Source Transmit Antenna Selection for Space Shift Keying With Cooperative Relays

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***Abstract*— In this letter, we propose a cooperative multiple-input multiple-output (MIMO) scheme combining transmit antenna selection (TAS) and space shift keying (SSK). In this scheme, source transmit antennas are selected and SSK is applied by using the selected antennas. Besides the direct link transmission, the relays, that decode the source signal correctly, take part in the transmission. Exact expressions and a considerably accurate approximate expression for the symbol error rate of the proposed SSK system are derived. It is shown that the proposed scheme outperforms the SSK system without TAS and also the conventional cooperative MIMO system, which employs source TAS, at practical signal-to-noise ratio values for especially high data rates and sufficient number of receive antennas at the destination.**

***Index Terms*— Space shift keying (SSK), antenna selection, cooperative relays.**

I. Introduction

Single radio frequency (RF) chain spatial modulation (SM) and space shift keying (SSK) systems entirely avoid inter-channel interference, require no synchronization among the transmit antennas and reduce the transceiver complexity [1]–[3]. However, conventional SM and SSK cannot provide any transmit diversity gain. Hence, poor error performance is observed when the number of receive antennas is not so many. On the other hand, studies in recent years on the SM/SSK schemes show that cooperative relaying [4]–[6] and/or transmit antenna selection (TAS) techniques [7], [8] provide diversity gain and improve the symbol error rate (SER) performance. In [4], a cooperative space-time shift keying concept is proposed. In [5] and [6], the performance of SM scheme with multiple decode-and-forward (DF) relays and SSK scheme with both amplify-and-forward (AF) and DF relaying are reported, respectively. In [7], the performance of SSK with an Euclidean distance based antenna selection technique is analyzed. In [8], a low complexity antenna selection scheme for the generic point-to-point SM is investigated with computer simulations and a better error performance compared to conventional MIMO with TAS is obtained as the number of receive antennas increases. However, to the best of our knowledge, the performance of the cooperative SSK scheme, which applies TAS at the source, has not been reported in the literature.

Motivated by all of the above, in this letter, we propose a cooperative SSK scheme which applies TAS at the source. Our contributions are summarized as follows. A novel SSK scheme, in which TAS is employed at the source, is proposed in this letter. Furthermore, we extend the scheme of [6], which is a multiple-input single-output (MISO) scheme with cooperative relays, to a new MIMO scheme with cooperative relays for arbitrary number of receive antennas. We derive closed-form expressions for the exact SER of the proposed system when the number of selected antennas is two. In addition, a sufficiently accurate approximate expression on the SER performance of the system is derived for 2^c selected antennas where $c > 1$ is an arbitrary integer number.

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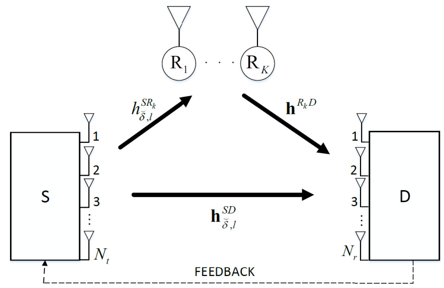

Fig. 1. System model of the SSK with cooperative relays and TAS.

II. System Model

We consider a cooperative relaying system with a single source (S) equipped with N_t transmit antennas, K single-antenna relays $(\mathrm{R}_1, \ldots, \mathrm{R}_K)$ and a destination (D) equipped with N_r receive antennas as shown in Fig. 1. At S, N_s antennas are selected from N_t transmit antennas based on the channel coefficients between S and D where we assume that N_s is an integer power of two. Perfect channel state information at D as well as an error-free feedback channel between D and S are assumed to be available. The selected transmit antenna subset information is sent by D to S through this feedback channel. At S, due to its simplicity and good performance [3], the SSK technique is applied.

