Dual-Mode Index Modulation Aided OFDM with Generalized Prefix

Yusuf Acar
Department of Electronics Engineering
Istanbul Kültür University
34156, Bakirkoy, Istanbul, Turkey
Email: y.acar@iku.edu.tr

Sultan Aldırmaz Çolak
Department of Electronics and Communication
Engineering, Kocaeli University
41380, Kocaeli, Turkey
Email: sultan.aldirmaz@kocaeli.edu.tr

Todor Cooklev
Wireless Technology Center
Purdue University Fort Wayne, USA
Email: cooklevt@pfw.edu

***Abstract*— Recently, a dual-mode OFDM relying on index modulation (DM-OFDM-IM) has been introduced to increase the data rate of the conventional IM based OFDM techniques. However, such a mechanism has bit error rate performance loss due to the deep fading channels such as the practical Rayleigh channels. In this work, to improve the BER performance of the DM-OFDM-IM technique, a new technique, that is called as DM-OFDM-IM with generalized prefix (DM-OFDM-IM-GP) is proposed. The simulation results illustrate that the proposed DM-OFDM-IM with GP achieves about 10 dB SNR gain over the existing DM-OFDM-IM at the spectral efficiency of 4, 2.22 and 1.33 bits/s/Hz in Rayleigh fading channel.**

Keywords—Index Modulation; Generalized Prefix; Orthogonal Frequency Division Multiplexing; Dual-Mode, Index Modulation, Spatial Modulation .

I. Introduction

The index modulation (IM) concept has attracted increasing attention as a promising technique for the new-generation wireless communication systems in the last decade. It has many significant advantages such as energy-efficiency, better bit-error-rate (BER), reduced peak-to-average power ratio (PAPR), higher robustness against the inter-carrier interference (ICI) [1]. However, the existing IM based OFDM schemes cause a low spectral efficiency due to its unused subcarriers.

In order to achieve a better performance and higher data rate, the dual-mode orthogonal frequency division multiplexing with index modulation (DM-OFDM-IM) scheme is introduced in [2]. This method uses all carriers within the entire sub-block to transfer more data. In the DM-OFDM-IM, all sub-carriers are divided into subblocks then each block is divided into two groups. Then, each group is modulated by a couple of dissimilar modulation scheme. It is clear that, to convey more data, the positions of the data symbols of each sub-block that employ different constellations are used. Therefore, DM-OFDM-IM uses the indices of subcarrier to transmit more data bits in addition to the well known two dimensional signal constellation. If the DM-OFDM-IM and existing IM based OFDM methods are compared, the total number of data bits or spectral efficiency of DM-OFDM-IM technique is greater than that of the existing OFDM schemes. Moreover, it is shown that a considerably better BER performance than that for the existing IM based OFDM schemes can be obtained with DM-OFDM-IM [2], [3]. Recently, in order to improve spectral efficiency of DM-OFDM-IM, a generalized DM-OFDM-IM (GDM-OFDM-IM) [3], quadrature DM-OFDM-IM (QDM-OFDM-IM) [4], and an adaptive DM-OFDM-IM schemes [5] are proposed. All these variants of DM-OFDM-IM have made additions to different aspects of the basic DM-OFDM-IM. For example, while in DM-OFDM-IM, the number of subcarriers modulated by the same constellation mode (Z_A) is constant; in GDM-OFDM-IM it is alterable for each subblock [3]. When Z_A increases, the gain of spectral efficiency increases too. In response to this benefit, the bit error rate performance of GDM-OFDM-IM is somewhat poor compared to DM-OFDM. In QDM-OFDM-IM scheme [4], two independent index selector boxs are used to determine the modulation scheme of the in-phase and quadrature part of the selected mapper. Moreover, M-pulse amplitude modulation (PAM) is used as distinguishable selected mappers. Unlike from [3] and [4], in [5] DM-OFDM-IM structure is conserved, however the modulation scheme in each subblock is selected from a set according to the instantenous average channel response of each subblock. At the cost of spectral efficieny gain, the receiver complexities of both these two schemes are more complex than that of DM-OFDM-IM.

