A Cooperative Spectrum Sharing Protocol Using STBC-SM at Secondary User

Mohammadreza Babaei, Ertugrul Basar and Ümit Aygölü

***Abstract*—In this paper, a new cooperative spectrum sharing protocol that employs space-time block coded spatial modulation (STBC-SM) at the secondary user (SU), is proposed for overlay cognitive radio (CR) networks. STBC-SM is applied at the secondary transmitter (ST) which transmits its data by both modulated symbols and antenna combinations while conveying PU's data only by modulated symbols. This protocol avoids interference at both PR and SR. Upper bounds on the bit error probabilities (BEP) of PU and SU are analytically derived for Rayleigh fading channels and supported via computer simulations. Theoretical and simulation results show that the proposed protocol significantly improves SU's BEP performance compared to the reference scheme which causes severe interference at both users by using superposition coding at ST and the non-cooperation case.**

***Index Terms*—Cognitive Radio, Spatial Modulation, STBC.**

I. Introduction

Nowadays, modern wireless communications demand a higher data rate transmission while it is faced with spectrum scarcity due to the poor management of the spectrum. Nevertheless, studies have shown that most of the spectrum is under-utilized in terms of the frequency band, time and geographical locations. Therefore, several approaches are proposed for sharing and efficiently utilizing the available spectrum. Cognitive radio (CR) is a promising approach to solve this problem [1]–[3]. In CR, the licensed spectrum of the primary users (PU) can be shared by the unlicensed secondary users (SU) by means of three basic paradigms which are called as interweave, underlay and overlay. In interweave paradigm, SU transmits by sensing the holes of the PU's spectrum. In underlay paradigm, SU is allowed to use the PU's spectrum subject to an interference constraint. Finally in overlay paradigm, SU cooperates with PU to improve its performance and to realize its transmission. On the other hand, spatial modulation (SM) is a promising mutiple-input-multiple-output (MIMO) transmission technique that draws attention in recent years [4]. In SM, information bits are conveyed by both modulated symbols and active antenna indices. Space time block coded spatial modulation (STBC-SM) is an emerging transmission scheme which combines the space time block coding (STBC) with SM by taking the advantages of both [5].

This work was supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK) under Grant No.114E607.
M. Babaei, E. Basar and Ü. Aygölü are with the Department of Electronics and Communication Eng, Istanbul Technical University, 34469, Istanbul, Turkey, e-mail:{babaei, basarer, aygolu}@itu.edu.tr.

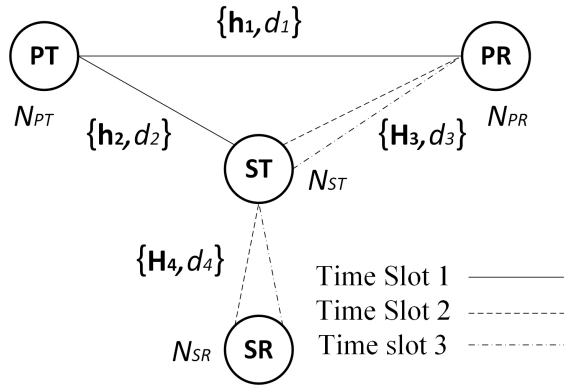

Fig. 1. Considered CR Network Configuration

In this study, a new spectrum sharing protocol which utilizes the STBC-SM scheme at SU is proposed. STBC-SM provides diversity for both PU and SU and increases the transmission rate of the system as well as it avoids interference at the receivers due to the single symbol decoding of Alamouti's STBC [6].

