LDPC Coded OFDM-IM Performance Evaluation Under Jamming Attack

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***Abstract*—Orthogonal frequency division multiplexing (OFDM) with index modulation (OFDM-IM) that carries part of the incoming bits by active subcarrier indices is a recently proposed multicarrier modulation technique. OFDM-IM is considered as a promising candidate for 5G and beyond, due to its superiority over OFDM. In this paper, we show that uncoded OFDM-IM can achieve better error performance than uncoded OFDM in the presence of barrage jamming (BJ). Low-density parity-check (LDPC) coding is used to further improve the robustness of OFDM-IM system against jamming attacks. We investigate the optimum log-likelihood ratio (LLR) values of index bits and modulation bits under a jamming attack. We also show the superior performance of coded OFDM-IM, when compared to classical OFDM, at a high code rate in the presence of BJ. We propose a new model for partial band jamming (PBJ) that can attack each subcarrier with different power by adjusting the jamming coefficients. Simulation results show that OFDM-IM is more robust against PBJ than BJ.**

***Index Terms*—Index modulation, jamming, log-likelihood ratio (LLR), low-density parity-check (LDPC), orthogonal frequency division multiplexing (OFDM), performance analysis.**

I. INTRODUCTION

The deployment of 5G network is in progress and the number of devices that consume high data rates will continue to increase. According to The International Telecommunication Union (ITU) forecast, data traffic will increase approximately $\%55$ annually and reach 5,016 exabytes (EB) per month in 2030 [1]. In the recent years, to meet the high data rate requirements, orthogonal frequency division multiplexing (OFDM) has been widely used by Wi-Fi, LTE, and 5G new radio (NR). OFDM is resilient to inter symbol interference (ISI) which occurs in frequency selective channels, so simpler channel equalization can be used. OFDM is also easy to be implemented due to the use of fast Fourier transform (FFT) block.

Recently, OFDM with index modulation (OFDM-IM) has been proposed and attracted significant attention in academia. OFDM-IM uses spatial modulation (SM) principle over its subcarriers and unlike the classical OFDM, OFDM-IM conveys information bits not only with M-ary constellation symbols but also with the active subcarrier indices [2]–[4]. In [5], subcarrier-level interleaver is used to improve the OFDM-IM performance by enhancing the Euclidean distances among possible transmitted symbols. Due to the use of interleaver and active subcarrier indices to carry information, OFDM-IM has a superior error performance compared to OFDM under the same spectral efficiency. OFDM-IM also offers a trade-off between the spectral efficiency and energy efficiency in comparison to the classical OFDM. These advantages make OFDM-IM a promising candidate for the 5G and beyond wireless communication [6].

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A wireless communication channel and protocols are open and accessible to illegitimate communication nodes. As a result, adversaries can learn network parameters and modify their signal to degrade the performance of a system severely [7]. With the deployment of 5G and beyond wireless communication technologies, the number of decentralized networks and Internet of Things (IoT) applications will increase and classical upper layer cryptographic algorithms are complex and challenging to implement for IoT due to the use of simple hardware and limited computational capacities. Security, secrecy, and privacy will also be the vital parameters in 6G network with the development of critical human-centric applications [8]. Therefore, wireless communication should be durable against physical layer attacks such as eavesdropping and jamming. Physical layer security (PLS) can be used as a complement to classical cryptographic algorithms and improve the system performance. Also, channel coding can be used to increase the bit error rate (BER) performance of a system effectively in the presence of jamming attack. Low-density parity-check (LDPC) codes are used in 5G as an enhanced mobile broadband (eMBB) data channel coding technique [9] and can be used to improve the robustness of OFDM-IM system against jamming attacks. While OFDM is resistant to ISI, it is vulnerable to jamming attacks. OFDM-IM has superiority when compared to OFDM in terms of BER performance for both uncoded and coded systems with high code rate, i.e. high spectral efficiency due to the inherently sparse nature of index modulation.

In [10]–[13], the performance of uncoded OFDM system has been studied in the presence of barrage jamming (BJ) which is the simplest jamming attack type. The performance of uncoded OFDM system has been also investigated under partial band jamming (PBJ) in [11], [13]–[16]. In [17], the resiliency of uncoded OFDM system is studied under noise jamming attacks, energy-efficient smart jammer attacks that can explore network parameters to modify jamming signal and disrupt communication effectively such as pilot jamming and control channel attacks. For example, in LTE, smart jammers

