A Low-Complexity ML Detection Algorithm for Spatial Modulation Systems With MPSK Constellation

Hongzhi Men and Minglu Jin

Abstract—**Spatial modulation (SM), which is a novel transmission scheme, is employed for active transmit antenna indexes and modulated signals to convey the information. To recover the transmitted information bits, the maximum likelihood (ML) joint detector is often used. However, its complexity linearly grows with the number of transmit antennas and the size of the signal set. A reduced-complexity ML optimal algorithm for SM systems with M-QAM has been proposed. However, for M-PSK modulation, there are not similar low-complexity ML detection algorithms yet to our knowledge. In this paper, a low-complexity ML detection algorithm for SM systems with M-PSK modulation is proposed. By exploiting the features of M-PSK constellation, we give the ML-estimated values of the transmitted symbols. Therefore, the ML search complexity is independent of the constellation size. Simulation results show that the proposed algorithm has the same performance as the ML-optimum detector and significant reduction in computational complexity compared with existing detectors for SM systems with M-PSK modulation.**

Index Terms—**Spatial modulation (SM), MPSK modulation, ML decoding, computational complexity.**

I. Introduction

ENHANCED radio services with heterogeneous applications demand high data rate and increased spectral efficiency that need to be enhanced in current wireless communication. To resolve this problem, Multiple-Input-Multiple-Output (MIMO) systems have been exploited in different ways to achieve multiplexing, diversity, or antenna gains. However, increased cost and complexity due to inter-channel interference (ICI), inter-antenna synchronization (IAS) and multiple radio frequency (RF) chains are main drawbacks of MIMO systems, which lead to restriction of its practical applications [1]. SM is developed to mitigate the practical limitation of MIMO systems as well as retaining the key advantages.

SM is a special low-complexity MIMO transmit scheme, which is proposed recently to employ the active transmit antenna indices (spatial constellation) and transmitted signals (signal constellation) to convey the information [2], [3]. The main characteristic of SM is that only one antenna is activated for data transmission at any signal duration. In SM, information bit-stream is divided into blocks and each block has $\log_2(N_t) + \log_2(M)$ bits, among which the first $\log_2(N_t)$ bits are used to select one antenna out of N_t transmit antennas for data transmission and the second $\log_2(M)$ bits are used to select transmitted symbol from M-ary modulation signal set [1], [4].

Compared with conventional MIMO systems, the above key features make SM detection more complicated, which needs to demodulate transmit antenna indices except for transmitted symbols. The detection algorithm is originally proposed in [5], estimating spatial constellation followed by signal constellation, which has low complexity but suboptimum performance. To improve the performance, Jeganathan *et al.* proposed a Maximum Likelihood (ML) optimum detector that detects spatial constellation and signal constellation jointly [6]. Subsequently, a variety of detectors such as sphere decoding (SD) [7]–[9], matched filters (MF) [5], [14], signal vector based detection (SVD) [10] etc had been developed to approach the optimal performance at low complexity. Recently, in [11], a hard-limiting ML optimum detector (HL-ML) was proposed to achieve optimal performance and low complexity, which is just for the SM systems with square or rectangular lattice constellations. While, SM systems with MPSK modulation have not been considered, and there are not similar low complexity ML detection algorithms yet in other papers to our knowledge. However, it is well known that the power efficiency of current power amplifiers is seriously affected by the linearity requirements of the modulation schemes. And the constant-envelope modulation (e.g., PSK) has less strict linearity requirements compared with non-constant envelope modulation schemes (e.g., QAM) [3], [12]. Thus, SM with constant-envelope modulation (e.g., PSK) can provide similar or even better performance in power consumption and energy efficiency than amplitude modulation schemes (e.g., QAM) [3], [13]. In turn, the increasing in the efficiency of power amplifiers can reduce the total power consumption of the transmitters [3]. Facing to the key challenge of future mobile communication, i.e., improving energy efficiency, SM with MPSK modulation will have good prospects. To this end, in this paper, we propose a low complexity ML detection algorithm (LC-ML) for SM systems with MPSK modulation.

In our algorithm, according to the features of MPSK constellation, we estimate the values of the transmitted symbols based on ML criterion directly. Therefore, the ML search space is independent to the signal constellation size. Subsequently, it obtains the transmitted symbol and finally predicts the transmitted antenna index accordingly.