To avoid the frequency selective channel effect, all DM-OFDM-IM systems use a cyclic prefix (CP) as a guard interval as in classical OFDM. However, investigation of new prefix methods for DM-OFDM-IM is an important missing issue in the literature. Addressing this gap, a new prefix method is proposed for DM-OFDM-IM technique in order to enhance BER in practical Rayleigh fading channel. The proposed system, for adding prefix, we implement a generalized prefix (GP) [6]–[8] and increases the frequency diversity gain in addition to the diversity gain brought by IM. Therefore, the proposed technique always achieves better results than the DM-OFDM-IM for deep fading channels. The simulation results illustrate that the performance enhancement is noticeable. In order to improve BER performance, the GP which is proposed in this paper can be used in the existing variants of DM-OFDM-IM.

The rest of the paper is organized as follows: In Section II, DM-OFDM-IM with GP is presented. The optimum GP calculation is explained in Section III. Then, Section IV gives computer simulation results. Finally, we conclude the paper with Section V.

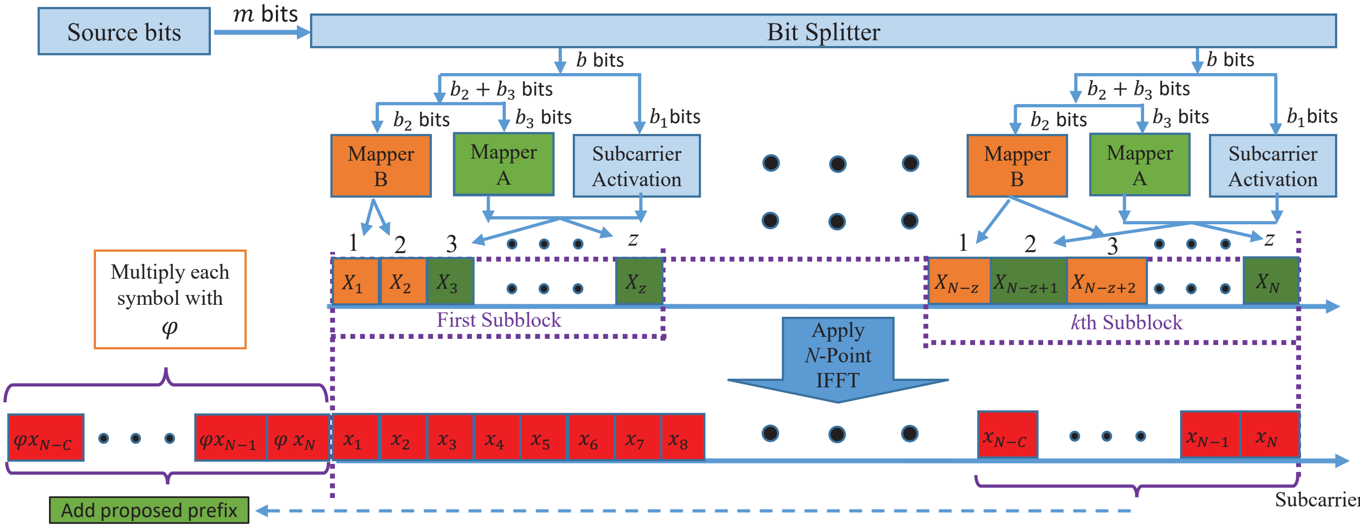

Fig. 1: Proposed DM-OFDM-IM-GP scheme.

