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A LOW-COMPLEXITY DETECTION ALGORITHM FOR SPATIAL MODULATION SYSTEMS WITH MULTIPLE PHASE SHIFT KEYING MODULATION

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Abstract. *The multiple phase shift keying (MPSK)-based spatial modulation (SM) has attracted widespread attention for its advantage of low dependence on linearity of power amplifier. There have been some low complexity detection algorithms, of which the computation complexity has not related to modulation order, but they often perform exhaustive search over transmit-antenna so that they are not suited to be used in large-scale transmit-antenna systems. A novel detection algorithm which combines low complexity algorithms with adaptive signal vector detection theory is proposed. The analysis and simulation results show it not only has a further significant reduction on computational complexity, but also remains same closely performance towards Maximum Likelihood (ML) optimum detection. So it offers a better trade-off between performance and complexity for MPSK-based SM systems.*

Keywords: Spatial modulation, MPSK modulation, Detection algorithm, Computational complexity

1. **Introduction.** Spatial modulation (SM) technology [1] can not only reduce the power consumption, but also transmit information by "SM constellation diagram" and the traditional constellation symbols. SM belongs to the single-RF (Radio Frequency) large-scale Multiple-Input Multiple-Output (MIMO) wireless systems family, which activates only one antenna for data transmitting at any signal duration compared to state-of-the-art high complexity and power-hungry classic MIMOs technology. These unique features of SM not only allow the high-rate MIMO system to possess low complexity of signal processing and circuitry complexity, but also allow SM to relax the inter-antenna synchronization requirements and inter-channel interference. Due to these properties, the detection algorithm of the SM receiver is more complicated than that of the conventional MIMO system.

At present, in addition to ML detector with exhaustive search [2], several low complexity detectors such as sphere decoding (SD) [3], matched filtering (MF) [4], and signal vector based detection (SVD) [5] had been proposed for SM detection. However, the computational complexity of these detectors is relevant to the modulation constellation size and becomes higher in case of high order modulation. Then a hard-limiting (HL) [6] detector of which the computational complexity is independent of modulation order was proposed, but it just applies to the systems with square or rectangle MQAM (multilevel quadrature amplitude modulation) modulation symbols. These non-constant envelope modulations which have strict linearity requirements of power amplifiers increase the difficulty of realizing and the power consumption of the system. In [7], a low complexity maximum likelihood detector (LC-ML) was proposed with MPSK modulation, and its computational complexity is not only similar to that of the HL but also independent of the constellation points. From the view of the power consumption and energy efficiency, the performance of this kind of constant-envelope spatial modulation system is better than that of the MQAM system. However, this detector is implemented by performing exhaustive search which is related to the number of transmit antenna, and the computational complexity in large scale MIMO system is dramatic high.

Different from previous work, we propose a low complexity adaptive signal vector based detection (LC-ASVD) for MPSK-based SM system. It significantly reduces detection complexity by dynamically adjusting the search space of candidate transmit antennas with the demand for symbol error rate (SER) threshold, while the performance remains almost the same as that of LC-ML.

The rest of the paper is organized as follows. In Section 2, we introduce the SM system model and its ML-optimal detection criterion. In Section 3, we present the LC-ASVD algorithm for SM systems under MPSK modulation. In Section 4, Some simulation results and computational complexity are provided to compare the performance of the proposed algorithm with other two kinds of algorithms. Finally, Section 5 ends up with conclusions.

2. **System Model.** Consider an SM system with N_t transmit antennas and N_r receiver antennas. The system is communicating over a quasi-static, frequency-flat fading channel yielding

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

where $x \in C^{N_t}$ is the transmitted vector, in which only the ith element $i \in \{1, 2, \ldots, N_t\}$ is non-zero, which is denoted by s with a complex symbol from the signal constellation set S ($s \in S$). S has M kinds of value (M is the modulation order) if the modulation mode is MPSK. $y \in C^{N_r}$ is the received vector, $H \in C^{N_r \times N_t}$ is the channel matrix, and $n \in C^{N_r}$ is the noise vector. The entries of channel matrix and noise vector are from $CN(0, 1)$ and $CN(0, \sigma^2)$ respectively. Assuming perfect channel state information (CSI) at the receiver, the channel model for the SM system can also be expressed as

$$y = h_l s + n \tag{2}$$

where h_l is the lth column of H. The optimal ML detection can be written as follows

$$(l_{ML}, s_{ML}) = \underset{l \in \{1,\ldots,N_t\},\ s \in S}{\arg\min} \|y - h_l s\|_2^2 \tag{3}$$

where l_{ML}, s_{ML} are the estimated activated antenna index and transmitted symbol respectively. The ML detection performs an exhaustive searching over transmit antennas and modulation symbols. Hence, the computational complexity is very high. There are $6N_r N_t M$ real-valued multiplications involved in it.

