Two-way Space Shift Keying with Relay Selection

Ferhat Yarkin, Ibrahim Altunbas and Ertugrul Basar

Abstract—**In this paper, a two-way multiple-input multiple-output (MIMO) space shift keying (SSK) scheme with relay selection is proposed for amplify-and-forward relaying. In this scheme, the sources exchange their SSK symbols via a selected relay node. We derive a theoretical upper-bound expression and we also perform an asymptotic performance analysis for the average error probability of the proposed system. It is shown that the proposed system outperforms conventional two-way SSK scheme without relay selection.**

Index Terms—**Two-way, space shift keying, amplify-and-forward, relay selection.**

I. INTRODUCTION

Multiple-input multiple-output (MIMO) systems provide important advantages, such as high data rates and improved error performance for modern wireless communication. However, such advantages come with the cost of using multiple radio-frequency (RF) chains at the transmitter, increasing the inter-channel interference (ICI) and the transceiver complexity as well as requiring synchronization among the transmit antennas. These costs have led to new solutions for the next generation MIMO systems [1]. Within this scope, highly bandwidth efficient and novel spatial modulation (SM) [2] and space shift keying (SSK) [3] techniques have been proposed. SM and SSK, depending on the one-to-one mapping between the information bits and transmit antenna indices, typically activate only one transmit antenna during a transmission interval and set the rest of the transmit antennas idle. Therefore, ICI is entirely avoided, the requirement for inter-antenna synchronization (IAS) among the transmit antennas is eliminated and the transceiver complexity is significantly reduced in SM and SSK. Furthermore, SSK is a special case of SM, which decreases the transceiver complexity compared to SM since it can be implemented with a very simple hardware that does not require I/Q modulation and the employment of an RF chain [4].

Cooperative communication improves the error performance and enhances the coverage of wireless networks. Furthermore, the cooperative networks can efficiently mitigate the effect of fading in wireless channels [5]. Due to their improved error performance and low complexity, the performance of SM and SSK in cooperative networks have been studied by many researchers. The performance of SSK with cooperative amplify-and forward (AF) and decode-and-forward (DF) relaying has been investigated in [6]. A cooperative DF relaying scheme with SSK and transmit antenna selection has been studied in [7]. The authors of [8] and [9] have investigated the performance of cooperative AF and DF relaying schemes with relay selection, respectively.

In addition to the advantages of cooperative communication, two-way relaying networks, in which two users exchange information with each other through multiple common relays, further improve the network capacity [10]. However, the studies on SM/SSK with two-way relaying are considerably limited. In [11] and [12], the authors have proposed two-way SSK systems with AF and DF relaying, respectively. On the other hand, relay selection improves the error performance of the cooperative networks compared to single-relay transmission without decreasing the spectral efficiency [13]. However, to the best of authors' knowledge, there is no study combining two-way SSK systems with relay selection in the literature.

In this paper, we propose a two-way MIMO-SSK scheme. In this scheme, we consider a two-way network topology, in which SSK modulation is applied at the multi-antenna transmitter and receiver nodes and AF relaying is employed at the single-antenna relays. Moreover, the information is conveyed by one source to the another source over a relay, which is selected based on the pairwise error probability (PEP) of the worst link. We derive theoretical upper-bound and asymptotic expressions for the average bit error probability (BEP) of the proposed system. We also compare the proposed system with conventional two-way SSK system and show that the proposed system outperforms the conventional system.

II. SYSTEM MODEL AND RELAY SELECTION CRITERION

A. System Model

We consider a two-way SSK system with K single-antenna AF relays (R_1, R_2,..., R_K) and two sources namely S_1 and S_2 equipped with N_{T_1} and N_{T_2} transmit antennas, respectively, as indicated in Fig. 1. We assume that there is no direct link transmission between the sources. The transmission occurs in a two-phase protocol. In the first phase, due to its satisfactory error performance and low complexity, SSK technique is applied at S_1 and S_2, where SSK symbols are transmitted from S_1 and S_2 to the relays. With $l_1 \in \{1, \ldots, N_{T_1}\}$ and $l_2 \in \{1, \ldots, N_{T_2}\}$ denoting the index of the activated antenna at S_1 and S_2, respectively, the received signal at the ith relay (R_i) can be written as

