Rectangular Differential OFDM with index modulation

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Abstract—Orthogonal Frequency Division Multiplexing (OFDM) with Index Modulation (OFDM-IM), which conveyed information bits via the activated indices and constellation symbols is a promising technique in the next wireless communications. In the OFDM-IM scheme, only part of subcarriers are activated to transmit information, the inactive subcarriers transmit zero symbols, so that the conventional differential coding is not suitable for the adjacent subcarriers. In order to address this issue, in this paper, a novel Rectangular Differential OFDM-IM (RD-OFDM-IM) scheme is proposed to exploit the benefits of OFDM-IM dispensing with Channel State Information (CSI). In the proposed RD-OFDM-IM scheme, N subcarriers are partitioned into G subblocks and index modulation is employed in each subblock first. Then rectangular differential coding is invoked during two adjacent subblocks, so that non-coherent detection can be employed for the proposed RD-OFDM-IM scheme. Simulation results are shown that the proposed RD-OFDM-IM scheme is capable of providing considerable performance gain over conventional Differential OFDM (D-OFDM) scheme with lower Peak Average Power Ratio (PAPR).

Index Terms—Orthogonal Frequency Division Multiplexing Index Modulation (OFDM-IM), Peak Average Power Ratio (PAPR), Differential coding.

I. INTRODUCTION

Index modulation (IM) [1]-[3], which employs the activate indices as well as Amplitude Phase Modulation (APM) symbols to convey information, is a recently developed high spectral digital modulation scheme. It has been widely used in the antenna-domain [4], code-domain [5] and subcarriers-domain [6]. Especially, Orthogonal Frequency Division Multiplexing (OFDM) with Index Modulation (OFDM-IM), which employs the index modulation concept into the subcarriers, is capable of offering high spectral efficiency and robustness against the frequency selective channel. To be more specific, since only part of subcarriers are utilized to transmit APM symbols, the OFDM-IM scheme exhibits lower Peak Average Power Ratio (PAPR) and Inter Carrier Interference [ICI] than the conventional OFDM scheme [7]. Furthermore, the researches have demonstrated in [6] that the OFDM-IM scheme is able to strike a flexible tradeoff among the spectrum efficiency, energy efficiency and Bit error ratio (BER) performance. Due to these advantages, OFDM-IM scheme is a promising physical layer candidate in future wireless communication.

Recently, the issues of OFDM-IM performances analysis, transceiver design, receiver design, and application

in practical communication have been investigated in [8]-[27]. To be more specific, in 2014, the tight upper bound on BER of the OFDM-IM was derived in [8]. In 2015, The BER performance analysis of the OFDM-IM with in-phase/quadrature was characterized in [9]. In 2017, the symbol error rate of the OFDM-IM was studied in [10], meantime, the performance analysis of the OFDM-IM scheme in single-cell and multi-cell were presented in [11]. The theoretical analysis results have shown that the OFDM-IM scheme is capable of providing a better BER performance than the classic OFDM at the low-to-mid spectral efficiency.

In order to further improve the BER performance and spectral efficiency of OFDM-IM scheme, some variants of OFDM-IM schemes have been studied in [12]-[20], which can be categorized as follows: subcarriers allocation and index combination design. Specifically, in [12]-[16], the subcarriers of OFDM-IM scheme are assigned in different interleaving ways to achieve performance gain by enlarging the Euclidean distance. In [17], a generalized OFDM-IM scheme with non-fixed number of activated subcarriers was studied first and then the quadrature IM concept was performed on subcarrier, which can significantly increase the spectral efficiency by increasing the number of bits that indices conveyed. In [18], an enhanced OFDM-IM scheme was studied, which explored the I- and Q- dimensions jointly for index modulation to increase the transmit rates and then a linear constellation precoded OFDM-IM scheme was investigated to achieve the diversity gain. Due to the inherent advantages of the OFDM-IM scheme, it has been widely studied in MIMO communication [21]-[24] and practical communication systems [25]-[27]. However, all the aforementioned studies assume perfect channel state information (CSI), which imposes extra complexity. Since there are part of subcarriers transmit zeros, conventional differential coding is not suitable for the adjacent subcarriers.

