Performance Analysis of Cooperative Spectrum Sharing for Cognitive Radio Networks Using Spatial Modulation at Secondary Users

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***Abstract*—In this paper, a new cooperative spectrum sharing protocol which avoids mutual interference between primary and secondary users by employing spatial modulation (SM) at the secondary transmitter (ST), is proposed for overlay cognitive radio networks. In the proposed protocol, ST cooperates with selective decode-and-forward (DF) relaying strategy to prevent error propagation. Primary transmitter (PT) exploits M-ary phase shift keying (M-PSK) modulation whereas ST utilizes SM (N_t transmit antennas and M-PSK). Since ST transmits PT's information by M-PSK symbols and its own information by antenna indexes, mutual interference at primary receiver (PR) and secondary receiver (SR) is removed. Upper bounds on the bit error probability (BEP) of the primary and secondary users are analytically derived and supported via computer simulation results which show that the proposed protocol significantly improves the bit error performance of both primary and secondary users compared to the non-cooperation case and the cooperative DF spectrum sharing protocol using superposition coding.**

I. INTRODUCTION

Cognitive radio networks are wireless networks which handle with the growing demand, scarcity and inefficient usage of the wireless spectrum [1]–[6]. Cognitive radio networks consist of two types of users: licensed spectrum users which are named primary users and unlicensed secondary users which are called cognitive radios. Since cognitive radios are allowed to utilize the same frequency band along with primary system under the condition that they improve or at least do not degrade the primary system's performance, they need to be self-aware learning devices which can sense the available spectrum, recognize the environment around them, adjust their parameters such as their frequencies, waveforms and access strategies [1]–[4]. Depending on the access strategies, there are three main approaches: underlay, overlay and interweave systems discussed in [5], [6]. Since both users are present in the spectrum at the same time in underlay and overlay systems, the main problem is how the mutual interference generated by each user can be avoided or mitigated.

On the other hand, SM is a multiple-input multiple-output (MIMO) technique that draws reasonable attention in recent years [7]–[9]. In SM, both the transmitter and the receiver have multiple antennas and antenna indexes are used apart from the conventional modulation techniques (M-PSK, M-QAM) to transmit information. SM reduces the complexity and cost of MIMO systems without system performance degradation in addition it provides high data rates. Inter-channel interference (ICI) which is a big problem in classical MIMO systems, is avoided due to the fact that only one antenna stays activated during each transmission interval. No synchronization is needed among antennas since only one RF chain is sufficient for transmission. Space-shift keying (SSK), a special form of SM, utilizes only antenna indexes to transmit information [10].

In the literature, several system designs and protocols are studied which aim to mitigate or remove the mutual interference generated by licenced and unlicensed users. In [11], a cooperative spectrum sharing technique for secondary access is proposed where secondary user operates as a DF relay to primary system. Secondary user recreates a superimposed signal comprising of primary and secondary signals with a power partition factor that allocates portions of the available secondary power to primary and secondary user's signals. In [12], a cognitive two-way relaying system is proposed where secondary signal is again superimposed to primary signal by adopting different cooperation strategies such as exclusive or (XOR)-based DF, amplify-and-forward (AF) and finally superposition-based DF (DF-SUP). Another cognitive two-way relaying system utilizing network coding for primary signals is investigated in [13]. Secondary user cooperates with the primary system as a DF relay and superimposes secondary information. All of these studies exploit a power partition factor like the work in [11] and the secondary user needs to dedicate most of its available power to primary transmission to guarantee the primary system's performance.

In this work, a new two-phase cooperative spectrum sharing protocol for cognitive radio networks based on overlay system paradigm is proposed where mutual interference is avoided through SM. While the primary user utilizes conventional M-PSK modulation, the secondary user employs SM (N_t transmit antennas and M-PSK modulation) and cooperates with the primary user by adopting DF relaying strategy to realize spectrum sharing. Denoting the transmitter-receiver pairs of primary and secondary systems by PT-PR and ST-SR, respectively, the transmission occurs in two time slots as follows: In the first time slot, primary signal x_p is transmitted from PT to both PR and ST. In the second time slot, if ST achieves to decode the primary signal x_p successfully, it transmits x_p to both PR and SR from the antenna whose index corresponds to its own information. However if ST fails to decode x_p at the first time slot, it stays silent and does not cooperate. Hence,

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the secondary system cannot share the licensed spectrum. In the proposed protocol, mutual interference of the two systems and power allocation problem are removed thanks to SM. Furthermore, the use of N_t antennas at ST for reception during the first time slot, results in higher probability of cooperation, and therefore the secondary user can actualize spectrum sharing more frequently.

