REPEATED IN-PHASE AND QUADRATURE INDEX MODULATION FOR OFDM

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Abstract

In this paper, we proposed the application of the repetition code to improve the performance of the index modulation for orthogonal frequency division multiplexing (IM-OFDM) system termed as repeated in-phase and quadrature index modulation for OFDM (RIQ-IM-OFDM). The proposed scheme can provide a superior performance over the benchmark systems at the same spectral efficiency. Unlike the classical IM-OFDM, RIQ-IM-OFDM activates only a subset of sub-carriers and uses the indices of active sub-carriers to carry additional data symbols in the index domain of both in-phase and quadrature dimensions. Then, active sub-carriers in each in-phase/quadrature component transmits the same M-ary symbol. Exploiting the in-phase/quadrature index modulation allows the system to attain improved spectral efficiency while using the repeated transmission provides the diversity gain in the frequency domain and thus improving the reliability of the conventional IM-OFDM as well as in-phase and quadrature index modulation for OFDM (IQ-IM-OFDM) systems.

Index terms

Index modulation, OFDM with in-phase/quadrature index modulation, IM-OFDM, frequency diversity, ML detection.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is known as an effective transmission technique thanks to the cancellation of inter-symbol interference and high spectral efficiency. Recently, a lot of studies have introduced novel OFDM schemes to improve the performance of the classical OFDM. One of the most typical techniques is index modulation for OFDM (IM-OFDM). Unlike the OFDM system, IM-OFDM only activates a subset of sub-carriers to carry data bits by using both the active sub-carriers and their indices. Due to the adjustable number of active sub-carriers, IM-OFDM can achieve the trade-off between the transmission reliability and spectral efficiency [1]. Since the first IM-OFDM system was reported in [2], the research on IM-OFDM has received much attention. For the reliability aspect, the authors in [3] used sub-carrier interleaving to enhance the error performance. The work in [4] proposed the simultaneous in-phase and quadrature index modulation for OFDM that could improve the spectral efficiency of the conventional IM-OFDM system. In another solution, the study in [5] was successfully exploited inactive sub-carriers to transmit additional

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information bits. Developing this idea, the multi-mode IM-OFDM was introduced in [6]. In this work, all sub-carriers were activated and various modes and their permutations were used to convey data bits. Thus, the spectral efficiency was improved. In order to simplify the system structure, a greedy detector (GD) for IM-OFDM was proposed and its bit error rate (BER) was analyzed under imperfect channel state information (CSI) in [7]. The authors in [8] investigated the impact of channel estimation errors on the symbol error probability (SEP) of IM-OFDM using both the maximum likelihood (ML) and GD detectors. Furthermore, performance analysis of IM-OFDM schemes has attracted a lot of interests. In particular, the BER expression for IM-OFDM was derived in [9]. The authors in [10] determined the outage probability of the IM-OFDM system over two-way diffused-power fading channels. For the diversity issue, the transmit diversity can be achieved by transmitting the in-phase and quadrature parts of complex symbols over two different active sub-carriers [11]. Additionally, the linear constellation pre-coding for IM-OFDM was proposed in [12] to improve both the diversity gain and spectral efficiency. The work in [13] introduced the diversity reception for IM-OFDM with GD to attain the improved diversity gain at low complexity detection. The idea of using repetition code for IM-OFDM as well as enhanced IM-OFDM systems to further improve the transmit diversity gain were reported in [14], [15], [16]. Aiming at further improving both the diversity gain and error performance, a lot of studies combined IM-OFDM with multiple input multiple output (MIMO) systems [17], [18]. To reduce the complexity, detectors based on the sequential Monte Carlo (SMC) were designed for MIMO- IM-OFDM which can achieve the near-optimal error performance at low complexity [19]. More recently, the authors in [20] introduced the first proposal of applying deep learning to detect data bits in the IM-OFDM systems. A lower order modulation variant was proposed for IM-OFDM in [21] to improve the spectral efficiency. In [22], Yoon derived the posterior probabilities of the low-density parity check (LDPC) coded bits of the IM-OFDM system to reduce the implementation complexity of LDPC decode without loss of the performance. The OFDM with hybrid number and index modulation was proposed in [23] to improve the error performance by using either number or index of active sub-carriers to transfer data bits. Besides, the distributed cooperative IM-OFDM system was presented in [24].

