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High-Dimensional OFDM With In-Phase/ Quadrature Index Modulation

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ABSTRACT In this paper, we propose a new modulation scheme for wireless communications called high-dimensional orthogonal frequency division multiplexing with in-phase/quadrature index modulation (HD-OFDM-IQ-IM). In the proposed scheme, coordinate values of a symbol of the HD signal constellations are separated. A part of the coordinate values of an HD symbol are mapped to the active in-phase component subcarriers and the rest are mapped to the active quadrature component subcarriers in each OFDM subblock. A simple rule to design the HD constellation using the Gray coding and mapping is also presented. The method increases the minimum Euclidean distance between symbols of an HD signal constellation by increasing the Hamming distance of the binary sequences. As the dimension of the constellation increases, more index patterns can be produced, thus improving spectral and energy efficiency of the HD-OFDM-IQ-IM scheme. A feasible selection of subcarrier component active patterns can also produce additional index patterns to enhance spectral efficiency without additional energy consumption. In the receiver, both maximum likelihood (ML) and reduced-complexity log-likelihood ratio (LLR) detection can be exploited. As a result, the proposed scheme has better bit error performance than the conventional OFDM system with IM techniques in the frequency selective Rayleigh fading channel. In particular, it is noted that the bit error rate (BER) in the high signal-to-noise ratio (SNR) region is tightly limited by the upper bound on bit error probability derived in this paper.

INDEX TERMS Index modulation (IM), orthogonal frequency division multiplexing (OFDM), high-dimensional (HD) signal constellation, spectral efficiency, energy efficiency, bit error rate (BER).

I. INTRODUCTION

Recently, index modulation (IM) techniques have been extensively studied for application to the underwater acoustic communications, next-generation wireless networks, and green radio communications [1]–[4].

Inspired by the spatial modulation technique that utilizes the antenna index and the signal constellation to convey information [5], both IM and orthogonal frequency division multiplexing (OFDM) are perfectly combined to improve spectral efficiency, energy efficiency, and system reliability compared to the classical OFDM systems. An early form of the modified OFDM employing IM technique called subcarrier index modulation OFDM (SIM-OFDM) is introduced in [6]. Later, an enhanced SIM-OFDM (ESIM-OFDM) is proposed to overcome the drawback of SIM-OFDM in which the number of active subcarriers in each OFDM block is varied. In this scheme, however, a higher order modulation format should be used to ensure spectral efficiency [7]. To solve the problems in [6] and [7], an OFDM with IM (OFDM-IM) is proposed. Here, all subcarriers in the OFDM block are regularly grouped, and information is transmitted by active subcarriers and index patterns [8]. In addition, an interleaving technique can be used to improve bit error performance in a low signal-to-noise ratio (SNR) region [9].

Two generalized forms of the OFDM-IM named OFDM-GIM1 and OFDM-GIM2 are presented in [10]. Unlike the conventional OFDM-IM scheme, the number of active subcarriers in a subblock is not fixed so that the spectral efficiency can be increased in OFDM-GIM1. In OFDM-GIM2, index modulation is separately performed on the in-phase and the quadrature component subcarriers

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for all OFDM subblocks. In [11], OFDM with hybrid in-phase/quadrature IM (OFDM-HIQ-IM) and linear constellation precoded OFDM-IQ-IM (LP-OFDM-IQ-IM) are proposed to enhance the spectral efficiency and diversity gain. According to the constellation modes, dual-, tri-, and multiple-mode OFDM-IM (called DM-OFDM, ZTM-OFDM-IM, and MM-OFDM-IM, respectively) are recently studied to improve system performance [12]–[15]. Furthermore, the layered OFDM-IM has also been presented in [16], where all subcarriers are divided into multiple layers. In each layer, index modulation and symbol mapping are performed using different signal constellations.

In various existing OFDM systems based on the IM technique, two-dimensional (2D) signal constellations are used for mapping the information bits into subcarriers. Multilevel phase shift keying (MPSK) and M-ary quadrature amplitude modulation (MQAM) are typical examples of those constellations. High-dimensional (HD) signal constellations can also be applied to digital communications, and provide reliable communication performance thanks to the larger minimum Euclidean distance (MED) than the corresponding low-dimensional signal constellations [17]. For example, [18] shows that a 3D-OFDM system significantly outperforms the classical OFDM using 2D constellation as a signal mapper. In the field of optical communications, HD modulation for optical OFDM has also been investigated in [19], where each HD signal vector is mapped to a subcarrier.

Taking advantage of the HD signal constellations and the IM technique, a new modulation scheme, HD OFDM with in-phase/quadrature IM (HD-OFDM-IQ-IM) is proposed in this paper. Here, only one HD symbol is transmitted by an OFDM subblock. We consider an IQ modulation format in which the index domain resource is efficiently used to improve spectral efficiency of the system. A part of the elements of the HD symbol are mapped to active in-phase component subcarriers, and the rest are modulated by active quadrature component subcarriers. For the HD signal constellations, the MEDs between adjacent symbols are enlarged so that error performance of the system can be improved. The number of index bits is also increased with the dimension, which results in enhancement of spectral efficiency. To apply more index activation patterns, a flexible selection of the number of HD symbol elements for the in-phase component and quadrature component mapping can further improve the spectral efficiency.

According to the index patterns, both improved and generalized forms of the HD-OFDM-IQ-IM are proposed as well. Since the spectral efficiency is increased without increasing the transmitted signal power, energy efficiency of the proposed schemes can be improved when the HD symbols are exploited for index modulation. An effective HD signal constellation design method based on the Gray coding and mapping for the proposed schemes is also provided. When a maximum likelihood (ML) detection is employed in the receiver, the theoretical upper bound on bit error probability of the proposed systems in the frequency selective Rayleigh fading channel is derived. In addition, we present a log-likelihood ratio (LLR) detection, which is exploited by various IM systems [20]–[23], to reduce complexity of the HD-OFDM-IQ-IM scheme. According to the simulation results, when all systems have the same spectral efficiency, the proposed HD-OFDM-IQ-IM scheme shows better bit error performance than the classical OFDM, OFDM-IM, and OFDM-GIM2. As the dimension of signal constellation increases, the spectral efficiency and error performance are improved. It is analyzed that the gain of error performance is due to an increase in the number of index bits produced by index modulation using HD symbols and an increase in the MED of the HD constellations.

