

A Low-Complexity Optimal Sphere Decoder for Differential Spatial Modulation

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Abstract—Motivated by the concept of spatial modulation (SM), a differential scheme has been recently proposed. This scheme, termed as differential (D)-SM, dispenses with channel estimation while maintains a similar bit error rate (BER) performance to SM. The conventional optimal DSM detector based on a maximum likelihood (ML) criterion, however, gives rise to prohibitive computational complexity when either the space-domain or signal-domain constellation size is large. In this paper, we propose a low-complexity yet optimal detection algorithm for DSM by utilizing sphere decoding (SD). The complexity analysis concerning Euclidian distance equation for DSM-SD is derived. Simulation results show that the proposed DSM-SD algorithm maintains an identical BER performance and achieves a significant reduction of computational complexity compared with the DSM-ML algorithm. The DSM-SD algorithm is especially efficient when the number of receive antennas is large. Moreover, compared with SD applied to SM, its application to DSM is verified to be more useful and attractive.

I. INTRODUCTION

Recently, SM has been considered as a promising single-radio-frequency multi-input multi-output (MIMO) transmission technique [1]–[5]. It features free inter-channel interference (ICI), free inter-antenna synchronization (IAS), low detection complexity, and high energy efficiency. The superiority of SM is attributed to the identity that only a single transmit antenna is activated at any time instant. However, channel state information (CSI), which is required by the ML detector, may not be available for SM. Since a single radio-frequency chain and multiple transmit antennas are used, it is impossible for SM to simultaneously transmit multiple pilot symbols to acquire accurate CSI. The channel estimation errors bring out a performance penalty on SM. It is complex and costly to obtain relatively accurate CSI, especially for fast time-varying channels. In order to bypass CSI estimation, our research group has proposed a novel differential scheme for SM in [6]–[8]. It is shown that DSM has the potential to restrict the signal-to-noise ratio (SNR) penalty compared with SM to be less than 3 dB for a target BER. DSM utilizes the antenna activation order to convey information, while SM utilizes the antenna index. When equipped with the same antenna configuration, DSM has to detect more information block candidates. A low-complexity detector is required especially

when the number of receive antennas as well as the space-domain and signal-domain constellation size are large.

The original detector for DSM is the ML detector proposed in [6]. It implements an exhaustive search on each element of all space-time block candidates to retrieve the original bit sequence. Therefore, it brings about prohibitive computational complexity especially when either the space-domain or signal-domain constellation size is large. To cope with this problem, the authors in [9] adopt a low-complexity DSM detector, which first reduces the candidate modulated symbols and then jointly detects space-domain and signal-domain information. The scheme in [9], however, cannot maintain the optimal BER performance although it approaches that of the ML detection. Therefore, we are driven to figuring out a low-complexity yet optimal detection algorithm for DSM.

SD is exactly such kind of method that we are pursuing [10]–[14]. However, these SD methods are not applicable to SM since they neglect the fundamental principle of SM, which activates only a single transmit antenna at any time instant. Recently, two modified SD methods tailored to SM, i.e., receiver-centric SD and transmitter-centric SD, are proposed in [15]–[17]. The receiver-centric SD method, termed as SM-SD in this paper, successively combines the received signal from each receive antenna as long as the cumulative Euclidean distance is no larger than the radius. The transmitter-centric SD method limits space-domain and signal-domain constellation size to reduce the search space. However, these two methods are only tailored to SM and not applicable to block-encoding DSM.

In this paper, we for the first time apply the tree search structure to DSM detector and the method is named as DSM-SD. It avoids an exhaustive search by detecting the points lying inside a sphere whose radius may update at the end of a loop. Our proposed DSM-SD method is investigated in Rayleigh fading channels. Simulation results show that the DSM-SD detector is capable of maintaining an optimal BER performance and provides a significant reduction in computational complexity in comparison with the DSM-ML detector. Moreover, the DSM-SD detector is particularly efficient when the number of receive antennas is large. Finally, simulation

