Outage Performance Analysis of Underlay Cognitive Radio Networks with Decode-and-Forward Relaying

Mustafa Namdar and Arif Basgumus

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.69244

Abstract

In this chapter, we evaluate the outage performance of decode-and-forward relaying in cognitive radio networks over Rayleigh fading channels, subject to the relay location for a secondary user. In particular, we obtain the optimal relay location in wireless communications systems for the cognitive radio networks, using differential evolution optimization algorithm. Then, we investigate the optimal transmission rate of the secondary user. We present the numerical results to validate the proposed theoretical analysis and to show the effects of the Rayleigh fading channel parameters for the whole system performance.

Keywords: cognitive radio networks, decode-and-forward relaying, differential evolution optimization algorithm, optimal relay location, outage probability

1. Introduction

Cognitive radio (CR) is a new approach for wireless communication systems to utilize the existing spectrum resources efficiently. Spectrum utilization can be increased by opportunistically allowing the unlicensed secondary user (SU) to utilize a licensed band in the absence of the primary user (PU) [1–4]. The ability of providing awareness about the usage of the frequency spectrum or the detection of the PU in a desired frequency band lets the SU access the radio communication channel without causing harmful interference to the PU [5–8].

Cooperative wireless communications, which depend on cooperation among distributed single-antenna wireless nodes, have emerged recently as an alternative to multi-antenna systems to obtain spatial diversity [9–13]. In a wireless communication system, when the source terminal does not have a good-enough link with the destination one, cooperative relaying can be utilized to improve spectral efficiency, combat with the effects of the channel fading and to increase the channel capacity. There are various cooperative relaying schemes and two of the most widely studied in the literature are amplify-and-forward (AF) and decode-and-forward (DF) protocols. Between them, the DF cooperation protocol is considered in this chapter, in which the relay terminal decodes its received signal and then re-encodes it before transmission to the destination [14]. In order to achieve higher outage performance, we investigate the DF relaying in CR networks over Rayleigh fading channels, subject to the relay location for a SU. Then, we obtain the optimal relay location for the CR networks and optimal transmission rate of the SU using the differential evolution (DE) optimization algorithm [15–17].

Most of the previous publications have studied the performance of cooperative communications techniques over different fading channels and under different constraints [18–26]. In [18], the authors derive the analytical error rate expressions to develop power allocation, relay selection and placements with generic noise and interference in a cooperative diversity system employing AF relaying under Rayleigh fading. Woong and Liuqing [19] address the resource allocation problem in a differentially modulated relay network scenario. It is shown to achieve the optimal energy distribution and to find optimal relay location while minimizing the average symbol error rate. The effect of the relay position on the end-to-end bit error rate (BER) performance is studied in [20]. Furthermore, Refs. [21–26] investigate the relay node placements minimizing the outage probability where the performance improvement is quantified. Although cooperative transmissions have greatly been considered in the above manuscripts, to the best of the our knowledge, there has not been any notable research for the relay-assisted CR networks based on the DE optimization algorithm. As far as we know, DE optimization algorithm has not been applied for obtaining the optimal location of the relaying terminal in CR networks over Rayleigh fading channels.

In summary, to fill the above-mentioned research gap, we here provide an optimization analysis yielding the optimal location of the relaying terminal for the SU in CR networks. Furthermore, we analyse the transmission rate for the SU over Rayleigh fading channels using DE optimization algorithm. As far as we know, DE optimization algorithm has not been applied for obtaining the optimal location of the relaying terminal and the transmission rate in CR networks over Rayleigh fading channels.

The rest of the chapter is organized as follows: the system model and performance analysis are described in Section 2 presenting the relay-assisted underlay cognitive radio networks. The numerical results and simulations are discussed in Section 3 with the DE optimization approach. Finally, Section 4 provides the concluding remarks.

2. System model and performance analysis

This section presents the system model for the CR networks with DF cooperative relaying protocol shown in **Figure 1**. We consider the method developed in [27] that the transmission links between the source-to-relay and relay-to-destination are subject to Rayleigh fading. In the

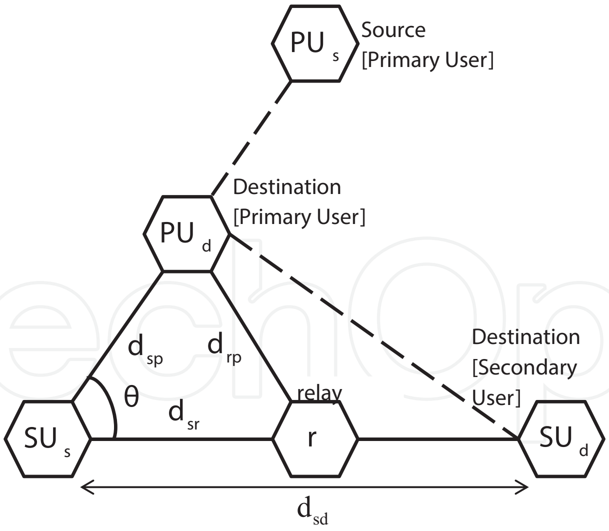

Figure 1. System model for cooperative relaying in cognitive radio networks [27].

system model for the cooperative relaying, we have both PU and SU, each with a source (PU_s and SU_s) and destination (PU_d and SU_d) nodes. Besides, the relay (r) is located in the same line between SU_s and SU_d. We assume that PU_s only transmits to the PU_d and SU_s utilize a two-phase cooperative transmission protocol causing interference to PU within a tolerable level. We also assume that equal-time allocation is implemented in the relayed transmission. In the first phase, SU_s transmits the signal to r. In the second phase of this transmission, r decodes its received signal and retransmits (forwards) it to the SU_d [27]. We denote the distance between the secondary source SU_s and the relay r as d_{sr}, the distance between the secondary source SU_d and the primary destination PU_d as d_{sp}, the distance between the secondary source SU_s and the secondary destination SU_d as d_{sd} and finally, the distance between the relay r and the primary destination PU_d as d_{rp}. We have

$$d_{rp}^2 = d_{sp}^2 + d_{sr}^2 - 2d_{sp}d_{sr}\cos\theta \tag{1}$$

where the cosine theorem is used. Here, θ is the angle between the horizontal axis and the line connecting the PU_d and SU_s nodes.

