Physical Communication 27 (2018) 161–169

Contents lists available at ScienceDirect

Physical Communication

journal homepage: www.elsevier.com/locate/phycom

Full length article

Space shift keying for multi-hop multi-branch networks

Ferhat Yarkin *, Ibrahim Altunbas, Ertugrul Basar

Electronics and Communication Engineering Department, Istanbul Technical University, 34469, Istanbul, Turkey

ARTICLE INFO

Article history:
Received 31 July 2017
Received in revised form 14 November 2017
Accepted 7 February 2018
Available online 10 February 2018

Keywords:
Amplify-and-forward
Cooperative networks
Decode-and-forward
Index modulation
Multi-hop relaying
Space shift keying

ABSTRACT

In this paper, we propose two different multi-hop multiple-input multiple-output (MIMO) space shift keying (SSK) schemes and investigate their error performance. In the first scheme, we consider a multi-hop multi-branch SSK system, in which the source and destination are equipped with multiple transmit and receive antennas, respectively. In this scheme, SSK is applied by using the source transmit antennas. Moreover, in each branch, single-antenna relays are used to amplify the transmitted signal from the source and forward it to the next relay until it reaches to the destination. In the second scheme, we consider a multi-hop MIMO-SSK system with path selection. In this scheme, the best path is selected among multiple branches and a multiple-antenna source communicates with a multiple-antenna destination via the relays of the selected path. Each relay is equipped with multiple transmit and receive antennas. Moreover, the source and all relays employ SSK modulation to transmit information bits and each relay in each path follows the decode-and-forward protocol. Approximate theoretical error probability expressions are derived for both schemes. Furthermore, an asymptotic symbol error probability performance analysis is also performed for the multi-hop MIMO-SSK system with path selection. It is shown that the proposed multi-hop SSK systems outperform conventional multi-hop M-PSK systems in terms of the error performance for especially high data rates and sufficient number of receive antennas at the receiving nodes.

1. Introduction

High data rates and improved error performance can be obtained by using multiple-input multiple-output (MIMO) systems at the expense of using multiple radio-frequency (RF) chains at the transmitter, which increase the inter-channel interference (ICI) and the transceiver complexity as well as require synchronization among the transmit antennas. These challenges have led researchers to seek new solutions for the next generation MIMO systems [1]. In this context, novel single-RF MIMO techniques namely spatial modulation (SM) and space shift keying (SSK) have been proposed [2]. In SM and SSK, depending on the one-to-one mapping between the information bits and transmit antenna indices, typically only one transmit antenna is activated in a transmission interval and the other antennas remain turned off. Therefore, SM and SSK entirely avoid ICI, require no inter-antenna synchronization (IAS) among the transmit antennas and reduce the transceiver complexity. SSK is a special case of SM, which further decreases the transceiver complexity since it can be implemented with a very simple hardware that does not require I/Q modulation as well as employment of a RF chain [2–4].

Cooperative communications improves the transmission reliability and extends the coverage of wireless networks. Moreover, the effect of fading in wireless channels can be efficiently mitigated by the cooperative networks [5–10]. Due to their satisfactory error performance and low complexity, many researchers have studied SM and SSK in cooperative networks [11–21]. A dual-hop amplify-and-forward (AF) relaying scheme with SSK modulation has been studied in [11]. Furthermore, a cooperative decode-and-forward (DF) relaying scheme with SM has been investigated in [12]. A cooperative DF relaying scheme with SSK modulation, which considers the decoding errors at the relays, has been proposed in [13]. SSK aided AF and DF relaying with relay selection have been investigated in [14] and [15], respectively. In [16], the performance of SSK modulation with source transmit antenna selection and multiple DF relays has been investigated. In [17], a distributed SM protocol, in which the index of the relay conveys information, has been proposed. An AF relaying-aided cooperative space–time SSK scheme has been proposed in [18]. A cooperative AF-MIMO relaying scheme combining SSK with the best and the partial relay selection has been proposed in [19]. Moreover, in [20], DF-MIMO relaying scheme, in which all the nodes are equipped with multiple transmit and/or receive antennas, has been studied. The outage probability of both classical SM and cooperative SM systems has been investigated in [21].

On the other hand, employing multiple relays between source and destination enables the division of long links into multiple

* Corresponding author.
E-mail addresses: yarkinf@itu.edu.tr (F. Yarkin), ibraltunbas@itu.edu.tr (I. Altunbas), basarer@itu.edu.tr (E. Basar).

https://doi.org/10.1016/j.phycom.2018.02.009
1874-4907/

shorter links and long distance communications can be provided by multi-hop networks via hopping through relaying nodes. This improves the error performance, extends battery life, and provides broader and cheaper coverage [22–25]. Furthermore, in multi-hop multi-branch networks, transmitted signal from the source reaches to the destination via multiple cooperative multi-hop branches and therefore, D receives different copies of the transmitted signal. Hence, in addition to the advantages of multi-hop relaying, cooperative diversity is also achieved in multi-branch schemes [26–29]. Multi-hop relaying has been studied in many standards, including LTE Release-10, IEEE 802.11s, IEEE 802.15.5, IEEE 802.16, IEEE 802.16e, IEEE 802.16j and IEEE 802.20, and it finds many applications in wireless, sensor and vehicular ad hoc networks, cellular networks as well as Internet of Things applications [30–32]. However, to the best of author's knowledge, available studies on SM/SSK with multi-hop multi-branch networks are considerably limited. In the comprehensive study of [33], the performance of SSK modulation in multi-hop diversity and multi-hop multi-branch networks with DF relays have been investigated.

Motivated by all of the above, in this paper, we propose two new MIMO-SSK schemes, one of them employing AF and the other one employing DF relaying, in multi-hop networks and aim to utilize the benefits of SSK modulation in multi-hop networks and obtain diversity gain by using multiple branches and receive antennas. The novel contributions of this paper can be summarized as follows:

1. A novel multi-hop multi-branch MIMO-SSK scheme is proposed. In this scheme, S and D are equipped with multiple transmit and receive antennas, respectively and SSK is applied only at S. Single-antenna fixed-gain AF relays are employed in each branch of this scheme. The major contributions and important results for the proposed system can be listed as follows:
   - We derive a considerably accurate lower-bound expression for the pairwise error probability (PEP) of multi-hop single-branch transmission and an approximate expression for the average bit error probability (BEP) of multi-hop multi-branch transmission. The derived expressions are shown to become consistent with computer simulation results.
   - More importantly, numerical results demonstrate that the proposed SSK system outperforms the classical single-input multiple-output (SIMO) M-PSK system employing fixed-gain AF relaying for especially high data rates and sufficient number of receive antennas at D.
2. A novel multi-hop multi-branch MIMO-SSK scheme with multiple transmit and receive-antenna relays is proposed. In this scheme, S and D are equipped with multiple antennas as well and SSK is applied at S and all of the relays. Note that our system model differs from that of [33] in the following aspects: First, we consider the error propagation in multi-hop DF relaying. Second, a path is selected among available branches and transmission occurs via the selected path instead of activating all of the branches. Our system model is inspired by the path selection schemes of [28] and [29] in which multi-hop DF protocol is adopted. The major contributions and important results for the proposed system can be listed as follows:
   - Unlike [28] and [29], in which the performance for conventional M-PSK modulation have been studied, we consider the SSK modulation in each transmitting node and derive a closed-form approximate symbol error probability (SEP) expression for SSK modulation. The derived approximate SEP expression is shown to become considerably accurate for especially high signal-to-noise ratio (SNR) region.
   - More importantly, numerical results show that the proposed multi-hop SSK system with path selection outperforms the conventional multi-hop M-PSK system with path selection [28,29] in terms of the SEP performance for especially high data rates and sufficient number of receive antennas at the receiving nodes.
3. Unlike [28] and [29], our first scheme is a more general MIMO scheme with arbitrary number of receive antennas. Within this perspective, our first scheme has a simpler structure with AF processing and single-antenna relays, while the second scheme is a more sophisticated one with multi-antenna relays.
4. The proposed SSK systems completely avoid ICI, eliminate the requirement of IAS in a multi-hop network and can be implemented with a very simple hardware that does not require I/Q modulation as well as the employment of an RF chain. It has been shown via computer simulations that our analytical results are considerably consistent with the simulation results.

