SCIENCE CHINA
Information Sciences

• RESEARCH PAPER •

September 2022, Vol. 65 192302:1–192302:14
https://doi.org/10.1007/s11432-021-3333-4

Low-complexity transmit antenna selection for offset spatial modulation

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Received 3 May 2021/Revised 21 June 2021/Accepted 8 September 2021/Published online 29 August 2022

Abstract Euclidean distance optimized antenna selection (EDAS) has been integrated with offset spatial modulation (OSM) for alleviating the effects of channel fading and increasing diversity gain, but the complexity of EDAS may become excessive upon increasing transmit antennas, particularly for the large-scale multiple-input multiple-output (MIMO) systems. In pursuit of low complexity, we conceive a novel transmit antenna selection (TAS) scheme for OSM, where the challenge of exhaustively searching all possible antenna subsets is tackled with the aid of a specific single tree search. Simulation results demonstrate the advantage of the proposed scheme in terms of significant search complexity reduction while achieving near-optimal bit error rate (BER) performance.

Keywords multiple input multiple output, offset spatial modulation, transmit antenna selection, Euclidean distance optimized antenna selection

Citation Chen H, Xiao Y, Fang S, et al. Low-complexity transmit antenna selection for offset spatial modulation. Sci China Inf Sci, 2022, 65(9): 192302, https://doi.org/10.1007/s11432-021-3333-4

1 Introduction

Spatial modulation (SM) is deemed to be a promising multiple-input multiple-output (MIMO) transmission technique due to its remarkable single-radio-frequency (RF) structure, which facilitates a low-complexity and low-cost MIMO implementation, while providing robust wireless transmission [1–3]. However, SM entails frequent toggling between the activated transmit antennas and the single RF chain, and hence the transmission rate may be constrained by the maximal switching frequency. Especially, with the advent of wireless communication networks towards the fifth generation (5G) and beyond [4], the RF switching frequency may be impractical to satisfy the demand for extremely high transmission rate (Gbps or even Tbps), which precludes the application of SM-MIMO in future high-rate wireless systems.

For alleviating the RF switching problem, offset spatial modulation (OSM) has recently been proposed [5], drawing wide attention as a benefit of its low switching frequency of the RF chain and considerable performance improvement, compared with conventional SM. More specifically, OSM dynamically adjusts the switching frequency of the activated antenna and the RF chain under different channel scenarios. For example, in some extreme cases where the devices are impervious to the momentary fluctuations of the channel, OSM can work without switching the RF chain in pursuit of a high transmission rate and the stability of the system performance, which is reminiscent of the dynamic relay access technique for device-to-device (D2D) aided system [6, 7] and the adjustable phase shift pilots (APSP) set allocation scheme in cell-free massive MIMO-OFDM systems [8]. Moreover, OSM maintains the single-RF structure with moderate computational complexity and hence may be more advantageous in future wireless communications. However, both the SM and OSM schemes have their limitations in conquering the severe impact of channel fading.

In the context of SM-MIMO, numerous studies were dedicated to tackling this problem for further improving the system performance [9–20]. In particular, transmit antenna selection (TAS) technique has

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been combined for the sake of improving the system diversity gain [10–15]. More specifically, the work of [10] has developed a capacity-optimized antenna selection (COAS) scheme by utilizing the Frobenius norm of the channel, which is analogous to the norm-based TAS approach proposed in [11]. Moreover, in [12], antenna correlation was considered, in order to mitigate the detection error induced by similar antennas. In contrast to the above-mentioned schemes, the Euclidean distance optimized antenna selection (EDAS) scheme greatly enhances the bit error rate (BER) performance at the cost of increased complexity [10]. As a further advance, a variety of TAS algorithms were proposed for reducing the complexity of EDAS [10,13–17]. For example, the authors of [10,13] conceived a TAS algorithm based on QR decomposition for reducing computational complexity. Furthermore, a tree search based TAS (TSAS) algorithm was provided in [17] as an efficient solution to reduce the search complexity.

More recently, as a further contribution to OSM, the TAS technique based on EDAS has been applied to OSM for further performance enhancement [21]. In addition, two novel TAS algorithms were designed for OSM, termed antenna selection based on grouped Euclidean distance (AS-GED) and antenna selection based on channel coefficient (AS-CC), which are capable of reducing the computational complexity [21]. However, to the best of authors' knowledge, it remains challenging for the TAS-aided OSM to simplify the search complexity in the current literature.

Against this background, we conceive a simplified variant of TSAS, termed single tree search based TAS (STSAS) scheme, for exhibiting a balanced tradeoff between BER performance and search complexity. More specifically, we firstly apply the TSAS algorithm to OSM. Then, the proposed STSAS scheme is particularly contrived for the OSM system, which restrains the growth of tree nodes upon exploiting the channel information, towards a near-optimum BER performance at significantly reduced search complexity.

The rest of this paper is organized as follows. Section 2 details the OSM system model and then introduces the structure of the EDAS scheme and its low-complexity algorithm. In Section 3, the TSAS algorithm is applied and the proposed STSAS scheme is also described, whereas the corresponding search complexity is derived in Section 4. In Section 5, the simulation results and comparisons are outlined. Finally, we conclude in Section 6.

2 Euclidean distance-based antenna selection for OSM

2.1 System model

The system model of OSM is portrayed in Figure 1, where the transmitter is equipped with an N_t-element antenna array and the receiver is assisted by a single antenna. Assume that the channel between the s-th transmit antenna and the receiver is a flat fading Rayleigh channel, and the corresponding channel gain h_s is independent and identically distributed (i.i.d) to complex Gaussian distribution $\mathcal{CN} \sim (0,1)$, where $s \in \{1,2,\ldots,N_t\}$. Furthermore, we assume that the M-ary quadrature amplitude modulation (QAM) or phase shift keying (PSK) symbol is denoted by s_m, where $m \in \mathbb{S} = \{1,2,\ldots,M\}$. At the transmitter, the input bits are firstly divided into two parts and then mapped to the M-ary QAM symbols s_m and the spatially modulated antenna index i, respectively. Next, unlike traditional SM, s_m and the index i are sent into the precoding block instead of directly transmitting the symbol s_m in the ith antenna. With the aid of the channel state feedback information, the symbol s_m for OSM can be precoded as

$$\tilde{s}_m = \beta \frac{h_i}{h_j} s_m, \tag{1}$$

where β is the normalized transmit power factor, with $\beta = |\frac{h_j}{h_i}|$, whereas $\frac{h_i}{h_j}$ represents the precoding parameter of the transmitted signal. Note that j represents the activated antenna index, which depends on the channel state information (CSI) rather than the input bits. In static OSM mode, the activated antenna index j is fixed and tyrannically selected from the transmit antennas, lending itself to a high transmission rate by avoiding switches among antennas. In dynamic OSM mode, a predefined antenna subset χ is given and then the activated antenna index j can be selected from χ on the basis of CSI, yielding