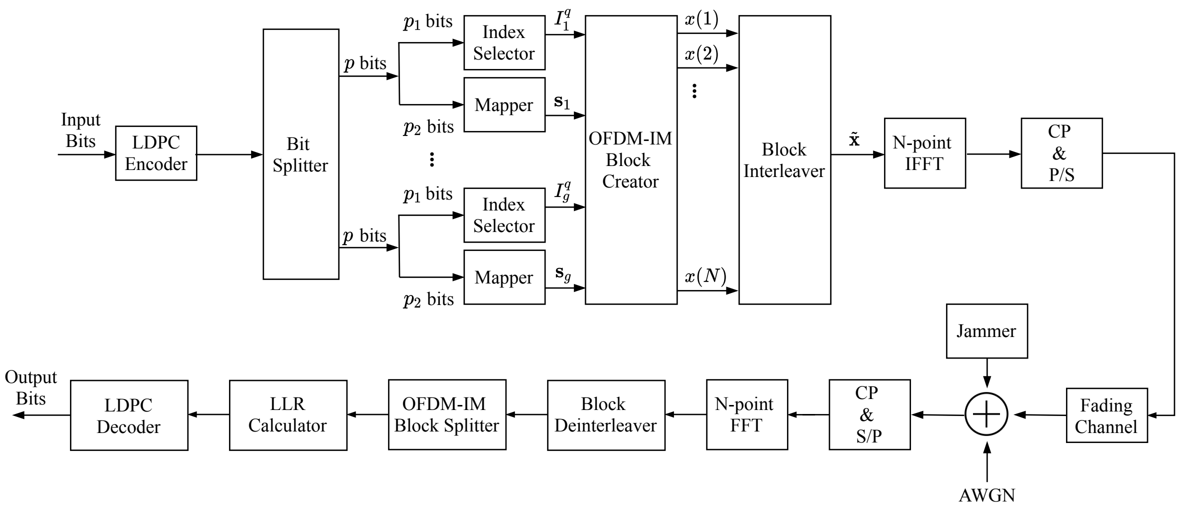

Fig. 1. Block diagram of LDPC Coded OFDM-IM transceiver in the presence of jamming attack.

can degrade the performance of the system by attacking specific signals or channels such as physical uplink control channel (PUCCH) that is conveyed in pre-determined subcarriers on the frame. In [18] and [19], the performance of LDPC coded OFDM has been investigated under a jamming attack. But, there are limited papers on this topic. In [18], the simple and robust receiver algorithms are proposed for channel estimation and decoding with imperfect channel estimation in the presence of PBJ attack. In [19], the securely precoded OFDM has been proposed for reliable communication under the smart jammer.

LDPC coded OFDM-IM system has been investigated in [20]–[22]. In [21], the joint phase-noise estimation and decoding algorithms are proposed for the LDPC coded OFDM-IM system in the presence of phase noise. In [20] and [22], sub-optimum log-likelihood ratio (LLR) values are used in the LDPC decoder. In [23], the optimum LLR calculation algorithm is given for OFDM-IM. But there is a gap in LDPC coded OFDM-IM researches and no paper deals with coded OFDM-IM under jamming attack in the literature. To the best of our knowledge, this is the first work that examines the performance of LDPC coded OFDM-IM in the presence of jamming attack. Our major contributions can be summarized as follows:

- We analyze and compare the performance of uncoded OFDM and uncoded OFDM-IM with different configuration in the presence of jamming attack. We verify that OFDM-IM has superiority in terms of BER performance when compared to OFDM under BJ.
- We use LDPC codes to improve the robustness of OFDM-IM system against jamming attacks and investigate the optimum LLR value for OFDM-IM under a jamming attack. The performance of LPDC coded OFDM-IM and OFDM systems are compared using computer simulations in different coding rates. We verify that coded OFDM-IM is more robust to BJ than coded OFDM at high data rates.
- Due to the effectiveness of a smart jammer, we propose a possible smart PBJ model that can attack each subcarrier with different power. We show that coded OFDM-IM is more resistant to PBJ compared to BJ.

The remainder of this paper is organized as follows. LDPC coded OFDM-IM system model and jamming attack types are discussed in Section II. In Section III, the optimum LLR calculation algorithm is introduced. Simulation results of performance are given in Section IV. Finally, Section V concludes the paper.

II. LDPC Coded OFDM-IM System Model

In this section, we present the block diagram of LDPC coded OFDM-IM system under a jamming attack in Fig. 1 and discuss the BJ and PBJ attacks. We also propose a new PBJ model and in this model, the jamming power distribution can be easily changed using jamming coefficients.