The rest of the paper is organized as follows. In Section II, we introduce the SM system model and its ML-optimal detection criterion. In Section III, we first describe the features of MPSK constellation, and then present the LC-ML detector for SM systems under MPSK modulation. Section IV compares

Manuscript received April 23, 2014; revised June 4, 2014; accepted June 4, 2014. Date of publication June 17, 2014; date of current version August 8, 2014. The associate editor coordinating the review of this paper and approving it for publication was Kiran K. Kuchi.

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Digital Object Identifier 10.1109/LCOMM.2014.2331283

the performance of the proposed algorithm with ML-optimum detector in terms of simulation results, and gives the computational complexity analysis. Finally, Section V ends up with conclusion.

Notation: $\|\cdot\|_2^2$ is the two-norm of a vector; $rnd(\cdot)$ is the integer that is nearest to a variable; $mod(\cdot,\cdot)$ is the modulo operation; $(\cdot)^*$ is the conjugate of a complex number; $\Re(\cdot)$ and $\Im(\cdot)$ are the real and imaginary parts of a variable; $(\cdot)^T$ and $(\cdot)^H$ are the transpose and conjugate transpose of a vector or a matrix.

II. System Model

In a SM system, there are N_t transmit antennas and N_r receive antennas. It communicates over a quasi-static frequency-flat fading channel, which can be modeled as:

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} \tag{1}$$

where $\mathbf{x} \in \mathbb{C}^{N_t}$ is the transmitted vector, in which only the $l_{th}, l \in \{1, 2, \ldots, N_t\}$ element is non-zero, denoted by s; s is a complex signal from the signal set $\mathcal{S}$ with $|\mathcal{S}| = M$; $\mathbf{y} \in \mathbb{C}^{N_r}$ is the received vector; $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix; $\mathbf{n} \in \mathbb{C}^{N_r}$ is the noise vector. The entries of $\mathbf{H}$ and $\mathbf{n}$ are from $\mathcal{CN}(0,1)$ and $\mathcal{CN}(0,\sigma^2)$. In rest of this paper, we consider that $\mathcal{S}$ is MPSK constellation signal set. Assuming perfect channel state information at receiver, the channel model for SM systems can also be expressed as:

$$\mathbf{y} = \mathbf{h}_l s + \mathbf{n} \tag{2}$$

where $\mathbf{h}_l$ is the l_{th} column of $\mathbf{H}$. As stated above, the ML criterion in SM systems can be written as:

$$(\hat{l}, \hat{s})_{ML} = \arg \min_{l \in L, s \in \mathcal{S}} \|\mathbf{y} - \mathbf{h}_l s\|_2^2 \tag{3}$$

where $\hat{l}, \hat{s}$ are the estimated activated antenna index and transmitted symbol respectively.

III. The Proposed Algorithm

In this section, we present a low-complexity detection scheme for SM systems under MPSK modulation, which can achieve optimal performance. In order to facilitate understanding the proposed algorithm, we first introduce the features of MPSK constellation.

A. MPSK Constellation

MPSK constellation points lie in the edge of one circle as shown in Fig. 1(a). Generally, if the initial phase of the MPSK modulation is 0, then the i_{th} signal point in this constellation can be expressed as:

$$s_i = A\left[\cos(\varphi_i) + J\sin(\varphi_i)\right] \quad i = 1\ 2\ \ldots\ M \tag{4}$$

where A is the amplitude of the signal point, and $\varphi_i = (2\pi/M)(i-1)$. If $\Psi = \{\varphi_i\}_{i=1}^M$ is defined, we can get that $\varphi_i/(2\pi/M) = (i-1), i \in \{1, 2, \ldots, M\}$.

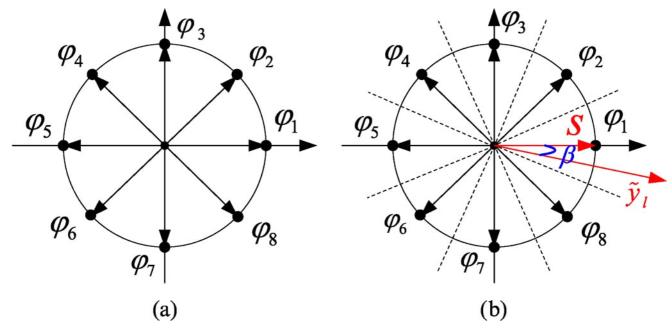

Fig. 1. (a) 8PSK Constellation. (b) the diagram of the optimization problem in (6), β is the included angle between $\tilde{y}_l$ and s.

