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Signal Detection Using Ordered Successive Interference Cancellation for Generalized Spatial Modulation Systems

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Abstract

In this paper, an improved ordered block minimum mean squared error (OB-MMSE) detector for generalized spatial modulation (GSM) systems is presented. It is based on an ordered successive interference cancellation (OSIC) technique. Its bit error rate (BER) performance and computational complexity are compared with those of the corresponding original OB-MMSE detector. It is shown that the proposed OSIC-based OB-MMSE detector outperforms the OB-MMSE detector in terms of BER without noticeable complexity increase.

Keywords: *spatial modulation (SM), generalized spatial modulation (GSM), multiple input multiple output (MIMO), ordered block minimum mean squared error (OB-MMSE), ordered successive interference cancellation (OSIC).*

1. Introduction

Spatial modulation (SM) approach [1-3] has been developed as a novel energy-efficient and low-complexity multiple input multiple output (MIMO) scheme. In SM, a single transmit antenna among N_T transmit antennas is allowed to be active for a signal transmission at each time slot, but the additional spatial dimension associated with antenna index is exploited to carry extra information bits. Then the spectral efficiency of SM is given by $\log_2(MN_T)$, where M is the symbol constellation size.

To further increase the transmission rates, generalized spatial modulation (GSM) [4,5] has been recently proposed, where multiple transmit antennas are simultaneously activated for spatial multiplexing in each time slot. However, GSM systems use the detection algorithm with higher complexity due to the presence of inter channel interference (ICI). The optimum maximum likelihood (ML) detector jointly searches all possible transmit antenna combinations (TACs) and the symbol vectors, which results in requiring prohibitively high computational complexity, especially for large-scale antenna systems with high-level signal constellations.

In recent years, several suboptimal detectors [5-8] have been proposed to reduce the complexity. In [5], a zero-forcing (ZF) receiver has been considered, but its error performance is considerably degraded when compared to optimal ML detection. In [6], an ordered-blocked minimum-mean-squared-error (OB-MMSE) detector has been proposed. It can achieve substantial reduction in complexity compared to ML. However its error performance may be still far from ML when the number of active transmit antennas is relatively large and/or the number of receive antennas is not relatively large enough [7].

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This work considers an ordered successive interference cancellation (OSIC) technique [9] to improve error performance. In OSIC, nulling and cancellation operations are taken by the optimal detection order, which is obtained by selecting a stream with the largest post-processing signal-to-interference-plus-noise ratio (SINR) at each stage of the detection process. MMSE and zero-forcing methods can be mostly employed for the nulling step. In this work, an improved OB-MMSE-OSIC detector for GSM is proposed with MMSE-OSIC instead of MMSE. It is shown that the complexity increase due to OSIC is minor while achieving significant enhancement of error performance compared to the OB-MMSE detector. To the best of knowledge, an OSIC-based detection scheme for GSM systems is not yet available in literature.

2. System Model

Consider a GSM system with N_T transmit antennas and N_R receive antennas, where N_P $\left(N_P < N_T\right)$ transmit antennas are activated for data transmission in each time slot. Thus the number of all possible transmit antenna combinations (TACs) can be given by $C_{N_P}^{N_T}$, which denotes the binomial coefficient. Among them, $N = 2^{\left\lfloor \log_2\left(C_{N_P}^{N_T}\right)\right\rfloor}$ transmit antenna combinations are selected to carry $B_1 = \log_2\left(N\right)$ bits of information, where $\lfloor \cdot \rfloor$ represents the floor operation. In a GSM scheme, the information bits are divided into two parts, B_1 bits are utilized for TAC mapping, $B_2 = N_P \log_2\left(M\right)$ bits are modulated for transmitting N_P M-ary QAM symbols by a spatial multiplexer. Then the transmit symbol vector $\mathbf{x}_{I_i}$ corresponding to a TAC I_i $\left(i \in \{1, 2, \cdots, N\}\right)$ can be formed as

$$\mathbf{x}_{I_i} = \left[\cdots, 0, s_{i_1}, 0, \cdots, 0, s_{i_2}, 0, \cdots, 0, s_{i_{N_P}}, 0, \cdots\right]^T \tag{1}$$

where there are N_P non-zero elements and the activated TA indices are indicated by $\left(i_1, i_2, \cdots, i_{N_P}\right)$. Here the symbol, s_{i_j}, $j = 1, 2, \cdots, N_P$, is drawn from the constellation set S of M-ary QAM.