II. DM-OFDM-IM WITH PROPOSED GENERALIZED PREFIX

Fig. 1 depicts the block diagram of the DM-OFDM-IM transmitter with proposed GP. As seen from the upper part of Fig. 1, the N sub-carriers are divided into $k = N/z$ subblocks to create the DM-OFDM-IM signals where each subblock contains z subcarriers and has b bits (i.e. total bits is $m = bk$). In the each subblock, the b bits are divided into three parts as $b = b_1 + b_2 + b_3$ for different goals. The first part that consists of b_1 bits is used to determine the subcarrier index set Z_A or Z_B (If one is known then the other can be determined. Thus, only one index selector information is needed for one subblock) and the second part that consists of b_2 bits which is used by constellation alphabets $\mathfrak{M}_A$ that corresponds to the subcarrier index set Z_A. Fig. 2 shows constellation of the quadrature phase shift keying (QPSK) modulation schemes with Gray coding. Finally the last b_3 bits is used by constellation alphabets $\mathfrak{M}_B$ which corresponds to the subcarrier index set Z_B. The index modulation operations for $z = 4$ and $i = 2$ can be clearly illustrated by Table I. In table, S_{A1}, S_{A2}, S_{B1} and S_{B2} represent the four symbols selected from the corresponding constellations $\mathfrak{M}_A$ and $\mathfrak{M}_B$. Assume that [1, 1] are index bits, then constellation $\mathfrak{M}_A$ is used for the 1st and 4th sub-carriers, and then the others are modulated by constellations $\mathfrak{M}_B$.

TABLE I: DM-OFDM-IM look-up table for $i = 2$ and $z = 4$.

Indices	Index bits	Subblocks
[1, 4]	[1, 1]	$[S_{A1}, S_{B1}, S_{B2}, S_{A2}]$
[3, 4]	[1, 0]	$[S_{B1}, S_{B1}, S_{A1}, S_{A2}]$
[2, 3]	[0, 1]	$[S_{B1}, S_{A1}, S_{A2}, S_{B2}]$
[1, 2]	[0, 0]	$[S_{A1}, S_{A2}, S_{B1}, S_{B2}]$

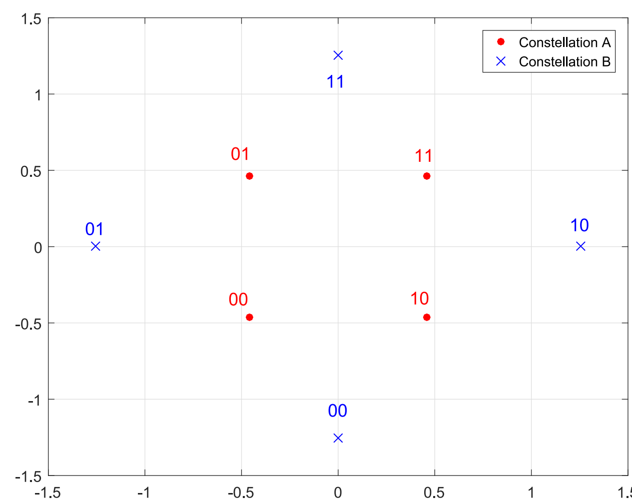

Fig. 2: QPSK constellation

The modulated frequency domain DM-OFDM-IM signal can be expressed as $\mathbf{X} = [X_1, X_2, \cdots, X_N]$ as shown in Fig. 1. To transform into time-domain DM-OFDM-IM signal an N-point IFFT operation given as $\mathbf{x} = [x_1, x_2, \cdots, x_N]^T = \mathscr{F}^{-1}$ ($\mathbf{X}$), where $\mathscr{F}^{-1}$ denotes inverse fast Fourier transform (IFFT). In the proposed system, we multiplied the last C samples of CP with a complex number $\varphi = \psi^N$ for the new prefix constructed. This is equivalent to [8]:

$$\mathbf{x_D} = [\text{diag}\{\mathbf{D}_\psi\}]^{-\mathbf{1}}\mathbf{x} \quad (1)$$

where $\text{diag}\{\mathbf{D}_\psi\}$ is a diagonal matrix with $\mathbf{D}_\psi = [1\ \psi\ \psi^2\ \cdots\ \psi^{N-1}]$. Then a GP is added which can be illustrated in matrix form

$$\mathbf{x}^\psi = \mathbf{G}_\psi \mathbf{x_D} \quad (2)$$

where $\mathbf{G}_\psi = \begin{bmatrix} \mathbf{O}_{Cp\times(N\text{ - }Cp)} & \varphi.\mathbf{I}_{Cp} \\ \mathbf{I}_N & \end{bmatrix}$, $\mathbf{I}_{Cp}$ shows the $Cp \times Cp$ identity matrix, $\mathbf{O}_{Cp\times(N-Cp)}$ denotes the $Cp \times (N - Cp)$ zero matrix and Cp is the length of guard interval. The ψ and φ are any complex numbers that have the relation $\varphi = \psi^N$. Their absolute values are determined as one for maintaining the same PAPR.

