IOSR Journal of Computer Engineering (IOSR-JCE)
e-ISSN: 2278-0661,p-ISSN: 2278-8727, Volume 20, Issue 4, Ver. III (Jul - Aug 2018), PP 38-42
www.iosrjournals.org

A Novel Analysis of Multiple-Input Multiple-Output OFDmwith Polarization Division Multiplexing

[1].S. Kiranmayi, [2.] K. Krishna Murthy.
Department of Electronics, V.S.R. Govt degree & P.G college, Movva,A.P,India.
professor P.B Siddhartha college of arts and science, Vijayawada,A.P,India.
Corresponding Author: S. Kiranmayi,

Abstract: *Orthogonal frequency division multiplexing withindex modulation (OFDM-PDM) is a novel multicarrier transmissiontechnique which has been proposed as an alternative toclassical OFDM. The main idea of OFDM-IM is the use of the indicesof the active subcarriers in an OFDM system as an additionalsource of information. In this work, we propose multiple-inputmultiple-output OFDM-IM (MIMO-OFDM-IM) scheme bycombining OFDM-IM and MIMO transmission techniques. Thelow complexity transceiver structure of the MIMO-FDM-IMscheme is developed and it is shown via computer simulations thatthe proposed MIMO-OFDM-IM scheme achieves significantlybetter error performance than classical MIMO-OFDM for severaldifferent system configurations. This work experimentally demonstrates a 60-GHz direct-detection PDM-OFDM system that does not require polarization tracking. The frequency offset of un-modulated optical carriers and a novel training symbol design enable the estimation of optical polarization mixing and wireless MIMO channels for signal demodulation.*

Index terms: *Optical fibre communication, Polarization division multiplexing, Millimetre wave communication, MIMO, OFDM modulation*

Date of Submission: 20-08-2018 Date of acceptance: 03-09-2018

I. Introduction

Orthogonal frequency division multiplexing(OFDM) has become the most popular multicarrier signalling format for high-speed wireless communications and hasbeen included in many standards such as Long-Term Evolution(LTE), IEEE 802.11 wireless local area network (WLAN)and digital video broadcasting (DVB). Due to its efficientimplementation and robustness to the frequency selectivity,OFDM and its combination with multiple-input multiple-output(MIMO) systems unsurprisingly appears as a strong alternativefor 5G networks [1].OFDM with index modulation (OFDM-IM) is a recently proposednovel scheme which transmits information not only by-aryconstellation symbols, but also by the indices of the activesubcarriers which are activated according to the incominginformation bits [2]. Subcarrier index modulation techniquesfor OFDM [2]–[4] have attracted considerable attention fromresearchers and have been investigated in some recent studiesdue to interesting trade-offs they offer in error performanceand spectral efficiency compared to classical OFDM systems[5]–[11]. The bit error probability of OFDM-IM is analyticallyderived in [5]. The spectral efficiency of OFDM-IM isimproved by selecting the active subcarriers in a more flexibleway in [6], where index modulation is applied for both in-phase and quadrature components of the subcarriers. In [7] and [8],the authors deal with the problem of selecting the optimalnumber of active subcarriers in OFDM-IM. More recently,

OFDM-IM is combined with coordinate interleaving to achieveadditional diversity gains in [9]. However, the combinationof OFDM-IM and MIMO transmission techniques remains anopen and interesting research problem.In this study, we propose MIMO-OFDM with index modulation

(MIMO-OFDM-IM) as an efficient alternative multicarriertransmission scheme for 5G networks by combining MIMOand OFDM-IM transmission techniques. In the proposedscheme, each transmit antenna transmits its own OFDM-IMframe as in Vertical Bell Labs layered space-time (V-BLAST)scheme [12], and at the receiver side, these OFDM-IM framesare separated and demodulated using a novel and low complexityminimum mean square error (MMSE) detection andlog-likelihood ratio (LLR) calculation based detector. It isshown via computer simulations that the MIMO-OFDM-IMscheme achieves significantly better bit error rate (BER) performance

than classical V-BLAST type MIMO-OFDM forseveral MIMO configurations.