It is assumed that the MIMO channel matrix is represented by $\mathbf{H} \in C^{N_R \times N_T}$, whose elements are independent and identically distributed (i.i.d.) random variables with circularly symmetric complex-valued Gaussian distribution $CN\left(0,1\right)$. Then the $N_R \times 1$ received signal vector can be expressed as

$$\mathbf{y} = \mathbf{H}\mathbf{x}_{I_i} + \mathbf{n} = \sum_{k=i_1}^{i_{N_P}} \mathbf{h}_k s_k + \mathbf{n} = \mathbf{H}_{I_i}\mathbf{s} + \mathbf{n} \tag{2}$$

wehre $\mathbf{s} = \begin{bmatrix} s_{i_1} & s_{i_2} & \cdots & s_{i_{N_P}} \end{bmatrix}^T$ is the transmit symbol vector associated with the TAC $I_i = \left(i_1, i_2, \cdots, i_{N_P}\right)$ and $\mathbf{n} = \begin{bmatrix} n_1 & n_2 & \cdots & n_{N_R} \end{bmatrix}^T$ is an $N_R \times 1$ complex additive white Gaussian noise (AWGN) vector with i.i.d. entries $n_r \sim CN\left(0, \sigma^2\right)$, $r = 1, 2, \cdots, N_R$, where σ^2 is the noise variance. Here $\mathbf{h}_k$ is the k-th column vector of $\mathbf{H}$ and $\mathbf{H}_{I_i} = \begin{bmatrix} \mathbf{h}_{i_1} & \mathbf{h}_{i_2} & \cdots & \mathbf{h}_{i_{N_P}} \end{bmatrix}$ is the sub-matrix of $\mathbf{H}$ associated with the TAC I_i .

The joint ML detector is given by

$$\left(\hat{\mathbf{I}}, \hat{\mathbf{s}}\right)_{ML} = \underset{I \in \Gamma, s \in \Omega}{\arg\min} \left\| \mathbf{y} - \mathbf{H}_I \mathbf{s} \right\|_F^2 \tag{3}$$

where $\Gamma = (I_1, I_2, \cdots, I_N)$ is the set of TACs and $\Omega = S^{N_P \times 1}$ is the set of all possible N_P-dimensional transmitted symbol vectors. Although the ML detector offers the optimal performance by exhaustively searching through all possible TACs and transmitted signal vectors, its complexity becomes huge for a large-dimension systems.

3. Proposed OSIC-based MMSE Detector

3.1 OB-MMSE Detector[6]

The OB-MMSE detector takes two separate stages for signal detection, one of the TAC set and the other for the symbol vector. The first stage is to prioritize TAC candidates, which will be tested for consecutive symbol detection. First, the ordering algorithm obtains $\mathbf{z}_l = \mathbf{h}_l^{\dagger}\mathbf{y}$ where $\mathbf{h}_l^{\dagger} = \mathbf{h}_l^H / \|\mathbf{h}_l\|^2$. Then a weighting factor w_i associated with the specific TAC set I_i is computed as $w_i = \sum_{q=1}^{N_P} |z_{i_q}|^2$. After N weighting factors $\mathbf{w} = (w_1, w_2, \cdots, w_N)$ are obtained, the ordered TACs indices are given as

$$[l_1, l_2, \cdots, l_N] = \arg \mathrm{sort}(\mathbf{w}) \tag{4}$$

where $\mathrm{sort}(\cdot)$ denotes a descending order function and l_1 is the index of the maximum element in $\mathbf{w}$. The second stage is to estimate an N_P-dimension symbol vector for each possible TAC by employing a minimum mean-squared error (MMSE) detector, which can be given as

$$\tilde{\mathbf{s}}_{l_i} = Q\left(\left(\mathbf{H}_{I_{l_i}}^H \mathbf{H}_{I_{l_i}} + \sigma^2 \mathbf{I}_{N_P}\right)^{-1} \mathbf{H}_{I_{l_i}}^H \mathbf{y}\right) \tag{5}$$

