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# Cooperative spectrum sharing protocol using spatial modulation

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**Abstract:** In this study, a new cooperative spectrum sharing protocol based on overlay system paradigm is proposed for different relaying strategies. In the considered model, a single-antenna primary transmitter (PT) communicates with a primary receiver (PR) by the assistance of a secondary transmitter (ST) which seeks an opportunity to realise spectrum sharing by adopting spatial modulation (SM). The proposed protocol consists of two time slots. In the first time slot, primary *M*-ary modulated signal is transmitted from PT to ST and PR. ST processes the received signal according to the relaying strategy it adopts and transmits the processed signal by SM to PR and secondary receiver (SR) in the second time slot. Thanks to SM at ST, primary information is carried by conventional *M*-ary modulation whereas secondary information is conveyed by antenna indices. Therefore, the need for superposition of different users' information and power allocation at ST are avoided. Upper bounds on bit error probability according to three different relaying strategies: fixed and incremental amplify-and-forward, and selective decode-and-forward, are derived for both users. The theoretical results are supported via computer simulations and error performance comparisons with two existing reference systems are performed to show the superiority of the proposed protocol.

## 1 Introduction

Cognitive radio (CR) is an effective solution to cope with the underutilisation and scarcity of the spectrum especially when the growing demand for wireless communications and advancing technologies are taken into account. Through dynamic spectrum access, secondary *(unlicensed)* users (SUs), also called CRs, profit by exploiting frequency bands of primary *(licensed)* users (PUs) [1]. Since PUs have priority on frequency bands, SUs are able to access licensed bands under certain conditions [2]. Consequently, they must be smart devices that have the ability to recognise the environment, adapt their transmission around them, and adjust their transmission parameters such as waveforms, frequencies, access strategies etc. [3]. Three main access strategies exist: underlay, overlay and interweave. In underlay strategy, SUs are allowed to utilise the licensed band through overlapping in frequency and time with PUs if the interference level of SUs at the primary receiver is below a given threshold. In overlay strategy, SUs realise spectrum sharing by cooperation to improve the performance of PUs. Therefore, transmission schemes of PUs and channel state information are known by them. In interweave strategy, SUs need to get information about the spectrum utilisation of PUs and exploit space-time-frequency vacancies referred as spectrum holes to communicate opportunistically without degrading the primary transmission [4–6].

Spatial modulation (SM) is a promising multiple-input multiple-output (MIMO) transmission technique to combat the drawbacks of conventional MIMO systems such as inter-channel interference (ICI) and inter-antenna synchronisation. In SM, only one transmit antenna is activated during one signalling interval which prevents ICI and reduces the receiver complexity. In addition, the need for synchronisation between transmit antennas is avoided in SM [7, 8]. Since the activated antenna index conveys information along with conventional *M*-ary modulation schemes, spectral efficiency is improved by SM systems [9]. The bits conveyed by antenna indices are mapped into spatial domain while the other bits are mapped into *M*-ary constellation [10, 11]. Space-shift keying (SSK) is a special form of SM which radiates a constant carrier signal from the activated antenna, i.e. only antenna indices convey information for SSK [12].

Cooperative communications concept realises a virtual antenna array by providing single-antenna nodes the ability to communicate with their destination nodes through cooperation of another node (relay). According to the behaviour of the relay, two main cooperative signalling modes exist which are also called fixed relaying strategies: amplify-and-forward (AF) and decode-and-forward (DF) [13].

CR and cooperative communications are combined in [14–17] where mitigation of mutual interference between PUs and SUs is intended. In [14], a PU communicates with its receiver by a secondary transmitter which acts as a selective DF relay for PU and realises spectrum sharing. In [15], the same model is used; however, SU adopts AF relaying. In both studies, SU exploits a power partitioning coefficient to create a superimposed signal which is composed of PU's and SU's information. At the secondary receiver, through cancellation of PU's interference, the performance of SU is improved; however, SU can allocate less power to its own communication. Similarly in [16, 17], cognitive two-way relaying systems have been proposed. While the former proposes to exploit XOR-based DF, superposition based-DF and AF relaying, the latter operates with network coding based DF relaying. In all of these studies, a power partitioning is required due to the superposition of users' information; therefore, mutual interference becomes the main problem.

As expected, SM is gaining more and more attention for CR networks and provides a solution to cope with mutual interference in CR networks. In [18], several techniques such as adaptive modulation, space-time block codes, power adaptation, transmit antenna selection, and reconfigurable antennas, are combined with SM and CR concepts. The trade-offs between performance, overall complexity, energy and spectral efficiency are investigated. In [19], the same authors have proposed adaptive SM for underlay CR networks where energy efficiency is improved by SM and average spectral efficiency is enhanced by adaptive modulation.

In this paper, through using SM at SU, a new cooperative spectrum sharing protocol aiming to mitigate the mutual interference and to eliminate power partitioning between users is proposed. The proposed protocol is based on the overlay system paradigm with two time slots. PU operates with conventional *M*-QAM modulation; while SU which cooperates with PU, employs

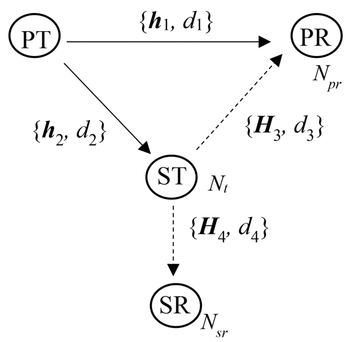


**Fig. 1** *Considered cognitive radio network configuration*

SM ($N_t$ antennas and $M$-QAM). Consequently, the need for superposition of PU's and SU's information is eliminated since information which belongs to different users, are carried in different domains while the performance of PU is improved. ST adopts three different relaying strategies:

- *AF relaying* in which ST amplifies and forwards the signal it received to PR after a power normalisation.
- *Incremental AF (IAF) relaying* in which ST amplifies and forwards the signal it received when the squared norm of channel fading coefficients vector of PT→PR channel is below a predefined threshold value. Otherwise, ST employs plain SSK modulation to carry out its own transmission.
- *Selective DF (SDF) relaying* in which ST sends the decoded primary signal along with its own information unless the squared norm of the channel fading coefficients vector of PT→ST channel is below a predefined threshold. Otherwise, ST remains silent not to cause error propagation and interference at PR.

Note that in IAF strategy, ST can amplify and forward the signal it receives along with its own information when the link between PT and PR is in outage; however, in SDF relaying strategy, ST remains silent when the link between PT and ST is in outage in order not to cause error propagation at PR, which is well-known for DF relaying strategy leading to degradation at the bit error performance.

The proposed protocol is compared with two existing reference protocols of [14, 15] for BPSK modulation as a special case which are modified for a fair comparison. The derivations are performed for the general $M$-QAM constellations.

The paper is organised as follows. System model is presented in Section 2. In Section 3, bit error probabilities (BEP) for PU and SU exploiting different relaying strategies are derived. In Section 4, performance evaluation results are given and comparisons are provided with reference systems. Finally, Section 5 concludes the paper.

*Notation:* Bold letters denote vectors as regular letters represent scalar variables. $E[\,.\,]$, $|\,.\,|$ and $\|\,.\,\|$ stand for expectation, absolute value and Frobenius norm operators, respectively. $(\,.\,)^{\mathrm{T}}$ denotes transposition while $(\,.\,)^{\mathrm{H}}$ stands for Hermitian transposition. $f_X(x)$ and $F_X(x)$ are probability density function (PDF) and cumulative distribution function (CDF) of a random variable (r.v.) $X$, respectively. Moment generating function (MGF) of a r.v. $X$ is given as $\mathscr{M}_X(-s) = E[\mathrm{e}^{-sx}] = \int_{-\infty}^{\infty} \mathrm{e}^{-sx} f_X(x)\,\mathrm{d}x$. Laplace transform of a function $g(x)$ is denoted as $G(s) = \mathscr{L}\{g(x)\} = \int_{-\infty}^{\infty} \mathrm{e}^{-sx} g(x)\,\mathrm{d}x$. $K_n(\,.\,)$ is the second order modified Bessel function while $W_{p,t}(\,.\,)$ is the Whittaker function. $\Upsilon(\,.\,,\,.\,)$ denotes the upper incomplete gamma function. $\mathrm{erf}(\,.\,)$ and $\mathrm{erfc}(\,.\,)$ are the error function and complementary error function, respectively. $\binom{a}{b}$ stands for the binomial coefficient. $\mathscr{CN}(0, \sigma^2)$ denotes circularly symmetric complex Gaussian distribution with zero mean and variance $\sigma^2$, while $\Gamma(q, r)$ stands for Gamma distribution with a shape parameter $q$ and a scale parameter $r$.

