Quy Nhon University - The Radio and Electronics Association of Vietnam

PROCEEDINGS OF THE 2017 INTERNATIONAL CONFERENCE ON ADVANCED TECHNOLOGIES FOR COMMUNICATIONS

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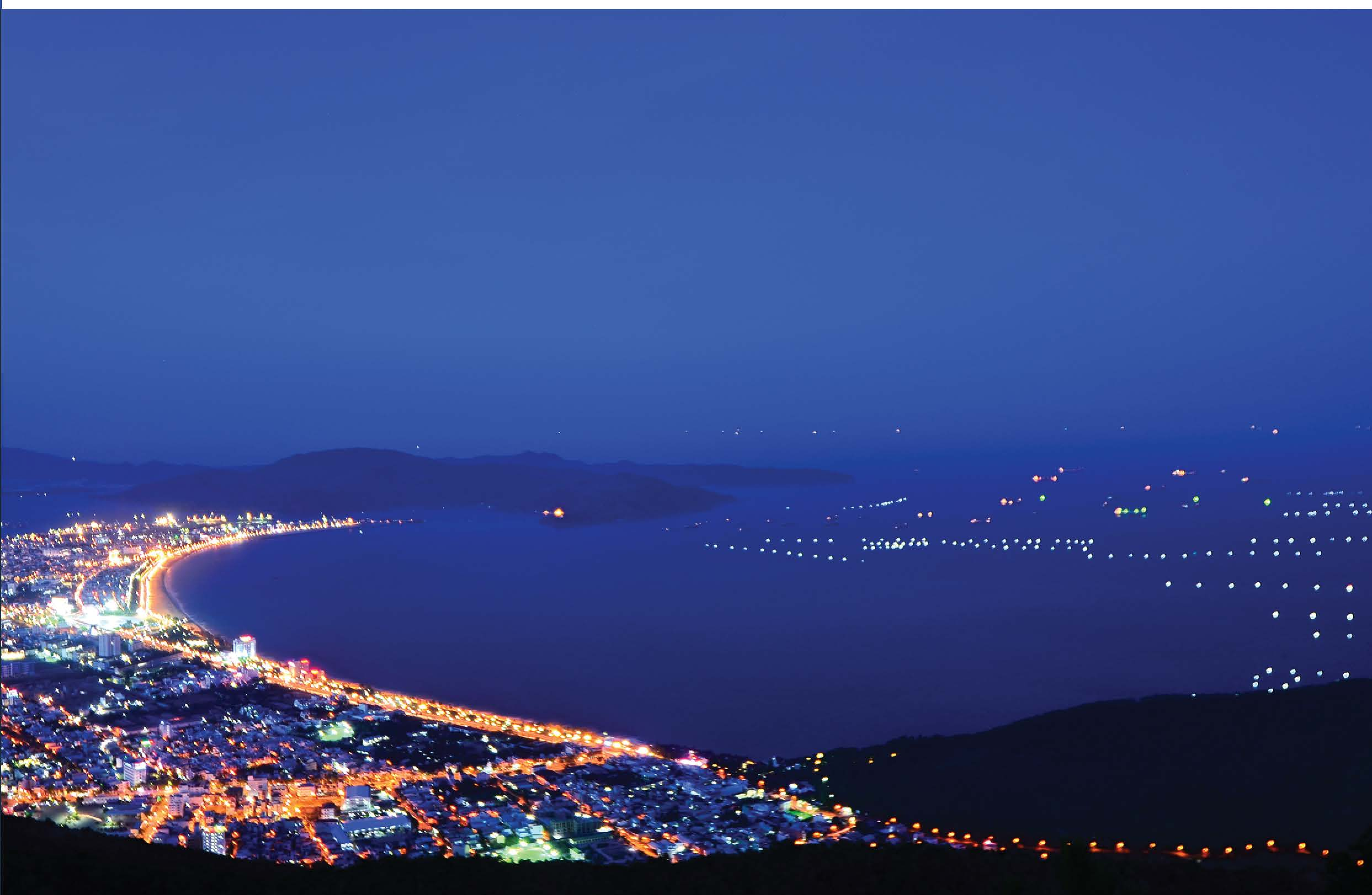

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PART B.

Repeated Index Modulation for OFDM with Space and Frequency Diversity

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***Abstract*—In this paper, an enhanced scheme of Index Modulation for Orthogonal Frequency Division Multiplexing (IM-OFDM), called Repeated IM-OFDM with Diversity Reception (ReIM-OFDM) is proposed. ReIM-OFDM achieves performance improvement over the convetional IM-OFDM at the same spectral efficiency by providing additional space and frequency diversity. Similar to IM-OFDM, the proposed ReIM-OFDM also activates K out of total N subcarriers to convey information bits using both the active sub-carriers and their indices. However, it differs from IM-OFDM in that all activated sub-carriers are modulated by the same M-ary data symbol. For signal combining, either Maximal Ratio Combining (MRC) or Selection Combining (SC) can be used in the spatial and sub-carriers domain to help ReIM-OFDM achieve both space and frequency diversity gain. In order to analyze performance of the system, the Moment Generating Function (MGF) is used to obtain the closed-form expressions for the pairwise index error probability (PEP) and the symbol error probability (SEP) in both cases: ReIM-OFDM-MRC and ReIM-OFDM-SC. Effects of various system parameters on the SEP are analyzed to select the best ReIM-OFDM configuration with minimum error probability. Our analysis proves the effectiveness of ReIM-OFDM over IM-OFDM at the same spectral efficiency.**

Keywords*—Index modulation, spatial diversity, ML detection, MGF, symbol error probability.