II. System Model and Protocol Description

The considered CR scheme is shown in Fig.1 for which primary transmitter (PT) has one antenna while secondary transmitter (ST), secondary receiver (SR) and primary receiver (PR) have four, N_{SR} and N_{PR} antennas, respectively. In Fig. 1, vectors $\mathbf{h}_1, \mathbf{h}_2$ and matrices $\mathbf{H}_3$, $\mathbf{H}_4$ stand for the channel fading coefficients between corresponding nodes. It is assumed that channel state information (CSI) is perfectly known at the receivers. All noise components are assumed to be samples of additive white Gaussian noise (AWGN) with distribution $C\mathcal{N}(0, N_0)$ where $\sigma^2 = N_0/2$ is the variance per dimension. d_i stands for the distance. The distances are normalized with respect to the link PT→PR where $d_1 = 1$. Bold capital and lower case letters denote matrices and vectors, respectively. $||\cdot||$, $(\cdot)^*$, $(\cdot)^H$ and $(\cdot)^T$ represent Frobenius norm, complex conjugate, Hermitian and transposition, respectively. Omitting indices for simplicity, all channels are exposed to Rayleigh fading with distribution $h \sim C\mathcal{N}(0, d^{-v})$ for which the path loss coefficient are taken as $v = 4$. The transmit power of PT and ST are denoted as P_p and P_s, respectively, where we assume $P_p = P_s = \rho$ in each signaling interval and Υ represents the signal constellation.

In this paper, the main attempt is to use the STBC-SM in an overlay CR system to provide diversity for both users and

978-1-5090-4086-5/16/$31.00 © 2016 IEEE

to increase the data rate of SU by transmitting its information bits also by antenna combinations additionally to modulated symbols. ST transmits PU's and SU's modulated symbols by two active antennas in the last two intervals by the well-known Alamouti STBC matrix [6]. If we assume that ST is equipped by four antennas then, based on [5], ST transmits the data by one of the following four STBC-SM codewords given as

$$\mathcal{X}_1=\{\mathbf{X}_{11},\mathbf{X}_{12}\}=\left\{\begin{pmatrix} x_p & x_s & 0 & 0\\ -x_s^* & x_p^* & 0 & 0\end{pmatrix},\begin{pmatrix} 0 & 0 & x_p & x_s\\ 0 & 0 & -x_s^* & x_p^*\end{pmatrix}\right\},$$
$$\mathcal{X}_2=\{\mathbf{X}_{21},\mathbf{X}_{22}\}=\left\{\begin{pmatrix} 0 & x_p & x_s & 0\\ 0 & -x_s^* & x_p^* & 0\end{pmatrix},\begin{pmatrix} x_s & 0 & 0 & x_p\\ x_p^* & 0 & 0 & -x_s^*\end{pmatrix}\right\}\varphi \tag{1}$$

where $\varphi = e^{j\theta}$, $\mathcal{X}_1$ and $\mathcal{X}_2$ are the codebooks and $\mathbf{X}_{i,j}$ for $i,j=1,2$ are the corresponding codewords for the secondary data blocks 00, 01, 10, 11. x_p and x_s represent PU's and SU's symbols, respectively. In order to maximize the diversity and coding gains of the system, the minimum coding gain distance (CGD) given in [5, Eqs.(5),(9)] is calculated as a function of θ for the 4-QAM. The optimum value of θ maximizing the minimum CGD is found as 0.61 radians. Note that PU and SU use the same constellation. Overall transmission consists of three time slots. In the first time slot, PT transmits its signal to both PR and ST. In the second and third time slots, ST transmits the PU's and SU's signals to both PR and SR using STBC-SM. If ST correctly decodes x_p, it considers one of the STBC-SM codewords based on the information bits of SU during the second and third time slots and transmits to PR and SR. Each receiver decodes its own signal thanks to Alamouti's STBC. In the case that ST fails to decode x_p, PR tries to decode the data only from the direct link PT→PR and SU transmits only its own signal. In the first time slot, the received signal vectors at PR and ST are given as

$$\mathbf{y}_1 = \sqrt{P_p}x_p\mathbf{h}_1 + \mathbf{n}_1 \tag{2}$$
$$\mathbf{y}_2 = \sqrt{P_p}x_p\mathbf{h}_2 + \mathbf{n}_2 \tag{3}$$

where $\mathbf{h}_1$ and $\mathbf{h}_2$ denote $1\times N_{PR}$ and 1×2 fading coefficients vectors of the links from PT→PR and PT→ST and $\mathbf{n}_1$ and $\mathbf{n}_2$ stand for $1\times N_{PR}$ and 1×2 AWGN noise vectors at PR and ST, respectively. Note that to use minimum number of RF chains, ST receives only by two of its antennas and applies maximum ratio combining (MRC) to decode the primary signal. The received signals at PR and SR during the second and third time slots are given as