Recently, Differential Spatial Modulation (DSM) has been studied in non-coherent communications scenarios [28]-[33], where information bits are conveyed by the activated antenna matrix index as well as the APM symbols. Then the differential OFDM-IM scheme based on the DSM concept is proposed in [34]-[35]. However, these schemes exhibit lower transmit rates than the conventional Spatial Modulation (SM) and OFDM-IM counterparts. In order to improve the transmit rate of conventional DSM [28]-[33],

a Rectangular DSM (R-DSM) scheme [36] was proposed for massive MIMO down link communication, which has the same transmit rate as the classic SM scheme and outperforms the existing DSM schemes [28]-[33]. Furthermore, this differential scheme has been applied into the MIMO-STBC [37] and MIMO-OFDM communication scenarios [38]. However, to the best of the authors' knowledge, how to apply the rectangular differential scheme into OFDM-IM system has not been investigated.

Motivated by the concept of the R-DSM scheme, in this paper, a novel Rectangular Differential OFDM-IM (RD-OFDM-IM) scheme is proposed to evaluate the performance of the OFDM-IM scheme dispensing with CSI. To be more specific, in the proposed RD-OFDM-IM scheme, the N subcarriers are partitioned into G subblocks. Index modulation is first employed in each subblock, and then rectangular differential coding is invoked during two adjacent subblocks. Simulation results are shown that the proposed RD-OFDM-IM scheme is capable of providing considerable performance gain over the conventional Differential OFDM (D-OFDM) scheme with lower PAPR.

The remainder of this paper is organized as follows. Section II gives a rudimentary introduction to the conventional R-DSM system. In Section III, the system model and non-coherent detection of the proposed RD-OFDM-IM scheme is introduced, while Section IV presents our simulation results. Finally, Section V concludes this paper.

Notation: $\|\cdot\|_F$ denotes the Frobenious norm of a matrix. $|\cdot|$ represents the magnitude of a complex quantity or the cardinality of a given set. $(\cdot)^T$, $(\cdot)^*$ and $(\cdot)^H$ stand for the transpose, conjugate and Hermitian transpose of a vector/matrix, respectively. $\min(x)$ gives the value of the smallest element of x .

II. A OVERVIEW OF THE R-DSM SYSTEM

We consider a R-DSM [36] system with N_t transmit and N_r receive antennas. Each W -length R-DSM frame consists of N_t -length reference symbols and $(W - N_t)$ -length data symbols. For the $k(k > N_t)$ -th time slot, the information bits of length $B_k = B_k^1 + B_k^2$ are partitioned into two groups: 1) $B_k^1 = \log_2(Q)$ bits are used to select one dispersion vector (DV) $\mathbf{A}_k$ out of Q DVs, where $\mathbf{A}_k$ is a $N_t \times 1$ vector with only one non-zero element 1; 2) $B_k^2 = \log_2(M)$ bits are modulated into a M -PSK symbols s_k to be transmitted by the selected DV $\mathbf{A}_k$, where M is the size of the PSK constellation diagram. Then, the k -th symbol vector $\mathbf{X}_k$ can be expressed as

$$\mathbf{X}_k = \mathbf{A}_k s_k \quad (k > N_t). \quad (1)$$

The k -th transmission vector $\mathbf{S}_k$ is obtained by the differential encoding as

$$\mathbf{S}_k = \mathbf{G}[\mathbf{S}_{k-1}] \mathbf{X}_k \quad (k > N_t), \quad (2)$$

where $\mathbf{G}[\alpha]$ is the function that transforms a vector $\alpha \in \mathbb{C}^{N_t}$ to a unitary matrix, which is defined by

$$\mathbf{G}[\alpha] = \begin{bmatrix} \alpha & \mathbf{E}\alpha & \mathbf{E}^2\alpha & \cdots & \mathbf{E}^{N_t-1}\alpha \end{bmatrix} \in \mathbb{C}^{N_t \times N_t}, \quad (3)$$

where $\mathbf{E}$ is the $N_t \times N_t$ right shift matrix as:

$$\mathbf{E} = \begin{bmatrix} 0 & 0 & \cdots & 0 & 1 \\ 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 \end{bmatrix}, \quad (4)$$

and $\mathbf{E}^k \alpha$ move the elements of α cyclically k positions as:

$$\alpha = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \mathbf{E}\alpha = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \mathbf{E}^2\alpha = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}, \mathbf{E}^3\alpha = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}. \quad (5)$$