Notation: Bold capital letters denote matrices, whereas bold lowercase letters denote vectors. $\mathrm{E}[\cdot]$, $Q(\cdot)$ and $G[\cdot]$ stand for the expectation operator, the Gaussian Q function [34, (26.2.3)] and the Meijer's G-function [34, (9.301)], respectively. $P(\cdot)$ denotes the probability of an event. $(\cdot)^H$, $|\cdot|$, $\|\cdot\|$ and $\mathrm{Re}\{\cdot\}$ denote Hermitian transposition, the absolute value, the Frobenius norm operation and the real part operator, respectively. Moreover, $\mathcal{CN}(\mu, \sigma^2)$ denotes complex normal distribution, where μ and σ^2 stand for the mean and variance of the distribution, respectively.

2. Space shift keying for multi-hop multi-branch AF relaying

2.1. System model

We consider a multi-hop system employing AF relaying with L parallel cooperative branches between the source (S) and the destination (D), as shown in Fig. 1. There are K_p $(1 \leq p \leq L)$ single-antenna fixed-gain AF relays in the pth branch. Furthermore, S and D are equipped with N_t and N_r transmit and receive antennas, respectively. We denote the m_pth relay in the pth branch by R_{p,m_p} $\left(1 \leq m_p \leq K_p\right)$. At S, due to its low complexity and good performance [3], the SSK technique is applied by using N_t antennas. We assume that perfect channel state information (CSI) is available at the receiving nodes for the proposed scheme. The performance analysis in the presence of channel estimation errors is beyond the scope of this paper. However, it is shown that cooperative networks [35] and SSK modulation [36] are quite robust to imperfect CSI. It is also assumed that coordination among the relays allows for accurate symbol-level timing synchronization at D and orthogonal channel allocation as in many studies such as [5,23–29]. However, the issue of how exactly the synchronization between relays is performed is beyond the scope of our study. Finally, all channel coefficients are assumed to follow complex Gaussian distribution with zero-mean and unit variance as in many studies [5].

At the first stage of the transmission, a group of information bits is mapped to the index of the transmit antenna at S. Therefore, only a single transmit antenna is activated at S with the transmitted energy of E_S. S transmits the SSK symbol to the first relay nodes of parallel branches using the activated antenna. Each relay in each branch amplifies its received signal and forwards it to the next relay of the same branch until it reaches D. Hence, D receives L

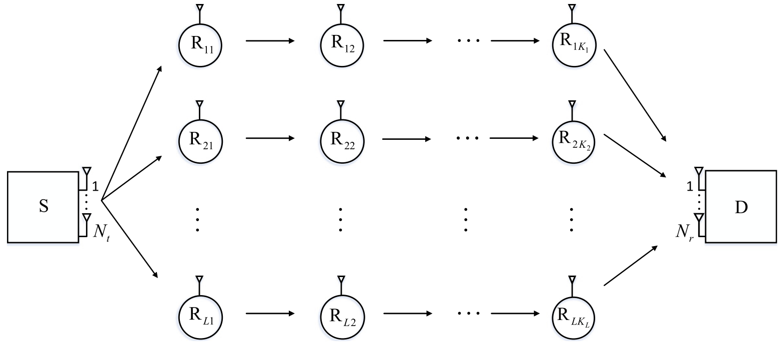

Fig. 1. System model of the multi-hop multi-branch SSK scheme with single-antenna AF relays.

different copies of the transmitted signal. Since each relay uses an orthogonal channel for its transmission, inter-relay interference is assumed to be zero. With $l \in \{1, \ldots, N_t\}$ denoting the active antenna index at S, the received signal at R_{p,m_p} is given as

$$y_{p,m_p} = \sqrt{E_S} h_p^l \prod_{i=1}^{m_p-1} A_{p,i} h_{p,i} + \sum_{k=1}^{m_p-1} n_{p,k} \prod_{i=k}^{m_p-1} A_{p,i} h_{p,i} + n_{p,m_p} \tag{1}$$

where h_p^l is the channel fading coefficient between S and $R_{p,1}$, and $h_p^l \sim \mathcal{CN}(0, 1)$. Furthermore, $A_{p,i}$ and $h_{p,i}$, $i = 1, 2, \ldots, m_p - 1$, denote the amplification factor at the ith relay in the pth branch and the channel fading coefficient between $R_{p,i}$ and $R_{p,i+1}$ where $h_{p,i} \sim \mathcal{CN}(0, 1)$, respectively. For the relay $R_{p,i}$, we assume a fixed-gain amplification factor as $A_{p,i} = \sqrt{\frac{1}{E_{p,i-1}+N_0}}$, where $E_{p,i}$ is the transmitted energy of the ith relay in the pth branch. For the ease of representation, we assume that $E_{p,0} = E_S$. Also, $n_{p,k}$, $k = 1, \ldots, m_p - 1$, is the additive white Gaussian noise (AWGN) sample at $R_{p,k}$, where $n_{p,k} \sim \mathcal{CN}(0, N_0)$.

At the last stage of the transmission, D receives different copies of the transmitted symbol from L parallel branches. Hence, the vector of received signals from the pth branch at D can be written as

$$\begin{aligned} \mathbf{y}_p &= \sqrt{E_S} h_p^l A_{p,K_p} \mathbf{h}_{p,K_p} \prod_{i=1}^{K_p-1} A_{p,i} h_{p,i} \\ &\quad + A_{p,K_p} \mathbf{h}_{p,K_p} \left(n_{p,K_p} + \sum_{k=1}^{K_p-1} n_{p,k} \prod_{i=k}^{K_p-1} A_{p,i} h_{p,i} \right) + \mathbf{n}_{p,K_p+1} \end{aligned} \tag{2}$$

where $\mathbf{h}_{p,K_p}$ and $\mathbf{n}_{p,K_p+1}$ denote $R_{p,K_p} - D$ channel fading coefficients vector and AWGN samples vector at D with dimensions $N_r \times 1$, respectively, whose elements are distributed with $\mathcal{CN}(0, 1)$ and $\mathcal{CN}(0, N_0)$, respectively. After the noise normalization, (2) can be rewritten as

$$\tilde{\mathbf{y}}_p = \frac{\mathbf{y}_p}{\sqrt{\Omega}} = \sqrt{G} h_p^l \mathbf{h}_{p,K_p} \prod_{i=1}^{K_p-1} h_{p,i} + \tilde{\mathbf{n}}_{p,K_p+1} \tag{3}$$

where $\Omega = 1 + A_{p,K_p}^2 \left\| \mathbf{h}_{p,K_p} \right\|^2 \left(1 + \sum_{k=1}^{K_p-1} \prod_{i=k}^{K_p-1} A_{p,i}^2 \left| h_{p,i} \right|^2 \right)$, $G = \frac{E_S \prod_{i=1}^{K_p} A_{p,i}^2}{\Omega}$ and $\tilde{\mathbf{n}}_{p,K_p+1}$ is the vector of AWGN samples, whose elements are distributed with $\mathcal{CN}(0, N_0)$.

Finally, D estimates the active transmit antenna index $(\hat{l})$ using maximum likelihood (ML) detector as follows

$$\begin{aligned} \hat{l} &= \arg \min_{n=1,\ldots,N_t} \sum_{p=1}^{L} \left\| \tilde{\mathbf{y}}_p - \sqrt{G} h_p^n \mathbf{h}_{p,K_p} \prod_{i=1}^{K_p-1} h_{p,i} \right\|^2 \\ &= \arg \max_{n=1,\ldots,N_t} \sum_{p=1}^{L} -\frac{1}{2} G \left| h_p^n \right|^2 \left\| \mathbf{h}_{p,K_p} \right\|^2 \prod_{i=1}^{K_p-1} \left| h_{p,i} \right|^2 \\ &\quad + \operatorname{Re} \left\{ \tilde{\mathbf{y}}_p \times \sqrt{G} \left(h_p^n \mathbf{h}_{p,K_p} \prod_{i=1}^{K_p-1} h_{p,i} \right)^H \right\}. \end{aligned} \tag{4}$$

2.2. Performance analysis

In this subsection, a considerably accurate lower-bound expression on the PEP of multi-hop single-branch SSK system and an approximate expression on the average BEP of multi-hop multi-branch SSK system are derived for the cases in which the numbers of transmit antennas are two ($N_t = 2$) and greater than two ($N_t > 2$) at the source, respectively.