$$y^{SR_i} = \sqrt{E_{S_1}} h_{l_1}^{S_1 R_i} + \sqrt{E_{S_2}} h_{l_2}^{S_2 R_i} + n^{R_i}, \ i = 1, 2, \ldots, K \tag{1}$$

where E_{S_1} and E_{S_2} are the transmitted signal energies of S_1 and S_2, respectively. $h_{l_1}^{S_1 R_i}$ and $h_{l_2}^{S_2 R_i}$ denote l_1th and l_2th elements of $\mathbf{h}^{S_1 R_i}$ and $\mathbf{h}^{S_2 R_i}$, whose dimensions are given as $1 \times N_{T_1}$ and $1 \times N_{T_2}$, respectively. The elements of $\mathbf{h}^{S_1 R_i}$ and $\mathbf{h}^{S_2 R_i}$ are distributed with $\mathcal{CN}(0, 1)$. Here, we
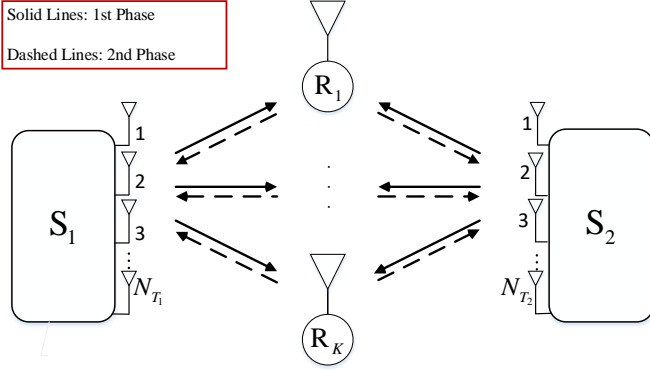
Fig. 1. System model of the two-way MIMO-SSK with cooperative AF relays.

define $\mathbf{h}^{S_1 R_i}$ and $\mathbf{h}^{S_2 R_i}$ as the vector of channel coefficients corresponding to S_1-R_i and S_2-R_i links, respectively. n^{R_i} is the additive white Gaussian noise (AWGN) sample at R_i, which is distributed with $n^{R_i} \sim \mathcal{CN}(0, N_0)$.

In the second phase, S_1 and S_2 remain silent and the relay R_λ, which is selected based on the pairwise error probabilities calculated for each way of transmission, amplifies the received signal and forwards it back to the sources by following the AF protocol. Note that the index λ stands for the selected relay and the relay selection criterion will be explained in the next subsection. The received signal vector at S_2 can be given as

$$\mathbf{y}^{R_\lambda S_2} = \sqrt{E_R E_{S_1}} A \mathbf{h}^{R_\lambda S_2} h_{l_1}^{S_1 R_\lambda} + \sqrt{E_R E_{S_2}} A \mathbf{h}^{R_\lambda S_2} h_{l_2}^{S_2 R_\lambda}$$
$$+ \sqrt{E_R} A \mathbf{h}^{R_\lambda S_2} n^{R_\lambda} + \mathbf{n}^{S_2} \quad (2)$$

where E_R is the transmitted energy of R_λ and $A = \frac{1}{\sqrt{E_{S_1} + E_{S_2} + 1}}$ is the fixed-gain amplification factor. $\mathbf{h}^{R_\lambda S_2}$ is the vector of channel fading coefficients between R_λ and S_2 whose dimensions are given as $N_{T_2} \times 1$ and elements are distributed with $\mathcal{CN}(0, 1)$. $h_{l_1}^{S_1 R_\lambda}$ and $h_{l_2}^{S_2 R_\lambda}$ denote l_1th and l_2th elements of $\mathbf{h}^{S_1 R_\lambda}$ and $\mathbf{h}^{S_2 R_\lambda}$, which have the same statistical properties as $\mathbf{h}^{S_1 R_i}$ and $\mathbf{h}^{S_2 R_i}$, respectively. Additionally, n^{R_λ} and $\mathbf{n}^{S_2}$ are the Gaussian noise sample and $N_{T_2} \times 1$ Gaussian noise vector of zero mean and variance N_0 at R_λ and S_2, respectively.

