Optimal One-Dimensional Relay Placement in Cognitive Radio Networks

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***Abstract*—In this work, we find the optimal relay location for a secondary user in a cognitive radio network subject to outage constraints. With selection decode-and-forward relay protocol, we formulate this problem as a nonlinear optimization problem, and then derive an approximation formulation that gives a close-optimal relay location, which means that we can use the approximation instead to solve the relay placement problem in cognitive radio networks. We find that the optimal relay location is determined by the relative locations of the primary destination, the secondary source and the secondary destination. Moreover, we analyze the sensitivity of optimal relay location to other key parameters such as path loss exponent, interference floor and outage constraint of the primary user, and outage constraint of the secondary user.**

I. Introduction

Cognitive radio technology [1] enables dynamic spectrum access [2] by letting unlicensed secondary users opportunistically exploit under-utilized spectrum. In cognitive radio networks, a secondary user can access licensed spectrum occupied by primary users if it does not interfere with primary users' transmissions. There are two methods to achieve this: spectrum overlay and spectrum underlay. In the first case, the secondary user cannot access the channel in presence of primary users' activities; while in the latter case, the secondary user can access the channel as long as the induced interference does not exceed the primary users' interference floor. We study the relay placement problem via spectrum underlay in this paper.

Cooperative communication is a promising technique to improve the performance of wireless networks, *e.g.*, cellular networks (*e.g.*, [3], [4]) and ad hoc networks (*e.g.*, [5], [6]). When the source node cannot reach the destination node due to a poor channel condition, the relay node can help to relay the signal for the source node and thus increase network capacity. This leads to the cooperative diversity that saves the source's transmit power.

Recently, cooperative communication techniques have been introduced in cognitive radio networks [7]–[14]. While previous work focused on resource allocation for cooperative communications in cognitive radio networks, we study the relay placement optimization in cognitive radio networks. For simplicity, we consider the one-dimensional case where the source and the destination of secondary user and the relay are on the same line. The relay adopts the selection decode-and-forward protocol [6]. With a Rayleigh block fading channel model, we calculate the maximum transmission rate of the secondary user subject to outage constraints. We formulate this problem as a nonlinear optimization problem, and derive an approximation formulation. We find that the optimal relay location is determined by the relative locations of the primary user and the secondary user, and the solution obtained from the approximation is close to the optimal solution. Surprisingly, we find out that the optimal relay placement is independent of several system parameters, including the interference constraint at the primary destination, the outage constraint of the primary user, and the background noise density. We also characterize the sensitivities of the optimal relay location in terms of path loss exponent and outage constraint of the secondary user.

The rest of this paper is organized as follows. Section II describes the network model. Section III formulates and analyzes the optimal relay placement problem. We obtain the optimal solutions for both the original problem and the approximation formulation. Section IV illustrates the results through extensive numerical results. Finally, Section V concludes this paper.

II. System Model

We consider a network scenario illustrated in Fig. 1. We have a primary user PU and a secondary user SU, each has a source and a destination. A relay r is placed on the same line determined by the secondary source SU_s and the secondary destination SU_d. Let d_{sr} be the distance between the secondary source SU_s and the relay r, d_{sp} be the distance between the secondary source SU_s and the primary destination PU_d, d_{sd} be the distance between the secondary source SU_s and the secondary destination SU_d, and angle $\theta = \angle PU_d - SU_s - SU_d$. Then the distance between the relay r and the primary destination PU_d is

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

We assume that the primary user source PU_s always transmits to the primary user destination PU_d. The SU transmits through the cooperative transmission without generating excessive interference to the PU. We consider the selection decode-and-forward relay protocol with time division (TD) orthogonal sub-channels similar as [6]. With this protocol, the cooperative transmission operates in two phases. First the secondary source SU_s transmits the signal to the relay r,

