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

Mustafa Namdar and Arif Basgumus

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 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
system model for the cooperative relaying, we have both PU and SU, each with a source (PU, and SU) and destination (PU and SU) nodes. Besides, the relay (r) is located in the same line between SU and SU. We assume that PU only transmits to the PU and SU 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 transmits the signal to r. In the second phase of this transmission, r decodes its received signal and retransmits (forwards) it to the SU [27]. We denote the distance between the secondary source SU and the relay r as d, the distance between the secondary source SU and the primary destination PU as d, the distance between the secondary source SU and the secondary destination SU as d, and finally, the distance between the relay r and the primary destination PU as d. We have

$$d^2 = d^2 + d^2 - 2d_d d_r \cos \theta$$  (1)

where the cosine theorem is used. Here, $\theta$ is the angle between the horizontal axis and the line connecting the PU and SU 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 $\varepsilon_P$. As the maximum transmitting power levels depend on the location of the relay, SU and $\varepsilon_P$, on the other hand, to maximize the data rate at the destination subject to the outage probability constraints, $\varepsilon_s$ 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 SU \(_s - r \) and \( r - SU_d \) 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 PU \(_d \) during the source and the relay transmission phase are respectively given by \( P_{\text{out,source}} = \exp \left( -P_o/P_s d_{sp}^\alpha \right) \) and \( P_{\text{out,relay}} = \exp \left( -P_o/P_r d_{rp}^\alpha \right) \) where \( P_s \) is the transmit power of the SU \(_s \) and \( P_r \) 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

\[
P_s = \frac{P_0 d_{sp}^\alpha}{-\ln(\epsilon_p)} \quad \text{(2)}
\]

\[
P_r = \frac{P_0 d_{rp}^\alpha}{-\ln(\epsilon_p)} \quad \text{(3)}
\]

respectively [27]. Here, \( \alpha \) 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 SU \(_s \) and SU \(_d \) terminals. The outage probability of the secondary user for the DF relaying can be expressed as follows [27]:

\[
P_{\text{out}} = \left( 1 - \exp \left( \frac{-g(R)}{2\gamma_{sd}} \right) \right) \left( 1 - \exp \left( \frac{-g(R)}{\gamma_{sr}} \right) \right) + \left( \frac{\gamma_{sr}}{\gamma_{sd}} - \frac{\gamma_{rd}}{\gamma_{sr}} \right) \exp \left( \frac{-g(R)}{\gamma_{sr}} \right) \exp \left( \frac{-g(R)}{\gamma_{rd}} \right) \exp \left( \frac{-g(R)}{\gamma_{sd}} \right)
\]

where \( R \) is the transmission rate for SU \(_s \) and \( g(R) = 2^R - 1 \). We have

\[
R = \frac{1}{2} \log_2 \left( 1 + \mu \sqrt{\epsilon_s} \left( \left( \frac{d_{sd}}{d_{sp}} \right)^{-\alpha} \left( \frac{d_{rd}}{d_{rp}} \right)^{-\alpha} \left( \frac{d_{sr}}{d_{sp}} \right)^{-\alpha} \right) / \left( \frac{d_{rd}}{d_{rp}} \right)^{-\alpha} + \left( \frac{d_{sr}}{d_{sp}} \right)^{-\alpha} \right) \right).
\]

Here, the outage probability for the secondary user is given by \( \epsilon_s = \left( \frac{1}{\gamma_{sr}} + \frac{1}{\gamma_{rd}} \right) / \gamma_{sd} g(R)^2 \). The average signal-to-noise ratios in the links PU \(_s \) to PU \(_d \), SU \(_s \) to \( r \), and \( r \) to SU \(_d \) are given by \( \bar{\gamma}_{sd} = \mu (d_{sd}/d_{sp})^{-\alpha}, \bar{\gamma}_{sr} = \mu (d_{sr}/d_{sp})^{-\alpha}, \) and \( \bar{\gamma}_{rd} = \mu (d_{rd}/d_{rp})^{-\alpha} \). We have \( \mu = P_0 / (-N_0 \ln(\epsilon_p)) \).

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 (SUr - r), \(d_{sr_{opt}}\) are provided with different \(\theta\) values, while \(d_{sp} = d_{sd}, d_{sp} = 2 d_{sd}\) and \(d_{sp} = 5 d_{sd}\). Besides, the maximum transmission rate values \(R_{\text{max}}\) for the secondary user, SU, are also illustrated in the same table. The results demonstrate that maximum transmission rate performance of the considered system increases while \(\theta\) and \(d_{sp}\) increases.