I. Introduction

Orthogonal frequency division multiplexing (OFDM) is an effective multi-carrier transmission technique which can meet the increasing demand for high-rate data communications over the frequency-selective fading channel. Index Modulation for OFDM (IM-OFDM), proposed by Basar [1] recently, is a special type of OFDM, which can balance the trade-off between error performance and spectral efficiency. The idea of IM-OFDM was inspired by the spatial modulation (SM) concept [2], which transmits data using both M-ary modulated symbols and transmit antenna indices. However, unlike SM, IM-OFDM exploits the sub-carrier indices to convey additional information bits without expanding transmission bandwidth.

Various IM-OFDM schemes have been proposed in the literature recently. In [3], the authors analyzed performance of IM-OFDM and successfully derived a closed-form expression for the approximated bit error rate (BER). In [4], the authors proposed a subcarrier interleaving method to increase the Euclidean distance between detected M-ary symbols, which help to improve BER performance. In a similar work, Basar proposed a coordinate interleaving scheme was proposed to increase the diversity gain of IM-OFDM [5]. In [6], the authors proposed a space-frequency coded index modulation scheme which achieves diversity order 2. Focusing on the signal detectors which can achieve space diversity gain at low-complexity, the work in [7] proposed a MIMO-IM-OFDM system with the maximum likelihood (ML) detection while [8] considered a sequential detector based on the Monte-Carlo (SMC) theory. In the more recent works, a low-complexity greedy detector was proposed for IM-OFDM and its BER performance was analyzed under imperfect channel state information (CSI) condition [9]. In [10], the instantaneous symbol error outage probability (ISEOP) of IM-OFDM system over two-way with diffused power (TWDP) fading channels was also investigated. In order to increase the diversity gain, an IM-OFDM system with diversity reception was introduced in [11].

However, it is worth noting that all the considered schemes could not achieve simultaneously improved error performance and spectral efficiency using low-complexity detection. The IM-OFDM systems in [6], [7], [8] can achieve the space diversity gain but their structures are still complex. The proposed systems in [12] and [13] attain increased spectral efficiency and transmission rate but sacrifice the system performance. The IM-OFDM system in [11] can achieve antenna diversity gain, however, joint space and frequency diversity was not successfully exploited.

Inspired by the previous works, in this paper, we propose a repeated IM-OFDM (abbr. as ReIM-OFDM) scheme which can exploit both space and frequency diversity for a single-input multiple-output (SIMO) system over the frequency-selective fading channel. While space diversity can be achieved by using either maximal ratio combining (MRC) or selection combining (SC), frequency diversity is obtained by allowing K activated subcarriers to transmit one M-ary modulated symbol simultaneously at a transmission interval. The proposed ReIM-OFDM scheme can achieve higher diversity gain and better error performance than the conventional IM-OFDM and IM-OFDM with diversity reception in [11] at the same spectral efficiency. In summary, the contributions of the paper are listed as follows:

- An IM-OFDM scheme with diversity enhancement, referred to as ReIM-OFDM, is proposed for a SIMO communication system in order to increase its error performance without sacrificing the spectral efficiency.
- The pairwise error probability (PEP) and the symbol error probability (SEP) of the proposed ReIM-OFDM scheme are analyzed in two cases: ReIM-OFDM using MRC (ReIM-OFDM-MRC) and ReIM-OFDM using SC (ReIM-OFDM-SC). The closed-form expressions for both PEP and SEP are derived using moment

generating function and validated using simulations.

- Performance evaluations are carried out for various system configurations to prove the effectiveness of the proposed ReIM-OFDM system.

The rest of this paper is outlined as follows. Section II describes the system model of the proposed ReIM-OFDM. The closed-form expressions for PEP and SEP are derived in Section III. Performance evaluations are presented in Section IV. Finally, Section V concludes the paper.

II. System Model

The block diagram of the proposed IM-OFDM system with space diversity is illustrated in Fig. 1. The considered SIMO system consists of a single-antenna device and a L-antenna base station. The channel is assumed to undergo the frequency-selective fading with the channel length D. In order to combat the frequency selectivity of the channel, the proposed system using a cyclic prefix length large than D. The IM-OFDM system has N_F sub-carriers which are divided into G groups, each with N-sub-carriers, $N = N_F/G$. Similar to the conventional IM-OFDM, only K out of N sub-carriers in each group are activated in accordance with the incoming data to convey information bits. The remaining $N-K$ inactive sub-carriers are zero padded. However, the conventional IM-OFDM delivers different M-ary data symbols over K active sub-carriers. Whereas, all the K active sub-carriers in our scheme are modulated by the same M-ary data symbol s. Moreover, the modulation type used in each group is independent from each other. This repeated and independent modulation is used to attain diversity gain in both the frequency and index domains. For signal reception, either MRC or SC diversity combiner can be used to achieve further space diversity. For the sake of simplicity, in the sequel, we will abbreviate our scheme as ReIM-OFDM, and as ReIM-OFDM-MRC or ReIM-OFDM-SC when the respective combiner is utilized.