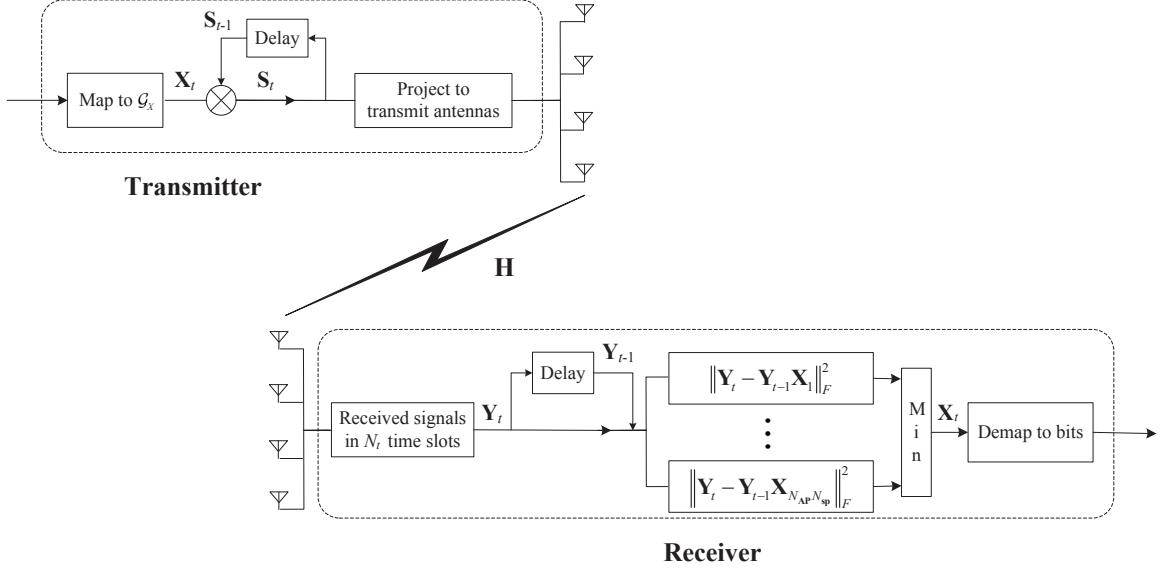


Fig. 1. DSM system model with ML detector.

results demonstrate that the proposed method achieves a more significant reduction in complexity compared with SM-SD.

The rest of this paper is organized as follows. Section II briefly reviews the system model of DSM with its ML detector. In Section III, we introduce the principle and conduct the theoretical complexity analysis of DSM-SD. Simulation results and analysis are presented in Section IV. Finally, conclusions are drawn in Section V.

II. REVIEW OF DSM WITH ML DETECTOR

The following notations are used throughout this paper. Bold and lowercase letters denote vectors, while bold and uppercase letters denote matrices. The notations $|\cdot|$ and $\|\cdot\|_F$ represent absolute value and Frobenius norm, respectively. $\lfloor \cdot \rfloor$ returns the largest integer no larger than the number.

In SM, the incoming bits at any time instant are mapped into another vector, which is determined by both the index of the activated antenna and the transmitted symbol. In this vector, the only nonzero element is drawn from the M -phase shift keying (PSK) constellation, while the other elements are set to 0.

Consider a DSM system equipped with N_t transmit antennas and N_r receive antennas, where the $N_t \times N_t$ space-time block \mathbf{X} is utilized to convey information. \mathbf{X} is constituted by the activation order of transmit antennas and the modulated symbols during N_t successive time instants, denoted as **AP** belonging to the set α and **sp** belonging to the set β , respectively. α has $2^{\lfloor \log_2(N_t!) \rfloor}$ elements whereas β has M^{N_t} elements. For simplicity, we define $N_{\text{AP}} = 2^{\lfloor \log_2(N_t!) \rfloor}$ and $N_{\text{sp}} = M^{N_t}$. Take $N_t = 2$ and $M = 2$ for example. One instance for **AP** is $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$, which indicates that transmit antenna 1 is activated at time instant 1 and transmit antenna 2 is activated at time instant 2. One instance for **sp** is $(1, -1)$, which indicates that the modulated symbol is 1

