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Resource Allocation for the Cognitive Coexistence of Ad-hoc and Cooperative Relay Networks

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Abstract—**In this paper, we study a cognitive coexistence strategy for heterogeneous networks. While a lot of previous works focused on spectrum underlay approaches for weak interference scenarios, a high power infrastructure (IS) transmitter creates a large dead zone for nearby ad-hoc (AH) links using the same spectrum. To address this problem, we propose to utilize a half-duplex decode-and-forward (DF) relay node to assist the IS transmitter. The transmission time and power of relay-assisted IS network is optimized to reduce its generated interference while still guaranteeing its quality-of-service (QoS) level. The resource allocation problem of relay-assisted IS network is formulated as a convex optimization problem, for which a tailored dual optimization method is proposed. Our numerical results show that our relay-assisted scheme can produce less interference and/or achieve a higher QoS level.**

I. INTRODUCTION

As wireless communication techniques develop rapidly, heterogeneous wireless communication systems need to be accommodated in limited frequency bandwidth. Traditional orthogonal spectral separation of heterogeneous systems is not efficient enough to support the continuous growth of wireless device deploying requirement, which makes spectrum sharing among heterogeneous systems more and more important.

Recently, spectrum underlay approaches have been studied intensively in cognitive radio (CR) networks [1]. In these studies, the secondary systems access the spectrum opportunistically, on condition that no significant interference is experienced by the primary system.

However, in some important application scenarios, e.g. the heterogeneous networks in the unlicensed bands, this weak interference assumption is not satisfied. A high power infrastructure (IS) transmitter creates a large dead zone for nearby ad-hoc (AH) links using the same spectrum. To address the interference issue in such scenarios, the authors of [2]-[3] proposed a cognitive coexistence strategy, in which the IS system transmits adaptively to reduce its generated interference to the AH networks while still maintaining a specified quality-of-service (QoS) level. We note that this strategy relies highly on the IS link's channel quality. When the IS link suffers from poor coverage or severe channel fading, it can be quite challenging for the IS system to achieve a good QoS, not to mention accommodating the AH networks.

On the other hand, cooperative relay is well-known as a powerful technique to provide better coverage or combat the channel fading [4]. It has been considered in different CR scenarios and provides substantial improvements, e.g. [5]-[7].

In this paper, we propose to utilize a half-duplex decode-and-forward (DF) relay node to assist the IS system to mitigate interference. Our aim here is to find the optimal transmission time and power allocation scheme for the relay-assisted IS system, so as to minimize the interference to the AH links subject to maintaining a specified QoS level. To the extent of authors' knowledge, this problem has not been addressed in the literature. This resource allocation problem is formulated as a convex optimization problem. Since the previous dual optimization method in [2]-[3] can not be applied in this problem, a modified layered optimization method is proposed to solve it. Our numerical results show that our relay-assisted scheme can produce less interference and/or achieve a higher QoS level since it has superior communication ability.

Potential applications for this work include the coexistence of wireless communication networks in the unlicensed band such as 802.16 (WIMAX) and 802.11 (WIFI) [8]-[9], accommodating device-to-device transmissions in relay-assisted cellular networks [10], and interference mitigation between military communication systems with different priorities [11].

II. SYSTEM MODEL

The system model is illustrated in Fig. 1(a). An IS system which consists of a base station (BS), an IS user and a cooperative relay node is considered. The relay-assisted uplink transmissions of the IS user cause strong interference to nearby AH links. To address this, the IS system transmits adaptively based on the sensing and predicting results of the AH links' behaviors. The optimal resource allocation for the IS system is studied which minimizes the generated interference to the AH links while still maintaining a specified QoS level.

Ad-hoc networks: The AH links operate in frequency bands which overlap with the IS system. As depicted in Fig. 1(b), different AH links (with different colors) operate in non-overlapping bands that each overlaps with a number of IS channels. We model the transmission behavior of each AH band by an ON/OFF continuous time Markov chain (CTMC).