Motivated by the idea of repeated IM-OFDM in [4], we propose the repeated in-phase and quadrature index modulation for OFDM scheme in which the index modulation was extended to both in-phase and quadrature branches, the repeated transmission was applied to all active sub-carriers in the in-phase or/and quadrature parts. Thus, the proposed system can achieve the improvement in terms of the error performance as well as the spectral efficiency over the conventional IM-OFDM. The paragraph of this paper is organized as follows. Section 2 and Section 3 present the system models of the proposed RIQ-IM-OFDM, RIQ-IM-OFDM-ext systems, respectively. The performances of proposed systems were evaluated in Section 4. Section 5 concludes the paper.

2. Proposal of RIQ-IM-OFDM System

The block diagram of a typical RIQ-IM-OFDM scheme is illustrated in Fig. 1.

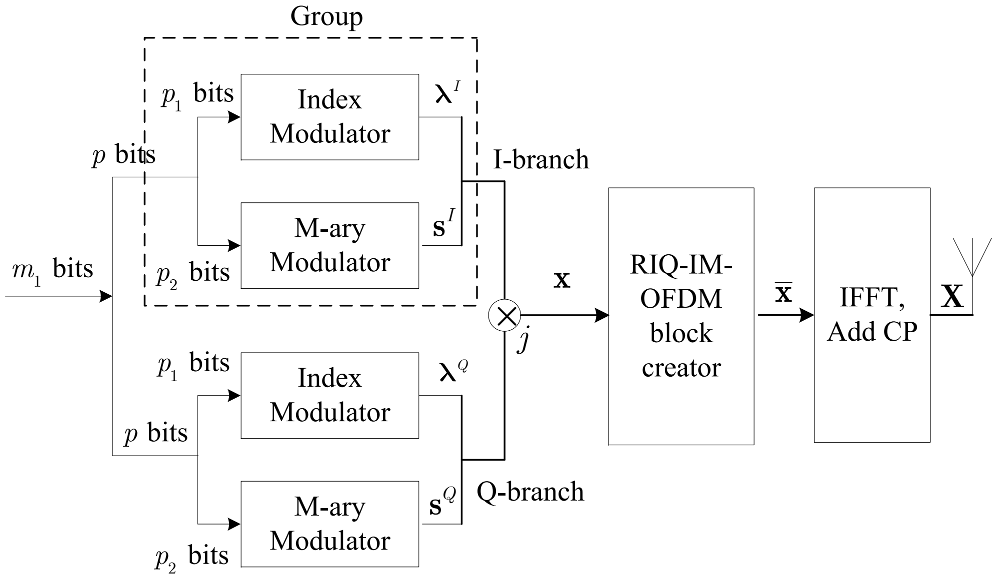

Fig. 1. Block diagram of a typical RIQ-IM-OFDM sub-block.

Assume that the OFDM system has N_c sub-carriers to transmit a total number of m information bits, which are divided into G sub-blocks of m_1 bits. Each sub-block is then separated into two groups. There are N subcarriers and p bits in each group that is utilized to generate the in-phase/quadrature component of a RIQ-IM-OFDM sub-block, i.e., $N = N_c/2G$ and $p = m/2G$. Similar to the conventional IM-OFDM system, each group of bits in RIQ-IM-OFDM scheme activates only K out of N sub-carriers. The remaining inactive sub-carriers are zero padded. However, unlike the conventional IM-OFDM as well as IQ-IM-OFDM system where K active sub-carriers transmit K different M-ary modulated data symbols. In our proposal, K active sub-carriers for each in-phase/quadrature part of the RIQ-IM-OFDM group transmit the same M-ary modulated symbol. As each sub-block operates independently, without loss of generality, we consider only one sub-block to explain the propose scheme.