at time instant 1 and the modulated symbol is -1 at time instant 2. Thus, we have $\alpha = \left\{ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \right\}$ and $\beta = \{(1, 1), (1, -1), (-1, 1), (-1, -1)\}$. The combination of **AP** and **sp** has a one-to-one mapping relationship with \mathbf{X} , which constitutes the set \mathcal{G}_X containing $N_{\text{AP}}N_{\text{sp}}$ elements. During time instants $(t-1)N_t + 1$ to tN_t , the actual transmitted block \mathbf{S}_t can be generated in a recursive manner according to

$$\mathbf{S}_t = \mathbf{S}_{t-1}\mathbf{X}_t. \quad (1)$$

In general, we suppose $\mathbf{S}_0 = \mathbf{I}_{N_t}$, where \mathbf{I}_{N_t} represents the $N_t \times N_t$ identity matrix. Corresponding to the t -th transmitted block, \mathbf{Y}_t , \mathbf{H}_t , and \mathbf{N}_t , indicate the received signal block, the channel matrix, and the independently distributed complex-Gaussian noise matrix whose entry has zero mean and variance N_0 , respectively. Consequently, we have

$$\mathbf{Y}_t = \mathbf{H}_t\mathbf{S}_t + \mathbf{N}_t \quad (2)$$

and

$$\mathbf{Y}_{t-1} = \mathbf{H}_{t-1}\mathbf{S}_{t-1} + \mathbf{N}_{t-1}. \quad (3)$$

We assume a quasi-static channel, in which case $\mathbf{H}_{t-1} = \mathbf{H}_t$. Substituting (1) and (3) into (2), we have

$$\mathbf{Y}_t = \mathbf{Y}_{t-1}\mathbf{X}_t - \mathbf{N}_{t-1}\mathbf{X}_t + \mathbf{N}_t. \quad (4)$$

In (4), the element of the noise item $-\mathbf{N}_{t-1}\mathbf{X}_t + \mathbf{N}_t$, denoted as n' , obeys the complex-Gaussian distribution with variance $2N_0$. Therefore, the optimal ML detector can be derived as

$$\hat{\mathbf{X}}_t = \arg \min_{\forall \mathbf{X} \in \mathcal{G}_X} \left(\|\mathbf{Y}_t - \mathbf{Y}_{t-1}\mathbf{X}\|_F^2 \right). \quad (5)$$

The DSM system model with ML detector is depicted in Fig. 1. In (5), \mathbf{X} adopts **AP** as the antenna activation order, where

the m -th transmit antenna is activated at the j -th time instant. Accordingly, (5) can be rewritten as

$$\begin{aligned} & (\hat{\mathbf{AP}}_{ML}, \hat{\mathbf{sp}}_{ML}) \\ &= \arg \min_{\forall \mathbf{AP} \in \alpha, \mathbf{sp} \in \beta} \sum_{i=1}^{N_r} \sum_{j=1}^{N_t} |\mathbf{Y}_t(i, j) - \mathbf{Y}_{t-1}(i, m) \mathbf{X}(m, j)|^2, \quad (6) \end{aligned}$$

where the notation t in $\hat{\mathbf{AP}}_{ML}$ and $\hat{\mathbf{sp}}_{ML}$ has been omitted for simplicity.

III. SPHERE DECODER FOR DSM

A. DSM-SD Algorithm

Due to the fact that a combination of \mathbf{AP} and \mathbf{sp} determines a certain \mathbf{X} , we express this one-to-one mapping relationship as $(\mathbf{AP}, \mathbf{sp}) \leftrightarrow \mathbf{X}$. As illustrated in (6), the ML detector implements an exhaustive search on $N_r \times N_t$ elements for each candidate combination $(\mathbf{AP}, \mathbf{sp})$. Motivated by the SD tree search structure presented in [15], we for the first time propose a DSM-SD algorithm, which avoids an exhaustive search by performing calculations only on paths lying inside the sphere.