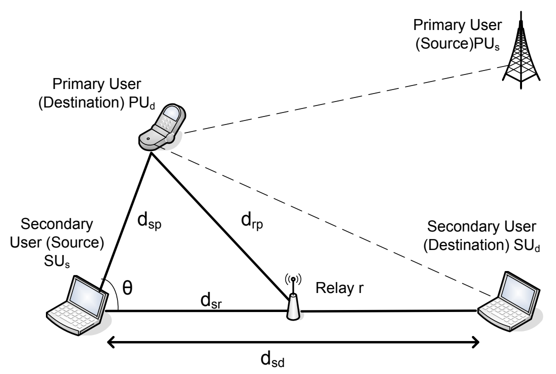


Fig. 1. The coexisting primary user and secondary user scenario.

and then the relay r decodes and retransmits the received signal to the secondary destination SU_d. If the relay r cannot decode the signal in the first phase, the secondary source SU_s will retransmit the signal in the second phase. For simplicity, the time allocation for source's transmission and relay's transmission are equal. These two phases together occupy a time block.

A. Performance Metric: Maximum Rate Subject to Outage Probabilities

We consider a Rayleigh block fading channel model, where the fading coefficients are constant over a block and independent over different blocks. A good communication performance metric for this block fading environment is maximum transmission rate of the secondary user subject to outage constraints. Outage probability here is defined as the probability of the instantaneous achievable rate of a channel below its target transmission rate.

In a cognitive radio network, the transmission of a primary user should be protected from the interference caused by either a secondary user or a relay. In spectrum underlay, the primary user has a maximum tolerable interference level (*e.g.*, interference floor) P_0 at the primary destination PU_d [15]. When the interference from the secondary user in the first phase or the relay in the second phase exceeds P_0, the primary user's transmission will be corrupted. Thus, the secondary user and the relay have to control their transmit power levels such that the outage probability of the primary user, *i.e.*, the probability of the interference exceeding P_0, is below an outage constraint ϵ_p. The maximum transmission power levels depend both on ϵ_p and the locations of the secondary source SU_s and relay r.

From the secondary user's point of view, it wants to maximize the data rate at the destination SU_d subject to the outage probability ϵ_s. The outage in this case is due to the fact that the channel conditions between the secondary source SU_s, the relay r, and the secondary destination SU_d can be poor due to Rayleigh fading.

For simplicity, we assume that the maximum transmit power of the transceivers of the secondary user and the relay are large enough such that their maximum allowable transmit power are only determined by the outage constraint of the primary user. We also assume that background noise, denoted by N_0, is homogeneous in the whole area.

III. Optimal Placement of Cognitive Relay

We first formulate the optimal relay placement problem in cognitive radio networks as a nonlinear optimization problem. Then we derive an approximation formulation that is easier to solve and leads to more insights.

A. Transmission Powers of Secondary Source and Relay

First we consider the interference caused by the secondary source and the relay at the primary destination. In the Rayleigh block fading channel, the received power at the destination follows exponential distribution with mean equal to $Pd^{-\alpha}$, where P is the transmit power of the source, d is the distance between two nodes, and α is the path loss exponent[1]. Therefore, the outage probability of the primary destination PU_d during the source transmission phase is

$$p^e_{s,p} \triangleq \Pr[P^r_{s,p} > P_0] = \exp\left(-\frac{P_0}{P_s d_{sp}^{-\alpha}}\right), \quad (2)$$

where $P^r_{s,p}$ is the received interference at the primary destination PU_d during this phase, and P_s is the transmit power of the secondary source SU_s. Similarly, the outage probability of the primary destination during the relay transmission phase is

$$p^e_{r,p} \triangleq \Pr[P^r_{r,p} > P_0] = \exp\left(-\frac{P_0}{P_r d_{rp}^{-\alpha}}\right), \quad (3)$$

where $P^r_{r,p}$ is the received interference at the primary destination PU_d during this phase, and P_r is the transmit power of the relay r.

