Comparison of Index Modulation Techniques in OFDM Systems under Jamming Attacks

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Abstract—**Index modulation (IM) is a promising technique for enhancing system resilience against jamming attacks in orthogonal frequency division multiplexing (OFDM) systems. Dual-mode IM OFDM (DM-OFDM) offers notable potential among the various types of IM techniques. Motivated by this fact, in this paper, we explore the robustness of DM-OFDM under jamming attacks in comparison to the traditional OFDM and OFDM-IM systems. Our investigation focuses on a practical resource mapping scenario relevant to 5G cellular standards. The key finding is that while the DM-OFDM system demonstrates strong performance under limited jamming, its advantage over the compared systems decreases as the jamming power increases. Nevertheless, the DM-OFDM system continues to show robustness when the impact of the jamming signals is restricted to a small subset of subcarriers.**

I. INTRODUCTION

Modern wireless communication systems, such as orthogonal frequency division multiplexing (OFDM) systems, are vulnerable to jamming attacks due to the potential for these attacks to cause severe demodulation errors that may not be correctable even with the use of error-correcting codes [1]. The jamming attacks can manifest in several patterns, including random jamming, barrage jamming, partial band jamming, tone jamming, sweep jamming, and arbitrary jamming [2]. In fact, with the recent advancement of smart jammers, the capacity of these attacks to degrade the performance of the modern communication systems has further increased [3].

To address the above problem, some researchers have focused on leveraging advanced modulation techniques for anti-jamming purposes. One representative example is index modulation (IM), whose potential as an anti-jamming technique has been demonstrated in OFDM systems [4]. By using index bits to select specific subcarriers for signal transmission, OFDM-IM in [5] avoids jamming with a certain probability, enhancing its robustness in some jamming environments. However, OFDM-IM still suffers from severe performance degradation when jamming signals are present on the selected subcarriers, which may result in errors in the index bits and a subsequent increase in bit error rate (BER) [6]. Another type of IM, called dual-mode IM OFDM (DM-OFDM) in [7], can address the limitation of OFDM-IM by activating all subcarriers. In particular, unlike OFDM-IM, DM-OFDM utilizes index bits to choose between two different constellation sets for each subcarrier when transmitting symbols.

Inspired by the difference between IM and DM techniques, in this paper, we investigate the potential of DM-OFDM as an effective solution for jamming-robust wireless communication. To this end, we examine the robustness of the DM-OFDM system under jamming attacks in a practical resource mapping context, where modulated signals are assigned to specific resource blocks, as seen in 5G cellular standards. Our simulation results demonstrate that, although the performance advantage of the DM-OFDM system over the traditional OFDM and OFDM-IM systems decreases as jamming power increases, the DM-OFDM system consistently outperforms both, particularly at a high signal-to-noise ratio (SNR) regime when the jamming signals affect only a small subset of subcarriers.

II. SYSTEM MODEL

In this section, we present the system model for OFDM, OFDM-IM, and the newly implemented DM-OFDM under jamming attacks. We begin by considering a multi-carrier communication system with K subcarriers. In this study, we assume the system operates with G transmission blocks, where each block consists of N subcarriers. At any given time, m information bits are received by the transmitter and are evenly divided among the G blocks, resulting in $p = m/G$ bits per block. Since the transmission processing is identical and independent for all blocks, we focus on the g-th block as a representative example, where $g \in \{1, \ldots, G\}$. We define the outcome of the transmission process for each block as $\mathbf{x}^{(g)} = [x_1^{(g)}, \ldots, x_N^{(g)}]$. By concatenating the vectors $\mathbf{x}^{(g)}$ for all g and processing them with an interleaver, the transmitted vector is expressed as

$$\begin{aligned}\mathbf{x} &= [x(1), \ldots, x(K)]^{\mathsf{T}} \\ &= [x_1^{(1)}, x_1^{(2)}, \ldots, x_1^{(G)}, \ldots, x_N^{(1)}, x_N^{(2)}, \ldots, x_N^{(G)}]^{\mathsf{T}}. \quad (1)\end{aligned}$$

At this stage, the process continues similarly to the conventional OFDM system. The first step involves applying a K-point inverse fast Fourier transform (IFFT), resulting in the time-domain signal $\mathbf{x}_T \triangleq [x_T(1), \ldots, x_T(K)]^{\mathsf{T}} = \frac{1}{\sqrt{K}} \mathbf{W}_K^{\mathsf{H}} \mathbf{x}$, where $\mathbf{W}_K$ represents the K-point discrete Fourier transform (DFT) matrix that satisfies $\mathbf{W}_K^{\mathsf{H}} \mathbf{W}_K = K\mathbf{I}_K$. Next, a cyclic prefix (CP) of length L, which consists of the samples $[x_T(K-L+1), \ldots, x_T(K)]$, is prepended to the beginning of $\mathbf{x}_T$. Finally, the signal is converted from parallel

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to serial format (P/S) and then transformed to analog before transmission.