In a cognitive radio network, the transmission of a primary user has to be protected from the interference caused by either a secondary user or a relay. The level of the interference induced on the primary user (P_0) must be kept below a maximum tolerable level. On the other hand, when the level of interference from the secondary user's activity in the first phase or the relay transmission in the second phase exceeds the prescribed limit of P_0, this situation results in a corruption in the transmission of the primary user. Thus, the transmitting power levels of the primary user and relay have to be controlled and must not exceed P_0. Also, the outage probability of the primary destination during the source and relay transmission phases must be equal to a certain predetermined value such as ε_P. As the maximum transmitting power levels depends on the location of the relay, SU_s and ε_P, on the other hand, to maximize the data rate at the destination subject to the outage probability constraints, ε_s is evaluated by the secondary user.

Here, we consider the worst case channel conditions, namely, Rayleigh fading, might cause some signal power loss between the $\mathrm{SU_s} - \mathrm{r}$ and $\mathrm{r} - \mathrm{SU_d}$ links, also assuming N_0, power spectral density for the background noise is similar in the whole environment for the presented system model. In the literature, the outage probabilities for the $\mathrm{PU_d}$ during the source and the relay transmission phase are respectively given by $\mathrm{P_{out,source}} = \exp\left(-\mathrm{P_o}/\mathrm{P_s d_{sp}^{-\alpha}}\right)$ and $\mathrm{P_{out,relay}} = \exp\left(-\mathrm{P_o}/\mathrm{P_r d_{rp}^{-\alpha}}\right)$ where $\mathrm{P_s}$ is the transmit power of the $\mathrm{SU_s}$ and $\mathrm{P_r}$ is the transmit power of the relay, r [27]. It is assumed that these equations are equal to one another in order to maximize the transmission rate, and thus, the transmit powers for the secondary user and the relay are given as

$$\mathrm{P_s} = \frac{\mathrm{P_0 d_{sp}^{\alpha}}}{-\ln\left(\varepsilon_\mathrm{p}\right)} \tag{2}$$

$$\mathrm{P_r} = \frac{\mathrm{P_0 d_{rp}^{\alpha}}}{-\ln\left(\varepsilon_\mathrm{p}\right)} \tag{3}$$

respectively [27]. Here, α is the path loss exponent, and $\ln(.)$ is the natural logarithm operator.

In this study, it is aimed to minimize the outage probability of the secondary user for the DF relaying scheme and to maximize the transmission rate, R subject to the outage constraints of the primary user. The main objective of the proposed optimization algorithm is to find the optimal relay location on the direct link between $\mathrm{SU_s}$ and $\mathrm{SU_d}$ terminals. The outage probability of the secondary user for the DF relaying can be expressed as follows [27]:

$$\begin{aligned} P_{\mathrm{out}} = &\left(1 - \exp\left(-\frac{g(R)}{2\overline{\gamma}_{\mathrm{sd}}}\right)\right)\left(1 - \exp\left(-\frac{g(R)}{\overline{\gamma}_{\mathrm{sr}}}\right)\right) \\ &+ \left(1 - \left(\frac{\overline{\gamma}_{\mathrm{sd}}}{\overline{\gamma}_{\mathrm{sd}} - \overline{\gamma}_{\mathrm{rd}}}\exp\left(-\frac{g(R)}{\overline{\gamma}_{\mathrm{sd}}}\right) + \frac{\overline{\gamma}_{\mathrm{rd}}}{\overline{\gamma}_{\mathrm{rd}} - \overline{\gamma}_{\mathrm{sd}}}\exp\left(-\frac{g(R)}{\overline{\gamma}_{\mathrm{rd}}}\right)\right)\right)\exp\left(-\frac{g(R)}{\overline{\gamma}_{\mathrm{sr}}}\right) \end{aligned} \tag{4}$$

where R is the transmission rate for $\mathrm{SU_s}$ and $\mathrm{g}(R) = 2^{2\,\mathrm{R}} - 1$. We have

$$R = \frac{1}{2}\log_2\left(1 + \mu\sqrt{\varepsilon_\mathrm{s}}\sqrt{\left(\left(\frac{\mathrm{d_{sd}}}{\mathrm{d_{sp}}}\right)^{-\alpha}\left(\frac{\mathrm{d_{rd}}}{\mathrm{d_{rp}}}\right)^{-\alpha}\left(\frac{\mathrm{d_{sr}}}{\mathrm{d_{sp}}}\right)^{-\alpha}\right)\Big/\left(\left(\frac{\mathrm{d_{rd}}}{\mathrm{d_{rp}}}\right)^{-\alpha} + \left(\frac{\mathrm{d_{sr}}}{\mathrm{d_{sp}}}\right)^{-\alpha}\right)}\right). \tag{5}$$

Here, the outage probability for the secondary user is given by $\varepsilon_\mathrm{s} = \left(\frac{1}{\overline{\gamma}_{\mathrm{sr}}} + \frac{1}{\overline{\gamma}_{\mathrm{rd}}}\right)\frac{1}{2\overline{\gamma}_{\mathrm{sd}}}\mathrm{g}(R)^2$. The average signal-to-noise ratios in the links $\mathrm{PU_s}$ to $\mathrm{PU_d}$, $\mathrm{SU_s}$ to r, and r to $\mathrm{SU_d}$ are given by $\overline{\gamma}_{\mathrm{sd}} = \mu\left(\mathrm{d_{sd}}/\mathrm{d_{sp}}\right)^{-\alpha}$, $\overline{\gamma}_{\mathrm{sr}} = \mu\left(\mathrm{d_{sr}}/\mathrm{d_{sp}}\right)^{-\alpha}$, and $\overline{\gamma}_{\mathrm{rd}} = \mu\left(\mathrm{d_{rd}}/\mathrm{d_{rp}}\right)^{-\alpha}$. We have $\mu = \mathrm{P_0}/\left(-N_0\ln\left(\varepsilon_\mathrm{p}\right)\right)$.

