Cooperative Spectrum Sharing Using Transmit Antenna Selection for Cognitive Radio Systems

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Abstract. In this paper, a spectrum sharing scheme that utilizes the two-phase cooperative decode-and-forward relaying protocol is proposed. The cooperation between primary (i.e. licensed) and secondary (i.e. unlicensed) system helps in achieving the desired target rate for the primary system and spectrum access for cognitive (i.e. secondary) system. In the proposed scheme, secondary transmitter which is equipped with multiple antennas uses transmit antenna selection to improve the primary's performance by reducing the interference level of secondary signal at primary receiver, while keeping the performance of secondary system unaffected. Closed form expressions for outage probability have been derived for both systems by varying transmit power level at secondary transmitter. The theoretical results have been compared with simulation results to validate the analysis done in this paper.

Keywords: Spectrum sharing · Transmit antenna selection

1 Introduction

Radio frequency (RF) spectrum, considered as the most limited resource for wireless communications has been congested due to its diversified use. However large portion of the spectrum remains unutilized because of the variation in spectrum utilization with respect to time and location. This unutilized spectrum is termed as "spectrum holes" or white spaces. Cognitive radio has emerged as a solution to address this spectrum scarcity problem [1]-[2]. Moreover, the generation of mobile system is continuously upgrading in every 10 years because of the growing demand of people in communicating as well as in accessing the information. Fifth generation wireless systems, commonly abbreviated as "5G", is the next step in this continuous innovation and evolution of wireless technology. 5G has been envisioned to support 1,000-fold gains in capacity. Cognitive radio can be seen as a promising step towards 5G technology. It can sense and identify the unused frequency bands and use them for its own (unlicensed) transmission. Beside the interweave technique [3]-[4], in which the underutilized spectrum is accessed opportunistically by the cognitive user, cooperative spectrum sharing

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[5] has been recently proposed as an alternative framework to realize a cognitive radio network. In cooperative spectrum sharing (CSS), secondary transmitter relays the data of primary system in order to get spectrum access over licensed band of primary user. In this architecture, primary and secondary system consists of transmitter receiver pair known as primary transmitter (PT) - primary receiver (PR) and secondary transmitter (ST) - secondary receiver (SR) respectively, are allowed to coexist in the same frequency band with the assurance that secondary system will improve the performance of primary system.

Substantial amount of literature has demonstrated the performance of conventional CSS protocol under decode and forward relaying [6]-[7]. In these schemes, whenever the instantaneous transmission rate of primary system drops below the target rate, it seeks cooperation from the neighbouring terminals which may help it in achieving the target rate. Secondary transmitter (ST) "disguises" itself as a relay and collaborates with primary system by forwarding its data to the destination. Primary system returns the favour by helping the secondary system with spectrum access. However, the performance of CSS protocols is limited by the interference tolerable at PR from ST. Moreover, most of these schemes have been confined to single antenna system. Recently, some work has also been proposed where multiple antenna CR system have been used to enhance the performance of both systems [8]-[9]. The authors in [8] proposed a scheme with multiple antennas at ST node which utilizes zero-forcing precoding technique in order to cancel the interference at PR caused due to presence of cognitive system. But the application of this precoding technique requires perfect transmit channel state information (CSI) at ST. Assuming that perfect transmit CSI is available at ST may not be practically feasible in the case of fading environment. Moreover, in [8], as ST is working as an amplify and forward relay, therefore while forwarding the data from PT to PR, it will amplify both the required signal as well as noise received from PT. In [9], authors have proposed a CSS scheme in which ST is equipped with two antennas. Both the antennas receive primary's data which is decoded at ST and then forward this data by selecting one of the two antennas randomly. This will improve the performance of primary system when compared to conventional CSS scheme because of increase in probability of successful decoding of primary's data. However it still suffers from the drawback on the amount of interference at PR due to presence of secondary system which is same as conventional CSS system.