We assume that the source has perfect channel state information (CSI) of the corresponding link for which it is acting as a destination. In addition to that, since the source has knowledge of the activated antenna index for the previous transmission phase and the corresponding CSI during the pilot transmission phase, it can efficiently eliminate the self-interference [11]. After the self-interference cancellation and the noise normalization, the received signal vector at S_2 can be written as

$$\breve{\mathbf{y}}^{R_\lambda S_2} = G \mathbf{h}^{R_\lambda S_2} h_{l_1}^{S_1 R_\lambda} + \breve{\mathbf{n}}^{S_2} \quad (3)$$

where $G = \sqrt{\frac{E_R E_{S_1} A^2}{E_R A^2 \|\mathbf{h}^{R_\lambda S_2}\|^2 + 1}}$ and $\breve{\mathbf{n}}^{S_2}$ is the $N_{T_2} \times 1$ Gaussian noise vector whose elements are distributed with $\mathcal{CN}(0, N_0)$. Note that, each source acts as a destination in the

second phase of the transmission and we prefer to present only one way (S_1-R_λ-S_2) of the transmission due to the analogy of two-way transmission. The source (S_2) applies maximum likelihood detection rule to estimate the index of the activated antenna at S_1 as in [6]–[8].

B. Relay Selection Criterion

Pairwise error probability (PEP) is the probability of the error event at the destination, which corresponds to deciding $\hat{l}_1 (\hat{l}_2)$ instead of $l_1 (l_2)$ as the index of active transmit antenna of S_1 (S_2). PEP expressions for the each way of two-way AF-SSK system without relay selection can be expressed as [8]

$$P(l_1 \to \hat{l}_1) = \mathrm{E}\left[Q\left(\sqrt{\gamma_{S_1 R_i S_2}}\right)\right], \quad (4)$$

$$P(l_2 \to \hat{l}_2) = \mathrm{E}\left[Q\left(\sqrt{\gamma_{S_2 R_i S_1}}\right)\right] \quad (5)$$

where $\gamma_{S_1 R_i S_2} = \frac{\gamma_{R_i S_2} \gamma_{S_1 R_i}}{\gamma_{R_i S_2} + C}$, $\gamma_{R_i S_2} = \frac{E_R \|\mathbf{h}^{R_i S_2}\|^2}{N_0}$, $\gamma_{S_1 R_i} = \frac{E_{S_1}\left|h_{l_1}^{S_1 R_i} - h_{\hat{l}_1}^{S_1 R_i}\right|^2}{2 N_0}$ and $C = \frac{1}{A^2 N_0}$. Furthermore, $\gamma_{S_2 R_i S_1} = \frac{\gamma_{R_i S_1} \gamma_{S_2 R_i}}{\gamma_{R_i S_1} + C}$, $\gamma_{R_i S_1} = \frac{E_R \|\mathbf{h}^{R_i S_1}\|^2}{N_0}$, $\gamma_{S_2 R_i} = \frac{E_{S_2}\left|h_{l_2}^{S_2 R_i} - h_{\hat{l}_2}^{S_2 R_i}\right|^2}{2 N_0}$. Also, $Q(t) = \int_t^\infty (1/\sqrt{2\pi}) e^{-z^2/2} dz$ is the Gaussian Q function. Note that we assume $N_{T_1} = N_{T_2} = N_T$ for simplicity.

Considering (4) and (5), we adopt a relay selection criterion, which minimizes the worst case PEP considering the two-way transmission. We define the worst case PEP as the maximum PEP performed by a one-way of the transmission. More clearly, we define the minimum values of $\gamma_{S_1 R_i S_2}$ and $\gamma_{S_2 R_i S_1}$ random variables for the pairwise transmit antenna elements as follows

$$\gamma_{S_1 R_i S_2}^{min} = \min_{l_1, \hat{l}_1 = 1, \ldots, N_T, l_1 \neq \hat{l}_1} \gamma_{S_1 R_i S_2}, \quad (6)$$

$$\gamma_{S_2 R_i S_1}^{min} = \min_{l_2, \hat{l}_2 = 1, \ldots, N_T, l_2 \neq \hat{l}_2} \gamma_{S_2 R_i S_1}. \quad (7)$$

Note that since the Gaussian Q function is a monotone decreasing function, the minimum values defined in (6) and (7) give the maximum PEP for S_1-R_i-S_2 and S_2-R_i-S_1 links, respectively. Since we are dealing with the minimization of the worst case PEP, we select the relay, which maximizes the minimum among $\gamma_{S_1 R_i S_2}^{min}$ and $\gamma_{S_2 R_i S_1}^{min}$. Therefore, the index of the selected relay can be given as

$$\lambda = \arg \max_{i=1,\ldots,K} \min\left\{\gamma_{S_1 R_i S_2}^{min}, \gamma_{S_2 R_i S_1}^{min}\right\}. \quad (8)$$

III. PERFORMANCE ANALYSIS

In this section, upper-bound and asymptotic bit error probability (BEP) expressions for the proposed two-way AF-SSK system with relay selection are derived.