The main contributions of this paper can be summarized as follows.

- A novel IQ-IM based OFDM system using HD signal constellation is proposed. In the previous OFDM system based on IM, an active complex subcarrier independently carries a 2D MPSK/MQAM symbol, or the real/imaginary part of the active subcarrier is modulated in the form of a pulse amplitude modulation (PAM) symbol. In the proposed scheme, however, the coordinate values of an HD symbol are individually modulated by active in-phase and quadrature component subcarriers. It implies that all active subcarrier components in a subblock are made up of an HD symbol.
- Spectral efficiency, energy efficiency, and bit error performance of the proposed scheme can be improved with increase in the dimension of HD signal constellations. Exploiting a normalized HD constellation, average power of the OFDM signal generated by the proposed scheme remains unchanged since every subblock contains one HD symbol. More index bits can be obtained without additional energy consumption for the HD symbol, improving the spectrum and energy efficiency of the transmission system. In addition, increased MED of the HD constellations compared to the traditional 2D ones also contributes to improving bit error performance of the system.
- A simple and practical design strategy for the HD constellation is also presented. The Gray coding and mapping rule ensure that the coordinate values have the same amplitude. Hence, the strategy is suitable for designing HD constellations with a constant envelope.

The rest of this paper is organized as follows. Section II describes the proposed HD-OFDM-IQ-IM scheme in detail. A design strategy for the HD signal constellations is also introduced. In Section III, we analyze spectrum and energy efficiency of the proposed scheme, and present the theoretical analysis on the MED of HD constellations and the upper bound on bit error probability. Simulation results and discussions are given in Section IV. Finally, some conclusions on the proposed systems are presented in Section V.

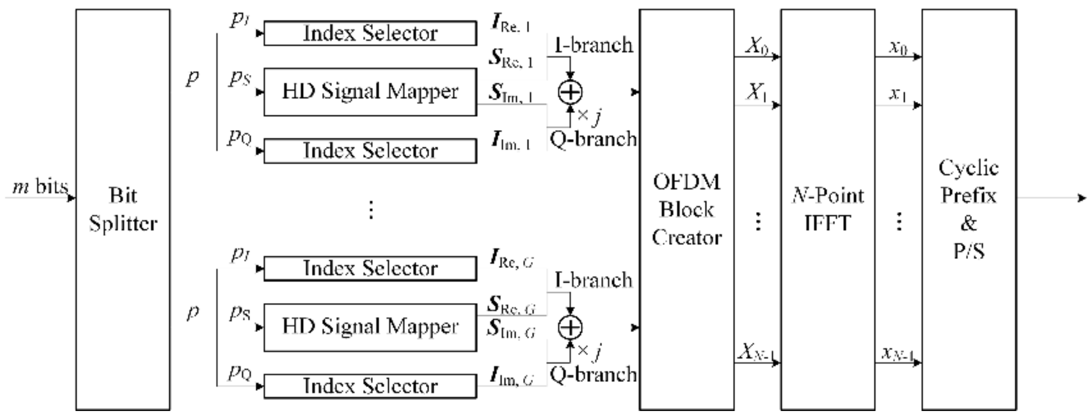

FIGURE 1. The structure of the proposed HD-OFDM-IQ-IM transmitter.

II. THE PROPOSED HD-OFDM-IQ-IM SYSTEM

A. SYSTEM MODEL

The structure of the proposed HD-OFDM-IQ-IM transmitter is illustrated in Fig. 1. We assume that an OFDM block carrying m information bits is split into G subblocks. Each subblock consists of n subcarriers, and transmits p information bits, that is, $G = m/p = N/n$, where N is the number of subcarriers in an OFDM block. In addition, a D-dimensional symbol $\boldsymbol{S}_D$ of an HD signal constellation with the size of M is represented as a column vector $(W_1\, W_2 \cdots W_d \cdots W_D)^T$, $1 \leq d \leq D$, where the superscript T denotes transposition operation. The coordinate value W_d is a nonzero real number aiming to distinguish whether the subcarrier component is activated or not.

Since every subblock has the same mapping process, we focus on the gth subblock, $1 \leq g \leq G$, to explain the proposed modulation scheme. In the gth subblock, p information bits are divided into three parts p_I, p_Q, and p_S. In the proposed HD-OFDM-IQ-IM scheme, only one HD symbol is transmitted by an OFDM subblock. A part of elements of the HD symbols are mapped into the active in-phase component subcarriers. It implies that a part of coordinate values are orderly modulated by means of the active in-phase component subcarriers. The remaining part of the same HD symbol are transmitted by the active quadrature component subcarriers. More specifically, for the in-phase component subcarriers of the gth subblock, k out of n subcarriers are activated to map the k elements of an HD symbol in sequence. The $p_I(= \lfloor \log_2 C(n,k) \rfloor)$ index bits decide the active pattern of the in-phase component, where $C(n,k)$ denotes the binomial coefficient and $\lfloor \cdot \rfloor$ is the well-known integer floor function. The selected index positions can be expressed as $\boldsymbol{I}_{\mathrm{Re},g} = [I_{\mathrm{Re},1}\, I_{\mathrm{Re},2} \cdots I_{\mathrm{Re},k}]$. As a result of the mapping operation, the output of I-branch can be represented as $\boldsymbol{S}_{\mathrm{Re},g} = [W_1(I_{\mathrm{Re},1})\; W_2(I_{\mathrm{Re},2}) \cdots W_k(I_{\mathrm{Re},k})]$. On the other hand, the rest $(D-k)$ elements are modulated into the quadrature components having $(D-k)$ active subcarriers, and the mapped output signal of Q-branch is $\boldsymbol{S}_{\mathrm{Im},g} = [W_{k+1}(I_{\mathrm{Im},1})\; W_{k+2}(I_{\mathrm{Im},2}) \cdots W_D(I_{\mathrm{Im},D-k})]$, where the index positions $\boldsymbol{I}_{\mathrm{Im},g} = [I_{\mathrm{Im},1}\, I_{\mathrm{Im},2} \cdots I_{\mathrm{Im},D-k}]$ are selected by the index bits $p_Q = \lfloor \log_2 C(n, D-k) \rfloor$. To ensure that one HD symbol is included in a subblock, $p_S(= \log_2 M)$ bits are combined with the signals of the I- and Q-branch to form a subblock signal. As an example, the modulation scheme for the HD-OFDM-IQ-IM $(n, k, D-k)$ with $n = 4$, $k = 3$, and $D = 5$ is given in Table 1.