where $Q(\cdot)$ denotes the digital demodulation function. Instead of detecting all the N possible TACs, the OB-MMSE detector can reduce the computational complexity by using the following termination condition

$$\left\|\mathbf{y} - \mathbf{H}_{I_{l_i}} \tilde{\mathbf{s}}_{l_i}\right\|_F^2 \le V_{th} \tag{6}$$

wehre $V_{th} = N_R \sigma^2$ is a preset termination threshold. That is, it terminates once the output $(I_{l_i}, \hat{s}_{l_i})$ meets the above. If no output satisfies the above, the final detection result is obtained as

$$(\hat{I}, \hat{s})_{OB} = \underset{(I,\mathbf{s}) \in A_{OB}}{\arg\min} \|\mathbf{y} - \mathbf{H}_I \mathbf{s}\|_F^2 \tag{7}$$

where $A_{OB} = \left((I_{l_1}, \tilde{\mathbf{s}}_{l_1}), (I_{l_2}, \tilde{\mathbf{s}}_{l_2}), \cdots, (I_{l_N}, \tilde{\mathbf{s}}_{l_N})\right)$.

3.2 OB-MMSE-OSIC Detector

The OB-MMSE-OSIC detector takes two separate stages for signal detection, one for the TAC set and the other for the symbol vector. The first stage, which is the same as that of original OB-MMSE detector [6], is to prioritize TAC candidates which will be tested for consecutive symbol detection. The second stage is to estimate an N_P-dimension symbol vector for each possible TAC by employing an MMSE-OSIC detector instead of the conventional block MMSE detection. Based on an optimal detection order, the OSIC detection for MMSE receiver cancels the interference by linearly weighting the received vector with a MMSE-based nulling vector. The optimal detection order is obtained by finding a stream with the maximum post-processing signal-to-interference-plus-noise ratio (SINR) at each detection step. The SINR at the t-th layer of the c-th detection step for MMSE-OSIC receiver is expressed as

$$SINR_{c,t} = \frac{1}{\sigma^2\left[\left(\mathbf{H}^H_{(N_P-c+1)}\mathbf{H}_{(N_P-c+1)}+\sigma^2\mathbf{I}_{N_P-c+1}\right)^{-1}\right]_{tt}}-1,\ \ c\in\{1,2,\cdots,N_P\},\ \ t\in\{1,2,\cdots,N_P-c+1\} \quad (8)$$

where $\mathbf{H}_{(N_P-c+1)}$ represents a reduced $N_R\times(N_P-1+1)$ submatrix at the c-th detection step associated with each TAC.

Instead of detecting $\tilde{\mathbf{s}}_{l_i}$ for all the N possible TACs, the OB-MMSE-OSIC detector can reduce the computational complexity by using the following termination condition $\left\|\mathbf{y}-\mathbf{H}_{I_{l_i}}\tilde{\mathbf{s}}_{l_i}\right\|_F^2\le V_{th}$ where V_{th} is a preset termination threshold. If no output satisfies the above, the final detection result is obtained as

$$\left(\hat{I},\hat{\mathbf{s}}\right)=\arg\min_{(I,\mathbf{s})\in\mathrm{A}}\left\|\mathbf{y}-\mathbf{H}_I\mathbf{s}\right\|_F^2 \quad (9)$$

where $A=\left(\left(I_{l_1},\tilde{\mathbf{s}}_{l_1}\right),\left(I_{l_2},\tilde{\mathbf{s}}_{l_2}\right),\cdots,\left(I_{l_N},\tilde{\mathbf{s}}_{l_N}\right)\right)$. The proposed OB-MMSE-OSIC detection algorithm can be described in Table 1, where $\mathbf{h}_k$, $\mathbf{g}_c^{(k_c)}$, $Q(\cdot)$, and $\mathbf{h}_{c,k_c}$, respectively, denote the k-th column vector of $\mathbf{H}$, the k_c-th row vector of $\mathbf{G}_c$, the digital demodulation function, and the k_c-th column vector of $\mathbf{H}_c$. Here $\mathbf{H}_c^{\bar{k}_c}$ describes the nulling of column k_c of $\mathbf{H}_c$. Note that the ordering algorithm in line 1 to line 7 of Table 1 is the same as that of original OB-MMSE detector.

