Greedy Detection for ReIQ System

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Abstract. This study introduces an enhanced index modulation scheme termed as repeated in-phase (I) and quadrature (Q) index modulation for OFDM (ReIQ). The ReIQ system uses activated subcarriers in each I and Q component to transmits the same data symbol. By doing so, ReIQ can attain improvement in both spectral efficiency and transmission reliability. The advanced detector, called as greedy detection (GD) for ReIQ is proposed to provide optimal reliability of the maximum likelihood (ML) detector and considerably decrease the computational complexity. Simulation results are introduced to demonstrate the superiority of ReIQ as well as low-complexity detector compared to benchmark systems even when the estimated channel errors appear at receivers.

Keywords: Index Modulation (IM), transmit diversity, OFDM-IMIQ, ML detection, greedy detection.

1 Introduction

In recent years, Index Modulation (IM) is a novel solution that attracted much attention of researchers. IM with OFDM is known as the effective IM model in the frequency domain. The IMOFDM system utilizes only a number of sub-carriers to transmit data bits which are conveyed by both complex symbols and the active subcarrier index [1].

To improve the reliability of IMOFDM, many studies have been introduced. By introducing the joint I/Q IM [2], each OFDM frame can convey more bits to obtain improved spectral efficiency. Recently, the dual-mode OFDM was introduced where inactive subcarriers are utilized as a supplement to convey more data bits. Besides, the multi-mode OFDM was introduced in [3].

Considering the diversity issue, I and Q parts of complex data symbols [4] were transferred over repeated distinguished sub-carriers to attain the diversity gain. IM-OFDM with simultaneous diversity reception and transmittion to improve diversity gain and decrease the complexity can be found in [5]. Besides, the IMOFDM principle was put into practice Multi-Input Multi-Output (MIMO) system [6]. Moreover, low complexity detectors for IMOFDM to reduce the complexity and still obtaining the optimum reliability of the ML detection was also introduced. Motivating the idea of IMOFDM [2], the repeated I/Q-IMOFDM scheme referred to as ReIQ is proposed, where the repeated transmission was put into all active subcarriers in I/Q parts to achieve improved reliability and data rate over the conventional IMOFDM. Furthermore, greedy detection with small complexity is introduced to allow the ReIQ system to be much more simply.

The paper is divided into five sections. Section 2 is the proposed scheme. Section 3 proposes the GD detector. The performances of ReIQ system with proposed detector is evaluated in section 4. Conclusions are presented in section 5.

2. Proposed scheme

Assuming that the OFDM system has N_c subcarriers to transmit m bits, which are subdivided into B subblocks with m_1 bits. Each subblock is then split into two groups. There are N_s subcarriers and p bits in each group that is utilized to create the I/Q component of a ReIQ subblock, i.e., $N_s = N_c / 2B$ and $p = m / 2B$. Like the conventional IMOFDM scheme, in each group of p bits in ReIQ scheme, only K_s out of N_s subcarriers are used. The remaining inactive subcarriers are 0 padded. Nevertheless, unlike the conventional IMOFDM as well as IQ-IMOFDM system where K_s active subcarriers transmit K_s different M-ary symbols. In the ReIQ system, K_s active subcarriers for each I/Q part deliver the same M-ary symbol. Since subblocks operate independently, the author addresses only one ReIQ subblock.

In a ReIQ subblock, m_1 bits are equally subdivided into two groups. For I/Q component per subblock, each p-bits group is then split into two components. The first part of $p_1 = \lfloor \mathbf{log}_2 C(K_s, N_s) \rfloor$ bits is the input of index modulator to select K_s subcarriers, where $C(K_s, N_s)$ presents the convolution K_s of N_s, $\lfloor \cdot \rfloor$ is the floor function. As a result, an index symbol is generated at the output of index modulator according to active subcarriers. The activated subcarrier index set in I/Q parts is given by $\theta^I = \left\{ \alpha_1^I, \ldots, \alpha_{K_s}^I \right\}, \theta^Q = \left\{ \alpha_1^Q, \ldots, \alpha_{K_s}^Q \right\}$, where $\alpha_k^I, \alpha_k^Q \in \left\{ 1, 2, \ldots, N_s \right\}$, $k = 1, 2, \ldots, K_s$. Thanks to use of repetition code at the transmitter, the index symbol for I/Q dimensions is respectively represented as $\boldsymbol{\lambda}^I = [\beta_1^I, \ldots, \beta_N^I]$, $\boldsymbol{\lambda}^Q = [\beta_1^Q, \ldots, \beta_N^Q]$, 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., $\boldsymbol{\lambda} \in \left\{ 0, 1 \right\}$. The index symbol is decided by either combination or look up table method [1].