TABLE 1. A look-up table for the HD-OFDM-IQ-IM(4, 3, 2).

p_I	$\boldsymbol{I}_{\mathrm{Re}}$	$\boldsymbol{S}_{\mathrm{Re}}$	p_Q	$\boldsymbol{I}_{\mathrm{Im}}$	$\boldsymbol{S}_{\mathrm{Im}}$
00	[1 2 3]	$[W_1\ W_2\ W_3\ 0]$	00	[1 2]	$[W_4\ W_5\ 0\ 0]$
01	[1 2 4]	$[W_1\ W_2\ 0\ W_3]$	01	[2 3]	$[0\ W_4\ W_5\ 0]$
10	[1 3 4]	$[W_1\ 0\ W_2\ W_3]$	10	[3 4]	$[0\ 0\ W_4\ W_5]$
11	[2 3 4]	$[0\ W_1\ W_2\ W_3]$	11	[1 4]	$[W_4\ 0\ 0\ W_5]$

With the IQ modulation approach, the output signal of the gth subblock can be expressed as $\boldsymbol{X}_{Tx,g} = \boldsymbol{S}_{\mathrm{Re},g} + j\boldsymbol{S}_{\mathrm{Im},g}$, where $j = \sqrt{-1}$. Concatenating all G subblocks at the OFDM block creator, the OFDM signal in the frequency domain can be built as

$$\boldsymbol{X}_{Tx} = [\boldsymbol{X}_{Tx,1}\, \boldsymbol{X}_{Tx,2} \cdots \boldsymbol{X}_{Tx,G}]. \tag{1}$$

The transmitted OFDM signal $\boldsymbol{x}_{Tx} = [x_0\;\; x_1 \cdots x_{N-1}]$ in the time domain can be obtained by N-point inverse fast Fourier transform (IFFT). Then, the cyclic prefix (CP) with the length of L is added to the transmitted signal $\boldsymbol{x}_{Tx}$. After parallel-to-serial (P/S) conversion, the OFDM signals are transmitted through a frequency selective Rayleigh fading channel.

A slowly time-varying multipath channel is modeled by its channel impulse response (CIR) $h = [h(1)\, h(2) \cdots h(v)]$, where $h(\lambda)$, $\lambda = 1, 2, \cdots, v$, are circularly symmetric complex Gaussian random variables with the distribution of $\mathcal{CN}(0, 1/v)$, where v is the number of propagation paths. The length of CP should be larger than the maximum delay spread of the propagation paths to eliminate the intersymbol interference (ISI). For the gth subblock, an ML detector takes into account all possible cases and makes a joint decision including in-phase and quadrature index bits and an HD symbol. Thus, the estimations of active indices and a transmitted

HD symbol can be determined by minimizing the following metric

$$(\hat{\boldsymbol{I}}_{\mathrm{Re},g}, \hat{\boldsymbol{I}}_{\mathrm{Im},g}, \hat{\boldsymbol{S}}_{D,g}) = \underset{\boldsymbol{I}_{\mathrm{Re},g}, \boldsymbol{I}_{\mathrm{Im},g}, \boldsymbol{S}_{D,g}}{\arg\min} \|\boldsymbol{X}_{Rx,g} - \boldsymbol{X}_{Tx,g}\boldsymbol{H}_{F,g}\|^2, \quad (2)$$

where $\boldsymbol{X}_{Rx,g}$ and $\boldsymbol{H}_{F,g}$ represent the vectors of received OFDM signal and corresponding transfer function of the channel for the gth subblock, respectively.

The computational complexity of the ML detector in terms of complex multiplications is $\mathcal{O}(2^{p_I}2^{p_Q}M)$ per subblock, which increases exponentially with p_I and p_Q. To reduce the complexity, an LLR-based detector can be employed in the proposed scheme. After the zero-forcing equalizer, the LLR technique is applied independently to the in-phase and quadrature components of the subblock signal. That is, the received OFDM signal after the equalizer is $X'_{Rx}(\alpha) = X_{Rx}(\alpha)/H(\alpha)$, $1 \leq \alpha \leq n$, where $X_{Rx}(\alpha)$ and $H(\alpha)$ represent subcarrier signals and transfer functions of the channel, respectively. For example, the LLR value for the in-phase component of a subblock can be computed as

$$\gamma(\alpha) = \ln(k) - \ln(n-k) + \frac{|H(\alpha)X^I_{Rx}(\alpha)|^2}{N_{0,F}} + \ln\left(\sum_{z=1}^{M'} \exp\left(-\frac{|H(\alpha)|^2}{N_{0,F}}|X^I_{Rx}(\alpha) - W_d(z)|^2\right)\right), \quad (3)$$

where $X^I_{Rx}(\alpha)$ and $N_{0,F}$ represent the in-phase component signal of $X'_{Rx}(\alpha)$ and the noise variance in the frequency domain, respectively. M' is the size of possible coordinate element W_d.

Exploiting the set of valid index patterns as shown in Table 1 (which is for HD-OFDM-IQ-IM(4, 3, 2)), the sum of the k largest LLR values is calculated to determine the index pattern used by the transmitter. With the same method, the sum of the rest $(D-k)$ largest values is computed to determine the index bits for the quadrature component subcarriers. Then the selected D LLR values are combined to demodulate the HD symbol in a subblock. In terms of the complex multiplications, the computational complexity of the LLR detector in (3) is $\mathcal{O}(M')$ per subcarrier. The complexity of demapping an HD symbol after the LLR detector is $\mathcal{O}(M)$ per subblock. Hence, the overall computational complexity of HD-OFDM-IQ-IM with the LLR detector and HD symbol demapping is $\mathcal{O}(2nM' + M)$ per subblock.