Since the system operation is similar for sub-carrier groups, without loss of generality, we will consider only one arbitrary group in our subsequent analysis. For each ReIM-OFDM group, there are p incoming bits which can be divided into 2 parts. The first part which consists of $p_1 = \lfloor \log_2 C(K,N) \rfloor$ bits are used as the index selector to activate K out of N available indices. The output of the index selector is an index symbol corresponding to a combination of active sub-carriers whose indices are in a set of θ, i.e., $\theta = \{\alpha_1, \dots, \alpha_K\}$, where $\alpha_K \in \{1, \dots, N\}$. Defining the index symbol by $\boldsymbol{\lambda} = [\beta_1, \dots, \beta_N]$ where $\beta_i = 1$ if $i \in \theta$ (meaning that the i-th sub-carrier is activated), else $\beta_j = 0$ if $j \notin \theta$, $i, j \in \{0, \dots, N\}$, i.e., $\boldsymbol{\lambda} \in \{0,1\}$. Let Φ be the set of all index symbols whose cardinality is given by $c = 2^{p_1}$. When N, K are large, the index symbols can be generated by the combination method, whereas they are selected using the look up table (LUT) in [1]. The second part contains the remaining $p_2 = \log_2 M$ bits which are fed to the M-ary modulator to generate a signal symbol s. The output of ReIM-OFDM is the signal vector $\mathbf{x}$ which is the product of the index symbol and data symbol s, i.e. $\mathbf{x} = \boldsymbol{\lambda} s$.

At the receiver, the received signal at the l-th antenna is given by

$$\mathbf{y}_l = \mathbf{H}_l \mathbf{x} + \mathbf{n}_l = \mathbf{H}_l \boldsymbol{\lambda} s + \mathbf{n}_l, \quad (1)$$

where $\mathbf{H}_l = \text{diag}(h_l(1), \dots, h_l(N))$ is the channel matrix which has only diagonal entries representing the gains of the L channels between the transmit antenna and the l-th receive antenna, $l = 1, 2, \dots, L$; $h_l(\alpha)$, $\alpha = 1, 2, \dots, N$, denotes the channel gain of the α-th sub-channel which can be modeled by an independent, complex-valued Gaussian random variable; $\mathbf{n}_l = [n(1), \dots, n(N)]^T$ represents the additive Gaussian noise vector at the N sub-channels on the l-th antenna branch. Distributions of $h_l(\alpha)$ and $n_l(\alpha)$ are $\mathcal{CN}(0,1)$ and $\mathcal{CN}(0, N_0)$, respectively, where N_0 is the noise variance. Suppose that $\mathbb{E}\{|s^2|\} = \omega E_s$, where E_s is the average power per M-ary data symbol s; $\omega = N/K$ is the power allocation coefficient and $\mathbb{E}$ denotes the expectation operation. As a result, the average signal-to-noise ratio (SNR) per active sub-carrier at the receiver is expressed as $\bar{\gamma} = \omega E_s / N_0$.

As illustrated in Fig. 1 after the fast Fourier transform (FFT) at the receiver, either MRC or SC can be used for signal combination from L antennas. A ML detector is used to jointly estimate the index symbols and the M-ary symbol s from all possible transmitted ReIM-OFDM signals. The received signal after the diversity combiner can be given by

$$\mathbf{y}_\chi = \mathbf{H} \boldsymbol{\lambda} s + \mathbf{n}, \quad (2)$$

where $\chi \in \{\text{MRC}, \text{SC}\}$, $\mathbf{H} \in \{\mathbf{H}_{\text{MRC}}, \mathbf{H}_{\text{SC}}\}$, $\mathbf{n} \in \{\mathbf{n}_{\text{MRC}}, \mathbf{n}_{\text{SC}}\}$ depending on the respective diversity combiner. If the MRC combiner is used, the received signals from antenna branches are combined using a complex vector $\mathbf{W}$:

$$\begin{aligned} \bar{\mathbf{y}}_{\text{MRC}} &= \mathbf{W}^H \mathbf{y} = \mathbf{W}^H \mathbf{H} \boldsymbol{\lambda} s + \mathbf{W}^H \mathbf{n}, \\ &= \mathbf{H}_{\text{MRC}} \boldsymbol{\lambda} s + \mathbf{n}_{\text{MRC}}, \end{aligned} \quad (3)$$

where the equivalent channel matrix for the case of MRC is $\mathbf{H}_{\text{MRC}} = \mathbf{W}^H \mathbf{H}$ with $\mathbf{H} = [\mathbf{H}_1^T, \dots, \mathbf{H}_L^T]^T$; $\mathbf{n}_{\text{MRC}} = \mathbf{W}^H \mathbf{n}$ is the noise vector at the combiner output and $\mathbf{n} = [\mathbf{n}_1^T, \dots, \mathbf{n}_L^T]^T$ is the noise vector per diversity branch. For the SC combiner, the channel matrix $\mathbf{H}_{\text{SC}} = \text{diag}(h_{\text{SC}}(1), \dots, h_{\text{SC}}(N))$, with $h_{\text{SC}}(j) = \max_l |h_l(j)|^2$ and $\mathbf{n}_{\text{SC}}$ denotes the noise vector of the diversity branch with the maximum SNR. The estimated signal at the receiver using the ML detector is given by

$$\hat{\mathbf{x}} = \left(\hat{\boldsymbol{\lambda}}, \hat{s}\right) = \underset{\boldsymbol{\lambda}, s}{\arg\min} \|\mathbf{y} - \mathbf{H}_l \boldsymbol{\lambda} s\|^2. \quad (4)$$