Our goal in this paper is to maximize the transmission rate R of the secondary user, thus the secondary source SU_s and the relay r should use their maximum allowable transmit power such that the outage probabilities $p^e_{s,p}$ and $p^e_{r,p}$ are equal to ϵ_p. From (2) and (3), we can derive

$$P_s = \frac{P_0 d_{sp}^{\alpha}}{-\ln \epsilon_p}, \quad (4)$$

$$P_r = \frac{P_0 d_{rp}^{\alpha}}{-\ln \epsilon_p}. \quad (5)$$

B. Problem Formulation

In the selection decode-and-forward scheme, the message is first broadcasted by the source. If the relay can decode the message, it will retransmit the message to the destination by using the repetition coding. Otherwise, the relay remains silent[2], and the source will retransmit the message. Here we assume that the achievable transmission rate is given by the Shannon capacity of an additive white Gaussian noise (AWGN) channel. Using Shannon capacity allows us to focus on the relay placement problem without worrying about the choice of practical signaling and coding schemes. With

[1]For simplicity of presentation, we ignore shadow fading here.

[2]We assume that there exist instant feedback from the relay to the source.

powerful coding schemes, transmission rates close to Shannon capacity can be obtained in practice.

Let us denote the instantaneous signal-to-noise ratios (SNRs) of links (SU_s, SU_d), (SU_s, r), and (r, SU_d) as γ_{sd}, γ_{sr}, and γ_{rd}, respectively. We further let R be the transmission rate of the secondary source SU_s, and function

$$g(R) = 2^{2R} - 1.$$

Then the instantaneous achievable rate of the secondary user [6, Sec. IV.C] is

$$R_{DF} = \begin{cases} \frac{1}{2}\log_2(1+2\gamma_{sd}), & \gamma_{sr} < g(R), \\ \frac{1}{2}\log_2(1+\gamma_{sd}+\gamma_{rd}), & \gamma_{sr} \geq g(R), \end{cases} \tag{6}$$

The outage probability of the secondary user is

$$\begin{aligned} p_{DF}^{e} &\triangleq \Pr[R_{DF} < R] \\ &= \Pr[\gamma_{sd} < \frac{g(R)}{2}] \cdot \Pr[\gamma_{sr} < g(R)] \\ &\quad + \Pr[\gamma_{sd}+\gamma_{rd} < g(R)] \cdot \Pr[\gamma_{sr} \geq g(R)]. \end{aligned} \tag{7}$$

In the Rayleigh block fading channel, the SNRs at the destinations of links (SU_s, SU_d), (SU_s, r), (r, SU_d) all follow exponential distribution with mean SNR $\overline{\gamma}_{sd}$, $\overline{\gamma}_{sr}$, and $\overline{\gamma}_{rd}$ respectively. That is,

$$Pr[\gamma_{sd} < r] = 1 - \exp\left(-\frac{r}{\overline{\gamma}_{sd}}\right), \tag{8}$$

$$Pr[\gamma_{sr} < r] = 1 - \exp\left(-\frac{r}{\overline{\gamma}_{sr}}\right), \tag{9}$$

$$Pr[\gamma_{rd} < r] = 1 - \exp\left(-\frac{r}{\overline{\gamma}_{rd}}\right), \tag{10}$$

where the average SNR values are

$$\overline{\gamma}_{sd} = \frac{\overline{P}_{s,d}}{N_0} = \frac{P_s d_{sd}^{-\alpha}}{N_0} = \frac{P_0}{-N_0 \ln \epsilon_p}\left(\frac{d_{sd}}{d_{sp}}\right)^{-\alpha}, \tag{11}$$

$$\overline{\gamma}_{sr} = \frac{\overline{P}_{s,r}}{N_0} = \frac{P_s d_{sr}^{-\alpha}}{N_0} = \frac{P_0}{-N_0 \ln \epsilon_p}\left(\frac{d_{sr}}{d_{sp}}\right)^{-\alpha}, \tag{12}$$

$$\overline{\gamma}_{rd} = \frac{\overline{P}_{r,d}}{N_0} = \frac{P_r d_{rd}^{-\alpha}}{N_0} = \frac{P_0}{-N_0 \ln \epsilon_p}\left(\frac{d_{rd}}{d_{rp}}\right)^{-\alpha}. \tag{13}$$