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The durations of ON and OFF states satisfy exponential distributions with parameter μ for the ON state and λ for the OFF state. The probability of the ON/OFF state for the AH band at time $t+\tau$ on condition of its previous state at time t is given by the probability transition matrix [12, p. 391]

$$P(\tau) = \frac{1}{\lambda+\mu}\left[\begin{array}{cc} \mu+\lambda e^{-(\lambda+\mu)\tau} & \lambda-\lambda e^{-(\lambda+\mu)\tau} \\ \mu-\mu e^{-(\lambda+\mu)\tau} & \lambda+\mu e^{-(\lambda+\mu)\tau} \end{array}\right]. \quad (1)$$

This CTMC model was also used in related publications [3], [13]-[15]. It strikes a good tradeoff between model accuracy and the facility of theoretical analysis.

Relay assisted infrastructure system: The IS system operates in frames of duration T, each frame has N channels. The channel power gains for IS user to relay link, relay to BS link and IS user to BS link in channel n are denoted by g_1^n, g_2^n and g_3^n, respectively. At the beginning of each frame, the IS user senses the ON/OFF state of the AH bands on a per channel base. Perfect sensing is assumed throughout the paper.

The relay node is required to operate in half-duplex mode due to practical considerations [16]. Here, we consider a time-division half-duplex relay scheme. More specifically, the IS user transmits to the relay node and the BS in the first half frame, i.e. $(0, T/2]$, and the relay node transmits to the BS in the second half frame, i.e. $(T/2, T]$, as shown in Fig. 1(b). We suppose that the IS user and relay node transmit t_1^n and t_2^n fractions of a frame on channel n, respectively. Thus, the half-duplex assumption can be given by $0 \le t_1^n, t_2^n \le 1/2$.

While the IS user interferes local AH links in the first hop, the relay node may either interfere the AH links or not in the second hop. More specifically, the relay node may interfere the AH links if it locates near the IS user and the AH nodes. On the other hand, the relay node can be far from the IS user and have good channel quality to the BS due to line-of-sight channel component or directional antenna elements. In such cases, the relay node's signal power can be quite small and causes little interference to the AH links. Both cases will be analyzed in the forthcoming section.

III. COGNITIVE COEXISTENCE STRATEGIES

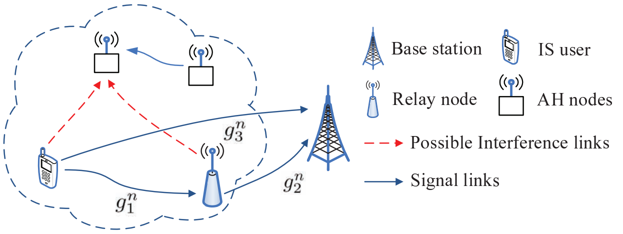
We model the interference between AH and cooperative relay networks by the average temporal overlap between the two systems, which the probability the AH link is affected by the cooperative relay network.

Following the monotonicity of transition probability density function (pdf) (see also the proof of [3, Lemma 1]), we can prove that the minimum average overlap is achieved if

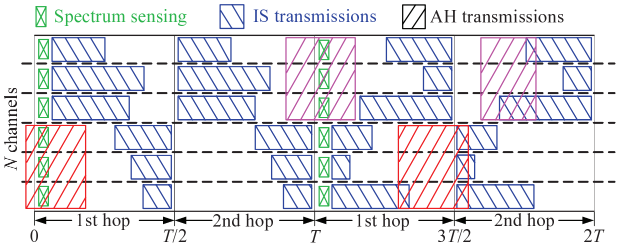
1) the IS user transmits at the beginning (end) of the first half frame , i.e. $[0, t_1^n T]$ ($[T/2 - t_1^n T, T/2]$) if the sensing outcome is idle (busy),
2) the relay node transmits the whole second half frame if it does not interfere the AH links; otherwise, the relay node transmits at the beginning (end) of the second half frame, i.e. $[T/2, t_2^n T + T/2]$ ($[T - t_2^n T, T]$) if the sensing outcome is idle (busy).

The case that the relay node interferes the AH links is depicted in Fig. 1.