For the optimization problem, a function is employed to minimize the outage probability and maximize the transmission rate for the DF relay-assisted CR system. DE optimization algorithm results show that the system performance can be significantly improved for the optimal value of the system parameters, seen in the following section.

3. Numerical results and simulations

In this section, the numerical results are illustrated through the performance analysis curves of the proposed underlay cognitive radio networks with DF relaying. The detailed optimization results with the DE algorithm for DF relaying scheme are listed in **Table 1**. Here, the results for the optimal transmission distances, between secondary user source to relay $(\mathrm{SU_s} - \mathrm{r})$, $\mathrm{d_{sr_{opt}}}$ are provided with different θ values, while $\mathrm{d_{sp}} = \mathrm{d_{sd}}$, $\mathrm{d_{sp}} = 2\,\mathrm{d_{sd}}$ and $\mathrm{d_{sp}} = 5\,\mathrm{d_{sd}}$. Besides, the maximum transmission rate values $(R_{\max})$ for the secondary user, $\mathrm{SU_s}$, are also illustrated in the same table. The results demonstrate that maximum transmission rate performance of the considered system increases while θ and $\mathrm{d_{sp}}$ increases.

The outage probability $(\mathrm{P_{out}})$ performance of the considered system is illustrated in **Figure 2** with varying θ values when $(\mathrm{P_o}/N_0) = 10$ dB, $\alpha = 4$, $\varepsilon_\mathrm{S} = 0.1$, $\varepsilon_\mathrm{p} = 0.05$, $\mathrm{d_{sp}} = 2\,\mathrm{d_{sd}}$ and $\mathrm{d_{sr}} = \mathrm{d_{sd}}/2$. It can be observed from the simulation results in **Figure 2** that the optimal θ angle can be calculated, where the best minimum of $\mathrm{P_{out}}$ is achieved.

$\mathbf{d_{sp} = d_{sd}}$			$\mathbf{d_{sp} = 2d_{sd}}$			$\mathbf{d_{sp} = 5d_{sd}}$		
θ (°)	$\mathbf{d_{sr_{opt}}}$	$\mathbf{R_{max}}$	**θ (°)**	$\mathbf{d_{sr_{opt}}}$	$\mathbf{R_{max}}$	**θ (°)**	$\mathbf{d_{sr_{opt}}}$	$\mathbf{R_{max}}$
10	0.8830	0.5825	10	0.5295	2.7317	10	0.5042	5.4225
20	0.7606	0.6666	20	0.5276	2.7367	20	0.5039	5.4232
30	0.6819	0.7432	30	0.5246	2.7447	30	0.5037	5.4243
40	0.6261	0.8110	40	0.5206	2.7552	40	0.5030	5.4258
50	0.5835	0.8715	50	0.5160	2.7677	50	0.5024	5.4276
60	0.5497	0.9254	60	0.5109	2.7814	60	0.5017	5.4297
70	0.5222	0.9737	70	0.5055	2.7959	70	0.5009	5.4319
80	0.4995	1.0166	80	0.5001	2.8106	80	0.5000	5.4344
90	0.4807	1.0547	90	0.4949	2.8250	90	0.4992	5.4368
100	0.4651	1.0882	100	0.4899	2.8387	100	0.4983	5.4393
110	0.4521	1.1173	110	0.4853	2.8514	110	0.4975	5.4417
120	0.4414	1.1422	120	0.4812	2.8629	120	0,4967	5.4439
130	0.4328	1.1631	130	0.4777	2.8729	130	0.4960	5.4458
140	0.4259	1.1800	140	0.4747	2.8813	140	0.4954	5.4475
150	0.4207	1.1931	150	0.4724	2.8880	150	0.4950	5.4489
160	0.4171	1.2024	160	0.4707	2.8928	160	0.4946	5.4499
170	0.4149	1.2080	170	0.4697	2.8957	170	0.4944	5.4505
180	0.4142	1.2098	180	0.4694	2.8966	180	0.4943	5.4507

Table 1. Optimization results for DF relaying with different θ values for $\mathrm{d_{sp}} = \mathrm{d_{sd}}$, $\mathrm{d_{sp}} = 2\,\mathrm{d_{sd}}$, and $\mathrm{d_{sp}} = 5\,\mathrm{d_{sd}}$.

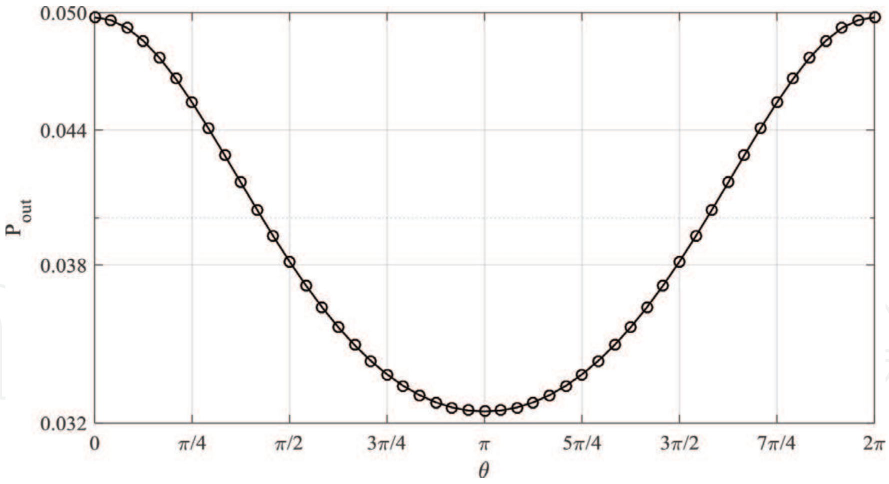

Figure 2. P_{out} for the considered underlay CR network with DF relaying under different θ values.