Upper bounds on the BEP of primary and secondary systems are analytically derived for Rayleigh flat fading channels. Computer simulation results, which consider variable modulation orders and number of antennas at ST, are shown to match with analytical performance curves. Furthermore, performance comparisons with non-cooperative case and the reference system given in [11] are provided.

The paper is organized as follows. In Section II, system configuration and the proposed protocol is explained. In Section III, analytical derivations for the BEP of primary and secondary systems are presented. Section IV is dedicated to performance results and comparisons. Finally, Section V concludes the paper.

II. SYSTEM MODEL AND PROTOCOL DESCRIPTION

The considered cognitive radio network with one primary and one secondary user is depicted in Fig.1. Overall transmission consists of two time slots where solid lines denote the first time slot while dotted ones are for the second time slot. In Fig.1, $d_i, i = 1,2,3,4$ denote the normalized distances according to the direct link, i.e., $d_1 = 1$ and $h_1, h_{2j}, h_{3j}, h_{4j}, (j = 1,2,....,N_t)$ stand for the fading coefficients which are assumed to be zero-mean complex Gaussian random variables (r.v.) with variance d_i^{-v} where ν is path-loss exponent. Perfect channel state information is available at the receivers and all noise components are assumed to be the samples of zero-mean additive white Gaussian noise (AWGN) with variance σ^2. The primary and secondary transmitter powers are denoted as P_p and P_s, respectively. Moment generating function (MGF) of a random variable (r.v.) X is $\mathcal{M}_X(t) = E[e^{tx}] = \int_{-\infty}^{\infty} e^{tx} f(x)dx$ where $f(x)$ is the probability density function (PDF) of X.

Primary user utilizes conventional M-PSK modulation whereas secondary user exploits SM (N_t antennas and M-PSK). In the first time slot, the received signals at PR and at the $j^{th}(j = 1,2,...,N_t)$ antenna of ST are given as

$$y_{PR1} = \sqrt{P_p} h_1 x_p + n_{PR1}, \tag{1}$$

$$y_{STj} = \sqrt{P_p} h_{2j} x_p + n_{STj} \tag{2}$$

where n_{PR1} and n_{STj} represent AWGN components at PR and the j^{th} antenna of ST, respectively. Acting as relay to improve the primary system performance, ST receives the primary signal sent from PT by its N_t antennas and generates $y_{ST} = \sum_{j=1}^{N_t} h_{2j}^* y_{STj}$ by maximum ratio combining (MRC) and decodes x_p from

$$\tilde{x}_p = \arg\min_{x_p} \left| y_{ST} - \sum_{j=1}^{N_t} |h_{2j}|^2 x_p \right|^2. \tag{3}$$

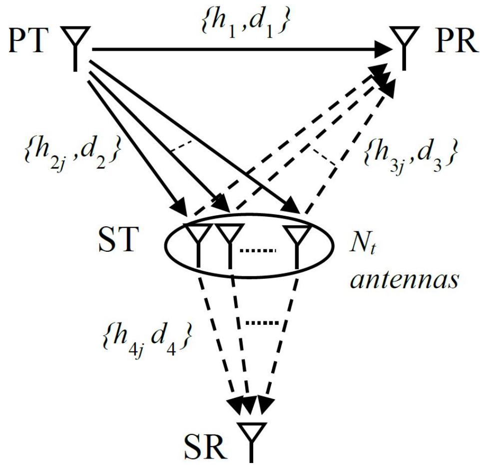

Fig. 1. Considered cognitive radio network configuration

If ST decodes x_p successfully, it determines the j^{th} antenna from its N_t transmit antennas according to its $n = \log_2 N_t$ information bits to be transmitted to SR, and ST broadcasts x_p to both PR and SR using its j^{th} antenna in the second time slot. The received signal at PR is written as

$$y_{PR2} = \sqrt{P_s} h_{3j} x_p + n_{PR2} \tag{4}$$

where h_{3j} is the fading coefficient between j^{th} antenna of ST and PR, n_{PR2} is the AWGN component at PR. x_p is maximum likelihood (ML) detected [8] as

$$\hat{x}_p = \arg\min_{x_p,j} \{ \left| y_{PR1} - \sqrt{P_p} h_1 x_p \right|^2 + \left| y_{PR2} - \sqrt{P_s} h_{3j} x_p \right|^2 \}. \tag{5}$$