2.2.1. Pairwise error probability

PEP , $P(l \to \hat{l})$, is the probability of the error event at D, which corresponds to deciding $\hat{l}$ instead of l as the index of active transmit antenna of S. Hence, using (4), the PEP can be obtained as follows

$$\begin{aligned} &P\left(l \to \hat{l}\right) \\ &= \Pr\left(\sum_{p=1}^{L} \left\| \tilde{\mathbf{y}}_p - x\sqrt{G} h_p^l \mathbf{h}_{p,K_p} \prod_{i=1}^{K_p-1} h_{p,i} \right\|^2 \right. \\ &\quad \left. > \sum_{p=1}^{L} \left\| \tilde{\mathbf{y}}_p - \sqrt{G} h_p^{\hat{l}} \mathbf{h}_{p,K_p} \prod_{i=1}^{K_p-1} h_{p,i} \right\|^2 \right) \\ &= \Pr\left(\sum_{p=1}^{L} G \left| h_p^l \right|^2 \left\| \mathbf{h}_{p,K_p} \right\|^2 \prod_{i=1}^{K_p-1} \left| h_{p,i} \right|^2 \right. \\ &\quad + 2\sqrt{G} \operatorname{Re} \left\{ \tilde{\mathbf{n}}_{p,K_p+1} \left(h_p^l \mathbf{h}_{p,K_p} \prod_{i=1}^{K_p-1} h_{p,i} \right)^H \right\} \\ &\quad < \sum_{p=1}^{L} 2G \operatorname{Re} \left\{ h_p^l \left(h_p^{\hat{l}} \right)^H \right\} \left\| \mathbf{h}_{p,K_p} \right\|^2 \prod_{i=1}^{K_p-1} \left| h_{p,i} \right|^2 \\ &\quad - G \left| h_p^{\hat{l}} \right|^2 \left\| \mathbf{h}_{p,K_p} \right\|^2 \prod_{i=1}^{K_p-1} \left| h_{p,i} \right|^2 \\ &\quad \left. + 2\sqrt{G} \operatorname{Re} \left\{ \tilde{\mathbf{n}}_{p,K_p+1} \left(h_p^{\hat{l}} \mathbf{h}_{p,K_p} \prod_{i=1}^{K_p-1} h_{p,i} \right)^H \right\} \right). \end{aligned} \tag{5}$$

This PEP expression can be rewritten as follows [23]

$$P(l \to \hat{l}) = \mathrm{E}\left[Q\left(\sqrt{\sum_{p=1}^{L}\gamma_{p,tot}}\right)\right] \quad (6)$$

where $\gamma_{p,tot} = \left(\sum_{t=0}^{K_p}\prod_{j=0}^{t}\frac{C_{p,j-1}}{\gamma_{p,j}}\right)^{-1}$. Here, $C_{p,-1} = 1$, $C_{p,j-1} = \frac{E_{p,j-1}}{N_0} + 1, j = 1, \ldots, K_p$, $\gamma_{p,0} = \frac{E_S\left|h_p^l - h_p^{\hat{l}}\right|^2}{2N_0}$ and $\gamma_{p,j} = \frac{E_{p,j}\left|h_{p,j}\right|^2}{N_0}$ for $j = 0, \ldots, K_p - 1$. Note that $\gamma_{p,K_p} = \frac{E_{p,K_p}\left\|\mathbf{h}_{p,K_p}\right\|^2}{N_0}$. Since $\gamma_{p,tot}$ is the sum of many dependent random variables, it is not easy to find an exact distribution for it. However, it can be upper-bounded as follows [23]

$$\gamma_{p,tot} \le \gamma^{b}_{p,tot} = \frac{1}{K_p+1}\prod_{j=0}^{K_p+1}\frac{\gamma_{p,j}{}^{(K_p+2-j)/(K_p+1)}}{C_{p,j-1}{}^{(K_p+1-j)/(K_p+1)}}. \quad (7)$$

Since $\gamma_{p,j}$ follows exponential distribution for $j = 0, \ldots, K_p - 1$ and γ_{p,K_p} follows chi-square distribution with $2N_r$ degrees of freedom, the probability density function (PDF) of $\gamma^{b}_{p,tot}$ can be obtained with the help of [23, (4)] as

$$f_{\gamma^{b}_{p,tot}}(r) = (K_p+1)Tr^{-1}G^{\lambda,0}_{0,\lambda}\left[Br^{K_p+1}\middle|\begin{matrix}-\\ \zeta_0,\ldots,\zeta_{K_p}\end{matrix}\right] \quad (8)$$

where $T = \frac{\prod_{i=1}^{K_p}(K_p+2-j)^{1/2}}{(\sqrt{2\pi})^{\frac{(K_p+1)K_p}{2}}\Gamma(N_r)}$, $\lambda = \frac{(K_p+1)(K_p+2)}{2}$, $B = (K_p+1)^{K_p+1}\prod_{j=0}^{K_p}C_{p,j}{}^{K_p-j} \times \prod_{i=1}^{K_p+1}\left(\frac{1}{(E_{p,i-1}/N_0)(K_p+2-i)}\right)^{K_p+2-i}$ and $\zeta_v = \Delta\big(K_p + 1 - v, 1\big)$, $v = 0, \ldots, K_p - 1$, where $\Delta(\kappa, \mu) = \frac{\mu}{\kappa}, \frac{\mu+1}{\kappa}, \ldots, \frac{\mu+\kappa-1}{\kappa}$. Note that $\zeta_{K_p} = N_r$. Using the PDF of $\gamma^{b}_{p,tot}$ ($f_{\gamma^{b}_{p,tot}}(r)$), a lower-bound on PEP corresponding to the single-branch (pth-branch) transmission can be formulated as [3]

$$P_p(l \to \hat{l}) \ge \int_0^\infty Q\left(\sqrt{r}\right)f_{\gamma^{b}_{p,tot}}(r)dr. \quad (9)$$

Using the Meijer's G-function representation of the Q function [37] and [38, (21)], the lower-bound on PEP given in (9) can be rewritten in closed form as

$$P_p(l \to \hat{l}) \ge \frac{TG^{\lambda,2N_p}_{2N_p,\lambda+N_p}\left[\frac{BN_p{}^{N_p}}{(1/2)^{N_p}}\middle|\begin{matrix}\Delta(N_p,1),\,\Delta(N_p,1/2)\\ \zeta_0,\ldots,\zeta_{K_p},\,\Delta(N_p,0)\end{matrix}\right]}{\left(\sqrt{2}\right)^{N_p+1}\left(\sqrt{\pi}\right)^{N_p}} \quad (10)$$

where $N_p = K_p + 1$ is the number of hops in the pth branch. Since D receives signals from L different branches, the overall average PEP can be lower-bounded as follows

$$P\left(l \to \hat{l}\right) \ge \mathrm{E}\left[Q\left(\sqrt{\sum_{p=1}^{L}\gamma^{b}_{p,tot}}\right)\right] = \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\prod_{p=1}^{L}M_{\gamma^{b}_{p,tot}}\left(\frac{1}{2\sin^2\theta}\right)d\theta \quad (11)$$

where $M_{\gamma^{b}_{p,tot}}(s)$ is the moment generating function (MGF) of $\gamma^{b}_{p,tot}$. Cumulative distribution function (CDF) of $\gamma^{b}_{p,tot}$ can be obtained as $F_{\gamma^{b}_{p,tot}}(r) = \int_0^r f_{\gamma^{b}_{p,tot}}(\gamma)d\gamma$. Using [38, (26)], $F_{\gamma^{b}_{p,tot}}(r)$ can be given in closed-form as

$$F_{\gamma^{b}_{p,tot}}(r) = TG^{\lambda,1}_{1,\lambda+1}\left[Br\middle|\begin{matrix}1\\ \zeta_0,\ldots,\zeta_{K_p},0\end{matrix}\right]. \quad (12)$$

Then, the MGF of $\gamma^{b}_{p,tot}$ can be expressed as

$$M_{\gamma^{b}_{p,tot}}(s) = s\int_0^\infty e^{-sr}F_{\gamma^{b}_{p,tot}}(r)dr. \quad (13)$$

By substituting (12) into (13) and using [34, (7.813)], a closed-form expression for $M_{\gamma^{b}_{p,tot}}(s)$ can be derived as

$$M_{\gamma^{b}_{p,tot}}(s) = TG^{\lambda,2}_{2,\lambda+1}\left[\frac{B}{s}\middle|\begin{matrix}0,\,1\\ \zeta_0,\ldots,\zeta_{K_p},0\end{matrix}\right]. \quad (14)$$

Substituting (14) into (11), a lower-bound on PEP can be obtained. To avoid numerical integration, (11) can be approximated as follows

$$P(l \to \hat{l}) \approx \frac{1}{\pi}\prod_{p=1}^{L}M_{\gamma^{b}_{p,tot}}\left(\frac{1}{2}\right). \quad (15)$$

Note that the PEP is equivalent to average BEP when $N_t = 2$ for SSK systems. We perform approximate BEP analysis in the next subsection for $N_t > 2$.