In every transmission of a sub-block, the incoming m_1-bits are equally divided into two groups. For the in-phase/quadrature component per sub-block, each group of p-bits are then split into two parts. The first part consists of $p_1 = \lfloor \log_2 C(K, N) \rfloor$ bits that is the input of index modulator to select K out of N sub-carriers, where $\lfloor \cdot \rfloor$ and $C(K, N)$ denote the binomial coefficient and the floor function, respectively. As a result, the output of index modulator is an index symbol which is generated according to the active sub-carriers. The set of indices of active subcarriers in the in-phase and quadrature components are independently given by

$$\theta^I = \left\{\alpha_1^I, \ldots, \alpha_K^I\right\}, \theta^Q = \left\{\alpha_1^Q, \ldots, \alpha_K^Q\right\}, \tag{1}$$

where $\alpha_k^I, \alpha_k^Q \in \{1, \ldots, N\}$, $k = 1, \ldots, K$. Due to the use of repetition code at the transmitter, the index symbol for the in-phase and quadrature dimensions can be respectively expressed as follows

$$\boldsymbol{\lambda}^I = [\beta_1^I, \ldots, \beta_N^I], \boldsymbol{\lambda}^Q = [\beta_1^Q, \ldots, \beta_N^Q]. \tag{2}$$

where $\beta_i^I = 1$ if $i \in \theta^I$, $\beta_i^Q = 1$ if $i \in \theta^Q$ and $\beta_i^I, \beta_i^Q = 0$ when $i \notin \theta^I, \theta^Q$, i.e., $\lambda \in \{0, 1\}$. At large N and K, the index symbol is decided by the combination method [1]. While N, K are small, the look up table is used as an example in Table 1.

Table 1. A look up table of RIQ-IM-OFDM signal when $N = 4$, $K = 2$, $p_1 = 2$.

p_1^I	θ^I	$\mathbf{x}^I$	p_1^Q	θ^Q	$\mathbf{x}^Q$
00	$\{1,2\}$	$\left[s^I, s^I, 0, 0\right]^T$	00	$\{1,3\}$	$\left[s^Q, 0, s^Q, 0\right]^T$
01	$\{2,3\}$	$\left[0, s^I, s^I, 0\right]^T$	01	$\{2,4\}$	$\left[0, s^Q, 0, s^Q\right]^T$
10	$\{3,4\}$	$\left[0, 0, s^I, s^I\right]^T$	10	$\{1,4\}$	$\left[s^Q, 0, 0, s^Q\right]^T$
11	$\{1,3\}$	$\left[s^I, 0, s^I, 0\right]^T$	11	$\{1,2\}$	$\left[s^Q, s^Q, 0, 0\right]^T$

The second part of incoming bits in each in-phase/quadrature group having $p_2 = \log_2 M$ bits is fed to the M-ary modulator to generate modulated data symbols. However, unlike the conventional IQ-IM-OFDM system where all active sub-carriers in the in-phase/quadrature dimension transmit different data symbols $\mathbf{s}^I = \left[s^I(\alpha_1), \ldots, s^I(\alpha_K)\right]$, $\mathbf{s}^Q = \left[s^Q(\alpha_1), \ldots, s^Q(\alpha_K)\right]$, where $s^I(\alpha_k), s^Q(\alpha_k) \in \mathcal{S}$ denotes the set of M-PAM signal constellation. In our proposal, all active sub-carriers in each I/Q-branch transmit the same data symbols s^I, s^Q, respectively. Accordingly, a transmitted signal vector in the in-phase dimension is generated by $\mathbf{x}^I = \boldsymbol{\lambda}^I s^I$.

Similarly, for the quadrature component, we have $\mathbf{x}^Q = \boldsymbol{\lambda}^Q s^Q$. Then, $\mathbf{x}^I$ and $\mathbf{x}^Q$ are combined to generate a transmitted signal vector as follows

$$\mathbf{x} = \mathbf{x}^I + j\mathbf{x}^Q. \tag{3}$$

The received signal of the RIQ-IM-OFDM is given as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}. \tag{4}$$