When ST erroneously decodes x_p, it stays silent in the second time slot and PR uses only the signal y_{PR1} received in the first time slot to decode the primary signal as

$$\hat{x}_p = \arg\min_{x_p,j} \left| y_{PR1} - \sqrt{P_p} h_1 x_p \right|^2. \tag{6}$$

When ST transmits in the second time slot, the received signal at SR can be written by

$$y_{SR} = \sqrt{P_s} h_{4j} x_p + n_{SR} \tag{7}$$

where h_{4j} is the fading coefficient between the j^{th} antenna of ST and SR, n_{SR} is the AWGN component at SR. y_{SR} can be conceived as an SSK signal [10] and the information conveyed by j can be obtained from

$$\hat{j} = \arg\min_{x_p,j} \left| y_{SR} - \sqrt{P_s} h_{4j} x_p \right|^2. \tag{8}$$

Note that since x_p is also sent from the j^{th} antenna of ST opposite to [10], it must be considered while decoding the antenna index in (8).

III. PERFORMANCE ANALYSIS

In this section, theoretical upper bound expressions for BEP of primary and secondary systems are derived for the proposed protocol. As stated above, the primary signal is transmitted using M-PSK modulation while the secondary signal is transmitted by antenna indexes. Since ST employs SM when cooperating, the mutual interference is removed at both receivers. In the sequel, it is assumed that $P_p = P_s = 1$.

A. BEP Analysis for Primary System

When PR decodes the SM signal transmitted from ST with the optimum receiver given in [8], it tries to correctly decode only the primary M-PSK signal. Hence, an error does not occur at PR even if the antenna index is erroneously decoded. Note that, if ST decodes x_p successfully in the first time slot, BEP of the multiple access channel (MAC) consisting of PT→ PR and ST→ PR links, is analyzed. Otherwise, the direct link PT→ PR is considered since ST stays silent in this case. In the light of these explanations, the BEP of primary system can be expressed as

$$P_b^p = \quad P_b^{PT\to PR} P_{PT\to ST} + (1 - P_{PT\to ST}) P_{MAC}^{PR} \tag{9}$$

where $P_b^{PT\to PR}$ is the BEP of the direct link, $P_{PT\to ST}$ is the symbol error probability (SEP) of the link PT→ ST and P_{MAC}^{PR} is the BEP of MAC with destination PR. For single-input single-output (SISO) systems using M-PSK modulation the BEP over Rayleigh flat fading channel is given as in [14] by

$$P_b^{PT\to PR} \cong \frac{1}{\max(\log_2 M, 2)} \times \sum_{i=1}^{\max(M/4,1)} \left(1 - \sqrt{\frac{\mu_i}{1+\mu_i}}\right) \tag{10}$$

where E_b denotes the transmitted energy per bit and

$$\mu_i = \frac{E_b \log_2 M}{N_0} \sin^2 \frac{(2i-1)\pi}{M}.$$

Since ST, which adopts selection relaying strategy, remains silent unless it decodes x_p successfully as a symbol, SEP is considered in spite of BEP for the performance of the link between PT→ST. ST has N_t antennas due to SM and it receives with all of its antennas and then combines them with MRC. Receive diversity is achieved by the channel between PT → ST and the probability of cooperation is increased. For single-input multiple-output (SIMO) systems using M-PSK modulation over Rayleigh flat fading channels, SEP has been calculated in [14] as

$$\begin{aligned} &P_{PT\to ST} = (M-1)/M \\ &- \frac{1}{\pi}\sqrt{\frac{c}{1+c}} \left\{ \left(\frac{\pi}{2} + \tan^{-1}\alpha\right) \sum_{k=0}^{N_t-1} \binom{2k}{k} \frac{1}{[4(1+c)]^k} \right. \\ &\left. + \sin(\tan^{-1}\alpha) \sum_{k=1}^{N_t-1} \sum_{i=1}^{k} \frac{T_{ik}}{(1+c)^k} \left[\cos(\tan^{-1}\alpha)\right]^{2(k-i)+1} \right\} \end{aligned} \tag{11}$$