2.2.2. Approximate analysis for $N_t > 2$

In the previous subsection, the approximate PEP for the multi-hop multi-branch AF-SSK system is derived in (15). We can substitute the derived approximate PEP expression into well-known union bound to get the approximate BEP for $N_t > 2$ as in [15]. Hence, the approximate BEP of the system can be given as

$$P_b \approx \frac{1}{N_t\log_2(N_t)}\sum_{l=1}^{N_t}\sum_{\hat{l}=1}^{N_t}N(l,\hat{l})P(l \to \hat{l}) \quad (16)$$

where $N(l, \hat{l})$ is the number of bits in error for the corresponding pairwise error event.

2.3. Numerical results

In this subsection, analytical expressions given in the previous subsections are verified through Monte Carlo simulations. We provide BER results of the proposed multi-hop multi-branch AF-SSK scheme for different number of S transmit antennas (N_t), relays (K_p), D receive antennas (N_r) and parallel branches (L). We also provide BER results corresponding to multi-hop multi-branch classical SIMO system with AF relays, in which M-QAM is applied at S, to compare with the proposed SSK system. The results are plotted as a function of E_S/N_0, where we assume the transmitted energy of all relays is equal to E_S, i.e., $E_{p,m_p} = E_S$.

In Fig. 2, the BER performance of the proposed AF-SSK system is given for $N_t = 2$, $K_p + 1 \in \{3, 4, 5\}$, $N_r = 4$ and $L = 1$. As seen from Fig. 2, the derived lower-bound on PEP for the single-branch transmission given in (10) is considerably accurate for especially low SNR values and the system performance degrades when the number of the relays/hops increases.

Fig. 3 shows the BER performance corresponding to the proposed multi-hop multi-branch AF-SSK system for $K_p + 1 = 3$ hops, $N_t \in \{2, 4, 8\}$, $L \in \{1, 2, 3\}$ and $N_r = 3$. As can be seen from Fig. 3, the analytical results match with the computer simulation results and the proposed approximation is sufficiently accurate for $N_t \in \{2, 4, 8\}$ and $L \in \{1, 2, 3\}$. Furthermore, Fig. 3 clearly indicates that the BER performance is improved when the number of branches (L) increases.

In Fig. 4, we compare the BER performance of the proposed SSK system with classical SIMO systems, in which M-QAM modulation is applied at single-antenna S, for different spectral efficiency values (η) in terms of bits/s/Hz. The curves in Fig. 4 are given for $\eta \in \{2, 4, 6\}$ bits/s/Hz, i.e., $N_t, M \in \{4, 16, 64\}$, $L = 2$, $K_1, K_2 = 4$ and $N_r = 4$. To make fair comparisons, the data rates for the SSK

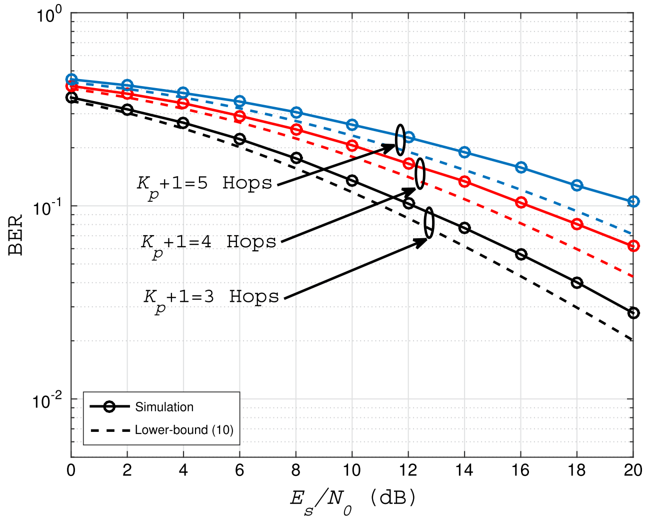

Fig. 2. BER performance of the proposed multi-hop multi-branch AF-SSK system for $N_t = 2$, $K_p + 1 \in \{3, 4, 5\}$, $N_r = 4$ and $L = 1$.

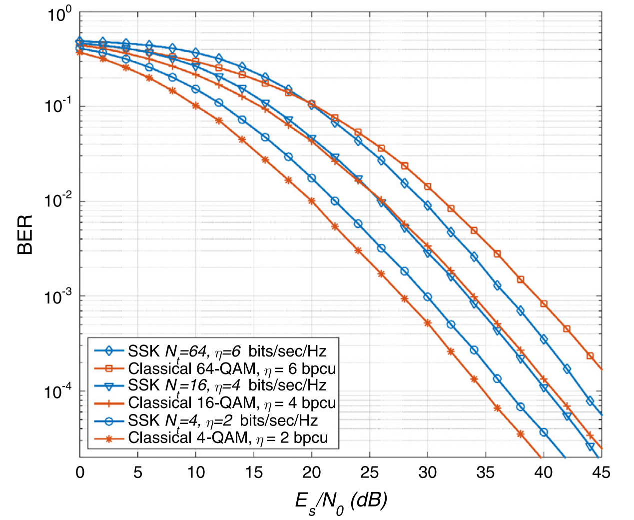

Fig. 4. BER performance comparison of the proposed multi-hop multi-branch SSK system with the classical SIMO system for $N_t, M \in \{4, 16, 64\}$, $L = 2$, $K_1 = K_2 = 4$ and $N_r = 4$.

and classical SIMO systems are assumed to be equal. As seen from Fig. 4, the classical SIMO scheme provides better BER performance at low data rates; however, the effectiveness of the proposed SSK scheme become more evident when the data rate is increased and the proposed SSK scheme outperforms the classical SIMO system for $\eta = 6$ bits/s/Hz at mid-to-high SNR values.

3. Space shift keying for multi-hop DF relaying with path selection

In this section, we propose a multi-hop MIMO DF-SSK scheme with path selection. Closed-form approximate and asymptotic SEP expressions are derived and theoretical and simulation results are provided for the proposed SSK scheme.

3.1. System model

The system model of the proposed multi-hop DF-SSK system is given in Fig. 5. We consider a multi-hop multi-branch system, in which S is equipped with N_t transmit antennas and D is equipped with N_r receive antennas. Furthermore, there are L branches and each branch consists of K relays, which are equipped with N_t transmit and N_r receive antennas. We denote the m_pth relay in the pth branch by R_{p,m_p} $\left(1 \le m_p \le K_p,\ 1 \le p \le L\right)$. Note that we assume all the branches have the same number of relays, in other words $K_p = K$, in the DF-SSK scheme for ease of representation. We also assume that the perfect CSI is available at the receiving nodes and the coordination among the relays allows for accurate symbol-level timing synchronization at D and orthogonal channel allocation. Furthermore, all channel coefficients follow complex Gaussian distribution with zero-mean and unit variance as in the first system, namely multi-hop multi-branch AF-SSK system.