3.3 Complexity Comparisons

In this section, the computational complexity is evaluated in terms of real-valued floating point operations (flops), which include real-valued multiplications and real-valued additions, as shown in [8]. The complexity of the original OB-MMSE detector is given by [8]

$$\begin{aligned}C_{OB-MMSE} &= 12N_RN_T+2N_T+N\left(N_P-1\right)\\ &+\left(4N_P^3+\left(12N_R+7\right)N_P^2+14N_RN_P+4N_R-1\right)\gamma_{OB-MMSE}\end{aligned} \quad (10)$$

where $\gamma_{OB-MMSE}$ denotes the average detecting number of GSM symbols for the OB-MMSE.

The complexity of the proposed OB-MMSE-OSIC detector can be counted as

$$\begin{aligned}C_{OB-MMSE-OSIC} &= 12N_RN_T+2N_T+N\left(N_P-1\right)\\ &+\left(4N_R-1+\sum_{c=1}^{N_P}\left(4\left(N_P-c+1\right)^3+\left(12N_R+7\right)\left(N_P-c+1\right)^2+6N_R\left(N_P-c+1\right)+3\right)\right)\gamma_{OB-MMSE-OSIC}\end{aligned} \quad (11)$$

where $\gamma_{OB-MMSE-OSIC}$ indicates the average detecting numbers of GSM symbols for the OB-MMSE-OSIC.

Table 1. OB-MMSE-OSIC detector

$\mathbf{h}_k^{\dagger} = \mathbf{h}_k^H / \|\mathbf{h}_k\|^2, \ k \in \{1, 2, \cdots, N_T\}$

for $i = 1, 2, \cdots, N$

  $\mathrm{z}_{i_q} = \mathbf{h}_{i_q}^{\dagger} \mathbf{y}, \ q \in \{1, 2, \cdots, N_P\}$

  $\alpha_i = \sum_{q=1}^{N_P} \left| \mathrm{z}_{i_q} \right|^2$

end for

$\boldsymbol{\alpha} = [\alpha_1, \alpha_2, \cdots, \alpha_N]$

$[l_1, l_2, \cdots, l_N] = \arg \operatorname{sort}(\boldsymbol{\alpha})$

$i = 1$

while $i \le N$

  $\mathbf{H}_1 = \mathbf{H}_{I_{l_i}}$

  $\mathbf{y}_1 = \mathbf{y}$

  for $c = 1, 2, \cdots, N_P$

    $\tilde{\mathbf{H}}_c = \mathbf{H}_c^H \mathbf{H}_c$

    $\boldsymbol{\Xi}_c = \left(\tilde{\mathbf{H}}_c + \sigma^2 \mathbf{I}_{N_P - c + 1} \right)^{-1}$

    $\mathrm{SINR}_{c,t} = \dfrac{1}{\sigma^2 [\boldsymbol{\Xi}_c]_{tt}} - 1, \ t \in \{1, 2, \cdots, N_P - c + 1\}$

    $k_c = \arg \max_{t = 1, 2, \cdots, N_P - c + 1} \mathrm{SINR}_t$

    $\mathbf{G}_c = \boldsymbol{\Xi}_c \mathbf{H}_c^H$

    $\mathbf{w}_{k_c}^T = \mathbf{g}_c^{(k_c)}$

    $\hat{s}_{k_c} = Q\left(\mathbf{w}_{k_c}^T \mathbf{y}_c \right)$

    $\mathbf{y}_{c+1} = \mathbf{y}_c - \mathbf{h}_{c,k_c} \hat{s}_{k_c}$

    $\mathbf{H}_{c+1} = \mathbf{H}_c^{\bar{k}_c}$

  end for

  $d_i = \left\| \mathbf{y} - \mathbf{H}_{I_{l_i}} \hat{\mathbf{s}}_{l_i} \right\|_F^2$

  if $d_i \le V_{th}$

    $(\hat{I}, \hat{\mathbf{s}}) = (I_{I_{l_i}}, \hat{\mathbf{s}}_{l_i})$, break;