B. Low Complexity ML Optimal Detection Algorithm

It is straightforward from (3) that ML criterion is equal to:

$$(\hat{l}, \hat{s})_{ML} = \arg \min_{l \in L} \left(\min_{s \in \mathcal{S}} \left(\|\mathbf{y} - \mathbf{h}_l s\|_2^2 \right) \right) \tag{5}$$

The inner optimization problem $(\hat{s})_{ML} = \arg\min_{s \in \mathcal{S}}(\|\mathbf{y} - \mathbf{h}_l s\|_2^2)$ in (5) also can be written as:

$$(\hat{s})_{ML} = \arg \min_{s \in \mathcal{S}} \left(|\tilde{y}_l - s|^2 \right) \tag{6}$$

where $\tilde{y}_l = (\mathbf{h}_l^H \mathbf{y}/\|\mathbf{h}_l\|^2)$. Now we denote $\tilde{y}_l$ and s as $\tilde{y}_l = r_l e^{j\theta_l}$, $s = e^{j\varphi}$ (for simplification, we assume that $A = 1$) in polar form, then

$$\begin{aligned}(\hat{s})_{ML} &= \arg \min_{s \in \mathcal{S}} \left(|\tilde{y}_l - s|^2 \right) \\ &= \arg \min_{\varphi \in \Psi} \left| r_l e^{j\theta_l} - e^{j\varphi} \right|^2 \\ &= \arg \min_{\varphi \in \Psi} (r_l e^{j\theta_l} - e^{j\varphi}) \left(r_l e^{j\theta_l} - e^{j\varphi} \right)^* \\ &= \arg \min_{\varphi \in \Psi} \left(|r_l|^2 + 1 - 2r_l \cos(\theta_l - \varphi) \right) \end{aligned} \tag{7}$$

Obviously, when the value l is given, the optimization problem in (7) has the equivalent form as follows:

$$(\hat{\varphi})_{ML} = \arg \max_{\varphi \in \Psi} (\cos(\theta_l - \varphi)) \tag{8}$$

where θ_l and φ satisfy the following conditions $0 \le \theta_l < 2\pi, 0 \le \varphi < 2\pi$, i.e., $0 \le |\theta_l - \varphi| < 2\pi$. If $|\theta_l - \varphi|$ satisfy the condition $0 \le |\theta_l - \varphi| < \pi$, then $\cos(\theta_l - \varphi)$ gets its maximum when $|\theta_l - \varphi|$ has minimum value. If $|\theta_l - \varphi|$ satisfy the condition $\pi \le |\theta_l - \varphi| < 2\pi$, then $\cos(\theta_l - \varphi)$ gets its maximum when $|\theta_l - \varphi|$ has maximum value. In Fig. 1(b), the optimization problem in (6), i.e., solving the transmitted signal s when the value of $\tilde{y}_l$ has been given, is described vividly. Actually, from Fig. 1(b), when the vector of the constellation point is closer to the receive signal vector $\tilde{y}_l$, the value of (7) becomes smaller. In this sense, the smaller the angle β between $\tilde{y}_l$ and s the larger $\cos(\theta_l - \varphi)$ is. Assuming $Q_{\hat{\varphi}} = \theta_l/(2\pi/M)$, thus, $\hat{\varphi}$ can be expressed as follows:

$$\begin{aligned} &0 \le Q_{\hat{\varphi}} < 0.5 \text{ or } M - 0.5 \le Q_{\hat{\varphi}} < M \Rightarrow \hat{\varphi} = 0 * \frac{2\pi}{M} \\ &\times m - 0.5 \le Q_{\hat{\varphi}} < m + 0.5 \Rightarrow \hat{\varphi} = m * \frac{2\pi}{M} \end{aligned} \tag{9}$$