In order to decrease the signaling overhead and complexity of the system as well as to simplify the mathematical analysis, antenna selection is performed by considering the channel fading coefficients corresponding to S-D link as in [9]. We use the antenna selection criterion proposed in [7]. In this selection scheme, available N_t transmit antennas are separated into (N_t/N_s) disjoint subsets. With $\delta = 1, 2, ..., N_t/N_s$ denoting the subset indices, the minimum squared Euclidean distance for each subset is given by $a_\delta = \min_{g,\hat{g}=1,\ldots N_s,\ g\neq\hat{g}} \left\|\mathbf{h}^{SD}_{\delta,g} - \mathbf{h}^{SD}_{\delta,\hat{g}}\right\|^2$ where $\mathbf{h}^{SD}_{\delta,g}$ and $\mathbf{h}^{SD}_{\delta,\hat{g}}$ respectively denote the gth and $\hat{g}$th columns of the $N_r \times N_s$ matrix $\mathbf{H}^{SD}_{\delta}$, which is the δth subset of the $N_r \times N_t$ S-D channel matrix $\mathbf{H}^{SD}$, whose entries are distributed with $\mathcal{CN}(0, 1)$. The selected subset $\breve{\delta}$ is the one that has the largest minimum squared Euclidean distance among all disjoint subsets [7], i.e, $\breve{\delta} = \arg\max_{\delta} \{a_\delta\}$. Hence, $a_{\breve{\delta}}$ denotes the minimum squared Euclidean distance for the selected subset.

The transmission occurs in a two-stage protocol. At the first stage, a group of information bits is mapped to the index of the selected antenna. Hence, only one transmit antenna is activated with a transmitted energy denoted by E_s. The other transmit antennas remain silent. With $l \in \{1, 2, \ldots, N_s\}$ denoting the active antenna index in the selected subset, the received signal at the kth relay and the received signal vector at D are given, respectively, as $y^{SR_k} = \sqrt{E_s} h^{SR_k}_{\breve{\delta},l} x + n^{SR_k}$ and $\mathbf{y}^{SD} = \sqrt{E_s}\mathbf{h}^{SD}_{\breve{\delta},l} x + \mathbf{n}^{SD}$ where x is the unit energy SSK signal transmitted from S. $h^{SR_k}_{\breve{\delta},l}$ denotes S-R$_k$ channel fading coefficient which belongs to the lth transmit antenna in the selected subset and it is distributed with $\mathcal{CN}(0, 1)$. $\mathbf{h}^{SD}_{\breve{\delta},l}$ denotes the lth column of the $N_r \times N_s$ matrix $\mathbf{H}^{SD}_{\breve{\delta}}$ which is the selected subset of the $N_r \times N_t$ S-D channel matrix $\mathbf{H}^{SD}$. n^{SR_k} and $\mathbf{n}^{SD}$ are additive white Gaussian noise (AWGN) sample at the kth relay and $N_r \times 1$ AWGN sample vector at D, respectively, whose elements are distributed with $\mathcal{CN}(0, N_0)$.

At the second stage, S remains silent, while the relays that correctly decode the active transmit antenna index forward the corresponding channel fading coefficient to D [6]. To determine the relays that decode correctly, cyclic redundancy check (CRC) is employed at S during transmission as in [4]. Hence, the relays are able to detect potential decoding errors to avoid error propagation. We define a decoding set as the relays which decode the active transmit antenna index correctly and we assume that the number of elements in this set is $T \in \{0, 1, 2, \ldots, K\}$. Hence, $T + 1$ orthogonal channels are required for the transmission. The signal vector received at D from kth relay is $\mathbf{y}^{R_k D} = \sqrt{E_r}\mathbf{h}^{R_k D} h^{SR_k}_{\breve{\delta},l} x + \mathbf{n}^{R_k D}$ where E_r is the energy of the relay's transmitted signal. $\mathbf{h}^{R_k D}$ is the channel fading coefficients vector between R$_k$ and D whose elements follow $\mathcal{CN}(0, 1)$. $\mathbf{n}^{R_k D}$ is the AWGN sample vector at D which has the same characteristics with $\mathbf{n}^{SD}$. Finally, a maximum likelihood (ML) detector is applied at D to estimate the active transmit antenna index [5].