A. LDPC Coded OFDM-IM

The transmitter conveys m coded bits in each LDPC coded OFDM-IM block on frequency selective Rayleigh fading channel. The information bits enter the LDPC encoder to generate coded bits. In the bit splitter, each m coded bits are divided into g groups each containing $p = p_1 + p_2$ bits, i.e. $m = gp$. The coded bits in each group are mapped to an OFDM-IM subblock of length $n = N/g$, where n and N are the number of subcarriers in a subblock and an OFDM-IM block, respectively. In each subblock, the index selector decides k active subcarriers out of n subcarriers based on a look-up table using first $p_1 = \lfloor \log_2(C(n,k)) \rfloor$ index bits of p bits, where $C(n,k)$ is the binomial coefficient and $\lfloor \cdot \rfloor$ is the floor function. The total number of active indices combinations (AICs) is $C(n,k)$ and the index selector uses only 2^{p_1} legal AICs. The mapper determines modulated symbols that are transmitted on the active subcarriers using the remaining $p_2 = k \log_2 M$ modulation bits, where M is the modulation order. Briefly, unlike the classical OFDM, coded bits are not only conveyed using modulated symbols but also by means of active subcarrier indices. Due to the use of subcarrier indices to convey bits, OFDM-IM has enhanced distance spectrum, i.e. improved Euclidean distance between possible sequences of subblocks [2]. A look-up table example for $n = 4, k = 2$ is presented in Table 1 and it is clear

TABLE I

A LOOK-UP TABLE FOR $(n, k) = (4, 2)$

p_1−bits	Active Indices Combinations (I_β^q)	OFDM-IM Subblocks
[0 0]	I_β^1 ={1, 2}	$[s_{\beta,1}\ s_{\beta,2}\ 0\ 0]^T$
[0 1]	I_β^2 ={2, 3}	$[0\ s_{\beta,2}\ s_{\beta,3}\ 0]^T$
[1 0]	I_β^3 ={3, 4}	$[0\ 0\ s_{\beta,3}\ s_{\beta,4}]^T$
[1 1]	I_β^4 ={1, 4}	$[s_{\beta,1}\ 0\ 0\ s_{\beta,4}]^T$

from Table 1 that OFDM-IM has enhanced distance spectrum in comparison to classical OFDM.

The output of the β-th index selector is given by $I_\beta^q = \{i_1, \dots, i_k\}$, where $\beta = 1, 2, \dots, g$, $q \in \{1, \dots, 2^{p_1}\}$, $i_\gamma \in \{1, \dots, n\}$ for $\gamma = 1, 2, \dots, k$, and $i_{\gamma_1} \neq i_{\gamma_2}$ if $\gamma_1 \neq \gamma_2$. Here, we omit the subscript β for the elements of I_β^q for brevity. The total number of coded bits transmitted in each OFDM-IM block is given by $m = m_1 + m_2$, where $m_1 = p_1 g = \lfloor \log_2(C(n,k)) \rfloor g$ is the total number of index bits carried by the positions of the active subcarriers and $m_2 = p_2 g = k(\log_2(M))g$ is the total number of information bits carried by the M-ary constellation symbols. $K = kg$ denotes the total number of active subcarriers in each OFDM-IM block. The vector at the output of the mapper containing k modulated symbols is given by

$$\mathbf{s}_\beta = [s_{\beta,i_1} \dots s_{\beta,i_k}], \tag{1}$$

where $s_{\beta,i_\gamma} \in \mathcal{S}$, $\gamma = 1, 2, \dots, k$, and $\mathcal{S}$ denotes the signal constellation which is normalized to unit average power by selecting $E\{\mathbf{s}_\beta \mathbf{s}_\beta^H\} = k$, where $(\cdot)^H$ denotes Hermitian transposition.

The OFDM-IM block creator generates subblocks using I_β^q and $\mathbf{s}_\beta$ for all β and the frequency-domain OFDM-IM block is produced by concatenating the g subblocks as $\mathbf{x} = [x(1)\ x(2) \dots x(N)]^T = [\mathbf{x}_1^T\ \mathbf{x}_2^T \cdots \mathbf{x}_g^T]^T$ where $x(\alpha) \in \{0, \mathcal{S}\}$, $\alpha = 1, \dots, N$ and $(\cdot)^T$ stands for transposition. The channel coefficients of the subcarriers of β-th subblock are correlated and the $g \times n$ block interleaver is used to convey subcarriers of β-th subblock through uncorrelated channels. In the block interleaver, the elements of $\mathbf{x}$ are written along the rows of a $g \times n$ matrix, and then the $g \times n$ matrix is read out along the columns to generate the block interleaved OFDM-IM signal as $\tilde{\mathbf{x}} = [\tilde{x}(1)\ \tilde{x}(2) \dots \tilde{x}(N)]^T$. Then, N-point IFFT is applied to $\tilde{\mathbf{x}}$ to produce time domain OFDM-IM block $\tilde{\mathbf{x}}_T = \frac{N}{\sqrt{K}} IFFT\{\tilde{\mathbf{x}}\} = \frac{1}{\sqrt{K}} \mathbf{W}_N^H \tilde{\mathbf{x}} = [\tilde{X}(1)\ \tilde{X}(2) \dots \tilde{X}(N)]^T$, where $\mathbf{W}_N$ is the discrete Fourier transform (DFT) matrix with $\mathbf{W}_N^H \mathbf{W} = N\mathbf{I}_N$. Here, $\mathbf{I}_N$ is the $N \times N$ identity matrix. The condition $E\{\mathbf{x}_T^H \mathbf{x}_T\} = N$ is satisfied due to the use of normalization factor $\frac{N}{\sqrt{K}}$. After the addition of a cyclic prefix (CP) of length N_{CP}, parallel to serial (P/S) and digital to analog conversions, the OFDM-IM signal is transmitted through a L-tap frequency selective Rayleigh fading channel which has $\mathcal{CN}(0, \frac{1}{L})$ circularly symmetric complex Gaussian distributed elements. It is assumed the wireless channel does not change throughout an OFDM-IM block and CP length N_{CP} is larger than L. In the presence of jamming attack, at the receiver, the frequency domain input-output relationship after cyclic prefix removing, analog to digital and serial to parallel conversion and FFT operation can be modeled as