In such a system, S communicates with D via half duplex DF relays of the best path as follows: The overall transmission occurs in $K + 1$ phases. In the first phase, a group of information bits are mapped to a transmit antenna index at S according to the SSK modulation. Due to the SSK mapping, only one transmit antenna

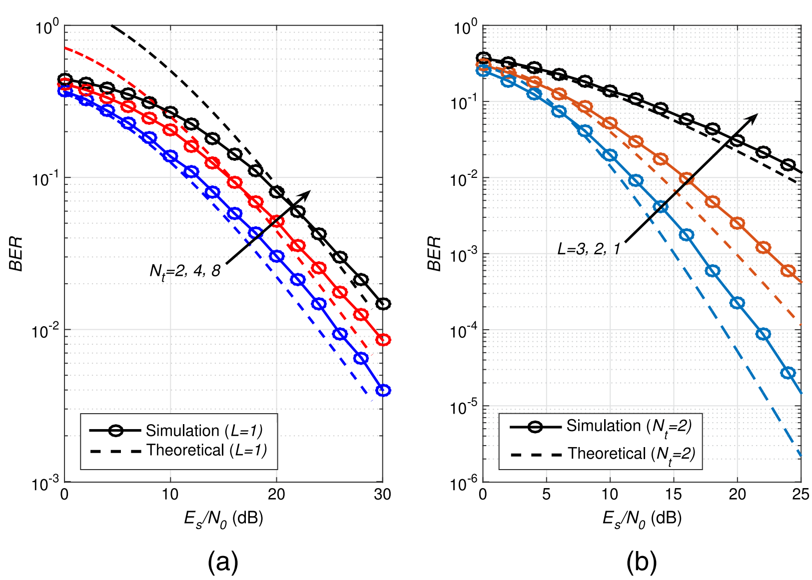

Fig. 3. BER performance of the proposed multi-hop multi-branch AF-SSK system: (a) $N_t \in \{2, 4, 8\}$, $K_p + 1 = 3$, $N_r = 3$ and $L = 1$; (b) $N_t = 2$, $K_p + 1 = 3$, $N_r = 3$ and $L \in \{1, 2, 3\}$.

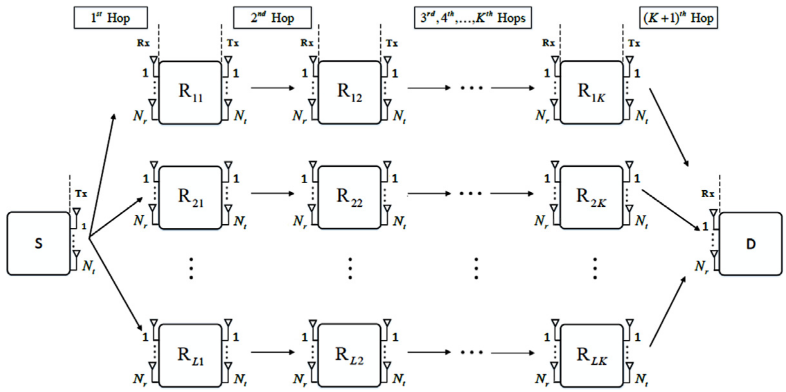

Fig. 5. System model of the multi-hop MIMO DF-SSK system with path selection.

is activated during the transmission and active antenna transmits a constant-parameter signal with the energy of E_S. In $K-1$ hops, after the first phase, the relays on the selected path decode their received signals according to ML detection and forward them with energy of E_S, using SSK modulation as in the first phase. Hence, information is conveyed hop by hop until it reaches D over the selected path. With l_i denoting the active transmit antenna index at the ith hop ($i = 1, \ldots, K+1$), the received signal vector at the ith hop of the pth branch can be given as

$$\mathbf{y}_{p,i} = \sqrt{E_S}\mathbf{h}_p^{l_i} + \mathbf{n}_{p,i} \tag{17}$$

where $\mathbf{h}_p^{l_i}$ is the l_ith column of $\mathbf{H}_{p,i}$, which is the channel matrix between the ith and $(i+1)$th nodes at the path p. Note that the elements of $\mathbf{H}_{p,i}$ are distributed with $\mathcal{CN}(0,1)$. $\mathbf{n}_{p,i}$ is the additive Gaussian noise vector at the ith hop of the pth branch, whose elements are distributed with $\mathcal{CN}(0, N_0)$. Since, the relays decode their received signals and then, forward them applying the SSK modulation, the system is exposed to error propagation. Finally, at the last phase of the transmission, D receives the signal from the last relay of the selected path and then decodes its received signal according to ML detection rule.

The PEP of end-to-end SSK systems depends on the Euclidean distances between channel fading coefficients corresponding to the transmit antennas [3]. Hence, we consider these Euclidean distances to perform the path selection in our system. Since each transmitting node uses SSK modulation to send information bits, PEP for the ith hop of the pth branch, or in other words, the probability that l_i is detected erroneously as $\hat{l}_i$, can be given as [3]

$$P\left(l_i \to \hat{l}_i\right) = \int_0^\infty Q\left(\sqrt{r}\right) f_{\gamma_{p,i}^{l_i,\hat{l}_i}}(r)\, dr \tag{18}$$

where $\gamma_{p,i}^{l_i,\hat{l}_i} = \frac{E_S \left\| \mathbf{h}_p^{l_i} - \mathbf{h}_p^{\hat{l}_i} \right\|^2}{2N_0}$. Here, $\mathbf{h}_p^{\hat{l}_i}$ denotes the vector of channel fading coefficients corresponding to $\hat{l}_i$th transmit antenna of the ith hop of the pth branch for $l_i \neq \hat{l}_i$. The best path is selected considering the squared Euclidean distances between channel fading coefficients for each hop as follows:

$$\gamma_{sel} = \max_{p=1,\ldots,L} \left\{ \min_{i=1,\ldots,K+1} \left\{ \min_{l_i,\hat{l}_i=1,\ldots,N_t,\; l_i\neq\hat{l}_i} \gamma_{p,i}^{l_i,\hat{l}_i} \right\} \right\}. \tag{19}$$

It is assumed that such the path selection procedure is performed by a central controller, in which the CSI of all paths is available, as in [39,40] and we have error-free feedback channels between the controller and the relays. Such an assumption is reasonable since the feedback is very reliable at very-low-rates and useful protocols can also be applied to overcome the effects of feedback errors [5].

3.2. Performance analysis

In this subsection, closed-form approximate and asymptotic SEP expressions of the proposed DF-SSK system are derived. Note that the reason why a SEP analysis is performed instead of a PEP analysis in here, is that the approximate expressions obtained with the SEP analysis are in a closer agreement with the computer simulation results compared to the union-bound expressions obtained with the PEP analysis at especially high data rates. Moreover, since the diversity order of the approximate SEP expression matches with the diversity order of the DF-SSK system, we perform asymptotic error probability analysis in this subsection unlike the AF-SSK system.

3.2.1. Approximate symbol error probability analysis

It is considerably difficult to derive the exact mathematical results for the proposed multi-hop DF-SSK system with path selection since we need to consider all error events occurred at each node. However, to simplify the analysis, the worst case PEP of the selected path can be used to determine the approximate SEP of the proposed system [29]. In SM/SSK systems, PEP is dependent to the difference of channel fading coefficients. We can define the Euclidean distance between channel fading coefficients corresponding to the l_ith and $\hat{l}_i$th transmit antennas as $\lambda_{p,i}^{l_i,\hat{l}_i} = \left\| \mathbf{h}_p^{l_i} - \mathbf{h}_p^{\hat{l}_i} \right\|^2$. Since $\mathbf{h}_p^{l_i}$ and $\mathbf{h}_p^{\hat{l}_i}$ follow complex Gaussian distribution, $\lambda_{p,i}^{l_i,\hat{l}_i}$ follows chi-square distribution and its CDF is given as [41]

$$F_{\lambda_{p,i}^{l_i,\hat{l}_i}}(r) = 1 - e^{-\frac{r}{2}} \sum_{z=0}^{N_r-1} \frac{1}{z!}\left(\frac{r}{2}\right)^z. \tag{20}$$

The minimum Euclidean distance for the ith hop can be expressed as

$$\lambda_{p,i} = \min_{l_i,\hat{l}_i=1,\ldots,N_t, l_i\neq\hat{l}_i} \lambda_{p,i}^{l_i,\hat{l}_i}. \tag{21}$$

Since we have $\binom{N_t}{2}$ squared Euclidean distances in each hop, CDF of $\lambda_{p,i}$ can be written with the help of order statistics as [42, (2.1.2)]

$$\begin{aligned} F_{\lambda_{p,i}}(r) &= 1 - \left[1 - F_{\lambda_{p,i}^{l_i,\hat{l}_i}}(r)\right]^{\binom{N_t}{2}} \\ &= 1 - \left[e^{-\frac{r}{2}} \sum_{z=0}^{N_r-1} \frac{1}{z!}\left(\frac{r}{2}\right)^z\right]^{\binom{N_t}{2}}. \end{aligned} \tag{22}$$

