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Space Shift Keying with Full Duplex Amplify and Forward Relaying

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***Abstract*—In this paper, we investigate the error performance of space-shift-keying (SSK) with full-duplex (FD) amplify-and-forward (AF) relaying over Rayleigh fading channels in the presence of residual loop interference. In the proposed system, the source and destination nodes are equipped with multiple antennas, while the relay node has a single transmit and receive antenna. An upper-bound for the bit error rate (BER) expression of the system is derived in a closed-form. The accuracy of the analytical results are validated via Monte Carlo type computer simulations. It is revealed that SSK with FD-AF relaying as a spectrum-efficient transmission scheme provides considerable error performance improvement in comparison with the conventional SSK with half-duplex (HD) AF relaying, especially for higher spectral efficiency values.**

I. Introduction

Spatial modulation (SM), as a promising technique for multiple-input multiple-output (MIMO) systems, uses the spatial domain to convey information bits in addition to the conventional amplitude and phase modulation (APM) [1]. In SM, the information bits regarding the spatial domain are carried by the transmit antenna indices via activating a single transmit antenna. Therefore, the requirement of multiple transmit radio frequency (RF) chains is relaxed in SM technique. Moreover, it is shown that SM with the optimum maximum likelihood (ML) detection provides error performance gains over popular MIMO techniques, e.g., V-BLAST architecture [2]. These properties of SM make it a strong candidate for next-generation wireless systems [3]. In space-shift-keying (SSK), as a special case of SM, all the information bits are conveyed via the transmit antenna indices by using a carrier with constant parameters at the receiver (e.g., $+1$ in baseband) instead of APM signals [4]. SSK technique guarantees almost identical error performance with SM as well as its lower complexity detection algorithm [4].

Cooperative communications, which provides coverage and capacity enhancement with the help of the relay nodes, has gained great attention in the past years [5]. There are two fundamental transmission protocols in cooperative networks as amplify-and-forward (AF) relaying and decode-and-forward (DF) relaying. SM/SSK techniques are also investigated in relay assisted cooperative networks with either single or multiple relay nodes [6]–[9]. In spite of the performance improvement due to the additional relay node, total transmission time increases when the conventional half-duplex (HD) relaying is used. Thus, the spectral efficiency of the cooperative systems decreases compared to the non-cooperative schemes. In order to utilize the relay nodes without the cost of the total transmission time, full-duplex (FD) transmission can be employed at the relays. Although FD communications is severely affected from the loop-interference (LI) at the receiver antenna, the recent developments on antenna technology and signal processing techniques make it a feasible solution [10], [11]. The experimental studies given in [12] indicate that approximately 74 dB cancellation can be achieved by several cancellation processes. However, LI cannot be completely removed and the remaining residual LI limits the performance of FD communications.

In the literature, there are two different studies that analyze SM technique with FD-DF relaying. In the first study, the FD relay node decodes the received signal from the source node and simultaneously retransmit the recovered information bits to the destination by using SM technique [13]. In [14], the performance of two-way FD-DF relaying is investigated where all source and relay nodes use SM technique and operates in FD mode. Moreover, the performance comparison between two-way FD-DF and two-way HD-DF relaying systems using SM techniques demonstrates that FD transmission provides a significant performance improvement.

To the best of authors' knowledge, this is the first attempt to analyze the performance of SSK with FD-AF relaying. The proposed scheme is called as SSK-FD-AF in the rest of the paper. The error performance of the SSK-FD-AF system over Rayleigh fading channels is investigated and an upper-bound for its bit error rate (BER) expression is derived in a closed-form. The theoretical analyses are verified by Monte Carlo type computer simulations. We observe that SSK-FD-AF systems outperform the conventional SSK with HD-AF relaying (SSK-HD-AF) systems as long as the efficiency of LI cancellation process improves and/or the spectral efficiency increases.

The rest of the paper is organized as follows. The system model and residual LI channel model of SSK-FD-AF system is introduced in Section II. In Section III, the BER expression of the proposed system is derived by using well known union-bound technique.The accuracy of analytical results are validated by computer simulations in Section IV. Finally, conclusions are presented in Section V.