The N_t -length reference symbols transmit the right shift matrix $\mathbf{E}$, i.e. for $k = 1, 2, \dots, N_t$, $\mathbf{S}_k = \mathbf{E}(:, k)$, where $\mathbf{E}(:, k)$ represents the k -th column of $\mathbf{E}$.

Let $\mathbf{H}_k \in \mathbb{C}^{N_r \times N_t}$ and $\mathbf{N}_k \in \mathbb{C}^{N_r \times N_t}$ be the channel matrix and noise matrix, whose elements obey the complex Gaussian distributions $\mathcal{CN}(0, 1)$ and $\mathcal{CN}(0, \sigma^2)$, respectively. The received k -th signal $\mathbf{Y}_k \in \mathbb{C}^{N_r}$ is represented by

$$\mathbf{Y}_k = \mathbf{H}_k \mathbf{S}_k + \mathbf{N}_k. \quad (6)$$

Assuming that $\mathbb{X} = [\mathbf{X}_1, \dots, \mathbf{X}_{2B}]$ represents all the transmit symbol set of R-DSM system, the Maximum Likelihood (ML) detection is formulated as follows:

$$\hat{\mathbf{X}}_k = \arg \min_{\mathbf{X}_k \in \mathbb{X}} \left\| \mathbf{Y}_k - \hat{\mathbf{Y}}_{k-1} \cdot \mathbf{X}_k \right\|_F^2 \quad (k > N_t), \quad (7)$$

where we have

$$\hat{\mathbf{Y}}_k = \hat{\mathbf{Y}}_{k-1} \mathbf{G}[\hat{\mathbf{X}}_k] \mathbf{V}_1 + \mathbf{Y}_k \mathbf{V}_2, \quad (8)$$

where $\mathbf{V}_1$ and $\mathbf{V}_2$ are defined as

$$\mathbf{V}_1 = \underbrace{\begin{bmatrix} \alpha & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}}_{N_t \times N_t}, \mathbf{V}_2 = \underbrace{\begin{bmatrix} 1 - \alpha & 0 & \cdots & 0 \end{bmatrix}}_{1 \times N_t}. \quad (9)$$

III. RECTANGULAR DIFFERENTIAL OFDM WITH INDEX MODULATION

Motivated by the concept of the R-DSM system, in this section, a novel RD-OFDM-IM scheme is proposed to exploit the performance of OFDM-IM scheme dispensing with CSI. The RD-OFDM-IM scheme works in detail as follows.

A. System Model

Fig. 1 presents the system model of the proposed RD-OFDM-IM scheme. As shown in Fig. 1, N subcarriers of one frame OFDM symbols are firstly divided into G subblock, so that each subblock contains $L = N/G$ subcarriers; Then the Phase Shift Keying (PSK) and Differential IM (D-IM) techniques using the R-DSM concept are employed for each subblock; The mapped OFDM-IM symbols are transformed into parallel to employ Inverse Fast Fourier Transform (IFFT). After adding the Cyclic Prefix (CP), the RD-OFDM-IM symbols are transmitted

Fig. 1. System model of the proposed RD-OFDM-IM scheme.