## 2 System model and protocol description

In Fig. 1, the considered CR network, which is based on overlay system paradigm, is given where transmitter-receiver pairs for PU and SU are denoted as PT-PR and ST-SR, respectively. PT is a single-antenna node while PR, ST and SR have $N_{\mathrm{pr}}, N_t$ and $N_{\mathrm{sr}}$ antennas, respectively. Complete transmission consists of two time slots. Solid lines represent the first time slot while dotted ones indicate the second time slot. The distances between nodes are represented by $d_i, i = 1, 2, 3, 4$ which are normalised according to the direct link, i.e. $d_1 = 1$. $\boldsymbol{h}_1$ and $\boldsymbol{h}_2$ denote vectors of the fading coefficients for PT→PR and PT→ST links, respectively. $\boldsymbol{h}_{3j}$ and $\boldsymbol{h}_{4j}$ are $j$th columns of the $N_{\mathrm{pr}} \times N_t$ and $N_{\mathrm{sr}} \times N_t$ channel matrices $\boldsymbol{H}_3$ and $\boldsymbol{H}_4$ which are composed of channel fading coefficients between ST→PR and ST→SR links, respectively. All fading coefficients are assumed to follow $\mathscr{CN}(0, d_i^{-\nu})$ where $\nu$ stands for path-loss exponent. We assume that the ideal channel state information is available only at the receivers. All complex noise components are assumed to be samples of zero-mean additive white Gaussian noise (AWGN) process with variance $N_0$.

PT operates with conventional $M$-QAM modulation while ST exploits SM ($N_{\mathrm{t}}$ antennas + $M$-QAM). In the first time slot, the primary $M$-QAM signal $x_p$ is sent by PT to PR and it is also received by ST which seeks to realise spectrum sharing by acting as relay for the transmission of PU. The received signals at PR are given as

$$\boldsymbol{y}_{\mathrm{PR}_1} = \boldsymbol{h}_1 x_p + \boldsymbol{n}_{\mathrm{PR}_1}, \tag{1}$$

where $\boldsymbol{h}_1 \in \mathbb{C}^{N_{\mathrm{pr}} \times 1}$ is the vector of channel fading coefficients between PT and $N_{\mathrm{pr}}$ antennas of PR and $\boldsymbol{n}_{\mathrm{PR}_1} \in \mathbb{C}^{N_{\mathrm{pr}} \times 1}$ represents the vector of AWGN components at PR. Since it employs a single RF chain, ST selects the antenna with the maximum squared absolute valued channel fading coefficient for reception, i.e. $\boldsymbol{h}_2 = [h_{21} h_{22} \cdots h_{2N_t}]^{\mathrm{T}}$, $h_{2\tilde{k}} = \max_{k = 1, 2, \ldots N_t} |h_{2k}|^2$. The received signal at ST is given by

$$y_{\mathrm{ST}} = h_{2\tilde{k}} x_p + n_{\mathrm{ST}} \tag{2}$$

where $n_{\mathrm{ST}}$ denotes the AWGN component at ST. ST processes this signal with reference to the relaying strategy it adopts and generates the signal $x_{\mathrm{ST}}$. For DF relaying, $x_{\mathrm{ST}} = \bar{x}_p$ which is obtained from

$$\bar{x}_p = \arg\min_{x_p} \left| y_{\mathrm{ST}} - h_{2\tilde{k}} x_p \right|^2. \tag{3}$$

For AF relaying, $x_{\mathrm{ST}} = \beta y_{\mathrm{ST}}$ where $\beta$ is the normalisation parameter given as

$$\beta = \frac{1}{\sqrt{E\left[|y_{\mathrm{ST}}|^2\right]}}. \tag{4}$$

In (4), $E\left[|y_{\mathrm{ST}}|^2\right]$ denotes the average energy of $y_{\mathrm{ST}}$. In the second time slot, ST activates its $j$th antenna according to its $n = \log_2 N_t$ bits and broadcasts $x_{\mathrm{ST}}$ to both PR and SR from this antenna. The received signals in the second time slot at PR are written as

$$\boldsymbol{y}_{\mathrm{PR}_2} = \boldsymbol{h}_{3j} x_{\mathrm{ST}} + \boldsymbol{n}_{\mathrm{PR}_2} \tag{5}$$

where $\boldsymbol{h}_{3j} \in \mathbb{C}^{N_{\mathrm{pr}} \times 1}$ is the vector of fading coefficients between $j$th antenna of ST and $N_{\mathrm{pr}}$ antennas of PR and $\boldsymbol{n}_{\mathrm{PR}_2} \in \mathbb{C}^{N_{\mathrm{pr}} \times 1}$ is the vector of AWGN components at PR. When ST adopts incremental or selective relaying, in some cases, PR must exploit only the direct link to obtain the primary information. In this case, $x_p$ is detected from

$$\hat{x}_p = \arg\min_{x_p} \| \boldsymbol{y}_{\mathrm{PR}_1} - \boldsymbol{h}_1 x_p \|^2. \tag{6}$$

In the cooperation case where ST applies SM, the decision metric at PR is given by

$$\hat{x}_p = \arg\min_{x_p, j} \left\{ || \boldsymbol{y}_{\mathrm{PR}1} - \boldsymbol{h}_1 x_p ||^2 + \| \boldsymbol{y}_{\mathrm{PR}2} - \boldsymbol{h}_{3j} x_{\mathrm{ST}} \|^2 \right\}. \tag{7}$$

When ST cooperates in the second time slot, the received signal vector at SR can be written as

$$\boldsymbol{y}_{\mathrm{SR}} = \boldsymbol{h}_{4j} x_{\mathrm{ST}} + \boldsymbol{n}_{\mathrm{SR}} \tag{8}$$

where $\boldsymbol{h}_{4j} \in \mathbb{C}^{N_{\mathrm{sr}} \times 1}$ is the vector of fading coefficients between the $j$th antenna of ST and $N_{\mathrm{sr}}$ antennas of SR, $\boldsymbol{n}_{\mathrm{SR}} \in \mathbb{C}^{N_{\mathrm{sr}} \times 1}$ is the vector of AWGN components at SR. The information conveyed by $j$ is detected from

$$\hat{j} = \arg\min_{x_p, j} \| \boldsymbol{y}_{\mathrm{SR}} - \boldsymbol{h}_{4j} x_{\mathrm{ST}} \|^2. \tag{9}$$

## 3 BEP analysis

In this section, BEPs of PU and SU are analytically derived for each relaying strategy. Since the average pairwise error probability (APEP) calculations are similar in all cases, we refer the readers to Appendix 1 and 2 for its derivation for PR and SR, respectively.

### 3.1 BEP analysis for primary user

BEP analysis of PU for AF, IAF and SDF relaying is performed in this subsection. Note that PU is interested in only $M$-QAM modulated signal.

*3.1.1 AF relaying:* ST amplifies the signal $y_{\mathrm{ST}}$, received by its selected antenna in the first time slot by using the parameter $\beta$, i.e. $x_{\mathrm{ST}} = \beta y_{\mathrm{ST}}$, and forwards this signal to both PR and SR. The received signals at PR in the first and second time slots are given in (1) and (5), respectively. For AF relaying strategy, (5) can be rewritten as

$$\begin{aligned} \boldsymbol{y}_{\mathrm{PR}2} &= \beta \boldsymbol{h}_{3j} y_{\mathrm{ST}} + \boldsymbol{n}_{\mathrm{PR}2} \\ &= \beta \boldsymbol{h}_{3j} h_{2\tilde{k}} x_p + \beta \boldsymbol{h}_{3j} n_{\mathrm{ST}} + \boldsymbol{n}_{\mathrm{PR}2} \\ &= \beta \boldsymbol{h}_{3j} h_{2\tilde{k}} x_p + \boldsymbol{n} \end{aligned} \tag{10}$$

where $\beta = 1/\sqrt{(|h_{2\tilde{k}}|^2 E_{\mathrm{s}} + N_0)}$ is a normalisation parameter to ensure the unit energy transmission from ST and $E_{\mathrm{s}}$ is the average signal energy of $M$-QAM signal constellation. In (10), $\boldsymbol{n} = \beta \boldsymbol{h}_{3j} n_{\mathrm{ST}} + \boldsymbol{n}_{\mathrm{PR}2}$ is the AWGN vector with components distributed as $\sim \mathscr{C}\mathscr{N}(0, \{(\beta^2 \| \boldsymbol{h}_{3j} \|^2 / N_{\mathrm{pr}}) + 1\} N_0)$. Equation (10) is rewritten with some modifications as

$$\dot{\boldsymbol{y}}_{\mathrm{PR}2} = A \boldsymbol{h}_{3j} x_p + \tilde{\boldsymbol{n}} \tag{11}$$

where $\tilde{\boldsymbol{n}} = \left[ (\beta \boldsymbol{h}_{3j} n_{\mathrm{ST}} + \boldsymbol{n}_{\mathrm{PR}2}) / \sqrt{(\beta^2 \| \boldsymbol{h}_{3j} \|^2 / N_{\mathrm{pr}}) + 1} \right]$ is the AWGN vector with components distributed as $\sim \mathscr{C}\mathscr{N}(0, N_0)$ and

$$A = \frac{\beta h_{2\tilde{k}}}{\sqrt{\beta^2 ( \| \boldsymbol{h}_{3j} \|^2 / N_{\mathrm{pr}}) + 1}}.$$

PR decodes the primary signal according to maximum likelihood (ML) detection from (1) and (11) as

$$\hat{x}_p = \arg\min_{x_p, j} \| \boldsymbol{y}_{\mathrm{PR}1} - \boldsymbol{h}_1 x_p \|^2 + \| \dot{\boldsymbol{y}}_{\mathrm{PR}2} - A \boldsymbol{h}_{3j} x_p \|^2. \tag{12}$$