Figure 3 shows the transmission rate over Rayleigh fading channel versus $(\mathrm{P_o}/N_0)$ when $\alpha = 4$, $\varepsilon_{\mathrm{S}} = 0.1$, $\varepsilon_{\mathrm{p}} = 0.05$, $\theta = \pi/2$, $\mathrm{d_{sp}} = 2\,\mathrm{d_{sd}}$ and $\mathrm{d_{sr}} = \mathrm{d_{sd}}/2$. The results clearly show that R increases with the increase of the $(\mathrm{P_o}/N_0)$.

The transmission rate (R) of the considered system for the $\mathrm{SU_s} - \mathrm{r}$ link with the normalized $\mathrm{d_{sd}}$ distance is illustrated in **Figure 4** when $(\mathrm{P_o}/N_0) = 10$ dB, $\alpha = 4$, $\varepsilon_{\mathrm{S}} = 0.1$, $\varepsilon_{\mathrm{p}} = 0.05$, $\theta = \pi/2$ and $\mathrm{d_{sp}} = 2\,\mathrm{d_{sd}}$. **Figure 4** indicates that the maximum transmission rate is achieved when the optimal transmission distances are used.

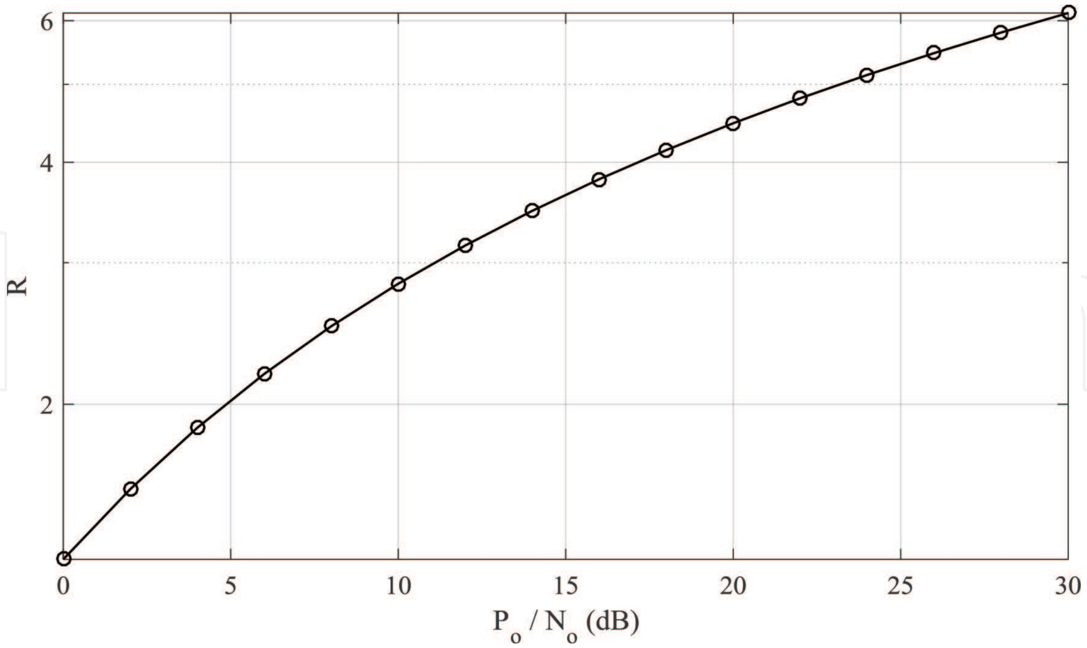

Figure 3. R vs. (P_o/N_0).

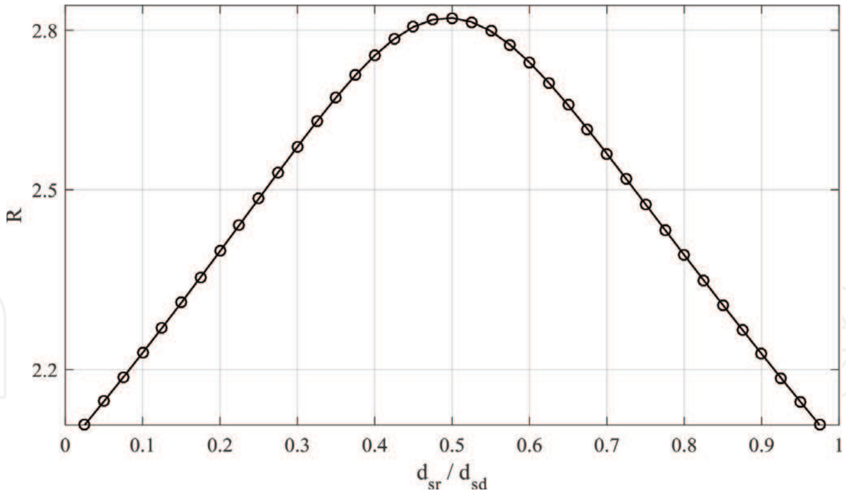

Figure 4. R vs. $(d_{\text{sr}}/d_{\text{sd}})$ for $(P_{\text{o}}/N_0) = 10$ dB.

