Multi-Antenna Selection using Space Shift Keying in MIMO Systems

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***Abstract*— We investigate the MIMO antenna selection using space shift keying (SSK) modulation and amplitude/phase modulation (APM). In the joint SSK and APM, both the constellation of APM and the antenna indexes of SSK convey information. The multiple-input multiple-output (MIMO) system increases the capacity and data rates at the cost of the multiple RF chains, which can be reduced by antenna selection techniques. In this paper, the antenna selection techniques are jointly designed with the SSK-based MIMO systems, and the decoding scheme achieving maximum-likelihood (ML) criterion is explicitly described. The proposed antenna selection criteria pursue the best antenna configuration by utilizing channel state information. The simulations demonstrate significant performance improvements of SSK-based MIMO systems over conventional systems.**

***Index Terms*— MIMO Systems, Spatial Modulation (SM), Space Shift Keying (SSK), Antenna Selection.**

I. Introduction

The demands for high spectral efficiency and data rate bring critical challenges in the next-generation wireless communications. One of the major technologies is the multiple-input multiple output (MIMO) systems. Various techniques in MIMO systems [1] have been developed, such as the vertical Bell Laboratories layered space-time (V-BLAST), orthogonal space time block codes (OSTBC), and pre-coding using singular value decomposition (SVD). The rationale of V-BLAST is to use space multiplexing which simultaneously convey symbols through different transmit antennas without using extra frequency bands. The OSTBC systems exploit the space and time domain to attain diversity gain. By using channel state information (CSI), the SVD technique decomposes the channel matrix and precodes the transmitted data to achieve the system metrics, e.g., the minimum bit error rate (BER) or decoding simplicity. However, these MIMO systems suffer from several disadvantages, such as inter-channel-interference (ICI), inter-antenna synchronization (IAS), and the power constraint of radio frequency (RF) chains. The space shift keying (SSK) modulation and antenna selection (AS) are capable of partially avoiding these issues.

The SSK modulation belongs to the category of spatial modulation [2], and the idea was initially conceptualized by Chau $et\ al.$ [3] to exploit the antenna indexes to convey information. In the standard SSK, only one antenna is activated to transmit data; therefore, the transmitter overhead, detection complexity, and the RF chains can be significantly reduced [4]. Several applications of SSK have been proposed and their performances were analyzed. In [4], the tight upper bounds of SSK bit error probability were derived and the performances were discussed under the channel errors and spatial correlation. However, the amplitude/phase modulation (APM) was not considered to cooperate with SSK in the work [4]. In [5], by using the opportunistic power allocation, the SSK MIMO systems obtain performance improvements and the closed form solution of the optimal power allocation was derived. The space time coding combined with SSK, named as space time shift keying (STSK) modulation, was proposed by Sugiura $et\ al.$ [6].

One option to reduce the RF chains is through the antenna selection. The overview of antenna selection technique was presented in [7] and two major approaches were introduced, i.e., the norm-based selection and successive selection. In [8], the post-processing SNRs of receiver antennas are adopted as the criteria to select the optimal antenna subset for linear receivers. In [9], with the assumption of a low-rate feedback link from the receiver to the transmitter, the multimode antenna selection criteria were proposed to dynamically select the number of substreams and their mapping to antennas based on the channel conditions. The symbols error rates in OSTBC systems using antenna subset selection are analyzed in [10].

In this paper, the MIMO systems jointly using APM and SSK modulation to convey information are studied. The maximum likelihood (ML) scheme is explicitly presented, and three antenna selection criteria are proposed to pursue the minimization of the symbol error rates with known CSI from the receiver. Furthermore, we conduct simulations and comparisons among various systems with fair configurations, where the same information bits per transmission in different systems are maintained. The simulations verify that the proposed multi-antenna selection criteria are beneficial to SSK-based MIMO systems.

Notation: Boldface lowercase and uppercase letters represent vectors and matrices, respectively. The $\|\cdot\|$ denotes the function of the l_2-norm of a vector. The $(\cdot)^T$ represents matrix transpose.