where $\mathbf{H} = \operatorname{diag}(h(1), \ldots, h(N))$ is the channel matrix and $h(\alpha)$, where $\alpha = 1, \ldots, N$, is a complex-valued Gaussian random variable that represents the fading channel over a sub-carrier α. The additive Gaussian noise vector is expressed by $\mathbf{n} = [n(1), \ldots, n(N)]^T$. The channel coefficient and noise on each sub-carrier follow the distributions $h(\alpha) \sim \mathcal{CN}(0, 1)$ and $n(\alpha) \sim \mathcal{CN}(0, N_0)$, where N_0 is the noise variance. Assume that $\mathbb{E}\{|s^2|\} = \omega E_s$, let us define the average signal to noise ratio (SNR) per sub-carrier by $\bar{\gamma} = \omega E_s/N_0$, where E_s is the average transmit power per M-ary modulated symbol and $\omega = N/K$ represents power allocation coefficient.

It can be seen that in each transmission per sub-block, total number of transmitted bits are $m_1 = 2p = 2(p_1 + p_2)$, where $p_1 = \lfloor \log_2 C(K,N) \rfloor$ and $p_2 = \log_2 M$ are the number of bits carried on index modulation and on M-ary modulated symbol, respectively. Therefore, the spectral efficiency of the RIQ-IM-OFDM system is given by

$$\bar{\Gamma}_{\text{RIQ-IM-OFDM}} = \frac{2\left(\lfloor \log_2 C(K,N) \rfloor + \log_2 M\right)}{N} [\text{bits/s/Hz}], \tag{5}$$

In order to detect the transmitted signal, the receiver employs an ML detector to jointly estimate the active indices and the corresponding data symbols as follows

$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} \|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2 = \arg\min_{\mathbf{x}} \left\{ \|\mathbf{H}\|^2 \left[\left\|\mathbf{r}^I - \mathbf{x}^I\right\|^2 + \left\|\mathbf{r}^Q - \mathbf{x}^Q\right\|^2 \right] \right\}. \tag{6}$$

Where $\mathbf{r}^I$ and $\mathbf{r}^Q$ denote the in-phase and quadrature parts of $\mathbf{r} = \mathbf{y}/\mathbf{H}$, respectively. It can be seen from equation (6) that the in-phase and quadrature components of RIQ-IM-OFDM sub-block can be detected independently. Thus, the detection of both components is conducted as follows

$$\hat{\mathbf{x}}^I = \left(\hat{\boldsymbol{\lambda}}^I, \hat{s}^I\right) = \arg\min_{\boldsymbol{\lambda}^I, s^I} \|\mathbf{H}\|^2 \left\|\mathbf{r}^I - \mathbf{x}^I\right\|^2, \tag{7}$$

$$\hat{\mathbf{x}}^Q = \left(\hat{\boldsymbol{\lambda}}^Q, \hat{s}^Q\right) = \arg\min_{\boldsymbol{\lambda}^Q, s^Q} \|\mathbf{H}\|^2 \left\|\mathbf{r}^Q - \mathbf{x}^Q\right\|^2. \tag{8}$$

It can be seen that the ML complexity in terms of complex multiplications in each I/Q branch is $\sim \mathcal{O}\left(2^{p_1} M\right)$ which increases linearly with M.

3. Proposal of RIQ-IM-OFDM-ext scheme

Following equation (6), the proposed RIQ-IM-OFDM system attains the improved spectral efficiency over the conventional IM-OFDM [1] when K is not large. However, the spectral efficiency of RIQ-IM-OFDM is lower than that of the conventional IQ-IM-OFDM and IM-OFDM at large K. This is a drawback of the proposed system compared to the systems without repeated transmission. In order to overcome this disadvantage, we proposed an extended RIQ-IM-OFDM scheme called as RIQ-IM-OFDM-ext with the system model as shown in Figure 2. In RIQ-IM-OFDM-ext, the second part of incoming bits consisting of $p_2 = K \log_2 M$ bits are modulated by one M-ary modulated symbol vector $\mathbf{s} = [s_1, s_2, \ldots, s_K]$, where $s_k \in \mathcal{S}$, $k = 1, \ldots, K$. Unlike the RIQ-IM-OFDM system, RIQ-IM-OFDM-ext repeatedly transmits the same modulated symbol vector over the active subcarriers of both in-phase and quadrature components.