Notation: Bold lower case letters denote vectors. $(\cdot)^T$ and $\|\cdot\|$ represents the transpose and the Frobenius

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norm of a vector, respectively. We use $\mathcal{CN}\left(0,\sigma^2\right)$ for the complex Gaussian random distribution consisting of independently Gaussian distributed $\mathcal{N}\left(0,\sigma^2/2\right)$ real and imaginary parts with zero-mean and $\sigma^2/2$ variance. $\Re\left[\cdot\right]$, $\mathrm{E}\left[\cdot\right]$ and $\mathrm{Var}\left[\cdot\right]$ stand for the real part, expectation and variance operators, respectively. $f_x\left(\cdot\right)$ and $F_x\left(\cdot\right)$ are the probability density function (PDF) and the cumulative distribution function (CDF) of a random variable (r.v.) x. $Q\left(y\right) = \left(1/\sqrt{2\pi}\right)\int_y^{\infty}\exp\left(-t^2/2\right)dt$ is the Q-function.

II. System Model

A. SSK-FD-AF Transmission

We consider a dual-hop one-way transmission scheme for the SSK-FD-AF system as shown in Fig. 1. As seen from the system model, the source node (S) has N_T transmit antennas and the destination node (D) has N_R receive antennas. SSK transmission scheme is employed at S in order to convey $\log_2\left(N_T\right)$ information bits in each symbol period. We assume that the direct link between S and D is strongly attenuated. Therefore, the communication between them can be established only via the relay node (R) consisting of single transmit and receive antenna. R operates in FD mode and uses the AF protocol to retransmit the received signal to D.

The received signal at R for time-slot n is given by

$$r\left[n\right] = \sqrt{P_S}\mathbf{h}_{SR}\mathbf{x}\left[n\right] + h_{LI}s\left[n\right] + w_R\left[n\right] \tag{1}$$

where P_S is the transmission power of S, $\mathbf{x}\left[n\right]$ is the $N_T\times 1$ deterministic unit power signal vector transmitted from S, $s\left[n\right]$ is the transmitted signal from R, $\mathbf{h}_{SR}$ is the $1\times N_T$ channel coefficient vector between S and R, h_{LI} is the residual LI channel coefficient at R and $w_R\left[n\right]$ is the additive white Gaussian noise (AWGN) signal. The entries of $\mathbf{h}_{SR}$ are independent and identically distributed (i.i.d.) according to $\mathcal{CN}\left(0,\Omega_{SR}\right)$. Similarly, h_{LI} and $w_R\left[n\right]$ are respectively distributed as $h_{LI}\sim\mathcal{CN}\left(0,\Omega_{LI}\right)$ and $w_R\left[n\right]\sim\mathcal{CN}\left(0,\sigma_R^2\right)$. The transmitted signal from S can be given by

$$\mathbf{x}\left[n\right] = [0 \ \cdots \ 0 \ \underbrace{1}_{k[n]^{\text{th}}\text{ position}} \ 0 \ \cdots \ 0]^T \tag{2}$$

where $k\left[n\right]\in\left\{1,2,\cdots,N_T\right\}$ is the index of the selected transmit antenna for time-slot n. By combining (1) and (2), the received signal at R can be rewritten as

$$r\left[n\right] = \sqrt{P_S}h_{SR}^{k[n]} + h_{LI}s\left[n\right] + w_R\left[n\right] \tag{3}$$

where $h_{SR}^{k[n]}$ is the $k\left[n\right]^{\text{th}}$ entry of $\mathbf{h}_{SR}$. According to the AF protocol, the transmitted signal from R is given by

$$s\left[n\right] = G_{AF}r\left[n-1\right] = G_{AF}\sum_{b=0}^{\infty}\left(G_{AF}h_{LI}\right)^b g\left[n-b\right] \tag{4}$$

where G_{AF} denotes the fixed amplification gain and $g\left[n\right] = \sqrt{P_S}h_{SR}^{k[n-1]} + w_R\left[n-1\right]$. In order to guarantee finite relay transmit power and prevent oscillations, the relay gain must be limited by $\left|h_{LI}\right|^2 < 1/G_{AF}^2$ [15]. Otherwise, the power of residual LI goes to infinity. When the gain condition is

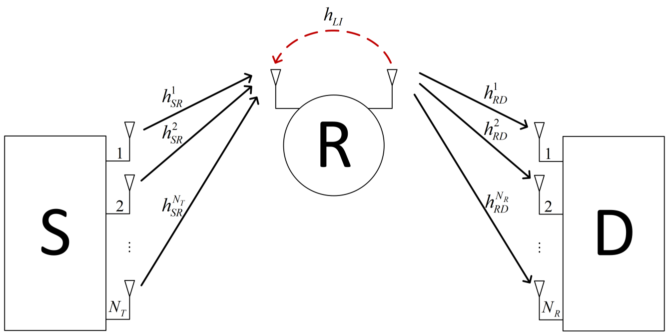

Fig. 1. SSK-FD-AF system model.