APEP for the multiple access channel (MAC) to PR which consists of PT→PR and ST→PR links, can be given by (from Appendix 1)

$$\mathrm{APEP} = \frac{1}{\pi} \int_0^{\pi/2} M_{\gamma_1}\left( \frac{-1}{4 N_0 \sin^2\theta} \right) M_{\gamma_{\mathrm{MAC}}}\left( \frac{-1}{4 N_0 \sin^2\theta} \right) \mathrm{d}\theta \tag{13}$$

where $\gamma_1 = \| \boldsymbol{h}_1 (x_p - \hat{x}_p) \|^2$ and its MGF is given for Rayleigh fading channel as

$$M_{\gamma_1}(-s) = \left[ \frac{1}{1 + s |x_p - \hat{x}_p|^2} \right]^{N_{\mathrm{pr}}}. \tag{14}$$

Furthermore in (13)

$$\gamma_{\mathrm{MAC}} = \frac{\gamma_2 \gamma_3}{(\gamma_4 / N_{\mathrm{pr}}) + E_{\mathrm{s}} \gamma_2 + N_0}$$

where $\gamma_2 = |h_{2\tilde{k}}|^2$, $\gamma_3 = \| \boldsymbol{h}_{3j} x_p - \boldsymbol{h}_{3\hat{j}} \hat{x}_p \|^2$ and $\gamma_4 = \| \boldsymbol{h}_{3j} \|^2$. To calculate the APEP, CDF and then MGF of $\gamma_{\mathrm{MAC}}$ are required; however, it is not feasible to continue the analysis since $\gamma_{\mathrm{MAC}}$ is composed of three different r.v.s and two of them, $\gamma_3$ and $\gamma_4$, are correlated. For the analysis to be tractable, the expected power of $\boldsymbol{h}_{3j}$, i.e. $E[\, \| \boldsymbol{h}_{3j} \|^2 \,] = N_{\mathrm{pr}} d_3^{-v}$, is used in spite of $\gamma_4$ in $\gamma_{\mathrm{MAC}}$. Therefore, $\gamma_{\mathrm{MAC}} \simeq (\gamma_2 \gamma_3 / (E s \gamma_2 + C))$ where $C = d_3^{-v} + N_0$. PDF of $\gamma_2$ can be given as $f_{\gamma_2}(x) = N_t / \Omega_2 \exp(-x/\Omega_2) [1 - \exp(-x/\Omega_2)]^{N_t - 1}, x \geq 0$ in which $\Omega_2 = d_2^{-v}$ while $\gamma_3 \sim \Gamma(N_{\mathrm{pr}}, \Omega_3)$ [20] where

$$\Omega_3 = \begin{cases} d_3^{-v} |x_p - \hat{x}_p|^2 & \text{if } j = \hat{j} \\ d_3^{-v} \left( |x_p|^2 + |\hat{x}_p|^2 \right) & \text{if } j \neq \hat{j}. \end{cases}$$

CDF of $\gamma_{\mathrm{MAC}}$ can be calculated with the help of (3.471.9 in [21]) as (see (15) and (16)) where $F_{\gamma_3}(.|\gamma_2)$ is the CDF of the r.v. $\gamma_3$ conditioned on $\gamma_2$. $M_{\gamma_{\mathrm{MAC}}}(-s)$ can be calculated from the Laplace transform of $F_{\gamma_{\mathrm{MAC}}}(z)$ (by using 6.643.3 in [21]) as (see (16)) where

$$\Delta = \frac{(-1)^n (m+1)! \binom{k}{m} \binom{N_t - 1}{n} N_t (Es)^m \sqrt{(C/\Omega_2)^{(k-m+1)}}}{\sqrt{\Omega_3^{(1+m+k)}} (n+1)^{m-k+1}}.$$

Since a closed-form solution cannot be found when (14) and (16) are substituted in the APEP of (13), the integral in (13) can be calculated numerically and the BEP of PU is given approximately as

$$P_{\mathrm{b}}^{\mathrm{MAC}} \simeq \frac{1}{M N_t} \sum_x \sum_{\hat{x}} \mathrm{APEP} \frac{n(x_p, \hat{x}_p)}{k} \tag{17}$$

$$\begin{aligned} F_{\gamma_{\mathrm{MAC}}}(z) &\simeq \int_0^\infty F_{\gamma_3}\left[ z \left( E_{\mathrm{s}} + \frac{C}{x} \right) \Big| \gamma_2 \right] f_{\gamma_2}(x)\, \mathrm{d}x \\ &= 1 - \sum_{k=0}^{N_{\mathrm{pr}} - 1} \sum_{m=0}^{k} \sum_{n=0}^{N_t - 1} \frac{2(-1)^n N_t (Es)^m}{k! (\sqrt{n+1})^{m-k+1}} \binom{k}{m} \binom{N_t - 1}{n} \left( \sqrt{\frac{C}{\Omega_2}} \right)^{k-m+1} \\ &\quad \times \left( \sqrt{\frac{z}{\Omega_3}} \right)^{m+k+1} \exp\left( -z \frac{Es}{\Omega_3} \right) K_{m-k+1}\left[ 2 \sqrt{\frac{zC}{\Omega_3 \Omega_2} (n+1)} \right] \end{aligned} \tag{15}$$

where $k = \log_2 M$ and $n(x_p, \hat{x}_p)$ denotes the number of erroneous bits related to $x_p$ when the SM symbol $x = (x_p, j)$ is transmitted and $\hat{x} = (\hat{x}_p, \hat{j})$ is decided.

*3.1.2 IAF relaying:* In this strategy, if the squared norm of channel fading coefficients vector of PT→PR link is below a given threshold, PR requests ST to forward the amplified primary signal, i.e. $x_{\mathrm{ST}} = \beta y_{\mathrm{ST}}$, and exploits MAC to PR. In this case, ST uses SM to simultaneously send the primary and secondary information. Otherwise, PR uses only the direct link to obtain the primary information and ST exploits SSK modulation to transmit its own information to SR in the second time slot.

When the squared norm of channel fading coefficient vector of PT→PR link is below a given threshold, an outage event occurs for this link whose probability is given as

$$P_{\mathrm{PT}\to\mathrm{PR}}^{\mathrm{out}} = \Pr\left(\| \boldsymbol{h}_1 \|^2 \le \gamma_{\mathrm{th}}^{\mathrm{IAF}}\right) = \Pr\left(\gamma_1 \le \gamma_{\mathrm{th}}^{\mathrm{IAF}}\right) = F_{\gamma_1}(\gamma_{\mathrm{th}}^{\mathrm{IAF}}) \quad (18)$$

where $\gamma_1 = \| \boldsymbol{h}_1 \|^2 \sim \Gamma(N_{\mathrm{pr}}, 1)$, and $\gamma_{\mathrm{th}}^{\mathrm{IAF}}$ is the optimum threshold value which gives minimum BER and determined via experiments.

BEP of PU for IAF relaying is calculated as

$$P_{\mathrm{b}}^{P} = P_{\mathrm{PT}\to\mathrm{PR}}^{\mathrm{out}} P_{\mathrm{b}}^{\mathrm{MAC}} + \left(1 - P_{\mathrm{PT}\to\mathrm{PR}}^{\mathrm{out}}\right) P_{\mathrm{b}}^{\mathrm{D}} \quad (19)$$

where $P_{\mathrm{b}}^{\mathrm{MAC}}$ is obtained using (17) and $P_{\mathrm{b}}^{\mathrm{D}}$ is the BEP of direct link conditioned on $\gamma_1 \ge \gamma_{\mathrm{th}}^{\mathrm{IAF}}$ which is expressed as

$$P_{\mathrm{b}}^{\mathrm{D}} = \int_{\gamma_{\mathrm{th}}^{\mathrm{IAF}}}^{\infty} P_{\mathrm{PT}\to\mathrm{PR}}(e|x) \frac{f_{\gamma_1}(x)}{(1 - F_{\gamma_1}(\gamma_{\mathrm{th}}^{\mathrm{IAF}}))} \mathrm{d}x\,. \quad (20)$$

and BEP of the PT→PR link conditioned on $x$, is given as

$$P_{\mathrm{PT}\to\mathrm{PR}}(e|x) = \frac{\sqrt{M} - 1}{M(\log_2 M)} \{(\sqrt{M} - 1) + 2\mathrm{erfc}(\sqrt{\alpha x}) - (\sqrt{M} - 1)\mathrm{erf}^2(\sqrt{\alpha x})\} \quad (21)$$

where $\alpha = 3Es/(2N_0(M - 1))$. The result of (20) is obtained as

$$P_{\mathrm{b}}^{\mathrm{D}} = \frac{\sqrt{M} - 1}{M(\log_2 M)} \{(\sqrt{M} - 1) + 2\Xi - (\sqrt{M} - 1)\mho\} \quad (22)$$