For more detail, an example of index selection and transmitted signal generation of RIQ-IM-OFDM-ext using look up table for $N = 4$, $K = 2$, $p_1 = 2$, $s_\chi, s_\varphi \in \mathcal{S}$, is presented in Table 2. The RIQ-IM-OFDM system, the spectral efficiency of the extended scheme is determined by

$$\bar{\Gamma}_{\text{RIQ-IM-OFDM-ext}} = \frac{2\lfloor \log_2 C(K,N) \rfloor + K \log_2 M}{N} [\text{bits/s/Hz}]. \tag{9}$$

For the detection, RIQ-IM-OFDM-ext jointly detects the indices of active subcarrier and data symbols using the ML detector similar to the RIQ-IM-OFDM system.

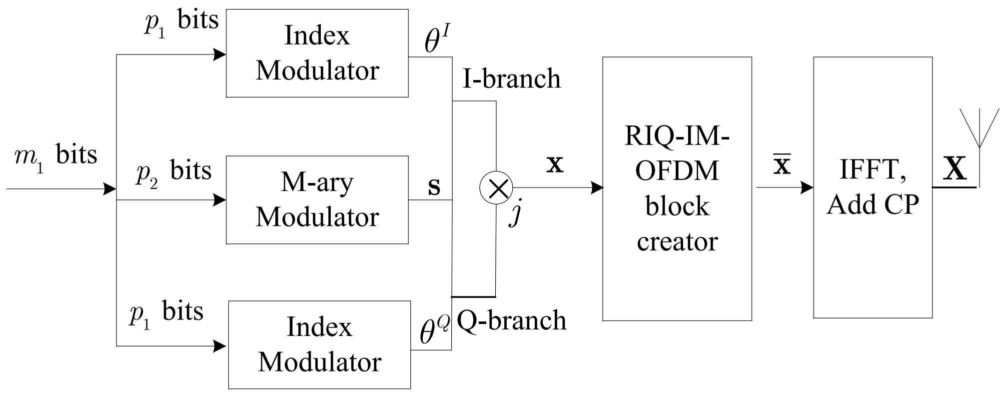

Fig. 2. Block diagram of a typical RIQ-IM-OFDM-ext sub-block.

Table 2. A look up table example of RIQ-IM-OFDM-ext when $N = 4$, $K = 2$, $p_1 = 2$.

p_1^I	θ^I	$\mathbf{x}^I$	p_1^Q	θ^Q	$\mathbf{x}^Q$
00	$\{1,2\}$	$[s_\chi, s_\varphi, 0, 0]^T$	00	$\{1,3\}$	$[s_\chi, 0, s_\varphi, 0]^T$
01	$\{2,3\}$	$[0, s_\chi, s_\varphi, 0]^T$	01	$\{2,4\}$	$[0, s_\chi, 0, s_\varphi]^T$
10	$\{3,4\}$	$[0, 0, s_\chi, s_\varphi]^T$	10	$\{1,4\}$	$[s_\chi, 0, 0, s_\varphi]^T$
11	$\{1,3\}$	$[s_\chi, 0, s_\varphi, 0]^T$	11	$\{1,2\}$	$[s_\chi, s_\varphi, 0, 0]^T$

4. Performance evaluation and discussion

In order to evaluate the performance of proposed systems, Monte-Carlo simulation is conducted and compared to the conventional IM-OFDM [1], IQ-IM-OFDM [4] systems. Assume that the channel over each sub-carrier is the Rayleigh fading channel and the CSI is perfectly known at the receiver. The ML detector is used in all schemes. For simplicity, system configuration with K out of N active sub-carriers and modulation order M is referred to as (N, K, M).

Figure 3 depicts the SEP performance of the proposed systems in comparison with the conventional IM-OFDM [1] and IQ-IM-OFDM systems [4] at the same spectral efficiency of 1.5 bits/s/Hz when $N = 4$, $K = \{1, 2, 3\}$, $M = \{2, 4\}$. It can be observed that the error performance of proposed systems outperforms that of the reference systems. Particularly, at $\text{SEP} = 10^{-4}$, RIQ-IM-OFDM and RIQ-IM-OFDM-ext achieve approximately 12 dB and 10 dB better than IM-OFDM, around 6.5 dB and 4.5 dB better than IQ-IM-OFDM, respectively. Besides, the RIQ-IM-OFDM-ext attains about 2 dB SNR gain compared to the RIQ-IM-OFDM system.