satisfied, the average transmission power at R for a given h_{LI} is obtained as [15, Eq. (5)]

$$\begin{aligned}\mathrm{E}\Big[\left|s[n]\right|^2\Big|h_{LI}\Big] &= G_{AF}^2\left(P_S\Omega_{SR}+\sigma_R^2\right)\sum_{b=0}^{\infty}\left(G_{AF}^2\left|h_{LI}\right|^2\right)^b \\ &= \frac{P_S\Omega_{SR}+\sigma_R^2}{\frac{1}{G_{AF}^2}-\left|h_{LI}\right|^2}.\end{aligned} \tag{5}$$

The fixed gain FD-AF systems are analyzed in [16], where the fixed amplification gain is set to

$$G_{AF} = \sqrt{\frac{P_R}{P_S\Omega_{SR}+P_R\Omega_{LI}+\sigma_R^2}} \tag{6}$$

in order to adjust the average transmission power at R to P_R. One can easily show that the average transmission power at R is equal to

$$\mathrm{E}\Big[\left|s\left[n\right]\right|^2\Big] = \mathrm{E}\left[\frac{P_S\Omega_{SR}+\sigma_R^2}{\frac{1}{G_{AF}^2}-\left|h_{LI}\right|^2}\right] = \frac{P_S\Omega_{SR}+\sigma_R^2}{\frac{1}{G_{AF}^2}-\Omega_{LI}} = P_R. \tag{7}$$

Afterwards, the received signal vector at D is given by

$$\begin{aligned}\mathbf{y}[n] &= \mathbf{h}_{RD}s\left[n\right] + \mathbf{w}_D\left[n\right] \\ &= \underbrace{G_{AF}\sqrt{P_S}h_{SR}^{k[n-1]}\mathbf{h}_{RD}}_{\text{Desired Signal}} + \underbrace{G_{AF}\mathbf{h}_{RD}h_{LI}s[n-1]}_{\text{Residual Loop - Interference}} \\ &\quad + \underbrace{G_{AF}\mathbf{h}_{RD}w_R\left[n-1\right] + \mathbf{w}_D\left[n\right]}_{\text{Noise}}\end{aligned} \tag{8}$$

where $\mathbf{h}_{RD}$ denotes the $N_R\times 1$ channel coefficient vector and $\mathbf{w}_D\left[n\right]$ represents the AWGN signal vector at D. The entries of $\mathbf{h}_{RD}$ and $\mathbf{w}_D\left[n\right]$ are i.i.d. according to $\mathcal{CN}\left(0,\Omega_{RD}\right)$ and $\mathcal{CN}\left(0,\sigma_D^2\right)$, respectively. For given $\mathbf{h}_{SR}$ and $\mathbf{h}_{RD}$, the expected value and variance of the complex Gaussian distributed $\mathbf{y}\left[n\right]$ are respectively given by

$$\begin{aligned}\mathrm{E}[\mathbf{y}[n]|\mathbf{h}_{SR},\mathbf{h}_{RD}] &= G_{AF}\sqrt{P_S}h_{SR}^{k[n-1]}\mathbf{h}_{RD}, \\ \mathrm{Var}[\mathbf{y}[n]|\mathbf{h}_{SR},\mathbf{h}_{RD}] &= G_{AF}^2\left\|\mathbf{h}_{RD}\right\|^2\left[\Omega_{LI}P_R+\sigma_R^2\right]+\sigma_D^2.\end{aligned} \tag{9}$$

For the detection rule, we have omitted the time-slot index n for brevity. Therefore, the optimum ML detection rule of the SSK-FD-AF system can be given by

$$\hat{k} = \arg\min_{1\le b\le N_T}\left\|\mathbf{y} - G_{AF}\sqrt{P_S}h_{SR}^{b}\mathbf{h}_{RD}\right\|^2 \tag{10}$$

where $\hat{k}$ is the determined transmit antenna index.

B. Residual LI Channel Model

The experimental results shows that the quality of LI cancellation is improved as long as the transmission power increases [12]. Therefore, the power of the residual LI channel Ω_{LI} is related to P_R and it is modeled as [14]

$$\Omega_{LI} = \beta P_R^{\lambda-1} \tag{11}$$

where β and λ are the constants that reflects the quality of LI cancellation ($0 \leq \lambda \leq 1$). By using (1), (7) and (11), the average LI power at R is found as $\mathrm{E}\left[|h_{LI}s\left[n\right]|^2\right] = \beta P_R^{\lambda}$. Therefore, the error performance of SSK-FD-AF system can be improved for the lower values of β and λ. Although $\lambda = 0$ is the optimistic case for FD transmission, it could be decreased to around 0.2 after cancellation processes [12].