Finally, the DM-OFDM-IM symbol is transmitted to a L-tap Rayleigh fading channel that is as given follows

$$\mathbf{h}_T = [h_T(1)\ \cdots\ h_T(L)]^T, \quad (3)$$

where $h_T(l), l = 1, \ldots, L$ are Gaussian random variables with the $\mathscr{CN}(0, \frac{1}{L})$. After removing the proposed generalized prefix, matrix multiplication is done with $\text{diag}\{\mathbf{D}_\psi\}$ and the fast Fourier transform (FFT) is applied at the receiver:

$$\mathbf{y} = \mathscr{F}\left[[\text{diag}\{\mathbf{D}_\psi\}]\mathbf{R}\mathbf{h}_T\mathbf{x}^\psi\right] + \mathbf{w}, \quad (4)$$

where $\mathbf{R} = [\mathbf{O}_{N\times C}\ \ \mathbf{I}_N\ \ \mathbf{O}_{N\times(L-1)}]$ and $\mathbf{w} = \mathscr{F}\left[[\text{diag}\{\mathbf{D}_\psi\}]\mathbf{R}\mathbf{n}\right]$ is a noise vector and $\mathbf{n}$ is the time domain noise vector.

It is known that the GP results the skew-circular convolution [9]. Nonetheless, the matrix product result is still in a diagonal matrix form and can be given as follows:

$$\mathbf{y} = \bar{\mathbf{h}}_F^\psi \mathbf{X} + \mathbf{w}, \quad (5)$$

where $\bar{\mathbf{h}}_F^\psi = \mathscr{F}\left[[\text{diag}\{\mathbf{D}_\psi\}]\mathbf{R}\mathbf{h}_T\mathbf{G}_\psi[\text{diag}\{\mathbf{D}\}]^{-\mathbf{1}}\right]\mathscr{F}^{-1}$. As a results, the fading channel becomes

$$\bar{\mathbf{h}}_F^\psi = \text{diag}[h_F^\psi(1)\ h_F^\psi(2)\ \cdots\ h_F^\psi(N)] \quad (6)$$

and

$$h_F^\psi(\alpha) = \sum_{n=1}^{N} \psi^{\text{n}} h_T[n]\, e^{-jwkn}. \quad (7)$$

It is clear that, the channel (3) has been converted a new channel as:

$$H^\psi(z) = \sum_{n=1}^{N} \psi^n h_T(n) z^{-n}, \quad (8)$$

where $\psi = e^{j\alpha}$ is a new coefficient. Note that $\psi = 1$ is the case which is the same to CP case. It is clear that, (7) and (8) strongly depend on ψ, so optimizing α is important.

III. Calculation of the Optimum ψ

The minimal probability of error approach is used to calculate ψ. The minimal probability of error approach is utilized for optimization which optimizes the probability of bit error $P_e(.)$ as follows:

$$\alpha^* = \arg \min_{\alpha\in\left[0, \frac{2\pi}{N}\right]} P_e(\psi)|_{\psi=e^{j\alpha}}, \quad (9)$$

where α^* is the best value that corresponds to the optimum frequency shift. In the simulation section, it is shown that the optimum value of α depends on the constellation size and channel length (i.e. $\alpha^* = \alpha(\mathfrak{M}_A, \mathfrak{M}_B, L)$). After calculation of ψ at the receiver, only optimum α^* must be sent to the transmitter for minimum overhead.