Figure 4 represents the SEP performance comparison of the proposed systems and the benchmark systems at higher spectral efficiency when $N = 8$, $K = \{2, 3, 4, 6\}$, $M = 4$. As seen from the figure, proposed systems attain better error performance than the conventional IM-OFDM and IQ-IM-OFDM. In particular, at the SEP of $\text{SEP} = 10^{-4}$, RIQ-IM-OFDM and RIQ-IM-OFDM-ext provide about 8 dB and 6.5 dB SNR gain

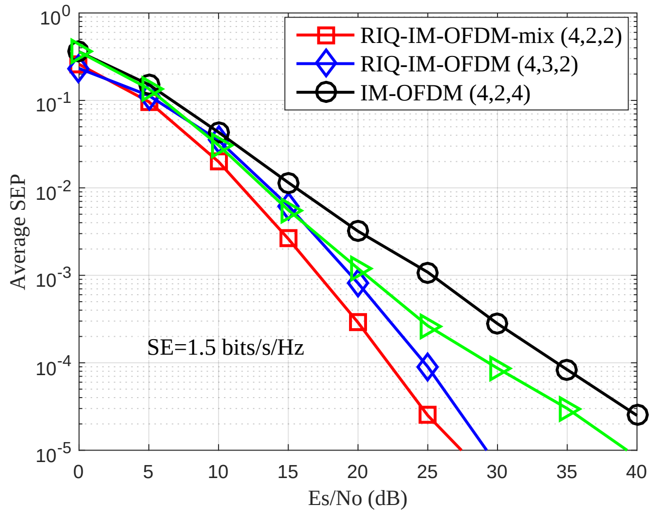

Fig. 3. The SEP performance of proposed systems and the conventional IM-OFDM, IQ-IM-OFDM systems at the spectral efficiency of 1.5 bits/s/Hz.

compared to IM-OFDM, 5 dB and 3.5 dB SNR gain over IQ-IM-OFDM, respectively. A possible explanation for this performance improvement might be that the proposed systems achieve the diversity gain in the frequency domain due to the repeated transmission. While the IM-OFDM and IQ-IM-OFDM systems without repetition code do not obtain the diversity gain.

Figure 5 depicts the impact of the number of active subcarriers on SEP of RIQ-IM-

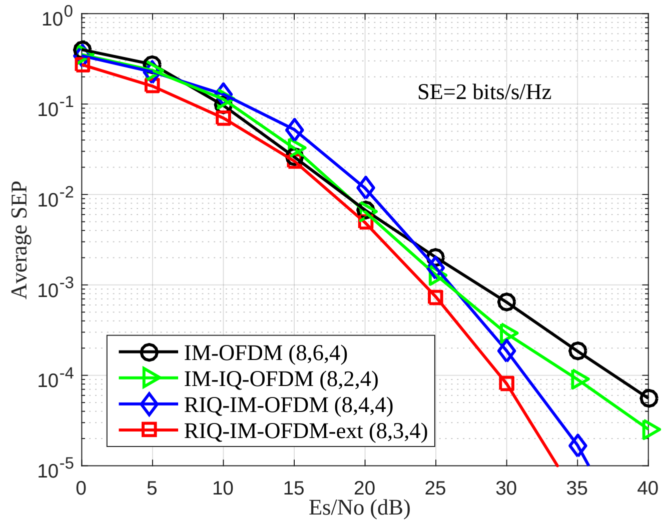

Fig. 4. Average SEP of RIQ-IM-OFDM, RIQ-IM-OFDM-ext and the conventional IM-OFDM, IQ-IM-OFDM when $N = 8,\ K = \{2, 3, 4, 6\},\ M = 4$.