II. System Model Of MIMO-OFDM-IM

The block diagram of the MIMO-OFDM-IM transceiveris shown in Fig. 1. We consider a MIMO system employingtransmit and receive antennas. As seen for the transmission of each frame, a total of informationbits enter the MIMO-OFDM-IM transmitter. These bitsare first split into groups and the corresponding bits areprocessed in each branch of the transmitter by the OFDM indexmodulators.The proposed DD-PDM optical transceiver is realized by generating two sets of polarization-orthogonal 60-GHz optical OFDM signals (un-modulated reference carriers and OFDM modulated carriers), as shown in Fig. 1. Note that this involves a frequency offset (Δf) equal to the OFDM subcarrier spacing between two polarization-orthogonal un-modulated reference carriers. This frequency offset converts optical polarization mixing into inter-subcarrier interference after photo detection. We designed appropriate training symbols to enable the estimation of channel state information (CSI), including polarization and 2x2 wireless MIMO mixing for signal demodulation. The basic signal transmission model can be expressed as follows:

Y = H*total*X + W(1)

where X is the transmitted signal matrix with dimensions of 2N by M. Y and W are received signals and Gaussian white noise with dimensions of 2N+2 by M, respectively. N and M are the subcarrier and frame number of the OFDM signal. total H represents the channel matrix expressed as follows:

$$\mathbf{H}^{total} = \begin{bmatrix} \mathbf{H}_1^{t_1} & 0 & & & & \\ \mathbf{H}_1^{t_2} & \mathbf{H}_2^{t_1} & \cdots & & 0 & \\ 0 & \mathbf{H}_2^{t_2} & & & & \\ & \vdots & \ddots & & \vdots & \\ & & & \mathbf{H}_{N-1}^{t_1} & 0 & \\ & 0 & \cdots & \mathbf{H}_{N-1}^{t_2} & \mathbf{H}_N^{t_1} & \\ & & & 0 & \mathbf{H}_N^{t_2} & \end{bmatrix} \quad (2)$$

where $t1n$ H and $t2n$ H are 2-by-2 matrixes expressed as

$$\mathbf{H}_n^{t_1} = \mathbf{H}_n^{w} \cdot \mathbf{H}^{b_1} \cdot \mathbf{H}^{p} \cdot \begin{bmatrix} h_{1,n} \\ h_{2,n} \end{bmatrix}_{diag} = \begin{bmatrix} h_{1,1}^{t_1}(n) & h_{1,2}^{t_1}(n) \\ h_{2,1}^{t_1}(n) & h_{2,2}^{t_1}(n) \end{bmatrix} \quad (3)$$

$$\mathbf{H}_n^{t_2} = \mathbf{H}_{n+1}^{w} \cdot \mathbf{H}^{b_2} \cdot \mathbf{H}^{p} \cdot \begin{bmatrix} h_{1,n} \\ h_{2,n} \end{bmatrix}_{diag} = \begin{bmatrix} h_{1,1}^{t_2}(n) & h_{1,2}^{t_2}(n) \\ h_{2,1}^{t_2}(n) & h_{2,2}^{t_2}(n) \end{bmatrix} \quad (4)$$

where s,n h is the channel response prior to the polarization beam splitter (PBS), where subscripts s and n respectively
denote different SOPs and the n-th OFDM subcarrier. H p is a 2-by-2 matrix expressed as follows:

$$\mathbf{H}^{p} = \begin{bmatrix} \cos(\theta) & -\sin(\theta)e^{j\Delta\phi} \\ \sin(\theta)e^{-j\Delta\phi} & \cos(\theta) \end{bmatrix} \quad (5)$$

which describes the polarization mixing of each OFDM subcarrier with various SOP, as shown in Fig. 1.It should be noted thatis irrelevant to the performance of the proposed DD-PDM system because the DD system cannot distinguish phase [16]. Thus, we investigate the system performance only under different. Similarly, Hb1 and Hb2 are calculated from the Jones matrix and expressed as

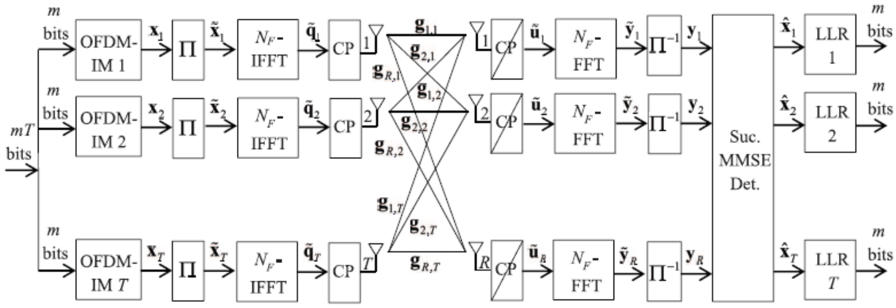
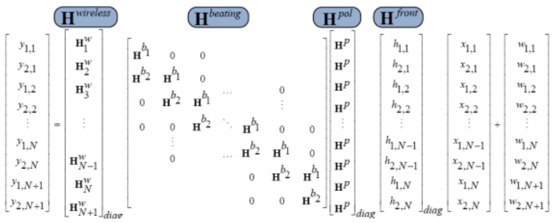