where $T_{ik} = \binom{2k}{k} / \left[\binom{2(k-i)}{k-i} 4^i \left[2(k-i)+1\right] \right]$, $\alpha = \sqrt{\frac{c}{1+c}} \cot\frac{\pi}{M}$, $c = E[|h_{2j}|^2] \frac{E_b \log_2 M}{N_0} \sin^2 \frac{\pi}{M}$ and $\binom{\cdot}{\cdot}$ is the binomial coefficient.

Upper bound on the BEP of MAC with destination PR is derived for the optimal SM receiver given in [8] as follows. When the SM signal $s = (j, x_p)$ is transmitted and $\hat{s} = (\hat{\jmath}, \hat{x}_p)$ is erroneously decided, from (5), the decision metric can be written as

$$m(y, x_p; h_1, h_{3j}) = |y_{PR1} - h_1 x_p|^2 + |y_{PR2} - h_{3j} x_p|^2$$

and the conditional pairwise error probability (CPEP) is defined as

$$\begin{aligned} &P^{MAC}(s \to \hat{s} \,|h_1, h_{3j}) \\ &= P\left(m(y, s; h_1, h_{3j}) \geq m(y, \hat{s}; h_1, h_{3\hat{\jmath}}) \,|h_1, h_{3j}\right) \\ &= P(D \geq 0 \,|h_1, h_{3j}) \end{aligned} \tag{12}$$

with

$$\begin{aligned} D = &-|h_1 x_p - h_1 \hat{x}_p|^2 - |h_{3j} x_p - h_{3\hat{\jmath}} \hat{x}_p|^2 \\ &- 2\,\mathrm{Re}\left\{ n_{PR1}^* (h_1 x_p - h_1 \hat{x}_p) + n_{PR2}^* (h_{3j} x_p - h_{3\hat{\jmath}} \hat{x}_p) \right\}. \end{aligned} \tag{13}$$

The expected value and variance of the decision variable D are computed as

$$E[D] = m_d = -\left(|h_1 \ x_p - h_1 \ \hat{x}_p|^2 + |h_{3j} \ x_p - h_{3\hat{\jmath}} \ \hat{x}_p|^2 \right)$$

and

$$Var(D) = \sigma_d^2 = 2N_0 \left(|h_1 x_p - h_1 \hat{x}_p|^2 + |h_{3j} x_p - h_{3\hat{\jmath}} \hat{x}_p|^2 \right)$$

where n_{PR1} and $n_{PR2} \sim \mathcal{CN}(0, N_0)$ are AWGN components at PR. Considering Craig's formula, which is given as $Q(x) = \frac{1}{\pi}\int_0^{\pi/2} \exp\left(-\frac{x^2}{2\sin^2\theta}\right) d\theta$, we obtain

$$\begin{aligned} &P^{MAC}(s \to \hat{s} \,|h_1, h_{3j}) = P(D \geq 0 \,|h_1, h_{3j}) = Q\left(-\frac{m_d}{\sigma_d}\right) \\ &= \frac{1}{\pi} \int_0^{\pi/2} \exp\left(-\frac{|h_1 x_p - h_1 \hat{x}_p|^2 + |h_{3j} x_p - h_{3\hat{\jmath}} \hat{x}_p|^2}{4N_0 \sin^2\theta} \right) d\theta. \end{aligned} \tag{14}$$

After taking the expected value of (14) over channel fading coefficients, average PEP (APEP) can be written by means of MGF as,

$$\begin{aligned} &P^{MAC}(s \to \hat{s}) = \\ &\frac{1}{\pi} \int_0^{\pi/2} E\left[\exp\left(-\frac{|h_1 x_p - h_1 \hat{x}_p|^2 + |h_{3j} x_p - h_{3\hat{\jmath}} \hat{x}_p|^2}{4N_0 \sin^2\theta} \right) \right] d\theta \\ &= \frac{1}{\pi} \int_0^{\pi/2} \left(\frac{\sin^2\theta}{\sin^2\theta + c_1} \right) \left(\frac{\sin^2\theta}{\sin^2\theta + c_2} \right) d\theta \\ &= \frac{1}{2} \sum_{k=1}^{2} \left(1 - \sqrt{\frac{c_k}{1+c_k}} \right) \prod_{n=1 (n \neq k)}^{2} \left(\frac{c_k}{c_k - c_n} \right) \end{aligned} \tag{15}$$