The detailed process for DSM-SD algorithm is illustrated as follows. C indicates the sphere radius, and δ and φ denote the summation of squared Euclidian distance and the search depth on each combination $(\mathbf{AP}, \mathbf{sp})$, respectively. The initial radius is set to be infinity to guarantee that the sphere contains the solution. For the combination $(\mathbf{AP}, \mathbf{sp})$, we successively calculate and accumulate the square of Euclidian distance on points which are inside the sphere. If δ is no less than C^2 , then we omit this combination $(\mathbf{AP}, \mathbf{sp})$ and continue to detect the next combination. Otherwise φ is self-added by 1. When a combination is found to be inside the sphere, C^2 is updated by δ . After all the $(\mathbf{AP}, \mathbf{sp})$ combinations are detected, we find out the combinations whose φ value reaches the maximum. The derived combinations maps into several information blocks \mathbf{X} , which constitute a new set \mathcal{G}_φ . Then we choose the combination $(\mathbf{AP}, \mathbf{sp})$ with minimum δ corresponding to \mathcal{G}_φ as the solution. Finally, the combination $(\hat{\mathbf{AP}}_{SD}, \hat{\mathbf{sp}}_{SD})$ is mapped into $\hat{\mathbf{X}}_{SD}$ and the incoming information bits are derived by decoding $\hat{\mathbf{X}}_{SD}$. The whole process of DSM-SD algorithm can be summarized in Table I.

B. Complexity analysis

For DSM-ML detector, the evaluation of (6) needs to be computed for all combinations of \mathbf{AP} and \mathbf{sp} . Each combination requires calculating $N_t N_r$ Euclidian distance equations. Thus, the total equation operation times, denoted as the computational complexity, can be written as

$$\phi_{DSM-ML} = N_{\mathbf{AP}} N_{\mathbf{sp}} N_t N_r. \quad (7)$$

For DSM-SD detector, we define

$$z_{(\mathbf{AP}, \mathbf{sp})}(i, j) = \mathbf{Y}_t(i, j) - \mathbf{Y}_{t-1}(i, m) \mathbf{X}_{(\mathbf{AP}, \mathbf{sp})}(m, j) \quad (8)$$

TABLE I
DSM-SD ALGORITHM

DSM-SD algorithm
1: for $\mathbf{AP} \in \alpha$
2: for $\mathbf{sp} \in \beta$
3: for $i = 1 : N_r$
4: for $j = 1 : N_t$
5: $\delta(\mathbf{AP}, \mathbf{sp}) += \mathbf{Y}_t(i, j) - \mathbf{Y}_{t-1}(i, m) \mathbf{X}(m, j) ^2$
6: if $\delta(\mathbf{AP}, \mathbf{sp}) \geq C^2$ then continue to the next $(\mathbf{AP}, \mathbf{sp})$
7: $\varphi(\mathbf{AP}, \mathbf{sp}) += 1$
8: end for
9: end for
10: $C^2 = \delta(\mathbf{AP}, \mathbf{sp})$
11: end for
12: end for
13: $\mathcal{G}_\varphi = \arg \max_{(\mathbf{AP}, \mathbf{sp})} (\varphi(\mathbf{AP}, \mathbf{sp}))$
14: $(\hat{\mathbf{AP}}_{SD}, \hat{\mathbf{sp}}_{SD}) = \arg \min_{(\mathbf{AP}, \mathbf{sp}) \leftrightarrow \mathbf{X} \in \mathcal{G}_\varphi} (\delta(\mathbf{AP}, \mathbf{sp}))$

and

$$\mathbf{Y}_t(i, j) = \mathbf{Y}_{t-1}(i, m') \mathbf{X}_t(m', j) + n', \quad (9)$$

where \mathbf{X}_t is the t -th information block and the m' -th transmit antenna is activated at the j -th time instant. Here and after, the subscript $(\mathbf{AP}, \mathbf{sp})$ indicates the correspondance to a certain combination $(\mathbf{AP}, \mathbf{sp})$. Then we have

$$\begin{aligned} z_{(\mathbf{AP}, \mathbf{sp})}(i, j) &= n' + \mathbf{Y}_{t-1}(i, m') \mathbf{X}_t(m', j) \\ &\quad - \mathbf{Y}_{t-1}(i, m) \mathbf{X}_{(\mathbf{AP}, \mathbf{sp})}(m, j). \end{aligned} \quad (10)$$