Fig. 1. Transceiver Structure of the MIMO-OFDM-PDM Scheme for a T * R MIMO System

which represents the state of mixing through the beating process, as shown in Fig. 2. In this beating process, the OFDM subcarrier is mixed with an adjacent subcarrier due to the frequency offset between the two un-modulated polarization-orthogonal reference carriers. As shown in Fig. 3, *w n* H is a 2-by-2 wireless MIMO channel matrix for each subcarrier, which is expressed as follows:

$$\mathbf{H}_n^w = \begin{bmatrix} h_{n,11}^w & h_{n,12}^w \\ h_{n,21}^w & h_{n,22}^w \end{bmatrix}. \qquad (6)$$

As shown in Eq. (5), the OFDM signal transmission model can be expressed in detail for each frame, wherein channel
matrix H*total* is summarized and separated into four submatrices, H*wireless*,H*beating*,H *pol,* and H *front.* Identifying the elements of H*total* for channel response equalization from CSI requires an appropriate training symbol



where □is the operator norm? A higher CN value indicates greater noise enhancement [8]. Nonetheless, the CN of the proposed DD-PDM-OFDM system as a function of antenna arrangement as well as SOP. Thus, we sought to simplify the system by assuming that the CN of the wireless channel is low, which can be achieved through the careful arrangement of the antenna [5]. Beyond the issue of noise enhancement in the wireless channel, the key issue is the beating channel matrix, H*beating,* which varies with SOP. We sought to prevent noise enhancement from SOP by inserting empty subcarriers to separate the beating channel matrix, H*beating,* into several independent sub-matrices. The signal can then be recovered using each of the inversed sub-matrices. A sufficiently small matrix size can eliminate any difference in the eigenvalues of each sub-matrix, thereby mediating the enhancement of noise associated with H*beating.* The CN calculation reveals only the average relative noise enhancement of all subcarriers, which means that the noise enhancement factor for each subcarrier (NEES) must be defined.□ □NEES can be obtained by calculating the column norm of the inversed beating H in log scale. The NEES calculations can then be used to illustrate the difference in noise enhancement among the subcarriers. Figure 1 presents simulation results showing the impact of SOP on the level of NEES for each subcarrier. NEES increases with SOP and becomes significantly large when the SOP approaches 45 degrees. The lowest NEES value is obtained for the subcarriers closest to the empty tones, whereas the highest NEES value is obtained in the middle of each subcarrier group. In this case, one empty carrier (tone) was inserted after every 10 subcarriers, which means that the bandwidth of each subcarrier group was approximately 234 MHz It should be clear from the explanation above that inserting a larger number of empty tones between modulated subcarriers reduces the degree to which noise is enhanced by the SOP. In other words, reducing the total number of subcarriers, Ng, in each subcarrier group results in a lower NEES. This is confirmed in, which shows that a small number of subcarriers in each group greatly lowers the minimum and maximum NEES values, even for the worst-case SOP value (=45 degrees). For instance, the maximum NEES value can be reduced from 13 dB to less than 6 dB at SOP = 45 degrees by organizing subcarriers into groups of 6; i.e., Ng = 6 instead of Ng = 40. Although reducing the number of subcarriers in each group improves system performance by reducing noise enhancement, this approach reduces spectral efficiency due to an increase in transmission overhead (non-data-carrying or empty subcarriers). For instance, at Ng = 2 (only two modulated subcarriers between empty tones), the maximum and minimum NEES can be lowered to less than 2 dB; however, this is achieved at the expense of a 33% reduction [i.e. 1/ (2+1)] in spectral efficiency. Thus, the proposed approach incurs a trade-off between reduction of noise enhancement and maintenance of high spectral efficiency. For instance, limiting transmission overhead to less than 15% would require 6 subcarriers in each group (Ng =6); however, we would have to live with a maximum noise enhancement factor of NEES = 6dB.

III. Simulation Results

In this section, we provide computer simulation resultsfor MIMO-OFDM-IM and classical V-BLAST typeMIMO-OFDM schemes employing BPSK, QPSK and 16-QAM(M=2,4 and 16) modulations and MMSE detection. We considerthree different T × R MIMO configurations: 2×2, 4×4 and 8×8. The following OFDM parameters are assumed in allMonte Carlo simulations: N=512, cp=16.