where $c_1 = |x_p - \hat{x}_p|^2 / (4N_0)$ and $c_2 = \lambda/(4N_0)$. If the antenna index is correctly decoded, $\lambda = d_3^{-\nu} |x_p - \hat{x}_p|^2$, else $\lambda = 2d_3^{-\nu}$. Then, the BEP upper bound of MAC is obtained by replacing (15) in

$$P_{MAC}^{PR} \leq \frac{1}{MNt} \sum\nolimits_s \sum\nolimits_{\hat{s}} P^{MAC}(s \to \hat{s}) \frac{e(s \to \hat{s})}{k} \tag{16}$$

where $e(s \to \hat{s})$ is the number of bits in error when s is erroneously decoded to $\hat{s}$ and $k = \log_2 M$. Finally, replacing (10), (11) and (16) in (9), the BEP upper bound for the primary system is obtained.

Note that since the primary system is concerned with only the M-PSK signal, it does not consider the erroneous antenna index detections.

B. BEP Analysis for Secondary System

ST exploiting SM, selects the antenna corresponding to its own information bits among its N_t transmit antennas and broadcasts the primary signal x_p from this antenna. Since the information is carried by antenna indexes for the secondary system, SR needs to determine only the transmit antenna index. BEP derivations for this case are similar to those of the primary system with some differences such as the decision metric which is $m(y, x_p; h_{4j}) = |y_{SR} - h_{4j}x_p|^2$ from (8) and the decision variable becomes

$$D = -|h_{4j}x_p - h_{4\hat{j}}\hat{x}_p|^2 - 2\,\mathrm{Re}\left\{n_{SR}^*(h_{4j}x_p - h_{4\hat{j}}\hat{x}_p)\right\}$$

where $n_{SR} \sim \mathcal{CN}(0, N_0)$. Therefore, the expected value and variance of D for secondary system change to

$$E[D] = m_d = -|h_{4j}x_p - h_{4\hat{j}}\hat{x}_p|^2$$

and

$$Var(D) = \sigma_d^2 = 2N_0\left(|h_{4j}x_p - h_{4\hat{j}}\hat{x}_p|^2\right).$$

CPEP for secondary system is calculated by using Craig's formula as

$$\begin{aligned} &P(D \geq 0\,|h_{4j}\,) = P^{ST\rightarrow SR}(s \rightarrow \hat{s}\,|h_{4j}\,) \\ &= Q\left(-\frac{m_d}{\sigma_d}\right) = \frac{1}{\pi}\int_0^{\pi/2}\exp\left(-\frac{|h_{4j}x_p - h_{4\hat{j}}\hat{x}_p|^2}{4N_0\sin^2\theta}\right)d\theta. \end{aligned} \tag{17}$$

APEP for the secondary system by taking the expected value of (17) with respect to channel fading coefficient h_{4j} can be written through MGF as

$$\begin{aligned} &P^{ST\rightarrow SR}(s \rightarrow \hat{s}) = \frac{1}{\pi}\int_0^{\pi/2} E\left[\exp\left(-\frac{|h_{4j}x_p - h_{4\hat{j}}\hat{x}_p|^2}{4N_0\sin^2\theta}\right)\right]d\theta \\ &= \frac{1}{\pi}\int_0^{\pi/2}\left(\frac{\sin^2\theta}{\sin^2\theta + \frac{\lambda}{4N_0}}\right)d\theta \ = \frac{1}{2}\left(1 - \sqrt{\frac{\frac{\lambda}{4N_0}}{1 + \frac{\lambda}{4N_0}}}\right) \end{aligned} \tag{18}$$

where $\lambda = 2d_4^{-\nu}$ in all cases due to the fact that erroneously decoded antenna index renders error. Decoding of the primary signal erroneously has no importance for the secondary system performance and the secondary system BEP is obtained by replacing (18) into the upper bound expression given by

$$P_b^s \leq \frac{1}{MNt}\sum\nolimits_s\sum\nolimits_{\hat{s}} P^{ST\rightarrow SR}(s \rightarrow \hat{s})\frac{e\,(s \rightarrow \hat{s})}{k} \tag{19}$$

where $k = \log_2 N_t$.