by the wireless channel. At the receiver, after removing the CP, Fast Fourier Transform (FFT) and non-coherent detection are employed for the RD-OFDM-IM symbols. To be more specific, the transmit information bits are divided into G groups as $B_1, \dots, B_g, \dots, B_G$. For the case of $g \leq L$, each subblock transmits the reference symbols, i.e. $\mathbf{X}(g) = \mathbf{E}(:, g)$, where $\mathbf{E}(:, g)$ represents the g -th column of $\mathbf{E}$ as

$$\mathbf{E} = \underbrace{\begin{bmatrix} 0 & 0 & \dots & 0 & 1 \\ 1 & 0 & \dots & 0 & 0 \\ 0 & 1 & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & 1 & 0 \end{bmatrix}}_L. \quad (10)$$

For the case of $g > L$, the information bits of length $B_g = B_g^1 + B_g^2$ carried by the g -th subblock are divided into two groups: 1) $B_g^1 = \log_2(L)$ bits are used to select one DV $\mathbf{A}_k(g)$ out of L DAs; 2) $B_g^2 = \log_2 M$ bits are modulated into a PSK symbol s_g . Then, the symbol vector $\mathbf{s}_g$ of the g -th subblock can be expressed as

$$\mathbf{s}(g) = \mathbf{A}_k(g) s_g, (g > L). \quad (11)$$

After finishing the differential encoding using the R-DSM concept, the g -th subblock transmission vector $\mathbf{x}(g) \in \mathbb{C}^L$ can be obtained by

$$\mathbf{x}(g) = \mathbf{G}[\mathbf{x}(g-1)] \mathbf{s}(g) (g > L), \quad (12)$$

where the operation $\mathbf{G}[\cdot]$ is defined by (3).

After completing the G subblocks mapping, the RD-OFDM-IM transmit symbols can be finally represented as

$$\tilde{\mathbf{x}} = \begin{bmatrix} \mathbf{x}(1)^T & \dots & \mathbf{x}(g)^T & \dots & \mathbf{x}(G)^T \end{bmatrix} \quad (13)$$

Example $L = 4, M = 1$: For the case of $L = 4, M = 1$, the transmission rate of each subblock is calculated as $(\log_2(L) + \log_2(2))/L = 3/4 = 0.75$ bit/symbol. The

corresponding right shift matrix $\mathbf{E}$ is given as

$$\mathbf{E} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}. \quad (14)$$

Hence, The first L subblocks transmit the reference symbols, as

$$\begin{aligned} \mathbf{x}(1)^T &= \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}; \mathbf{x}(2)^T = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix}; \\ \mathbf{x}(3)^T &= \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}; \mathbf{x}(4)^T = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}. \end{aligned} \quad (15)$$

For the 5-th subblock, assuming that the bit sequence is given as $[1 \ 0 \ 0]^T$, the first $B_5^1 = 2$ bits $[1 \ 0]^T$ is used to map a DV as $\mathbf{A}_3(5)$ and $B_5^2 = 1$ bit $[0]$ is mapped to the BPSK symbol $s_5 = +1$ as

$$\mathbf{s}(5) = (+1) \times \mathbf{A}_3(5) = \begin{bmatrix} 0 \\ 0 \\ +1 \\ 0 \end{bmatrix}. \quad (16)$$

By employing the operation $\mathbf{G}$ on $\mathbf{x}(4)$, we have

$$\mathbf{G}[\mathbf{x}(4)] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (17)$$

Then, the 5-th transmission vector $\mathbf{x}(5)$ is calculated as

$$\begin{aligned} \mathbf{x}(5) &= \mathbf{G}[\mathbf{x}(4)] \mathbf{s}(5) \\ &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ +1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ +1 \\ 0 \end{bmatrix}. \end{aligned} \quad (18)$$

For the 6-th subblock, assuming that the bit sequence is $\mathbf{b}(5)$ is $[0 \ 1 \ 1]^T$, the 6-th transmission vector is calculated

as

$$\begin{aligned} \mathbf{x}(6) &= \mathbf{G}[\mathbf{x}(5)] \mathbf{s}(6) \\ &= \begin{bmatrix} 0 & 0 & +1 & 0 \\ 0 & 0 & 0 & +1 \\ +1 & 0 & 0 & 0 \\ 0 & +1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ -1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -1 \end{bmatrix}. \end{aligned} \quad (19)$$