The remaining part of incoming bits in each I/Q group having $p_2 = \mathbf{log}_2 M$ bits is put to M-ary modulator to establish complex symbols. Unlike the conventional IQ-IMOFDM system where all activated subcarriers in the I/Q dimension transmit different data symbols $\mathbf{s}^I = \left[s^I_{\alpha_1},\ldots,s^I_{\alpha_{K_s}}\right]$, $\mathbf{s}^Q = \left[s^Q_{\alpha_1},\ldots,s^Q_{\alpha_{K_s}}\right]$, with $s^I_{\alpha_k}, s^Q_{\alpha_k} \in \mathcal{S}$ 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. As a result, a transmitted signal vector in the I-dimension is generated by $\mathbf{x}^I = \boldsymbol{\lambda}^I s^I$. Similarly, for the Q-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

$$\mathbf{x}_t = \mathbf{x}^I + j\mathbf{x}^Q . \tag{1}$$

Signal at the ReIQ receiver is expressed b

$$\mathbf{y}_r = \mathbf{H}\mathbf{x}_t + \mathbf{n} . \tag{2}$$

Where $\mathbf{H} = \mathrm{diag}\left(h_1,\ldots,h_{N_s}\right)$ is the channel matrix, and h_α, where $\alpha = 1,\ldots,N_s$, is a Gaussian distributed random variable that represents the fading channel over a subcarrier α. The AWGN noise is expressed by vector $\mathbf{n} = \left[n_1,\ldots,n_{N_s}\right]^T$. On every subcarrier, h_α and n_α have distributions $\mathcal{CN}(0,1)$ and $\mathcal{CN}(0,N_0)$ in which N_0 is noise variance. Assume $\mathbb{E}\left\{\left|s^2\right|\right\} = \delta E_s$, the signal to noise ratio (SNR) per subcarrier is determined by $\psi = \delta E_s / N_0$, with E_s is the transmit energy of M-ary symbol and $\delta = N_s / K_s$ represents power allocation component.

In practical system, errors can appear in the channel estimation process. The estimated channel satisfies the condition $\tilde{h}_\alpha = h_\alpha + e_\alpha$, where e_α is error of estimated channel, $e_\alpha \sim \left(0,\varepsilon^2\right), \tilde{h}_\alpha \sim \mathcal{CN}\left(0,1+\varepsilon^2\right)$, where ε^2 is the error variance.

The receive side utilizes ML detector to simultaneously detect the active indices and the corresponding data symbols.

$$\hat{\mathbf{x}}_r = \arg\min_{\mathbf{x}_t} \left\|\mathbf{y}_r - \tilde{\mathbf{H}}\mathbf{x}_t\right\|^2 . \tag{3}$$

From equation (3), ML has the complexity which investigated via complex multiplications in each I/Q branch $\mathcal{O}\left(2^{p_1} M^{K_s}\right)$ which increases exponentially with M.

3. Proposal of GD detector

In this section, the GD detector obtaining the near-optimum reliability of the ML detection is introduced. The GD divided detection process to two steps: the first one is used for detection of the indices of active subcarriers,

$\hat{\theta}^I = \left\{\hat{\alpha}_1^I,\ldots,\hat{\alpha}_{K_s}^I\right\}, \theta^Q = \left\{\hat{\alpha}_1^Q,\ldots,\hat{\alpha}_{K_s}^Q\right\}$ based on the K_s largest received energies $\left|y_\alpha\right|^2$. Then, the second step conducts recovery for symbols corresponding to active sub-carriers as follows

$$\begin{aligned} \hat{x}_{\hat{\alpha}} &= \mathop{\mathbf{arg\,min}}_{x_{\hat{\alpha}}\in\mathcal{S}} \left\| y_{\hat{\alpha}} - \tilde{h}_{\hat{\alpha}} x_{\hat{\alpha}} \right\|^2, \\ &= \mathop{\mathbf{arg\,min}}_{x_{\hat{\alpha}}\in\mathcal{S}} \left\{ \left|\tilde{h}_{\hat{\alpha}}\right|^2 \left[\left| r_{\hat{\alpha}}^I - x_{\hat{\alpha}}^I \right|^2 + \left| r_{\hat{\alpha}}^Q - x_{\hat{\alpha}}^Q \right|^2 \right] \right\}. \end{aligned} \tag{4}$$

Where $r_{\hat{\alpha}}^I$ and $r_{\hat{\alpha}}^Q$ denote the I/Q parts of $r_\alpha = y_\alpha / \tilde{h}_\alpha$, respectively. It can be seen that I/Q components of the ReIQ sub-block can be detected independently. Thus, the detection of each I/Q component is conducted as follows

$$\hat{x}_{\hat{\alpha}}^I = \mathop{\mathbf{arg\,min}}_{x^I} \left|\tilde{h}_{\hat{\alpha}}\right|^2 \left| r_{\hat{\alpha}}^I - x_{\hat{\alpha}}^I \right|, \tag{5}$$

$$\hat{x}_{\hat{\alpha}}^Q = \mathop{\mathbf{arg\,min}}_{x^Q} \left|\tilde{h}_{\hat{\alpha}}\right|^2 \left| r_{\hat{\alpha}}^Q - x_{\hat{\alpha}}^Q \right|. \tag{6}$$

GD estimates active subcarrier indices without the exhausted estimation of available index combinations. This allows to decrease complexity of M-ary symbol detection. The complexity of GD detector is $\sim \mathcal{O}\left(N + KM\right)$ which linearly increases with M.