A. Upper-Bound Expression For Bit Error Probability

Since the relay selection is performed to minimize the worst case PEP for the two-way of transmission, PEP conditioned on the channel coefficients can be upper-bounded by

$$P(l_1 \rightarrow \hat{l}_1 | \mathbf{h}^{S_1 R_\lambda}, \mathbf{h}^{R_\lambda S_2}) < Q\left(\sqrt{\gamma_{S_1 R_\lambda S_2}}\right) \qquad (9)$$

where $\gamma_{S_1 R_\lambda S_2} = \max_{i=1,...,K} \min\left\{\gamma^{min}_{S_1 R_i S_2}, \gamma^{min}_{S_2 R_i S_1}\right\}$. Averaging (9) over $\mathbf{h}^{S_1 R_\lambda}$ and $\mathbf{h}^{R_\lambda S_2}$ and using [14, (32)], the unconditional PEP upper-bound is obtained as

$$P(l_1 \rightarrow \hat{l}_1) < \frac{1}{2}\sqrt{\frac{1}{2\pi}} \int_0^\infty \frac{1}{\sqrt{x}} e^{-\frac{x}{2}} F_{\gamma_{S_1 R_\lambda S_2}}(x) dx \qquad (10)$$

where $F_{\gamma_{S_1 R_\lambda S_2}}(x)$ is the cumulative distribution function (CDF) of $\gamma_{S_1 R_\lambda S_2}$.

Using (10), an upper bound on the average BEP is given by the well-known union bound as

$$P_b < \frac{1}{N_T \log_2 N_T} \sum_{l_1=1}^{N_T} \sum_{\hat{l}_1=1}^{N_T} P(l_1 \rightarrow \hat{l}_1) N(l_1, \hat{l}_1) \qquad (11)$$

where $N(l_1, \hat{l}_1)$ stands for the number of bits in error for the corresponding pairwise error event. It should be also noted that since we assume the same configuration at both nodes, this upper-bound expression is valid for the two-way of the transmission.

$\gamma_{S_1 R_i}$ is distributed with exponential distribution and its CDF is given by $F_{\gamma_{S_1 R_i}}(x) = 1 - e^{\frac{-x}{P_{S_1}}}$ where $P_{S_1} = \frac{E_{S_1}}{N_0}$. Moreover, $\gamma_{R_i S_2}$ follows chi-square distribution with the $2N_T$ degrees of freedom. Hence, the PDF of $\gamma_{R_i S_2}$ can be written as [6], [8] $f_{\gamma_{R_i S_2}}(x) = \frac{x^{N_T - 1} e^{-\frac{x}{P_R}}}{(P_R)^{N_T} \Gamma(N_T)}$ where $P_R = \frac{E_R}{N_0}$ and $\Gamma(.)$ is the Gamma function [15, (8.310.1)]. Using the CDF of $\gamma_{S_1 R_i}$ and the PDF of $\gamma_{R_i S_2}$, the CDF of $\gamma_{S_1 R_\lambda S_2}$ $\left(F_{\gamma_{S_1 R_\lambda S_2}}(x)\right)$ can be expressed as [6], [8]

$$F_{\gamma_{S_1 R_\lambda S_2}}(x) = \int_0^\infty F_{\gamma_{S_1 R_i}}\left(\left(\frac{u+C}{u}\right)x\right) f_{\gamma_{R_i S_2}}(u) du. \qquad (12)$$