At the receiver, after deinterleaving and removing the CP, a K-point DFT is performed on the received time-domain signal. With perfect synchronization assumed, the received vector in the frequency domain can be expressed as:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{C}\mathbf{z} + \mathbf{w}, \tag{2}$$

where $\mathbf{H} = \mathsf{diag}(\mathbf{h})$, $\mathbf{C} = \mathsf{diag}(\mathbf{c})$, $\mathbf{h} \triangleq [h(1), \ldots, h(K)]$ is a frequency-domain channel vector distributed as $\mathcal{CN}(0, \mathbf{I}_K)$, $\mathbf{w}$ is a frequency-domain noise vector distributed as $\mathbf{w} \sim \mathcal{CN}(\mathbf{0}, \sigma_w^2 \mathbf{I}_K)$, $\mathbf{c} \in \{0,1\}^K$ is the indicator vector specifying the jamming pattern that may change over time, and $\mathbf{z}$ is a frequency-domain jamming vector distributed as $\mathbf{z} \sim \mathcal{CN}(\mathbf{0}, \sigma_z^2 \mathbf{I}_K)$. To capture a power constraint, we assume that the expected value of the squared norm of the transmitted vector is normalized, i.e., $\mathbb{E}[\|\mathbf{x}\|^2] = K$.

III. TRANSMISSION AND RECEPTION SCHEMES

In this section, we introduce the transmission techniques for OFDM, OFDM-IM, and DM-OFDM systems, as well as the corresponding maximum likelihood (ML) detection method at the receiver. Since transmission and reception are performed on a block-by-block basis, the system model is described for each block as follows:

$$\mathbf{y}^{(g)} = \mathbf{H}^{(g)}\mathbf{x}^{(g)} + \mathbf{C}^{(g)}\mathbf{z}^{(g)} + \mathbf{w}^{(g)}, \tag{3}$$

where each vector is N-dimensional and each matrix is $N \times N$ for all $g \in \{1, \ldots, G\}$.

A. OFDM System

In the OFDM system, the transmitter uses a symbol constellation set $\mathcal{S}$ of order M, comprising 2^M symbols. For the g-th block of the OFDM system, we assume that $p = MN$. For example, with BPSK modulation, each group of N bits is mapped to a symbol from the constellation set based on a specific mapping rule. Each of these symbols is transmitted over a single subcarrier, leading to $x_n^{(g)} \in \mathcal{S}$ for all $n \in \{1, \ldots, N\}$.

In the OFDM system, the transmitted signals x_n, for all $n \in \{1, \ldots, N\}$, are mutually independent. At the same time, both noise and jamming signals follow a circularly symmetric complex Gaussian distribution, as discussed in Sec. II. Consequently, based on (3), the ML detection rule to estimate the transmitted signal at subcarrier n of g-th block can be expressed as:

$$\hat{x}_n^{(g)} = \underset{x_n^{(g)} \in \mathcal{S}}{\operatorname{argmin}} \, |y_n^{(g)} - h_n^{(g)} x_n^{(g)}|^2, \tag{4}$$

for all $g \in \{1, \ldots, G\}$ and $n \in \{1, \ldots, N\}$.

B. OFDM-IM System

In the OFDM-IM system, each group of p bits is used to generate the OFDM-IM block, which consists of N subcarriers. The fundamental principle behind this design is to activate N_A subcarriers out of the total N, while the remaining $N - N_A$ subcarriers being deactivated. The first p_1 bits from the p bits are used to identify the indices of the N_A active subcarriers within the block, while the remaining p_2 bits determine the symbols mapped to these active subcarriers. This design leads to the expressions $p_1 = \lfloor \log_2(C(N, N_A)) \rfloor$ and $p_2 = N_A \log_2 M$, where $C(N, N_A)$ is the number of possible ways to select N_A elements from N, and M is the modulation order of the constellation set $\mathcal{S}$.