3. **The Proposed LC-ASVD Algorithm.** To reduce the computational complexity of (3), we try to decrease the number of candidate antenna number and modulation symbols. [7] presents an LC-ML detector under MPSK modulation without searching the signal set. According to the range of the received signal, the modulation signal s_l can be directly computed by using (4). So the computational complexity is independent of modulation order.

$$s_l = e^{j\tilde{\varphi}} \tag{4}$$

where $\tilde{\varphi} = \mathrm{mod}(round(Q_{\tilde{\varphi}}), M) \times (2\pi/M)$, $round(\cdot)$ and $\mathrm{mod}(\cdot)$ are the integral and the modulus operation respectively, and $Q_{\tilde{\varphi}} = \theta_l/(2\pi/M)$, where θ_l is the corresponding angel of $\tilde{y}_l$, $\tilde{y}_l = \frac{h_l^H y}{\|h_l\|^2}$. In [7], (5) was used to search over all transmit antennas after the corresponding modulation signal was found. This approach contributes large computations which makes the complexity of LC-ML detector be still large, especially in the case of large number of transmit antennas.

$$\left(\tilde{l}\right)_{\text{ML}} = \arg\min_{l\in N_t} \|h_l\|_2^2 - (1 - 2 \times \text{Re}(\tilde{y}_l \times (s_l)^*)) \tag{5}$$

Based on LC-ML, we propose a lower complexity and adaptive signal vector [8] based detection (LC-ASVD) for SM systems. The basic idea is as follows. First, search out the corresponding candidate antenna number set $\bar{L}_{asvd}$ (it is far less than N_t) which satisfies the threshold of error probability. Then, calculate the modulation symbols corresponding to the candidate antenna by using (4). Finally, find out the minimum value according to (5) while $l \in \bar{L}_{asvd}$, and this minimum value is the activated transmit antenna index. The whole process of the algorithm is explained in the following, where $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} \text{dt}$.

Initial values: given N_t, $l = 0$, the threshold of error probability P_{th}, $\varsigma_{th} = Q^{-1}(P_{th})$, signal-to-noise ratio (SNR) ρ.

(1) For $j = 1$: ML

$G(j) = \frac{\left|h_j^H y\right|^2}{\|h_j\|^2}$

End

$j_{asvd} = \arg \max_{j\in\{1,2,\ldots,N_t\}} G(j)$

(2) For $i = 1$: ML

Using decision conditions $\|h_i\|^2 \le \frac{2\varsigma_{th}^2}{\rho}$ or $\lambda_{j_{asvd}}(i) \le \delta_{i,j_{asvd}} + \varsigma_{th}\sqrt{\frac{2\delta_{i,j_{asvd}}\left(1-\delta_{i,j_{asvd}}\right)}{\rho\|h_i\|^2-2\varsigma_{th}^2}}$,

select out all match antenna indexes, $l = l + 1$, $j(l) = i$;

where $\delta_{i,j_{asvd}} = \frac{\left|h_i^H h_{j_{asvd}}\right|^2}{\|h_i\|^2\left\|h_{j_{asvd}}\right\|^2}$, $\lambda_{j_{asvd}}(i) = \frac{G(j_{asvd})}{G(i)} \ge 1$

End

(3) Combine antenna index j with j_{asvd} to form an array $\bar{L}_{asvd}$, $\bar{L}_{asvd} = \{j_{asvd,}j\}$

(4) For $m = 1$: length($\bar{L}_{asvd}$)

Compute $\tilde{y}_{\bar{L}_{asvd}(m)}$, compute $s_{\bar{L}_{asvd}(m)}$ by using (4);

$J(m) = \left\|h_{\bar{L}_{asvd}(m)}\right\|_2^2 - \left(1 - 2 \times \text{Re}\left(\tilde{y}_{\bar{L}_{asvd}(m)} \times \left(s_{\bar{L}_{asvd}(m)}\right)^*\right)\right)$

End

Find out the minimum value of J and the corresponding index value $\tilde{m}$; thus, $\bar{L}_{asvd(\tilde{m})}$ and $s_{\bar{L}_{asvd(\tilde{m})}}$ are the estimate transmit antenna index and modulation symbol respectively.