where

$$\Xi = \frac{1}{(1 - F_{\gamma_1}(\gamma_{\mathrm{th}}^{\mathrm{IAF}}))(N_{\mathrm{pr}} - 1)!} \left[\mathrm{erfc}\left(\sqrt{\alpha\gamma_{\mathrm{th}}^{\mathrm{IAF}}}\right)\Upsilon(N_{\mathrm{pr}}, \gamma_{\mathrm{th}}^{\mathrm{IAF}}) - (N_{\mathrm{pr}} - 1)!\sqrt{\frac{\alpha}{\pi}} \sum_{m=0}^{N_{\mathrm{pr}}-1} \frac{\Upsilon(m + 0.5, \gamma_{\mathrm{th}}^{\mathrm{IAF}}(1 + \alpha))}{m!(1 + a)^{m+0.5}}\right]$$

and $\mho = \int_{\gamma_{\mathrm{th}}^{\mathrm{IAF}}}^{\infty} \mathrm{erf}^2(\sqrt{\alpha x}) f_{\gamma_1}(x|\gamma_1 \ge \gamma_{\mathrm{th}}^{\mathrm{IAF}})\,\mathrm{d}x$ which is numerically calculated. APEP for IAF relaying is given as

$$\mathrm{APEP} \simeq \frac{1}{\pi} \int_0^{\pi/2} M_{\gamma_1}\left(\frac{-|x_p - \hat{x}_p|^2}{4N_0 \sin^2\theta}\right) M_{\gamma_{\mathrm{MAC}}}\left(\frac{-1}{4N_0 \sin^2\theta}\right) \mathrm{d}\theta \quad (23)$$

where $M_{\gamma_{\mathrm{MAC}}}(-s)$ is the same as defined in (16) and $M_{\gamma_1}(-s)$ can be calculated from

$$M_{\gamma_1}(-s) = \int_0^{\gamma_{\mathrm{th}}^{\mathrm{IAF}}} \mathrm{e}^{-xs} f_{\gamma_1}(x|\gamma_1 \le \gamma_{\mathrm{th}}^{\mathrm{IAF}})\,\mathrm{d}x \quad (24)$$

where $f_{\gamma_1}(\,.\,|\gamma_1 \le \gamma_{\mathrm{th}}^{\mathrm{IAF}})$ is the PDF of $\gamma_1$ conditioned on $\gamma_1 \le \gamma_{\mathrm{th}}^{\mathrm{IAF}}$ and is obtained from [22] as

$$f_{\gamma_1}(x|\gamma_1 \le \gamma_{\mathrm{th}}^{\mathrm{IAF}}) = \frac{f_{\gamma_1}(x)}{F_{\gamma_1}(\gamma_{\mathrm{th}}^{\mathrm{IAF}})}, \quad x \le \gamma_{\mathrm{th}}^{\mathrm{IAF}}\,.$$

With the help of (3.351.1 in [21]), the closed-form solution of (24) is found as

$$M_{\gamma_1}(-s) = \left(\frac{1}{1+s}\right)^{N_{\mathrm{pr}}} \frac{1}{F_{\gamma_1}(\gamma_{\mathrm{th}}^{\mathrm{IAF}})} \left[1 - \exp\left[-\gamma_{\mathrm{th}}^{\mathrm{IAF}}(1+s)\right] \sum_{k=0}^{N_{\mathrm{pr}}-1} \frac{1}{k!}\left[\gamma_{\mathrm{th}}^{\mathrm{IAF}}(1+s)\right]^k\right]. \quad (25)$$

APEP is obtained by substituting (25) in (23) and calculating the integral numerically. $P_{\mathrm{b}}^{\mathrm{MAC}}$ can be found from (17) by using the result of (23). After $P_{\mathrm{b}}^{\mathrm{MAC}}$ is substituted in (19) with $P_{\mathrm{b}}^{\mathrm{D}}$ of (20), BEP of PU is finally obtained for IAF relaying.

*3.1.3 SDF relaying:* In this scenario, ST decodes the primary signal in the first time slot, i.e. $x_{\mathrm{ST}} = \tilde{x}_p$, and activates $j$th antenna among its $N_t$ transmit antennas based on its own information, then forwards the primary regenerated signal from its $j$th antenna if the squared norm of chosen channel fading coefficient of PT→ST link, i.e. $|h_{2\tilde{k}}|^2$, is above a predetermined optimum threshold, i.e. $\gamma_{\mathrm{th}}^{\mathrm{SDF}}$, which minimises the BER for PU, found via experiments, i.e. $|h_{2\tilde{k}}|^2 > \gamma_{\mathrm{th}}^{\mathrm{SDF}}$. Otherwise, an outage event occurs for PT→ST link. The outage probability of the PT→ST link can be expressed as

$$\begin{aligned} P_{\mathrm{PT}\to\mathrm{ST}}^{\mathrm{out}} &= \Pr\left(|h_{2\tilde{k}}|^2 \le \gamma_{\mathrm{th}}^{\mathrm{SDF}}\right) = F_{\gamma_2}\left(\gamma_{\mathrm{th}}^{\mathrm{SDF}}\right) \\ &= \left[1 - \exp\left(-\frac{\gamma_{\mathrm{th}}^{\mathrm{SDF}}}{\Omega_2}\right)\right]^{N_t} \end{aligned} \quad (26)$$

where $\gamma_2 = |h_{2\tilde{k}}|^2$. When ST cooperates, PR decodes $x_p$ by the ML detector as

$$\hat{x}_p = \arg\min_{x_p, j} \left\{\| \boldsymbol{y}_{\mathrm{PR}1} - \boldsymbol{h}_1 x_p \|^2 + \| \boldsymbol{y}_{\mathrm{PR}2} - \boldsymbol{h}_{3j} x_p \|^2\right\}. \quad (27)$$

APEP of the PU for SDF relaying is given by

$$\begin{aligned} \mathrm{APEP} &= \frac{1}{\pi} \int_0^{\pi/2} M_{\gamma_1}\left(\frac{-1}{4N_0 \sin^2\theta}\right) M_{\gamma_{\mathrm{MAC}}}\left(\frac{-1}{4N_0 \sin^2\theta}\right) \mathrm{d}\theta \\ &= \frac{1}{\pi} \int_0^{\pi/2} \prod_{l=1}^{2} \left(\frac{\sin^2\theta}{\sin^2\theta + c_l}\right)^{N_{\mathrm{pr}}} \mathrm{d}\theta \end{aligned} \quad (28)$$

where $\gamma_1 = \| \boldsymbol{h}_1(x_p - \hat{x}_p) \|^2$, $\gamma_{\mathrm{MAC}} = \| \boldsymbol{h}_{3j} x_p - \boldsymbol{h}_{3\hat{j}} \hat{x}_p \|^2$, $c_1 = (|x_p - \hat{x}_p|^2 / 4N_0)$, and $c_2 = (\lambda / 4N_0)$ with

$$\lambda = \begin{cases} d_3^{-v} |x_p - \hat{x}_p|^2 & \text{if } j = \hat{j} \\ d_3^{-v}\left(|x_p|^2 + |\hat{x}_p|^2\right) & \text{if } j \ne \hat{j}\,. \end{cases}$$

$$\begin{aligned} M_{\gamma_{\mathrm{MAC}}}(-s) &\simeq s\mathscr{L}\left\{F_{\gamma_{\mathrm{MAC}}}(z)\right\} \\ &= 1 - s \sum_{k=0}^{N_{\mathrm{pr}}-1} \sum_{m=0}^{k} \sum_{n=0}^{N_t-1} \frac{\Delta \exp((C(n+1))/(2\Omega_2(Es + s\Omega_3)))}{(\sqrt{(Es/\Omega_3) + s})^{m+k+2}} \\ &\quad \times \sqrt{\frac{\Omega_3 \Omega_2}{C(n+1)}} W_{-((m+k+2)/2), ((m-k+1)/2)}\left[\frac{C(n+1)}{\Omega_2(Es + s\Omega_3)}\right] \end{aligned} \quad (16)$$

The closed-form expression for (28) is given [23] as

$$\begin{aligned}\mathrm{APEP} = \frac{(c_1/c_2)^{N_{\mathrm{pr}}-1}}{2((c_2-c_1)/c_2)^{2N_{\mathrm{pr}}-1}}\Bigg[&\sum_{k=0}^{N_{\mathrm{pr}}-1}\left(\frac{c_2-c_1}{c_1}\right)^k \mathfrak{I}_k I_k(c_2)\\ &-\frac{c_1}{c_2}\sum_{k=0}^{N_{\mathrm{pr}}-1}\left(\frac{c_2-c_1}{c_2}\right)^k \mathfrak{R}_k I_k(c_1)\Bigg]\end{aligned} \tag{29}$$

where

$$\mathfrak{I}_k = \frac{(-1)^{N_{\mathrm{pr}}+k-1}(2N_{\mathrm{pr}}-1-k)!}{(N_{\mathrm{pr}}-k-1)!(2N_{\mathrm{pr}}-1)!}\prod_{n=1,n\neq k+1}^{N_{\mathrm{pr}}}(2N_{\mathrm{pr}}-n)$$

$$\mathfrak{R}_k = \sum_{n=0}^{N_{\mathrm{pr}}-1}\frac{(-1)^{N_{\mathrm{pr}}-1-n}\binom{k}{n}\binom{N_{\mathrm{pr}}-1}{n}}{(N_{\mathrm{pr}}-1)!\binom{2N_{\mathrm{pr}}-1}{n}}\prod_{m=1,m\neq n+1}^{N_{\mathrm{pr}}}(2N_{\mathrm{pr}}-m)$$

and

$$I_k(c) = 1-\sqrt{\frac{c}{1+c}}\left[1+\sum_{n=1}^{k}\frac{(2n-1)!!}{n!2^n(1+c)^n}\right]$$

with double factor denoting the product of only odd integers from 1 to $2n-1$. $P_{\mathrm{b}}^{\mathrm{MAC}}$ is upper bounded by using (29) in

$$P_{\mathrm{b}}^{\mathrm{MAC}} \le \frac{1}{MN_t}\sum_x\sum_{\hat{x}}\mathrm{APEP}\frac{n(x_p,\hat{x}_p)}{k}. \tag{30}$$