B. HIGH-DIMENSIONAL SIGNAL CONSTELLATION DESIGN

The constellation design is a crucial issue in the proposed modulation scheme. In the classical OFDM and the conventional OFDM-IM systems, 2D constellations such as multilevel PSK or QAM are usually exploited. For the 3D cube constellation, the MED increment is about 41.42% compared with 8QAM constellation under the average power of unity [18]. Two simple 3D signal constellations with the Gray coding are shown in Fig. 2 [18], [24]. As mentioned above,

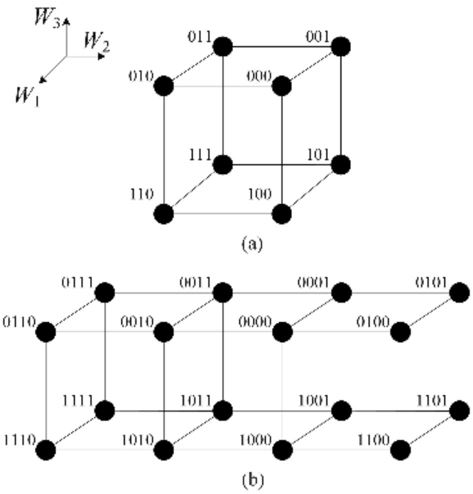

FIGURE 2. The examples of simple 3D signal constellations with the Gray coding (a) 8-ary (Cube) (b) 16-ary.

all coordinate values of the HD symbols must have nonzero real numbers in the proposed modulation scheme. Then, it is possible to apply the Gray mapping rule to an HD signal constellation for the new index modulations.

Assuming that the dimension of a target HD constellation with M symbols is D, the design algorithm is as follows:

Step 1: Generate M binary sequences $b_S = (b_{i-1,\beta}\ b_{i-2,\beta} \cdots b_{0,\beta})$, $1 \leq \beta \leq M$, where i $(= \log_2 M)$ is the length of the sequences. Arrange the sequences starting with all zero sequence and the Hamming distance between neighboring sequences being one to meet the constraint of the Gray coding.

Step 2: Append $(D-i)$ '0' and '1' bit alternately at the lowest significant bit position of b_S, to obtain D-bit long binary sequences $b_D = (b_{i-1,\beta}\ b_{i-2,\beta} \cdots b_{0,\beta} b_{D-i-1,\beta}\ b_{D-i-2,\beta} \cdots\ b_{0,\beta})$. Then, the Hamming distance of b_D is increased by one. Therefore, when dimension of the constellation is increased, the Hamming distance can also be increased.

Step 3: Execute the Gray coding and mapping rule. That is, the bit '0' is replaced by an amplitude of A, and $-A$ is for bit '1'.

In Table 2, an example of the HD signal constellation design is presented in detail, where the size of constellation, which is the same as the number of symbols of the signal constellation, is 8 and the range of constellation dimension is from 3 to 6. Specifically, for $M = 8$ and $D = 3$, the resultant constellation is the same as Fig. 2 (a). Since all symbols have the same amplitude, the strategy is suitable for the design of HD hypercube constellations.

III. PERFORMANCE ANALYSIS

A. MINIMUM EUCLIDEAN DISTANCE

The MED is one of the key parameters for determining anti-noise capability of a constellation. Due to the symmetricity, the MED of an HD signal constellation designed by the

TABLE 2. The Gray coding and mapping for HD signal constellations ($M = 8$).

Dimension	Bit sequence with Gray coding								Coordinate	Coordinate values							
	0	0	0	0	1	1	1	1	W_3	A_ψ	A_ψ	A_ψ	A_ψ	$-A_\psi$	$-A_\psi$	$-A_\psi$	$-A_\psi$
3D	0	0	1	1	1	1	0	0	W_2	A_ψ	A_ψ	$-A_\psi$	$-A_\psi$	$-A_\psi$	$-A_\psi$	A_ψ	A_ψ
	0	1	1	0	0	1	1	0	W_1	A_ψ	$-A_\psi$	$-A_\psi$	A_ψ	A_ψ	$-A_\psi$	$-A_\psi$	A_ψ
	0	0	0	0	1	1	1	1	W_4	A_ψ	A_ψ	A_ψ	A_ψ	$-A_\psi$	$-A_\psi$	$-A_\psi$	$-A_\psi$
4D	0	0	1	1	1	1	0	0	W_3	A_ψ	A_ψ	$-A_\psi$	$-A_\psi$	$-A_\psi$	$-A_\psi$	A_ψ	A_ψ
	0	1	1	0	0	1	1	0	W_2	A_ψ	$-A_\psi$	$-A_\psi$	A_ψ	A_ψ	$-A_\psi$	$-A_\psi$	A_ψ
	1	0	1	0	1	0	1	0	W_1	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ
	0	0	0	0	1	1	1	1	W_5	A_ψ	A_ψ	A_ψ	A_ψ	$-A_\psi$	$-A_\psi$	$-A_\psi$	$-A_\psi$
	0	0	1	1	1	1	0	0	W_4	A_ψ	A_ψ	$-A_\psi$	$-A_\psi$	$-A_\psi$	$-A_\psi$	A_ψ	A_ψ
5D	0	1	1	0	0	1	1	0	W_3	A_ψ	$-A_\psi$	$-A_\psi$	A_ψ	A_ψ	$-A_\psi$	$-A_\psi$	A_ψ
	1	0	1	0	1	0	1	0	W_2	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ
	0	1	0	1	0	1	0	1	W_1	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$
	0	0	0	0	1	1	1	1	W_6	A_ψ	A_ψ	A_ψ	A_ψ	$-A_\psi$	$-A_\psi$	$-A_\psi$	$-A_\psi$
	0	0	1	1	1	1	0	0	W_5	A_ψ	A_ψ	$-A_\psi$	$-A_\psi$	$-A_\psi$	$-A_\psi$	A_ψ	A_ψ
6D	0	1	1	0	0	1	1	0	W_4	A_ψ	$-A_\psi$	$-A_\psi$	A_ψ	A_ψ	$-A_\psi$	$-A_\psi$	A_ψ
	1	0	1	0	1	0	1	0	W_3	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ
	0	1	0	1	0	1	0	1	W_2	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$
	1	0	1	0	1	0	1	0	W_1	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ	$-A_\psi$	A_ψ