Based on the similar operations, the RD-OFDM-IM transmit symbols are finally formulated as

$$\begin{aligned} \tilde{\mathbf{x}} &= [\underbrace{0 \ 1 \ 0 \ 0}_{\mathbf{x}(1)^T}, \underbrace{0 \ 0 \ 1 \ 0}_{\mathbf{x}(2)^T}, \underbrace{0 \ 0 \ 0 \ 1}_{\mathbf{x}(3)^T}, \\ &\quad \underbrace{1 \ 0 \ 0 \ 0}_{\mathbf{x}(4)^T}, \underbrace{0 \ 0 \ +1 \ 0}_{\mathbf{x}(5)^T}, \underbrace{0 \ 0 \ 0 \ -1}_{\mathbf{x}(6)^T}, \dots] \end{aligned} \quad (20)$$

B. Non-coherent Detection

Let $H_k \in \mathbb{C}^{1 \times 1}$ and $n_k \in \mathbb{C}^{1 \times 1}$ be the frequency channel coefficient and noise element, whose elements obey the complex Gaussian distributions $\mathcal{CN}(0, 1)$ and $\mathcal{CN}(0, \sigma^2)$, respectively. The N subcarriers received signal $\mathbf{y} \in \mathbb{C}^N$ is represented by

$$\underbrace{\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}}_{\mathbf{y}} = \underbrace{\begin{bmatrix} H_1 & 0 & \cdots & 0 \\ 0 & H_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & H_N \end{bmatrix}}_{\mathbf{H}} \underbrace{\begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \vdots \\ \tilde{x}_N \end{bmatrix}}_{\tilde{\mathbf{x}}} + \underbrace{\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix}}_{\mathbf{n}}. \quad (21)$$

According to (21), the g -th subblock receive signal can be expressed as

$$\underbrace{\begin{bmatrix} y_g^1 \\ y_g^2 \\ \vdots \\ y_g^L \end{bmatrix}}_{\mathbf{y}(g)} = \underbrace{\begin{bmatrix} H_{g,1} & 0 & \cdots & 0 \\ 0 & H_{g,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & H_{g,L} \end{bmatrix}}_{\mathbf{H}(g)} \underbrace{\begin{bmatrix} x_g^1 \\ x_g^2 \\ \vdots \\ x_g^L \end{bmatrix}}_{\mathbf{x}(g)} + \underbrace{\begin{bmatrix} n_g^1 \\ n_g^2 \\ \vdots \\ n_g^L \end{bmatrix}}_{\mathbf{n}(g)}. \quad (22)$$

Next, the non-coherent detection will be introduced in detail as follows.

1) *Detection for Specific Examples:* In this subsection, the detection for the above mentioned examples is introduced as follows. For the 5-th subblock detection, the receiver signal can be expressed as

$$\begin{aligned} \mathbf{y}(5) &= \mathbf{H}(5)\mathbf{x}(5) + \mathbf{n}(5) \\ &= \mathbf{H}(5)\mathbf{G}[\mathbf{x}(4)]\mathbf{s}(5) + \mathbf{n}(5). \end{aligned} \quad (23)$$

Assuming that $\mathbf{H}(1) \approx \mathbf{H}(2) \cdots \approx \mathbf{H}(5)$, the value of $\mathbf{H}(5)\mathbf{G}[\mathbf{x}(4)]$ can be expressed as

$$\hat{\mathbf{y}}(4) = \mathbf{H}(5)\mathbf{G}[\mathbf{x}(4)] = [\mathbf{y}(4) \ \mathbf{y}(1) \ \mathbf{y}(2) \ \mathbf{y}(3)]. \quad (24)$$

Then the 5-th subblock signal can be detected as

$$\hat{\mathbf{s}}(5) = \arg \min_{\mathbf{s}(5) \in \mathbb{S}} \|\mathbf{y}(5) - \hat{\mathbf{y}}(4)\mathbf{s}(5)\|_F^2 \quad (25)$$

where $\mathbb{S}$ represents the set of transmit symbols.