  else

    $i = i + 1$

  end if

end while

if $i > N$

  $v = \arg \min_i d_i, \ i \in \{1, 2, \cdots, N\}$

  $(\hat{I}, \hat{\mathbf{s}}) = (I_{I_{l_v}}, \hat{\mathbf{s}}_{l_v})$

end if

4. Simulation Results

In this section, the bit error rate (BER) performance and complexity of the proposed OB-MMSE-OSIC detector, the original OB-MMSE detector, and the optimal ML detector are compared. The threshold for the OB-MMSE-OSIC and OB-MMSE methods is set as $V_{th} = N_R\sigma^2$. In the simulations, QPSK is employed to modulate the symbols, and the channel is assumed to be Rayleigh faded. It is also assumed that the channel state information is available at the receiver.

Figure 1, (a) and (b), respectively, show the BER performance and complexity for the GSM system with $N_T = 8$, $N_P = 3$, and $N_R = 4$. It is observed that the proposed OB-MMSE-OSIC detector offers significant BER performance gains over the original OB-MMSE with small complexity addition. The OB-MMSE-OSIC outperforms OB-MMSE by about 5.5 dB at the BER of 10^{-4}. The OSIC employed in the second stage of the OB-MMSE algorithm achieves an improved performance in comparison to the MMSE detector. Furthermore, it is shown that the OB-MMSE-OSIC detector offers nearly optimal performance for the given system parameters. On the other hand, the OB-MMSE-OSIC detector can achieve a significant complexity reduction of about 90.78% compared to the ML detector in high SNR rages while the OB-MMSE detector achieves about 93.25% complexity reduction over the ML.

In Figure 2, (a) and (b), the BER results and complexity, respectively, versus SNR in decibels are presented under $N_T = 16$, $N_P = 4$, and $N_R = 4$. The simulation results also show that the proposed OB-MMSE-OSIC detector provides much better BER performance than the original OB-MMSE. The BER performance gap between the proposed OB-MMSE-OSIC and the OB-MMSE is bigger with minor complexity increase. The poor performance of the conventional OB-MMSE is due to the larger number of activated antennas for spatially multiplexed data transmission, which increases inter-antenna interferences.

5. Conclusion

We have proposed an OSIC-based detection scheme for GSM systems with respect to the MMSE criterion. The MMSE-OSIC detection replaces the MMSE detection with employing the same ordering algorithm used in the OB-MMSE. It is found that the OB-MMSE-OSIC detector achieve a much better BER performance compared with the original OB-MMSE without noticeable complexity addition.