method introduced in Section II can be simply computed as

$$d_E = \sqrt{\sum_{1}^{d_H}\left[\frac{A}{A_u} - \left(-\frac{A}{A_u}\right)\right]^2} = \frac{2A}{A_u}\sqrt{d_H}, \tag{4}$$

where d_H stands for the minimum Hamming distance of neighboring binary sequences in Table 2, and A_u is a normalization factor. According to (4), the MEDs of the constellations shown in Table 2 are listed in Table 3, where all constellations are normalized to have the same average power of unity, that is, $A^2 = 1$, $A_u^2 = D$ and $A_\psi = \sqrt{A/A_u}$, where the subscript ψ, $3 \leq \psi \leq 6$, represents dimension of the constellations. The MEDs of 8QAM and 16QAM are also presented for comparison, and the 3D signal constellations are shown in Fig. 2. Table 3 shows that the MEDs of HD signal constellations are larger than the corresponding 2D ones, which lead performance improvement of the proposed system. For example, the 5D 16-ary constellation has two times larger MED than the 2D one.

TABLE 3. The MED values of the designed HD signal constellations.

Constellation	2D	3D	4D	5D	6D
8-ary	0.8165	1.1547	1.4142	1.2649	1.1547
16-ary	0.6325	0.7559	1.0000	1.2649	1.1547

B. SPECTRAL AND ENERGY EFFICIENCY

Spectral and energy efficiency of the proposed HD-OFDM-IQ-IM scheme are analyzed in this subsection. Since one symbol of an HD signal constellation is contained in an OFDM subblock, the extra information bits are implicitly conveyed by the in-phase and quadrature index activation patterns, respectively. Thus, spectral efficiency of the HD-OFDM-IQ-IM($n, k, D-k$) can be computed as

$$SE_{HD} = \frac{G \times \left(\lfloor \log_2 C(n,k) \rfloor + \lfloor \log_2 C(n, D-k) \rfloor + \log_2 M\right)}{N+L}. \tag{5}$$

In the HD-OFDM-IQ-IM scheme, the index modulation is separately performed on the in-phase component and the quadrature component subcarriers. The spectral efficiency of the scheme can be improved by associating the in-phase indices with the quadrature indices to produce more index patterns [21]. Then, the spectral efficiency of the improved HD-OFDM-IQ-IM (IHD-OFDM-IQ-IM) scheme can be calculated as

$$SE_{IHD} = \frac{G \times \left(\lfloor \log_2 C(n,k) \times C(n, D-k) \rfloor + \log_2 M\right)}{N+L}. \tag{6}$$

In each subblock of the HD-OFDM-IQ-IM and the IHD-OFDM-IQ-IM scheme, the number of active in-phase component subcarriers is fixed to k. However, the number k may be changed to further improve spectral efficiency of the proposed scheme. Refer to [10], a generalized form of the proposed HD-OFDM-IQ-IM scheme named GHD-OFDM-IQ-IM can be designed. The spectral efficiency of the GHD-OFDM-IQ-IM is given as

$$SE_{GHD} = \frac{G \times \left(\left\lfloor \log_2 \sum_{k_r \in \boldsymbol{K'}} C(n, k_r) \times C(n, D-k_r) \right\rfloor + \log_2 M\right)}{N+L}, \tag{7}$$

where k_r denotes the selectable number of active in-phase component subcarriers in a subblock. Thus, the number of possible index activation patterns can be increased.

In the case of $D = 4$, $M = 8$, $n = 4$, $k = 2$, and $\boldsymbol{K'} = \{1, 2, 3\}$, the number of information bits carried by an OFDM subblock is 7, 8, and 9 when the corresponding spectral efficiency of the HD-, IHD-, and GHD-OFDM-IQ-IM scheme is 1.5556, 1.7778, and 2.0000 bits/s/Hz, respectively. The spectral efficiencies of the IHD- and GHD-OFDM-IQ-IM scheme are increased as compared with the HD-OFDM-IQ-IM because they include more index activation patterns.

TABLE 4. Comparison of the energy efficiencies of the classical OFDM with QPSK, OFDM-IM with QPSK, OFDM-GIM2 with BPSK, and HD-OFDM-IQ-IM with $M = 16$ under the same spectral efficiency.

	Classical OFDM	OFDM-IM	OFDM-GIM2	6D-OFDM-IQ-IM, $n = 4$	8D-OFDM-IQ-IM, $n = 8$
Spectral efficiency [bits/s/Hz]	1.7778	1.7778	1.7778	1.7778	1.7778
Average power [Watt]	1	0.75	1	0.25	0.125
Energy efficiency [bits/Joule]	1.7778	2.3704	1.7778	7.1112	14.2224

The spectral efficiencies of the proposed schemes with respect to the dimension are compared in Fig. 3, where $n = 8$, $M = 8$, $k = \lceil D/2 \rceil$ and $\boldsymbol{K'} = \{1, 2, \cdots, D\}$. $\lceil \cdot \rceil$ is the integer ceiling function. Fig. 3 demonstrates that the GHD-OFDM-IQ-IM scheme has higher spectral efficiency than the others.