$$j = \arg\max_{k\in\chi} |h_k|\,. \tag{2}$$

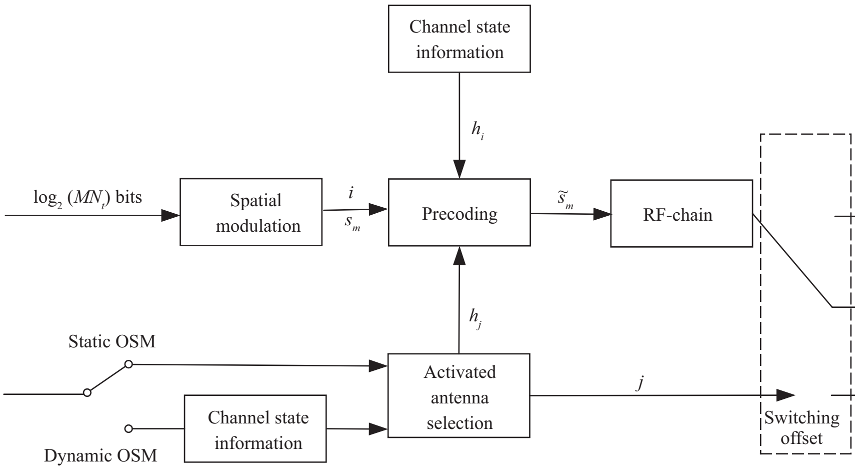

Figure 1 The system model of OSM.

Therefore, the transmitted signal of the OSM system $\widetilde{\boldsymbol{x}}_{j,m}$ can be expressed as

$$\widetilde{\boldsymbol{x}}_{j,m} = \begin{bmatrix} 0, \ldots, \tilde{s}_m, \ldots, 0 \\ \uparrow \\ j^{\text{th}} \end{bmatrix}^{\mathrm{T}}. \tag{3}$$

At the receiver side, since the activated one is the j-th antenna, the precoding parameter $\frac{1}{h_j}$ will be eliminated and then the received signal can be formulated as

$$y = \rho \boldsymbol{H} \widetilde{\boldsymbol{x}}_{j,m} + n = \rho h_j \tilde{s}_m + n = \rho \beta h_i s_m + n, \tag{4}$$

where ρ is the transmit power factor and n is additive Gauss white noise obeying $\mathcal{CN} \sim (0,1)$, while $\boldsymbol{H}$ denotes the corresponding channel matrix between transmit antennas and receive antenna.

It is noteworthy that, compared with the conventional SM scheme, static OSM connects the RF chain with a fixed antenna, circumventing the frequent switching problem at the cost of moderate performance loss. Moreover, exploiting the fact that the channel is almost static within the coherent time, dynamic OSM significantly reduces the switching frequency by regarding the RF switching time as the channel coherent time, while improving the system performance upon setting proper antenna subset. In pursuit of further performance improvement, the TAS technique has been introduced to select appropriate antenna subset χ, and hence to provide additional diversity gain. More details are shown in Subsection 2.2.

2.2 EDAS scheme and its low-complexity algorithm

For the OSM system using maximum likelihood detection, in order to improve the detection performance, the EDAS scheme has been amalgamated with OSM in [21], selecting the optimal antenna subset with maximum minimum Euclidean distance. More specifically, assume that N_s antennas are selected out of N_t ones based on the EDAS criterion, and let all possible antenna subsets and the optimal one be denoted by $\mathcal{I}$ and I_{AS}, respectively, whereas defining all possible transmit vectors in the activated antenna j as $\mathcal{X}_j$, the EDAS scheme for OSM can be expressed as

$$I_{\text{AS}} = \arg\max_{I \in \mathcal{I}} \left\{ \min_{\widetilde{\boldsymbol{x}}_{j,m} \neq \widetilde{\boldsymbol{x}}_{j,n} \in \mathcal{X}_j} \left\| \boldsymbol{H}_I \left(\widetilde{\boldsymbol{x}}_{j,m} - \widetilde{\boldsymbol{x}}_{j,n} \right) \right\|_F^2 \right\}. \tag{5}$$

For the sake of simplicity, we assume that the receiver already has obtained the normalized transmit power factor β in the following analysis. Hence, let $\mathcal{X}_{N_s}$ denote all possible transmit vectors of the predefined antenna subsets I, and Eq. (5) can be further simplified into

$$I_{\text{AS}} = \arg\max_{I \in \mathcal{I}} \left\{ \min_{\boldsymbol{x}_{p,m} \neq \boldsymbol{x}_{q,n} \in \mathcal{X}_{N_s}} \left\| \boldsymbol{H}_I \left(\boldsymbol{x}_{p,m} - \boldsymbol{x}_{q,n} \right) \right\|_F^2 \right\} \tag{6}$$

with

$$\boldsymbol{x}_{g,h} = \begin{bmatrix} 0, \ldots, s_g, \ldots, 0 \\ \uparrow \\ h^{\text{th}} \end{bmatrix}^{\mathrm{T}} \in \mathbb{C}^{N_s \times 1}, \tag{7}$$

where $g \in \{p, q\}$, $h \in \{m, n\}$, and s_p and s_q are the transmit symbol selected from the M-ary constellation set, respectively.

However, the EDAS scheme with exhaustive search requires traversing all possible antenna subsets, which imposes high complexity. Hence, the author of [21] conceived a novel low-complexity TAS algorithm for OSM, namely AS-GED, which jointly considers the power factor β and minimum Euclidean distance, to reduce the computational complexity at a moderate BER performance degradation. More specifically, since the pairwise error probability (PEP) of OSM could be formulated as [5]

$$p(\boldsymbol{x}_{p,m} \to \boldsymbol{x}_{q,n}) = \frac{1}{2}\{1 - \mathrm{E}[g(\beta)]\} \tag{8}$$

with

$$g(\beta) = \sqrt{\frac{\rho\beta^2}{2 + \rho\beta^2}}, \tag{9}$$

a higher power factor β can enhance the BER performance of OSM. Hence, the transmit antennas are partitioned into two groups for the sake of enlarging the power factor β. For the former, $\lceil \frac{N_t}{2} \rceil$ antennas with larger channel gain are obtained, while in the latter, $N_t - \lceil \frac{N_t}{2} \rceil$ antennas are obtained, where $\lceil \cdot \rceil$ rounds the number to its nearest integer. Let T_{S1} and T_{S2} denote these two groups respectively, and then these groups are detailed as

$$\begin{cases} T_{S1} = \left\{ h_1, h_2, \ldots, h_{\lceil \frac{N_t}{2} \rceil} \right\} \\ T_{S2} = \left\{ h_{\lceil \frac{N_t}{2} \rceil + 1}, \ldots, h_{N_t} \right\} \end{cases}, \quad |h_1| \geqslant |h_2| \geqslant \cdots \geqslant |h_{N_t}|. \tag{10}$$