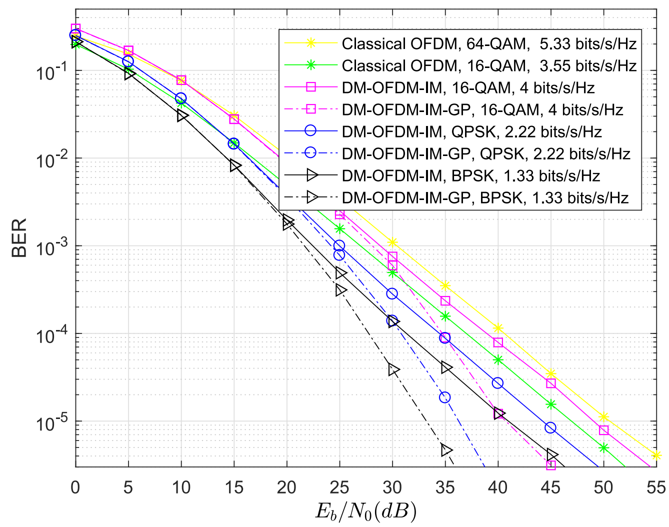

Fig. 3: BER of proposed scheme and DM-OFDM-IM-GP with $L = 10$, $C = 16$.

IV. Simulation Examples

The BER performance of DM-OFDM-IM-GP system is given for different constellation alphabets $\mathfrak{M}_A$ and $\mathfrak{M}_B$ by assuming frequency selective Rayleigh channels. The number of sub-carriers N is set to 128 and each OFDM symbol is divided into $k = 32$ subblock (i.e. $z = 4$). The SNR is described as E_b/N_0 where N_0 is the power of noise and E_b is bit energy. A maximum likelihood (ML) detector and new constellation design in [2] is used. The number of modulated symbol is determined as $i = 2$ for each constellation design.

The BERs of DM-OFDM-IM and proposed system are given in Fig. 3 as functions of the SNR. As shown from Fig. 3, the DM-OFDM-IM with GP achieves approximately 9.4dB, 10.2dB and 10.3dB better BER performance than the DM-OFDM-IM with classical CP for 16-QAM, QPSK and BPSK, respectively at BER= 3×10^{-6}.

Fig. 4 shows the BER performance of the DM-OFDM-IM with GP with the increasing the channel length. This figure shows that the performance improvement of the proposed prefix method gets better as the channel length L increases.

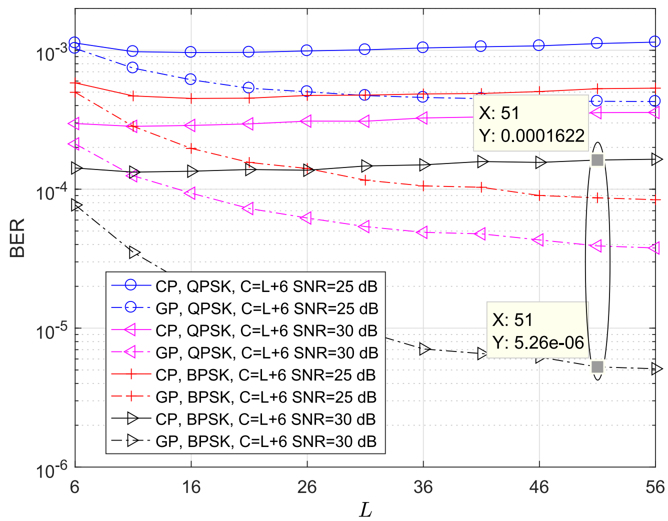

Fig. 4: BER performance of proposed scheme with varying L values.