$$\tilde{y}(\alpha) = \tilde{x}(\alpha)h(\alpha) + w(\alpha) + d(\alpha)j(\alpha), \tag{2}$$

where $\alpha = 1, \dots, N$ and $\tilde{y}(\alpha), h(\alpha), w(\alpha), d(\alpha)$ and $j(\alpha)$ are received signal, channel frequency response, circularly symmetric complex Gaussian noise, jamming coefficient and base jamming signal in the frequency domain, respectively. $d(\alpha)j(\alpha)$ corresponds to the jamming signal. Here, jamming type can be changed by means of jamming coefficients. The jamming signal is added directly to the received signal, and this approach is common in the literature [24], [25]. $h(\alpha), w(\alpha)$, and $j(\alpha)$ follow circularly symmetric complex Gaussian distributions $\mathcal{CN}(0,1)$, $\mathcal{CN}(0, N_{0,F})$ and $\mathcal{CN}(0, N_{J,F})$, respectively and $N_{J,F}$ is the variance of the frequency domain base jamming signal $j(\alpha)$, while $N_{0,F}$ is the noise variance in frequency domain. $N_{0,F}$ is related with the noise variance in the time domain, denoted as $N_{0,T}$, via $N_{0,F} = (K/N)N_{0,T}$.

The frequency domain output of the block deinterleaver can be written as

$$y(\alpha) = x(\alpha)\breve{h}(\alpha) + \breve{w}(\alpha) + \breve{d}(\alpha)\breve{j}(\alpha), \tag{3}$$

where $\breve{h}(\alpha), \breve{w}(\alpha), \breve{d}(\alpha)$ and $\breve{j}(\alpha)$ denote deinterleaved versions of $h(\alpha), w(\alpha), d(\alpha)$ and $j(\alpha)$, respectively. At the OFDM-IM block splitter, the signal divided into subblocks and the LLR calculator block determines the LLR values of coded index and modulation bits in each subblock. $y(\alpha), \breve{h}(\alpha), \breve{w}(\alpha), \breve{d}(\alpha)$ and $\breve{j}(\alpha)$ can be represented with vectors $\mathbf{y}, \breve{\mathbf{h}}, \breve{\mathbf{w}}, \breve{\mathbf{d}}$ and $\breve{\mathbf{j}}$, respectively, as $\mathbf{y} = [\mathbf{y}_1^T\ \mathbf{y}_2^T \cdots \mathbf{y}_g^T]^T$, $\breve{\mathbf{h}} = [\breve{\mathbf{h}}_1^T\ \breve{\mathbf{h}}_2^T \cdots \breve{\mathbf{h}}_g^T]^T$, $\breve{\mathbf{w}} = [\breve{\mathbf{w}}_1^T\ \breve{\mathbf{w}}_2^T \cdots \breve{\mathbf{w}}_g^T]^T$, $\breve{\mathbf{d}} = [\breve{\mathbf{d}}_1^T\ \breve{\mathbf{d}}_2^T \cdots \breve{\mathbf{d}}_g^T]^T$ and $\breve{\mathbf{j}} = [\breve{\mathbf{j}}_1^T\ \breve{\mathbf{j}}_2^T \cdots \breve{\mathbf{j}}_g^T]^T$. After that, (3) can be rewritten for the β-th subblock in the frequency domain as

$$\mathbf{y}_\beta = \mathbf{X}_\beta \breve{\mathbf{h}}_\beta + \breve{\mathbf{w}}_\beta + \breve{\mathbf{D}}_\beta \breve{\mathbf{j}}_\beta \tag{4}$$

where $\mathbf{X}_\beta = \mathrm{diag}(\mathbf{x}_\beta)$ and $\breve{\mathbf{D}}_\beta = \mathrm{diag}(\breve{\mathbf{d}}_\beta)$. $\mathbf{x}_\beta = [x_\beta(1)\ \ x_\beta(2) \dots x_\beta(n)]$ denotes the β-th subblock, where $x_\beta(u)$ is given by $(u = 1, \dots, n)$

$$x_\beta(u) = \begin{cases} s_{\beta,u}, & u \in I_\beta^q \\ 0, & u \notin I_\beta^q \end{cases}. \tag{5}$$

The iterative LDPC decoder decides input bits by means of the LLRs.