At the receiver, to perform ML detection, joint detection of each OFDM-IM block is required based on the received signals. The ML detection rule for estimating the transmitted vector in the g-th block can be formulated as:

$$\hat{\mathbf{x}}^{(g)} = \underset{\mathbf{x}^{(g)} \in \mathcal{S}^N}{\operatorname{argmin}} \, \|\mathbf{y}^{(g)} - \mathbf{h}^{(g)}\mathbf{x}^{(g)}\|^2, \quad \forall g \in \{1, \ldots, G\}. \tag{5}$$

C. DM-OFDM System

In the DM-OFDM system, each group of p bits is used to generate a block which consists of N subcarriers. Unlike the OFDM-IM system, where only a subset of subcarriers is activated, the DM-OFDM system activates all N subcarriers in each block. DM-OFDM is distinguished by its use of two distinct constellation sets, $\mathcal{S}_A$ and $\mathcal{S}_B$, with sizes M_A and M_B, respectively. The first p_1 bits of the p bits are employed by the index selector to divide the block's indices into two subsets, labeled $\mathcal{I}_A$ and $\mathcal{I}_B$. The remaining p_2 bits are then processed by mappers A and B, which correspond to the constellation sets $\mathcal{S}_A$ and $\mathcal{S}_B$. Given that $N = N_A + N_B = |\mathcal{I}_A| + |\mathcal{I}_B|$, the values of p_1 and p_2 are calculated as $p_1 = \lfloor \log_2 \left(\frac{N!}{N_A! N_B!} \right) \rfloor$ and $p_2 = N_A \log_2(M_A) + N_B \log_2(M_B)$. For instance, if both mappers use QPSK and $N_A = N_B = 2$, an example of a feasible constellation design is provided in Table I.

TABLE I
A LOOK UP TABLE FOR $(N, N_A, N_B) = (4, 2, 2)$

p_1-bits	Two index subsets	$\boldsymbol{x}_g$
[0 0]	$\mathcal{I}_A = \{1,\ 2\}, \mathcal{I}_B = \{3,\ 4\}$	$[\mathcal{S}_A^{(1)}\ \ \mathcal{S}_A^{(2)}\ \ \mathcal{S}_B^{(1)}\ \ \mathcal{S}_B^{(2)}]^\mathsf{T}$
[0 1]	$\mathcal{I}_A = \{2,\ 3\}, \mathcal{I}_B = \{1,\ 4\}$	$[\mathcal{S}_B^{(1)}\ \ \mathcal{S}_A^{(1)}\ \ \mathcal{S}_A^{(2)}\ \ \mathcal{S}_B^{(2)}]^\mathsf{T}$
[1 0]	$\mathcal{I}_A = \{3,\ 4\}, \mathcal{I}_B = \{1,\ 2\}$	$[\mathcal{S}_B^{(1)}\ \ \mathcal{S}_B^{(2)}\ \ \mathcal{S}_A^{(1)}\ \ \mathcal{S}_A^{(2)}]^\mathsf{T}$
[1 1]	$\mathcal{I}_A = \{1,\ 4\}, \mathcal{I}_B = \{2,\ 3\}$	$[\mathcal{S}_A^{(1)}\ \ \mathcal{S}_B^{(1)}\ \ \mathcal{S}_B^{(2)}\ \ \mathcal{S}_A^{(2)}]^\mathsf{T}$

At the receiver, ML detection requires joint detection of each DM-OFDM block based on the received signals, similar to the process in the OFDM-IM system. The ML detection rule for estimating the transmitted vector in the g-th block can be formulated as:

$$\hat{\mathbf{x}}^{(g)} = \underset{\mathbf{x}^{(g)} \in \{\mathcal{S}_\mathcal{A} \cup \mathcal{S}_\mathcal{B}\}^N}{\operatorname{argmin}} \, \|\mathbf{y}^{(g)} - \mathbf{h}^{(g)}\mathbf{x}^{(g)}\|^2, \quad \forall g \in \{1, \ldots, G\}. \tag{6}$$

In the estimate of transmitted vector $\mathbf{x}^{(g)}$, there are N_A symbols from $\mathcal{S}_\mathcal{A}$ and N_B symbols from $\mathcal{S}_\mathcal{B}$.

IV. NUMERICAL RESULTS

In this section, we use simulations to evaluate the BERs of the baseline systems, OFDM and OFDM-IM, under jamming attacks, and compare them to the newly implemented DM-OFDM. We assume a frequency-selective Rayleigh fading

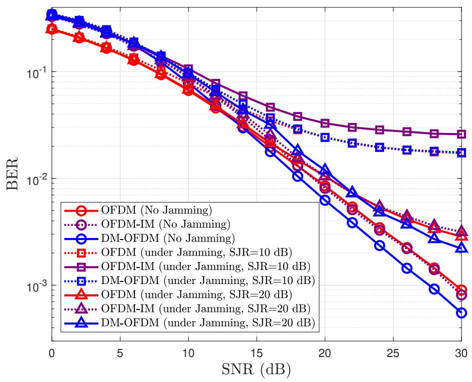

Fig. 1. BER comparison of the OFDM, OFDM-IM, and DM-OFDM systems with and without the jamming attack.