III. Error Performance Analysis

A. Exact Analysis for $N_s = 2$

In order to simplify the analysis and provide exact expressions, we consider $N_s = 2$. The error probability of the DF relaying protocol highly depends on the correct detection of the relays [6]. If none of the relays decode correctly, the error performance depends only on the direct link between S and D. The average error probability of this case is denoted by $\bar{P}_1(\varepsilon)$. If the relays decode correctly and then forward, D combines the signal received from S with the signals received from the relays and the average error probability of this scenario is denoted by $\bar{P}_2(\varepsilon)$. Hence, the overall SER of the DF relaying system can be formulated as

$$\bar{P}(\varepsilon) = \underbrace{P_{SR}(T=0)P_{SD}(\varepsilon)}_{\bar{P}_1(\varepsilon)} + \underbrace{\sum_{\upsilon=1}^{K} P_{SR}(T=\upsilon)P_{SD-RD}(\varepsilon|T=\upsilon)}_{\bar{P}_2(\varepsilon)} \quad (1)$$

where $P_{SR}(T = 0)$ and $P_{SR}(T = \upsilon)$ denote the probability that the number of elements in the decoding set is zero and υ, respectively. $P_{SD}(\varepsilon)$ is the average error probability of S-D link when all relays decode incorrectly, whereas the error probability of the combined signals from S and $T = \upsilon$ relays is denoted by $P_{SD-RD}(\varepsilon|T = \upsilon)$. In order to consider all possible values of υ, see the summation at the right side of (1).

The average error probability that a relay decodes the transmit antenna index incorrectly as $\hat{l}$ is given by $P_{SR_k}(\varepsilon) = \frac{1}{2} - \frac{1}{2}\sqrt{\frac{E_s/2N_0}{1+E_s/2N_0}}$ [3]. Since $P_{SR}(T = 0)$ is the probability that all the relays decode the transmit antenna index incorrectly, it can be given as $P_{SR}(T = 0) = \left(P_{SR_k}(\varepsilon)\right)^K$. If none of the relays decodes correctly, only the direct link between S and D exists. In that case, the average SER of S-D link can be written as $P_{SD}(\varepsilon) = E\left[Q\left(\sqrt{\gamma^{SD}_{sel}}\right)\right]$ where $Q(u) = \int_u^\infty \left(1/\sqrt{2\pi}\right)\mathrm{e}^{-t^2/2}\,dt$ and $\gamma^{SD}_{sel} = \frac{E_s a_{\breve{\delta}}}{2N_0}$. Considering the selection criterion given in Section II, the probability density function (PDF) of γ^{SD}_{sel} can be expressed with the help of order statistics as $f_{\gamma^{SD}_{sel}}(r) = \binom{N_t}{2}\left(F_{\gamma^{SD}}(r)\right)^{\binom{N_t}{2}-1} f_{\gamma^{SD}}(r)$ where $\gamma^{SD} = \frac{E_s a_\delta}{2N_0}$. $F_{\gamma^{SD}}(r)$ and $f_{\gamma^{SD}}(r)$ are the cumulative distribution function (CDF) and PDF of γ^{SD}, respectively. Note that γ^{SD} follows chi-square distribution with $2N_r$ degrees of freedom. Using [10, eq. (14)], the PDF of γ^{SD}_{sel} can be rewritten as $f_{\gamma^{SD}_{sel}}(r) = \sum_{z=0}^{\left(\frac{N_t}{2}-1\right)} \sum_{i_1=0}^{N_r-1} \cdots \sum_{i_z=0}^{N_r-1} \binom{\frac{N_t}{2}-1}{z} \frac{\binom{N_t}{2}(-1)^z r^{\beta-1} e^{-r\left(\frac{z+1}{E_s/N_0}\right)}}{\left(\prod_{m=1}^{z} i_m!\right)(E_s/N_0)^\beta \Gamma(N_r)}$ where $\beta = N_r + \sum_{m=1}^{z} i_m$ and $\Gamma(.)$ is the Gamma function [11, eq. (8.310.1)]. The average SER of S-D link can then be calculated as $P_{SD}(\varepsilon) = \int_0^\infty Q\left(\sqrt{r}\right) f_{\gamma^{SD}_{sel}}(r)dr$. After transformation of the variables, the closed form expression for $P_{SD}(\varepsilon)$ can be derived, with the help of [12, eq. (3.63)], as