C. Spectral Efficiency of SSK-FD-AF and SSK-HD-AF

The transmission from S to D can be accomplished in one time-slot in SSK-FD-AF systems as expressed in the previous section. However, it can be completed in two time-slots with the conventional SSK-HD-AF systems, i.e., R listens the signal transmitted by S in the first time-slot and retransmits it to D in the second time-slot [6]. Thus, the spectral efficiency expressions of SSK-FD-AF and SSK-HD-AF systems are respectively given by

$$\begin{aligned} \eta_{FD} &= \log_2\left(N_T\right), \\ \eta_{HD} &= \frac{1}{2}\log_2\left(N_T\right) \end{aligned} \tag{12}$$

which means the number of transmit antennas in SSK-HD-AF systems should be as many as the square of the transmit antennas in SSK-FD-AF systems in order to achieve the same spectral efficiency.

III. BER Performance

In this section, an upper-bound for the BER performance of SSK-FD-AF systems is derived by using pairwise error probability (PEP) approach. By taking into consideration the gain condition defined in Section II-A, similar to [16, Eq. (8)], PEP expression of SSK-FD-AF system can be written in terms of conditional PEP (CPEP) expressions and given by

$$\begin{aligned} P\left(k \to \hat{k}\right) = F_{\gamma_{LI}}\left(C\right)P\left(k \to \hat{k}\middle|\,\gamma_{LI} < C\right) \\ + \bar{F}_{\gamma_{LI}}\left(C\right)P\left(k \to \hat{k}\middle|\,\gamma_{LI} \geq C\right) \end{aligned} \tag{13}$$

where $\gamma_{LI} = P_R|h_{LI}|^2/\sigma_R^2$, $\bar{\gamma}_{LI} = P_R\Omega_{LI}/\sigma_R^2$, $F_{\gamma_{LI}}\left(x\right) = 1 - \exp\left(-x/\bar{\gamma}_{LI}\right)$, $\bar{F}_{\gamma_{LI}}\left(\cdot\right) = 1 - F_{\gamma_{LI}}\left(\cdot\right)$, and $C = P_R/G_{AF}^2\sigma_R^2$. When $\gamma_{LI} \geq C$ (i.e., $|h_{LI}|^2 \geq 1/G_{AF}^2$), the gain condition does not satisfied and the power of the interference signal goes to infinity. Consequently, the received signal at D is purely random and $P\left(k \to \hat{k}|\gamma_{LI} \geq C\right) = \frac{1}{N_T}$. So, PEP can be rewritten as

$$P\!\left(k\!\to\!\hat{k}\right)\!=\!\left[1\!-\!\exp\!\left(\frac{-C}{\bar{\gamma}_{LI}}\right)\right]\!\left[P\!\left(k\!\to\!\hat{k}\middle|\gamma_{LI}\!<\!C\right)\!+\!\frac{1}{N_T}\right]\!+\!\frac{1}{N_T}. \tag{14}$$

In order to calculate PEP, it is required to obtain the CPEP of SSK-FD-AF system for given $\mathbf{h}_{SR}$ and $\mathbf{h}_{RD}$ when $\gamma_{LI} < C$ as follows

$$\begin{aligned} &P\left(k \to \hat{k}\middle|\,\mathbf{h}_{SR}, \mathbf{h}_{RD}, \gamma_{LI} < C\right) \\ &\quad= P\bigg\{\left\|\mathbf{y}\!-\!G_{AF}\sqrt{P_S}h_{SR}^{k}\mathbf{h}_{RD}\right\|^2 \\ &\qquad \geq \left\|\mathbf{y}\!-\!G_{AF}\sqrt{P_S}h_{SR}^{\hat{k}}\mathbf{h}_{RD}\right\|^2\bigg\} \\ &\quad= P\Big\{G_{AF}\sqrt{P_S}\|\mathbf{h}_{RD}\|^2\left(\left|h_{SR}^{k}\right|^2\!-\!\left|h_{SR}^{\hat{k}}\right|^2\right) \\ &\qquad -2\Re\left[\left(h_{SR}^{k} - h_{SR}^{\hat{k}}\right)\mathbf{y}^H\mathbf{h}_{RD}\right] \geq 0\Big\} \!=\! P(\xi \geq 0) \end{aligned} \tag{15}$$