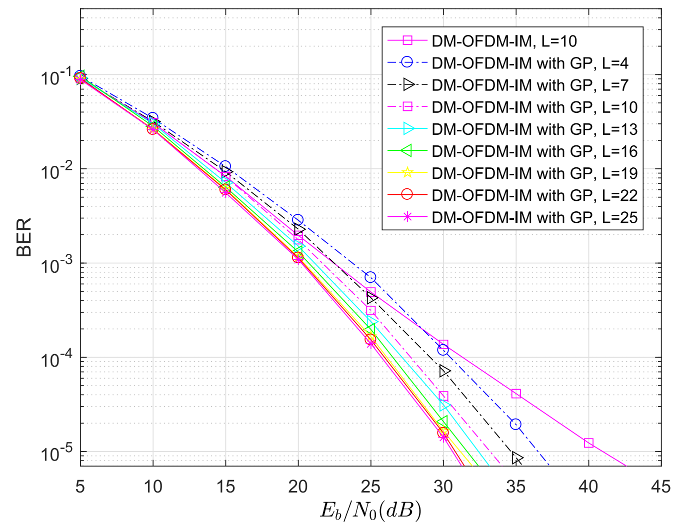

Fig. 5: The effect of different different channel length on BER performance of proposed scheme for BPSK.

Because higher values of L causes more fluctuations and deep fade effects. As an example, the DM-OFDM-IM with BPSK, $L = 51$ and $C = 57$ archives BER= 0.000162 at SNR= 30dB while the DM-OFDM-IM with GP method leads to BER= 5×10^{-6}. Therefore, improvement ratio of proposed DM-OFDM-IM with GP method is 30 times better than DM-OFDM-IM with CP.

The effect of the channel length on BER performance is illustrated in Fig. 5. It is shown that DM-OFDM-IM method with GP achieve about 10 dB better compare to conventional DM-OFDM-IM method at BER= 5×10^{-6}.

Moreover, from the simulation results, we observe that BER gap between provided CP and GP increases at high SNR value. In Fig. 4, for $L = 51$ and QPSK scheme, while $SNR = 25dB$ BER equals to 1×10^{-3} and 4×10^{-4} , when $SNR = 30dB$ BER equals to 3×10^{-4} and 4×10^{-4} for classical CP and GP, respectively.

V. Conclusion

In this work, a generalized prefix structure is proposed for a DM-OFDM-IM schemes for deep fading channels such as Rayleigh channels. The proposed method improved the performance of the DM-OFDM-IM significantly for practical Rayleigh channels especially high SNR.

References

[1] E. Basar, M. Wen, R. Mesleh, M. Di Renzo, Y. Xiao, and H. Haas, "Index modulation techniques for next-generation wireless networks," *IEEE Access*, vol. 5, pp. 16 693–16 746, 2017.

[2] T. Mao, Z. Wang, Q. Wang, S. Chen, and L. Hanzo, "Dual-mode index modulation aided ofdm," *IEEE Access*, vol. 5, pp. 50–60, 2017.

[3] T. Mao, Q. Wang, and Z. Wang, "Generalized dual-mode index modulation aided ofdm," *IEEE Communications Letters*, vol. 21, no. 4, pp. 761–764, 2017.

[4] A. Bouhlel, S. Ikki, and A. Sakly, "Quadrature dual mode index modulation," *IEEE Wireless Communications Letters*, 2018.

[5] S. A. Çolak, Y. Acar, and E. Basar, "Adaptive dual-mode ofdm with index modulation," *Physical Communication*, vol. 30, pp. 15–25, 2018.

[6] T. Cooklev, H. Dogan, R. J. Cintra, and H. Yildiz, "A generalized prefix construction for ofdm systems over quasi-static channels," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 8, pp. 3684–3693, 2011.

[7] Y. Acar and T. Cooklev, "High performance ofdm with index modulation," *Physical Communication*, vol. 32, pp. 192–199, 2019.

[8] H. Yıldız, Y. Acar, T. Cooklev, and H. Dogan, "Generalised prefix for space–time block-coded orthogonal frequency division multiplexing wireless systems over correlated multiple-input multiple-output channels," *IET Communications*, vol. 8, no. 9, pp. 1589–1598, 2014.

[9] S. A. Martucci, "Symmetric convolution and the discrete sine and cosine transforms," *IEEE Transactions on Signal Processing*, vol. 42, no. 5, pp. 1038–1051, 1994.