III. Error Performance Analysis

A. Performance of ReIM-OFDM-MRC

1) PEP analysis for ReIM-OFDM-MRC: An error occurs when the receiver incorrectly detects an M-ary symbol and/or an index of active sub-carriers. We first analyze the index detection error using the well-known conditional pairwise index-detection error probability (PEP) of the ML detector. PEP is defined as the probability that the receiver mistakenly decides the i-th index vector with the j-th index vector while the i-th index vector was transmitted. PEP can be given by

$$P(\boldsymbol{\lambda}_i \to \boldsymbol{\lambda}_j | \boldsymbol{\lambda}_i) = Q\left(\sqrt{\frac{\varphi E_s \|\mathbf{H}_l \boldsymbol{\lambda}_i - \mathbf{H}_l \boldsymbol{\lambda}_j\|^2}{2N_0}}\right), \quad (5)$$

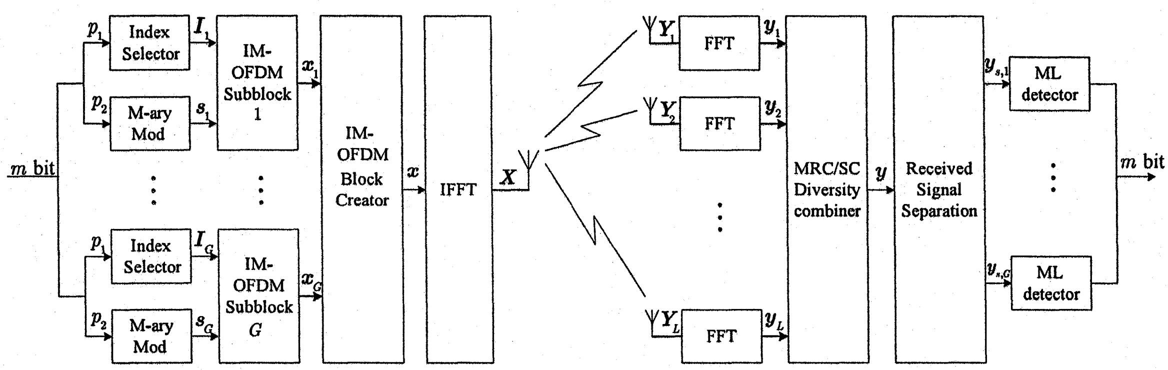

Fig. 1. Block diagram of the ReIM-OFDM system.

where $\boldsymbol{\lambda}_i$ and $\boldsymbol{\lambda}_j$ represent the transmitted and the detected index vector, respectively. $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp\left(-\frac{y^2}{2}\right) dy$ is the Gaussian probability integral [14].

Expanding (5) using the Hamming distance between $\boldsymbol{\lambda}_i$ and $\boldsymbol{\lambda}_j$ we can have PEP given by

$$P_{\mathrm{MRC}}(\boldsymbol{\lambda}_i \to \boldsymbol{\lambda}_j) = Q\left(\sqrt{\frac{\gamma_{\alpha}^{\mathrm{MRC}} + \gamma_{\tilde{\alpha}}^{\mathrm{MRC}}}{2}}\right), \quad (6)$$

where $\alpha \in \theta_i$, $\tilde{\alpha} \in \theta_j$ such that $\alpha, \tilde{\alpha} \notin \theta_i \cap \theta_j$ with α and $\tilde{\alpha}$ denoting the active and inactive sub-carrier; θ_i and θ_j represent the corresponding index set of vectors $\boldsymbol{\lambda}_i$, $\boldsymbol{\lambda}_j$, respectively. $\gamma_{\alpha} = \bar{\gamma}|h(\alpha)|^2$ is referred to as the instantaneous SNR per sub-carrier.

Using the union bound, the probability of incorrect index detection of $\boldsymbol{\lambda}_i$ can be given by

$$\mathrm{PEP}_i^{\mathrm{MRC}} \leq \sum_{i=1, j\neq i}^{c} P_{\mathrm{MRC}}(\boldsymbol{\lambda}_i \to \boldsymbol{\lambda}_j). \quad (7)$$

Consequently, we have the instantaneous PEP of ReIM-OFDM-MRC given by

$$\mathrm{PEP}_{\mathrm{MRC}} = \frac{1}{c}\sum_{i=1}^{c} \mathrm{PEP}_i^{\mathrm{MRC}} \leq \frac{1}{c} \sum_{i=1, j\neq i}^{c} P_{\mathrm{MRC}}(\boldsymbol{\lambda}_i \to \boldsymbol{\lambda}_j). \quad (8)$$

Furthermore, let Ω_i denote the set of indices j $(j \neq i)$ such that $\boldsymbol{\lambda}_j$ satisfies the Hamming distance with $\boldsymbol{\lambda}_i$. The cardinality of Ω_i is denoted by η_i. Using equations (6) and (7) and noting that $\mathrm{PEP}_i^{\mathrm{MRC}}$ is constrained by the following condition $P_{\mathrm{MRC}}(\boldsymbol{\lambda}_i \to \boldsymbol{\lambda}_j | j \in \Omega_i)$, we have

$$\sum_{i=1, j\neq i}^{c} P_{\mathrm{MRC}}(\boldsymbol{\lambda}_i \to \boldsymbol{\lambda}_j) \approx \sum\nolimits_{j\in\Omega_i} P_{\mathrm{MRC}}(\boldsymbol{\lambda}_i \to \boldsymbol{\lambda}_j).$$