BEP of PU for SDF relaying is calculated as

$$P_{\mathrm{b}}^{P} = P_{\mathrm{PT}\to\mathrm{ST}}^{\mathrm{out}}P_{\mathrm{b}}^{\mathrm{D}} + (1-P_{\mathrm{PT}\to\mathrm{ST}}^{\mathrm{out}})[P_{\mathrm{b}}^{\mathrm{ST}}P_{\mathrm{prop}} + (1-P_{\mathrm{b}}^{\mathrm{ST}})P_{\mathrm{b}}^{\mathrm{MAC}}] \tag{31}$$

where $P_{\mathrm{prop}}$ is the error propagation probability, which is equal to $d_3^{-v}/(1+d_3^{-v})$ for $N_{\mathrm{pr}}=1$ and, it is also numerically verified that $P_{\mathrm{prop}} \simeq d_3^{-v}/(1+d_3^{-v})$ for $N_{\mathrm{pr}}>1$. $P_{\mathrm{b}}^{\mathrm{ST}}$ is the BEP of PT→ST link given that $\gamma_2 > \gamma_{\mathrm{th}}^{\mathrm{SDF}}$ which is calculated as

$$P_{\mathrm{b}}^{\mathrm{ST}} = \int_{\gamma_{\mathrm{th}}^{\mathrm{SDF}}}^{\infty}P_{\mathrm{PT}\to\mathrm{ST}}(e|\gamma)\frac{f_{\gamma_2}(\gamma)}{1-F_{\gamma_2}(\gamma_{\mathrm{th}}^{\mathrm{SDF}})}\mathrm{d}\gamma \tag{32}$$

where $P_{\mathrm{PT}\to\mathrm{ST}}(e|x)$ is the error probability for $M$-QAM modulation conditioned on $x$ which is given in (21). The closed-form solution of (32) can be calculated by computer software.

$P_{\mathrm{b}}^{\mathrm{D}}$ is the BEP of direct link over Rayleigh fading channels which is given as

$$P_{\mathrm{b}}^{\mathrm{D}} = \frac{\sqrt{M}-1}{M(\log_2 M)}\left\{(\sqrt{M}-1)+4\left(\frac{1-\sqrt{\Theta}}{2}\right)-(\sqrt{M}-1)\Phi\right\} \tag{33}$$

where

$$\Theta = \frac{3E_{\mathrm{b}}(\log_2 M)}{3E_{\mathrm{b}}(\log_2 M)+2N_0(M-1)}, \quad \Phi = \frac{4}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\Theta^{n+1}.$$

### *3.2 BEP analysis for secondary user*

In this section, BEP analysis of SU for AF, IAF and SDF relaying scenarios is performed. Note that SU is interested in only antenna indices.

*3.2.1 AF relaying:* Similar to the PU's analysis, (8) can be rewritten as

$$\boldsymbol{y}_{\mathrm{SR}} = \beta\boldsymbol{h}_{4j}h_{2\tilde{k}}x_p + \beta\boldsymbol{h}_{4j}n_{\mathrm{ST}} + \boldsymbol{n}_{\mathrm{SR}} = \beta\boldsymbol{h}_{4j}h_{2\tilde{k}}x_p + \boldsymbol{n} \tag{34}$$

where $\boldsymbol{h}_{4j} \in \mathbb{C}^{N_{\mathrm{sr}}\times 1}$ is the vector of fading coefficients for the channel between $j$th antenna of ST and $N_{\mathrm{sr}}$ antennas of SR, $\boldsymbol{n} = \beta\boldsymbol{h}_{4j}n_{\mathrm{ST}} + \boldsymbol{n}_{\mathrm{SR}} \in \mathbb{C}^{N_{\mathrm{sr}}\times 1}$ is the AWGN vector with components distributed as $\sim \mathscr{CN}(0,((\beta^2 \parallel \boldsymbol{h}_{4j}\parallel^2/N_{\mathrm{sr}})+1)N_0)$. Equation (34) is rewritten as

$$\dot{\boldsymbol{y}}_{\mathrm{SR}} = B\boldsymbol{h}_{4j}x_p + \tilde{\boldsymbol{n}} \tag{35}$$

where

$$B = \frac{\beta h_{2\tilde{k}}}{\sqrt{\beta^2(\parallel \boldsymbol{h}_{4j}\parallel^2/N_{\mathrm{sr}})+1}}$$

with $\beta = 1/\sqrt{|h_{2\tilde{k}}|^2E_{\mathrm{s}}+N_0}$. SR detects the secondary information by the ML detector as

$$\hat{j} = \arg\min_{x_p, j} \parallel \dot{\boldsymbol{y}}_{\mathrm{SR}} - B\boldsymbol{h}_{4j}x_p\parallel^2. \tag{36}$$

APEP is expressed for AF relaying as

$$\mathrm{APEP} = \frac{1}{\pi}\int_0^{\pi/2}M_{\gamma_{\mathrm{SR}}}\left(\frac{-1}{4N_0\sin^2\theta}\right)\mathrm{d}\theta \tag{37}$$

where $\gamma_{\mathrm{SR}} = |B|^2 \parallel \boldsymbol{h}_{4j}x_p - \boldsymbol{h}_{4\hat{j}}\hat{x}_p\parallel^2$. Substituting $B$ into $\gamma_{\mathrm{SR}}$, we obtain

$$\gamma_{\mathrm{SR}} = \frac{|h_{2\tilde{k}}|^2\parallel \boldsymbol{h}_{4j}x_p - \boldsymbol{h}_{4\hat{j}}\hat{x}_p\parallel^2}{|h_{2\tilde{k}}|^2E_{\mathrm{s}} + (\parallel \boldsymbol{h}_{4j}\parallel^2/N_{\mathrm{sr}})+N_0} = \frac{\gamma_2\gamma_4}{\gamma_2E_{\mathrm{s}}+(\gamma_5/N_{\mathrm{sr}})+N_0}$$

where $\gamma_4 \sim \Gamma(N_{\mathrm{sr}},\Omega_4)$, $\Omega_4 = d_4^{-v}(|x_p|^2+|\hat{x}_p|^2)$ and $\gamma_5 = \parallel \boldsymbol{h}_{4j}\parallel^2$. For the analysis to be tractable, we use the expected power of $\boldsymbol{h}_{4j}$, i.e. $E[\parallel \boldsymbol{h}_{4j}\parallel^2] = N_{\mathrm{sr}}d_4^{-v}$. Therefore

$$\gamma_{\mathrm{SR}} \simeq \frac{|h_{2\tilde{k}}|^2\parallel \boldsymbol{h}_{4j}x_p - \boldsymbol{h}_{4\hat{j}}\hat{x}_p\parallel^2}{|h_{2\tilde{k}}|^2E_{\mathrm{s}}+d_4^{-v}+N_0} = \frac{\gamma_2\gamma_4}{\gamma_2E_{\mathrm{s}}+C}$$

where $C = d_4^{-v}+N_0$. Following the similar steps as in the APEP calculation of PU when AF relaying is adopted, the MGF of $\gamma_{\mathrm{SR}}$ can be obtained as (see (38) and ) where (see equation below)

$$\begin{aligned}M_{\gamma_{\mathrm{SR}}}(-s) \simeq 1 - s\sum_{k=0}^{N_{\mathrm{sr}}-1}\sum_{m=0}^{k}\sum_{n=0}^{N_t-1}\Delta\sqrt{\frac{\Omega_4\Omega_2}{C(n+1)}}&W_{-((m+k+2)/2),((m-k+1)/2)}\\ \times\left[\frac{C(n+1)}{\Omega_2(Es+s\Omega_4)}\right]&\end{aligned} \tag{38}$$

$$\Delta = \frac{(-1)^n(m+1)!\binom{k}{m}\binom{N_t-1}{n}N_t(Es)^m\sqrt{(C/\Omega_2)^{(k-m+1)}}\exp((C(n+1))/(2\Omega_2(Es+s\Omega_4)))}{\sqrt{\Omega_4^{(1+m+k)}}(n+1)^{(m-k+1)}(\sqrt{(Es/\Omega_4)+s})^{m+k+2}}.$$

APEP is calculated by substituting (38) in (37). Since a closed-form solution cannot be found for the integral of (37), it can be calculated numerically. Finally, the BEP of SU can be approximated as

$$P_{\mathrm{b}}^{\mathrm{SM}} \simeq \frac{1}{MN_t}\sum_{x}\sum_{\hat{x}}\mathrm{APEP}\frac{n(j,\hat{j})}{k} \tag{39}$$

where $k = \log_2 N_t$ and $n(j, \hat{j})$ is the number of erroneous bits related to $j$ when the SM symbol $x = (x_p, j)$ is transmitted and $\hat{x} = (\hat{x}_p, \hat{j})$ is decided.