For the 6-th subblock detection, the receiver signal can be expressed as

$$\begin{aligned} \mathbf{y}(6) &= \mathbf{H}(6)\mathbf{x}(6) + \mathbf{n}(6) \\ &= \mathbf{H}(6)\mathbf{G}[\mathbf{x}(5)]\mathbf{s}(6) + \mathbf{n}(6) \\ &= \mathbf{H}(6)\mathbf{G}[\mathbf{G}[\mathbf{x}(4)]\mathbf{s}(5)]\mathbf{s}(6) + \mathbf{n}(6) \\ &= \mathbf{H}(6)\mathbf{G}[\mathbf{x}(4)]\mathbf{G}[\mathbf{x}(5)]\mathbf{s}(6) + \mathbf{n}(6) \end{aligned} \quad (26)$$

Assuming that $\mathbf{H}(5) \approx \mathbf{H}(6)$, we have

$$\begin{aligned} \hat{\mathbf{y}}(5) &= \mathbf{H}(6)\mathbf{G}[\mathbf{x}(4)]\mathbf{G}[\mathbf{x}(5)] \\ &= \hat{\mathbf{y}}(4)\mathbf{G}[\mathbf{x}(5)] \end{aligned} \quad (27)$$

Then the 6-th subblock signal can be detected as

$$\hat{\mathbf{s}}(6) = \arg \min_{\mathbf{s}(6) \in \mathbb{S}} \|\mathbf{y}(6) - \hat{\mathbf{y}}(5)\mathbf{s}(6)\|_F^2. \quad (28)$$

In order to reduce the effects of error propagation, a forgetting factor α is employed in the signal detection. According to (27) and (3), we have

$$\hat{\mathbf{y}}(5) = \hat{\mathbf{y}}(4)\mathbf{G}[\mathbf{x}(5)] \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} + \mathbf{y}(5) [1 \ 0 \ 0 \ 0]. \quad (29)$$

After employing the forgetting factor α using the method [34], the value of $\hat{\mathbf{y}}(5)$ can be represented as

$$\hat{\mathbf{y}}(5) = \hat{\mathbf{y}}(4)\mathbf{G}[\mathbf{x}(5)] \begin{pmatrix} \alpha & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} + \mathbf{y}(5) [1 - \alpha \ 0 \ 0 \ 0]. \quad (30)$$

2) *Generalized Detection:* For the g -th subblock, the corresponding receiver signal can be expressed as

$$\begin{aligned} \hat{\mathbf{y}}(g-1) &= \mathbf{H}(g)\mathbf{G}[\mathbf{x}(g-2)]\mathbf{G}[\mathbf{x}(g-1)] \\ &= \hat{\mathbf{y}}(g-2)\mathbf{G}[\mathbf{x}(g-1)] \\ &= \hat{\mathbf{y}}(g-2)\mathbf{G}[\mathbf{x}(g-1)]\mathbf{V}_1 + \mathbf{y}(g-1)\mathbf{V}_2, \end{aligned} \quad (31)$$

with

$$\mathbf{V}_1 = \underbrace{\begin{bmatrix} \alpha & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & \cdots & 1 \end{bmatrix}}_{L \times L}, \mathbf{V}_2 = \underbrace{[1 - \alpha, 0, \dots, 0]}_{1 \times L}. \quad (32)$$

Hence, the g -th subblock detection can be expressed as

$$\hat{\mathbf{s}}(g) = \arg \min_{\mathbf{s}(g) \in \mathbb{S}} \|\mathbf{y}(g) - \hat{\mathbf{g}}(g-1)\mathbf{s}(g)\|_F^2 \ (g > L). \quad (33)$$

IV. SIMULATION RESULTS

In this section, the performances of the proposed RD-OFDM-IM scheme are presented under quasi-static Rayleigh fading channel. In all our simulation results, the BER of these systems are evaluated through Monte Carlo simulations and $\alpha = 0.80$ is employed.