In this paper, we have proposed a transmit antenna selection [10] based scheme with multiple antennas at ST node which can alleviate the drawbacks of [6]-[7], [9]. Moreover, unlike [8], proposed scheme doesn't require perfect CSI, it just requires partial CSI feedback to select the best among the set of antennas at ST (that maximizes the post processing SNR at PR). This reduces the transmitter complexity and lowers the feedback bandwidth while preserving the gains from diversity [11]-[12]. In the proposed scheme, once primary and secondary system enter into CSS, PT broadcasts its data in half of the overall time slot (represented as phase 1) which is received by all the present nodes i.e. PR, ST and SR. After receiving primary's data ST will try to decode it. In the remaining half of the time slot (phase 2), ST chooses the antenna having larger instantaneous gain between ST and PR for primary's data transmission and secondary's data is transmitted via other antenna which has comparatively lower gain as shown in Fig. 1. Finally, the data received in both the phases, is decoded using maximum rate combining (MRC) at PR. However, if ST fails to decode primary's data, it will remain silent in phase 2. This technique is advantageous in two ways; first, we can improve the performance of primary system by reducing the interference caused due to secondary's data at PR. Second, the performance of secondary system is unaffected because of interference cancellation at SR. Moreover, when ST works as a pure relay and transfer only primary's data, in such a scenario, ST can also be seen as a selection combiner [13]. Consequently, PR will receive its signal from a selection combiner and a direct link (PT-PR). The performance of primary as well as secondary system has been analysed by deriving the closed form expressions for outage probability. The results demonstrate the considerable improvement in the performance of primary system along with spectrum access for secondary system.

Throughout this paper, a complex Gaussian random variable (RV) Z with mean μ and variance σ^2 is denoted as $Z \sim \mathcal{CN}(\mu, \sigma^2)$. An exponentially distributed RV X with mean $\frac{1}{\lambda}$ is denoted as $X \sim \varepsilon(\lambda)$. $\sim$ is used to indicate "has the distribution of" and i.i.d is used to represent independent and identically distributed. The transpose of a matrix A is denoted by A^T. $f_X(x)$ symbolizes the probability density function (PDF) of RV X and $f_{X,Y}(x, y)$ symbolizes the joint PDF of RVs X and Y. Moreover, $F_X(x)$ symbolizes the cumulative distribution function (CDF) of RV X and $F_{X,Y}(x, y)$ symbolizes the joint CDF of RVs X and Y. The rest of the paper is organized as follows. Section 2 describes the proposed system model and obtains the analytical results for outage probability of primary and secondary systems. Section 3 discusses the simulation results and finally section 4 concludes the paper.

2 Model Description with Performance Analysis

2.1 System Model

The primary and secondary system consists of transmitter receiver pair known as PT-PR and ST-SR respectively. We have considered multiple antennas at ST, named as ST1 and ST2.[1] Channels between the links are modeled as Rayleigh flat fading channels and the channel coefficients between PT-PR, PT-SR, PT-ST(1), PT-ST(2), ST(1)-PR, ST(2)-PR, ST(1)-SR, ST(2)-SR is $h_1, h_2, h_3, h_4, h_5, h_6, h_7, h_8$ respectively. Here, $h_i \sim \mathcal{CN}(0, d_i^{-v})$ where, v is the path loss component and d_i is the normalized distance between the corresponding link. The normalization is done with respect to the distance between PT-PR link therefore, $d_1 = 1$. The instantaneous gain of each channel is given as $\gamma_i = |h_i|^2$ where, $\gamma_i \sim \varepsilon(d_i^v)$.

[1] For ease of analysis, we have assumed that ST is equipped with two antennas, however the results obtained can be easily extrapolated to scenarios where ST is equipped with multiple (>2) antennas.

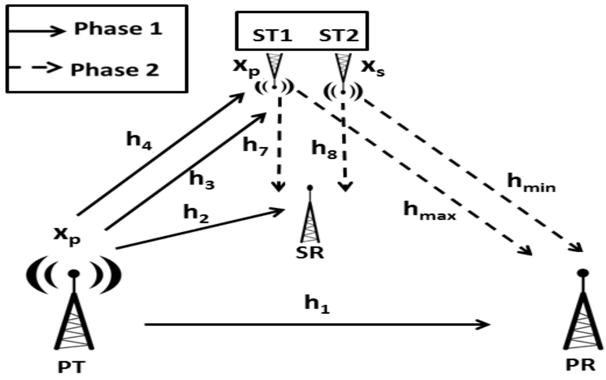

Fig. 1. Transmission Phases

2.2 System Equations

In transmission phase 1, PT broadcasts primary signal i.e. x_p which is received by all the nodes. Therefore, signal received at PR is given as