Therefore, the PEP in (8) can be approximated by

$$\begin{aligned} \mathrm{PEP}_{\mathrm{MRC}} &\leq \frac{1}{c}\sum_{i=1}^{c}\sum_{j\in\Omega_i} P_{\mathrm{MRC}}(\boldsymbol{\lambda}_i \to \boldsymbol{\lambda}_j), \\ &= \frac{1}{c}\sum_{i=1}^{c}\sum_{j\in\Omega_i} P_{\mathrm{MRC}}(\alpha \to \tilde{\alpha}), \end{aligned} \quad (9)$$

where $P_{\mathrm{MRC}}(\alpha \to \tilde{\alpha}) = Q\left(\frac{\gamma_{\alpha}^{\mathrm{MRC}} + \gamma_{\tilde{\alpha}}^{\mathrm{MRC}}}{2}\right) = Q\left(\frac{\gamma_{\Sigma}^{\mathrm{MRC}}}{2}\right)$ represents the PEP that the receiver mistakenly detects an active sub-carrier $\alpha \in \theta_i$ by an inactive sub-carrier $\tilde{\alpha} \in \theta_j$, $\gamma_{\Sigma}^{\mathrm{MRC}} = \gamma_{\alpha}^{\mathrm{MRC}} + \gamma_{\tilde{\alpha}}^{\mathrm{MRC}}$.

Thus, the average PEP of ReIM-OFDM-MRC can be approximated by

$$\overline{\mathrm{PEP}}_{\mathrm{MRC}} \leq \frac{1}{c}\sum_{i=1}^{c}\sum_{j\in\Omega_i} \mathbb{E}_{\gamma_{\Sigma}^{\mathrm{MRC}}}\left\{Q\left[\sqrt{\frac{\gamma_{\Sigma}^{\mathrm{MRC}}}{2}}\right]\right\}. \quad (10)$$

Using the approximation $Q(x) \approx \frac{1}{12}e^{-\frac{x^2}{2}} + \frac{1}{4}e^{-\frac{2}{3}x^2}$ [15], equation (10) can be rewritten as

$$\overline{\mathrm{PEP}}_{\mathrm{MRC}} \approx \mathbb{E}_{\gamma_{\Sigma}^{\mathrm{MRC}}}\left\{\frac{\sum_{i=1}^{c}\eta_i}{c}\left(\frac{1}{12}e^{-\frac{\gamma_{\Sigma}^{\mathrm{MRC}}}{4}} + \frac{1}{4}e^{-\frac{\gamma_{\Sigma}^{\mathrm{MRC}}}{3}}\right)\right\}. \quad (11)$$

Using the MGF defined in [14]: $\mathcal{M}_{\gamma}(s) = \mathbb{E}_{\gamma}\{e^{-s\gamma}\}$. The MGF of $\gamma_{\Sigma}^{\mathrm{MRC}}$ can be then defined as

$$\mathcal{M}_{\gamma_{\Sigma}^{\mathrm{MRC}}}(s) = \mathcal{M}_{\gamma}^{2L}(s) = \frac{1}{(1-\bar{\gamma}s)^{2L}}. \quad (12)$$

Then it is possible to obtain the closed-form expression for the approximate average PEP of Re-IM-MRC as

$$\begin{aligned} \overline{\mathrm{PEP}}_{\mathrm{MRC}} &\leq \frac{\sum_{i=1}^{c}\eta_i}{12c}\left[\mathcal{M}_{\gamma_{\Sigma}^{\mathrm{MRC}}}\left(-\frac{1}{4}\right) + 3\mathcal{M}_{\gamma_{\Sigma}^{\mathrm{MRC}}}\left(-\frac{1}{3}\right)\right], \\ &= \frac{\sum_{i=1}^{c}\eta_i}{12c}\left[\frac{16^L}{(4+\bar{\gamma})^{2L}} + \frac{3^{2L+1}}{(3+\bar{\gamma})^{2L}}\right]. \end{aligned} \quad (13)$$

From (13), it is clear that the average PEP only depends on N and K because $\bar{\gamma} = \frac{NE_s}{KN_0}$ and $c = 2^{\lfloor \log_2 C(K,N) \rfloor}$. Furthermore, for a given N and K, the PEP is only affected by the index symbol $\boldsymbol{\lambda}$ via the term $\sum_{i=1}^{c}\eta_i$.

2) SEP analysis for ReIM-OFDM-MRC: The SEP represents the probability that the receiver incorrectly detects the M-ary symbol and/or the index symbol. Thus, the instantaneous SEP of the system and its average value can be upper bounded by

$$\text{SEP} \leq \frac{1}{c}\sum_{i=1}^{c}\frac{1}{2}\left[\sum\nolimits_{j\in\Omega_i} P\left(\alpha \to \tilde{\alpha}\right) + P_M\right], \tag{14}$$

where P_M denotes the instantaneous SEP of the M-ary symbol. For the case of MRC, the average SEP is given by

$$\overline{\text{SEP}}_{\text{MRC}} \leq \frac{\overline{\text{PEP}}_{\text{MRC}} + \overline{P}_{M_{\text{MRC}}}}{2}, \tag{15}$$

where the average SEP of the M-ary symbol is defined as $\overline{P}_{M_{\text{MRC}}} \approx 2Q\left(\sqrt{2\gamma_{\Sigma\alpha}^{\text{MRC}}}\sin\left(\pi/M\right)\right)$ [14], $\gamma_{\Sigma\alpha}^{\text{MRC}} = \sum_{l=1}^{L}\sum_{k=1}^{K}\gamma_{l,\alpha_k}$ and $\alpha_k \in \theta_i$. Using the same approximation of the Q-function in (11), $\overline{P}_{M_{\text{MRC}}}$ can be given by

$$\overline{P}_{M_{\text{MRC}}} \approx \frac{1}{6}\left(e^{-\rho\gamma_{\Sigma\alpha}^{\text{MRC}}} + 3e^{-\frac{4\rho\gamma_{\Sigma\alpha}^{\text{MRC}}}{3}}\right), \tag{16}$$

where $\rho = \sin^2\left(\pi/M\right)$. Using the MGF approach for the random variable $\gamma_{\Sigma\alpha}^{\text{MRC}}$, the MGF of $\gamma_{\Sigma\alpha}^{\text{MRC}}$ given by

$$\mathcal{M}_{\gamma_{\Sigma\alpha}^{\text{MRC}}}\left(s\right) = \mathcal{M}_{\gamma}^{LK}\left(s\right) = \frac{1}{\left(1-\overline{\gamma}s\right)^{LK}}. \tag{17}$$