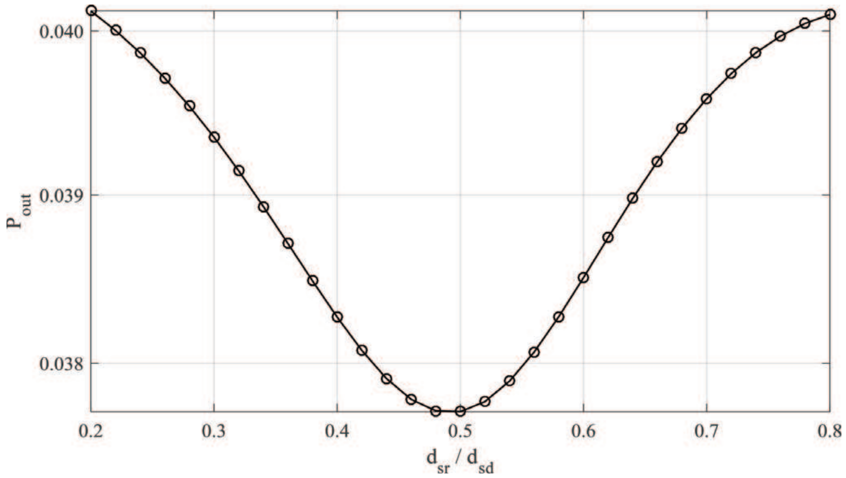

Figure 5. P_{out} for varying $(d_{\text{sr}}/d_{\text{sd}})$ with $(P_{\text{o}}/N_0) = 10$ dB.

Figure 5 depicts the outage probability performance as a function of $(\mathrm{d}_{\text{sr}}/\mathrm{d}_{\text{sd}})$. Here, $(\mathrm{P}_{\text{o}}/N_0) = 10$ dB, $\alpha = 4$, $\varepsilon_{\text{S}} = 0.1$, $\varepsilon_{\text{p}} = 0.05$, $\theta = \pi/2$ and $\mathrm{d}_{\text{sp}} = 2\,\mathrm{d}_{\text{sd}}$. The results obtained in **Figure 4** closely match with the results in **Figure 5**. Therefore, it can be deduced that the optimal placement of the relay terminal can be performed based on $(\mathrm{d}_{\text{sr}}/\mathrm{d}_{\text{sd}}) = 0.5$, which leads to the midpoint of the transmission link of $\mathrm{SU}_{\text{s}} - \mathrm{SU}_{\text{d}}$ as the optimal position.

In **Figure 6**, the transmission rate for the $\mathrm{PU}_{\text{d}} - \mathrm{SU}_{\text{s}}$ link is monitored for the normalized d_{sd} distance over Rayleigh fading channel while $(\mathrm{P}_{\text{o}}/N_0) = 10$ dB, $\alpha = 4$, $\varepsilon_{\text{S}} = 0.1$, $\varepsilon_{\text{p}} = 0.05$, $\theta = \pi/2$ and $\mathrm{d}_{\text{sr}} = \mathrm{d}_{\text{sd}}/2$. In addition, P_{out} performance analysis is also studied for the transmission link for $\mathrm{PU}_{\text{d}} - \mathrm{SU}_{\text{s}}$ with the normalized distance of d_{sd} and demonstrated in **Figure 7** using the same parameters in **Figure 6**.

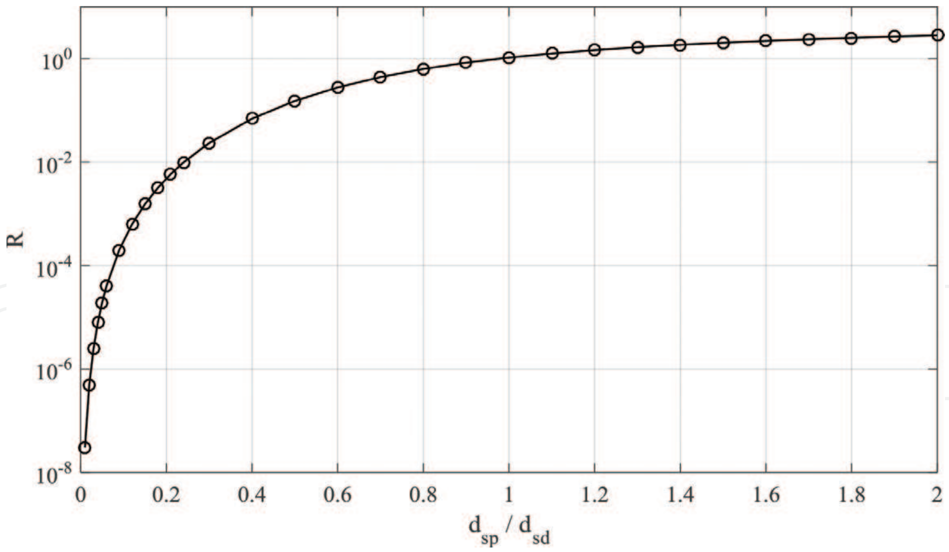

Figure 6. R vs. $(d_{\mathrm{sp}}/d_{\mathrm{sd}})$ over Rayleigh fading channel while $(P_{\mathrm{o}}/N_0) = 10$ dB.