We define $\mu_{(\mathbf{AP}, \mathbf{sp})}(i, j) = \mathbf{Y}_{t-1}(i, m') \mathbf{X}_t(m', j) - \mathbf{Y}_{t-1}(i, m) \mathbf{X}_{(\mathbf{AP}, \mathbf{sp})}(m, j)$, therefore the probability density function (PDF) of $z_{(\mathbf{AP}, \mathbf{sp})}(i, j)$ is

$$\begin{aligned} f_Z(z_{(\mathbf{AP}, \mathbf{sp})}(i, j) | \mathbf{X}_t, \mathbf{Y}_{t-1}, N_0) \\ = \frac{1}{\pi N_0} e^{-\frac{|z_{(\mathbf{AP}, \mathbf{sp})}(i, j) - \mu_{(\mathbf{AP}, \mathbf{sp})}(i, j)|^2}{N_0}}. \end{aligned} \quad (11)$$

The DSM-SD algorithm implements the accumulation of squared Euclidian distances until the k -th level

$$\begin{aligned} \gamma_{(\mathbf{AP}, \mathbf{sp})}(k) &= \sum_{(i, j)} |\mathbf{Y}_t(i, j) - \mathbf{Y}_{t-1}(i, m) \mathbf{X}_{(\mathbf{AP}, \mathbf{sp})}(m, j)|^2 \\ &= \sum_{(i, j)} |z_{(\mathbf{AP}, \mathbf{sp})}(i, j)|^2. \end{aligned} \quad (12)$$

In other words, the calculation times of Euclidian distance equation is k which satisfies $1 \leq k \leq N_t N_r$. For analysis, we have the following definition

$$\kappa_{(\mathbf{AP}, \mathbf{sp})}(k) = \sum_{(i, j)} \left| \frac{z_{(\mathbf{AP}, \mathbf{sp})}(i, j)}{\sqrt{N_0}} \right|^2. \quad (13)$$

Accordingly, the probability of having a combination $(\mathbf{AP}, \mathbf{sp})$ at the k -th level inside the sphere with radius C is

$$\begin{aligned} p_{(\mathbf{AP}, \mathbf{sp}, C)}(k) &= \Pr(\gamma_{(\mathbf{AP}, \mathbf{sp})}(k) \leq C^2 | \mathbf{X}_t, \mathbf{Y}_{t-1}, N_0) \\ &= \Pr\left(\kappa_{(\mathbf{AP}, \mathbf{sp})}(k) \leq \left(\frac{C}{\sqrt{N_0}}\right)^2 | \mathbf{X}_t, \mathbf{Y}_{t-1}, N_0\right). \end{aligned} \quad (14)$$

$\kappa_{(\mathbf{AP}, \mathbf{sp})}(k)$ obeys the non-central chi-squared distribution, which has a non-central parameter

$$\lambda_{(\mathbf{AP}, \mathbf{sp})}(k) = \sum_{(i,j)} |\mu_{(\mathbf{AP}, \mathbf{sp})}(i, j)|^2 / N_0. \quad (15)$$

The probability of having a combination $(\mathbf{AP}, \mathbf{sp})$ at the k -th level inside the sphere with radius C can be rewritten by utilizing the generalised Marcum's Q function [13, Eq. (2-3-35)] as

$$p_{(\mathbf{AP}, \mathbf{sp}, C)}(k) = 1 - Q_k\left(\sqrt{\lambda_{(\mathbf{AP}, \mathbf{sp})}(k)}, \frac{C}{\sqrt{N_0}}\right). \quad (16)$$

If $p_{(\mathbf{AP}, \mathbf{sp}, C)}(N_t N_r)$ is larger than the threshold value ς , C is updated by

$$C^2 = \sum_{\forall(i,j)} |n' + \mu_{(\mathbf{AP}, \mathbf{sp})}(i, j)|^2. \quad (17)$$

Therefore, the total equation operation times for each combination $(\mathbf{AP}, \mathbf{sp})$ is

$$\phi_{(\mathbf{AP}, \mathbf{sp})} = \sum_{k=1}^{N_t N_r} p_{(\mathbf{AP}, \mathbf{sp}, C)}(k) \quad (18)$$

and the total equation operation times for DSM-SD algorithm is

$$\phi_{DSM-SD} = \sum_{\forall \mathbf{AP} \in \alpha} \sum_{\forall \mathbf{sp} \in \beta} \phi_{(\mathbf{AP}, \mathbf{sp})}. \quad (19)$$

IV. SIMULATION RESULTS AND ANALYSIS

We perform Monte Carlo simulations to validate the proposed DSM-SD detector. In our simulations, binary PSK (BPSK) and Rayleigh slowly fading channel are assumed. The number of transmit antennas is chosen as $N_t = 4$. In the following, we present the BER performance and computational complexity of the proposed DSM-SD detector as well as the relative comparisons.