Equation (16) can be now given by

$$\overline{P}_{M_{\text{MRC}}} \approx \frac{1}{6}\left[\frac{1}{\left(1+\rho\overline{\gamma}\right)^{LK}} + \frac{3}{\left(1+\frac{4\rho\overline{\gamma}}{3}\right)^{LK}}\right]. \tag{18}$$

Following the same steps in (13), (15) and (18), the average SEP for the ReIM-OFDM-MRC can be approximated by

$$\begin{aligned}\overline{\text{SEP}}_{\text{MRC}} \leq & \frac{\sum_{i=1}^{c}\eta_i}{24c}\left[\frac{16^L}{\left(4+\overline{\gamma}\right)^{2L}} + \frac{3^{2L+1}}{\left(3+\overline{\gamma}\right)^{2L}}\right], \\ & + \frac{1}{12}\left[\frac{1}{\left(1+\rho\overline{\gamma}\right)^{LK}} + \frac{3}{\left(1+\frac{4\rho\overline{\gamma}}{3}\right)^{LK}}\right].\end{aligned} \tag{19}$$

Note from (19) that as the $\overline{\gamma}$ increases to infinity, we have $\overline{\text{SEP}}_{\text{MRC}} \approx \overline{\gamma}^{-2L}$. This means that the achievable diversity order of the ReIM-OFDM-MRC is $2L$.

B. Performance of ReIM-OFDM-SC

1) PEP analysis for ReIM-OFDM-SC: The PEP of ReIM-OFDM-SC can be derived using the similar method for the ReIM-OFDM-MRC. However, ReIM-OFDM-SC uses the diversity branch with the highest SNR. In order to find the instantaneous SNR of the ReIM-OFDM-SC, we can use the probability density function (PDF) of the effective SNR for SC given in [11] as follows

$$f_{\gamma}\left(\gamma_\alpha\right) = \frac{L}{\overline{\gamma}}\sum_{l=0}^{L-1}\binom{L-1}{l}\left(-1\right)^l e^{-\gamma_\alpha\frac{l+1}{\overline{\gamma}}}. \tag{20}$$

Note that

$$\gamma_\alpha^{\text{SC}} = \max_{l=1,L}\gamma_{l,\alpha}^{\text{SC}},$$

where $\gamma_{l,\alpha}^{\text{SC}}$ denotes the instantaneous SNR of the l-th branch at sub-carrier α. Hence, the MGF of the random variable $\gamma_\alpha^{\text{SC}}$ can be given by

$$\mathcal{M}_{\gamma_\alpha^{\text{SC}}}\left(z\right) = L\sum_{l=0}^{L}\binom{L-1}{l}\frac{\left(-1\right)^l}{l+1-z\overline{\gamma}}. \tag{21}$$

The MGF of $\gamma_\Sigma^{\text{SC}} = \gamma_\alpha^{\text{SC}} + \gamma_{\tilde{\alpha}}^{\text{SC}}$ can be obtained by

$$\mathcal{M}_{\gamma_\Sigma^{\text{SC}}}\left(z\right) = \mathcal{M}_{\gamma_\alpha^{\text{SC}}}^2\left(z\right).$$

Similar to equation (13), the approximate PEP of the ReIM-OFDM-SC is given by

$$\begin{aligned}\overline{\text{PEP}}_{\text{SC}} \leq & \frac{\sum_{i=1}^{c}\eta_i}{12c}\left[\mathcal{M}_{\gamma_\Sigma^{\text{SC}}}\left(-\frac{1}{4}\right) + 3\mathcal{M}\gamma_\Sigma^{\text{SC}}\left(-\frac{1}{3}\right)\right], \\ = & \frac{L^2\sum_{i=1}^{c}\eta_i}{12c}\left(\overline{\text{PEP}}_1 + 3\overline{\text{PEP}}_2\right),\end{aligned} \tag{22}$$

where $\overline{\text{PEP}}_1$ and $\overline{\text{PEP}}_2$ are defined as

$$\begin{aligned}\overline{\text{PEP}}_1 &= \left[\sum_{l=0}^{L-1}\binom{L-1}{l}\frac{4(-1)^l}{4l+4+\overline{\gamma}}\right]^2, \\ \overline{\text{PEP}}_2 &= \left[\sum_{l=0}^{L-1}\binom{L-1}{l}\frac{3(-1)^l}{3l+3+\overline{\gamma}}\right]^2.\end{aligned} \tag{23}$$