On the other hand, the minimum Euclidean distance for the pth branch can be expressed as

$$\lambda_p = \min_{i=1,\ldots,K+1} \lambda_{p,i}. \tag{23}$$

Therefore, the CDF of λ_p can be written as

$$F_{\lambda_p}(r) = 1 - \left[1 - F_{\lambda_{p,i}}(r)\right]^{K+1} = 1 - \left[e^{-\frac{r}{2}} \sum_{z=0}^{N_r-1} \frac{1}{z!}\left(\frac{r}{2}\right)^z \right]^{(K+1)\binom{N_t}{2}}. \tag{24}$$

Considering (19), the selected path has the largest minimum squared Euclidean distance among all branches. Hence, we can define this distance (λ_{sel}) as follows

$$\lambda_{sel} = \max_{p=1,\ldots,L} \lambda_p. \tag{25}$$

Therefore, the CDF of λ_{sel} can be expressed as

$$F_{\lambda_{sel}}(r) = \left[F_{\lambda_p}(r)\right]^L = \left[1 - \left[1 - F_{\lambda_{p,i}^{l_i,\hat{l}_i}}(r)\right]^{\binom{N_t}{2}(K+1)} \right]^L = \left[1 - \left[e^{-\frac{r}{2}} \sum_{z=0}^{N_r-1} \frac{1}{z!}\left(\frac{r}{2}\right)^z \right]^{\binom{N_t}{2}(K+1)} \right]^L. \tag{26}$$

By applying binomial expansion, the CDF of λ_{sel} can be rewritten as

$$F_{\lambda_{sel}}(r) = \sum_{\nu=0}^{L} \sum_{t=0}^{M_\nu} \binom{L}{\nu} (-1)^\nu C_t\left(N_r, N_t, \nu\right) e^{-\frac{r}{2}\binom{N_t}{2}(K+1)\nu} r^t \tag{27}$$

where $M_\nu = (N_r - 1)\binom{N_t}{2}(K+1)\nu$ and $C_t(N_r, N_t, \nu)$ is the coefficient of r^t in the expansion of

$$\left[\sum_{z=0}^{N_r-1} \frac{1}{z!}\left(\frac{r}{2}\right)^z \right]^{K_\nu} \tag{28}$$

where $K_\nu = \binom{N_t}{2}(K+1)\nu$. Using the nearest neighbor approach, the approximate SEP of the system can be given as [43]

$$P_s \approx \frac{2}{N_t} \int_0^\infty Q\left(\sqrt{\frac{E_S r}{2N_0}}\right) f_{\lambda_{sel}}(r)\, dr. \tag{29}$$

The PDF $f_{\lambda_{sel}}(r)$ is obtained by taking the derivative of $F_{\lambda_{sel}}(r)$ as

$$f_{\lambda_{sel}}(r) = \sum_{\nu=0}^{L} \sum_{t=0}^{M_\nu} \binom{L}{\nu} (-1)^\nu C_t\left(N_r, N_t, \nu\right) e^{-\frac{r}{2}\binom{N_t}{2}(K+1)\nu} \times \left[t r^{t-1} - \binom{N_t}{2}(K+1)\frac{\nu}{2} r^t \right]. \tag{30}$$

By substituting (30) into (29) and evaluating the integral with the help of [44, (3.63)], approximate SEP of the proposed system can be obtained in the closed-form as

$$\begin{aligned} P_s \approx \frac{2}{N_t} \sum_{\nu=1}^{L} \sum_{t=0}^{(N_r-1)K_\nu} \binom{L}{\nu} (-1)^\nu C_t\left(N_r, N_t, \nu\right) \\ \times \frac{t!}{{K_\nu}^t} \left[1 - \left(\frac{2K_\nu}{E_S/N_0} + 1 \right)^{-1/2} \right]^t \\ - \frac{1}{2} \left[1 - \left(\frac{2K_\nu}{E_S/N_0} + 1 \right)^{-1/2} \right] \sum_{u=0}^{t} 2^{-u} \binom{t+u}{u} \\ \times \left[1 + \left(\frac{2K_\nu}{E_S/N_0} + 1 \right)^{-1/2} \right]^u \\ \times \sum_{u=0}^{t-1} 2^{-u} \binom{t-1+u}{u} \left[1 + \left(\frac{2K_\nu}{E_S/N_0} + 1 \right)^{-1/2} \right]^u. \end{aligned} \tag{31}$$

3.2.2. Asymptotic symbol error probability analysis

Considering the well-known behavior of the PDFs of the direct and relaying links around the origin [45], the diversity and coding gains of the system, G_d and G_c, respectively, can be derived. Hence, the asymptotic SEP of the proposed system at high SNR values can be given as [45]

$$\bar{P}_s(\varepsilon) \approx \left(G_c E_S/N_0\right)^{-G_d}. \tag{32}$$

Taking the derivative of (24), the PDF of λ_p can be obtained as

$$f_{\lambda_p}(r) = (K+1)\binom{N_t}{2} \times \left[e^{-\frac{r}{2}} \sum_{z=0}^{N_r-1} \frac{1}{z!}\left(\frac{r}{2}\right)^z \right]^{(K+1)\binom{N_t}{2}-1} \frac{e^{-r/2} r^{N_r-1}}{\Gamma(N_r)2^{N_r}}. \tag{33}$$

The PDF of λ_p around the origin can be written as

$$f_{\lambda_p}(r) = \frac{(K+1)\binom{N_t}{2} r^{N_r-1}}{\Gamma(N_r)2^{N_r}} + HOT, \quad r \to 0^+ \tag{34}$$

where HOT stands for the higher order terms. Note that λ_p denotes the minimum squared Euclidean distance in the pth branch. Using (34) and [45], the diversity and coding gains provided by the pth branch can be given as $G_d^p = N_r$ and $G_c^p = \frac{1}{2}\left[\binom{N_t}{2}\frac{(K+1)\Gamma(N_r+1/2)}{2\sqrt{\pi}(N_r!)}\right]^{-\frac{1}{N_r}}$, respectively. Since we consider the path with the largest minimum Euclidean distance, using [45, Eq. (15)], the diversity and coding gains provided by the proposed system can be written respectively as

$$G_d = \sum_{p=1}^{L} G_d^p = \sum_{p=1}^{L} N_r = LN_r, \tag{35}$$

$$G_c = \left[\frac{2^{L-1}\pi^{(L-1)/2}\Gamma\left(LN_r + 1/2\right)}{\left(G_c^p\right)^{LN_r}\left(N_r + 1/2\right)^L} \right]^{-\frac{1}{LN_r}}. \tag{36}$$

3.3. Numerical results

In this subsection, the analytical expressions given in the previous subsections for DF-SSK system are verified through Monte Carlo simulations. Moreover, SER comparisons are performed with the classical multi-hop SIMO schemes in which the M-PSK modulation is used instead of SSK modulation in each hop, the transmitting and receiving nodes are equipped with one transmit and multiple receive antennas, respectively. We consider the system models of [28] and [29] for the classical multi-hop SIMO scheme; however, the only difference between the classical multi-hop SIMO scheme and the system models of [28] and [29] is that the receiving nodes are equipped with single receive antennas for the given references. The SER results of the proposed SSK system are provided for different number of transmit antennas N_t, branches L, relays K and receive antennas N_r.

Fig. 6 depicts the SER performance of the proposed multi-hop DF-SSK system with path selection. The curves in Fig. 6 are given for $L \in \{1, 2, 3\}$, $K+1 = 5$, $N_t \in \{2, 4\}$ and $N_r = 3$. As seen from Fig. 6, computer simulation results match the analytical SEP and diversity order results given in the previous subsection. Moreover, Fig. 6 indicates that the SER performance is improved and a diversity gain is obtained when the number of branches increases. According to the asymptotic analysis, the asymptotic diversity orders of the curves corresponding to the proposed SSK systems for $L = 1$, 2 and 3 are calculated as $LN_r = 3$, 6 and 9, respectively. It can be verified from the slopes of the SER curves given in Fig. 6(a) that these values are consistent with the computer simulation results.