Figs. 2 and 3 compare the BER performance and computational complexity of DSM-SD versus DSM-ML in the case of $N_r = 3$, respectively. As shown in Fig. 2, the DSM-SD algorithm has an identical BER performance to the conventional DSM-ML algorithm. In other words, the DSM-SD algorithm is proved to be an optimal detection method. The reasons for the results are twofold. First of all, DSM-SD is essentially based on the same principle as DSM-ML, which searches all the candidate space-time information blocks and avoids missing the optimal solution. The second reason is that the initial sphere radius is set to be infinity as mentioned above.

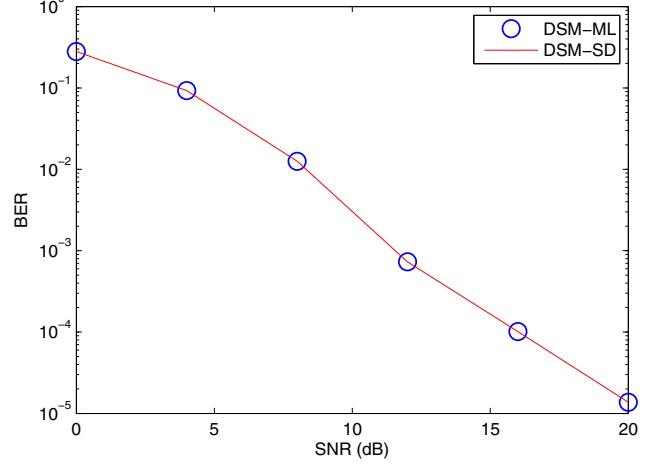


Fig. 2. BER performance comparison between DSM-SD and DSM-ML for the case of $N_r = 3$.

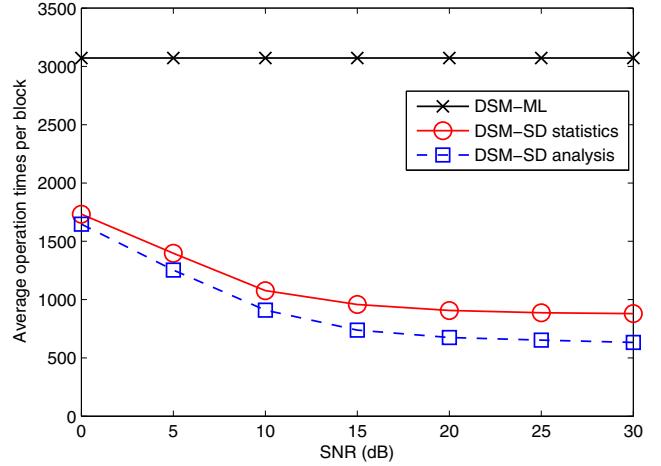


Fig. 3. Computational complexity comparison between DSM-SD and DSM-ML for the case of $N_r = 3$.

Fig. 3 shows the comparison of computational complexity. In Fig. 3, the computational complexity is defined as the average operation times of the Euclidian distance equations for each information block. The operation times for DSM-ML is given in (7), while the operation times for DSM-SD can be derived by simulation statistics or analysis. Comparing the complexity curve generating from statistics, we see that DSM-SD has a lower complexity than DSM-ML over the entire SNR region. For DSM-SD, the complexity curve through statistics approaches the analytical one over the entire SNR region, which corroborates that simulation results are plausible.