4. **Simulation Results Analysis.**

In this section, the performance of LC-ASVD algorithm with different modulation order is presented and compared with LC-ML detector correspondingly. Subsequently, we analyze the computational complexity of LC-ASVD algorithm and compare it with other existing algorithms.

4.1. **Simulation results.**

Consider an SM system having $N_r = 4$ receive antennas and $N_t = 4$ transmit antennas, communicating over a quasi-static frequency-flat fading channel, employing 8PSK, 16PSK and 32PSK modulations as the signal sets, respectively. Figure 1 shows both simulation results of LC-ASVD algorithm and LC-ML algorithm. It can be readily observed that both algorithms have the similar performance under the different modulation order. The curves of both algorithms with the same modulation order are almost overlapping especially in the case of low SNR region. The LC-ASVD algorithm almost shows no performance loss compared with the optimum LC-ML algorithm.

4.2. **Complexity analysis.**

Using the same complexity analysis in [6-8], we calculate the total number of the real-valued multiplications (division is also considered as multiplication) involved to analyze the complexity of computation. Table 1 compares the computational complexity of the three algorithms which almost approach the optimal

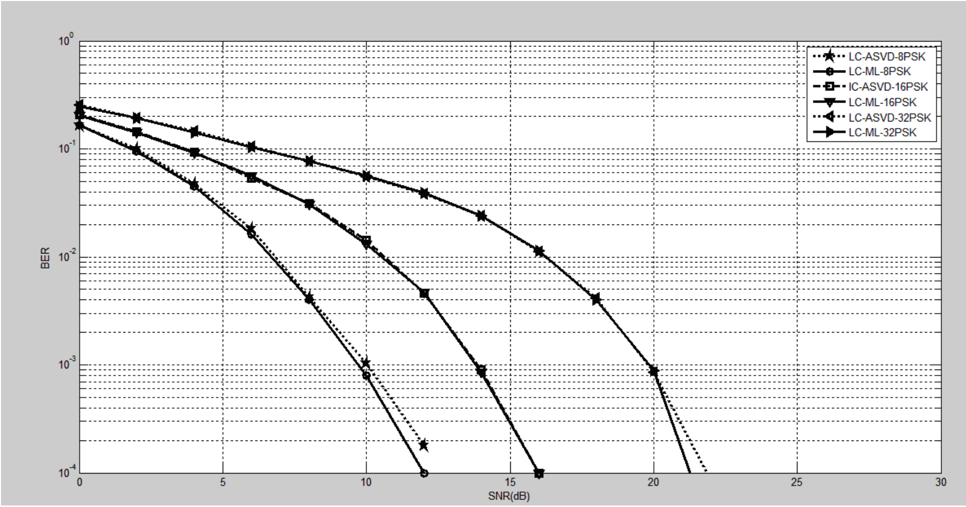

FIGURE 1. Bit error ratio (BER) performance of SM versus antennas with $N_r = 4$, $N_t = 4$

TABLE 1. Complexity comparison among three algorithms

Detectors	Computation complexity
ML [6]	$6N_rN_tM$
LC-ML [7]	$(6N_r + 9)N_t$
LC-ASVD	$(6N_r + 4)N_t + 9\bar{L}_{asvd}$

performance under MPSK modulation. Here we present the complexity analysis of LC-ASVD algorithm as follows only, for those of ML and LC-ML are given in [6] and [7] respectively.

1) The computation of $G(j)$ needs $(6N_r + 3)N_t$ real-valued multiplications (RVM).

since: $h_j^H y$ takes $4N_r$ RVM; $\|h_j\|_2^2 = (R(h_j))^T R(h_j) + (I(h_j))^T I(h_j)$ takes $2N_r$ RVM; $|\cdot|^2$ takes 2 RVM; the real division takes 1 RVM.

2) $\lambda_{j_{asvd}}(i)$ $(i \neq j_{asvd})$ takes 1 RVM, which results in a total complexity of N_t operations.

3) Given the received signal y, getting $\tilde{y}_l$ while $l \in \bar{L}_{asvd}$ needs $2\bar{L}_{asvd}$ RVM. Noting $h_j^H y$ and $||h_j||_2^2$ have been computed in step (1), the computation of $\tilde{y}_l$ takes only 2 RVM (the imaginary part divided by the real part).

4) Getting the transmit symbol s according to (4) takes 3 RVM, which results in a total complexity of $3\bar{L}_{asvd}$ operations.