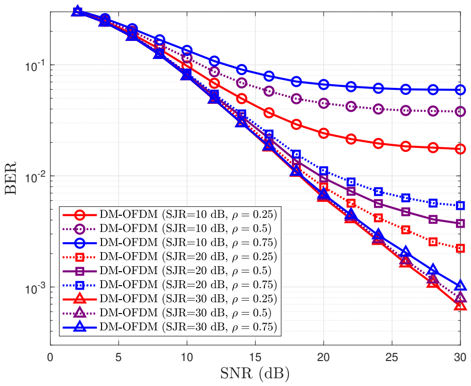

Fig. 2. BER comparison of the DM-OFDM system under the jamming attack with different parameters.

channel with perfect channel estimation. The SNR is defined as SNR $= \frac{1}{\sigma_w^2}$, and the signal-to-jamming ratio (SJR) is defined as SJR $= \frac{1}{\sigma_z^2}$. We consider a random jamming pattern in which, during each time slot, the jamming signal randomly affects a number of $\|\mathbf{c}^{(g)}\|_0$ subcarriers out of the N available subcarriers in each block. Additionally, the ratio of jammed subcarriers to the total number of subcarriers in the block is denoted by ρ, which is calculated as $\rho = \frac{\|\mathbf{c}^{(g)}\|_0}{N}$.

We consider a scenario where $p = 10$ information bits are mapped to a block with $N = 4$ subcarriers. Given $N = 4$, each OFDM symbol consists of 256 blocks, utilizing a total of $K = 1024$ subcarriers for data transmission. In the OFDM system, the first two subcarriers of the $N = 4$ block are modulated using $M = 2$ (i.e., QPSK), while the remaining two subcarriers are modulated using $M = 3$ (i.e., 8-QAM) to maintain comparable spectral efficiency (SE = 2.5 bps/Hz) across all systems being compared. For the OFDM-IM system, we set $p_1 = p_2 = 2$, $N_A = 2$, and use $M = 4$ (i.e., 16-QAM). In the DM-OFDM system, we also set $p_1 = p_2 = 2$, $N_A = N_B = 4$, and define the constellation sets as $\mathcal{S}_A = a \times \{-1-j, 1-j, 1+j, -1+j\}$ and $\mathcal{S}_B = a \times \{1+\sqrt{3}, (1+\sqrt{3})j, -1-\sqrt{3}, -(1+\sqrt{3})j\}$, with $a = (3+\sqrt{3})^{-\frac{1}{2}}$ as a normalization factor.

In Fig. 1, we compare the BERs of the OFDM, OFDM-IM, and DM-OFDM systems with and without the jamming attack ($\rho = 0.25$). Fig. 1 shows that the DM-OFDM system outperforms the OFDM and OFDM-IM systems when the SNR exceeds 15 dB. However, under jamming, the performance gap between the DM-OFDM and the baseline systems diminishes as the SJR decreases (i.e., as the jamming power increases). This is because, in the DM-OFDM system, it becomes challenging not only to detect the correct symbol on the affected subcarrier but also to accurately identify the two index subsets. We note that the DM-OFDM system is more robust than the OFDM-IM system, which also needs to identify the indices of the active signals. In contrast, in the OFDM system, the jamming signal on a specific subcarrier only disrupts the single modulated symbol transmitted on that subcarrier, without affecting the others.

In Fig. 2, we compare the BERs of the DM-OFDM system under jamming attacks with different values of ρ, the ratio of ajmmed subcarriers. The results demonstrate that, as intuitively expected, the DM-OFDM system shows robustness when a small number of subcarriers are jammed. We note that the BER gap increases as the SJR decreases, indicating the system's sensitivity to more severe jamming attacks. This implies that although the DM-OFDM system effectively handles scenarios with limited jamming, its performance degrades more noticeably as the intensity of the jamming attack increases.

V. CONCLUSION

In this paper, we investiaged the robusteness of the DM-OFDM system under jamming attacks in comparison to the traditional OFDM and OFDM-IM systems. Our key finding is that while the DM-OFDM system demonstrates strong performance under limited jamming, particularly at a high SNR region, its advantage over the baseline systems diminishes as the intensity of the jamming attack increases. Nevertheless, the DM-OFDM system continues to demonstrate robustness under jamming attacks when the impact is confined to a small subset of subcarriers.

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