For simplicity, let

$$\mu = P_0/(-N_0 \ln \epsilon_p), \tag{14}$$

then we have

$$\overline{\gamma}_{sd} = \mu\left(\frac{d_{sd}}{d_{sp}}\right)^{-\alpha}, \overline{\gamma}_{sr} = \mu\left(\frac{d_{sr}}{d_{sp}}\right)^{-\alpha}, \overline{\gamma}_{rd} = \mu\left(\frac{d_{rd}}{d_{rp}}\right)^{-\alpha}. \tag{15}$$

Then, from Equation (7), the outage probability of the secondary user is

$$\begin{aligned} p_{DF}^{e} = &\left(1 - \exp\left(-\frac{g(R)}{2\overline{\gamma}_{sd}}\right)\right) \cdot \left(1 - \exp\left(-\frac{g(R)}{\overline{\gamma}_{sr}}\right)\right) \\ &+ \left(1 - \left(\frac{\overline{\gamma}_{sd}}{\overline{\gamma}_{sd} - \overline{\gamma}_{rd}} \exp\left(-\frac{g(R)}{\overline{\gamma}_{sd}}\right)\right.\right. \\ &\left.\left. + \frac{\overline{\gamma}_{rd}}{\overline{\gamma}_{rd} - \overline{\gamma}_{sd}} \exp\left(-\frac{g(R)}{\overline{\gamma}_{rd}}\right)\right)\right) \cdot \exp\left(-\frac{g(R)}{\overline{\gamma}_{sr}}\right). \end{aligned} \tag{16}$$

Note that Equation (16) does not hold when $\overline{\gamma}_{sd} = \overline{\gamma}_{rd}$. In that case, the locations of the secondary source and the relay coincide with each other. However, this situation will not occur as the relay cannot offer any benefits to the secondary user. Thus, Equation (16) holds in real situations.

Our objective is to maximize the transmission rate R of the secondary user subject to the outage constraints of the primary user and the secondary user. The primary user's outage constraint has been taken care when calculating the transmission powers in (4) and (5). The optimization problem can be formulated as follows subject to outage constraint of the secondary user and location of the relay:

$$\begin{aligned} \max_{d_{sr}, R} \quad & R \\ s.t. \quad & p_{DF}^{e} \leq \epsilon_s, \\ & 0 < d_{sr} < d_{sd}. \end{aligned} \tag{17}$$

From the expressions of mean SNRs in (15), we find that all distances d_{sd}, d_{sr}, and d_{rd} can be normalized with distance d_{sp}. This means that the optimal relay location is determined by the normalized distances and the angle θ. In other words, the optimal relay location is related to the relative locations of the primary destination, the secondary source and the secondary destination.

Next we rewrite the Problem (17) into an equivalent but simpler form. Given a fixed parameter μ in (14), we find that the relay placement d_{sr} that maximizes transmission rate R in Problem (17) also maximizes $g(R)/\mu$ with the same set of constraints. This is because the $g(R)/\mu$ is an increasing function of R. We also observe that all mean SNRs in (15) have a common coefficient μ. Let $\rho(R) = g(R)/\mu$. With Equation (16), the optimal relay location can be obtained by solving the following problem:

$$\begin{aligned} \max_{d_{sr}, R} \quad & \rho(R) \\ s.t. \quad & p_{DF}^{e}(\rho(R)) \leq \epsilon_s, \\ & 0 < d_{sr} < d_{sd}, \end{aligned} \tag{18}$$

where

$$p_{DF}^e(\rho(R)) = \left(1-\exp\left(-\rho(R)\left(\frac{d_{sd}}{d_{sp}}\right)^{\alpha}\right)\right) \cdot \left(1-\exp\left(-\rho(R)\left(\frac{d_{sr}}{d_{sp}}\right)^{\alpha}\right)\right) + \left(1-\left(\frac{\left(\frac{d_{sd}}{d_{sp}}\right)^{-\alpha}}{\left(\frac{d_{sd}}{d_{sp}}\right)^{-\alpha}-\left(\frac{d_{rd}}{d_{rp}}\right)^{-\alpha}}\exp\left(-\rho(R)\left(\frac{d_{sd}}{d_{sp}}\right)^{\alpha}\right) + \frac{\left(\frac{d_{rd}}{d_{rp}}\right)^{-\alpha}}{\left(\frac{d_{rd}}{d_{rp}}\right)^{-\alpha}-\left(\frac{d_{sd}}{d_{sp}}\right)^{-\alpha}}\exp\left(-\rho(R)\left(\frac{d_{rd}}{d_{rp}}\right)^{\alpha}\right)\right)\right) \cdot \exp\left(-\rho(R)\left(\frac{d_{sr}}{d_{sp}}\right)^{\alpha}\right). \quad (19)$$