*3.2.2 IAF relaying:* There are two different transmission scenarios for SU with IAF relaying strategy:

- *Scenario 1:* When the direct link between PT and PR is in outage, ST cooperates and broadcasts the amplified primary signal from its $j$th antenna by using SM as in AF relaying. Secondary information is detected for this scenario from

$$\hat{j} = \arg\min_{x_p, j} \| \dot{\boldsymbol{y}}_{\mathrm{SR}} - B\boldsymbol{h}_{4j}x_p \|^2 \tag{40}$$

  which is given in the previous subsection.
- *Scenario 2:* When an outage event does not occur for PT→PR link, PR does not need the amplified copy of the primary signal from ST. Therefore, ST exploits SSK modulation for its own information and sends an SSK signal to SR. In this case, secondary information is detected from

$$\hat{j} = \arg\min_{j} \| \boldsymbol{y}_{\mathrm{SR}} - \boldsymbol{h}_{4j} \|^2. \tag{41}$$

BEP of SU for IAF relaying is given as

$$P_{\mathrm{b}}^{S} = P_{\mathrm{b}}^{\mathrm{SM}}P_{\mathrm{PT}\to\mathrm{PR}}^{\mathrm{out}} + P_{\mathrm{b}}^{\mathrm{SSK}}(1 - P_{\mathrm{PT}\to\mathrm{PR}}^{\mathrm{out}}) \tag{42}$$

where $P_{\mathrm{b}}^{\mathrm{SM}}$ stands for *Scenario 1* and is obtained from (39). $P_{\mathrm{PT}\to\mathrm{PR}}^{\mathrm{out}}$ is the outage probability of the direct link which was given in (18). $P_{\mathrm{b}}^{\mathrm{SSK}}$ is upper bounded for *Scenario 2* by

$$P_{\mathrm{b}}^{\mathrm{SSK}} \le \frac{1}{N_{\mathrm{t}}}\sum_{j=1}^{N_{\mathrm{t}}}\sum_{\hat{j}=1}^{N_{\mathrm{t}}}\mathrm{APEP}_{\mathrm{SSK}}\frac{n(j,\hat{j})}{\log_2 N_{\mathrm{t}}} \tag{43}$$

where $n(j, \hat{j})$ is the number of the erroneous bits in detection of antenna indices when the SSK symbol $j$ is transmitted and $\hat{j}$ is decided, and $\mathrm{APEP}_{\mathrm{SSK}}$ is given as

$$\begin{aligned}\mathrm{APEP}_{\mathrm{SSK}} &= \frac{1}{\pi}\int_0^{\pi/2} M_{\gamma_{\mathrm{SR}}}\left(\frac{-1}{4N_0\sin^2\theta}\right)\mathrm{d}\theta = \frac{1}{\pi}\int_0^{\pi/2}\left[\frac{\sin^2\theta}{\sin^2\theta + c}\right]^{N_{\mathrm{sr}}}\mathrm{d}\theta \\ &= \frac{1}{2}\left[1 - \psi(c)\sum_{k=0}^{N_{\mathrm{sr}}-1}\binom{2k}{k}\left(\frac{1-\psi^2(c)}{4}\right)^k\right]\end{aligned} \tag{44}$$

where $\gamma_{\mathrm{SR}} = \| \boldsymbol{h}_{4j} - \boldsymbol{h}_{4\hat{j}} \|^2$, $\psi(c) = \sqrt{(c/(1+c))}$, $c = (\lambda/4N_0)$ and $\lambda = 2d_4^{-\nu}$. Finally, BEP for SU in case of IAF relaying is obtained by (42) after (44) is substituted in (43).

*3.2.3 SDF relaying:* When SDF relaying is adopted, ST cooperates only when PT→ST link is not in outage. Otherwise, ST remains silent. When ST cooperates, the secondary information is detected from

$$\hat{j} = \arg\min_{x_p, j} \| \boldsymbol{y}_{\mathrm{SR}} - \boldsymbol{h}_{4j}x_p \|^2. \tag{45}$$

APEP is given by

$$\begin{aligned}\mathrm{APEP} &= \frac{1}{\pi}\int_0^{\pi/2} M_{\gamma_{\mathrm{SR}}}\left(\frac{-1}{4N_0\sin^2\theta}\right) \\ &= \frac{1}{\pi}\int_0^{\pi/2}\left[\frac{\sin^2\theta}{\sin^2\theta + c}\right]^{N_{\mathrm{sr}}}\mathrm{d}\theta \\ &= \frac{1}{2}\left[1 - \zeta(c)\sum_{k=0}^{N_{\mathrm{sr}}-1}\binom{2k}{k}\left(\frac{1-\zeta^2(c)}{4}\right)^k\right]\end{aligned} \tag{46}$$

where $\gamma_{\mathrm{SR}} = \| \boldsymbol{h}_{4j}x_p - \boldsymbol{h}_{4\hat{j}}\hat{x}_p \|^2$, $\zeta(c) = \sqrt{(c/(1+c))}$, $c = (\lambda/4N_0)$ and $\lambda = d_4^{-\nu}(|x_p|^2 + |\hat{x}_p|^2)$. BEP can be upper bounded by

$$P_{\mathrm{b}}^{\mathrm{SM}} \le \frac{1}{MN_t}\sum_{x}\sum_{\hat{x}}\mathrm{APEP}\frac{n(j,\hat{j})}{k} \tag{47}$$

## 4 Performance evaluation

In this section, we provide theoretical and computer simulations results for the proposed protocol and make comparisons with two reference systems in [14, 15], respectively, where both users exploit conventional $M$-QAM modulation and superposition coding. As aforementioned earlier, ST adopts SDF and AF relaying in [14, 15], respectively; however, we have modified these reference systems and protocols to make fair comparisons by adopting receive antenna selection at ST and exploiting multi-antenna receivers. Comparisons are made in terms of $E_{\mathrm{b}}/N_0$ where $E_{\mathrm{b}}$ is the average energy per bit at PT for all relaying strategies. BER performances of the considered systems are compared for $M = 2, 4$ and 16 and the distance between PT and ST is taken as $d_2 = 0.5$ for all modulation orders. $d_2 = 0.8$ is also considered for the $M = 4, N_t = 4$ and $N_{\mathrm{pr}} = 2$ case. It is assumed that $d_3 = |d_1 - d_2|$ and $d_4 = d_1 = 1$. The distance between PT and SR in [14, 15] is considered as $d_5 = 0.5$. Note that in both modified reference systems, ST allocates 75, 93.75 and 99.6% of its power for the transmission of primary signal for $M = 2, 4$ and 16, respectively.

Threshold values are obtained by a semi-analytic method as follows: In the first time slot, the received signal-to-noise ratio (SNR) values at ST and PR, which are $|h_{2\tilde{k}}|^2 E_{\mathrm{s}}/N_0$ for SDF relaying and $\| \boldsymbol{h}_1 \|^2 E_{\mathrm{s}}/N_0$ for IAF relaying, respectively, are compared with a positive number $\gamma$ to determine whether ST will be active or not. The comparison is made for all values of $\gamma$ in the range of 1 to 500 for SDF relaying and of 100 to 500 for IAF relaying. The BEP of PR is calculated by substituting all values of $\gamma N_0/E_{\mathrm{s}}$ instead of $\gamma_{\mathrm{th}}^{\mathrm{IAF(SDF)}}$ for each SNR value in (19) and (31). The $\breve{\gamma}$ value, which provides the minimum BEP at PR, is obtained. Finally, the threshold value for SDF or IAF is obtained as $\gamma_{\mathrm{th}} = \breve{\gamma}N_0/E_{\mathrm{s}}$ .In Figs. 2–5, the BER performance curves of PU are provided for $M = 2, 4$ and 16, and compared with the case without spectrum sharing in addition to the modified two reference systems. It can be seen from Figs. 2–5 that the BER performance of PU is improved by cooperation and the proposed protocol which adopts SDF relaying provides the best BER performance, while the proposed protocol with AF and IAF relaying provides equivalent BER performances. In Figs. 2 and 3, the BER performance curves of PU are depicted for $M = 2$, $d_2 = 0.5$ when $N_{\mathrm{pr}} = 1$ and $N_{\mathrm{pr}} = 2$, respectively. In Fig. 2, the best BER performance is obtained when SDF relaying is adopted for the proposed protocol. In Fig. 2, PU for IAF and AF relaying exhibits equivalent BER performances since PR requires an amplified copy of the primary signal frequently. Compared with the modified reference system in [14], the proposed protocol adopting SDF relaying provides better BER performance in all cases. When ST adopts AF or IAF relaying, it provides a better BER performance than that of [15] in all cases.