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

| \(d_{sp} = d_{sd}\) | \(d_{sp} = 2d_{sd}\) | \(d_{sp} = 5d_{sd}\) |
|---------------------|---------------------|---------------------|
| \(\theta\) | \(d_{sr_{opt}}\) | \(R_{\text{max}}\) | \(\theta\) | \(d_{sr_{opt}}\) | \(R_{\text{max}}\) | \(\theta\) | \(d_{sr_{opt}}\) | \(R_{\text{max}}\) |
| 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 \(\theta\) values for \(d_{sp} = d_{sd}, d_{sp} = 2 d_{sd}\), and \(d_{sp} = 5 d_{sd}\).
Figure 3 shows the transmission rate over Rayleigh fading channel versus $P_o/N_0$ when $\alpha = 4$, $\varepsilon_S = 0.1$, $\varepsilon_p = 0.05$, $\theta = \pi/2$, $d_{sp} = 2d_{sd}$ and $d_{sr} = d_{sd}/2$. The results clearly show that $R$ increases with the increase of the $(P_o/N_0)$.

The transmission rate ($R$) of the considered system for the SU_s – r link with the normalized $d_{sd}$ distance is illustrated in Figure 4 when $(P_o/N_0) = 10$ dB, $\alpha = 4$, $\varepsilon_S = 0.1$, $\varepsilon_p = 0.05$, $\theta = \pi/2$ and $d_{sp} = 2d_{sd}$. Figure 4 indicates that the maximum transmission rate is achieved when the optimal transmission distances are used.
Figure 5 depicts the outage probability performance as a function of \( \frac{d_{sr}}{d_{sd}} \). Here, \( P_o/N_0 \) = 10 dB, \( \alpha = 4 \), \( \varepsilon_s = 0.1 \), \( \varepsilon_p = 0.05 \), \( \theta = \pi/2 \) and \( d_{sp} = 2d_{sd} \). 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 \( \frac{d_{sr}}{d_{sd}} = 0.5 \), which leads to the midpoint of the transmission link of SU_s – SU_d as the optimal position.

In Figure 6, the transmission rate for the PU_d – SU_s link is monitored for the normalized \( d_{sd} \) distance over Rayleigh fading channel while \( P_o/N_0 \) = 10 dB, \( \alpha = 4 \), \( \varepsilon_s = 0.1 \), \( \varepsilon_p = 0.05 \), \( \theta = \pi/2 \) and \( d_{sr} = d_{sd}/2 \). In addition, \( P_{out} \) performance analysis is also studied for the transmission link for PU_d – SU_s with the normalized distance of \( d_{sd} \) and demonstrated in Figure 7 using the same parameters in Figure 6.
Figure 6. $R$ vs. $(d_{sp}/d_{sd})$ over Rayleigh fading channel while $(P_o/N_0) = 10$ dB.

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

Figure 8. $(d_{se}/d_{sd})$ vs. $R$ over Rayleigh fading channel with different $\theta$ values for $(P_o/N_0) = 10$ dB, $d_{sp} = d_{sd}$, $d_{sp} = 2d_{sd}$ and $d_{sp} = 5d_{sd}$.
The normalized $d_{sr}$ distance varying with the transmission rate $R$ over Rayleigh fading channel for different $\theta$ values and transmission links, $d_{sp} = d_{sd}$, $d_{sp} = 2d_{sd}$ and $d_{sp} = 5d_{sd}$ are shown in Figure 8. Besides, in Figure 9, $d_{sr}/d_{sd}$ normalized distances are calculated for the different $\theta$ 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 $\theta$ values for $d_{sp} = d_{sd}$, $d_{sp} = 2d_{sd}$ and $d_{sp} = 5d_{sd}$, while $(P_o/N_0) = 10$ dB is depicted in Figure 10. The figure demonstrates the effect of $d_{sp}$ with varying $\theta$ angles. The results show that the maximum transmission rate of the considered system increases while $\theta$ 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 $d_{sp}/d_{sd}$ increases, the system performance also increases when $\theta$ is in the interval of $[0 - \pi]$. In other words, these results also prove that the $R$ performance is directly related with the PU $\rightarrow$ SU $\rightarrow$ transmission link. While in case of $d_{sp}$ distance is increased, the maximum transmission is achieved.

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

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

In this chapter, we present a comprehensive performance analysis of the outage probability ($P_{out}$) 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 PU$_d$ – SU$_s$, SU$_s$ – r and PU$_d$ – r transmission links, respectively. We then present the effect of the $\theta$ angle, between PU$_d$ – SU$_s$ link and the horizontal axis, on the $P_{out}$ and $R$ performance. The numerical results, validates the theoretical analysis, show that $d_{sp}$ distance and $\theta$ angle, which is in the interval of $[0 - \pi]$, have significant performance improvement on the transmission rate and the outage probability.

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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
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