Equation (19) suggests that the only variables in Problem (18) are $\rho(R)$ and d_{sr}. The optimal solution d_{sr}^* of Problem (18) only depends on the normalized distances and path loss coefficient α (in (19)) as well as the outage constraint ϵ_s of the secondary user (in the first constraint of Problem (18)).

As Problem (17) and (18) have the same optimal relay location, then such location is *independent* of interference floor P_0, the background noise N_0, and the outage constraint ϵ_p of the primary user. We note, however, the maximum achievable rate R depends on these parameters.

C. Approximation

Ideally, we want to obtain the closed form optimal solutions of Problem (18). However, this turns out to be very difficult (if not impossible) due to the complex nature of Equation (16). To obtain more insights, we will look at an approximation formulation that leads to very close to optimal relay location. The effectiveness of the approximation will be demonstrated through extensive numerical results in Section IV.

The starting point of approximation is the assumption that the outage probability of secondary user ϵ_s should be small. Suppose $\epsilon_s \to 0$, we have $g(R)/\mu \to 0$ [16]. Then we have

$$\begin{aligned} &\lim_{\frac{g(R)}{\mu}\to 0} p_{DF}^e = \\ &\lim_{\frac{g(R)}{\mu}\to 0} \Pr[\gamma_{sd} < \frac{g(R)}{2}]\Pr[\gamma_{sr} < g(R)] + \\ &\lim_{\frac{g(R)}{\mu}\to 0} \Pr[\gamma_{sd}+\gamma_{rd} < g(R)]\Pr[\gamma_{sr} \geq g(R)] \\ &= \frac{g(R)^2}{2\overline{\gamma}_{sd}\overline{\gamma}_{sr}} + \frac{g(R)^2}{2\overline{\gamma}_{sd}\overline{\gamma}_{rd}}. \end{aligned} \quad (20)$$

Combined with the fact that $p_{DF}^e = \epsilon_s$ at the optimal solution, we have

$$\epsilon_s = \left(\frac{1}{2\overline{\gamma}_{sd}\overline{\gamma}_{sr}} + \frac{1}{2\overline{\gamma}_{sd}\overline{\gamma}_{rd}}\right) \cdot g(R)^2. \quad (21)$$

That is,

$$R = \frac{1}{2}\log_2\left(1+\mu\sqrt{\epsilon_s}\sqrt{\frac{\left(\frac{d_{sd}}{d_{sp}}\right)^{-\alpha}\left(\frac{d_{rd}}{d_{rp}}\right)^{-\alpha}\left(\frac{d_{sr}}{d_{sp}}\right)^{-\alpha}}{\left(\frac{d_{rd}}{d_{rp}}\right)^{-\alpha}+\left(\frac{d_{sr}}{d_{sp}}\right)^{-\alpha}}}\right). \quad (22)$$

So our rate maximization problem (18) can be approximated as follows:

$$\begin{aligned} \max_{d_{sr}} \quad & \frac{1}{2}\log_2\left(1+\mu\sqrt{\epsilon_s}\sqrt{\frac{\left(\frac{d_{sd}}{d_{sp}}\right)^{-\alpha}\left(\frac{d_{rd}}{d_{rp}}\right)^{-\alpha}\left(\frac{d_{sr}}{d_{sp}}\right)^{-\alpha}}{\left(\frac{d_{rd}}{d_{rp}}\right)^{-\alpha}+\left(\frac{d_{sr}}{d_{sp}}\right)^{-\alpha}}}\right) \\ \text{s.t.} \quad & 0 < d_{sr} < d_{sd}. \end{aligned} \quad (23)$$