In order to obtain the possible antenna subset with larger power factor β, the AS-GED algorithm selects $N_s/2$ antennas from T_{S1} and T_{S2}, respectively. For the first group T_{S1}, let the channel vectors be constituted by h_1 and other $N_s/2 - 1$ components in T_{S1} be denoted by $\boldsymbol{H}_{h_1, T_{S1}}$, and assume that $\mathcal{I}_{h_1, T_{S1}}$ represents the set of corresponding antenna subsets, and then the criterion of selecting the set I_{p_1} with maximum minimum Euclidean distance could be written as

$$I_{p_1} = \underset{I \in \mathcal{I}_{h_1, T_{S1}}}{\arg\max} \left\{ \min_{\substack{\boldsymbol{H}_I \in \boldsymbol{H}_{h_1, T_{S1}} \\ \boldsymbol{x}_1 \neq \boldsymbol{x}_2 \in \mathcal{X}_{N_s/2}}} \left\| \boldsymbol{H}_I (\boldsymbol{x}_1 - \boldsymbol{x}_2) \right\|_F^2 \right\}. \tag{11}$$

As for the second group T_{S2}, the channel components of the selected antenna set I_{p_1} are assumed to be $\widehat{T}_{S1}$, and we also assume that $\boldsymbol{H}_{\widehat{T}_{S1}, T_{S2}}$ denotes the channel matrix composed by $\widehat{T}_{S1}$ and $N_s/2$ components in T_{S2}. Then, the selection criterion of the second group is analogous to the first one, which can be expressed as

$$I_{\mathrm{AS}} = \underset{I \in \mathcal{I}_{\widehat{T}_{S1}, T_{S2}}}{\arg\max} \left\{ \min_{\substack{\boldsymbol{H}_I \in \boldsymbol{H}_{\widehat{T}_{S1}, T_{S2}} \\ \boldsymbol{x}_1 \neq \boldsymbol{x}_2 \in \mathcal{X}_{N_s}}} \left\| \boldsymbol{H}_I (\boldsymbol{x}_1 - \boldsymbol{x}_2) \right\|_F^2 \right\}, \tag{12}$$

where $\mathcal{I}_{\widehat{T}_{S1}, T_{S2}}$ represents the set of corresponding antenna sets.

By dividing the channel vectors into two groups, AS-GED reduces the complexity of calculating the Euclidean distance, since the number of possible antenna subsets is smaller. Moreover, AS-GED ensures the selected antenna subset has more prominent power factors. Therefore, the AS-GED algorithm achieves a near-optimal BER performance compared to the conventional EDAS with significant complexity reduction.

3 Proposed low search complexity antenna selection scheme

3.1 Tree search based TAS scheme for OSM

In the context of OSM, the AS-GED algorithm was developed in order to jointly consider the power factors and the minimum Euclidean distance, which is capable of reducing the computational complexity. However, to the best of the authors' knowledge, the search complexity reduction problem of OSM has not been considered in the current literature yet, which is as important as computational complexity reduction. Hence, in this contribution, we first apply the TSAS scheme [17] to OSM, which assists us in efficiently finding the optimal antenna subset, with the aim of reducing the excessive search complexity. The derivation of the equivalent criterion of EDAS is given in Subsection 3.1.1, followed by the specific TSAS algorithm steps.

3.1.1 *The derivation of the equivalent criterion of EDAS*

In order to facilitate the analysis, we assume that $\mathcal{I}$ denotes the set of all possible antenna subsets and then the EDAS criterion can be rewritten as

$$I_{\mathrm{AS}} = \arg\max_{I\in\mathcal{I}} \left\{\min \boldsymbol{D}(I)\right\}, \tag{13}$$

where $\boldsymbol{D}(I)$ is a sub-matrix obtained by discarding the rows and columns of $\boldsymbol{D}$ that are not in the antenna subset I, and $\{\min \boldsymbol{D}(I)\}$ denotes the minimum non-zero elements of $\boldsymbol{D}(I)$. Moreover, the Euclidean distance matrix $\boldsymbol{D}$ can be detailed as

$$\boldsymbol{D} = \begin{bmatrix} d_{1,1} & d_{1,2} & \dots & \dots & d_{1,N_t} \\ 0 & d_{2,2} & \dots & \dots & d_{2,N_t} \\ 0 & 0 & d_{3,3} & \dots & d_{3,N_t} \\ 0 & 0 & 0 & \dots & \dots \\ 0 & 0 & 0 & \dots & d_{N_t,N_t} \end{bmatrix} \in \mathbb{R}^{N_t\times N_t} \tag{14}$$

with

$$d_{p,q} = \begin{cases} \min\limits_{s_m,s_n\in\mathbb{S}} \left\|h_p s_m - h_q s_n\right\|_F^2, & p>q, \\ \min\limits_{s_m\neq s_n\in\mathbb{S}} \left\|h_p\right\|_F^2 \left|s_m - s_n\right|^2, & p=q, \end{cases} \tag{15}$$

where h_p and h_q represent the pth and qth elements of the channel $\boldsymbol{H}\in\mathbb{C}^{1\times N_t}$, respectively. Note that the smaller the Euclidean distance element $d_{p,q}$ is, the closer the modulated constellation signals are. Therefore, in order to avoid two modulated signals being too close, the minimum Euclidean distance element of the matrix $\boldsymbol{D}$ should be discarded. To expound further, let d_{p^*,q^*} denote the minimum element in matrix $\boldsymbol{D}$, where p^* and q^* represent the located row and column of the minimum element, respectively. It is straightforward that

$$\min \boldsymbol{D}\left(I_{\mathrm{AS}}\right) > \min \boldsymbol{D} = d_{p^*,q^*}, \tag{16}$$

which implies that the minimum element of $\boldsymbol{D}$ is not generated by the optimal antenna subset I_{AS}. Based on (16), the relationship between transmit antenna indices $\{p^*,q^*\}$ and I_{AS} can be formulated as

$$\left(I_{\mathrm{AS}}\subset\mathbb{T}\backslash\{p^*\}\right)\vee\left(I_{\mathrm{AS}}\subset\mathbb{T}\backslash\{q^*\}\right)=1, \tag{17}$$

where $\mathbb{T}=\{1,2,\dots,N_t\}$. Thus, we can obtain the optimal antenna subset by searching two sets, namely, $\mathbb{T}/\{p^*\}$ and $\mathbb{T}/\{q^*\}$, with lower dimensions. To summarize, the equivalent selection criterion of EDAS can be defined as

$$I_{\mathrm{AS}} = \arg\max_{I\in\left\{I_{\mathrm{AS}}^{p^*}, I_{\mathrm{AS}}^{q^*}\right\}} \left\{\min \boldsymbol{D}(I)\right\}, \tag{18}$$

where

$$I_{\mathrm{AS}}^{p^*} = \arg\max_{I\in\mathbb{I}^{p^*}} \left\{\min \boldsymbol{D}^{p^*}(I)\right\}, \tag{19}$$

and

$$I_{\mathrm{AS}}^{q^*} = \arg\max_{I\in\mathbb{I}^{q^*}} \left\{\min \boldsymbol{D}^{q^*}(I)\right\}, \tag{20}$$