II. Signal Model

We consider the MIMO system consisting of M_T transmitting antennas and M_R receiving antennas. The $M_R \times M_T$ Rayleigh flat channel matrix $\mathbf{H}$ is assumed and all the entries are independent and identically distributed (i.i.d) complex Gaussian random variables. The system transmits symbols through $L(\leq M_T)$ out of the M_T transmitting antennas,

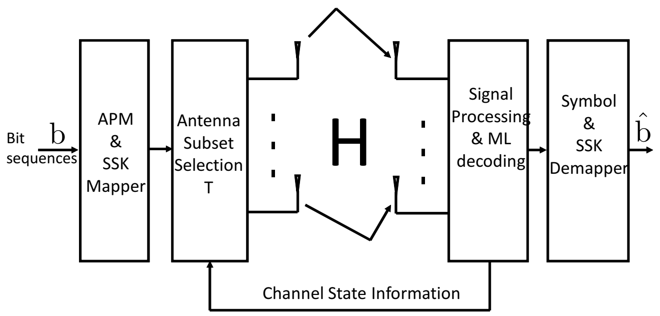

Fig. 1. Block diagram of an antenna selection SSK-based system.

where the L antennas are to be selected through the proposed selection criteria in the Sec. III-B. The L is usually set as, but not limited to, the power of 2. The $\mathbf{I}_{M_T}$ represents the identity matrix of dimension $M_T \times M_T$. The $M_T \times L$ channel selection matrix $\mathbf{T}$ is comprised of L different columns of $\mathbf{I}_{M_T}$, and satisfies the property $\mathbf{T}^T\mathbf{T} = \mathbf{I}_L$. Therefore, the signal is transmitted over an $M_R \times L$ "$effective\ channel$" matrix $\mathbf{HT}$(denoted as $\mathbf{P}$). The channel matrix $\mathbf{H}$ is assumed perfectly known to the receiver and transmitter.

Figure 1 presents an overview of MIMO systems using antenna selections and space shift keying. The bit sequences $\mathbf{b} = [b_1, \cdots, b_k]$ are modulated jointly by APM and SSK modulations, whose arrangements are described as follows. Each group of m_b bits is divided into two parts, i.e., the m_{APM} bits for APM and the m_{SSK} bits for SSK with $m_b = m_{APM} + m_{SSK}$. The m_{APM} bits are mapped to a conventional APM symbol x, e.g., QAM or PSK. In SSK, the antenna indexes are used to convey information, and only $n_T(\ll L = 2^{m_{SSK}})$ antennas are allowed to be active in each transmission. In other words, the number of combinations of antenna indexes is related to the number of antennas allowed to be active. There are $\binom{L}{n_T}$ constellation points in the set of antenna combinations $\mathcal{X}$. In this work, n_T=1 is used and $\binom{L}{1}$ constellation points are generated by SSK. Using m_{SSK}=3 as an example, there exist 8 constellation points with bit mappings shown in the TABLE I. In other words, the antennas are activated by mappings of m_{SSK} bits, and the $L\times 1$ transmit symbol vector $\mathbf{x}$ is specified as

$$\mathbf{x} = [0, \cdots, 0, x_j, 0, \cdots, 0]^T, \tag{1}$$

where L equals to $2^{m_{SSK}}$ and the subscript index j of x is determined by the source information and the mapping rule of SSK. Without loss of generality, the symbol vector $\mathbf{x}$ is assumed to meet the unit power constraint, i.e., $E[\mathbf{x}^H\mathbf{x}] = 1$. The baseband received signal is modeled as

$$\mathbf{y} = \mathbf{HTx} + \mathbf{n} = \mathbf{Px} + \mathbf{n}, \tag{2}$$

where $\mathbf{y}$ denotes the $M_R \times 1$ receive complex symbol vector and $\mathbf{n}$ denotes the $M_R \times 1$ receive complex noise vector with entries being independent and identically distributed (i.i.d) Gaussian random variables $\mathcal{CN}(0, \sigma_n^2)$. Since there is only