$$\begin{aligned} P_{SD}(\varepsilon) = \binom{N_t}{2} \sum_{z=0}^{\frac{N_t}{2}-1} \sum_{i_1=0}^{N_r-1} \cdots \sum_{i_z=0}^{N_r-1} \binom{\frac{N_t}{2}-1}{z} (-1)^z (\beta-1)! \\ \times \frac{\left(1-\alpha^{-\frac{1}{2}}\right)^\beta (2z+2)^{-\beta}}{\left(\prod_{m=1}^{z} i_m!\right)\Gamma(N_r)} \sum_{j=0}^{\beta-1} 2^{-j} \binom{\beta-1+j}{j} \\ \times \left(1+\alpha^{-\frac{1}{2}}\right)^j \end{aligned} \quad (2)$$

where $\alpha = 1 + \left(2z+2\right)/\left(E_s/N_0\right)$.

Let us consider the case that the number of elements in the decoding set is not zero, i.e., $T \neq 0$. In this case, D combines the signal received from S-D link with signals received from the υ relays. Considering all possible values of υ, the average SER of this case can be given as [6]

$$\bar{P}_2(\varepsilon) = \sum_{\upsilon=1}^{K} \binom{K}{\upsilon} \frac{\left(1-P_{SR_k}(\varepsilon)\right)^\upsilon}{\left(P_{SR_k}(\varepsilon)\right)^{\upsilon-K}} E\left[Q\left(\sqrt{\gamma^{SD}_{sel} + \sum_{k=1}^{\upsilon} \gamma^{SR_k D}}\right)\right]$$

where $\gamma^{SR_k D} = \xi\kappa$ with $\xi = \left\|\mathbf{h}^{R_k D}\right\|^2$ and $\kappa = \frac{E_r\left|h^{SR_k}_{\breve{\delta},l} - h^{SR_k}_{\breve{\delta},\hat{l}}\right|^2}{2N_0}$. Hence, ξ follows chi-square distribution with $2N_r$ degrees of freedom and κ follows exponential distribution.

Therefore, the PDF of γ^{SR_kD} can be written as $f_{\gamma^{SR_kD}}(r) = \frac{2r^{\frac{N_r-1}{2}}}{\Gamma(N_r)(E_r/N_0)^{\frac{N_r+1}{2}}} K_{N_r-1}\left(2\sqrt{\frac{r}{E_r/N_0}}\right)$ where $K_\phi(u)$ is the ϕth-order modified Bessel function of the second kind [11, eq. (8.432.1)]. After taking the Laplace transform of this PDF by using [11, eq. (6.643.3)], moment generating function (MGF) of γ^{SR_kD} is given by

$$M_{\gamma^{SR_kD}}(s) = \left(\frac{E_r}{N_0}s\right)^{-\frac{N_r}{2}} e^{\left(\frac{N_0}{2E_r s}\right)} W_{-\frac{N_r}{2},\,\frac{N_r-1}{2}}\left(\frac{N_0}{E_r s}\right) \tag{3}$$

where $W_{\nu,\mu}(u)$ is the Whittaker function [11, eq. (9.222.2)].

On the other hand, the MGF of γ_{sel}^{SD} can be given as

$$\begin{aligned} &M_{\gamma_{sel}^{SD}}(s) \\ &= (N_t/2)\sum_{z=0}^{\left(\frac{N_t}{2}-1\right)} \sum_{i_1=0}^{N_r-1}\cdots\sum_{i_z=0}^{N_r-1}\binom{\frac{N_t}{2}-1}{z} \\ &\quad\times\frac{(-1)^z\Gamma(\beta)}{\left(\prod_{m=1}^{z} i_m!\right)(z+1+(E_s/N_0)s)^{\beta}\Gamma(N_r)}. \end{aligned} \tag{4}$$