B. Jamming Attack Types

The jamming signal disturbs the received signal similar to the additive Gaussian noise and increases the noise floor. For BJ and PBJ, we examine jamming coefficients. We define the ratio of jamming to signal bandwidth as

$$\rho = \frac{d_c}{N}, \tag{6}$$

where d_c is the total number of nonzero $d(\alpha)$ values, $\alpha = 1, \dots, N$ for an OFDM-IM block.

1) Barrage Jamming: In the presence of BJ, which is the simplest jamming attack type, the jammer power is distributed uniformly through the whole frequency bandwidth of OFDM-IM subcarriers and the total Gaussian noise variance that disrupts received signal in the frequency domain becomes $N_{J,F} + N_{0,F}$. The relation between jamming variance in the time domain denoted as $N_{J,T}$, and the frequency domain is expressed as

$$N_{J,F} = \frac{K}{N} N_{J,T}. \tag{7}$$

In BJ, all the jamming coefficients are selected 1, i.e., $d(\alpha) = 1$ for $\alpha = 1, \dots, N$ and $\rho = 1$.

2) Partial Band Jamming: We propose a new model for PBJ that can attack to each subcarrier with different power by selecting the number of d_c jamming coefficients that are real numbers and $d(\alpha) \geq 0$ independently. As a result, jammer power is distributed non-uniformly over a portion of the total frequency band of the OFDM-IM subcarriers and the received OFDM-IM signal has two frequency bands that are jammed and unjammed at the receiver. In the presence of PBJ, $\mathbf{d}$ satisfies the power constraint $||\mathbf{d}||^2 = N\rho$ to keep the average jammer power constant, where $0 < \rho \leq 1$ and the relation between $N_{J,T}$ and $N_{J,F}$ is given by

$$N_{J,F} = \frac{K}{N\rho} N_{J,T}. \tag{8}$$

III. LLR Calculation Algorithm

The LLR calculator provides the logarithm of the ratio of the a posteriori probabilities for both the index bits and modulation bits. Due to the dependence of subcarriers within a subblock, the LLR values of p bits that are transmitted with a subblock are calculated using the all received signals in a subblock [23]. The set of all legal AICs is given by $I_\beta = \{I_\beta^1, I_\beta^2, \dots, I_\beta^{2^{p_1}}\}$. We define $I_\beta^{l,0}$ and $I_\beta^{l,1}$ as the sets of elements that transmit 0 and 1 as the l-th index bit, respectively, where $l = 1, \dots, p_1$. Legal AICs are shown for $n = 4, k = 2$ in Table 1 and the sets of elements that transmit 0 and 1 as the first index bit are $I_\beta^{1,0} = \{I_\beta^1, I_\beta^2\}$ and $I_\beta^{1,1} = \{I_\beta^3, I_\beta^4\}$, respectively. We define $\mathcal{S}^k$ as the set of all possible $\mathbf{s}_\beta$ in equation (1). $\mathcal{S}_{v,0}^k$ and $\mathcal{S}_{v,1}^k$ that are the subsets of $\mathcal{S}^k$ indicate the set of elements that transmits 0 and 1 as the v-th modulation bit, respectively.

We assume that all possible transmitted vectors in a subblock have the same a priori probabilities. As a result, the a posteriori probabilities calculations can be simplified by omitting the a priori probabilities. The a posteriori probability of l-th bit within p_1 index bits that are transmitted in β-th subblock, $b_\beta^{I,l}$, is given by

$$p\left(b_\beta^{I,l} = \lambda | \mathbf{y}_\beta\right) \propto \sum_{\mathbf{x}_\beta \in I_\beta^{l,\lambda}} \sum_{\mathbf{s}_\beta \in \mathcal{S}^k} p(\mathbf{y}_\beta | \mathbf{x}_\beta), \tag{9}$$

where $\lambda = 0, 1$ and $l = 1, \cdots, p_1$. All subcarriers are orthogonal to each other in a subblock [23]. As a result, $p(\mathbf{y}_\beta | \mathbf{x}_\beta)$ is calculated as

$$p(\mathbf{y}_\beta | \mathbf{x}_\beta) = \prod_{u=1}^{n} p\left(y_\beta(u) | x_\beta(u)\right). \tag{10}$$