In Fig. 3, the BER performance of PU is given for $N_{\mathrm{pr}} = 2$. The proposed protocol using SDF relaying exhibits the best BER performance in Fig. 3 since the probability of correct decisions at PR increases as the number of antennas at PR increases. It is

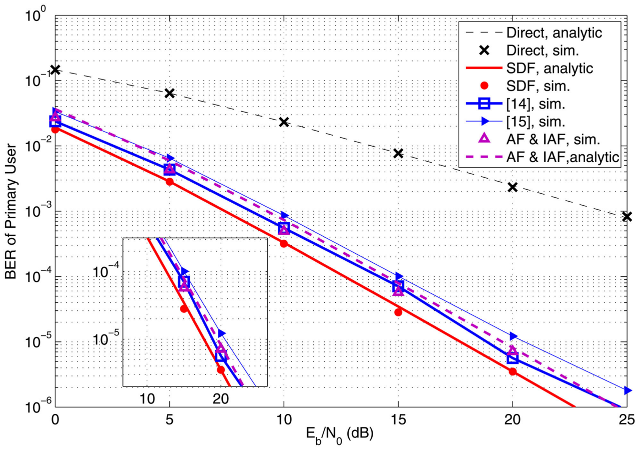


**Fig. 2** *BEP performance of PU for* $M = 2$, $N_t = 2$, $N_{pr} = 1$ *and* $d_2 = 0.5$

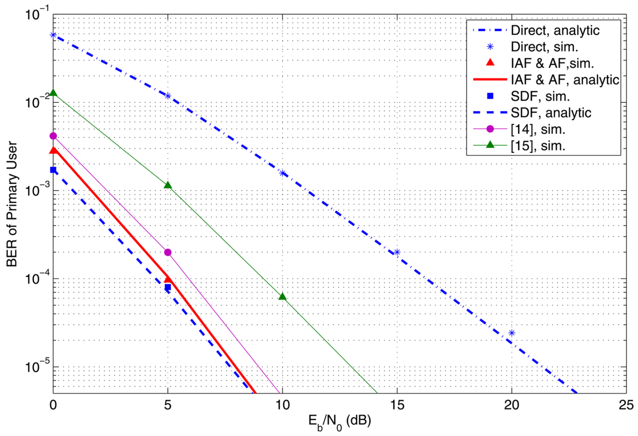


**Fig. 3** *BEP performance of PU for* $M = N_t = N_{pr} = 2$ *and* $d_2 = 0.5$

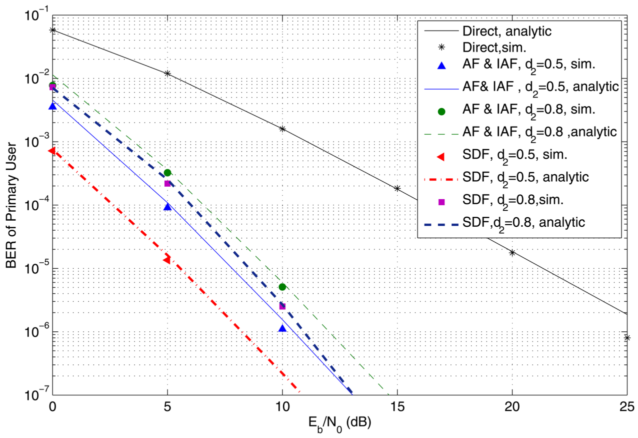


**Fig. 4** *BEP performance of PU for* $M = 4$, $N_t = 4$, $N_{pr} = 2$ *when* $d_2 = 0.5$ *and* $d_2 = 0.8$

observed from Fig. 3 that the proposed protocol outperforms the modified schemes of [14, 15] in all cases.

In Fig. 4, the BER performances of PU are provided in terms of the distance ($d_2$) between PT and ST. BER performances of PU are provided for $M = 4, N_t = 4$ and $N_{\rm pr} = 2$ when $d_2 = 0.5$ and $d_2 = 0.8$ It can be seen from Fig. 4 that the proposed protocol adopting SDF gives the best BER performance. As $d_2$ increases from 0.5 to 0.8, it provides the worse BER performance since the quality of PT→ST link decreases.

In Fig. 5, the BER performance curves of PU are given for $N_t = 4$ when $M = 4$ and 16 and $N_{\rm pr} = 2$. The proposed protocol adopting SDF relaying with $M = 4$ provides the best BER performance. It exhibits 2.25 dB improvement compared with that of AF and IAF relaying at a BER value of $10^{-6}$. When $M = 16$, the

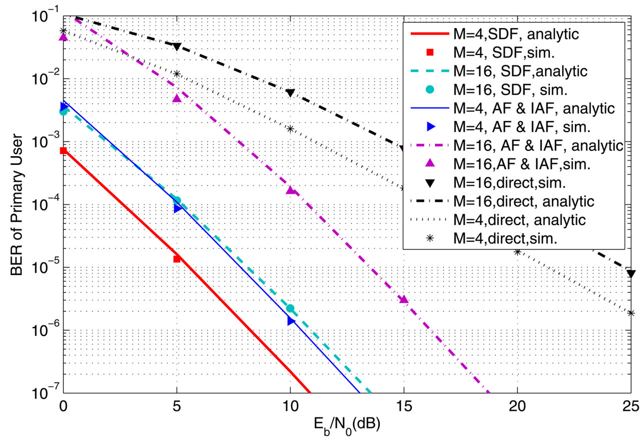


**Fig. 5** *BEP performance of PU for* $M = 4$ *and* 16, $N_t = 4, N_{pr} = 2$ *and* $d_2 = 0.5$

proposed protocol for SDF relaying provides 5 dB enhancement compared with that of AF and IAF relaying at a BER value of $10^{-5}$. Note that when $M > 2$, the reference schemes cannot realise spectrum sharing since ST must allocate its 93% or more of its power to PU. Hence we only consider the case of BPSK.

Finally, in Figs. 6 and 7, the BER performance curves of SU are provided for $M = 2$ and 16, respectively. Note that $N_{\rm sr} = 2$ while $N_t = 2$ for Fig. 6 and $N_t = 4$ for Fig. 7. In Fig. 6, the proposed protocol using SDF, AF and IAF relaying strategies are compared with two modified reference schemes. It can be seen from Fig. 6 that IAF relaying provides the best BER performance. AF relaying reaches the BER value of $10^{-3}$ at 16 dB while the modified reference scheme of [15] reaches this value at 17 dB. SDF relaying provides about 1.2 dB enhancement in $E_{\rm b}/N_0$ compared with the modified reference scheme of [15] for a BER value of $10^{-3}$. In Fig. 7, SDF relaying exhibits the best BER performance for SU. Moreover, by operating IAF relaying, the BER performance of SU approaches to that of SDF relaying at high SNR values since ST switches to SSK modulation. As seen from Fig. 7, for higher values of as above 20 dB, which provide much lower BER values, computer simulation results and upper bound curves are in perfect match for AF and IAF relaying. In AF relaying, the SU realises spectrum sharing in all cases. Note that for $M = 16$ in two modified reference schemes, SU cannot realise spectrum sharing since ST allocates 99% of its power for the PU's transmission.

In addition, upper-bounds become tighter for lower modulation order ($M$) and number of transmit antennas at ST ($N_t$) in SM and, asymptotically converge to the computer simulation curves at high SNR values. We observe from Figs. 2, 3 and 6 that the theoretical curves are in very close agreement with the computer simulation curves for smaller constellations.

## 5 Conclusion

In this paper, a new cooperative spectrum sharing protocol for CR networks using SM at SU has been proposed where ST communicates with its receiver by also acting as relay for PU. Under three different relaying strategies, BEP performances of both users have been investigated and compared with two modified reference systems and the non-cooperation case. Thanks to SM, antenna indices carry secondary information as ordinary $M$-ary modulation conveys the primary information at ST. Therefore, ST can use its whole transmission power for both PU's and its own transmission. Moreover, the need for superposition at ST and the link between PT and SR is eliminated. Consequently, SU's transmission takes place in favourable conditions while the BER performance of PU is improved due to cooperation. In terms of the considered relaying scenarios, it has been shown that SDF relaying provides the best BER performance for PU. By adopting incremental relaying in AF, ST can switch to the use of SSK modulation to convey its own information. Furthermore, the proposed protocol has shown better BER performance compared

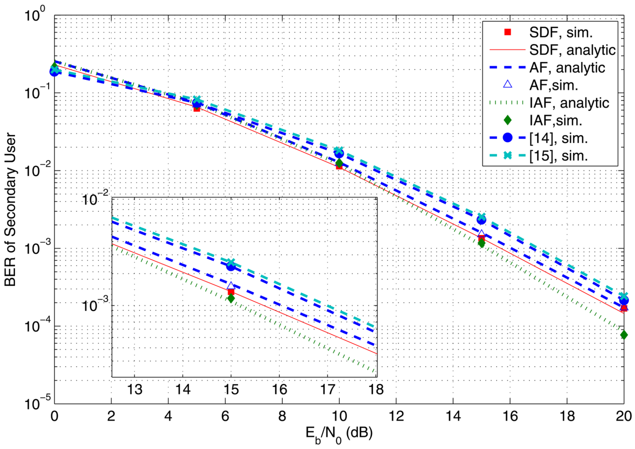


**Fig. 6** *BEP performance of SU for* $M = 2$, $N_t = N_{sr} = N_{pr} = 2$ *and* $d_2 = 0.5$

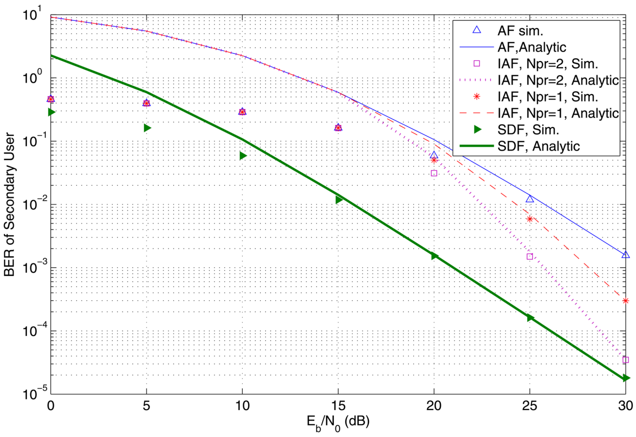


**Fig. 7** *BEP performance of SU for* $M = 16$, $N_t = 4$, $N_{sr} = 2$ *and* $d_2 = 0.5$

with two modified reference schemes based on superposition coding. The extension of the proposed protocol to the case of multiple secondary transmitters employing beamforming methods for interference cancellation can be considered as a future work.