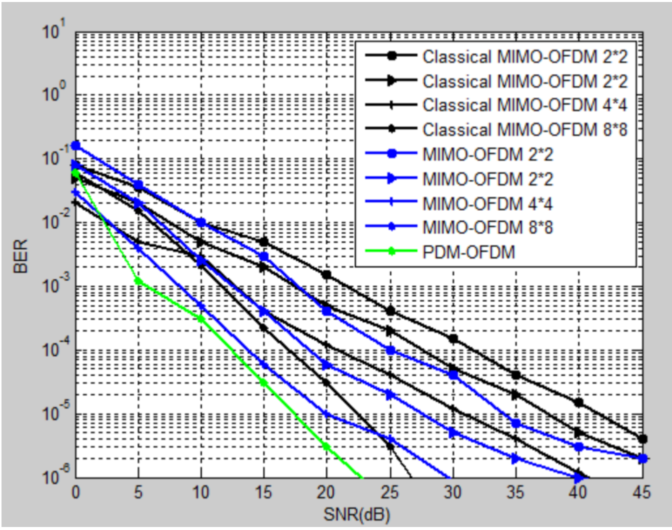


Fig. 2. Performance comparison of MIMO-OFDM and MIMO-OFDM-PDM(N=4, K=2,) for BPSK modulation (M=2), MMSE/ML detection.

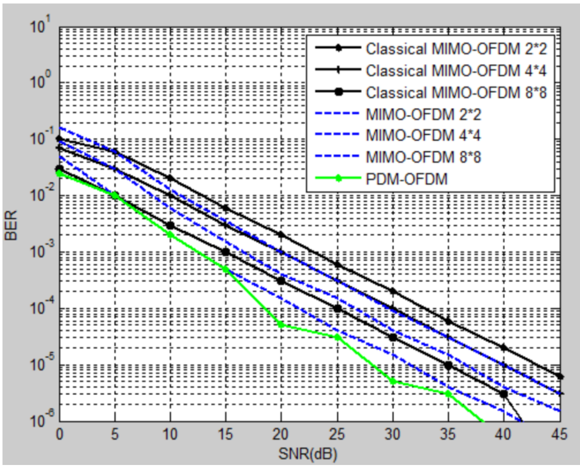


Fig. 3. Performance comparison of MIMO-OFDM and MIMO-OFDM-PDM(N=4, K=3,) for QPSK modulation(M=4), MMSE detection.

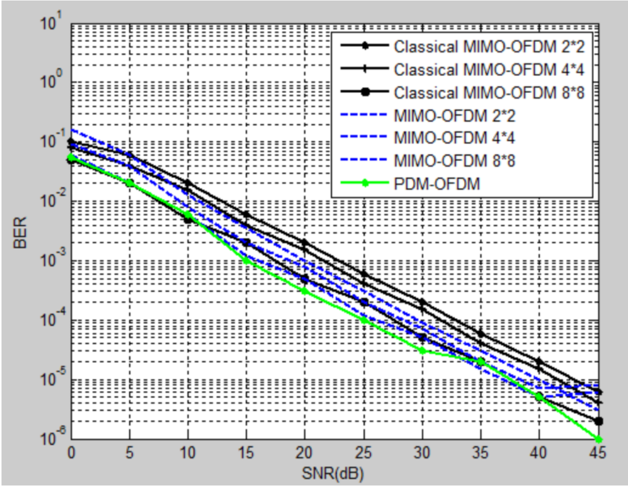


Fig. 4. Performance comparison of MIMO-OFDM and MIMO-OFDM-PDM(N=4, K=3,) for QPSK modulation(M=8), MMSE detection.

In Figs. 3 and 4, we extend our simulations to higher spectral efficiency values and compare the BER performance of the proposed MIMO-OFDM-IM scheme (N=4, K=3,) with classical MIMO-OFDM for M=4 and 16, respectively. As seen from Figs. 3 and 4, the proposed scheme still maintains its advantage over classical MIMO-OFDM in all considered configurations. It is interesting to note that the proposed scheme has the potential to achieve close or better BER performance thanthe reference scheme, even using a lower order MIMO system in most cases.

IV. Conclusions And Future Work

A novel scheme called MIMO-OFDM with index modulation has been proposed as an alternative multicarrier transmission technique for 5G networks. It has been shown via extensive computer simulations that the proposed scheme can provide significant BER performance improvements over classical MIMO-OFDM for several different configurations. The following points remain unsolved in this study: i) performance analysis, ii) the selection of optimal N and K values,diversitytechniques for MIMO-OFDM-PDM, implementation scenarios for high mobility.

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* S. Kiranmayi,. " A Novel Analysis of Multiple-Input Multiple-Output OFDmwith Polarization Division Multiplexing." IOSR Journal of Computer Engineering (IOSR-JCE) 20.4 (2018): 38-42.