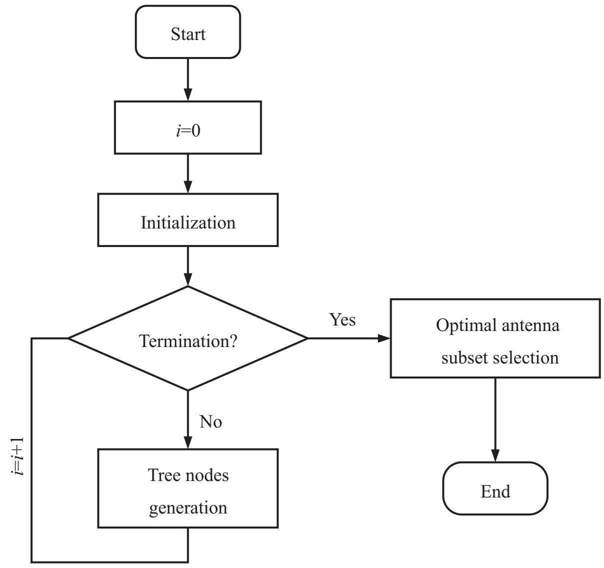

Figure 2 Flowchart depicting the structure of TSAS used in the OSM system.

where $\mathbb{I}^{p^*}$ and $\mathbb{I}^{q^*}$ denote the sets of enumerations of all possible antenna subsets over $\mathbb{T}/\{p^*\}$ and $\mathbb{T}/\{q^*\}$, respectively, and $\boldsymbol{D}^k \in \mathbb{R}^{(N_t-1)\times(N_t-1)}$ $(k \in \{p^*, q^*\})$ is the sub-matrix derived by deleting all the elements in the kth row and kth column of $\boldsymbol{D}$. With the aid of (19) and (20), the conventional EDAS criterion can be applied to the Euclidean matrix with a smaller dimension, leading to search complexity reduction without performance loss. Similarly, the selection criterion in (18) can be further adopted in the generated sub-matrices, until satisfying the termination conditions. Based on the above-mentioned equivalent criterion, a TSAS scheme has been introduced into OSM for efficiently finding the optimal antenna subset without performance degradation.

3.1.2 *The TSAS scheme*

Figure 2 portrays a flowchart of the TSAS scheme employed in the OSM system, where the specific steps are as follows.

(1) Initialization. The initialization block of the TSAS in Figure 2 generates the Euclidean distance matrix $\boldsymbol{D}$ according to (14) and (15). Then, based on (16), the minimum Euclidean distance element of the matrix $\boldsymbol{D}$ should be discarded in the iteration.

(2) Tree nodes generation. In the tree nodes generation block of Figure 2, the Euclidean distance matrix $\boldsymbol{D}$ is deemed to be the parent node. During the ith loop, as we mentioned before, the minimum element of the matrix should be deleted for the sake of enhancing the receiver's performance. To expound further, after confirming the minimum element d_{p^*,q^*}, the parent node is expanded into two child nodes $\boldsymbol{D}^k$ upon deleting all the elements in the kth column and kth row of matrix $\boldsymbol{D}$, with $k \in \{p^*, q^*\}$. Next, by letting $\boldsymbol{D} = \boldsymbol{D}^k$ and repeating the delete operation until satisfying the termination conditions, a full binary tree is generated, and its leaf nodes indicate the possible antenna subsets with larger Euclidean distance.

(3) Termination and optimal antenna subset selection. Finally, when the dimension of the sub-matrices $\boldsymbol{D}^k$ is N_s, the iteration process will be terminated. In the termination block, $2^{N_t-N_s}$ tree nodes generated in the final iteration are collected as the possible antenna subsets, ensuring that the candidates of the antenna subsets have considerable Euclidean distance. Then, in order to select the optimal antenna subset $I_{\rm AS}$, each antenna subset should find the minimum element from its corresponding Euclidean distance matrix, and the one with the largest minimum Euclidean distance is deemed to be the optimal antenna subset. Assume that $\mathcal{I}_p$ denotes the set of these possible antenna subsets, the selection criterion can be expressed as

$$I_{\rm AS} = \arg\max_{I\in\mathcal{I}_p} \{\min \boldsymbol{D}(I)\}\,. \tag{21}$$

It is worth noting that the TSAS scheme searches the leaf nodes to find the optimal antenna subset, circumventing the excessive complexity induced by searching all possible antenna subsets.

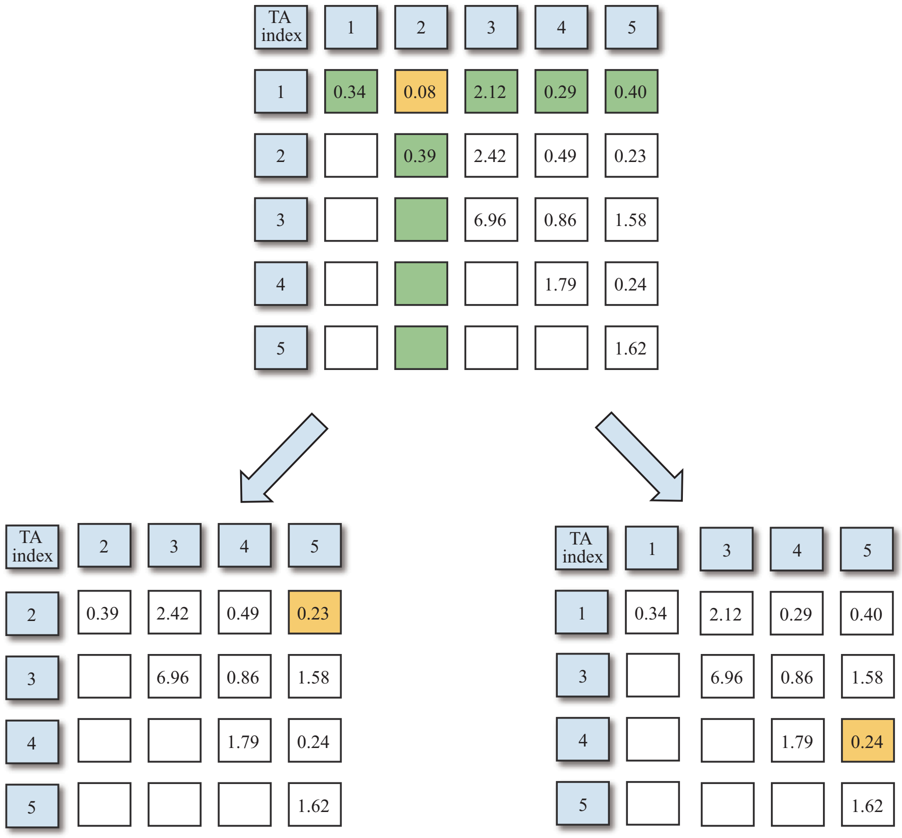

Figure 3 (Color online) An example of the TSAS scheme.