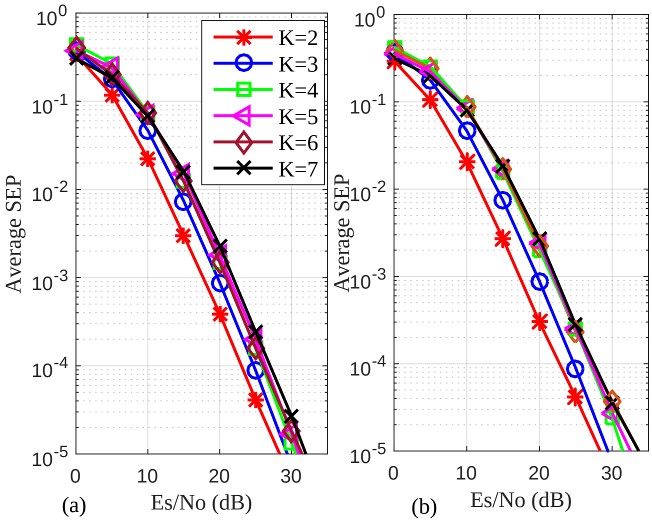

Fig. 5. The impact of K on the SEP performance of RIQ-IM-OFDM (a) and RIQ-IM-OFDM-ext (b) when $N = 8$, $K = \{1, 2, \ldots, 7\}$, $M = 2$.

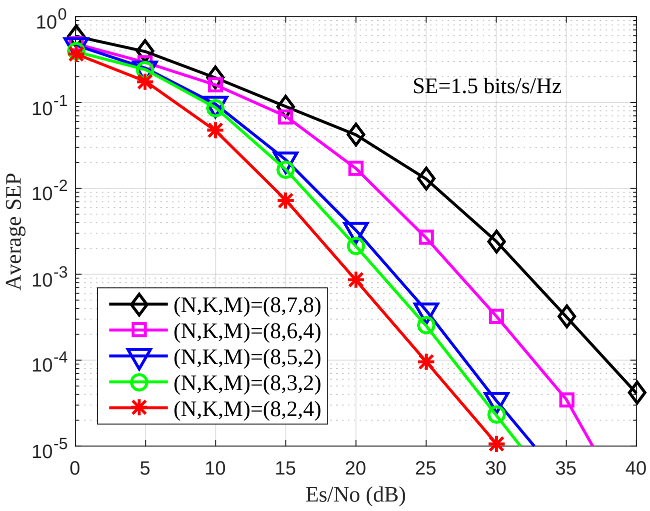

Fig. 6. The impact of K on the SEP performance of RIQ-IM-OFDM at the same spectral efficiency of 1.5 bits/s/Hz when $N = 8$, $K = \{2, 3, 5, 6, 7\}$, $M = \{2, 4, 8\}$.

OFDM (a) and RIQ-IM-OFDM-ext (b) at the fixed values of $N = 8$, $K = \{1, 2, \ldots, 7\}$, $M = 2$. It can be observed that when $K \geq 4$, there is not much difference in the SEP of both proposed systems. The best SEP performance is achieved at $K = 2$. In Figure 6, the impact of K on the SEP performance of RIQ-IM-OFDM at the same spectral efficiency of 1.5 bits/s/Hz is evaluated. It is clear that the system attains better performance when reducing K. RIQ-IM-OFDM at $K = 2$ provides the best performance with SNR gains of 1 dB over the scheme at $K = 3$. Thus, we should choose the value of K is not much larger than 2 for the best system configuration.

The comparison among spectral efficiency of proposed systems and the benchmark systems when $N = 8$, $K = \{1, 2, \ldots, 7\}$, $M = 4$ is shown in Figure 7. As seen from the figure, at $K \leq 4$, i.e., $K \leq N/2$, both RIQ-IM-OFDM and RIQ-IM-OFDM-ext systems achieve higher spectral efficiency than the classical IM-OFDM. However, when $K \geq 4$, the spectral efficiency of RIQ-IM-OFDM reduces and is lower than that of the IM-OFDM system.