Following (16), the instantaneous SEP of the M-ary symbol of the ReIM-OFDM-SC can be approximated by

$$\overline{P}_{M_{\text{SC}}} \approx \frac{L^2}{6}\left(\overline{P}_{M_{\text{SC}_1}} + 3\overline{P}_{M_{\text{SC}_2}}\right), \tag{24}$$

where $\overline{P}_{M_{\text{SC}_1}}$ and $\overline{P}_{M_{\text{SC}_2}}$ are respectively given by

$$\begin{aligned}\overline{P}_{M_{\text{SC}_1}} &= \left[\sum_{l=0}^{L-1}\binom{L-1}{l}\frac{(-1)^l}{l+1+\rho\overline{\gamma}}\right]^K, \\ \overline{P}_{M_{\text{SC}_2}} &= \left[\sum_{l=0}^{L-1}\binom{L-1}{l}\frac{3(-1)^l}{3l+3+4\rho\overline{\gamma}}\right]^K.\end{aligned} \tag{25}$$

Consequently, the approximate expression for the average SEP of the ReIM-OFDM-SC is given by

$$\begin{aligned}\overline{\text{SEP}}_{\text{SC}} \approx & \frac{L^2\sum_{i=1}^{c}\eta_i}{24c}\left(\overline{\text{PEP}}_1 + 3\overline{\text{PEP}}_2\right) \\ & + \frac{L^2}{12}\left(\bar{P}_{M_{\text{SC}_1}} + 3\bar{P}_{M_{\text{SC}_2}}\right).\end{aligned} \tag{26}$$

where $\overline{\text{PEP}}_1$, $\overline{\text{PEP}}_2$, and $\overline{P}_{M_{\text{SC}_1}}$, $\overline{P}_{M_{\text{SC}_2}}$ are given in (23) and (25), respectively.

IV. Performance Evaluation and Discussion

In this section, we present the performance evaluation results for the proposed ReIM-OFDM systems. The SEP of the two ReIM-OFDM schemes under different scenarios are evaluated and compared with the conventional IM-OFDM in [1] and the IM-OFDM with diversity reception in [11]. The channel is assumed to undergo the frequency-selective

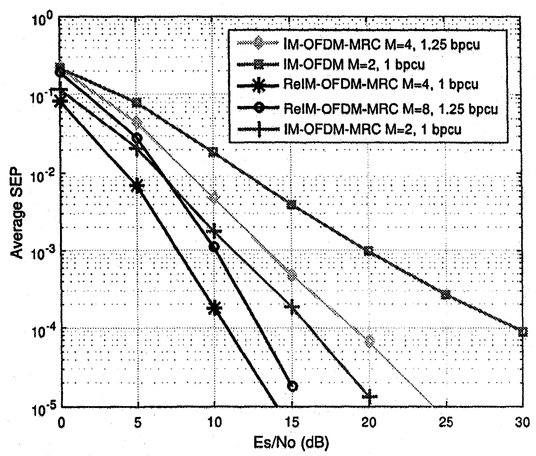

Fig. 2. SEP performance comparison of ReIM-OFDM-MRC, conventional IM-OFDM, and IM-OFDM-MRC.

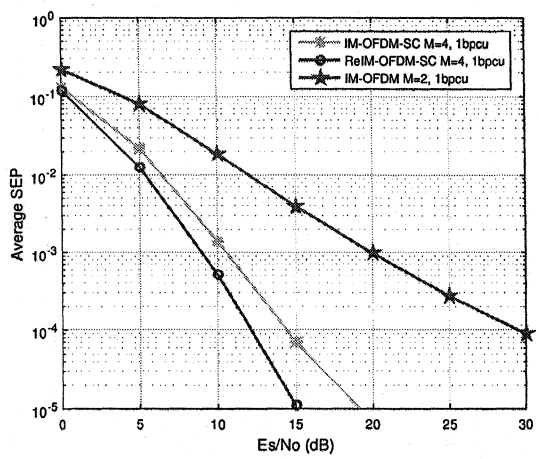

Fig. 3. SEP performance comparision of ReIM-OFDM-SC, conventional IM-OFDM and IM-OFDM-SC.

Rayleigh fading with the delay spread D shorter than the cyclic prefix length of OFDM. This assumption guarantees that the frequency selectivity of the channel is perfectly equalized and no inter-symbol interference (ISI) appears in the system. The channel state information (CSI) is known perfectly at the receiver side. Simulation results are used to verify the theoretical analysis.

A. SEP performance evaluation

Fig. 2 depicts the SEP performance of the ReIM-OFDM-MRC compared with the conventional IM-OFDM, and the IM-OFDM-MRC system with ML detection in [11], $N = 4$, $K = 2$, and $L = 2$. It can be seen from the figure that, at the same spectral efficiency, the proposed ReIM-OFDM-MRC system outperforms the IM-OFDM-MRC thanks to the frequency diversity. Since the proposed ReIM-OFDM-MRC system uses 2 activated sub-carriers ($K = 2$), it achieves the maximum diversity order $2L = 4$, whereas the IM-OFDM-MRC can only has diversity order $L = 2$. As expected the plotted SEP curves show the diversity order 4 for the ReIM-OFDM-MRC while only 2 for the IM-OFDM-MRC. The conventional IM-OFDM system exhibits the worst performance as no spatial diversity is used, i.e. $L = 1$. This system attains only diversity order 1.

Fig. 3 illustrates the SEP performance of the ReIM-OFDM-SC in comparison with the conventional IM-OFDM, and the IM-OFDM-SC system at the spectral efficiency of 1 bpcu. It can be realized that when SC is used, the proposed ReIM-OFDM system also outperforms the other related systems. However, the correct diversity orders of the three systems are not easy to deduce due to use of SC.

The effect of increasing the spatial diversity branches on the SEP performance of the proposed ReIM-OFDM system when using MRC and SC is illustrated in Fig. 4. As can be seen from the figure, the performance of both ReIM-OFDM-MRC and ReIM-OFDM-SC are significantly improved when increasing the number of space diversity branches. However, the ReIM-OFDM-MRC achieves more performance improvement as MRC can provide higher diversity gain than SC.