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## 8 Appendix

### *8.1 Appendix 1: APEP calculation at PR*

The received signals at PR in the first time slot and the modified received signals in the second time slot are given, respectively, by

$$\boldsymbol{y}_{\mathrm{PR}1} = \boldsymbol{h}_1 x_p + \boldsymbol{n}_{\mathrm{PR}1} \tag{48}$$

$$\dot{\boldsymbol{y}}_{\mathrm{PR}2} = A\boldsymbol{h}_{3j} x_p + \tilde{\boldsymbol{n}}\,. \tag{49}$$

When the SM signal $x = (j, x_p)$ is transmitted and it is detected as $\hat{x} = (\hat{j}, \hat{x}_p)$, APEP is calculated as follows. PR decodes $x_p$ according to the ML detector from

$$\hat{x}_p = \arg\min_{x_p, j} \left\{ \| \boldsymbol{y}_{\mathrm{PR}1} - \boldsymbol{h}_1 x_p \|^2 + \| \dot{\boldsymbol{y}}_{\mathrm{PR}2} - A\boldsymbol{h}_{3j} x_p \|^2 \right\}. \tag{50}$$

Then, CPEP is calculated from (50) as

$$\begin{aligned}\mathrm{CPEP} &= P\Big(\| \boldsymbol{y}_{\mathrm{PR}1} - \boldsymbol{h}_1 x_p \|^2 + \| \dot{\boldsymbol{y}}_{\mathrm{PR}2} - A\boldsymbol{h}_{3j} x_p \|^2 \\ &\quad \geq \| \boldsymbol{y}_{\mathrm{PR}1} - \boldsymbol{h}_1 \hat{x}_p \|^2 + \| \dot{\boldsymbol{y}}_{\mathrm{PR}2} - A\boldsymbol{h}_{3\hat{j}} \hat{x}_p \|^2 \Big| \boldsymbol{h}_1, \boldsymbol{h}_{3j}\Big) \\ &= P\big(D \geq 0 \big| \boldsymbol{h}_1, \boldsymbol{h}_{3j}\big)\end{aligned} \tag{51}$$

with the decision variable given by

$$\begin{aligned}D = &-\| \boldsymbol{h}_1 x_p - \boldsymbol{h}_1 \hat{x}_p \|^2 - |A|^2 \| \boldsymbol{h}_{3j} x_p - \boldsymbol{h}_{3\hat{j}} \hat{x}_p \|^2 \\ &-2\mathrm{Re}\left\{ \boldsymbol{n}_{\mathrm{PR}1}^{\mathrm{H}} (\boldsymbol{h}_1 x_p - \boldsymbol{h}_1 \hat{x}_p) + A\tilde{\boldsymbol{n}}^{\mathrm{H}} (\boldsymbol{h}_{3j} x_p - \boldsymbol{h}_{3\hat{j}} \hat{x}_p) \right\}.\end{aligned} \tag{52}$$

The expected value and variance of $D$ are given, respectively, as

$$\begin{aligned} m_D &= -\| \boldsymbol{h}_1 x_p - \boldsymbol{h}_1 \hat{x}_p \|^2 - |A|^2 \| \boldsymbol{h}_{3j} x_p - \boldsymbol{h}_{3\hat{j}} \hat{x}_p \|^2, \\ \sigma_D^2 &= 2N_0 (\| \boldsymbol{h}_1 x_p - \boldsymbol{h}_1 \hat{x}_p \|^2 + |A|^2 \| \boldsymbol{h}_{3j} x_p - \boldsymbol{h}_{3\hat{j}} \hat{x}_p \|^2)\,. \end{aligned}$$

Using Craig's formula

$$Q(x) = \frac{1}{\pi} \int_0^{\pi/2} \exp\left( -\frac{x^2}{2\sin^2\theta} \right) \mathrm{d}\theta,$$

we obtain

$$\begin{aligned}\mathrm{CPEP} &= P(D \ge 0 | \boldsymbol{h}_1, \boldsymbol{h}_{3j}) = Q\left(-\frac{m_D}{\sigma_D}\right) \\ &= \frac{1}{\pi}\int_0^{\pi/2} \exp\left(-\frac{\gamma_1 + \gamma_{\mathrm{MAC}}}{4N_0 \sin^2\theta}\right) \mathrm{d}\theta .\end{aligned} \tag{53}$$

By calculating the expected value of (53) over channel fading coefficients, APEP is obtained as

$$\mathrm{APEP} = \frac{1}{\pi}\int_0^{\pi/2} M_{\gamma_1}\left(\frac{-1}{4N_0 \sin^2\theta}\right) M_{\gamma_{\mathrm{MAC}}}\left(\frac{-1}{4N_0 \sin^2\theta}\right) \mathrm{d}\theta \tag{54}$$

where $\gamma_1 = \| \boldsymbol{h}_1(x_p - \hat{x}_p) \|^2$, $\gamma_{\mathrm{MAC}} = |A|^2 \| \boldsymbol{h}_{3j} x_p - \boldsymbol{h}_{3\hat{j}} \hat{x}_p \|^2$. Note that for SDF relaying, $\dot{\boldsymbol{y}}_{\mathrm{PR}_2} = \boldsymbol{y}_{\mathrm{PR}_2}$ and $A = 1$.

### 8.2 Appendix 2: APEP calculation at SR

When ST exploits SM, the modified received signal vector at SR in the second time slot is given by

$$\dot{\boldsymbol{y}}_{\mathrm{SR}} = B\boldsymbol{h}_{4j} x_p + \tilde{\boldsymbol{n}} . \tag{55}$$

The antenna index is detected from

$$\hat{j} = \arg\min_{x_p, j} \| \dot{\boldsymbol{y}}_{\mathrm{SR}} - B\boldsymbol{h}_{4j} x_p \|^2 . \tag{56}$$

With some modifications in APEP calculation of the PU, decision variable for the SU can be written by $D = -|B|^2 \| \boldsymbol{h}_{4j} x_p - \boldsymbol{h}_{4\hat{j}} \hat{x}_p \|^2 - 2\mathrm{Re}\left\{ B\tilde{\boldsymbol{n}}^{\mathrm{H}} (\boldsymbol{h}_{4j} x_p - \boldsymbol{h}_{4\hat{j}} \hat{x}_p) \right\}$. The expected value and variance of $D$ are given, respectively, as

$$\begin{aligned} m_D &= -|B|^2 \| \boldsymbol{h}_{4j} x_p - \boldsymbol{h}_{4\hat{j}} \hat{x}_p \|^2, \\ \sigma_D^2 &= 2N_0 |B|^2 \| \boldsymbol{h}_{4j} x_p - \boldsymbol{h}_{4\hat{j}} \hat{x}_p \|^2 . \end{aligned}$$

CPEP can be written as

$$\begin{aligned}\mathrm{CPEP} &= P(D \ge 0 | \boldsymbol{h}_{4j}) = Q\left(-\frac{m_D}{\sigma_D}\right) \\ &= \frac{1}{\pi}\int_0^{\pi/2} \exp\left(-\frac{|B|^2 \| \boldsymbol{h}_{4j} x_p - \boldsymbol{h}_{4\hat{j}} \hat{x}_p \|^2}{4N_0 \sin^2\theta}\right) \mathrm{d}\theta .\end{aligned} \tag{57}$$

For SU, APEP is obtained as

$$\mathrm{APEP} = \frac{1}{\pi}\int_0^{\pi/2} M_{\gamma_{\mathrm{SR}}}\left(\frac{-1}{4N_0 \sin^2\theta}\right) \mathrm{d}\theta \tag{58}$$

where $\gamma_{\mathrm{SR}} = |B|^2 \| \boldsymbol{h}_{4j} x_p - \boldsymbol{h}_{4\hat{j}} \hat{x}_p \|^2$. Note that for SDF relaying, $\dot{\boldsymbol{y}}_{\mathrm{SR}} = \boldsymbol{y}_{\mathrm{SR}}$ and $B = 1$. In addition, when ST exploits SSK modulation as in IAF relaying, $B = x_p = 1$ can be considered.