The computational complexity reduction of DSM-SD for $N_r = 3$ and $N_r = 8$ is depicted in Fig. 4. It should be noted that we adopt the computational complexity reduction proportion of DSM-SD with respect to DSM-ML in this figure. More specifically, the indicator representing the reduction of

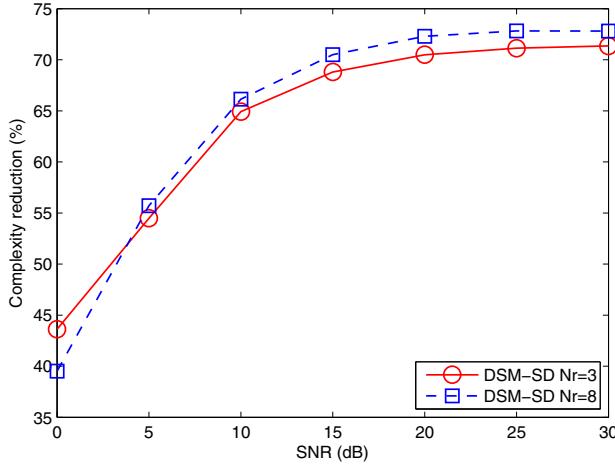


Fig. 4. Computational complexity reduction of DSM-SD for $N_r = 3$ and $N_r = 8$.

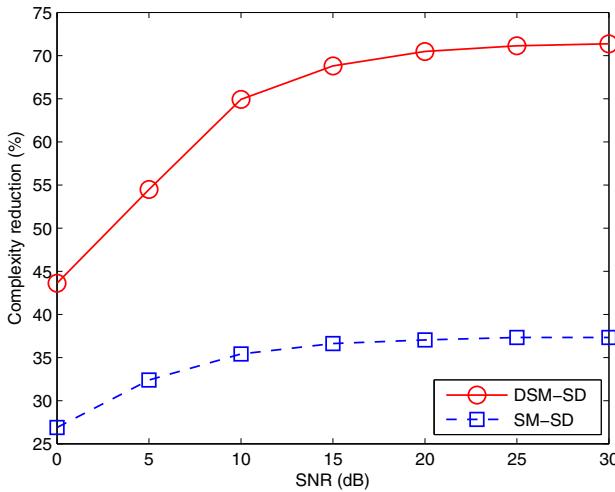


Fig. 5. Computational complexity reduction comparison between DSM-SD and SM-SD for the case of $N_r = 3$.

computational complexity for DSM is given by

$$CR_{DSM} (\%) = 100 \times \frac{\phi_{DSM-ML} - \phi_{DSM-SD}}{\phi_{DSM-ML}}, \quad (20)$$

where ϕ_{DSM-SD} is derived through statistics. When the SNR is larger than 5 dB, the complexity reduction proportion of DSM-SD can be slightly enhanced if we adopt a larger N_r . Since DSM-SD reduces the receive search space, the efficiency of DSM-SD gets more significant when we equip more receive antennas.

Fig. 5 compares the complexity reduction proportion between DSM-SD and SM-SD for $N_r = 3$. Similar to (20), the reduction of computational complexity for SM is presented as

$$CR_{SM} (\%) = 100 \times \frac{\phi_{SM-ML} - \phi_{SM-SD}}{\phi_{SM-ML}}. \quad (21)$$

Based on the SM-ML detection formula [9, Eq. (8)], the total operation times of Euclidian distance equation can be expressed as

$$\phi_{SM-ML} = N_t M N_r, \quad (22)$$

while the total operation times for SM-SD, ϕ_{SM-SD} , is derived through statistics. It is apparent that DSM-SD significantly outperforms SM-SD in complexity reduction. Therefore, the efficiency of SD method employed in DSM is demonstrated.

V. CONCLUSIONS

In this paper, we for the first time proposed the DSM-SD method. DSM-SD utilizes the tree search structure to avoid the exhaustive search adopted by the conventional DSM-ML detector. Simulation results demonstrated that DSM-SD retains an optimal BER performance and achieves relatively low complexity. Moreover, the complexity reduction proportion of DSM-SD was shown to get larger with the increase of the receive antenna number. Compared with SM-SD, DSM-SD achieved a more significant reduction in computational complexity. Thus, the utilization of SD in DSM is verified to be more useful and attractive in comparison with SM.

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