Finding the optimal solution of Problem (23) is equivalent of solving the following problem:

$$\begin{aligned} \max_{d_{sr}} \quad & \frac{\left(\frac{d_{sd}}{d_{sp}}\right)^{-\alpha}\left(\frac{d_{rd}}{d_{rp}}\right)^{-\alpha}\left(\frac{d_{sr}}{d_{sp}}\right)^{-\alpha}}{\left(\frac{d_{rd}}{d_{rp}}\right)^{-\alpha}+\left(\frac{d_{sr}}{d_{sp}}\right)^{-\alpha}} \\ \text{s.t.} \quad & 0 < d_{sr} < d_{sd}. \end{aligned} \quad (24)$$

Compared with Problem (18), the approximation formulation (24) is independent of the outage constraint ϵ_s of the secondary user. This is because the rate function under low outage probability in (22) is a monotonic increasing function of the product of the outage constraint ϵ_s and the polynomial expression of normalized distances. Thus, the optimal relay location under a value of ϵ_s is also optimal under any other value of ϵ_s. However, the rate function with an arbitrary outage probability does not have such a property, and hence the optimal relay placement of Problems (17) and (18) depends on the value of ϵ_s. In the next section, we will demonstrate the effectiveness of the approximation formulation (23) through extensive simulation results.

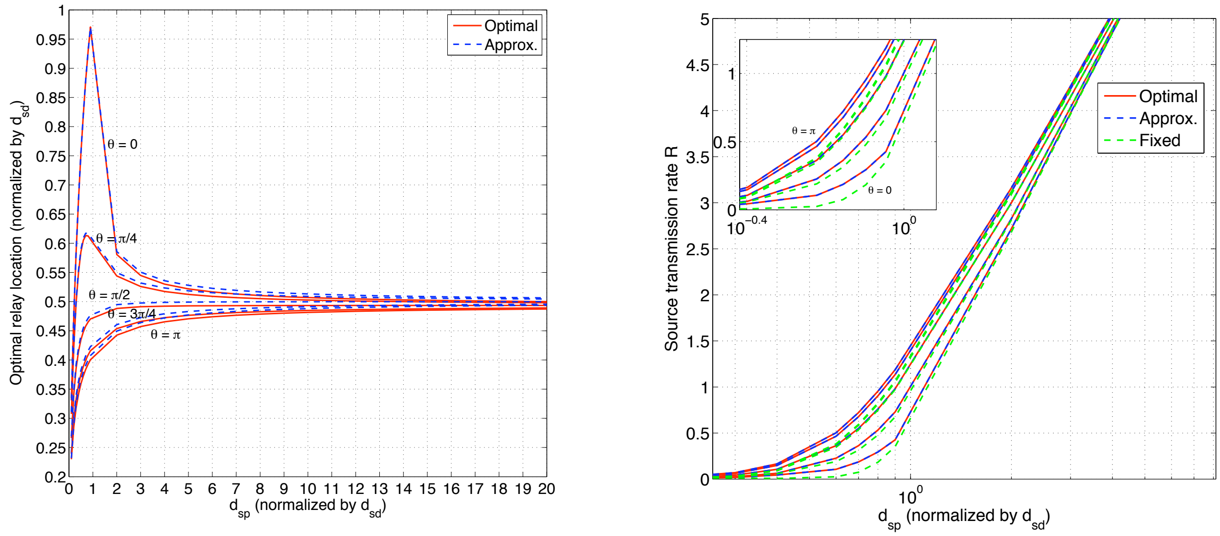
IV. Results and Discussion

In this section, we provide some results about the optimal relay location in cognitive radio networks. Problem (17) and (23) are both nonlinear optimization problems which are difficult to solve in closed form. However, they both have only one variable d_{sr}[3]. Thus, we can use an efficient one-dimensional search algorithm to find the exact optimal solutions for both problems.