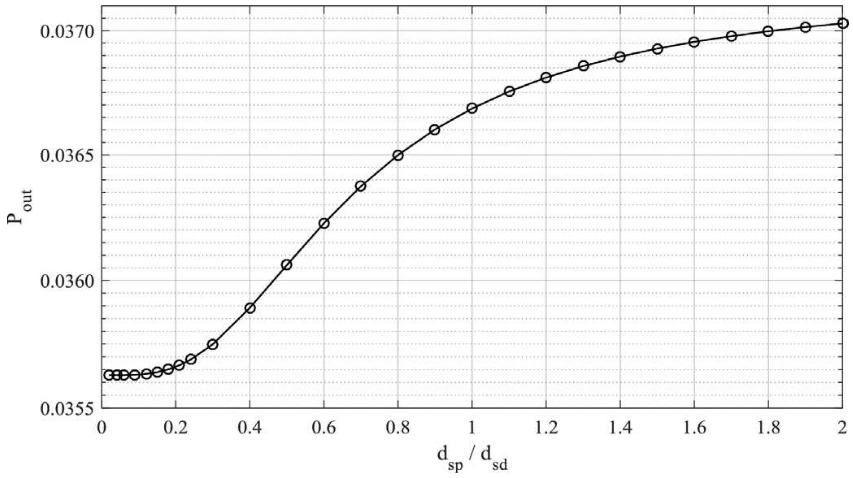

Figure 7. P_{out} performance with varying $(d_{\mathrm{sp}}/d_{\mathrm{sd}})$ while $(P_{\mathrm{o}}/N_0) = 10$ dB.

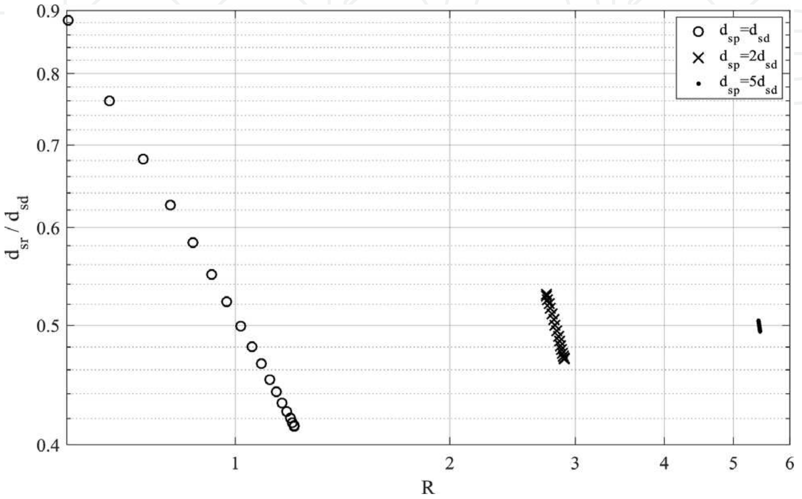

Figure 8. $(d_{\mathrm{sr}}/d_{\mathrm{sd}})$ vs. R over Rayleigh fading channel with different θ values for $(P_{\mathrm{o}}/N_0) = 10$ dB, $d_{\mathrm{sp}} = d_{\mathrm{sd}}$, $d_{\mathrm{sp}} = 2\,d_{\mathrm{sd}}$ and $d_{\mathrm{sp}} = 5\,d_{\mathrm{sd}}$.

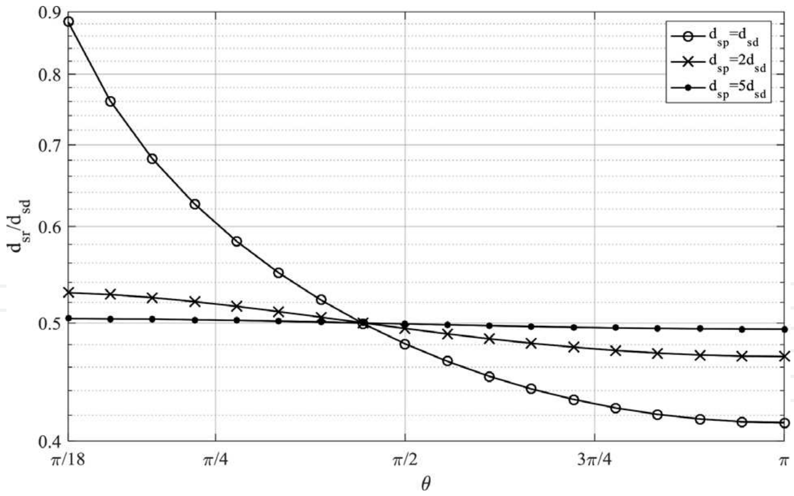

Figure 9. (d_{sr}/d_{sd}) vs. θ values for $d_{sp} = d_{sd}$, $d_{sp} = 2\, d_{sd}$ and $d_{sp} = 5\, d_{sd}$ while $(P_o/N_0) = 10$ dB.

The normalized d_{sr} distance varying with the transmission rate R over Rayleigh fading channel for different θ values and transmission links, $d_{sp} = d_{sd}$, $d_{sp} = 2\, d_{sd}$ and $d_{sp} = 5\, d_{sd}$ are shown in **Figure 8**. Besides, in **Figure 9**, d_{sr}/d_{sd} normalized distances are calculated for the different θ angles with varying d_{sp} values. Here, both figures are plotted for the values of $(P_o/N_0) = 10$ dB, $\alpha = 4$, $\varepsilon_S = 0.1$ and $\varepsilon_p = 0.05$.

The maximum transmission rate varying with different θ values for $d_{sp} = d_{sd}$, $d_{sp} = 2\, d_{sd}$ and $d_{sp} = 5\, d_{sd}$, while $(P_o/N_0) = 10$ dB is depicted in **Figure 10**. The figure demonstrates the effect of d_{sp} with varying θ angles. The results show that the maximum transmission rate of the considered system increases while θ and d_{sp} increases.

Finally, the maximum transmission rate, varying with the normalized distance for different d_{sp} values, is depicted in **Figure 11**. It is seen that while the d_{rp}/d_{sd} increases, the system performance also increases when θ is in the interval of $[0 - \pi]$. In other words, these results also prove that the R performance is directly related with the $PU_d - SU_s$ transmission link. While in case of d_{sp} distance is increased, the maximum transmission is achieved.