An example of the TSAS scheme is depicted in Figure 3. Assume that the TAS-aided OSM system is equipped with $N_t = 5$, $N_s = 4$, $N_r = 1$, and the Euclidean distance matrix $\boldsymbol{D}$ calculated by (14) and (15) has already been known. In the original matrix $\boldsymbol{D}$, the minimum element is $d_{1,2}$. In order to obtain the possible antenna subsets, the 1st row and 1st column are deleted to generate the child node $\boldsymbol{D}^1$, and the generation of $\boldsymbol{D}^2$ is similar to $\boldsymbol{D}^1$. Next, notice that the dimension of $\boldsymbol{D}^1$ and $\boldsymbol{D}^2$ is 4, and the iteration is terminated. Finally, after comparing the minimum elements of $\boldsymbol{D}^1$ and $\boldsymbol{D}^2$, the optimal antenna subset is identified, i.e., $\{1, 3, 4, 5\}$. It is remarkable that the result is the same as that of the exhaustive search scheme.

3.2 Proposed single tree search based TAS scheme

With the aid of TSAS, the search complexity of finding the optimal antenna subset is reduced, while keeping the same BER performance comparable to that of the EDAS scheme. Nevertheless, since the number of tree nodes exponentially increases with antenna scale and each tree node needs to find its minimum element, consequently, abundant repeated comparisons are introduced upon increasing the antenna scale, particularly in the context of a large-scale OSM scenario. Hence, inspired by the idea of jointly considering the power factor and minimum Euclidean distance [21], we conceive a STSAS scheme to tackle this problem, achieving a trade-off between search complexity and BER performance. The simplified tree node generation criterion of STSAS is shown in Subsection 3.2.1, followed by the specific STSAS algorithm steps.

3.2.1 *The simplified tree node generation criterion of STSAS*

In order to suppress the excessive growth of tree nodes, a simplified tree node generation criterion is devised. More specifically, Eq. (16) can be transformed into

$$(p^* \notin I_{\rm AS}) \vee (q^* \notin I_{\rm AS}) = 1, \tag{22}$$

which implies that the p^*th and q^*th antennas do not belong to the optimal antenna subset $I_{\rm AS}$ at the same time. Hence, the p^*th or q^*th antenna can be discarded to approach the optimal antenna subset. For the sake of restraining the growth of tree nodes, the new criterion of tree node generation is proposed to delete one of these two antennas, which is given as

$$\boldsymbol{D} \to \boldsymbol{D}^k, \quad k = p^* \text{ or } q^*, \tag{23}$$

where k depends on situations. It is noteworthy that, compared with the original full binary tree search structure, each node produces only one child node based on the specific criterion, which is capable of further simplifying the search tree structure. More specifically, let l represent the antenna index with the largest channel gain, the generation criterion consists of two situations: $l \in \{p^*, q^*\}$ and $l \notin \{p^*, q^*\}$.

For the first situation, according to the precoding rule of dynamic OSM in (2), it is reasonable to retain the antenna with the largest channel norm. Hence, STSAS generates single tree nodes by deleting all the elements in the kth row and kth column, where k is the element of the set $\{p^*, q^*\}$ that is not equal to l.

As for the second situation, bear in mind the benefit of acquiring the high power factor β in (8) and (9), the STSAS scheme can retain the antenna with a more significant power factor and delete the smaller one. Assume that $\|h_{p^*}\|_F^2 > \|h_{q^*}\|_F^2$, and the power factor of these two antennas has the following relationship:

$$\beta_{p^*} = \left|\frac{h_l}{h_{p^*}}\right| < \beta_{q^*} = \left|\frac{h_l}{h_{q^*}}\right|, \tag{24}$$

otherwise, $\beta_{p^*} > \beta_{q^*}$. Consequently, in analogy to the first situation, all the elements in the kth row and kth column are excluded, where k is the element of the set $\{p^*, q^*\}$ that has larger channel norm. In conclusion, the value of k is given as

$$k = \begin{cases} q^*, l \in \{p^*, q^*\}, \ l = p^*, \\ p^*, l \in \{p^*, q^*\}, \ l = q^*, \\ q^*, l \notin \{p^*, q^*\}, \ \|h_{p^*}\|_F^2 < \|h_{q^*}\|_F^2, \\ p^*, l \notin \{p^*, q^*\}, \ \|h_{p^*}\|_F^2 > \|h_{q^*}\|_F^2. \end{cases} \tag{25}$$

Using this simplified tree node generation criterion, the STSAS scheme prunes the tree node based on the peculiarity of the OSM system, which jointly considers the power factor and minimum Euclidean distance. More specifically, the generation of tree node aims at finding the potential antenna subsets with larger Euclidean distance, and the power factors are introduced to further suppress the growth of tree node while ensuring the performance of OSM. Therefore, the pruned tree generated by STSAS can assist us in achieving a substantial complexity reduction at the cost of moderate BER performance degradation.

3.2.2 *The STSAS scheme*

Figure 4 depicts a flowchart of the STSAS scheme adopted in the OSM system, where the specific steps are as follows.

(1) Initialization. The initialization block of Figure 4 is analogous to Figure 2, where the Euclidean distance matrix $\boldsymbol{D}$ is given by (14) and (15). Moreover, the channel vector $\boldsymbol{H}$ has to be known, which can be expressed as

$$\boldsymbol{H} = [h_1, h_2, \ldots, h_{N_t}] \in \mathbb{C}^{1\times N_t}. \tag{26}$$

On the basis of the Euclidean distance matrix and channel norm, STSAS utilizes the simplified criterion to find the sub-optimal antenna subset.

(2) Single tree nodes generation. For the sake of further reducing the search complexity, we consider the effect of power factor β to simplify the process of tree nodes generation. During the ith loop, after confirming the corresponding row and column of the minimum element of matrix $\boldsymbol{D}$, the parent node produces one child node based on (25). Then, a single tree is generated by repeating the delete operation until the termination conditions are satisfied.

(3) Obtain sub-optimal antenna subset. The termination condition is similar to the TSAS scheme. Nevertheless, the STSAS scheme has only one tree node in the final iteration, and hence the searches in (21) can be omitted.