4. Performance evaluation

The Monte-Carlo simulation is introduced to compare the symbol error probability (SEP) of ReIQ with IMOFDM [1] and IQ-IMOFDM systems [2]. SEP of the ReIQ scheme using the proposed GD detector compared to ML and the benchmarks is depicted in Figure 1. Assume that CSI is perfect at the receiver. It is clear that the GD detector provides the similar SEP to ML while the computational complexity significantly reduces. There is not many differences in SEP of ReIQ when utilizing ML as and GD detectors. ReIQ achieves better performance than the benchmarks. Particularly, at SEP=10^{-4}, ReIQ obtains approximately 9.5 dB and 5 dB gains compared to IM-OFDM and IQ-IM-OFDM, respectively.

Figure 2 presents the SEP of the ReIQ system compared to the IM-OFDM [1] as well as IQ-IM-OFDM [2] systems in the imperfect CSI condition. It can be seen that when the values of error variance increase, the error performance of considered systems is reduced. The error floors occur at the high SNR region.

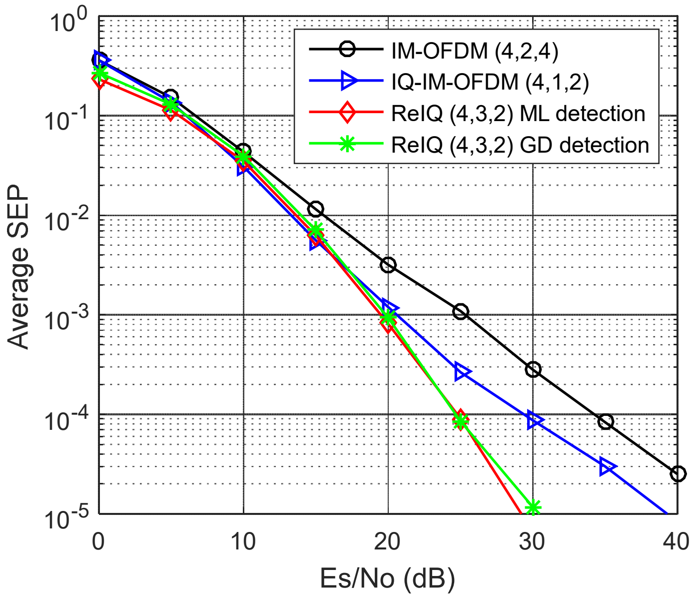

Fig. 1. SEP of ReIQ using proposed detector compared to benchmarks at the same data rate and perfect CSI condition.

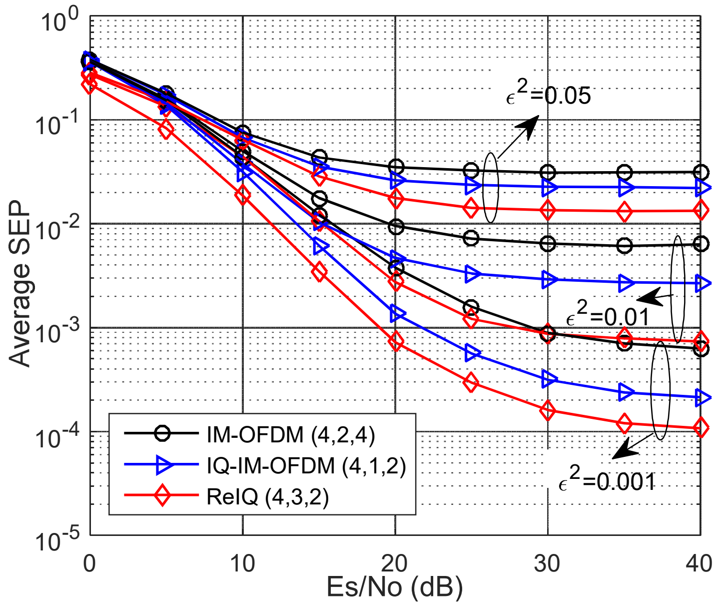

Fig.2. The SEP of ReIQ and benchmarks at the same data rate and imperfect CSI condition.

Besides, even at imperfect CSI condition, the error performance of ReIQ still outperforms that of the benchmark systems.

5. Conclusion

In this research, the author proposed low-complexity detector and investigated the SEP performance of the ReIQ system in the perfect and imperfect CSI conditions. The proposed GD detector can considerably reduce the computational complexity of ReIQ detection while enjoying nearly optimal performance of the ML detection. Furthermore, even in the imperfect CSI condition, ReIQ still outperforms the benchmark systems. With their simply and reliability, the proposals will be suitable to IoT communications in which symbol error performance is preferred to the data rate.

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