Figure 2 shows the optimal relay location d_{sr} and the corresponding optimal transmission rate R of the secondary user obtained by the original formulation (17) and the approximation formulation (23) respectively. For each curve, we fix the angle θ and change the distance between the secondary source and the primary destination d_{sp}.

From Fig. 2a, we find that solving the approximation formulation (23) leads to a very close-optimal relay location

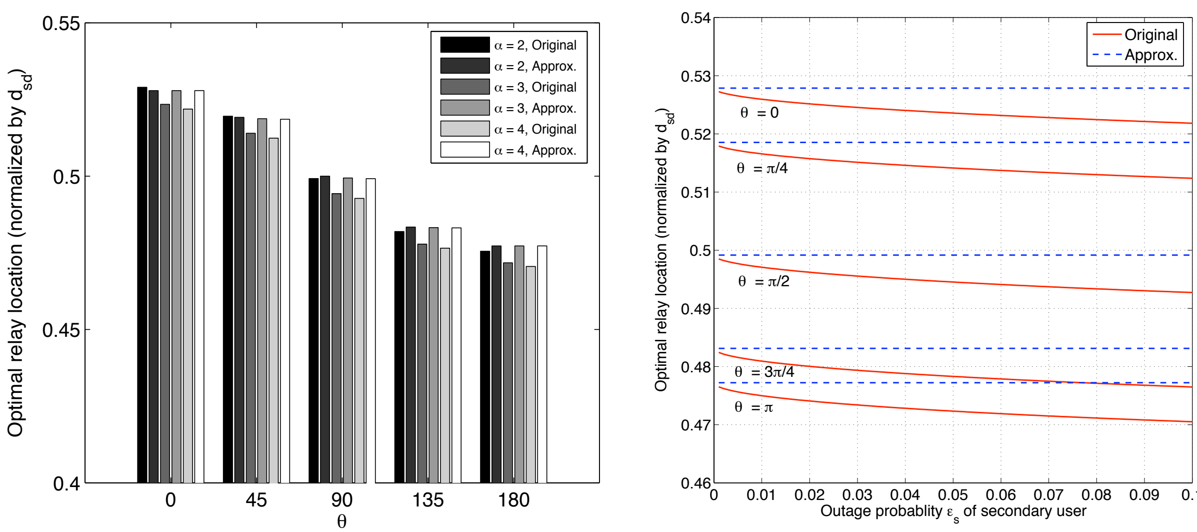
[3]The variable rate R in Problem (17) can be eliminated by setting the first inequality constraint to equality.



(a) Optimal relay location.

(b) Optimal rate.

Fig. 2. The optimal relay location d_{sr} and the corresponding optimal transmission rate R with $\alpha = 4$, $\epsilon_p = 0.05$, $P_0/N_0 = 10dB$, and $\epsilon_s = 0.1$.



(a) Path loss exponent α.

(b) Outage constraint ϵ_s of secondary user.

Fig. 3. Sensitivity analysis of other parameters.

for the secondary user. When the distance between the secondary source and the primary destination d_{sp} is large (e.g., $d_{sp} \geq 10$), the optimal location of relay r is very close the middle point of the secondary source SU_s and the secondary destination SU_d. This is the consistent with the result in the literature without interference constraint. By comparing curves with different values of $\theta \in [0, \pi]$, we observe that when θ increases, the optimal location of the relay r moves towards the secondary source SU_s.

From Fig. 2b, we observe that when $d_{sp}/d_{sd} \geq 1$, the impact of θ on the determination of the optimal relay location is limited. This implies that when the primary user is sufficiently far away from the secondary user, we can ignore its location and just consider its interference floor P_0 and outage constraint ϵ_p.

Next we study the sensitivity of the optimal relay location to other key system parameters. Figure 3a shows the influence of path loss exponent α on the optimal relay location. From this figure, we see that α has a very small impact on the optimal location selection, and the approximation formulation can find the near-optimal location. Figure 3b shows the impact of outage constraint ϵ_s of secondary user on the optimal relay location. From the analysis in the previous section, we know that it has no impact on the optimal solution obtained by the approximation formulation in the low outage probability regime, and we validate our analysis with this figure. However, as implied by the curves obtained with the original formulation, ϵ_s has non-negligible influence on the optimal location of a relay when it is relatively large. In practice, the outage probability is typically much less than 0.1, and thus the approximation formulation leads to very close to optimal relay position.