where ξ is a Gaussian distributed r.v. with the expected value and variance as

$$\begin{aligned} &\mathrm{E}[\xi|\mathbf{h}_{SR},\mathbf{h}_{RD},\gamma_{LI}\!<\!C] \!=\! -G_{AF}\sqrt{P_S}\|\mathbf{h}_{RD}\|^2\big|h_{SR}^{k}\!-\!h_{SR}^{\hat{k}}\big|^2, \\ &\mathrm{Var}[\xi|\mathbf{h}_{SR},\mathbf{h}_{RD},\gamma_{LI}\!<\!C] \!=\! 2\left|h_{SR}^{k} - h_{SR}^{\hat{k}}\right|^2\|\mathbf{h}_{RD}\|^2 \\ &\qquad \times\left(\frac{P_R\|\mathbf{h}_{RD}\|^2}{D} + \sigma_D^2\right) \end{aligned} \tag{16}$$

where $D = \frac{P_R}{G_{AF}^2\left(\Omega_{LI}P_R+\sigma_R^2\right)}$. Therefore, CPEP expression given in (15) can be rewritten as

$$P\left(k \to \hat{k}\middle|\,\mathbf{h}_{SR}, \mathbf{h}_{RD}, \gamma_{LI} < C\right) \!=\! Q\left(\sqrt{\frac{\gamma_{SR}^{k\to\hat{k}}\gamma_{RD}}{\gamma_{RD} + D}}\right) \tag{17}$$

where $\gamma_{SR}^{k\to\hat{k}} = \frac{P_S\left|h_{SR}^{k}-h_{SR}^{\hat{k}}\right|^2}{2\left(\Omega_{LI}P_R+\sigma_R^2\right)}$ and $\gamma_{RD} = \frac{P_R\|\mathbf{h}_{RD}\|^2}{\sigma_D^2}$. It is important to note that $\gamma_{SR}^{k\to\hat{k}}$ and γ_{RD} follow exponential and chi-square distributions, respectively. Therefore, their PDF expressions are given as $f_{\gamma_{SR}^{k\to\hat{k}}}\left(x\right) = \frac{\exp(-x/\bar{\gamma}_{SR})}{\bar{\gamma}_{SR}}$ and $f_{\gamma_{RD}}\left(x\right) = \frac{x^{N_R-1}\exp(-x/\bar{\gamma}_{RD})}{\Gamma(N_R)\bar{\gamma}_{RD}^{N_R}}$ where $\bar{\gamma}_{SR} = \frac{P_S\Omega_{SR}}{\left(\Omega_{LI}P_R+\sigma_R^2\right)}$ and $\bar{\gamma}_{RD} = \frac{P_R\Omega_{RD}}{\sigma_D^2}$. By defining, $\gamma_{SRD}^{k\to\hat{k}} = \gamma_{SR}^{k\to\hat{k}}\gamma_{RD}/\left(\gamma_{RD} + D\right)$, integrating the above CPEP expression over the PDF of $\gamma_{SRD}^{k\to\hat{k}}$ and using [17, Eq. (32)], the required CPEP expression in (14) can be obtained as

$$\begin{aligned} P\!\left(k\!\to\!\hat{k}\middle|\gamma_{LI}\!<\!C\right) &= \int_{x=0}^{\infty} Q\left(\sqrt{x}\right)f_{\gamma_{SRD}^{k\to\hat{k}}}\left(x\right)dx \\ &= \frac{1}{2\sqrt{2\pi}}\int_{x=0}^{\infty}\frac{\exp\left(-x/2\right)}{\sqrt{x}}F_{\gamma_{SRD}^{k\to\hat{k}}}(x)dx. \end{aligned} \tag{18}$$

Then, the CDF of $\gamma_{SRD}^{k\to\hat{k}}$ can be obtained as follows

$$\begin{aligned} F_{\gamma_{SRD}^{k\to\hat{k}}}\left(x\right) &= P\left(\frac{\gamma_{SR}^{k\to\hat{k}}\gamma_{RD}}{\gamma_{RD} + D} \leq x\right) = 1 - \frac{\exp\left(-x/\bar{\gamma}_{SR}\right)}{\Gamma\left(N_R\right)\bar{\gamma}_{RD}^{N_R}} \\ &\quad \times \int_{y=0}^{\infty} y^{N_R-1}\exp\left(-\frac{y}{\bar{\gamma}_{RD}} - \frac{xD}{y\bar{\gamma}_{SR}}\right)dy. \end{aligned} \tag{19}$$