Energy efficiency is defined as the ratio of the spectral efficiency per unit bandwidth and the average power per subcarrier [25]. Since only one HD symbol is transmitted by a subblock, the average power of signals transmitted in the three schemes is invariable even if dimension of the constellations is varied. As the number of index bits increases with the signal dimension and the index bits consume no extra energy, the spectral efficiency and energy efficiency of the proposed schemes can be improved simultaneously. Energy efficiencies of the proposed scheme and the conventional systems are presented in Table 4, where all systems are set to have the same spectral efficiency for convenient comparison. Since it is assumed that QPSK is exploited as a signal mapper for the classical OFDM, its spectrum efficiency and energy efficiency are the same. In the case of OFDM-IM with QPSK, 3 out of 4 subcarriers are activated in each subblock. In OFDM-GIM2 with $n = 4$ and HD-OFDM-IQ-IM schemes, half of the in-phase or quadrature component subcarriers are activated. For example, in the case of OFDM-IM with QPSK, three QPSK symbols should be transmitted in a subblock ($n = 4$) to ensure spectral efficiency of 1.7778 bits/s/Hz. Assuming that average power of the QPSK constellation is normalized, total power of the subblock signals is 3 [Watt], so the average power per subcarrier is computed as $3/4 = 0.75$ [Watt]. In the conventional OFDM, which uses normalized QPSK as the signal mapper, each subcarrier transmits one QPSK symbol, so the average power per subcarrier is 1 [Watt]. According to Table 4, it can be noted that the proposed scheme has higher energy efficiency than the conventional ones under the same spectral efficiency. In the proposed scheme, since only one HD symbol is included in each subblock, the average power is reduced, and thus energy efficiency is increased. It is a useful advantage of the proposed HD-OFDM-IQ-IM.

C. UPPER BOUND ON BIT ERROR PROBABILITY

When an ML detector is exploited in the receiver, bit error performance of the HD-OFDM-IQ-IM scheme may be estimated by average pairwise error probability (APEP) which can apply a theoretical upper bound. We consider a subblock in an OFDM block as a whole for analysis, because all HD symbol elements are simultaneously modulated into the in-phase and quadrature components.

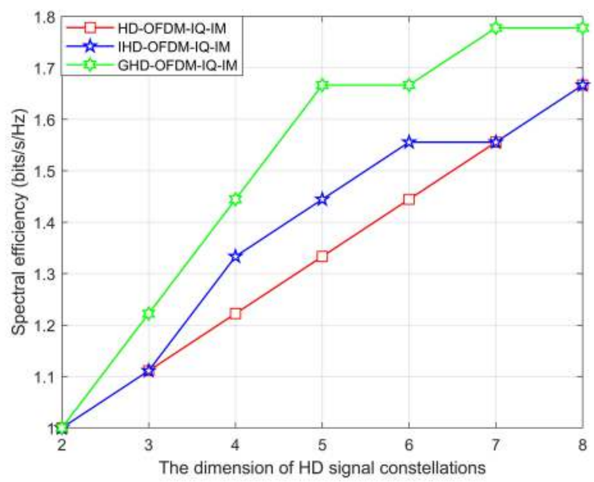

FIGURE 3. The spectral efficiency with respect to the dimension of signal constellations when $n = 8$ and $M = 8$.

The conditional PEP of the event that $\mathbf{X}$ is transmitted and $\hat{\mathbf{X}}$ is detected can be expressed by

$$\Pr(\mathbf{X} \to \hat{\mathbf{X}}|\mathbf{H}_F) = Q\left(\sqrt{\frac{1}{2N_{0,F}}\|(\mathbf{X}-\hat{\mathbf{X}})\mathbf{H}_F\|^2}\right), \quad (8)$$

where $Q(\cdot)$ denotes the Gaussian Q-function. $\mathbf{H}_F$ and $N_{0,F}$ are the channel fading coefficients and the noise variance in the frequency domain, respectively. $\mathbf{X}$ is an $n \times n$ diagonal matrix with main diagonal elements $X_{1,g}, \ldots, X_{n,g}$. Since the Gaussian Q-function is well approximated as

$$Q(x) \approx \frac{1}{12}\exp\left(-\frac{1}{2}x^2\right) + \frac{1}{4}\exp\left(-\frac{2}{3}x^2\right), \quad (9)$$

the unconditioned PEP can be calculated as [8]

$$\Pr(\mathbf{X} \to \hat{\mathbf{X}}) = \frac{1/12}{\det\left(\mathbf{I}_n + \frac{1}{4N_{0,F}}\mathbf{K}_n\mathbf{A}\right)} + \frac{1/4}{\det\left(\mathbf{I}_n + \frac{1}{3N_{0,F}}\mathbf{K}_n\mathbf{A}\right)}, \quad (10)$$

where

$$\mathbf{A} = (\mathbf{X}-\hat{\mathbf{X}})^H(\mathbf{X}-\hat{\mathbf{X}}). \quad (11)$$

$\mathbf{I}_n$ is the $n \times n$ identity matrix. $\mathbf{K}_n = E\{\mathbf{H}_F\mathbf{H}_F^H\}$ represents the expectation with respect to the channel coefficients. The superscript H denotes Hermitian transpose. Then, the bit error probability of the proposed HD-OFDM-IQ-IM system can be upper bounded by

$$P_e = \frac{1}{p_{\mathbf{X}} \times 2^{p_{\mathbf{X}}}}\sum_{\mathbf{X},\hat{\mathbf{X}}}\Pr(\mathbf{X} \to \hat{\mathbf{X}})e(\mathbf{X}, \hat{\mathbf{X}}), \quad (12)$$

where $p_{\mathbf{X}}$ is the number of bits for a subblock, and $e(\mathbf{X}, \hat{\mathbf{X}})$ represents the number of bit errors for the corresponding pairwise error event.

IV. SIMULATION RESULTS AND DISCUSSIONS

To examine performance of the proposed systems, computer simulation has been carried out, and compared with the classical OFDM, OFDM-IM(n, k'), and OFDM-GIM2(n, k_I, k_Q). The parameter k' of the OFDM-IM scheme is the number of active subcarriers in a subblock. k_I and k_Q of the OFDM-GIM2 scheme represent the number of active subcarriers in the in-phase and quadrature components, respectively. In all simulations, we apply the following system parameter: $N = 128$, $v = 10$, and $L = 16$. And an ML and an LLR detector are employed in the receiver. The number of transmitted HD-OFDM-IQ-IM signals is 10^6. The SNR is defined as $E_b/N_{0,T}$, where $E_b = E_s \times (N + L)/m$ is the average transmitted energy per bit and $N_{0,T}$ is the noise variance in the time domain. E_s denotes the average energy per subcarrier. We also present the theoretical upper bounds of the proposed HD-OFDM-IQ-IM schemes for a reference.