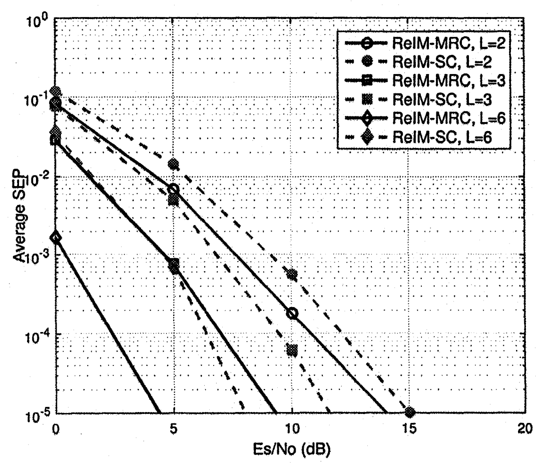

Fig. 4. SEP performance of ReIM-OFDM-MRC and ReIM-OFDM-SC with $L = 2, 3, 6$

B. Theoretical analysis verification

In order to verify the theoretical analysis, simulated SEP curves are compared with those obtained by the analytical results for different M, N, and K in Fig. 5. As realized from the figure, the curves obtained by the approximate SEPs given in (19) and (26) well match with those by simulations for both ReIM-OFDM-MRC and ReIM-OFDM-SC. This verifies our theoretical analysis.

C. Effect of K on the SEP performance

Fig. 6 illustrates the impact of the number of active sub-carriers K on the SEP of ReIM-OFDM-MRC and ReIM-OFDM-SC at the same spectral efficiency of 0.875 bpcu. We can see that, for the ReIM-OFDM-MRC, the best SEP performance can be obtained with $K = 2$. Similar observation can also be made with the ReIM-OFDM-SC. Hence, we should choose K not larger than 2. This statement is appropriate since our analysis results in (19) and (26) have proved that the maximum diversity order is limited by $2L$.

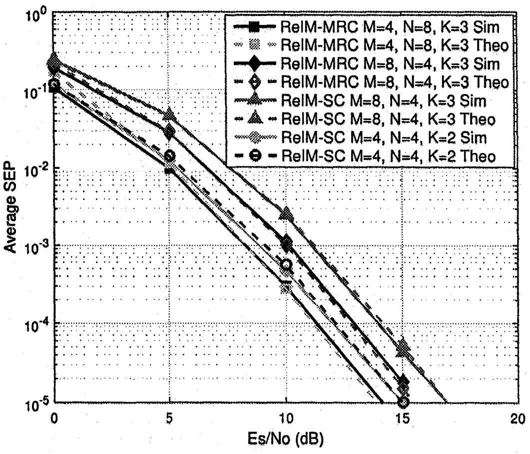

Fig. 5. Theoretical analysis verification for ReIM-OFDM-MRC and ReIM-OFDM-SC.

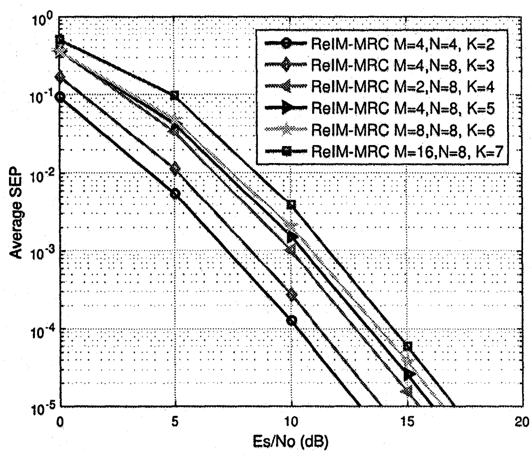

Fig. 6. The effect of K on the SEP of ReIM-OFDM-MRC with different parameters.

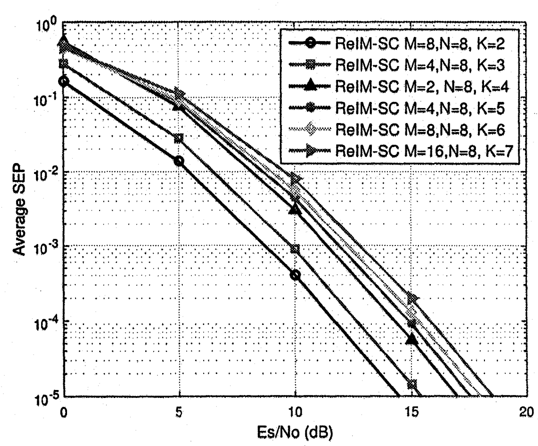

Fig. 7. The effect of K on the SEP of ReIM-OFDM-SC with different parameters.

V. Conclusion

In this paper, we have introduced an enhanced IM-OFDM scheme, i.e. ReIM-OFDM, which can exploit both space and frequency diversity for SIMO communication systems. The proposed scheme was shown to outperform the conventional IM-OFDM and the IM-OFDM with diversity reception at the same spectral efficiency. Using mathematical approximations we have also successfully obtained the closed-form expression of PEP and SEP in both cases: ReIM-OFDM-MRC and ReIM-OFDM-SC. Our expressions of PEP and SEP can be used to analyze the performance of our proposed scheme and investigate impacts of ReIM-OFDM parameters on the performance. In the future work, we intend to analyze the performance of the ReIM-OFDM scheme with multipath diversity.

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