By applying [18, Eq. (3.471.9)], the above integration can be solved and the CDF of $\gamma_{SRD}^{k\to\hat{k}}$ is found as

$$F_{\gamma_{SRD}^{k\to\hat{k}}}\left(x\right) = 1 - \frac{2\left(x\mu\right)^{N_R/2}}{\Gamma\left(N_R\right)\exp\left(x/\bar{\gamma}_{SR}\right)}K_{N_R}\left(2\sqrt{x\mu}\right) \tag{20}$$

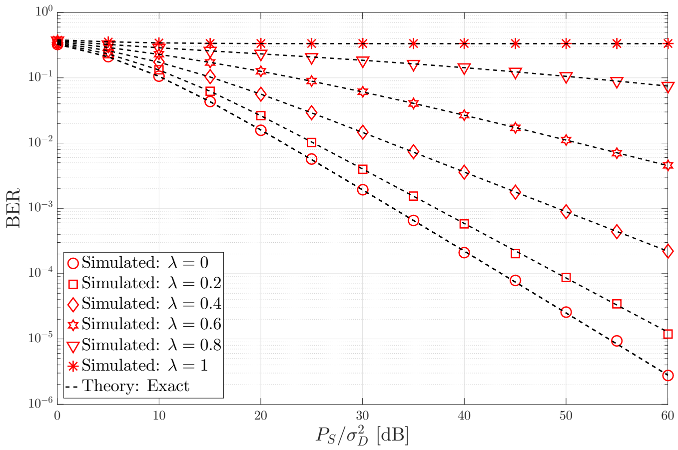

Fig. 2. BER performance of SSK-FD-AF systems versus P_S/σ_D^2 for different values of λ where $\eta = 1$ [bit/s/Hz], $N_T = 2$, $N_R = 1$, $P_R = 4P_S$ and $\beta = 0$ dB.

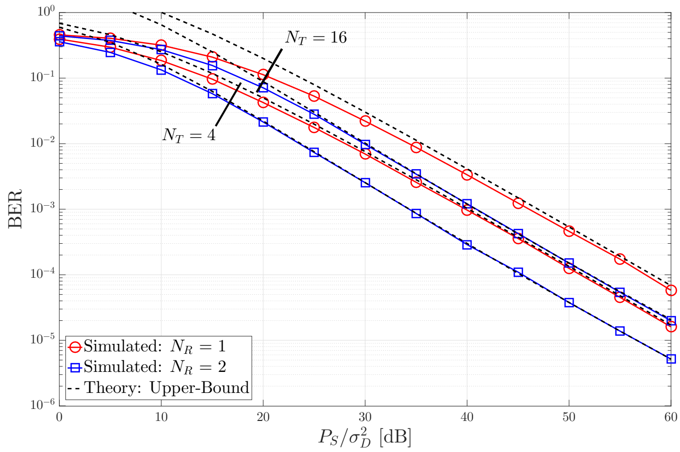

Fig. 3. BER performance of SSK-FD-AF systems versus P_S/σ_D^2 for $N_R \in \{1, 2\}$ where $\eta \in \{2, 4\}$ [bits/s/Hz], $N_T \in \{4, 16\}$, $P_R = P_S$, $\lambda = 0.25$ and $\beta = -10$ dB.

where $\mu = D/\left(\bar{\gamma}_{SR}\bar{\gamma}_{RD}\right)$ and $K_{N_R}(\cdot)$ is the N_R^{th} order modified Bessel function of second kind [18, Eq. (8.407.1)]. By substituting (20) into (18), we can write

$$P\left(k\to\hat{k}\middle|\,\gamma_{LI}<C\right)=\frac{1}{2}-\frac{\mu^{N_R/2}}{\sqrt{2\pi}\Gamma\left(N_R\right)}\times\int_0^\infty\frac{x^{(N_R-1)/2}K_{N_R}\left(2\sqrt{x\mu}\right)}{\exp\left(\omega x\right)}dx \tag{21}$$

where $\omega = 0.5 + 1/\bar{\gamma}_{SR}$. By using [18, Eq. (6.643.3)], the required CPEP expression is derived as