The search process of STSAS is exemplified in Figure 5. Consider the same scenario given in the example of TSAS, the proposed STSAS scheme has the following steps to find the sub-optimal antenna

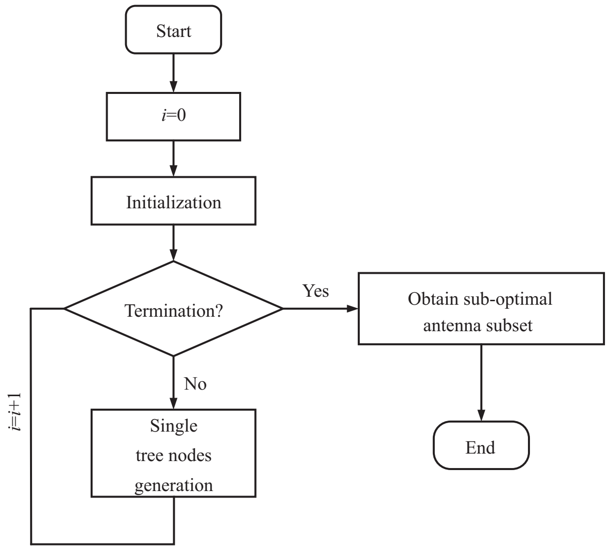

Figure 4 Flowchart depicting the structure of STSAS used in the OSM system.

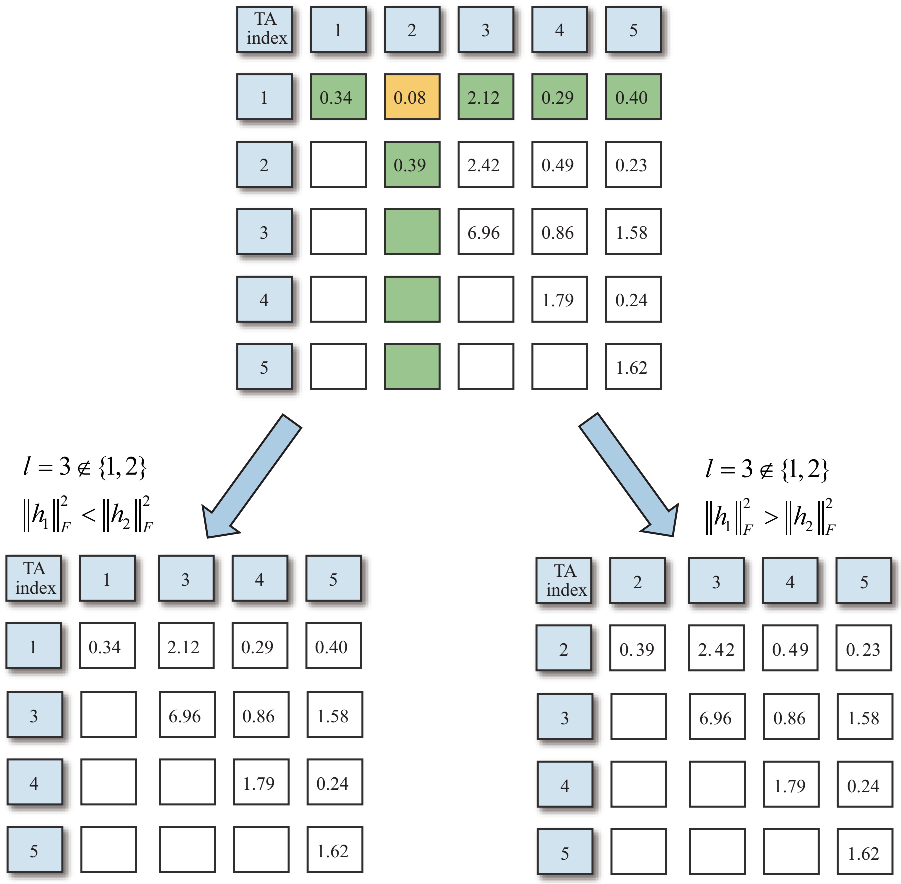

Figure 5 (Color online) An example of the STSAS scheme.

subset, while we assume $l = 3$. First, we find that the minimum element of the matrix $\boldsymbol{D}$ is $d_{p^*,q^*} = 0.08$, where $(p^*, q^*) = (1, 2)$. Then, if $\|h_1\|_F^2 < \|h_2\|_F^2$, according to (25), the elements of the 2nd row and column are deleted to generate the child node, which implies that the 2nd transmit antenna should be excluded. Since the dimension of the child node is 4, the generation is terminated and the selected antenna subset is $\{1, 3, 4, 5\}$. Note that if $\|h_1\|_F^2 > \|h_2\|_F^2$, the selected antenna subset will be different from that obtained by TSAS. Upon the channel state information, the proposed STSAS scheme prunes a full binary tree into a single tree, thus preventing excessive searches in the large-scale antenna scenarios.

4 Complexity analysis

4.1 The search complexity of EDAS

In terms of search complexity, the EDAS scheme exhaustively searches all possible antenna subsets to find the optimal one. First, each antenna subset requires $C^2_{N_s+1}-1$ comparisons to find its minimum element, while the number of the possible candidate antenna subsets is $C^{N_s}_{N_t}$. Then, $C^{N_s}_{N_t}-1$ comparisons are needed to find the optimal antenna subset among $C^{N_s}_{N_t}$ antenna subsets. Therefore, the search complexity of the EDAS scheme can be expressed as

$$\mathcal{O}^{\rm sc}_{\rm EDAS} = C^{N_s}_{N_t}(C^2_{N_s+1}-1) + C^{N_s}_{N_t} - 1. \tag{27}$$

As for the TSAS scheme combined with EDAS, in the ith level, we obtain 2^i sub-matrices of dimension N_t-i, each having $C^2_{N_t+1-i}$ non-zero elements. Therefore, each sub-matrix needs $C^2_{N_t+1-i}-1$ comparisons to find the minimum element, where $i\in\{0,1,\ldots,N_t-N_s\}$. Finally, in the last iteration, $2^{N_t-N_s}-1$ comparisons are required to obtain the optimal antenna subset. Hence, the search complexity of the applied TSAS scheme can be expressed as

$$\mathcal{O}^{\rm sc}_{\rm TSAS} = \sum_{i=0}^{N_t-N_s} 2^i(C^2_{N_t+1-i}-1) + 2^{N_t-N_s} - 1, \tag{28}$$

which can be simplified into

$$\mathcal{O}^{\rm sc}_{\rm TSAS} = \left(N_s^2+3N_s+3\right)2^{N_t-N_s} - \frac{N_t^2+5N_t+8}{2}. \tag{29}$$

For the proposed STSAS scheme in conjunction with EDAS, the search complexity can be easily deduced from TSAS. In contrast to the TSAS scheme, in the ith level, STSAS generates only one sub-matrix with size $(N_t-i)\times(N_t-i)$. What is more, the final iteration directly obtains the antenna subset, dispensing with the comparisons. Hence, the search complexity of STSAS can be written as

$$\mathcal{O}^{\rm sc}_{\rm STSAS} = \sum_{i=0}^{N_t-N_s-1} (C^2_{N_t+1-i}-1). \tag{30}$$

And Eq. (30) could be further simplified to

$$\mathcal{O}^{\rm sc}_{\rm STSAS} = \frac{(N_t-N_s)^3}{6} + \frac{(N_t-N_s)(N_t+1)(N_s+1)}{2} - \frac{7(N_t-N_s)}{6}, \tag{31}$$

while the proof of (31) is shown in Appendix A.