IV. PERFORMANCE EVALUATION

In this section, BEP performance of the proposed protocol is evaluated via computer simulations for different values of N_t and M and compared with the theoretical results of the previous section. Performance comparisons with non-cooperation case and the spectrum sharing protocol given in [11] which exploits M-PSK at both users and the superposition coding technique at ST, are presented. During computer simulations and for analytical curves, the path-loss exponent was taken as $\nu = 4$. The system topology was assumed collinear as in [11] where PT and PR are on the coordinates (0,0) and (1,0) while ST moves through X pivot where SR is between PT and ST. The distances were taken as $d_3 = |1 - d_2|$, $d_4 = d_2/2$. All results are shown for $d_2 = 0.5$ and $d_2 = 0.8$ in addition the distance between PT→SR in [11] equals to 0.5.

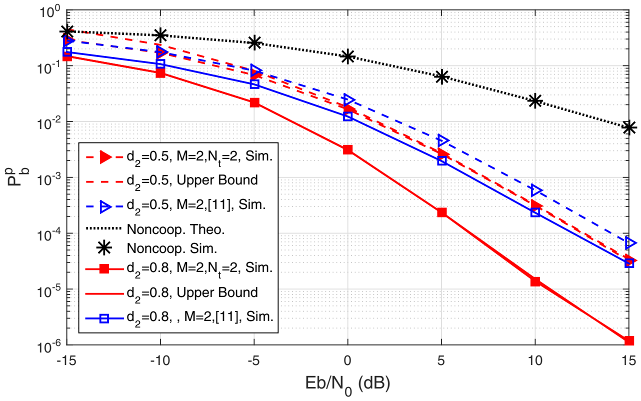

Fig. 2. BEP performance of primary system for $M = 2$, $N_t = 2$

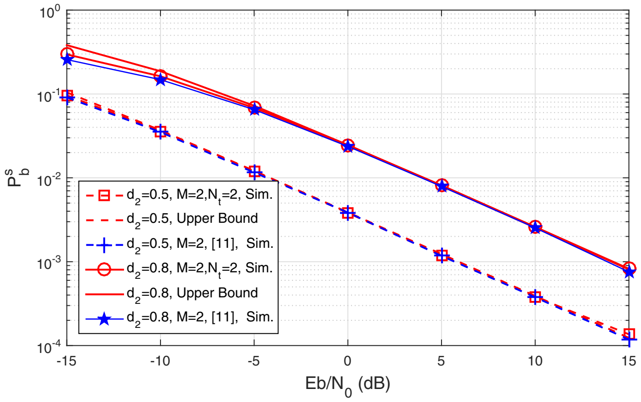

Fig. 3. BEP performance of secondary system for $M = 2$, $N_t = 2$

In terms of primary system BEP performance which is given in Fig.2 for $M = 2$ and $N_t = 2$, the proposed protocol shows better performance compared to two reference schemes, thanks to SM which removes the interference of the ST. Note that for the reference protocol in [11], $M = 2$ for both users and ST allocates %75 of its available power for primary signal which leads to a degradation in primary system's performance along with interference generated by secondary system. Fig.2 illustrates that when $P_b^p = 10^{-4}$ is considered, the proposed protocol outperforms the protocol given in [11] with 1.5 dB and 5.5 dB gains in E_b/N_0 for $d_2 = 0.5$ and $d_2 = 0.8$ respectively and for all values of d_2, cooperative communication is always preferred to non-cooperative case. The secondary system BEP performance is shown in Fig.3 for $M = 2$ and $N_t = 2$. As seen from Fig.3, the proposed protocol and that of [11] give comparable secondary system performance as we might expect in the light of the explanations in [10], and probability of cooperation is higher for the proposed protocol due to $N_t = 2$ antennas at ST hence secondary system realizes spectrum sharing more frequently and it reaches higher throughput.