V. Conclusion

In this paper, we study the optimal relay placement problem in cognitive spectrum underlay networks. For simplicity, We focus on the one-dimensional case. We consider the selection decode-and-forward relay protocol with Rayleigh blocking fading channel model. In such an environment, a natural metric to evaluate the performance of the secondary user is its maximum transmission rate subject to outage constraints. We formulate this problem as a nonlinear optimization problem, and further derive an equivalent formulation that illustrate several interesting insights of the optimal relay position. We further derive an approximation formulation in the low outage probability regime.

We find that the optimal relay location is determined by the relative locations of the primary destination, the secondary source, and the secondary destination. It is independent of the interference constraint at the primary destination, the outage constraint of the primary user, and the background noise density. We also find that the approximation formulation gives a close to optimal relay location. This implies that we can use the approximation formulation when determining the optimal relay location in cognitive radio networks. The sensitivities of optimal relay location to other key system parameters are also investigated. The path loss exponent has only small impact on the optimal relay location, for both original formulation and approximation formulation. The outage constraint of secondary user can influence the optimal relay location, but the impact is small under a low outage probability as in practice.

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References

[1] J. Mitola III and G. Maguire Jr., "Cognitive radio: making software radios more personal," *IEEE In Personal Communications*, vol. 6, no. 4, pp. 1–18, Aug. 1999.

[2] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Computer Networks*, vol. 50, no. 13, pp. 2127–2159, September 2006.

[3] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity - part i: System description," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1927–1938, Nov. 2003.

[4] ——, "User cooperation diversity - part ii: Implementation aspects and performance analysis," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1939–1948, Nov. 2003.

[5] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2415–2425, October 2003.

[6] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[7] T. Fujii and Y. Suzuki, "Ad-hoc cognitive radio - development to frequency sharing system by using multi-hop network," in *Proc. IEEE DySPAN*, 2005.

[8] J. Mietzner, L. Lampe, and R. Schober, "Distributed transmit power allocation for relay-assisted cognitive-radio systems," in *Proc. IEEE ACSSC*, 2007.

[9] K. Hamdi and K. B. Letaief, "Cooperative communications for cognitive radio networks," in *Proc. PGNet*, 2007.

[10] K. B. Letaief and W. Zhang, "Cooperative communications for cognitive radios," *Proc. of the IEEE*, vol. 97, no. 5, pp. 878–893, May 2009.

[11] M. Xie, W. Zhang, and K.-K. Wong, "A geometric approach to improve spectrum efficiency for cognitive relay networks," *IEEE Transactions on Wireless Communications*, vol. 9, no. 1, pp. 268–281, Jan. 2010.

[12] Q. Zhang, J. Jia, and J. Zhang, "Cooperative relay to improve diversity in cognitive radio networks," *IEEE Communications Magazine*, vol. 47, no. 2, pp. 111–117, Feb. 2009.

[13] K. Lee and A. Yener, "Outage performance of cognitive wireless relay networks," in *Proc. IEEE GLOBECOM*, 2006.

[14] H. A. Suraweera, P. J. Smith, and N. A. Surobhi, "Exact outage probability of cooperative diversity with opportunistic spectrum access," in *Proc. IEEE ICC Workshops*, 2008.

[15] Federal Communication Commission, "Establishment of interference temperature metric to quantify and manage interference and to expand available unlicensed operation in certain fixed mobile and satellite frequency bands," *ET Docket 03-289, Notice of Inquiry and Proposed Rulemaking*, 2003.

[16] A. S. Avestimehr and D. N. C. Tse, "Outage capacity of the fading relay channel in the low-SNR regime," *IEEE Transactions on Information Theory*, vol. 53, no. 4, pp. 1401–1415, April 2007.