$$P\left(k\to\hat{k}\middle|\,\gamma_{LI}<C\right)=\frac{1}{2}-\frac{(\mu/\omega)^{N_R/2}\,\Gamma\!\left(N_R+\frac{1}{2}\right)}{2\sqrt{2\mu}\Gamma\left(N_R\right)}\times\exp\left(\frac{\mu}{2\omega}\right)W_{-\frac{N_R}{2},\frac{N_R}{2}}\!\left(\frac{\mu}{\omega}\right) \tag{22}$$

where $W_{\cdot,\cdot}(\cdot)$ is the Whittaker function [18, Eq. (9.220.4)]. Finally, by combining (14) and (22), the PEP expression of the SSK-FD-AF system can be found as

$$P\!\left(k\to\hat{k}\right)=\left[1-\exp\left(\frac{-C}{\bar{\gamma}_{LI}}\right)\right]\!\left[\frac{1}{2}-\frac{(\mu/\omega)^{N_R/2}\,\Gamma\!\left(N_R+\frac{1}{2}\right)}{2\sqrt{2\mu}\,\Gamma\!\left(N_R\right)}\times\exp\left(\frac{\mu}{2\omega}\right)W_{-\frac{N_R}{2},\frac{N_R}{2}}\!\left(\frac{\mu}{\omega}\right)+\frac{1}{N_T}\right]+\frac{1}{N_T}. \tag{23}$$

At the last step, the BER expression of SSK-FD-AF system obtained via the union bound technique [2] is given by

$$P_b\leq\sum_{k=1}^{N_t}\sum_{\hat{k}=1}^{N_t}\frac{N\!\left(k,\hat{k}\right)P\left(k\to\hat{k}\right)}{\log_2\left(N_T\right)N_T} \tag{24}$$

where $N\!\left(k,\hat{k}\right)$ represents the number of bit errors associated with the corresponding pairwise error event. It is worth to mention that the above expression is equal to the exact BER of SSK-FD-AF system for $N_T = 2$ and it is the upper-bound BER expression for $N_T > 2$. Furthermore, the derived BER expression for SSK-FD-AF systems are also valid for SSK-HD-AF systems by letting $\beta = 0$ in (11).

IV. Numerical Results

Theoretical and Monte Carlo simulation results for the BER performance of SSK-FD-AF systems over Rayleigh fading channels are represented throughout this section. The accuracy of the theoretical analysis is validated by different computer simulation scenarios. Moreover, the BER performance of SSK-FD-AF systems are compared with the conventional SSK-HD-AF systems. During the numerical analyses, we assume that $\Omega_{SR} = \Omega_{RD} = 1$ and $\sigma_D^2 = \sigma_R^2$.

Fig. 2 demonstrates the BER performance of SSK-FD-AF systems versus P_S/σ_D^2 for $\lambda \in \{0, 0.2, 0.4, 0.6, 0.8, 1\}$, where $\eta = 1$ [bit/s/Hz], $N_T = 2$, $N_R = 1$, $P_R = 4P_S$ and $\beta = 0$ dB. It is shown that the exact theoretical results obtained from (24) are perfectly matched with the computer simulations, which proves the correctness of our analysis. As seen from the curves, the BER of SSK-FD-AF systems takes lower values as long as the values of λ decrease, i.e., the efficiency of LI cancellation process increases. For instance, there is 5.5 dB difference for $\lambda = 0$ and $\lambda = 0.2$ at a BER value of 10^{-4}.

The BER performance of SSK-FD-AF systems versus P_S/σ_D^2 for different values of N_R is plotted in Fig. 3. Here, we assume that $\eta \in \{2, 4\}$ [bits/s/Hz], $N_T \in \{4, 16\}$, $P_R = P_S$, $\lambda = 0.25$ and $\beta = -10$ dB. It is observed that the computer simulation results are tightly upper-bounded by the theoretical results, especially for higher values of P_S/σ_D^2. Additionally, we show that the the increase of number of receive antennas at the destination (N_R) provides a coding gain. To illustrate, there is approximately 5.9 dB and 5.5 dB performance improvement when N_R is increased from 1 to 2 for $N_T = 4$ and $N_T = 16$ scenarios, respectively.