Combining all of the terms found in this section, the exact expression for the average SER can be given as

$$\begin{aligned} \bar{P}(\varepsilon) &= \left(P_{SR_k}(\varepsilon)\right)^K P_{SD}(\varepsilon) + \sum_{\upsilon=1}^{K}\binom{K}{\upsilon}\left(P_{SR_k}(\varepsilon)\right)^{K-\upsilon} \\ &\quad\times\left(1-P_{SR_k}(\varepsilon)\right)^{\upsilon}\frac{1}{\pi}\int_0^{\frac{\pi}{2}} M_{\gamma_{sel}^{SD}}\left(\frac{1}{2\sin^2(\vartheta)}\right) \\ &\quad\times\prod_{k=1}^{\upsilon} M_{\gamma^{SR_kD}}\left(\frac{1}{2\sin^2(\vartheta)}\right)d\vartheta. \end{aligned} \tag{5}$$

B. Approximate Analysis for $N_s = 2^c$

In this subsection, we derive the approximate SER expression of the proposed system for $N_s = 2^c$, where $c \in \mathbb{Z}$ and $c > 1$, using the nearest neighbor approximation of the instantaneous SER [13, eq. (5.45)]. Based on this approximation, the SER of S-D and S-R$_k$ links can be given as $P_\lambda(\varepsilon) \approx dQ\left(\sqrt{E_s\left\|\mathbf{h}_{\delta,l}^{\lambda} - \mathbf{h}_{\hat{\delta},\hat{l}}^{\lambda}\right\|^2/2N_0}\right)$ where the index λ stands for SD and SR_k, respectively, and d is the average number of neighbors within the Euclidean distance given in the Q function. Considering the selection criterion given in Section II, we have $d = 2/N_s$ for each subset. To find the approximate statistics for the selected subset, we assume that $\binom{N_s}{2}$ squared Euclidean distances within the each subset is independent and these distances follow chi-square distribution as in the exact analysis. Therefore, the approximate SER of S-D link can be written as [7]

$$\begin{aligned} &P_{SD}(\varepsilon) \\ &\approx \frac{2N_t\binom{N_s}{2}}{(N_s)^2\Gamma(N_r)}\sum_{z=0}^{\frac{N_t}{N_s}-1}\sum_{t=0}^{M}\binom{\frac{N_t}{N_s}-1}{z}C_t(N_r,N_s,z)\left(\frac{E_s}{N_0}\right)^t \\ &\quad\times(-1)^z(q_t!)\left(\frac{1-b_z^{-\frac{1}{2}}}{2\omega_z}\right)^{(q_t+1)}\sum_{p=0}^{q_t}\binom{q_t+p}{p}\left(\frac{1+b_z^{-\frac{1}{2}}}{2}\right)^p \end{aligned} \tag{6}$$

where $b_z = \left(\frac{4\omega_z}{(E_s/N_0)^2}+1\right)$, $\omega_z = \binom{N_s}{2}(z+1)$, $M = (N_r-1)(\omega_z-1)$, $q_t = N_r+t-1$ and $C_t(N_r,N_s,z)$ is the coefficient of r^t in the expansion of $\left[\sum_{i=0}^{N_r-1}\frac{(rN_0/E_s)^i}{i!}\right]^{\omega_z-1}$. Note that we also use (6) to find $P_{SR_k}(\varepsilon)$ by replacing E_r with E_s and considering $N_r = 1$.

On the other hand, the MGF of γ_{sel}^{SD} can be written as

$$\begin{aligned} M_{\gamma_{sel}^{SD}}(s) &= \frac{\frac{N_t}{N_s}\binom{N_s}{2}}{(E_s/N_0)^{N_r}(N_r-1)!}\sum_{z=0}^{\frac{N_t}{N_s}-1}\sum_{t=0}^{M}(-1)^z \\ &\quad\times\binom{\frac{N_t}{N_s}-1}{z}C_t(N_r,N_s,z) \\ &\quad\times\Gamma(N_r+t)\left(s+\frac{\omega_z}{E_s/N_0}\right)^{-(N_r+t)}. \end{aligned} \tag{7}$$

Since TAS is performed on the S-D link, statistics for the S-R$_k$ links do not change. Hence, the MGF of γ^{SR_kD} can be expressed as given in (3). As a result, the approximate SER of the proposed system can be given by substituting the (3), (6) and (7) into (5).