here $m = \{1, \ldots, M-1\}$. In fact, $\hat{\varphi}$ can be obtained directly without above comparisons. Assuming that the active antenna index is l, from (9) we can get that:

$$\hat{\varphi} = mod\,(rnd(Q_{\hat{\varphi}}), M) * \frac{2\pi}{M} \tag{10}$$

Thus, the complexity of optimization problem in (6) is now constant and does not depend on the signal constellation size. After getting ML estimation on $\hat{\varphi}$, we can compute the corresponding signal $s(\hat{\varphi})$ using (4). Then, the obtained signal is substituted into (3) to estimate the transmitted antenna index. That is:

$$(\hat{l})_{ML} = \arg\min_{l \in L} \|\mathbf{y} - \mathbf{h}_l s(\hat{\varphi})\|_2^2 \tag{11}$$

where $s(\hat{\varphi}) = e^{j\hat{\varphi}}$. To reduce the computational complexity of (11), consider that:

$$\begin{aligned}\|\mathbf{y}-\mathbf{h}_l s(\hat{\varphi})\|_2^2 &= \|\mathbf{y}\|_2^2 + \|\mathbf{h}_l\|_2^2 \,|s(\hat{\varphi})|^2 - 2\Re\left(\mathbf{h}_l^H \mathbf{y}\,(s(\hat{\varphi}))^*\right)\\ &= \|\mathbf{y}\|_2^2 + \|\mathbf{h}_l\|_2^2 - 2\|\mathbf{h}_l\|_2^2 \Re\left(\tilde{y}_l\,(s(\hat{\varphi}))^*\right)\\ &= \|\mathbf{y}\|_2^2 + \|\mathbf{h}_l\|_2^2\,(1 - 2\Re\left(\tilde{y}_l\,(s(\hat{\varphi}))^*\right))\end{aligned} \tag{12}$$

From (11) and (12) we obtain that:

$$(\hat{l})_{ML} = \arg\min_{l \in L} \|\mathbf{h}_l\|_2^2\,(1 - 2\Re\left(\tilde{y}_l\,(s(\hat{\varphi}))^*\right)) \tag{13}$$

For above optimization problem, we do not need to compute $\|\mathbf{h}_l\|_2^2$ again, thus, the computational complexity is reduced significantly.

The proposed algorithm is summarized in Algorithm 1.

Algorithm 1: LC-ML, Algorithm for SM with MPSK

For $l = 1 : N_t$
1: Compute $\tilde{y}_l$ according to $\tilde{y}_l = (\mathbf{h}_l^H \mathbf{y}/\|\mathbf{h}_l\|_2^2)$
2: Using (10), compute $\hat{\varphi}_l$
3: Exploiting $\hat{\varphi}_l$, get the corresponding transmitted signal $\hat{s}_{\hat{l}}$
4: Compute J_l, where $J_l = \|\mathbf{h}_l\|_2^2(1 - 2\Re(\tilde{y}_l(s(\hat{\varphi}_l))^*))$
End for
Find the minimum value of J_l. Output $\hat{l}$ and $\hat{s}_{\hat{l}}$

IV. Simulation Results and Analysis

In this section, the performance of the proposed algorithm is presented and compared with ML-optimum detector. Subsequently, we analyze the computational complexity of the proposed algorithm and compare it with other existing algorithms.

A. Simulation Results

In order to verify the proposed algorithm has the optimal performance, 16PSK, 32PSK, 64PSK and 128PSK modulations are used as transmitted signal sets in a SM system having $N_t = 4$ transmit antennas and $N_r = 2$ receive antennas. Assume that the channel is a flat block fading one. In order to compare their Symbol Error Rate (SER) performance, the proposed algorithm and ML-optimum detector are utilized to detect the transmitted information bits respectively.