In Fig. 4, the BER performance comparison between SSK-FD-AF and SSK-HD-AF systems is represented for different spectral efficiencies as $\eta \in \{1, 2, 4\}$ [bits/s/Hz] when $N_R = 1$, $P_R = P_S$, $\lambda = 0.2$ and $\beta = 0$ dB. As explained in Section II-C, the number of transmit antennas for both systems are different due to the FD and HD transmission. In order to ensure the same spectral efficiency values, $N_T \in \{2, 4, 16\}$

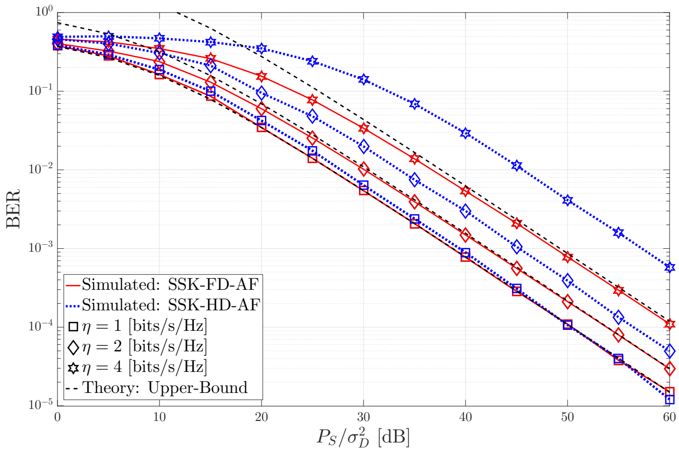

Fig. 4. BER performance comparison of SSK-FD-AF and SSK-HD-AF systems versus P_S/σ_D^2 for $\eta \in \{1, 2, 4\}$ [bits/s/Hz] where $N_R = 2$, $P_R = P_S$, $\lambda = 0.2$ and $\beta = 0$ dB.

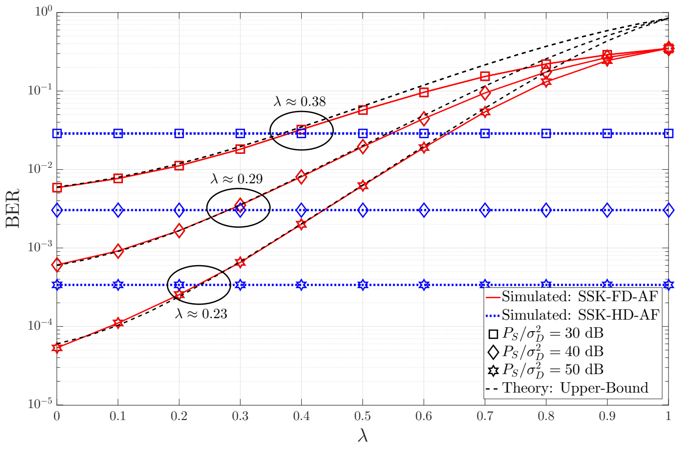

Fig. 5. BER performance comparison of SSK-FD-AF and SSK-HD-AF systems versus λ for $P_S/\sigma_D^2 \in \{30, 40, 50\}$ dB where $\eta = 3$ [bits/s/Hz], $N_R = 2$, $P_R = P_S$ and $\beta = 0$ dB.

transmit antennas are employed for SSK-FD-AF systems, while the number of transmit antennas for SSK-HD-AF systems is set to $N_T \in \{4, 16, 256\}$. Although the BER performance of both systems are close to each other for $\eta = 1$ [bit/s/Hz], SSK-FD-AF systems provide quite better performance compared to SSK-HD-AF systems considering higher spectral efficiencies. For example, the performance improvement at a BER value of 10^{-3} for the increasing values of η are respectively found as 0.7 dB, 3.2 dB and 8.5 dB. In a nutshell, it is convenient to use SSK-FD-AF systems in order to meet the higher spectral efficiency requirements.

In Fig. 5, the BER performance of SSK-FD-AF and SSK-HD-AF systems is plotted versus λ for $P_S/\sigma_D^2 \in \{30, 40, 50\}$ dB where $\eta = 3$ [bits/s/Hz], $N_R = 2$, $P_R = P_S$ and $\beta = 0$ dB. As mentioned earlier, λ is the constant representing the quality of LI cancellation, so the performance of SSK-HD-AF systems is independent from λ. It is shown that SSK-FD-AF systems can provide better BER performance according to the quality of LI cancellations.

V. Conclusions

The BER performance of SSK-FD-AF systems has been investigated over Rayleigh fading channels. An upper-bound BER expression is derived in a closed-form. Then, the accuracy of theoretical analysis has been verified by computer simulations for various scenarios. It has been shown that the BER performance of SSK-FD-AF systems is highly dependent to the quality of LI cancellation process. Moreover, we have shown that SSK-FD-AF systems perform considerably better than the conventional SSK-HD-AF systems, especially for the increasing values of spectral efficiency.

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