$$\mathbf{Y}_3 = \sqrt{P_s}\mathbf{X}_x\mathbf{H}_3 + \mathbf{N}_3 \tag{4}$$
$$\mathbf{Y}_4 = \sqrt{P_s}\mathbf{X}_x\mathbf{H}_4 + \mathbf{N}_4 \tag{5}$$

where $\mathbf{H}_3$ and $\mathbf{H}_4$ represent $4\times N_{PR}$ fading coefficients matrices of the links ST→PR and ST→SR for $N_{PR}=N_{SR}$, $\mathbf{N}_3$ and $\mathbf{N}_4$ stand for $2\times N_{PR}$ AWGN noise matrices at PR and SR and $\mathbf{X}_x$ is the codeword selected from (1), respectively.

III. Performance Analysis

In this section, theoretical upper bound expressions for the bit error probability (BEP) of PU and SU in the context of the proposed spectrum sharing protocol are derived. Note that, when PR or SR decodes the signals transmitted from ST they try to correctly acquire only their own signal; therefore, if the antenna combination is erroneously decoded at PR, an error would not occur. Furthermore, BEP of SU is similar to the STBC-SM scheme given in [5].

A. Primary user BEP performance

The overall BEP upper bound for PU can be expressed as,

$$P^b_{PR} \le P^b_{PT\to PR}P^s_{PT\to ST} + (1-P^s_{PT\to ST})P^b_{MAC} \tag{6}$$

where P^b_{MAC} is the BEP at PR when ST successfully decodes the received signal at first time slot. Here, MAC denotes the multiple access channel formed by the PT→PR and ST→PR links. $P^b_{PT\to PR}$ is the BEP of the direct link and $P^s_{PT\to ST}$ denotes the symbol error probability (SEP) of the link PT→ST. For the link PT→ST, SEP is considered since ST cooperates only when it correctly decodes the symbol x_p and in practice if the signal-to-noise ratio (SNR) is above a predefined threshold, ST will assume that the received symbol block is correctly decoded.

1) Calculation of P^b_{MAC}: An upper bound on the BEP for the MAC link with destination PR is derived by considering the STBC-SM protocol. The received signals for the MAC when ST correctly decodes the signal x_p at first time slot can be rewritten from (2) and (4) as

$$\mathbf{Y}_{MAC} = \sqrt{\rho}\mathbf{X}_M\mathbf{H}_{MAC} + \mathbf{N}_{MAC} \tag{7}$$

where $\mathbf{H}_{MAC} = \begin{bmatrix}\mathbf{h}_1^T & \mathbf{H}_3^T\end{bmatrix}^T$ and $\mathbf{N}_{MAC} = \begin{bmatrix}\mathbf{n}_1^T & \mathbf{N}_3^T\end{bmatrix}^T$ are the channel fading coefficients and AWGN matrices with dimensions $5\times N_{PR}$ and $3\times N_{PR}$, respectively. We assume that $\mathbf{H}_{MAC}$ is perfectly known at PR and remains constant during the transmission of one codeword and independently changes from a codeword to another. $\mathbf{X}_M$ is the 3×5 STBC-SM transmission matrix and is given as

$$\mathbf{X}_M = \left\{\begin{pmatrix} x_p & \mathbf{0}_{1\times 4}\\ \mathbf{0}_{2\times 1} & \mathbf{X}_{11}\end{pmatrix},\begin{pmatrix} x_p & \mathbf{0}_{1\times 4}\\ \mathbf{0}_{2\times 1} & \mathbf{X}_{12}\end{pmatrix},\right.$$
$$\left.\begin{pmatrix} x_p & \mathbf{0}_{1\times 4}\\ \mathbf{0}_{2\times 1} & \mathbf{X}_{21}\end{pmatrix},\begin{pmatrix} x_p & \mathbf{0}_{1\times 4}\\ \mathbf{0}_{2\times 1} & \mathbf{X}_{22}\end{pmatrix}\right\} \tag{8}$$

