high-rank line-of-sight MIMO channels," *IEEE Trans. Wireless Commun.*, vol. 6, no. 4, pp. 1420–1425, 2007.

[16] I. Sarris and A. Nix, "Design and performance assement of maximum capacity MIMO architectures in line-of-sight," *Proc. IEEE*, vol. 153, no. 4, pp. 482–488, 2006.

[17] E Torkildson, U. Madhaow, and M. Rodwell, "Indoor millimeter wave MIMO: Feasibility and performance," in *IEEE Trans. Wireless Commun.*, vol. 10, no. 12, pp. 4150–4160, 2011.

[18] J. Armstrong, "OFDM for optical communications," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 189–204, 2009.

[19] N. Cvijetic "OFDM for next-generation optical access networks," *J. Lightw. Technol.*, vol. 30, no. 4, pp. 384–398, 2012.

[20] I. Barhumi, G. Leus, and M. Moonen, "Optimal training design for MIMO OFDM systems in mobile wireless channels," *IEEE Trans. Signal Process.*, vol. 41, pp. 1615–1624, 2003.

[21] D. Tse, "Fundamentals of wireless communication," Dept. Electron. Eng., Dept. of EECS, U.C. Berkeley, ch. 7, pp. 290–302.

[22] W. J. Jiang, C. T. Lin, A. Ng'oma, P. T. Shih, J. Chen, M. Sauer, F. Annunziata, and S. Chi, "Simple 14 Gbps short-range radio-over-fiber system employing a single-electrode MZM for 60 GHz wireless applications," *IEEE J. Lightw. Technol.*, vol. 28, no. 16, pp. 2238–2246, Aug. 2010.

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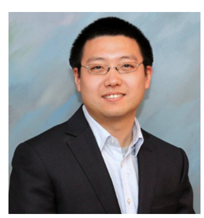

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