TABLE I
EXAMPLE OF THE SSK MAPPING RULE IN THE CASE OF USING 4-QAM MODULATION OF APM

$m_{APM} = 2, m_{SSK} = 3, L = 8, c = (\pm 1 \pm 1i)/\sqrt{2}$		
$\mathbf{b} = [b_1\ b_2\ b_3]$	antenna index j	$\mathbf{x} = [x_1\ x_2\ x_3\ x_4\ x_5\ x_6\ x_7\ x_8]^T$
[0 0 0]	1	$c * [1\ 0\ 0\ 0\ 0\ 0\ 0\ 0]^T$
[0 0 1]	2	$c * [0\ 1\ 0\ 0\ 0\ 0\ 0\ 0]^T$
[0 1 0]	3	$c * [0\ 0\ 1\ 0\ 0\ 0\ 0\ 0]^T$
[0 1 1]	4	$c * [0\ 0\ 0\ 1\ 0\ 0\ 0\ 0]^T$
[1 0 0]	5	$c * [0\ 0\ 0\ 0\ 1\ 0\ 0\ 0]^T$
[1 0 1]	6	$c * [0\ 0\ 0\ 0\ 0\ 1\ 0\ 0]^T$
[1 1 0]	7	$c * [0\ 0\ 0\ 0\ 0\ 0\ 1\ 0]^T$
[1 1 1]	8	$c * [0\ 0\ 0\ 0\ 0\ 0\ 0\ 1]^T$

one nonzero term in the symbol vector $\mathbf{x}$, the equation (1) represents that the j^{th} antenna is used and the (2) can be equivalently expressed as

$$\mathbf{y} = \mathbf{p}_j x_j + \mathbf{n}, \tag{3}$$

where the $M_R \times 1$ vector $\mathbf{p}_j$ denotes j^{th} column of $\mathbf{P}$. It is noted that the choice of j^{th} column depends on the SSK part of transmitted bit sequences and only one column of $\mathbf{P}$ is triggered in the case of n_T=1.

III. Proposed Approach

In this section, the ML decoding is briefly reviewed. The ML detector achieves optimal performance at the expense of complexity. We also propose antenna selection criteria of choosing columns of $\mathbf{H}$ to further reduce bit error rate (BER) of the SSK systems.

A. ML Decoding Scheme

For the signal model in (2), the ML detection of symbol vector $\mathbf{x}$ can be written as

$$\begin{aligned}\tilde{\mathbf{x}}_{ML} &= \arg\min_{\mathbf{x}\in\Omega} ||\mathbf{y} - \mathbf{HTx}||^2 \\ &= \arg\min_{\mathbf{x}\in\Omega} ||\mathbf{y} - \mathbf{Px}||^2,\end{aligned} \tag{4}$$

where Ω denotes the set of $\binom{L}{n_T}$ legal active antenna combination with each active antennas carrying the pre-designated APM constellations. In our case, due to the sparsity of symbol vector $\mathbf{x}$ with only $n_T(= 1 \ll L)$ symbols in SSK, the ML decoding algorithm has low complexities. It is noted that there are two parts of information symbols to be detected, i.e., symbols of APM and antenna index of SSK. By (4), the ML criterion can be explicitly written as

$$[\tilde{x}_j^{ML}, \tilde{j}] = \arg \min_{x_j \in \mathbb{S}, j \in \{1,\ldots,\binom{L}{n_T}\}} ||\mathbf{y} - \mathbf{p}_j x_j||^2, \tag{5}$$

where $\mathbb{S}$ denotes the legal APM constellation set, $\tilde{j}$ denotes the detected antenna index used by SSK, and $\tilde{x}_j^{ML}$ denotes the ML detected symbol. By (5), the steps of the ML decoding scheme are summarized as

Step 1): Designate an initial D_{ML}.

Step 2): Find all the $\binom{L}{n_T}$ combinations of possible antenna indexes. Since $n_T = 1$ is assumed in our work, the following steps are performed for L times.

Step 3): Compute $\bar{D}_{ML} = \|\mathbf{y} - \mathbf{p}_j x_j\|^2$ for all possible symbols $x_j \in \mathbb{S}$. If $\bar{D}_{ML} \leq D_{ML}$, let $D_{ML} = \bar{D}_{ML}$ and $\tilde{x}_j^{ML} = x_j$. Renew the antenna index $\tilde{j}$ if $\bar{D}_{ML} \leq D_{ML}$.

Step 4): After repeating step 3 for L legal antenna combinations, the final $\bar{x}_{ML}$ is the detected symbol of APM and the recorded antenna index $\tilde{j}$ can be de-mapped by the SSK mapping table.