The likelihood probability of u-th subcarrier in the β-th subblock is calculated as

$$p\left(y_\beta(u) | x_\beta(u)\right) = \frac{1}{\pi(\check{d}_\beta^2(u) N_{J,F} + N_{0,F})} \exp\left(-\frac{\left|y_\beta(u) - \check{h}_\beta(u) x_\beta(u)\right|^2}{\check{d}_\beta^2(u) N_{J,F} + N_{0,F}}\right), \tag{11}$$

where $u = 1, \dots, n$ and, $y_\beta(u), x_\beta(u), \check{d}_\beta(u)$,and $\check{h}_\beta(u)$ are the u-th element of $\mathbf{y}_\beta, \mathbf{x}_\beta, \check{\mathbf{d}}_\beta$, and $\check{\mathbf{h}}_\beta$, respectively. $(\check{d}_\beta^2(u) N_{J,F} + N_{0,F})$ is the summation of the variances of jamming signal and Gaussian noise that effect the u-th subcarrier in the β-th subblock. The LLR value of $b_\beta^{I,l}$ is given as

$$L\left(b_\beta^{I,l}\right) = \ln \frac{p\left(b_\beta^{I,l} = 0 | \mathbf{y}_\beta\right)}{p\left(b_\beta^{I,l} = 1 | \mathbf{y}_\beta\right)}. \tag{12}$$

The active indices are not known at the receiver, so all possible AICs are taken into account to calculate the LLR values of modulation bits. Similar to (9), the a posteriori probability of v-th bit within p_2 modulation bits that are transmitted in β-th subblock, $b_\beta^{S,v}$, is obtained as [23]

$$p\left(b_\beta^{S,v} = \lambda | \mathbf{y}_\beta\right) \propto \sum_{\mathbf{x}_\beta \in I_\beta} \sum_{\mathbf{s}_\beta \in \mathcal{S}_{v,\lambda}^k} p(\mathbf{y}_\beta | \mathbf{x}_\beta), \tag{13}$$

where $\lambda = 0, 1$ and $v = 1, \cdots, p_2$. The LLR value of $b_\beta^{S,v}$ is given by

$$L\left(b_\beta^{S,v}\right) = \ln \frac{p\left(b_\beta^{S,v} = 0 | \mathbf{y}_\beta\right)}{p\left(b_\beta^{S,v} = 1 | \mathbf{y}_\beta\right)}. \tag{14}$$

IV. Numerical Results

In this section, simulation results are presented for both LDPC coded and uncoded OFDM-IM and OFDM systems with BPSK modulation under the Rayleigh fading channel in the presence of BJ and PBJ. In all simulations we use the following parameters: $N = 128, N_{CP} = 16$, and $L = 10$. Spectral efficiency of the coded OFDM-IM system is $\eta = mR/(N + N_{CP})$ bit/sn/Hz, where R denotes the code rate and for a fair comparison, we take spectral efficiency of the OFDM-IM and OFDM system the same. We define SNR as $E_b/N_{0,T}$ where $E_b = (N + N_{CP})/(mR)$ [joules/bit] is the average transmitted energy per bit. We define signal-to-jamming ratio (SJR) as $E_b/N_{J,T}$, where $N_{J,T}$ is the variance of the base jamming signal in the time domain. In the presence of BJ, all the jamming coefficients are selected 1. Irregular $(2304, 1152)$ LDPC code of rate $1/2$ and $(576, 432)$ LDPC code of rate $3/4$ based on WiMAX standard are used to analyze the BER performance in the presence of jamming attack. In the LDPC decoder, iterative Log-SPA (logarithmic sum product algorithm) is used and the maximum number of iterations is set to 50.

In Fig. 2, we compare the performance of uncoded OFDM, $n = 4, k = 2$ OFDM-IM and $n = 2, k = 1$ OFDM-IM schemes in the presence of BJ with different SJR values. As

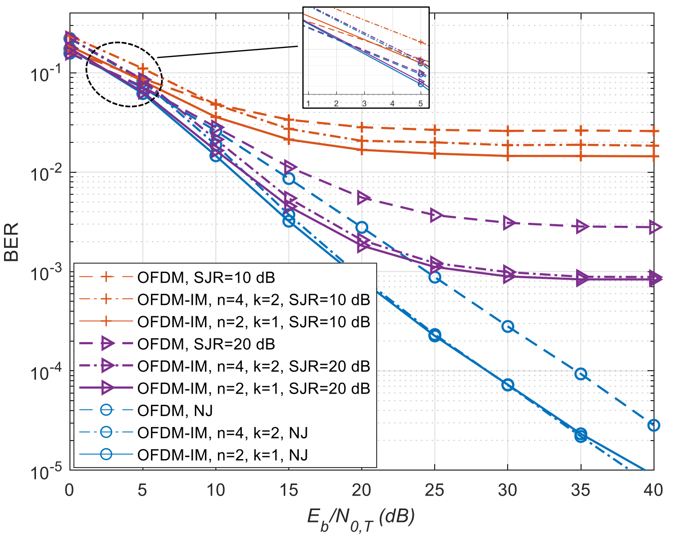

Fig. 2. Comparison of BER performance of uncoded OFDM and OFDM-IM with different parameters under BJ ($\eta = 0.88$ bit/sn/Hz).