5) Searching transmit antenna according to (5) takes $4\bar{L}_{asvd}$ RVM, in which (6) needs 2 RVM and $2\|h_l\|_2^2 R\left(\tilde{y}_l\left(s\left(\hat{\phi}_l\right)^*\right)\right)$ needs 2 RVM.

$$R\left(\tilde{y}_l\left(s\left(\hat{\phi}_l\right)^*\right)\right) = R\left(\tilde{y}_l\right) R\left(s\left(\hat{\phi}_l\right)\right) + I\left(\tilde{y}_l\right) I\left(s\left(\hat{\phi}_l\right)\right) \tag{6}$$

Then, the total computational complexity of LC-ASVD is $(6N_r+4)N_t+9\bar{L}_{asvd}$. The correlation value $\delta_{i,j_{asvd}}$ between different transmit antennas in the algorithm is not included because it can be calculated in advance for preparation.

From Table 1, it is clear that only the computational complexity of ML algorithm grows linearly with the modulation order M. The higher the M is, the far larger the complexity of the ML is as compared with the other algorithms. It is also shown that LC algorithm has relevantly small complexity, and the proposed LC-ASVD algorithm has smaller complexity than LC-ML algorithm (when $\bar{L}_{asvd} < \frac{5}{9}N_t$). Therefore, in the large antenna scale of SM system, the computational complexity of LC-ASVD is totally smaller

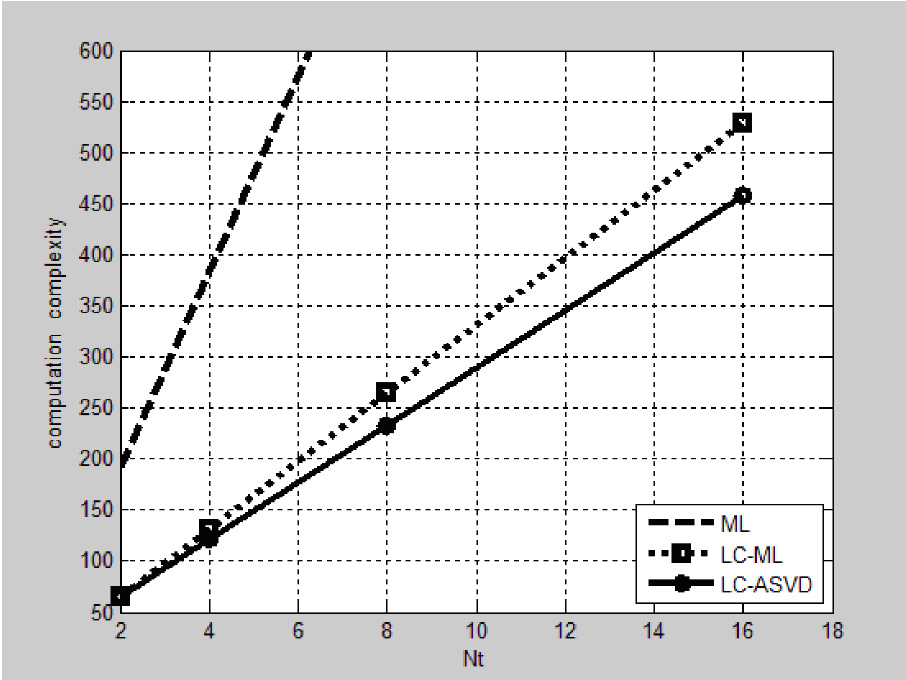

FIGURE 2. Computation complexity comparison with $M = 4$, $N_r = 4$

than that of LC-ML and the complexity gap between the two algorithms will be larger with the increasing number of transmit antennas. The comparison among algorithms will be shown in Figure 2.

5. **Conclusions.** A new detection scheme is proposed for the MPSK modulation SM system. It does not need to perform signal symbol searching so the computational complexity is uncorrelated with the modulation order. By using the theory of adaptive signal vector detection, the algorithm narrows the search region of transmit antenna which can further reduce the computational complexity compared with the similar detection algorithm of LC-ML, especially with the increase of the transmit number. Compared with the hard-limiting detector which can only be used in the SM system of square or rectangle modulation, the proposed detector under MPSK modulation has lower requirement on the linearity of the power amplifier and can improve the energy efficiency of the system. It offers a best trade-off among the exciting schemes for SM systems, especially in the case of large scale transmit antenna occasions. Our future work will apply the proposed schemes into the differential spatial modulation [9] system, coherent and differential space-time shift keying [10] system.

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