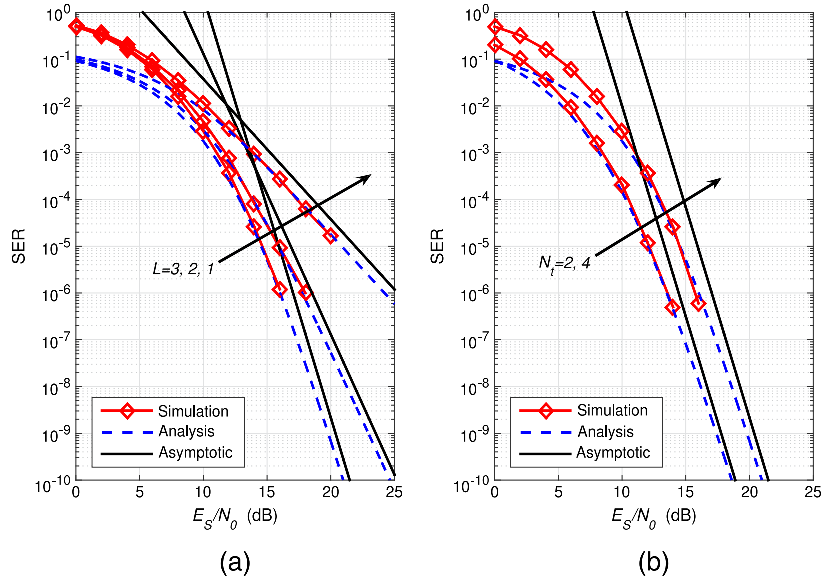

Fig. 6. SER performance of the proposed multi-hop SSK system with path selection: (a) $L \in \{1, 2, 3\}$, $K + 1 = 5$, $N_t = 4$ and $N_r = 3$; (b) $L = 3$, $K + 1 = 5$, $N_t \in \{2, 4\}$ and $N_r = 3$.

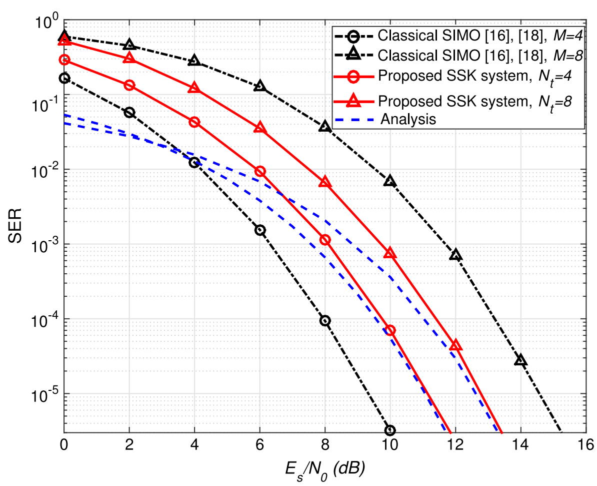

Fig. 7. SER performance comparison of the proposed multi-hop SSK system and classical SIMO system [28,29] for $N_t, M \in \{2, 4\}$, $L = 4$, $K + 1 = 4$ and $N_r = 4$.

In Fig. 7, we compare the SER performance of the proposed multi-hop SSK and classical SIMO schemes with path selection for different data rates $\eta \in \{2, 3\}$ bits/s/Hz, i.e., $N_t, M \in \{4, 8\}$, where the derived analytical SEP curves are shown with dashed lines. Note that a mapping between information bits and amplitude and/or phase modulated symbols is not performed in the SSK modulation, consequently, the number of the transmit antennas is used to determine the data rate. The curves in Fig. 7 are given for $L = 4$, $K + 1 = 4$, $N_t, M \in \{4, 8\}$ and $N_r = 4$. As seen from Fig. 7, the derived approximate SEP expression is considerably accurate for especially high SNR region and the effectiveness of the proposed multi-hop SSK scheme with path selection against the classical multi-hop SIMO [28,29] scheme becomes more evident at higher data rates. Fig. 7 shows that the classical multi-hop SIMO scheme outperforms the proposed multi-hop SSK scheme for $\eta = 2$ bits/s/Hz, i.e., $N_t = M = 4$, by approximately 1.8 dB; however the proposed multi-hop SSK scheme outperforms the classical multi-hop SIMO scheme for $\eta = 3$ bits/s/Hz, i.e., $N_t = M = 8$, by approximately 1.8 dB at a SER value of 10^{-4}.

4. Conclusion

In this paper, we have proposed two novel MIMO-SSK schemes for multi-hop relaying networks. In the first scheme, we have considered SSK modulation for a multi-hop multi-branch network employing AF relaying and in the second scheme, we have considered SSK modulation for a multi-hop network with DF relays and path selection. We have derived error probability expressions for both schemes. Furthermore, the proposed SSK systems have been compared with the conventional schemes and it has been proved that the effectiveness of the proposed SSK schemes compared to the conventional schemes become more evident for especially high data rates and sufficient number of receive antennas. Obtained results have revealed that SSK is a promising technique with its simple transceiver structure and remarkable error performance for next-generation multi-hop relaying networks.

Acknowledgment

This work was supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under Grant no. 114E607.

The work of E. Basar was supported by the Turkish Academy of Sciences Outstanding Young Scientist Award Programme (TUBA-GEBIP).

References

[1] E. Basar, Index modulation techniques for 5G wireless networks, IEEE Commun. Mag. 54 (7) (2016) 168–175.
[2] M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, L. Hanzo, Spatial modulation for generalized MIMO: Challenges, opportunities, and implementation, Proc. IEEE 102 (1) (2014) 56–103.
[3] J. Jeganathan, A. Ghrayeb, L. Szczecinski, A. Ceron, Space shift keying modulation for MIMO channels, IEEE Trans. Wirel. Commun. 8 (7) (2009) 3692–3703.
[4] R. Mesleh, O. Hiari, A. Younis, S. Alouneh, Transmitter design and hardware considerations for different space modulation techniques, IEEE Trans. Wirel. Commun. PP (99) (2017) 1.
[5] J.N. Laneman, D.N.C. Tse, G.W. Wornell, Cooperative diversity in wireless networks: Efficient protocols and outage behavior, IEEE Trans. Inform. Theory 50 (12) (2004) 3062–3080.
[6] H. Li, Q. Zhao, Distributed modulation for cooperative wireless communications, IEEE Signal Process. Mag. 23 (5) (2006) 30–36.
[7] C.X. Wang, X. Hong, X. Ge, X. Cheng, G. Zhang, J. Thompson, Cooperative MIMO channel models: A survey, IEEE Commun. Mag. 48 (2) (2010) 80–87.