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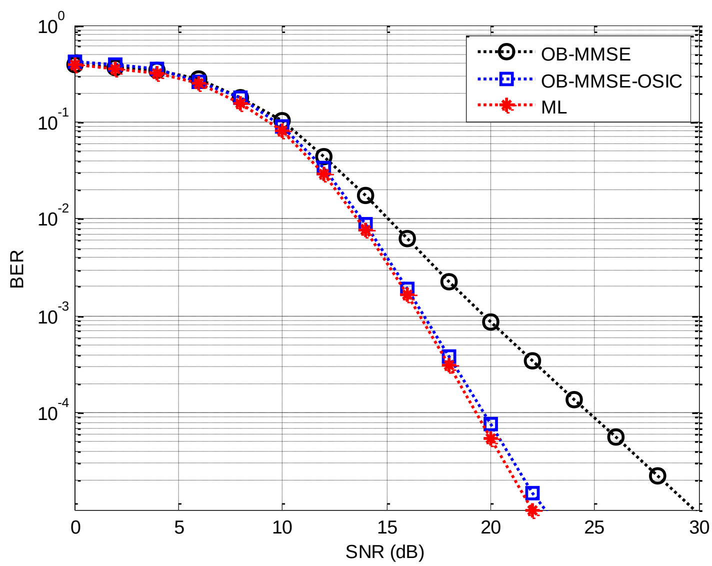
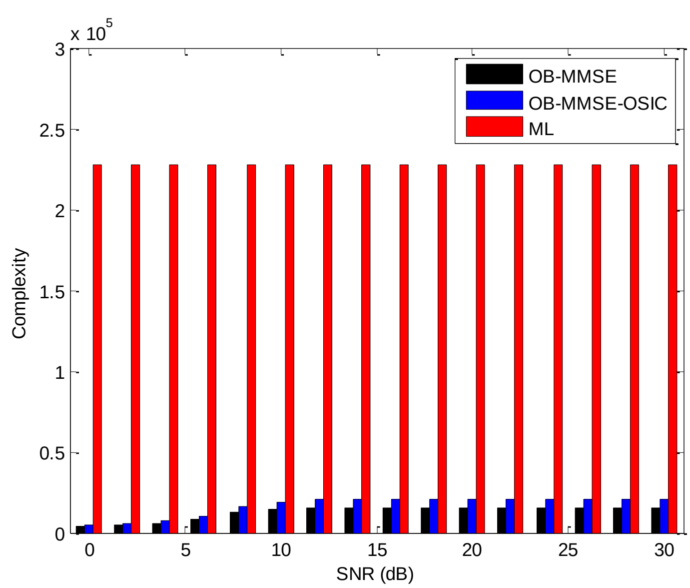
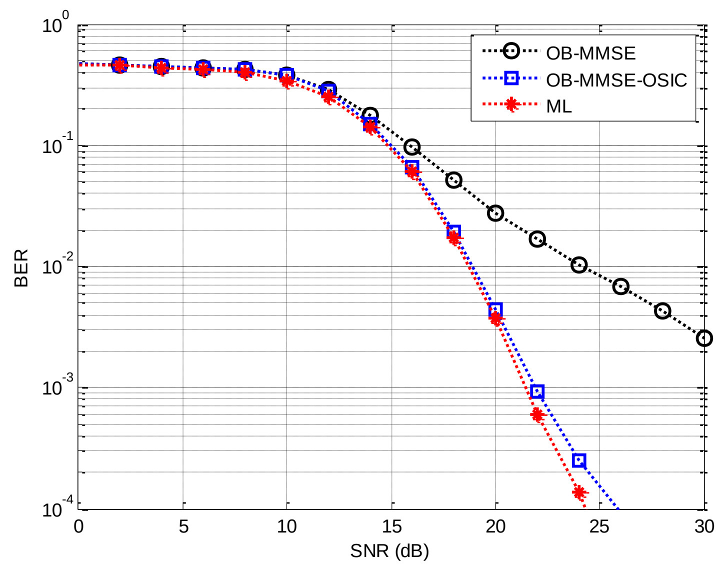


(a) BER

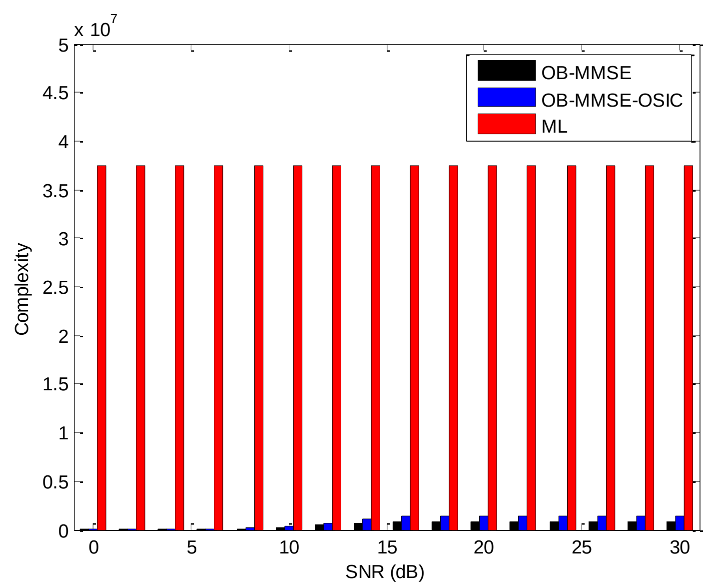


(b) Complexity

Figure 1. BER and Complexity comparison for a GSM system with $N_T = 8$**,** $N_P = 3$**, and** $N_R = 4$



(a) BER



(b) Complexity

Figure 2. BER and Complexity comparison for a GSM system with $N_T = 16$, $N_P = 4$, **and** $N_R = 4$