Furthermore, considering the well-known behavior of the PDFs of the direct and relaying links around the origin and using [14, eqs. (13) and (15)], the diversity and coding gains of the system can be derived for $N_r > 1$, respectively, as $G_d = K + N_tN_r/N_s$ and

$$G_c = \left[\frac{2^{G_d-1}\,\Gamma(1/2+G_d)(N_tN_r/N_s)!}{\sqrt{\pi}\Gamma(1+G_d)(N_r-1)^K\left(\binom{N_s}{2}/N_r!\right)^{-N_t/N_s}}\right]^{-\frac{1}{G_d}}. \tag{8}$$

Hence, the approximate SER of the proposed system at high signal-to-noise ratio (SNR) values can be given as $\bar{P}(\varepsilon) \approx (G_cE_s/N_0)^{-G_d}$ [14], where we assume $E_s = E_r$.

IV. Numerical Results

In this section, analytical expressions given in the previous section are verified through Monte Carlo simulations. For comparison, we also provide SER results of conventional cooperative MIMO system, in which SNR optimized TAS is applied at S with ML detection at D. Results are plotted as a function of E_{tot}/N_0 where $E_{tot} = E_s + E_r$. In figures, $(N_t/N_s, K, N_r)$ and $(N_t/N_s, K, N_r)$ (Q-QAM) stand for the SSK and conventional QAM MIMO systems, respectively, where N_s antennas are selected from N_t antennas at S and there are K single-antenna relays and N_r receive antennas at D. Here, Q denotes the constellation size.

In Fig. 2, the SER performance of the SSK system $(N_t/2, K, N_r)$ is given for $N_t \in \{2,4,6,8\}, K \in \{1,3,5\}$ and $N_r \in \{1,3\}$. Here, the system $(N_t/2,3,1)$(Ex. TAS) and the system $(2/2,3,1)$(no TAS) correspond to the conventional cooperative SSK system with exhaustive TAS and without TAS [6], respectively. Fig. 2 clearly indicates that simulation results match the analytical SER and diversity order results given in previous section and the system performance is improved when the number of available transmit antennas N_t increases. On the other hand, the SSK system $(N_t/2,3,1)$(Ex. TAS) outperforms the proposed SSK system. However, our proposed system provides a remarkable complexity reduction against the SSK system with exhaustive TAS. It is easy to verify that the complexity in terms of real multiplications imposed by the

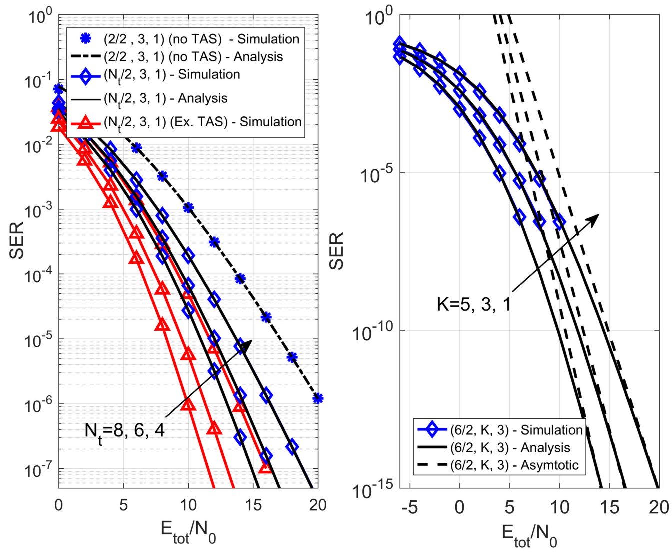

Fig. 2. SER performance of the SSK system $(N_t/2, K, N_r)$ with $N_t \in \{2, 4, 6, 8\}$, $K \in \{1, 3, 5\}$ and $N_r \in \{1, 3\}$.