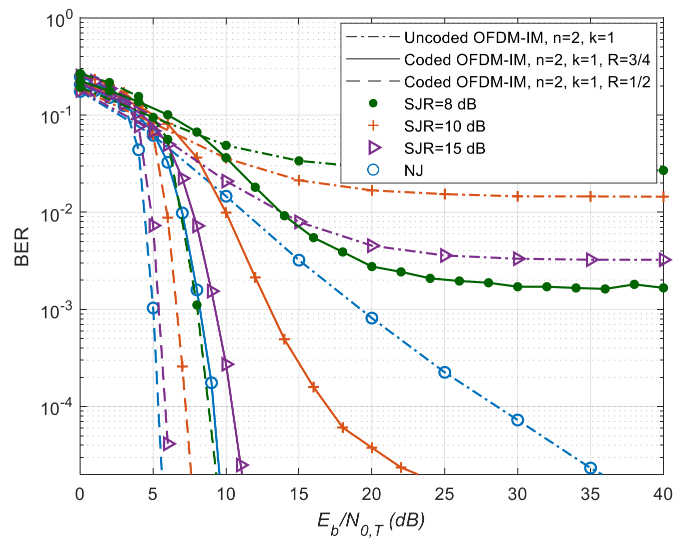

Fig. 3. Comparison of BER performance of uncoded and LDPC coded OFDM-IM with different code rates under BJ.

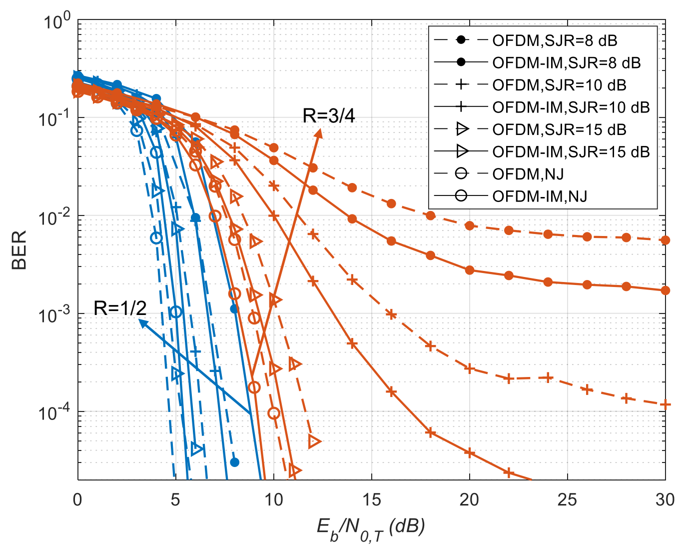

Fig. 4. Comparison of BER performance of LDPC coded OFDM-IM and OFDM with different code rates in the presence of BJ.

seen from Fig. 2, at a BER value 10^{-3} without jamming attack, the two OFDM-IM schemes achieve approximately 5 dB better BER performance than OFDM, due to their enhanced distance spectrum. The two OFDM-IM schemes are also more resistant to the BJ attack compared to OFDM. But, both in the presence of BJ with SJR $=$ 20 dB and in the absence of jamming attack, OFDM has better BER performance than $n = 2, k = 1$ OFDM-IM scheme when SNR is lower than approximately 2 dB. In Fig. 2, in the low and mid SNR regions, OFDM-IM with $n = 2, k = 1$ outperforms OFDM-IM with $n = 4, k = 2$ in terms of BER performance when there is no jamming attack due to the effect of dense distance spectrum of $n = 4, k = 2$ OFDM-IM scheme. The performance of uncoded system at low SNR region is critical when coding is applied due to coding gain. Therefore, we configure parameters of LDPC coded OFDM-IM as $n = 2$ and $k = 1$ in the following figures.

In Fig. 3, in the presence of BJ attack, we choose $n = 2, k = 1$ and compare the BER performance of uncoded OFDM-IM, $R = 1/2$ and $R = 3/4$ LDPC coded OFDM-IM systems that have 0.88, 0.44 and 0.66 bit/sn/Hz spectral efficiency values, respectively. Both $R = 1/2$ and $R = 3/4$ coded systems show superiority in BER performance compared to uncoded system with and without jamming attack. At SJR $=$ 10 dB, coded systems have considerable better BER performance than uncoded system that has an error floor at BER $=$ 0.014. $R = 1/2$ coded system also achieves nearly 6.5 dB better BER performance than $R = 3/4$ coded system by reducing its spectral efficiency.