which is selected based on SU's information bits where $\mathbf{0}_{a\times b}$ is the $a\times b$ all-zero matrix. Maximum likelihood (ML) decoder at SR must search over all possible $\omega = c\times M_s\times M_s$ transmission matrices where $c=4$ is the number of codewords. PU's and SU's signal constellation sizes are $M_p = M_s = 4$. ML detector decides to the transmission matrix which minimizes the following metric

$$\hat{\mathbf{X}}_M = \underset{\mathbf{X}_M}{\operatorname{argmin}}||\mathbf{Y}_{MAC} - \sqrt{\rho}\mathbf{X}_M\mathbf{H}_{MAC}||^2. \tag{9}$$

To obtain a lower detection complexity than (9), (7) can be expressed in equivalent form as

$$\mathbf{y} = \sqrt{\rho}\mathcal{H}_{MAC}\mathbf{x} + \mathbf{n} \tag{10}$$

where $\mathbf{x} = \begin{bmatrix}x_p & x_p & x_s\end{bmatrix}^T$ is the equivalent data vector, $\mathbf{y}$ and $\mathbf{n}$ are the $3N_{PR}\times 1$ vectors and $\mathcal{H}_{MAC}$ represents the

$$\mathcal{H}_0=\begin{pmatrix} h_1 & 0 & 0 \\ 0 & h_{1,1} & h_{1,2} \\ 0 & h_{1,2}^* & -h_{1,1}^* \\ \vdots & \vdots & \vdots \\ h_{nR} & 0 & 0 \\ 0 & h_{nR,1} & h_{nR,2} \\ 0 & h_{nR,2}^* & -h_{nR,1}^* \end{pmatrix}, \mathcal{H}_1=\begin{pmatrix} h_1 & 0 & 0 \\ 0 & h_{1,3} & h_{1,4} \\ 0 & h_{1,4}^* & -h_{1,3}^* \\ \vdots & \vdots & \vdots \\ h_{nR} & 0 & 0 \\ 0 & h_{nR,3} & h_{nR,4} \\ 0 & h_{nR,4}^* & -h_{nR,3}^* \end{pmatrix}, \mathcal{H}_2=\begin{pmatrix} h_1 & 0 & 0 \\ 0 & h_{1,2}\varphi & h_{1,3}\varphi \\ 0 & h_{1,3}^*\varphi^* & -h_{1,2}^*\varphi^* \\ \vdots & \vdots & \vdots \\ h_{nR} & 0 & 0 \\ 0 & h_{nR,2}\varphi & h_{nR,3}\varphi \\ 0 & h_{nR,3}^*\varphi^* & -h_{nR,2}^*\varphi^* \end{pmatrix}, \mathcal{H}_3=\begin{pmatrix} h_1 & 0 & 0 \\ 0 & h_{1,4}\varphi & h_{1,1}\varphi \\ 0 & h_{1,1}^*\varphi^* & -h_{1,4}^*\varphi^* \\ \vdots & \vdots & \vdots \\ h_{nR} & 0 & 0 \\ 0 & h_{nR,4}\varphi & h_{nR,1}\varphi \\ 0 & h_{nR,1}^*\varphi^* & -h_{nR,4}^*\varphi^* \end{pmatrix}$$

$3N_{PR}\times 3$ channel matrix which has four different realizations and is given at the top of the third page where $h_{i,j}$ is the channel fading coefficient between jth transmit and ith receive antennas of ST→PR link and h_i for $i=1,...,N_{PR}$ are the channel coefficients of PT→PR link. Applying the decoding steps of the STBC-SM scheme, PR estimates x_p and x_s from the following metrics, respectively:

$$\hat{x}_p = \underset{x_p\in\Upsilon}{\operatorname{argmin}}||\mathbf{y}-\sqrt{\rho}\mathbf{H}_{l,1,2}\mathbf{x}_{1,2}||^2,$$
$$\hat{x}_s = \underset{x_s\in\Upsilon}{\operatorname{argmin}}||\mathbf{y}-\sqrt{\rho}\mathbf{h}_{l,3}x_s||^2 \quad (11)$$