By substituting $F_{\gamma_{S_1 R_i}}(x)$ and $f_{\gamma_{R_i S_2}}(x)$ into (12) and evaluating the integral using [15, (3.381.4)] and [15, (3.471.9)], $F_{\gamma_{S_1 R_\lambda S_2}}(x)$ can be written as

$$F_{\gamma_{S_1 R_\lambda S_2}}(x) = 1 - \frac{2e^{-\frac{x}{P_{S_1}}}}{\Gamma(N_T)} \left(\sqrt{\beta x}\right)^{N_T} K_{N_T}\left(2\sqrt{\beta x}\right) \qquad (13)$$

where $\beta = C/P_{S_1} P_R$ and $K_v(u)$ is the vth order modified Bessel funciton of the second kind [15, (8.432.1)]. Since the $\gamma^{min}_{S_1 R_i S_2}$ is the minimum among $\binom{N_T}{2}$ random variables for the pairwise transmit antenna elements, the CDF of $\gamma^{min}_{S_1 R_i S_2}$ can be given by using order statistics [16, (2.1.2)] as

$$F_{\gamma^{min}_{S_1 R_i S_2}}(x) = 1 - \left[\frac{2e^{-\frac{x}{P_{S_1}}}}{\Gamma(N_T)} \left(\sqrt{\beta x}\right)^{N_T} K_{N_T}\left(2\sqrt{\beta x}\right)\right]^{\binom{N_T}{2}}. \qquad (14)$$

Since we define $\gamma_{S_1 R_\lambda S_2}$ as $\gamma_{S_1 R_\lambda S_2} = \max_{i=1,...,K} \min\left\{\gamma^{min}_{S_1 R_i S_2}, \gamma^{min}_{S_2 R_i S_1}\right\}$ where $\gamma^{min}_{S_1 R_i S_2}$ and $\gamma^{min}_{S_2 R_i S_1}$ follow the same distribution, the CDF of $\gamma_{S_1 R_\lambda S_2}$ can be given as [16, (2.1.2) and (2.1.1)]

$$F_{\gamma_{S_1 R_\lambda S_2}}(x) = \left[1 - \left(\frac{2e^{-\frac{x}{P_{S_1}}}}{\Gamma(N_T)}(\beta x)^{\frac{N_T}{2}} K_{N_T}\left(2\sqrt{\beta x}\right)\right)^{2\binom{N_T}{2}}\right]^K. \qquad (15)$$

By substituting (10) and (15) into (11) and evaluating the integral numerically, an upper-bound to average BEP of the system can be obtained. For the ease of brevity, we assume that $E_{S_1} = E_{S_2}$ and all the relays have the same power. It is also important to note that the derived analytical upper-bound is valid for each way of the transmission since S_1-R_i-S_2 and S_2-R_i-S_1 links have the same properties.

B. Asymptotic Expression For Bit Error Probability

By using the Taylor series expression [15, (1.211.1)] and the definition of the modified Bessel function of the second kind [15, (8.446)], the CDF of $\gamma_{S_1 R_\lambda S_2}$ given in (15) can be written for high signal-to-noise ratio (SNR) values ($P_{S_1} >> 1$) as

$$F_{\gamma_{S_1 R_\lambda S_2}}(x) = x^K \left[2\binom{N_T}{2}\right]^K \left[\frac{\beta}{N_T - 1} + \frac{1}{P_{S_1}}\right]^K + \text{HOT} \qquad (16)$$

where HOT stands for the higher order terms. By substituting (16) into (10) and using [15, (3.381.4)], a closed-form asymptotic PEP expression for the derived upper-bound can be obtained as

$$P(l_1 \rightarrow \hat{l}_1) < \frac{2^{2K-1}}{\sqrt{\pi}} \left[\binom{N_T}{2}\left(\frac{\beta}{N_T - 1} + \frac{1}{P_{S_1}}\right)\right]^K + \Gamma\left[K + \frac{1}{2}\right]. \qquad (17)$$

By substituting (10) and (17) into (11), a closed-form asymptotic BEP expression for the derived upper-bound can be obtained. As can easily be seen from (17), the diversity order of the system is K.

IV. NUMERICAL RESULTS

In this section, theoretical upper-bound and asymptotic expressions given in the previous section are validated through computer simulations. We provide bit error rate (BER) results for the proposed two-way MIMO-SSK system. The BER results are plotted as a function of E_T/N_0 where $E_T = E_{S_1} + E_{S_2} + E_R$. For simplicity, we assume $E_{S_1} = E_{S_2} = E_R$. In the figures, $(N_T, K/1, N_T)$ stands for the proposed two-way MIMO-SSK system, where N_T transmit and receive antennas are available at the sources for the SSK system and one relay is selected among K relays.