$$y_{PR}^{(1)} = \sqrt{P_p} x_p h_1 + n_{11} \tag{1}$$

where, P_p is the power assigned to PT and $n_{ij} \sim \mathcal{CN}(0, \sigma^2)$ is the AWGN in i^{th} phase of transmission at j^{th} receiver and j=1,2,3 corresponds to PR, SR, ST respectively. The signal received at SR in phase 1 is given by

$$y_{SR}^{(1)} = \sqrt{P_p} x_p h_2 + n_{12}. \tag{2}$$

Since ST is equipped with two antennas, hence the signal received at ST can be given as

$$\begin{bmatrix} y_{ST}^{(1)} \\ y_{ST}^{(2)} \end{bmatrix} = \sqrt{P_p} \begin{bmatrix} h_3 \\ h_4 \end{bmatrix} x_p + n_{13}. \tag{3}$$

In transmission phase 2, ST decodes the primary signal (i.e. x_p) and transmits it along with its own signal (i.e. x_s). As ST has two antennas, in order to reduce interference at PR, it will transmit x_p and x_s from the antenna which provides maximum and minimum instantaneous gain between ST-PR respectively. Therefore, signal received at PR in phase 2 is given by

$$y_{PR}^{(2)} = \left[h_{\max}\ h_{\min} \right] z + n_{21} \tag{4}$$

where, $h_{\max} = \begin{cases} h_5 \text{ if } \gamma_5 > \gamma_6 \\ h_6 \text{ if } \gamma_5 \le \gamma_6 \end{cases}$, $h_{\min} = \begin{cases} h_6 \text{ if } \gamma_5 > \gamma_6 \\ h_5 \text{ if } \gamma_5 \le \gamma_6 \end{cases}$,
$z = \left[\sqrt{\alpha P_s} x_p \ \sqrt{(1-\alpha) P_s} x_s \right]^T$, α and $(1-\alpha)$ is the fraction of power provided by the secondary transmitter to transmit primary signal and secondary signal

respectively. Therefore the signal received at PR in the both phases can be written as

$$\begin{bmatrix} y_{PR}^{(1)} \\ y_{PR}^{(2)} \end{bmatrix} = \begin{bmatrix} \sqrt{P_p} h_1 & 0 \\ \sqrt{\alpha P_s} h_{\max} & \sqrt{(1-\alpha) P_s} h_{\min} \end{bmatrix} \begin{bmatrix} x_p \\ x_s \end{bmatrix} + \begin{bmatrix} n_{11} \\ n_{21} \end{bmatrix}. \quad (5)$$

Now, the signal received at SR in phase 2 is given by

$$y_{SR}^{(2)} = [h_7 \; h_8] z + n_{22} \quad (6)$$

where, $z = \left[\sqrt{\alpha P_s} x_p \; \sqrt{(1-\alpha) P_s} x_s\right]^T$. Using (2), SR will estimate the primary signal (i.e $\hat{x_p}$) which helps in cancelling the x_p signal received in phase 2 and hence the overall signal received at SR after applying interference cancellation is given as

$$y_{SR} = \sqrt{(1-\alpha) P_s} h_8 x_s + n_{22}. \quad (7)$$

2.3 Outage Probability of Primary System

Outage at primary system occurs when system fails to achieve the target transmission rate (R_{pt}). There are two such cases: In first case, outage occurs if ST is unable to decode the primary signal in phase 1 and along with this, the link between PT-PR also fails to achieve R_{pt}, or in second case, outage occur if ST successfully decodes x_p but still overall rate achieved at PR is less than R_{pt}. Therefore, the expression for outage probability at primary system is given as

$$P_{out}^{PR} = P[R_{11} < R_{pt}] P[R_{13} < R_{pt}] + P[R_{13} > R_{pt}] P[R_{MRC} < R_{pt}] \quad (8)$$

where, R_{11} is the transmission rate achieved in phase 1 between PT-PR link, R_{13} is the transmission rate achieved between PT-ST in phase 1 and R_{MRC} is the rate achieved at PR after applying MRC of both transmission phases. Solving for (8),

$$R_{11} = \frac{1}{2} \log_2 \left(1 + \frac{P_p \gamma_1}{\sigma^2}\right). \quad (9)$$

The factor $\frac{1}{2}$ is due to the fact that the whole transmission is divided into two phases.

$$P[R_{11} < R_{pt}] = P\left[\gamma_1 < \frac{\sigma^2 \rho}{P_p}\right] = 1 - e^{-\frac{\sigma^2 \rho}{P_p}}. \quad (10)$$

as, $\rho = 2^{2R_{pt}} - 1, \gamma_1 \sim \varepsilon(1)$.