Firstly, Fig. 2 plots the performance of the RD-OFDM-IM scheme with $N = 1024$ subcarriers under different configurations, where $(L, 1)$ represents one subcarrier out of L subcarriers is activated. To be more specific, $(4, 1)$

Fig. 2. Performance comparison between the proposed RD-OFDM-IM scheme and classic D-OFDM scheme.

Fig. 3. Performance comparison between the proposed RD-OFDM-IM scheme and classic OFDM-IM scheme.

with QPSK modulation and (2,1) with QPSK modulation are employed to achieve 1 bit/symbol, (8,1) with QPSK modulation is employed to achieve 0.625 bit/symbol, as well as (8,1) with BPSK modulation is employed to achieve 0.5 bit/symbol. The performance of the D-OFDM scheme with BPSK at 1 bit/symbol is added as benchmark. Observe from Fig. 2 that the proposed RD-OFDM-IM scheme is capable of outperforming classic D-OFDM scheme by around 2 dB performance gain at $\text{BER}=10^{-5}$ at the same transmit rate 1 bit/symbol. The proposed RD-OFDM-IM scheme with (8,1)-BPSK modulation is capable of outperforming classic OFDM by around 4 dB performance gain at $\text{BER}=10^{-5}$ at the cost of slight performance rate. The performance of the differential OFDM-IM schemes in [34]-[35] approaches that of classic D-OFDM scheme. This implies that the proposed RD-OFDM-IM scheme is capable of provides considerable performance gains over the differential schemes in [34]-[35].

Fig. 3 compares the performance of the proposed RD-OFDM-IM scheme with conventional OFDM-IM scheme [6] with the same transmit rates as 0.5 bit/symbol, 0.625 bit/symbol and 1 bit/symbol. Observe from Fig. 3 that when compared with the coherent OFDM-IM scheme, the

Fig. 4. Performance of the proposed RD-OFDM-IM scheme with different number of subcarriers.

Fig. 5. PAPR comparison between the proposed RD-OFDM-IM scheme and classic D-OFDM scheme.

performance loss of the proposed RD-OFDM-IM scheme is around 2 dB, which is smaller than the well-known 3 dB [27].

Fig. 4 portrays the performance of the proposed RD-OFDM-IM scheme with different number of subcarriers. (8,1)-BPSK and (4,1)-QPSK are employed for the proposed RD-OFDM-IM scheme. Observe from Fig. 4 that the performance of the proposed RD-OFDM-IM scheme with (8,1)-BPSK configuration improves significantly as the number of subcarrier increases. The similar trend can be observed in (4,1)-QPSK-aided RD-OFDM-IM scheme.

Finally, Fig. 5 compares the PAPR performance of the proposed RD-OFDM-IM scheme with classic D-OFDM scheme. (2,1)-BPSK, (4,1)-QPSK as well as (4,1)-BPSK are employed for the proposed RD-OFDM-IM scheme to achieve 1 bit/symbol, 1 bit/symbol and 0.75 bit/symbol. BPSK is employed for the classic D-OFDM scheme to achieve 1 bit/symbol. Observe from Fig. 5 that the proposed RD-OFDM-IM schemes with (2,1)-BPSK and (4,1)-QPSK modulations exhibit lower PAPR than the classic D-OFDM scheme at the same transmit rate 1 bit/symbol. As the transmit rate decreases, the PAPR advantage of the proposed RD-OFDM-IM scheme becomes more dominant.

V. CONCLUSION

In this paper, a novel rectangular differential OFDM with index modulation scheme termed as RD-OFDM-IM is proposed dispensing with CSI. In the proposed RD-OFDM-IM scheme, rectangular differential coding is employed between two adjacent subblocks, so that non-coherent detection can be effectively employed at the receiver. Simulation results are shown that the proposed RD-OFDM-IM scheme is capable of reducing the complexity of channel estimation for OFDM-IM scheme at the cost of only 2 dB performance loss. Furthermore, the proposed RD-OFDM-IM scheme is capable of outperforming classic D-OFDM scheme with lower PAPR performance at low transmit rate.

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