The bit error rates (BERs) of OFDM-IM(4, 1) with 32QAM, OFDM-GIM2(4, 2, 1) with BPSK, HD-OFDM-IQ-IM$(n, k, D - k)$ using the ML detector are shown in Fig. 4, where the parameters of all schemes are set to have the same spectral efficiency of 1.5556 bits/s/Hz. The proposed HD-OFDM-IQ-IM schemes with 4D, 5D, and 6D signal constellations have better bit error performance than the OFDM-IM with 2D constellation and OFDM-GIM2 with 3D constellation. Since three BPSK symbols carried by a subblock make up a 3D 8-ary signal constellation presented in Table 2, OFDM-GIM2(4, 2, 1) with BPSK is equivalent to the proposed HD-OFDM-IQ-IM(4, 2, 1) with 3D constellation. Due to increased MED of the HD signal constellation, error performance of the proposed HD-OFDM-IQ-IM scheme in the high SNR region is remarkably improved with the signal dimension. For instance, performance gain of the HD-OFDM-IQ-IM(4, 2, 2) scheme over the OFDM-GIM2(4, 2, 1) is about 5.0 dB at the BER of 10^{-6}. It is also shown that the theoretical upper bound of the bit error probability of the proposed schemes fits tightly in the high SNR region rather than the low SNR region.

Error performance of the classical OFDM with QPSK, OFDM-IM(4, 3) with QPSK, OFDM-GIM2(4, 2, 2) with BPSK, and HD-OFDM-IQ-IM$(n, k, D - k)$ with $M = 16$ for all spectral efficiency of 1.7778 bits/s/Hz are compared in Fig. 5. The OFDM-GIM2(4, 2, 2) with four BPSK symbol is equivalent to the proposed HD-OFDM-IQ-IM(4, 2, 2) with 4D constellation. When 5D and 6D symbols are exploited, the proposed system outperforms the conventional modulation schemes. The HD-OFDM-IQ-IM(4, 3, 3) scheme has about 5.0 dB improved BER as compared with the OFDM-GIM2(4, 2, 2) at the BER of 10^{-6}. In addition, the theoretical upper bounds for the proposed scheme with 5D and 6D constellations fit very well to the simulation results in the high SNR region.

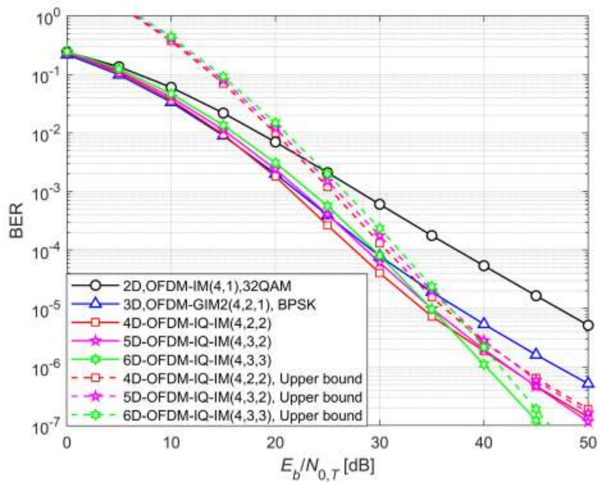

FIGURE 4. Error performance of the OFDM-IM with 32QAM, OFDM-GIM2 with BPSK, and HD-OFDM-IQ-IM with $M = 8$ when spectral efficiency is 1.5556 bits/s/Hz.

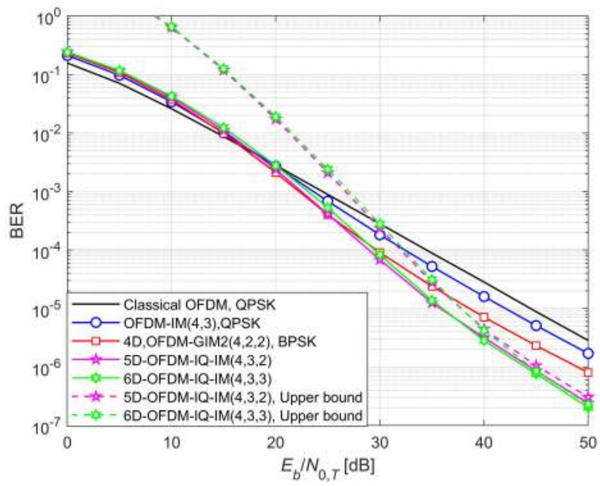

FIGURE 5. Error performance of the classical OFDM with QPSK, OFDM-IM with QPSK, OFDM-GIM2 with BPSK, and HD-OFDM-IQ-IM with $M = 16$ when spectral efficiency is 1.7778 bits/s/Hz.

In Fig. 6 and Fig. 7, we present BERs of the proposed HD-OFDM-IQ-IM scheme according to the dimension of signal constellations having the size of $M = 8$ and 16 for $n = 8$, respectively. Here, the same scheme with 2D 8QAM and 16QAM are also plotted for comparison. It is shown that the higher the dimension of signal constellation, the better the spectral efficiency and error performance of the proposed scheme. Compared to the HD-OFDM-IQ-IM(8, 1, 1), the HD-OFDM-IQ-IM(8, 3, 3) scheme has an increased spectral efficiency of more than 40% and an improved error performance of about 10.6 dB at the BER of 10^{-6} in Fig. 6. It is analyzed that the spectral efficiency of the proposed scheme is improved as the number of index bits transmitted by a subblock increases with the signal dimension. Since a subblock transmits only one HD symbol without changing average transmit power, improvement in the spectral efficiency of the proposed scheme leads to an increase in energy efficiency.

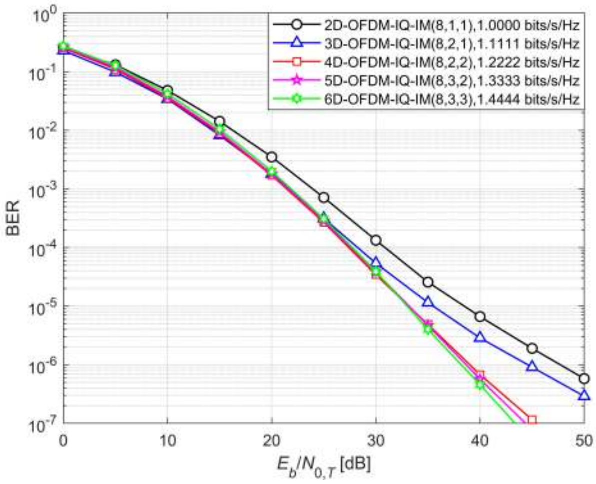

FIGURE 6. BER of the HD-OFDM-IQ-IM for $n = 8$ and $M = 8$.