where $\mathbf{x}_{1,2}=\begin{bmatrix} x_p & x_p \end{bmatrix}^T$, $\mathcal{H}_{MAC}=\begin{bmatrix} \mathbf{h}_{l,1} & \mathbf{h}_{l,2} & \mathbf{h}_{l,3} \end{bmatrix}$ and $\mathbf{h}_{l,j}$ for $j=1,2,3$ is a column vector. $\mathbf{H}_{l,1,2}$ is the matrix containing the two first columns of $\mathcal{H}_{MAC}$. Considering the antenna combination l, the metrics for ML decoding are given as

$$m_{p,l} = \min_{x_p\in\Upsilon}||\mathbf{y}-\sqrt{\rho}\mathbf{H}_{l,1,2}\mathbf{x}_{1,2}||^2,$$
$$m_{s,l} = \min_{x_s\in\Upsilon}||\mathbf{y}-\sqrt{\rho}\mathbf{h}_{l,3}x_s||^2. \quad (12)$$

ML decoder chooses antenna combination with the minimum metric as $\hat{l}=\underset{l}{\operatorname{argmin}}\ (m_{p,l}+m_{s,l})$ and replaces $\hat{l}$ in (11) to obtain $(\hat{x}_p,\hat{x}_s)$. Finally, PR considers only $\hat{x}_p$ and ignores $\hat{x}_s$ and the antenna combination $\hat{l}$.

Theoretical Analysis of the MAC link: This section concerns with the BEP upper bound of the MAC link in which $k_p=\log_2 M_p$ bits are transmitted during three time slots by one of the STBC-SM codewords. The conditional pairwise error probability (CPEP) of the MAC link can be expressed as

$$P(\mathbf{X}_M\rightarrow\hat{\mathbf{X}}_M|\mathbf{H}_{MAC})=Q\left(\sqrt{\frac{\rho}{2}}||(\mathbf{X}_M-\hat{\mathbf{X}}_M)\mathbf{H}_{MAC}||\right) \quad (13)$$

where $Q(x)=\left(1/\sqrt{2\pi}\right)\int_x^\infty \exp(-y^2/2)dy$. Averaging over the channel matrix with Rayleigh fading coefficients and using the moment generation function (MGF), the PEP can be calculated as [7]

$$P(\mathbf{X}_M\rightarrow\hat{\mathbf{X}}_M)=\frac{1}{\pi}\int_0^{\pi/2}\left(\frac{1}{1+\xi}.\frac{1}{1+\kappa}.\frac{1}{1+\beta}\right)^{N_{PR}}d\phi \quad (14)$$

where $\xi=(\rho\lambda_{i,j,1}/4\sin^2\phi)$, $\kappa=(\rho\lambda_{i,j,2}/4\sin^2\phi)$, $\beta=(\rho\lambda_{i,j,3}/4\sin^2\phi)$, $\lambda_{i,j,1}$, $\lambda_{i,j,2}$ and $\lambda_{i,j,3}$ are the eigenvalues of the 3×3 distance matrix $(\mathbf{X}_M-\hat{\mathbf{X}}_M)(\mathbf{X}_M-\hat{\mathbf{X}}_M)^H$. Therefore, the BEP upper bound of the MAC link is obtained by substituting (14) in

$$P_{MAC}^b\leq\frac{1}{\omega}\sum_{i=1}^{\omega}\sum_{j=1,i\neq j}^{\omega}\frac{P\left(\mathbf{X}_M\rightarrow\hat{\mathbf{X}}_M\right)n_{i,j}}{k_p} \quad (15)$$

where $n_{i,j}$ is the number of erroneous bits between the matrices $\hat{\mathbf{X}}_M$ and $\mathbf{X}_M$ with respect to PU.