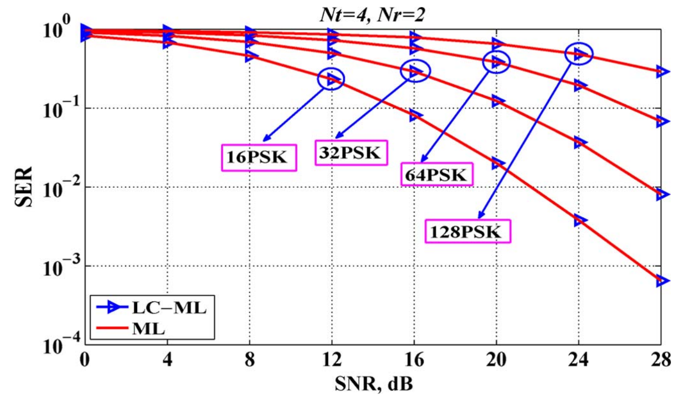

Fig. 2. SER comparison of LC-ML detector with that of ML-optimum detector in an SM system having $N_t = 4$, $N_r = 2$ and using 16-, 32-, 64-, and 128-PSK signal sets over Rayleigh fading channel.

Fig. 2 represents SER performance of the proposed algorithm (LC-ML in Fig. 2) and ML-optimum detector (ML in Fig. 2). It can be clearly seen from Fig. 2 that LC-ML algorithm has the same performance with ML-optimum detector.

B. Complexity Analysis

In this subsection, we analyze the complexity of LC-ML detector by exploiting the concept of the computational complexity in [11]. It is defined as the total number of the real-valued multiplications (division is also considered as multiplication) involved in an algorithm. We give the computational complexity of ML detector, MF detector, SVD detector, SD detector (including SM-Rx detector and SM-Tx detector) and the proposed detector as follows.

1) The computational complexity of ML detector
Consider the ML criterion $(\hat{l}, \hat{s})_{ML} = \arg\min_{l \in L, s \in \mathcal{S}} \|\mathbf{y} - \mathbf{h}_l s\|_2^2$. Obviously, the search space size is $N_t M$. Computing $\mathbf{h}_l s$ and $\|\mathbf{y} - \mathbf{h}_l s\|_2^2 = (\Re(\mathbf{y} - \mathbf{h}_l s))^2 + (\Im(\mathbf{y} - \mathbf{h}_l s))^2$ needs $4N_r$ and $2N_r$ real-valued multiplications respectively. Hence, the computational complexity of ML detector is $6N_r N_t M$.
2) The computational complexity of MF detector
From Appendix A-A in [11], we know that the computational complexity of MF detector is $12N_r N_t + (N_t + 4)M$.
3) The computational complexity of SVD detector
From Appendix A-B in [11], the computational complexity of SVD detector is $(6N_r + 4)N_t + 2N_r + 6N_r M$.
4) The Computational complexity of SM-Rx
According to (26) in [7], i.e., $C_{Rx-SD} = 3\sum_{l=1}^{N_t}\sum_{s=1}^{M} \tilde{N}_r(l, s)$, where $\tilde{N}_r(l, s) \in \{1 \ldots 2N_r\}$, we compute the computational complexity of SM-Rx detector via simulation as done in [7].
5) The Computational complexity of SM-Tx
According to Section IV-C in [7], we can obtain the complexity of SM-Tx detector. Here, we just consider the fixed computational complexity, i.e., the calculation of $\bar{\mathbf{D}}$ using Cholesky decomposition, $\bar{\mathbf{G}}$, $\bar{\mathbf{z}}$ and $\bar{\rho}$. Hence, the fixed computational complexity is $(4(N_t)^3/3) + N_t(4N_r N_t + 6N_r + 6N_t + 3)$.

TABLE I
COMPARISON OF THE ABOVE 6 ALGORITHMS

Detectors	**SER Performance**	**Computational Complexity**
ML	optimal	$6N_rN_tM$
MF	sub-optimal	$12N_rN_t + (N_t + 4)M$
SVD	sub-optimal	$(6N_r + 4)N_t + 2N_r + 6N_rM$
SM-Rx	sub-optimal	$3\sum_{l=1}^{N_t}\sum_{s=1}^{M}\tilde{N}_r(l, s)$
SM-Tx	sub-optimal	$\frac{4N_t^3}{3}+(4N_r+6)N_t^2+6N_rN_t+3N_t$
LC-ML	optimal	$(6N_r + 9)N_t$