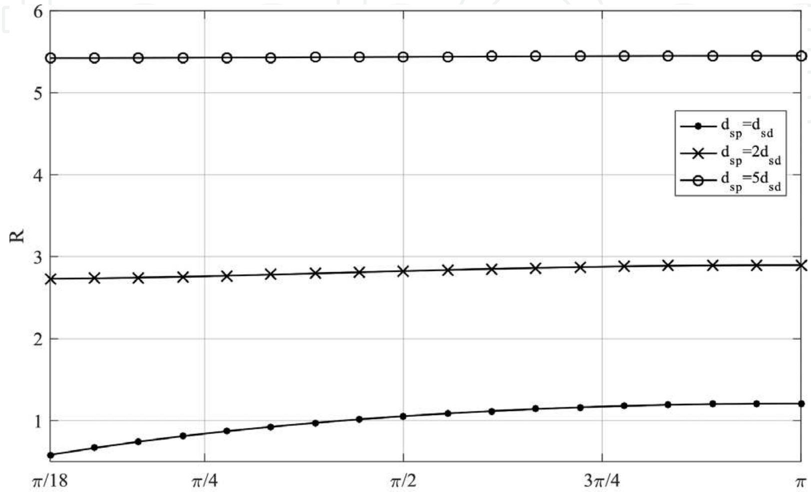

Figure 10. Maximum transmission rate varying with different θ values for $d_{sp} = d_{sd}$, $d_{sp} = 2\, d_{sd}$ and $d_{sp} = 5\, d_{sd}$ while $(P_o/N_0) = 10$ dB.

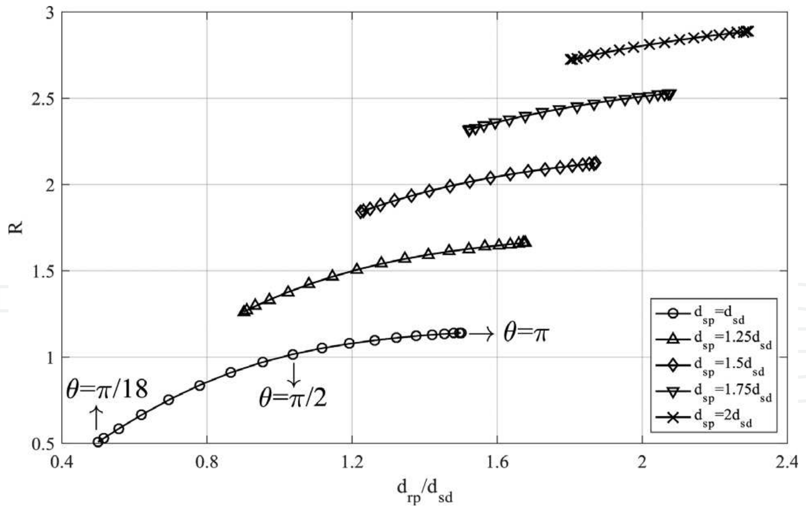

Figure 11. Maximum transmission rate varying with d_{rp} values normalized with d_{sd}, for different $PU_{\mathrm{d}} - SU_{\mathrm{s}}$ distance while $d_{\mathrm{sr}} = d_{\mathrm{sd}}/2$ and $(P_{\mathrm{o}}/N_0) = 10$ dB.

4. Conclusions

In this chapter, we present a comprehensive performance analysis of the outage probability ($\mathrm{P}_{\mathrm{out}}$) and transmission rate (R) of the underlay cognitive radio networks with decode-and-forward relaying over Rayleigh fading channel. We provide a rigorous data for the optimal locations of the relay terminal using differential evolution optimization algorithm. We investigate the maximum transmission rate of the secondary user, and the outage probability subject to the distance of d_{sp}, d_{sr}, d_{rp}, normalized with d_{sd} between $\mathrm{PU}_{\mathrm{d}} - \mathrm{SU}_{\mathrm{s}}$, $\mathrm{SU}_{\mathrm{s}} - \mathrm{r}$ and $\mathrm{PU}_{\mathrm{d}} - \mathrm{r}$ transmission links, respectively. We then present the effect of the θ angle, between $\mathrm{PU}_{\mathrm{d}} - \mathrm{SU}_{\mathrm{s}}$ link and the horizontal axis, on the $\mathrm{P}_{\mathrm{out}}$ and R performance. The numerical results, validates the theoretical analysis, show that d_{sp} distance and θ angle, which is in the interval of $[0 - \pi]$, have significant performance improvement on the transmission rate and the outage probability.

Acknowledgements

This work was supported in part by the Research Fund of Dumlupinar University under Scientific Research Project BAP/2016-84.

Author details

Mustafa Namdar* and Arif Basgumus

*Address all correspondence to: mustafa.namdar@gmail.com

Department of Electrical and Electronics Engineering, Dumlupinar University, Kutahya,
Turkey

References

[1] Yucek T, Arslan H. A survey of spectrum sensing algorithms for cognitive radio applications. IEEE Communications Surveys & Tutorials. 2009;**11**(1):116–130. DOI: 10.1109/SURV.2009.090109

[2] Ma J, Li GY, Juang BH. Signal processing in cognitive radio. Proceedings of the IEEE. 2009;**97**(5):805–823. DOI: 10.1109/JPROC.2009.2015707

[3] Letaief KB, Zhang W. Cooperative communications for cognitive radio networks. Proceedings of the IEEE. 2009;**97**(5):878–893. DOI: 10.1109/JPROC.2009.2015716

[4] Akyildiz IF, Lee WY, Vuran MC, Mohanty S. NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey. Computer Networks. 2006;**50**(13):2127–2159. DOI: 10.1016/j.comnet.2006.05.001