2) Calculation of $P_{PT\rightarrow ST}^s$ and $P_{PT\rightarrow PR}^b$: A single-input-multiple-output (SIMO) system is considered for the link PT→ST and the SEP for the proposed protocol is calculated by the MRC technique. For MRC with L independent and identically distributed Rayleigh fading channels, the probability density function (pdf) of SNR (γ) can be expressed as [8]

$$p_{MRC}(\gamma)=\frac{\gamma^{L-1}}{(L-1)!\bar{\gamma}_c^L}\exp(-\frac{\gamma}{\bar{\gamma}_c}) \quad (16)$$

where L is taken equal to two for the sake of minimum RF chain utilization and $\bar{\gamma}_c$ is the average SNR per channel defined as $\bar{\gamma}_c=\frac{E_s}{N_0}E[h_{21}^2]=\frac{E_s}{N_0}E[h_{22}^2]$ with E_s being the average energy per symbol. SEP of the link $P_{PT\rightarrow ST}^s$ can be derived by averaging CSEP [7] over the pdf of γ in Rayleigh fading channel given in (16) as

$$P_{PT\rightarrow ST}^s=\int_0^\infty P(e|\gamma)P_{MRC}(\gamma)d\gamma. \quad (17)$$

Average SEP for the link PT→ST over Rayleigh fading under SIMO reception can be obtained numerically from [8][1]. When ST cannot successfully decode the primary signal and PR has to decode x_p by only considering the direct link, assuming Gray coding of the constellation symbols, the BEP of $P_{PT\rightarrow PR}^b$ can be expressed as

$$P_{PT\rightarrow PR}^b\simeq P_{PT\rightarrow ST}^s/k_p \quad (18)$$

where for the link PT→PR, we assume $L=N_{PR}$ which indicates the number of the antennas at PR and $k_p=\log_2 M_p$.

Finally, by substituting (17), (18) and (15) in (6) the overall BEP of PU can be calculated. Note that, PU cares only its own information and does not consider the erroneous antenna combinations and SU's modulated symbols since Alamouti STBC allows single symbol decoding.

[1]The term $(2k-1)$ in the denominator of (18) in [8] should be corrected as $(2k+1)$.

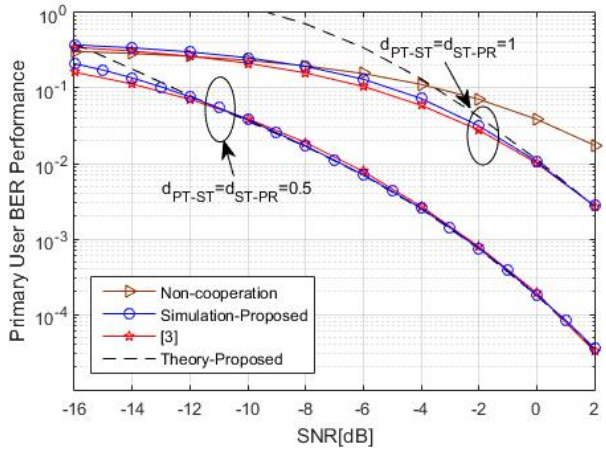

Fig. 2. Primary User BER Performance for $M_p = M_s = 4$.

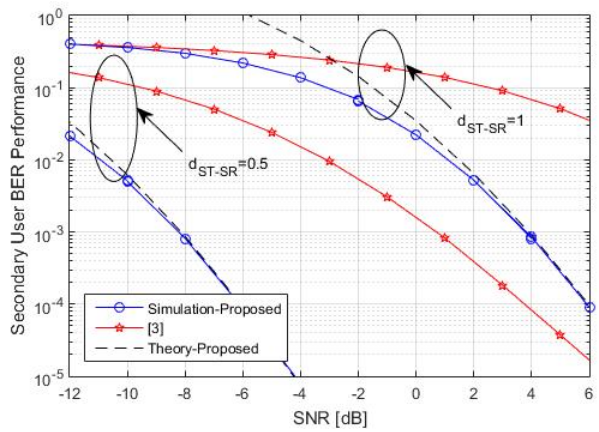

Fig. 3. Secondary User BER Performance for $M_p = M_s = 4$.