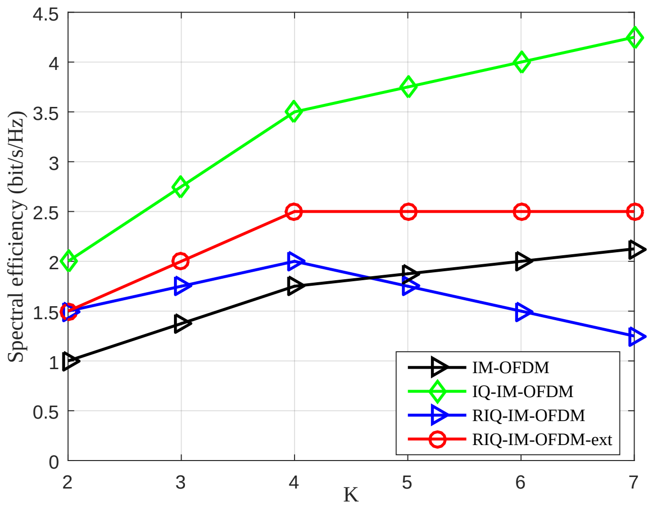

Fig. 7. The spectral efficiency of the proposed systems compared to that of IM-OFDM, IQ-IM-OFDM when $N = 8$, $K = \{1, 2, \ldots, 7\}$, $M = 4$.

This drawback of RIQ-IM-OFDM can be solved by RIQ-IM-OFDM-ext scheme that achieves higher spectral efficiency than that of RIQ-IM-OFDM and IM-OFDM even at large K. However, K should be selected not much larger than 2 to guarantee the best error performance. Thus, it is clear that two proposed systems can provide the significant improvement in terms of the error performance as well as the spectral efficiency over the conventional IM-OFDM.

5. Conclusion

In this paper, we have proposed two enhanced IM-OFDM systems referred to as RIQ-IM-OFDM and RIQ-IM-OFDM-ext. By exploiting the repeated transmission in in-phase and quadrature dimensions, the proposed systems can considerably improve the transmission reliability and spectral efficiency of the conventional IM-OFDM system. The impacts of system parameters on the error performance is also investigated that allows to select the best configuration for future IM-OFDM system. With their simply and reliability, the proposals will be suitable to machine type or device to device communications, where high reliability is more important at low spectral efficiency. Future work will include a comprehensive theoretical analysis to provide more insight into the performance behaviors, and effective receiver with minimum performance loss will be designed.

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ĐIỀU CHẾ CHỈ SỐ ĐỒNG PHA VÀ VUÔNG PHA LẶP LẠI CHO HỆ THỐNG OFDM

Lê Thị Thanh Huyền, Trần Xuân Nam

Tóm tắt

Trong bài báo này, chúng tôi đề xuất giải pháp ứng dụng mã lặp để cải thiện phẩm chất hệ thống điều chế chỉ số cho OFDM (IM-OFDM: index modulation for orthogonal frequency division multiplexing), với tên gọi điều chế chỉ số đồng pha và vuông pha lặp lại cho hệ thống OFDM (RIQ-IM-OFDM: repeated in-phase and quadrature index modulation for OFDM). Mô hình đề xuất có thể đem lại phẩm chất vượt trội so với các mô hình truyền thống tại cùng hiệu quả phổ. Không giống với mô hình IM-OFDM truyền thống, RIQ-IM-OFDM kích hoạt chỉ một tập con các sóng mang con và sử dụng chỉ số của các sóng mang con kích hoạt để mang thêm các symbol dữ liệu trên cả miền đồng pha và vuông pha. Sau đó, các sóng mang con đã kích hoạt trên miền đồng pha/vuông pha phát đi cùng một symbol dữ liệu đã được điều chế M-mức. Khai thác điều chế chỉ số đồng pha/vuông pha cho phép hệ thống cải thiện được hiệu quả phổ, trong khi sử dụng phát lặp đem lại độ lợi phân tập trên miền tần số và do vậy sẽ cải thiện được độ tin cậy của hệ thống IM-OFDM cũng như điều chế chỉ số đồng pha/vuông pha cho OFDM (IQ-IM-OFDM: in-phase/quadrature index modulation for OFDM) truyền thống.