B. Proposed Antenna Selection Criteria

According to (3) and (5), the decoding performance depends on the column p_j of $\mathbf{P}$. Although the sparse property of transmit symbol vector reduces the complexities of the ML detection scheme significantly, the information symbol carried on the antenna is hardly distinguishable and prone to errors if $\|\mathbf{p}_j\|^2$ is small. In other words, the larger channel gain mitigates the disturbances of the noises. Therefore, the antennas corresponding to the column vectors in the channel matrix $\mathbf{H}$ with larger l_2 norm are favorable. Summarizing the above, the antenna selection criteria are designed as follows

I): ASC1- Pursue h_j with larger l_2 norm:

$$\arg \max_{j \in \{1,\ldots,M_T\}} ||\mathbf{h}_j||^2. \tag{6}$$

By performing L times of $ASC1$, the $M_T \times L$ antenna-selection matrix $\mathbf{T}_{ASC1}$ is determined in terms of $\mathbf{e}_{i_1}, \ldots, \mathbf{e}_{i_L}$ which $\mathbf{e}_i$ denotes the $M_T \times 1$ vector with a 1 in the ith element and zeros elsewhere. The antenna-selection matrix $\mathbf{T}$ can be expressed as

$$\mathbf{T}_{ASC1} = [\mathbf{e}_{i_1}\mathbf{e}_{i_2} \cdots \mathbf{e}_{i_L}], \tag{7}$$

where $i_1, i_2, \cdots, i_L$ satisfy

$$||\mathbf{h}_{i_1}||^2 \geq ||\mathbf{h}_{i_2}||^2 \geq \cdots \geq ||\mathbf{h}_{i_L}||^2. \tag{8}$$

Through $ASC1$, the probability error rate of symbol detection is expected to be reduced efficiently.

Besides influence of channel gains on the decoding performance, the similar column vectors of $\mathbf{H}$ causes $ambiguity$ of detection, particularly for the detecting antenna index j. In our design, the $similarity$ of two distinct column vectors $\mathbf{h}_k$ and $\mathbf{h}_l$ is measured by $||\mathbf{h}_k - \mathbf{h}_l||^2$. In other words, the small value of $||\mathbf{h}_k - \mathbf{h}_l||^2$ renders the two indices corresponding to the two columns hardly distinguishable. The detection of the antenna index j will be prone to errors due to the ambiguity with the index k.

The error probability of SSK is derived in [4]. The average BER for SSK is given as

$$P_{e,bit} \leq \sum_l \sum_k (N(l,k)/M_T) P(\mathbf{x}_l \to \mathbf{x}_k), \tag{9}$$

where $N(l,k)$ denotes the number of error bits between the symbol vector $\mathbf{x}_l$ and $\mathbf{x}_k$, and $P(\mathbf{x}_l \to \mathbf{x}_k)$ is defined as the pairwise error probability (PEP) of decision on $\mathbf{x}_k$ when $\mathbf{x}_l$ is transmitted. The PEP conditioned on $\mathbf{H}$ can be expressed as the following:

$$P(\mathbf{x}_l \to \mathbf{x}_k \mid \mathbf{H}) = Q(\sqrt{\kappa}), \tag{10}$$

where $Q(x) = \int_x^\infty (1/2\pi) e^{-t^2/2} dt$. The parameter κ is defined as

$$\kappa = (\rho/2n_T)||\mathbf{h}_l - \mathbf{h}_k||^2, \tag{11}$$

where ρ denotes the SNR value.

By following the above, the antenna selection criterion can be described as

II): ASC2- Pursue the maximization of l_2 norm of difference between h_k and h_l:

$$\arg \max_{k,l \in \{1,\ldots,M_T\}} ||\mathbf{h}_k - \mathbf{h}_l||^2. \tag{12}$$

By performing $ASC2$, the $M_T \times L$ antenna-selection matrix $\mathbf{T}_{ASC2}$ is determined in the following steps

Step 1): Two candidates of column vector $\mathbf{h}_k, \mathbf{h}_l$ are engendered by performing the $ASC2$.

Step 2): Calculate $D_{hk} = \sum_{m=1,m\neq l}^{M_T} ||\mathbf{h}_k - \mathbf{h}_m||^2$ and $D_{hl} = \sum_{m=1,m\neq k}^{M_T} ||\mathbf{h}_l - \mathbf{h}_m||^2$.

Step 3): If $D_{hk} \leq D_{hl}$, let $i_1 = l$; otherwise, $i_1 = k$.

Step 4): Repeat step 1 to step 3 until $i_1, i_2 \cdots, i_L$ is decided.