B. Secondary user BEP performance

SR considers only the second and third time slots during which its own information is transmitted. The proposed protocol guarantees the periodic transmission of the SU even ST could not correctly decode the PU's signal while other systems given in the literature stay silent when ST is unable to correctly decode the PU's signal. SU uses STBC-SM scheme and transmits its information both by antenna combinations and modulated symbols. Based on [5], the upper bound of BEP for the SU can be given as

$$P^b \leq \frac{1}{\omega} \sum_{i=1}^{\omega} \sum_{j=1, i \neq j}^{\omega} \frac{P\left(\mathbf{X}_i \rightarrow \mathbf{X}_j\right) n_{i,j}}{k_s}. \tag{19}$$

In (19), $k_s = \log_2 M_s + \log_2 c$ is the number of transmitted secondary bits and $n_{i,j}$ is the number of erroneous bits for SU.

IV. Performance Evaluation

In this section, we present the PU's and SU's BER performance results for the proposed CR scheme based on the analytical results of the previous sections and computer simulations. In the proposed protocol, PT and ST transmit with total powers of ρ and 4ρ, where PU and SU consume total powers of 3ρ and 2ρ, respectively. The same power consumptions are assumed for PU and SU when [3] is considered, to make a fair comparison. The power allocation factor α for 4-QAM is taken as 0.93 from [3]. Furthermore, all links are assumed equidistant for the proposed CR scheme and for that of [3]. Markers with solid lines in Figs. 2 and 3 denote the simulation results and dashed lines are for theoretical upper bounds. As seen from Figs. 2 and 3, simulation curves and the theoretical upper bounds match very well for the proposed protocol with increasing SNR values.

In Fig. 2, we compare PU's BER performance for the proposed spectrum sharing protocol. From Fig. 2, 3 and 9 dB SNR gains are provided at a BER value of 10^{-2} with $d_{ST \rightarrow SR} = 0.5$ and $d_{ST \rightarrow SR} = 1$, respectively, compared to the non-cooperation case. The proposed protocol provides comparable BER performance for PU with that given in [3]. However, from Fig. 3, significant improvements are obtained in SU's BER performance compared to that of [3]. Nearly, 10 dB and 6 dB SNR gains are provided at a BER value of 10^{-4} with $d_{ST \rightarrow SR} = 0.5$ and at a BER value of 10^{-1} with $d_{ST \rightarrow SR} = 1$, respectively, compared to [3].

V. Conclusion

In this paper, a new protocol for cooperative spectrum sharing in overlay CR networks has been introduced. This protocol utilizes the STBC-SM at SU to provide interference-free transmission between PU and SU. Theoretical upper bounds on the BER of PU and SU are analytically derived and supported via computer simulations. The results show that the new protocol not only provides significant improvement in the SU's BER performance compared to the reference CR protocol but also an increase in SU's spectral efficiency without compromising PU's BER performance.

References

[1] E. Biglieri, A. J. Goldsmith, L. J. Greenstein, N. B. Mandayam, and H. V. Poor, *Principles of Cognitive Radio*. Cambridge University Press, New York, 2013.

[2] M. Babaei and Ü.Aygölü, "Interference-free spectrum sharing in cognitive radio based on combined CIOD and STBC," in *2016 Int. Wireless Commun. and Mobile Computing Conf. (IWCMC)*, Sept. 2016, pp. 626–631.

[3] Y. Han, A. Pandharipande, and S. H. Ting, "Cooperative decode-and-forward relaying for secondary spectrum access," *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 4945–4950, Oct. 2009.

[4] R. Y. Mesleh, H. Haas, S. Sinanovic, C. W. Ahn, and S. Yun, "Spatial modulation," *IEEE Trans. Veh. Tech.*, vol. 57, no. 4, pp. 2228–2241, July 2008.

[5] E. Basar, Ü.Aygölü, E. Panayirci, and H. V. Poor, "Space-time block coded spatial modulation," *IEEE Trans. Commun.*, vol. 59, no. 3, pp. 823–832, Mar. 2011.

[6] S. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[7] J. G. Proakis and M. Salehi, *Digital Communications*. McGraw-Hill, New York, 2008.

[8] J. Lu, T. Tjhung, and C. Chai, "Error probability performance of L-branch diversity reception of MQAM in Rayleigh fading," *IEEE Trans. Commun.*, vol. 46, no. 2, pp. 179–181, Feb. 1998.