$$R_{13} = \frac{1}{2} \log_2 \left(1 + \frac{P_p \gamma_3}{\sigma^2} + \frac{P_p \gamma_4}{\sigma^2}\right) \quad (11)$$

and

$$P[R_{13} < R_{pt}] = P\left[\gamma_3 + \gamma_4 < \frac{\sigma^2 \rho}{P_p}\right]. \quad (12)$$

We assume that the distances between the antennas at ST is negligible as compare to distance between the nodes, hence $d_3 = d_4, d_5 = d_6, d_7 = d_8$. Therefore, γ_3 and γ_4 are i.i.d and hence $f_{\gamma_3,\gamma_4}(\gamma_3,\gamma_4) = f_{\gamma_3}(\gamma_3)f_{\gamma_4}(\gamma_4)$ where,

$$f_{\gamma_3} = \begin{cases} d_3^v e^{-d_3^v \gamma_3} & \gamma_3 > 0 \\ 0 & \text{otherwise.} \end{cases}$$

Therefore,

$$\begin{aligned} P[R_{13} < R_{pt}] &= \int_0^{\frac{\sigma^2\rho}{P_p}} \int_0^{\frac{\sigma^2\rho}{P_p}-\gamma_4} f_{\gamma_3,\gamma_4}(\gamma_3,\gamma_4) d\gamma_3 d\gamma_4 \\ &= 1 - \left[\left(1 + \frac{\sigma^2\rho}{P_p} d_3^v\right) e^{-\frac{\sigma^2\rho}{P_p} d_3^v} \right]. \end{aligned} \tag{13}$$

Moreover,

$$P[R_{13} > R_{pt}] = \left[\left(1 + \frac{\sigma^2\rho}{P_p} d_3^v\right) e^{-\frac{\sigma^2\rho}{P_p} d_3^v} \right]. \tag{14}$$

The rate at PR after MRC is obtained as

$$R_{\text{MRC}} = \frac{1}{2} \log_2(1 + \text{SNR}_{\text{MRC}}) \tag{15}$$

where, $\text{SNR}_{\text{MRC}} = \frac{P_p\gamma_1}{\sigma^2} + \frac{\alpha P_s \gamma_{\max}}{(1-\alpha)P_s\gamma_{\min}+\sigma^2}$, $\gamma_{\max} = \max(\gamma_5,\gamma_6), \gamma_{\min} = \min(\gamma_5,\gamma_6)$. Therefore,

$$P[R_{MRC} < R_{pt}] = P\left[\frac{P_p\gamma_1}{\sigma^2} + \frac{\alpha P_s \gamma_{\max}}{(1-\alpha)P_s\gamma_{\min}+\sigma^2} < \rho \right]. \tag{16}$$

After solving, we get

$$\begin{aligned} P[R_{MRC} < R_{pt}] = 1 - e^{-\frac{\sigma^2}{P_p}(\rho - \frac{\alpha}{1-\alpha})} + \frac{2}{n} e^{-\frac{d_5^v \sigma^2 \rho}{\alpha P_s} + \frac{mp}{n}} \\ \left(Ei\left[\frac{p\sigma^2}{P_p}\left(\rho - \frac{\alpha}{1-\alpha}\right) - \frac{mp}{n} \right] - Ei\left[-\frac{mp}{n} \right] \right) \end{aligned} \tag{17}$$

where, $\alpha \le \frac{\rho}{\rho+1}$, $m = \left(\frac{1-\alpha}{\alpha}\right)\rho + 1$, $n = \left(\frac{1-\alpha}{\alpha}\right)\frac{P_p}{\sigma^2}$, $p = \frac{d_5^v P_p}{\alpha P_s} - 1$ and Ei represents the exponential integral defined as $Ei(x) = -\int_{-x}^{\infty} \frac{e^{-t}}{t} dt$. For detailed derivation of (17), please refer to Appendix A. After substituting (10), (13), (14) and (17) in (8), we get