[5] Namdar M, Ilhan H, Durak-Ata L. Spectrum sensing for cognitive radio with selection combining receiver antenna diversity. In: IEEE 21st Signal Processing and Communications Applications Conference, April 2013; Girne, Northern Cyprus. pp. 1–4

[6] Namdar M, Sahin B, Ilhan H, Durak-Ata L. Chirp-z transform based spectrum sensing via energy detection. In: IEEE 20th Signal Processing and Communications Applications Conference, April 2012; Mugla, Turkey. pp. 1–4

[7] Namdar M, Ilhan H, Durak-Ata L. Partial spectrum utilization for energy detection in cognitive radio networks. In: IEEE International Congress on Ultra Modern Telecommunications and Control Systems, October 2012; St. Petersburg, Russia. pp. 989–994

[8] Namdar M, Ilhan H, and Durak-Ata L. Dispersed chirp-z transform-based spectrum sensing and utilization in cognitive radio networks. IET Signal Processing. 2014;**8**(4):320–329. DOI: 10.1049/iet-spr.2013.0127

[9] Namdar M, Ilhan H, and Durak-Ata L. Optimal detection thresholds in spectrum sensing with receiver diversity. Wireless Personal Communications, 2016;**87**(1):63–81. DOI: 10.1007/s11277-015-3026-6

[10] Sendonaris A, Erkip E, Aazhang B. User cooperation diversity—part I: System description. IEEE Transactions on Communications. 2003;**51**(11):1927–1938. DOI: 10.1109/TCOMM.2003.818096

[11] Sendonaris A, Erkip E, Aazhang B. User cooperation diversity—part II: Implementation aspects and performance analysis. IEEE Transactions on Communications. 2003;**51**(11):1939–1948. DOI: 10.1109/TCOMM.2003.819238

[12] Laneman JN, Wornell GW. Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks. IEEE Transactions on Information Theory. 2003;**49**(10):2415–2425. DOI: 10.1109/TIT.2003.817829

[13] Laneman JN, Tse DNC, Wornell GW. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. IEEE Transactions on Information Theory. 2004;**50**(12):3062–3080. DOI: 10.1109/TIT.2004.838089

[14] Ilhan H. Performance analysis of cooperative vehicular systems with co-channel interference over cascaded Nakagami-m fading channels. Wireless Personal Communications. 2015;**83**:203–214. DOI: 10.1007/s11277-015-2389-z

[15] Basgumus A, Hicdurmaz B, Temurtas H, Namdar M, Altuncu A, Yilmaz G. Optimum transmission distance for relay-assisted free-space optical communication systems. Elsevier Optik. 2016;**127**(16):6490–6497. DOI: 10.1016/j.ijleo.2016.04.070

[16] Basgumus A, Namdar M, Yilmaz G, Altuncu A. Performance comparison of the differential evolution and particle swarm optimization algorithms in free-space optical communications systems. Advances in Electrical and Computer Engineering. 2015;**15**(2):17–22. DOI: 10.4316/AECE.2015.02003

[17] Basgumus A, Namdar M, Yilmaz G, Altuncu A. Performance analysis of the differential evolution and particle swarm optimization algorithms in cooperative wireless communications. In: Baskan O. editor. Optimization Algorithms-Methods and Applications. Rijeka, Croatia: InTech. 2016. ISBN: 978-953-51-2593-8. DOI: 10.5772/62453

[18] Nasri A, Schober R, Blake IF. Performance and optimization of cooperative diversity systems in generic noise and interference. In: IEEE International Communications Conference. May 2010; Cape Town, South Africa. pp. 1132–1143

[19] Woong C, Liuqing Y. Optimum resource allocation for relay networks with differential modulation. IEEE Transactions on Communicaitons. 2008;**56**(4):531–534. DOI: 10.1109/TCOMM.2008.060104

[20] Mohammed H, Khalaf TA. Optimal positioning of relay node in wireless cooperative communication networks. In: IEEE 9th International Computer Engineering Conference, December 2013; pp. 122–127

[21] Lloyd E, Xue G. Relay node placement in wireless sensor networks. IEEE Transactions on Computers. 2007;**56**(1):134–138. DOI: 10.1109/TC.2007.250629

[22] Han B, Li J, Su J. Optimal relay node placement for multi-pair cooperative communication in wireless networks. In: IEEE Wireless Communications and Networking Conference, April 2013; San Francisco, USA. pp. 4724–4729

[23] Yue H, Pan M, Fang Y. Glisic S. Spectrum and energy efficient relay station in placement in cognitive radio networks. IEEE Journal on Selected Areas in Communications. 2013;**31**(5):883–893. DOI: 10.1109/JSAC.2013.130507

[24] Palombara CL, Tralli V, Masini BM, Conti A. Relay-assisted diversity communications. IEEE Transactions on Vehicular Technology. 2013;**62**(1):415–421. DOI: 10.1109/TVT.2012.2218841

[25] Ikki SS, Aissa S. Study of optimization problem for amplify-and-forward relaying over Weibull fading channels. In: IEEE 72nd Vehicular Technology Conference Fall, September 2010; Ottowa, Canada. pp. 1–5

[26] Han L, Mu J, Wang W, Zhang B. Optimization of relay placement and power allocation for decode-and-forward cooperative relaying over correlated shadowed fading channels.

EURASIP Journal on Wireless Communications and Networking. 2014;**2014**(41):1–7. DOI: 10.1186/1687-1499-2014-41

[27] Zhu J, Huang J, Zhang W. Optimal one-dimensional relay placement in cognitive radio networks. In: IEEE International Conference on Wireless Communications & Signal Processing, October 2010; Suzhou, China. pp. 1–6