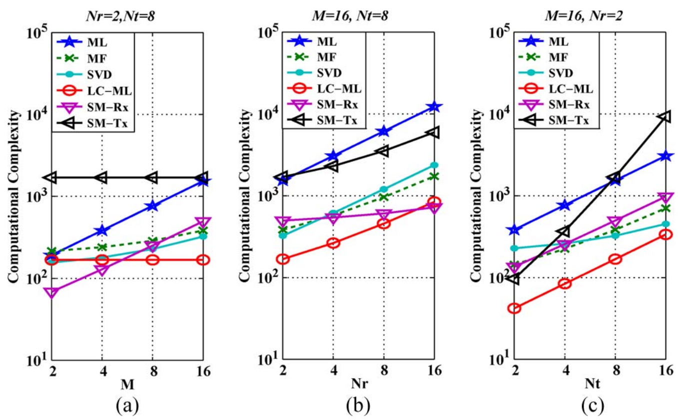

Fig. 3. Comparison of the computational complexity per symbol detection of the proposed detector with that of other existing detection schemes as a function of (a) signal constellation size M (b) number of receive antennas N_r (c) number of transmit antennas N_t.

6) The computational complexity of the proposed detector
   a) Given l, the computation of $\tilde{y}_l$ takes $6N_r + 2$ real-valued multiplications, since the number of real-valued multiplications involved in $\mathbf{h}_l^H\mathbf{y}$, $\|\mathbf{h}_l\|_2^2 = (\Re(\mathbf{h}_l))^T\Re(\mathbf{h}_l) + (\Im(\mathbf{h}_l))^T\Im(\mathbf{h}_l)$, and $(\Re(\mathbf{h}_l^H\mathbf{y}) + \Im(\mathbf{h}_l^H\mathbf{y}))/\|\mathbf{h}_l\|_2^2$ are $4N_r$, $2N_r$ and 2 respectively.
   b) After getting $\tilde{y}_l$, according to (10), the calculation of $\hat{\varphi}$ needs 3 real-valued multiplications. *Notations*: The calculation of $Q_{\hat{\varphi}}$ also needs 1 real-valued multiplication, and $2\pi/M$ is considered as a constant.
   c) Given $\hat{\varphi}$, getting $\hat{s}_{\hat{l}}$ does not need real-valued multiplication. The calculation of $J_l = \|\mathbf{h}_l\|_2^2(1 - 2\Re(\tilde{y}_l s(\hat{\varphi}_l)^*))$ needs 4 real-valued multiplications. *Notation*: $\|\mathbf{h}_l\|_2^2$ has been computed in step a) and $\Re(\tilde{y}_l(s(\hat{\varphi}_l))^*) = \Re(\tilde{y}_l)\Re(s(\hat{\varphi}_l)) + \Im(\tilde{y}_l)\Im(s(\hat{\varphi}_l))$ takes 2 real-valued multiplications.

   It can be concluded that we do not have to search the signal set, and just search the antenna indices space. Thus, the computational complexity of LC-ML is $(6N_r + 9)N_t$.

Table I gives the summary of the computational complexity of these 6 algorithms.

In order to compare the computational complexity of all these algorithms, Fig. 3 gives the comparison results in terms of the variation of M, N_r and N_t. Note that the computational complexity of the SM-Rx detector is obtained at SNR $= 20$ dB. Also, note that the true computational complexity of the SM-Tx detector must be higher than the value considered by us.

In Fig. 3(a), assuming that $N_t = 8$, $N_r = 2$, the signal constellation size M changes. It is clear that the computational complexity of LC-ML detector does not grow with M. Furthermore, our detector has more significant advantage with the increase of M.

Fig. 3(b) shows the computational complexity by changing N_r when N_t and M equal 8 and 16 respectively. From Fig. 3(b), one can see easily that the proposed detector has significant reduction in computational complexity. Though the computational complexity of SM-Rx detector is smaller than that of the proposed detector when N_r is large, the proposed detector has the optimal performance.

Finally, we consider that $N_r = 2$, $M = 16$ and different N_t. Via observing Fig. 3(c), it can also be concluded that LC-ML detector has the smallest computational complexity compared with other existing detectors.

V. CONCLUSION

In this letter, for the SM system under MPSK modulation, we present a new detection scheme based on ML optimal detection criterion, whose computational complexity no longer increases with the signal constellation size. Compared with the existing detectors of SM system, the performance of the proposed detector is the same as the ML-optimum detector despite its significant reduction in computational complexity.

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