$$\begin{aligned} P_{out}^{PR} = (1 - e^{-\frac{\sigma^2\rho}{P_p}}) \left(1 - \left[\left(1 + \frac{\sigma^2\rho}{P_p} d_3^v\right) e^{-\frac{\sigma^2\rho}{P_p} d_3^v} \right] \right) + \left(\left[\left(1 + \frac{\sigma^2\rho}{P_p} d_3^v\right) e^{-\frac{\sigma^2\rho}{P_p} d_3^v} \right] \right) \\ \left(1 - e^{-\frac{\sigma^2}{P_p}(\rho - \frac{\alpha}{1-\alpha})} + \frac{2}{n} e^{-\frac{d_5^v \sigma^2 \rho}{\alpha P_s} + \frac{mp}{n}} \left(Ei\left[\frac{p\sigma^2}{P_p}\left(\rho - \frac{\alpha}{1-\alpha}\right) - \frac{mp}{n} \right] - Ei\left[-\frac{mp}{n} \right] \right) \right) \end{aligned} \tag{18}$$

Special case when α=1 ST acts as a selection combiner. In such senerio, $\text{SNR}_{\text{MRC}} = \frac{P_p\gamma_1}{\sigma^2} + \frac{P_s\gamma_{\max}}{\sigma^2}$. Therefore (16) reduces to,

$$P[R_{MRC} < R_{pt}] = P\left[\frac{P_p\gamma_1}{\sigma^2} + \frac{P_s\gamma_{\max}}{\sigma^2} < \rho\right] \tag{19}$$

After solving,

$$\begin{aligned} P[R_{MRC} < R_{pt}] =& e^{-g}\left(\frac{e^{((2\mu g)-2\psi)}}{2\mu-1} - \frac{2e^{((\mu g)-\psi)}}{\mu-1} - 1\right) \\ & - \left(\frac{e^{2\psi}}{2\mu-1} - \frac{2e^{-2\psi}}{\mu-1} - 1\right) \end{aligned} \tag{20}$$

where, g=$\frac{\rho\sigma^2}{P_P}$, $\psi = \frac{d_5^v\rho\sigma^2}{P_s}$ and $\mu = \frac{d_5^v P_p}{P_s}$. For detailed derivation of (20), please refer Appendix B.

2.4 Outage Probability of Secondary System

Outage probability of a secondary system is the probability by which secondary receiver fails to decode secondary signal with the target rate i.e. R_{st}. If in phase 1, links between PT-ST and PT-SR fails in decoding x_p, interference cancellation at SR in phase 2 is not possible and hence outage will be declared for secondary system. The outage probability for secondary system can be given as [6]

$$P_{out}^{SR} = 1 - P[R12 > Rpt]P[R13 > Rpt]P[RSR2 > Rst] \tag{21}$$

where, R_{12} is the transmission rate achieved between PT-SR link in phase 1, R_{13} is the transmission rate achieved at ST in phase 1 (given in (14)) and R_2^{SR} is the rate achieved at SR in phase 2. Solving for (21),

$$R_{12} = \frac{1}{2}\log_2\left(1 + \frac{P_p\gamma_2}{\sigma^2}\right). \tag{22}$$

Therefore,

$$P[R_{12} > R_{pt}] = P\left[\gamma_2 > \frac{\rho\sigma^2}{P_p}\right] = e^{-\frac{d_2^v\rho\sigma^2}{P_p}}. \tag{23}$$

Moreover,

$$R_2^{SR} = \frac{1}{2}\log_2\left(1 + \frac{P_s(1-\alpha)\gamma_7}{\sigma^2}\right). \tag{24}$$

Therefore,

$$P[R_2^{SR} > R_{st}] = P\left[\gamma_7 > \frac{\rho_s\sigma^2}{P_s(1-\alpha)}\right] = e^{-\frac{d_7^v\rho_s\sigma^2}{P_s(1-\alpha)}} \tag{25}$$

where, $\rho_s = 2^{2R_{st}} - 1$.

After substituting (23), (14) and (25) in (21), we get

$$P_{out}^{SR} = 1 - \left[\left(\left(1 + \frac{\sigma^2\rho}{P_p}d_3^v\right)e^{-\frac{\sigma^2\rho}{P_p}d_3^v}\right)e^{-\frac{d_2^v\rho\sigma^2}{P_p}}e^{-\frac{d_7^v\rho_s\sigma^2}{P_s(1-\alpha)}}\right] \tag{26}$$

3 Simulation Results and Discussion

In this section, we have discussed the analytical and simulation results for outage probability. We have compared our results with the scheme in [9], where they randomly pick an antenna at ST for transmission. Fig 2 shows the simulation model of the proposed scheme, in which for the ease of analysis all nodes are assumed to be collinear. The value of d (distance between PT-ST) is considered to be 0.5 and 0.8. The target rate chosen for primary and secondary system is 1 i.e. $R_{pt} = R_{st} = 1$, and we have considered $\frac{P_p}{\sigma^2} = 5$dB.