It is noted that the purpose of step 2 and step 3 is to find the most $dissimilar$ vector among all column vectors in the sense of of square difference. As a result, the antenna-selection matrix $\mathbf{T}_{ASC2}$ can be expressed as

$$\mathbf{T}_{ASC2} = [\mathbf{e}_{i_1}\mathbf{e}_{i_2} \cdots \mathbf{e}_{i_L}], \tag{13}$$

where $i_1, i_2, \cdots, i_L$ satisfy the criteria $ASC2$.

Finally, a joint antenna selection criteria of $ASC1$ and $ASC2$ is proposed to consider the channel gain and the similarity among all column vectors at the same time.

III): ASC3- Joint Selection Criterion Combining ASC1 and ASC2:

For the L antennas to be selected in $\mathbf{T}_{ASC3}$, the first $L/2$ antenna indexes are decided by $ASC1$ and the remaining $L/2$ antenna indexes are decided by $ASC2$. The antenna-selection matrix $\mathbf{T}_{ASC3}$ can be expressed as

$$\mathbf{T}_{ASC3} = [\mathbf{e}_{i_1} \cdots \mathbf{e}_{i_{L/2}} \mathbf{e}_{i_{L/2+1}} \cdots \mathbf{e}_{i_L}], \tag{14}$$

where $i_1, \cdots, i_{L/2}$ satisfy the criteria $ASC2$ and $i_{L/2+1}, \cdots, i_L$ satisfy the criteria $ASC3$.

IV. Simulation Results

The performance of proposed antenna selection criteria are verified by Monte Carlo simulations. A $M_R \times M_T$ MIMO system over Rayleigh fading channel with i.i.d. AWGN is considered. We define the SNR Υ as $\mathrm{E}[(\mathbf{Hx})^H(\mathbf{Hx})]/\mathrm{E}[\mathbf{n}^H\mathbf{n}]$. Two main scenarios in the simulation are considered:

1): a 16×4 MIMO system with 4-QAM modulation, and $m_b = 5$ bits per transmission ($m_{APM} = 2, m_{SSK} = 3$).

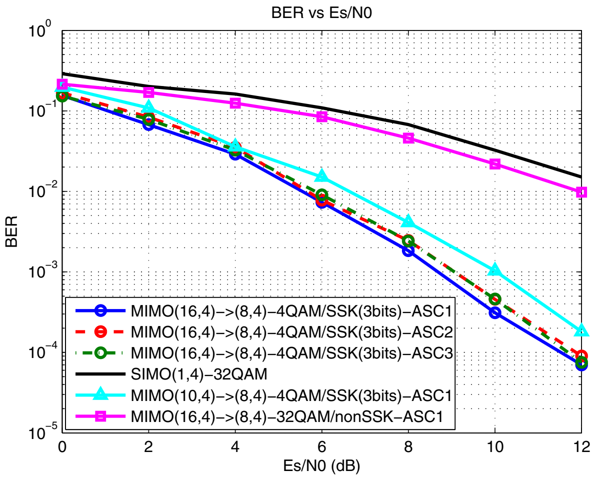

Fig. 2. BER versus SNR performance of the 16×4 and 10×4 SSK-based MIMO with 4-QAM modulation, the 16×4 non-SSK-based MIMO with 4-QAM modulation, and 1×4 SIMO with 32-QAM modulation in using ASC1, ASC2, and ASC3.

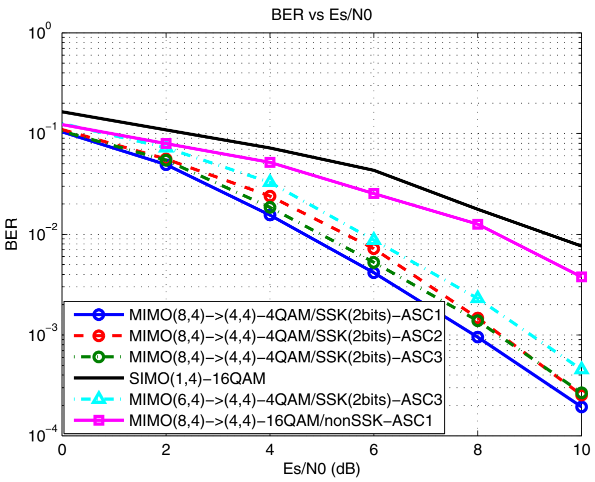

Fig. 3. BER versus SNR performance of the 8×4 and 6×4 SSK-based MIMO with 4-QAM modulation, the 8×4 non-SSK-based MIMO with 4-QAM modulation, and 1×4 SIMO with 16-QAM modulation in using ASC1, ASC2, and ASC3.