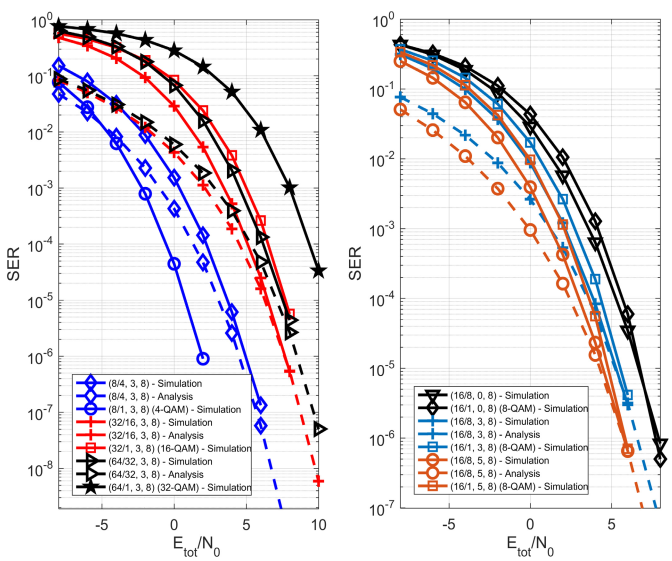

Fig. 3. SER performance comparison of the SSK system $(N_t/N_s, K, N_r)$ with conventional cooperative MIMO system $(N_t/1, K, N_r)(Q\text{-QAM})$ for $N_t \in \{8, 16, 32, 64\}$, N_s, $Q \in \{4, 8, 16, 32\}$, $K \in \{0, 3, 5\}$, $N_r = 8$.

antenna selection method used in the proposed scheme can be formulated as $2\,(N_t/N_s\,)\binom{N_s}{2}N_r$ while the complexity of the exhaustive TAS can be given as $2\binom{N_t}{2}N_r$. Hence, for the case of $(8/2, 3, 1)$, complexities of the antenna selection method used in the proposed scheme and the exhaustive TAS can be calculated as 8 and 56, respectively.

Fig. 3 compares the SER performance of the proposed SSK system $(N_t/N_s, K, N_r)$ with conventional cooperative MIMO system $(N_t/1, K, N_r)(Q\text{-QAM})$ using TAS for $N_t \in \{8, 16, 32, 64\}$, N_s, $Q \in \{4, 8, 16, 32\}$, $K \in \{0, 3, 5\}$ and $N_r = 8$. In order to make fair comparisons, data rates of the SSK and conventional MIMO systems are assumed to be equal. As seen from Fig. 3, the derived approximate SER expression is considerably accurate for especially high SNR region and the effectiveness of the proposed SSK scheme against the conventional cooperative MIMO systems is observed at higher data rates. Fig. 3 indicates that the conventional cooperative MIMO system $(8/1, 3, 8)$(4-QAM) outperforms the proposed SSK system $(8/4, 3, 8)$ by approximately 2.7 dB; however, the proposed SSK system $(64/32, 3, 8)$ outperforms the conventional cooperative MIMO system $(64/1, 3, 8)$(32-QAM) by approximately 3.2 dB at a SER value of 10^{-4}. It is important to note that the proposed scheme cannot provide complexity advantage against the conventional MIMO scheme with TAS since the complexity of the TAS for conventional MIMO scheme can be given as $2N_tN_r$. Furthermore, the performance of the proposed SSK system is improved when the number of relays increases. Beside, as seen from Fig. 3, the addition of the relays is more beneficial for the proposed SSK system than the conventional MIMO system.

V. Conclusion

In this letter, we have investigated a SSK system with TAS and cooperative relays. It has been shown that the proposed SSK system outperforms the existing SSK system with multiple relays [6]. It has been also demonstrated that the proposed SSK system outperforms conventional cooperative MIMO system with TAS and the addition of relays is more beneficial for the proposed SSK system than conventional MIMO with TAS for especially high data rates and sufficient number of receive antennas at D.

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