[8] J.M. Paredes, B.H. Khalaj, A.B. Gershman, Cooperative transmission for wireless relay networks using limited feedback, IEEE Trans. Signal Process. 58 (7) (2010) 3828–3841.
[9] B. Maham, A. Hjørungnes, Asymptotic performance analysis of amplify-and-forward cooperative networks in a Nakagami-*m* fading environment, IEEE Commun. Lett. 13 (5) (2009) 300–302.
[10] B. Maham, A. Hjørungnes, Opportunistic relaying for MIMO amplify-and-forward cooperative networks, Wirel. Pers. Commun. 68 (3) (2013) 1067–1091.
[11] R. Mesleh, S. Ikki, M. Alwakeel, Performance analysis of space shift keying with amplify and forward relaying, IEEE Commun. Lett. 15 (12) (2011) 1350–1352.
[12] R. Mesleh, S.S. Ikki, Performance analysis of spatial modulation with multiple decode and forward relays, IEEE Wirel. Commun. Lett. 2 (4) (2013) 423–426.
[13] N. Ma, A. Wang, Y. Ji, H. Shi, Cooperative space shift keying for multiple-relay network, IEEE Commun. Lett. 18 (4) (2014) 712–715.
[14] R. Mesleh, S.S. Ikki, Space shift keying with amplify-and-forward MIMO relaying, Trans. Emerg. Tel. Technol. 26 (4) (2015) 520–531.
[15] P. Som, A. Chockalingam, Bit error probability analysis of SSK in DF relaying with threshold-based best relay selection and selection combining, IEEE Commun. Lett. 18 (1) (2014) 18–21.
[16] F. Yarkin, I. Altunbas, E. Basar, Source transmit antenna selection for space shift keying with cooperative relays, IEEE Commun. Lett. 21 (5) (2017) 1211–1214.
[17] S. Narayanan, M.D. Renzo, F. Graziosi, H. Haas, Distributed spatial modulation: A cooperative diversity protocol for half-duplex relay-aided wireless networks, IEEE Trans. Veh. Technol. 65 (5) (2016) 2947–2964.
[18] D. Yang, C. Xu, L.L. Yang, L. Hanzo, Transmit-diversity-assisted space-shift keying for colocated and distributed/cooperative MIMO elements, IEEE Trans. Veh. Technol. 60 (6) (2011) 2864–2869.
[19] O.C. Oztoprak, F. Yarkin, I. Altunbas, E. Basar, Performance analysis of space shift keying for af relaying with relay selection, AEU-Int. J. Electron. Commun. 81 (2017) 74–82.
[20] G. Altin, E. Basar, U. Aygolu, M.E. Celebi, Performance analysis of cooperative spatial modulation with multiple-antennas at relay, in: 2016 IEEE International Black Sea Conference on Communications and Networking, BlackSeaCom, Varna, Bulgaria, 2016, pp. 1–5.
[21] G. Altin, U. Aygolu, E. Basar, M.E. Celebi, Outage probability analysis of cooperative spatial modulation systems, in: 2016 23rd International Conference on Telecommunications, ICT, Thessaloniki, Greece, 2016, pp. 1–5.
[22] A. Radwan, H.S. Hassanein, Nxg04-3: Does multi-hop communication extend the battery life of mobile terminals? in: IEEE Globecom 2006, 2006, pp. 1–5.
[23] G.K. Karagiannidis, T.A. Tsiftsis, R.K. Mallik, Bounds for multihop relayed communications in Nakagami-*m* fading, IEEE Trans. Commun. 54 (1) (2006) 18–22.
[24] A. Adinoyi, H. Yanikomeroglu, Cooperative relaying in multi-antenna fixed relay networks, IEEE Trans. Wirel. Commun. 6 (2) (2007) 533–544.
[25] J. Zhang, L. Fei, Q. Gao, X.H. Peng, Energy-efficient multihop cooperative miso transmission with optimal hop distance in wireless ad hoc networks, IEEE Trans. Wirel. Commun. 10 (10) (2011) 3426–3435.
[26] A. Ribeiro, X. Cai, G.B. Giannakis, Symbol error probabilities for general cooperative links, IEEE Trans. Wirel. Commun. 4 (3) (2005) 1264–1273.
[27] G. Pan, E. Ekici, Q. Feng, Performance analysis of multi-branch multi-hop wireless relay systems over log-normal channels, IEEE Trans. Wirel. Commun. 13 (1) (2014) 223–233.
[28] M.R. Bhatnagar, R.K. Mallik, O. Tirkkonen, Performance evaluation of best-path selection in a multihop decode-and-forward cooperative system, IEEE Trans. Veh. Technol. 65 (4) (2016) 2722–2728.
[29] M.R. Bhatnagar, Performance analysis of a path selection scheme in multi-hop decode-and-forward protocol, IEEE Commun. Lett. 16 (12) (2012) 1980–1983.
[30] K. Navaie, H. Yanikomeroglu, Multi-route and Multi-user Diversity, Springer Netherlands, Dordrecht, 2006, pp. 223–241.
[31] A.M. Khodaian, B.H. Khalaj, Delay-constrained utility maximisation in multi-hop random access networks, IET Commun. 4 (16) (2010) 1908–1918.
[32] Q. Li, R.Q. Hu, Y. Qian, G. Wu, Cooperative communications for wireless networks: techniques and applications in LTE-advanced systems, IEEE Wirel. Commun. 19 (2).
[33] P. Som, A. Chockalingam, Performance analysis of space-shift keying in decode-and-forward multihop mimo networks, IEEE Trans. Veh. Technol. 64 (1) (2015) 132–146.
[34] I. Gradshteyn, I. Ryzhik, Table of Integrals Series Products, seventh ed., Academic Press, New York, 2007.
[35] B. Gedik, M. Uysal, Impact of imperfect channel estimation on the performance of amplify-and-forward relaying, IEEE Trans. Wirel. Commun. 8 (3) (2009) 1468–1479.
[36] M.D. Renzo, H. Haas, Space shift keying (SSK) modulation with partial channel state information: Optimal detector and performance analysis over fading channels, IEEE Trans. Commun. 58 (11) (2010) 3196–3210.
[37] Wolfram, Complementary error function: representations through more general functions, Feb. 2001. URL http://functions.wolfram.com/GammaBetaErf/Erfc/26/02/01/.
[38] V.S. Adamchik, O.I. Marichev, The algorithm for calculating integrals of hypergeometric type functions and its realization in reduce system, in: Proc. Int. Conf. Symbolic and Algebraic Comput, ISSAC '90, ACM, New York, NY, USA, 1990, pp. 212–224. URL http://doi.acm.org/10.1145/96877.96930.
[39] B. Gui, L. Dai, L.J. Cimini, Routing strategies in multihop cooperative networks, IEEE Trans. Wirel. Commun. 8 (2) (2009) 843–855.
[40] F.A. Khan, F. Yilmaz, M.S. Alouini, Generalized routing protocols for multihop relay networks, in: Proc. Int. Wireless Communications and Mobile Computing Conf., IWCMC, 2011, pp. 754–759.
[41] J. Proakis, M. Salehi, Digital Communications, McGraw-Hill international ed., McGraw-Hill, 2008.
[42] H. David, H. Nagaraja, Order Statistics Wiley Series in Probability and Statistics, Wiley, 2004.
[43] A. Goldsmith, Wireless Communications, Cambridge University Press, New York, NY, USA, 2005.
[44] S. Verdu, Multiuser Detection, Cambridge Univ. Press, Cambridge, U.K., 1998.
[45] Z. Wang, G.B. Giannakis, A simple and general parameterization quantifying performance in fading channels, IEEE Trans. Commun. 51 (8) (2003) 1389–1398.

Ferhat Yarkin received his B.Sc. and M. Sc. degrees with high honors, all in electronics and communication engineering, from Istanbul Technical University, Turkey, in 2015 and 2017, respectively. Currently, he is a Ph.D. student and research assistant at Istanbul Technical University, Electronics and Communication Engineering Department, and a member of the Wireless Communication Research Group. He has served as a reviewer for IEEE and ELSEVIER journals. His research interests include MIMO systems, cooperative communication, spatial modulation and channel modulation.

Ibrahim Altunbas was born in Sütçüler, Isparta, Turkey, in 1967. He received the B.Sc., M.Sc. and Ph.D. degrees, all in electronics and communication engineering, from Istanbul Technical University, Istanbul, Turkey, in 1988, 1992 and 1999, respectively. From 1992 to 1999, he was a Research Assistant, from 1999 to 2006, he was an Assistant Professor and from 2006 to 2011 he was an Associate Professor at Istanbul Technical University. He is currently a Professor at the same university. Between January 2001–November 2001, he was a Visiting Researcher at Texas A&M University, USA. Between November 2001–September 2002 and June 2015–August 2015, he was a Postdoctoral Fellow and a Visiting Researcher, respectively at the University of Ottawa, Canada. His research interests include digital communications, information theory, error control coding and modulation, turbo coding, LDPC coding, iterative decoding, MIMO systems, space–time coding, cooperative communication, network coding, spatial modulation, full-duplex communication and channel modulation.

Ertugrul Basar Ertugrul Basar received the B.S. degree (Hons.) from Istanbul University, Turkey, in 2007, and the M.S. and Ph.D. degrees from Istanbul Technical University in 2009 and 2013, respectively. From 2011 to 2012, he was with the Department of Electrical Engineering, Princeton University, Princeton, NJ, USA as a visiting research collaborator. He was an Assistant Professor with Istanbul Technical University from 2014 to 2017, where he is currently an Associate Professor of Electronics and Communication Engineering. He is an inventor of three pending patents on index modulation schemes. His primary research interests include MIMO systems, index modulation, cooperative communications, OFDM, and visible light communications.

Recent recognition of his research includes the Turkish Academy of Sciences Outstanding Young Scientist Award in 2017, the first-ever IEEE Turkey Research Encouragement Award in 2017, and the Istanbul Technical University Best Ph.D. Thesis Award in 2014. He is also the recipient of four Best Paper Awards including one from the IEEE International Conference on Communications 2016. He has served as a TPC member for several IEEE conferences and is a regular reviewer for various IEEE journals. Dr. Basar currently serves as an Associate Editor of the IEEE Communications Letters and the IEEE Access, and as an Editor of Physical Communication (Elsevier).