4.2 The search complexity of AS-GED

Similarly, the proposed STSAS scheme can also be applied to AS-GED for a further significant complexity reduction. First, we discuss the search complexity of AS-GED. To obtain the set I_{p_1} from the first group $\mathcal{I}_{h_1,T_{S1}}$, $C^{N_s/2-1}_{\lceil N_t/2\rceil-1}$ possible combinations need to be searched for their minimum element, while each combination entails $C^2_{N_s/2+1}-1$ comparisons. Then, in order to find the final antenna subset from $\mathcal{I}_{\widehat{T}_{S1},T_{S2}}$, each candidate combination requires $C^2_{N_s+1}-1$ comparisons and the number of the candidate combinations is $C^{N_s/2}_{N_t-\lceil N_t/2\rceil}$. Hence, the search complexity of AS-GED can be given as

$$\begin{aligned}\mathcal{O}^{\rm sc}_{\rm AS\text{-}GED} &= C^{N_s/2-1}_{\lceil N_t/2\rceil-1}\times\left(C^2_{N_s/2+1}-1\right) + \left(C^{N_s/2-1}_{\lceil N_t/2\rceil-1}-1\right)\\ &\quad + C^{N_s/2}_{N_t-\lceil N_t/2\rceil}\times\left(C^2_{N_s+1}-1\right) + \left(C^{N_s/2}_{N_t-\lceil N_t/2\rceil}-1\right)\\ &= C^{N_s/2-1}_{\lceil N_t/2\rceil-1}\times C^2_{N_s/2+1} + C^{N_s/2}_{N_t-\lceil N_t/2\rceil}\times C^2_{N_s+1} - 2. \end{aligned} \tag{32}$$

As for the proposed STSAS scheme combined with AS-GED (AS-GED-STS), the search complexity is divided into two parts. For the first group $\mathcal{I}_{h_1,T_{S1}}$, the dimension of the initial Euclidean distance matrix is $\lceil N_t/2\rceil$, and the iteration ends when the dimension of the sub-matrix is $N_s/2$. Moreover, to confirm the final antenna subset, the dimension of the second group's Euclidean distance matrix increases to $N_s/2 + N_t - \lceil N_t/2\rceil$, and the iteration will not be terminated until the size of the sub-matrix is $N_s \times N_s$. Therefore, according to (30), the search complexity of AS-GED-STS can be expressed as

$$\mathcal{O}^{\text{sc}}_{\text{AS-GED-STS}} = \sum_{i=0}^{\lceil N_t/2\rceil - N_s/2-1} (C^2_{\lceil N_t/2\rceil+1-i} - 1) + \sum_{i=0}^{N_t-\lceil N_t/2\rceil - N_s/2-1} (C^2_{N_s/2+N_t-\lceil N_t/2\rceil+1-i} - 1). \tag{33}$$

5 Performance evaluation

In this section, our simulation results are presented for the sake of demonstrating the advantage of the proposed STSAS scheme in the context of BER performance and search complexity. Unless otherwise specified, the channel state information is assumed to be known by the transmitter. We compare the BER performance with the optimal EDAS, TSAS, AS-GED, AS-CC [21] schemes, followed by their search complexity evaluation.

5.1 BER performance

Figure 6 characterizes the BER performance of the STSAS scheme in the context of $N_r = 1$, $N_s = 8$, $N_t = 10$ and QPSK. For comparison, the BER performance of the optimal EDAS, TSAS and AS-CC schemes is also considered. It can be seen in Figure 6 that the applied TSAS scheme achieves the identical BER performance to the optimal EDAS, while the proposed STSAS scheme outperforms its AS-CC counterpart and achieves near-optimal BER performance. The results of this figure are in agreement with previous analyses, by demonstrating that the TSAS scheme is capable of finding the optimal antenna subset, and the STSAS scheme sacrifices the BER performance for the sake of effectively searching the possible antenna subsets. Similar trends are also valid for Figure 7, where N_t increases from 10 to 17. It is worth mentioning that, compared to the configuration in Figure 6, STSAS approximately exhibits 0.7 dB performance loss at a BER of 10^{-4}. The reason for this degradation is that with the increase of N_t, the STSAS scheme searches fewer antenna subsets in comparison to TSAS, which reflects the increased degree of pruning, leading to moderate performance loss.

As an effective search scheme, STSAS can also be combined with AS-GED to reduce its search complexity. Compared with the AS-GED scheme, the AS-GED-STS scheme utilizes the power factor for efficiently searching the possible antenna subsets instead of exhaustively searching all possible antenna subsets in each group. Figure 8 shows the BER performance of AS-GED and AS-GED-STS, and the simulation results follow similar trends in Figures 6 and 7. In Figure 8, in the context of $N_r = 1$, $N_s = 8$, $N_t = 12$, the AS-GED-STS scheme approximately achieves the same BER performance with the AS-GED scheme, and exhibits 1 dB performance loss compared to that of EDAS at a BER of 10^{-4}. Thus, STSAS is capable of constituting a beneficial trade-off between the achievable BER performance and the search complexity in the context of the OSM system considered.

5.2 Search complexity

To further characterize the performance of the proposed STSAS scheme, Figure 9 depicts the search complexity of the above-mentioned schemes against N_t for $N_s = 8$. Observe from Figure 9 that as expected, with the increase of N_t, STSAS significantly reduces the search complexity compared with the optimal EDAS scheme. For example, the order of search complexity is reduced from 10^6 to 10^3 when $N_t = 17$ and $N_s = 8$, at the cost of a slight degradation in BER performance. What is more, the curves of STSAS and AS-GED-STS illustrate that the proposed scheme can be adopted in many TAS calculation complexity reduction schemes, to further reduce its search complexity. In conclusion, the proposed STSAS scheme avoids the exhaustive search after calculating the Euclidean distance matrix, using an effective single tree search to reduce the search complexity.

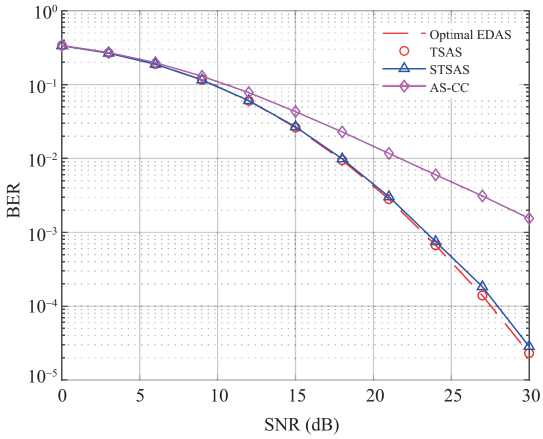

Figure 6 (Color online) BER performance of the optimal EDAS, TSAS, STSAS, AS-CC schemes in a QPSK scenario employing $N_r = 1$, $N_s = 8$ and $N_t = 10$.