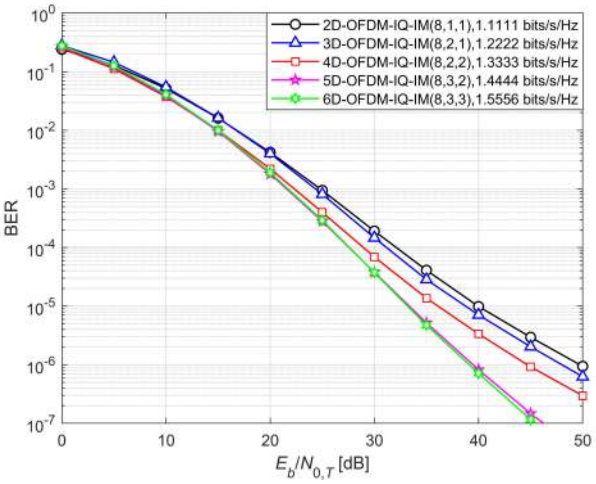

FIGURE 7. BER of the HD-OFDM-IQ-IM for $n = 8$ and $M = 16$.

In Fig. 8, we compare BER of the HD-OFDM-IQ-IM (4, 2, 2) with those of the IHD-OFDM-IQ-IM(4, 2, 2) and GHD-OFDM-IQ-IM(4, {1, 3}) for $n = 4$ and $M = 8$, where the 4D signal constellation is used. It is shown that the IHD-OFDM-IQ-IM(4, 2, 2) has almost the same performance as the HD-OFDM-IQ-IM(4, 2, 2). The GHD-OFDM-IQ-IM(4, 2, 2) has slightly lower BER than others at the high SNR region. It can also be noted that both the improved and the generalized form have about 14.28% higher spectral efficiency than the HD-OFDM-IQ-IM scheme.

BERs of the HD-OFDM-IQ-IM scheme according to the detectors are compared in Fig. 9. Unlike the ML detector, the LLR detector, which is a suboptimal detector, independently computes LLR values for in-phase and quadrature components. Then, the index bits are determined by demodulating the subblock HD signals using the D LLR values. The HD-OFDM-IQ-IM system with LLR detector has slightly worse bit error performance than that with the optimal ML detector. Despite the performance degradation, the LLR detector significantly reduces the required computational

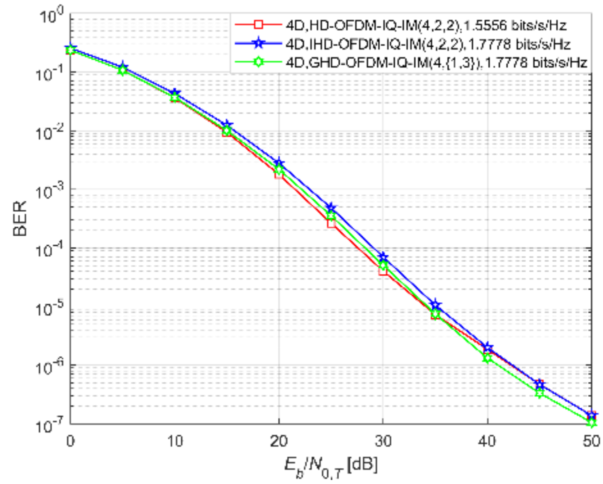

FIGURE 8. Bit error performance of the HD-, IHD-, and GHD-OFDM-IQ-IM scheme with $n = 4$ and $M = 8$.

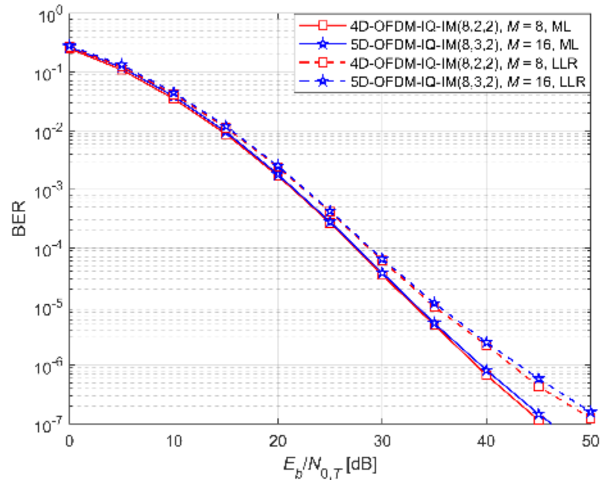

FIGURE 9. BER of the proposed HD-OFDM-IQ-IM scheme with ML and LLR detector.

complexity in the receiver. For example, the computational complexity of HD-OFDM-IQ-IM(8, 3, 2) shown in Fig. 9 is $\mathcal{O}(8192)$ when the optimal ML is used. However, when the LLR detector is employed, the complexity decreases to $\mathcal{O}(48)$, where the size of coordinate element W_d is $M' = 2$. Though the complexity of ML detector increases, the benefits of the proposed modulation scheme are worthwhile.

V. CONCLUSIONS

In this paper, a new OFDM-IM scheme using high-dimensional signal constellation and in-phase/quadrature index selectors is studied. In addition, the improved and generalized forms of the proposed HD-OFDM-IQ-IM scheme are also presented. Since the proposed scheme is designed to transmit one HD symbol in an OFDM subblock, the number of index bits can be increased with the dimension of signal constellation so that spectral efficiency of the proposed scheme can be improved. The simple and effective design strategy of HD signal constellations increases MED, which contributes to improving bit error performance of the system. Computer simulation proves that as the dimension of signal constellation increases, the proposed HD-OFDM-IQ-IM scheme has lower BER than the conventional OFDM-IM scheme with 2D constellation, and spectral efficiency and energy efficiency are also improved.

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