Fig 2 depicts the BER performance of the proposed SSK system $(N_T, K/1, N_T)$ for $N_T \in \{2, 4, 8\}$ and $K \in \{4, 6\}$. As can be observed from Fig. 2, the theoretical upper-bound results match with the computer simulation results and the asymptotic BER curves derived in the previous section approaches to the upper-bound curves at high SNR values. According to the asymptotic analysis, the asymptotic diversity orders
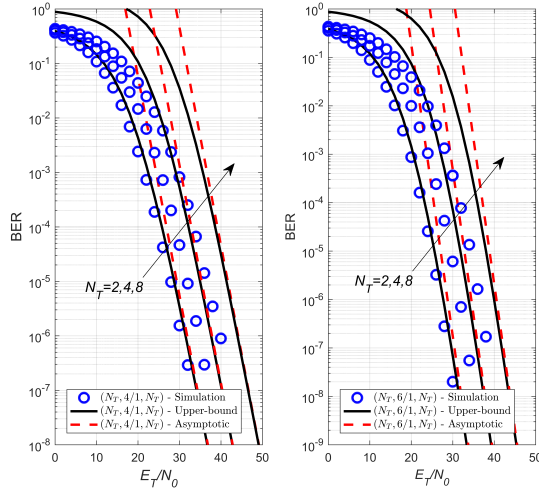
Fig. 2. The BER performance of the proposed two-way MIMO-SSK system for $N_T \in \{2, 4, 8\}$ amd $K \in \{4, 6\}$.
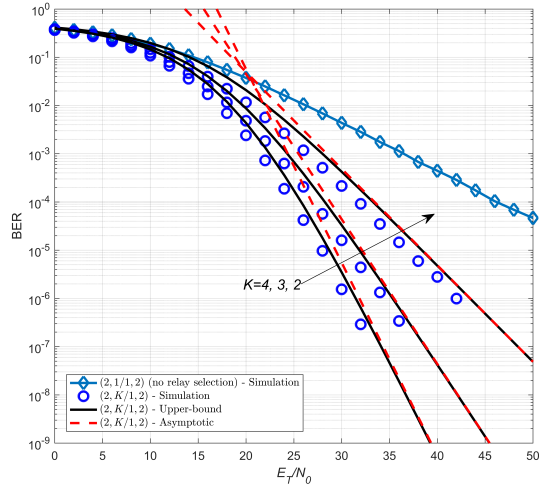

Fig. 3. The BER performance comparison of the proposed two-way MIMO-SSK system $(2, K/1, 2)$ with the conventional two-way MIMO-SSK system $(2, 1/1, 2)$ for $K \in \{2, 3, 4\}$.

of the curves corresponding to the proposed SSK systems is equal to the number of relays (K) in the system. It can be observed from the slopes of the BER curves given in Fig. 2 that the asymptotic BER results are consistent with the computer simulation results.

Fig. 3 compares the BER performance of the proposed two-way SSK system with the conventional two-way SSK system without relay selection. In Fig. 3, the BER of the proposed SSK system $(2, K/1, 2)$ is given for $K \in \{2, 3, 4\}$. Here, the system $(2, 1/1, 2)$ (no relay selection) corresponds to the conventional two-way SSK system without relay selection. As seen from Fig. 3, the proposed system considerably outperforms the two-way SSK system without relay selection by introducing additional diversity gain to the system. Moreover, the theoretical upper-bound and asymptotic results match with the simulation results and the derived upper-bound is suffi-

ciently tight for the BER performance of the proposed system. According to the asymptotic analysis, the asymptotic diversity orders of the curves corresponding to the proposed SSK systems for $K = 1, 2, 3$ and 4 are calculated as $K = 1, 2, 3$ and 4, respectively. It can be verified from the slopes of the BER curves given in Fig. 3 that these values are consistent with the computer simulation results.

V. CONCLUSION

In this paper, we have proposed a two-way MIMO-SSK scheme with relay selection. In this scheme, we have considered SSK modulation at the sources of a two-way network employing AF relaying. Upper-bound and asymptotic expressions have been derived for the proposed system. Furthermore, the proposed scheme has been compared with a conventional two-way SSK scheme and it has been observed that the proposed SSK scheme outperforms the conventional schemes. Our results have demonstrated that SSK is a promising technique with its simple transceiver structure and considerable error performance for next generation two-way networks.

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