2): a 8×4 MIMO system with 4-QAM modulation, and $m_b = 4$ bits per transmission ($m_{APM} = 2, m_{SSK} = 2$).

The legends in the figures are described as

A): $MIMO(M_T, M_R){-}{>}(L, M_R)$-QQAM/SSK($m_{SSK} bits$)-$ASCx$: This expression represents that the antenna selection criterion $ASCx$ is employed to select L antennas from M_T antennas for transmissions. The bit sequences are divided into two parts of APM and SSK which are modulated by $Q(= 2^{m_{APM}})$-QAM and SSK modulation (antenna index $j = 1, \ldots, L = 2^{m_{SSK}}$), respectively. It is noted that $m_b = m_{APM} + m_{SSK}$.

B): $MIMO(M_T, M_R){-}{>}(L, M_R)$-QQAM/nonSSK-$ASCx$: This expression represents that the antenna selection criterion $ASCx$ is employed to select L antennas from M_T antennas for transmissions. All bit sequences are only modulated by $Q(= 2^{m_b})$-QAM without using SSK modulation. The signal power of the modulated symbols of Q-QAM are divided L and distributed on all L transmit antennas.

C): $SIMO(M_T, M_R){-}QQAM$: This expression represents that the bit sequences are only modulated by $Q(= 2^{m_b})$-QAM and transmitted on the single antenna.

A. Fair Comparisons

To conduct fair comparisons, the transmit data rates per channel use are designed to be the same for all systems. For the first scenario, the data rate is 5 bits per channel use. In the 16×4 or 10×4 SSK-based MIMO system, due to the antenna selection criterion applied, there are only $8(= 2^3)$ transmit antennas used for SSK modulation. Thus, 4-QAM of symbol modulation is employed to make up the 5 bits per channel use. In the 1×4 SIMO system or 16×4 non-SSK-based MIMO system the SSK modulation is not used and the bit streams need to be modulated by $32(= 2^5)$-QAM. Furthermore, it should be noted that when the antenna selection criteria are employed to select 8 transmit antennas, the difference of transmit symbol vector $\mathbf{x}$ between the case of 16×4 SSK-based MIMO system and the case of 16×4 non-SSK-based MIMO system is as the follows

I): $SSK\text{-}Based$:

$$\mathbf{x}_{SSK} = (1/\sqrt{2})[0, \cdots, 0, x_j, 0, \cdots, 0]^T, \qquad x_j \in \{\pm 1 \pm 1i\}, \tag{15}$$

where the vector divided by $\sqrt{2}$ is to meet the unit power constraint.

II): $Non\text{-}SSK\text{-}Based$:

$$\begin{aligned} \mathbf{x}_{nonSSK} &= (x/\sqrt{20} * \sqrt{8}) * [1, \cdots, 1, \cdots, 1]^T, \\ x &\in \{\pm 1 \pm 1i, \pm 3 \pm 1i, \pm 1 \pm 3i, \pm 3 \pm 3i, \\ &\quad \pm 1 \pm 5i, \pm 5 \pm 1i, \pm 3 \pm 5i, \pm 5 \pm 3i\}. \end{aligned} \tag{16}$$

For the second scenario, the data rate is given by 4 bits per channel use. In the 8×4 or 6×4 SSK-based MIMO system, since the antenna selection criteria are employed, only $4(= 2^2)$ transmit antennas are used for SSK modulation. It should be noted that when the antenna selection criteria is employed to select 4 transmit antenna, the difference of transmit symbol vector $\mathbf{x}$ between the case of 8×4 SSK-based MIMO system and the case of 8×4 non-SSK-based MIMO system is as follows

I): $SSK\text{-}Based$: This case is the same as the equation (15).