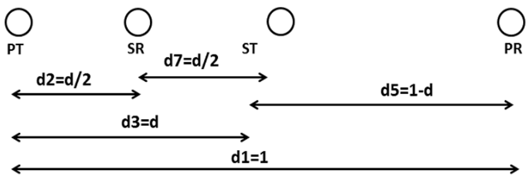

Fig. 2. System Model

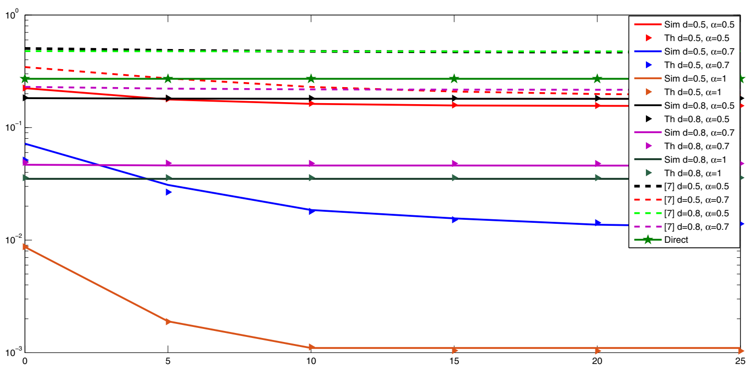

Fig. 3. Outage Probability of Primary System

Fig. 3 and Fig. 4 shows the outage probability of primary and secondary system respectively with respect to $\frac{P_s}{\sigma^2}$. From the plots it is quite obvious, that the outage probability of both primary as well as secondary system is continuously decreasing with the increase in power at secondary transmitter. However this decrement gradually reduces after 10dB because the outage probability also

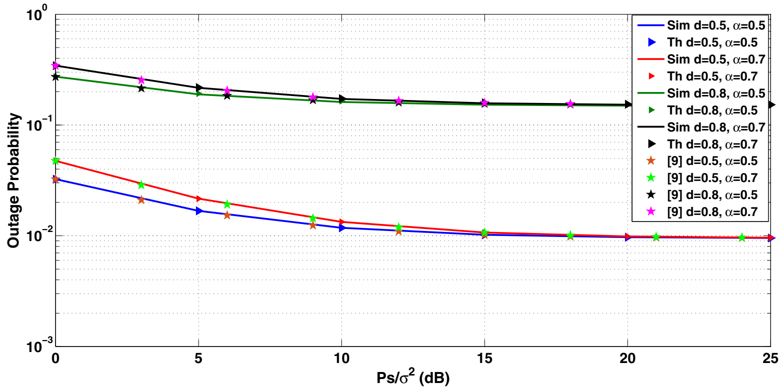

Fig. 4. Outage Probability of Secondary System

depends on the successful decoding of primary's data at ST in phase 1 (from (8 and 21)). The results are shown for two different values of α i.e. 0.5 and 0.7. By transmitting x_s from channel having less instantaneous gain, interference level at PR get reduced which results in considerable improvement in the performance of primary system (approximately 10 times at d = 0.5 and $\alpha = 0.7$ for $\frac{P_s}{\sigma^2}$ = 5dB) compared to [9]. Even when half of the power of ST ($\alpha = 0.5$) is allocated to secondary signal, the performance of proposed scheme is still far better than that of [9] with an improvement of approximately 5 times. It is also obvious from Fig. 4 that notwithstanding the improvement in the performance of primary system, we are still able to retain the performance of secondary system as in [9]. Furthermore, we also demonstrate the results for the case wherein ST acts as a pure relay ($\alpha = 1$) i.e. it is transmitting only primary's data with the channel having larger instantaneous gain. For such scenario the proposed scheme works as a selection combiner in phase 2.

4 Conclusion

In this paper, two phase cooperative spectrum sharing scheme with decode and forward relay at secondary system has been proposed. The proposed technique utilizes transmit antenna selection scheme at secondary transmitter in order to reduce interference at primary receiver due to presence of secondary signal. The perfect agreement between the simulated results and the analytically obtained closed form expression for outage probability validated theoretical analysis presented in the paper.

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