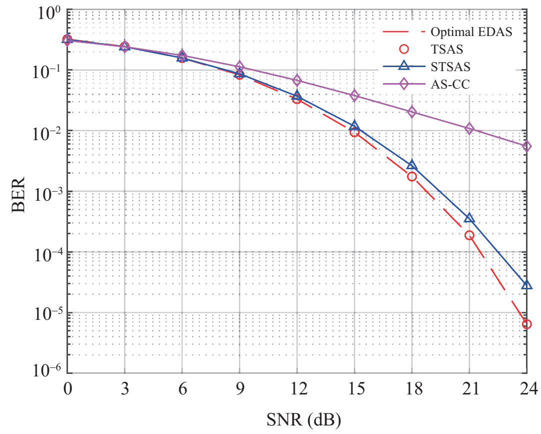

Figure 7 (Color online) BER performance of the optimal EDAS, TSAS, STSAS, AS-CC schemes in a QPSK scenario employing $N_r = 1$, $N_s = 8$ and $N_t = 17$.

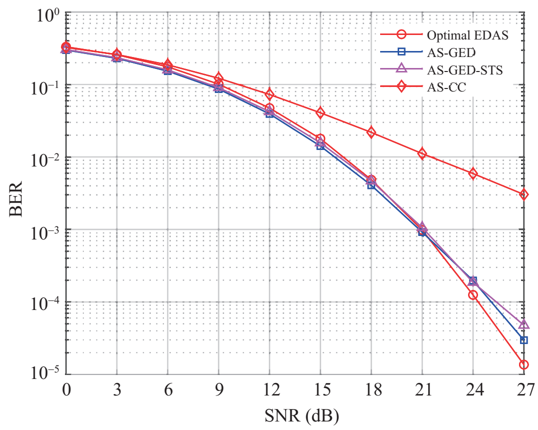

Figure 8 (Color online) BER performance of the optimal EDAS, AS-GED, AS-GED-STS, AS-CC schemes in a QPSK scenario employing $N_r = 1$, $N_s = 8$ and $N_t = 12$.

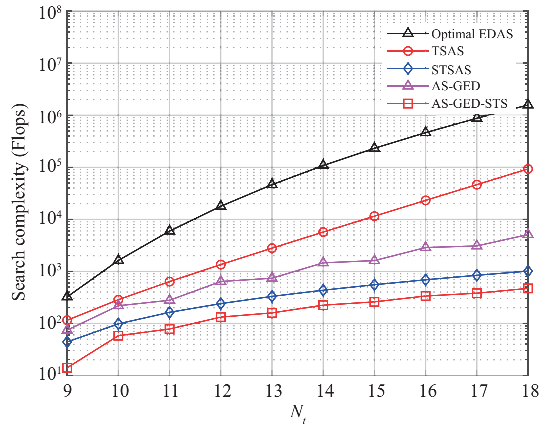

Figure 9 (Color online) Search complexities of various TAS schemes for different transmit antenna numbers N_t with $N_s = 8$.

Table 1 Search complexities of various TAS schemes with $N_t = 12$, $N_s = 8$ and SNR = 10 dB

TAS method	Search complexity	Search complexity saving factor (%)
Optimal EDAS	17819	–
TSAS	1350	92.42
STSAS	240	98.65
AS-GED	638	96.42
AS-GED-STS	132	99.65

Table 1 shows the search complexity for the optimal EDAS, TSAS, STSAS, AS-GED and AS-GED-STS schemes at SNR = 10 dB, with $N_t = 12$ and $N_s = 8$, respectively. From this table, we observe that the search complexity of STSAS is reduced by 82.2% in comparison to TSAS and the search complexity of AS-GED-STS is only 20.7% of AS-GED. This result also validates our analysis.

6 Conclusion

In this paper, a novel TAS scheme has been proposed, which jointly considers the power factor and the Euclidean distance to prune the search tree, leading to significant search complexity reduction. In addition, the proposed STSAS scheme may be readily integrated with existing computational complexity reduction schemes, without substantially modifying their regime. These properties render our STSAS design eminently applicable for employment in the OSM-MIMO system, particularly for large-scale antenna scenarios.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant No. 61771106) and National Key R&D Program of China (Grant No. 2020YFB1807203).

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Appendix A

First, let $m = N_t$, $n = N_s$. Eq. (30) can be rewritten as

$$\begin{aligned} f(m,n) &= \sum_{i=0}^{m-n-1} \left(C_{m+1-i}^{2} - 1 \right) \\ &= \frac{1}{2} \sum_{i=0}^{m-n-1} i^2 - \frac{2m+1}{2} \sum_{i=0}^{m-n-1} i + \sum_{i=0}^{m-n-1} \frac{m^2+m-2}{2}. \end{aligned} \tag{A1}$$

Letting $S_1 = \frac{1}{2}\sum_{i=0}^{m-n-1} i^2$, we have

$$\begin{aligned} S_1 &= \frac{1}{2} \sum_{i=0}^{m-n-1} i^2 = \frac{1}{2} \sum_{i=1}^{m-n-1} i^2 \\ &= \frac{1}{2} \times \frac{(m-n-1)(m-n)(2m-2n-1)}{3} \\ &= \frac{(m-n)}{2} \times \frac{(m-n-1)(2m-2n-1)}{3}. \end{aligned} \tag{A2}$$

What is more, let $S_2 = -\frac{2m+1}{2}\sum_{i=0}^{m-n-1} i$ and then this term can be simplified as

$$\begin{aligned} S_2 &= -\frac{2m+1}{2}\sum_{i=0}^{m-n-1} i \\ &= -\frac{2m+1}{2} \times (0+1+\cdots+m-n-1) \\ &= -\frac{2m+1}{2} \times \frac{(m-n)(m-n-1)}{2} \\ &= -\frac{(m-n)}{2} \times \frac{(2m+1)(m-n-1)}{2}. \end{aligned} \tag{A3}$$

Furthermore, the last term $S_3 = \sum_{i=0}^{m-n-1} \frac{m^2+m-2}{2}$ is not correlated with i, hence, the term can be expressed as

$$\begin{aligned} S_3 &= \sum_{i=0}^{m-n-1} \frac{m^2+m-2}{2} \\ &= \frac{(m-n)}{2} \times \frac{m^2+m-2}{2}. \end{aligned} \tag{A4}$$

Substituting (A2), (A3) and (A4) into (A1), and letting $m = N_t$, $n = N_s$, Eq. (31) can be obtained.