In Fig.4, the primary system BEP performance is shown for

$M = 4$ and $N_t = 4$. Note from Fig.4 that, the proposed protocol significantly improves the primary system performance compared to the non-cooperation case. Compared with the protocol given in [11] where $M = 4$ for both users and ST employs $\%93.75$ of its available power for primary transmission, there is a threshold value for the distance of the link PT→ ST which is $d_2^{th} = 0.63$ so that when $d_2 > d_2^{th}$, primary system performance for the proposed protocol becomes better than that of [11]. Errors in determination of the transmitted antenna index of ST at PR, degrade the primary system performance. When ST moves closer to PR, primary system performance of the new protocol improves and it becomes better than that of [11]. For example, at $P_b^p = 10^{-4}$, for the primary system, the proposed protocol provides 7.3 dB improvements in E_b/N_0 compared to that of [11] for $d_2 = 0.8$. Even when we consider $d_2 = 0.8$ for the proposed protocol and $d_2 = 0.5$ for that of [11], 6 dB improvement in E_b/N_0 is achieved. From Fig.5 which depicts the secondary system performance for $M = 4$ and $N_t = 4$, it is observed that the secondary system performance is considerably improved compared to that of [11]. The proposed protocol reaches $P_b^s = 10^{-3}$ at 8.83 dB, while that of [11] at 11.87 dB for $d_2 = 0.5$.

In all figures, as d_2 increases, upper bounds converge to exact results due to reduction in antenna index detection errors at receivers.

V. CONCLUSION

In this paper, a new spectrum sharing protocol where a secondary user cooperates with a primary user to access the licensed spectrum, is proposed for overlay cognitive radio networks. It is shown that using SM at ST in cooperative spectrum sharing for cognitive radio, improves the primary and secondary system performance compared to the protocol given in [11] which employs conventional M-PSK modulation at both users and superposition coding at ST. The main reason of this improvement is that the mutual interference is removed by SM since the secondary information is carried by antenna indexes while the primary information is carried by M-PSK modulated signal. On the other hand, in the proposed protocol, all available power at ST is used for both systems and power allocation problem is avoided. The constraint for higher modulation orders which is the result of using most of the power at ST for primary transmission in [11], is not a limitation anymore. In addition, the need for the link between PT → SR which is requisite in [11], is eliminated. For the proposed protocol, the probability of cooperation is increased and consequently the secondary system shares the licensed spectrum more frequently because of all N_t antennas of ST used when reception.

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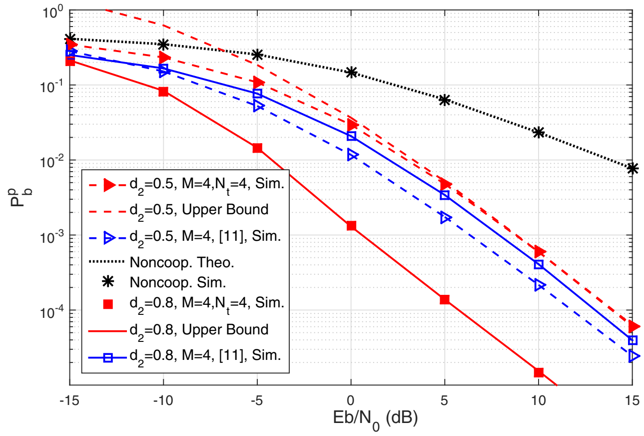

Fig. 4. BEP performance of primary system for $M = 4$, $N_t = 4$

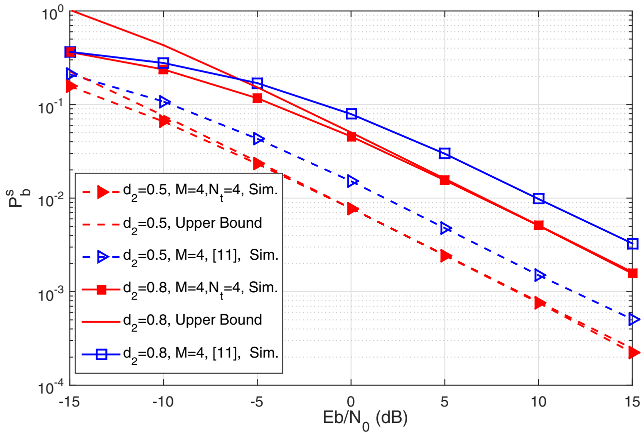

Fig. 5. BEP performance of secondary system for $M = 4$, $N_t = 4$

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