Fig. 4 shows a comparison of the BER performance of LDPC coded OFDM and OFDM-IM with $n = 2, k = 1$. $R = 1/2$ and $R = 3/4$ coded systems have 0.44 and 0.66 bit/sn/Hz spectral efficiency values, respectively. As seen from Fig. 4, the rate $1/2$ LDPC code is more resilient against jamming attacks than the rate $3/4$ LDPC code. However, the rate $3/4$ LDPC code has higher spectral efficiency and can be more suitable for high-speed wireless communication. It can also compensate disruptive jamming impact on the OFDM-IM system effectively at SJR $=$ 10 or over. In Fig. 4, OFDM has better performance than OFDM-IM when LDPC code of rate 1/2 is used. On the other hand, OFDM-IM outperforms OFDM in terms of BER when LDPC code of rate 3/4 is used. As an example, at a BER value 10^{-3} with SJR $=$ 10 dB, OFDM with $R = 1/2$ performs almost 0.9 dB better BER performance than OFDM-IM with $R = 1/2$, while OFDM-IM with $R = 3/4$ achieves approximately 3 dB better BER performance than OFDM with $R = 3/4$.

In Fig. 5, we compare BJ and PBJ ($\rho = 0.5$) impacts on the performance of LDPC coded OFDM-IM with $n = 2, k = 1$, and $R = 3/4$. We discuss two different PBJ scenarios as Scenario 1 (S1) and Scenario 2 (S2). We select the $d(\alpha)$ values as $d(1) = d(2) = ... = d(64) = 1$, $d(65) = d(66) = ... = d(128) = 0$ in S1, while $d(1) = d(2) = ... = d(32) = \sqrt{2/3}$, $d(33) = d(34) = ... = d(64) = \sqrt{4/3}$, $d(65) = d(66) = ... = d(128) = 0$ in S2. For a fair comparison we select the

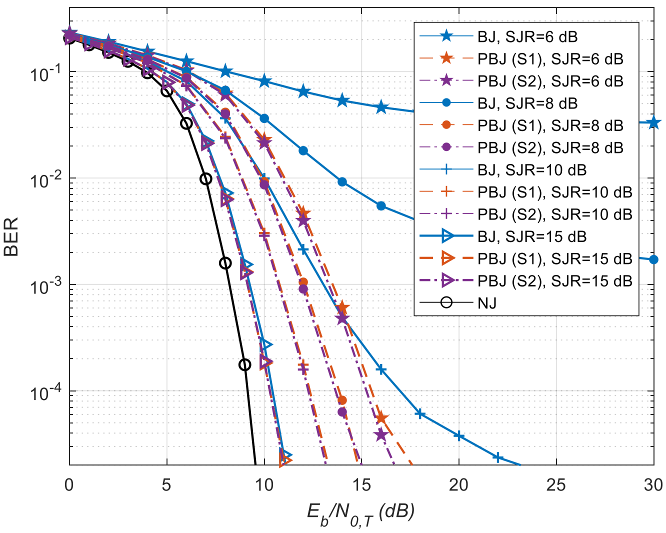

Fig. 5. BJ and PBJ ($\rho = 0.5$) impacts on the performance of LDPC coded OFDM-IM ($R = 3/4, \eta = 0.66$ bit/sn/Hz).

same average BJ and PBJs powers, i.e. $N_{J,T}$ is the same for the BJ and PBJs and PBJs satisfy the $||\mathbf{d}||^2 = N\rho$ condition. From this figure, we can observe that the LDPC coded OFDM-IM scheme is more robust against PBJs compared to BJ especially when SJR is low, i.e jamming power is high. This is observed because in iterative decoding algorithm, Log-SPA, unjammed subcarriers affect all LLR values and increase BER performance. BJ is also capable to affect BER performance of the OFDM-IM system more than PBJs despite distributed jamming power due to low SJR value. The BER performance of S1 and S2 are also nearly the same.

V. Conclusion

In this paper, we analyze the performance of uncoded and LDPC coded OFDM-IM systems and compare these systems to coded and uncoded OFDM in terms of BER performance under BJ attack. We show that uncoded OFDM-IM with $n = 2, k = 1$ is more robust to BJ attack than OFDM. Uncoded and coded OFDM-IM systems are also compared to show superior BER performance of coded systems compared to uncoded system with and without jamming attack. We examine the performance of LDPC coded OFDM-IM and OFDM in different coding rates. It has been shown that, in the presence of BJ, OFDM has better performance than OFDM-IM at the low data rate, i.e. low code rate, while OFDM-IM has a significantly better BER performance than OFDM at the high data rate. As a result, coded OFDM-IM is more suitable for applications where high date rates are needed. We have proposed a new model for PBJ that can attack each subcarrier with different power by selecting the jamming coefficient for each subcarrier. We also show that LDPC coded OFDM-IM has superior performance under PBJ and it is more resistant against PBJ than BJ attacks.

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