II): $Non\text{-}SSK\text{-}Based$:

$$\begin{aligned} \mathbf{x}_{nonSSK} &= (x/\sqrt{10} * \sqrt{4}) * [1, \cdots, 1, \cdots, 1]^T, \\ x &\in \{\pm 1 \pm 1i, \pm 3 \pm 1i, \pm 1 \pm 3i, \pm 3 \pm 3i\}. \end{aligned} \tag{17}$$

B. BER v.s. SNR

The ML decoding scheme is adopted in MIMO and SIMO to perform simulations. In Figure 2, the BER performance of the 16×4 and 10×4 SSK-based MIMO, 16×4 non-SSK-based MIMO, and 1×4 SIMO system are presented. The antenna selection criteria $ASC1, ASC2, ASC3$ are used to select 8 transmit antennas. In the cases where the $ASC1$, $ASC2$ or $ASC3$ are employed, the 16×4 SSK-based MIMO system completely outperforms the 1×4 SIMO system. The performance improvements come from that the SSK-based MIMO system exploits the spatial diversity. At the same time, by the use of channel state information (CSI) at transmitter, the well-conditioned channels are selected to ensure that the probability error rate of SSK de-mapping can be reduced significantly. On the contrary, the 1×4 SIMO system suffers from performance loss due to higher order modulation that has closer decision boundaries among distinct symbols in the detection domain.

In using the $ASC1$ to perform antenna selection, the 16×4 SSK-based MIMO system entirely outperforms the 16×4 non-SSK-based MIMO system. This observation shows that the performance of the jointly using symbol modulation and SSK modulation is superior to only using symbol modulation. On the other hand, the 16×4 non-SSK-based MIMO system transmits 32-QAM symbols through 8 transmit antennas. However, the performance of the 16×4 non-SSK-based MIMO system obtains small gain compared with the 1×4 SIMO system. The observation shows the system performance is dominated by the decision boundaries in detection domain for systems without SSK modulation.

The 16×4 SSK-based MIMO system outperforms the 10×4 SSK-based MIMO system by 1.5 dB at BER $= 10^{-3}$ in using $ASC1$. The gain is obtained by exploiting the CSI, since there are more channels for selection in the 16×4 SSK-based MIMO system than in the 10×4 SSK-based MIMO system. This shows that CSI and the spatial diversity provided by more channels are beneficial in selecting the better conditioned channels for SSK modulation. Moreover, the BER performance of the 16×4 SSK-based MIMO system with $ASC1$ closely follows systems using $ASC2$ and $ASC3$. This observation implies that the effects of selecting channels with larger gain are comparable to the avoidance of similar channels.

The BER performances of the 8×4 and 6×4 SSK-based MIMO, 8×4 non-SSK-based MIMO, and 1×4 SIMO system are shown in Figure 3. There are 4 transmit antennas selected by the antenna selection criteria $ASC1$, $ASC2$, and $ASC3$. The 8×4 SSK-based MIMO system substantially outperforms the 1×4 SIMO system in using $ASC1, ASC2$ or $ASC3$. It can be expected that the SSK-based MIMO system achieves better performance than the 1×4 SIMO system due to the lower order modulation. However, the BER gap between the 8×4 SSK-based MIMO system and the 1×4 SIMO system decreases when compared with previous cases. This is because the difference of decision boundaries between 16-QAM and 4-QAM are smaller than the difference of decision boundaries between 32-QAM and 4-QAM as in the previous case.

Similar to the previous cases, in using the $ASC3$ to perform the antenna selection, the 8×4 SSK-based MIMO system outperforms the 8×4 non-SSK-based MIMO system. Compared with the 1×4 SIMO system, the 8×4 non-SSK-based MIMO system transmits 16-QAM symbols over 4 transmit antennas, but acquires little performance gain. The 8×4 SSK-based MIMO system outperforms the 6×4 SSK-based MIMO system by 0.5 dB at BER $= 10^{-3}$ when the $ASC3$ is used. The performance improvement is insignificant, since there is little extra spatial diversity provided from the 8×4 SSK-based MIMO system than the 6×4 SSK-based MIMO system. The BER performances of the 8×4 SSK-based MIMO system with $ASC1$, $ASC2$ and $ASC3$ are very close, which is similar to the observations in the previous cases.

V. Conclusion

In this paper, three kinds of antenna selection criteria and the ML decoding scheme are proposed for SSK-based MIMO systems. In order to minimize the probability of error, the first antenna selection criteria $ASC1$ is to find the largest l_2 norm of column vector of channel matrix. Moreover, the similarity of two column vectors in channel matrix is considered by the second antenna selection criterion $ASC2$ to reduce the error probability in SSK modulation. The third antenna selection criteria $ASC3$ is a hybrid design of jointly using $ASC1$ and $ASC2$. The simulations show that the SSK-based MIMO systems with antenna selections entirely outperform the non-SSK-based MIMO and SIMO systems. Furthermore, the antenna selection criteria are verified to improve system performance with more spatial diversity provided from MIMO channels.

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