We denote the normalized average overlap as $\phi_{x,y}(t)$, where $x \in \{0,1\}$ is the sensing outcome ($x = 1$ denotes busy and $x = 0$ represents idle), $y \in \{1,2\}$ denotes that the overlap is in the first or second half frame. By integrating the transition pdf, we derive $\phi_{x,y}(t)$. For the idle case, we have



(a) System setup



(b) Physical layer transmission structure

Fig. 1. System setup and physical layer transmission structure of coexisting ad-hoc and cooperative relay networks.

$$\begin{aligned}\phi_{0,1}(t) &= \frac{1}{T}\int_0^{tT} \Pr(X(t)=1|X(0)=0)dt \\ &= \frac{\lambda}{(\lambda+\mu)T}\left\{tT + \frac{1}{\lambda+\mu}\left[e^{-(\lambda+\mu)tT}-1\right]\right\} \quad (2)\end{aligned}$$

and

$$\begin{aligned}\phi_{0,2}(t) &= \frac{1}{T}\int_{T/2}^{tT+T/2} \Pr(X(t)=1|X(0)=0)dt \\ &= \frac{\lambda}{(\lambda+\mu)T}\left\{tT + \frac{1}{\lambda+\mu} e^{-(\lambda+\mu)T/2}\left[e^{-(\lambda+\mu)tT}-1\right]\right\}. \quad (3)\end{aligned}$$

In the case of a busy sensing outcome, we can obtain

$$\begin{aligned}\phi_{1,1}(t) &= \frac{1}{T}\int_{T/2-tT}^{T/2} \Pr(X(t)=1|X(0)=1)dt \\ &= \frac{\lambda}{(\lambda+\mu)T}\left\{tT + \frac{\mu/\lambda}{\lambda+\mu} e^{-(\lambda+\mu)T/2}\left[e^{(\lambda+\mu)tT}-1\right]\right\} \quad (4)\end{aligned}$$

and

$$\begin{aligned}\phi_{1,2}(t) &= \frac{1}{T}\int_{T-tT}^{T} \Pr(X(t)=1|X(0)=1)dt \\ &= \frac{\lambda}{(\lambda+\mu)T}\left\{tT + \frac{\mu/\lambda}{\lambda+\mu} e^{-(\lambda+\mu)T}\left[e^{(\lambda+\mu)tT}-1\right]\right\}. \quad (5)\end{aligned}$$

It is easy to prove that the expected overlap expressions (2)-(5) are strictly convex on t by showing that their secondary derivations are strictly positive. We can show that less interference is generated by transmitting on the channels with idle sensing outcome, since

$$\phi_{0,1}(t) < \phi_{0,2}(t) < \frac{\lambda t}{\lambda+\mu} < \phi_{1,2}(t) < \phi_{1,1}(t), \quad t > 0. \quad (6)$$

We now formulate the transmission time and power allocation problem for DF relay scheme.

A. Transmission time and power allocation

In [17], the authors presented the achievable data rate of half-duplex DF relay scheme with multi-channel transmission

$$\begin{aligned} R_{DF} &= \min\{R_1, R_2\} \\ &= \min\left\{ \sum_{n\in\mathcal{A}} t_1^n \mathcal{C}\left(\frac{\kappa P_s^n g_1^n}{t_1^n}\right) + \sum_{n\in\mathcal{A}^c} t_1^n \mathcal{C}\left(\frac{\kappa P_s^n g_3^n}{t_1^n}\right), \right. \\ &\left. \sum_{n=1}^{N}\left[t_1^n \mathcal{C}\left(\frac{\kappa P_s^n g_3^n}{t_1^n}\right) + t_2^n \mathcal{C}\left(\frac{\kappa P_r^n g_2^n}{t_2^n}\right)\right]\right\}, \end{aligned} \tag{7}$$

where $\mathcal{C}(x) = \log(1+x)$, $\mathcal{A} \doteq \{n | g_1^n > g_3^n, n = 1, \cdots, N\}$ and $\mathcal{A}^c$ is the complementary set of $\mathcal{A}$, κ is a normalization factor[1], $P_s^n = \overline{P_s^n}/n_0 W$ and $P_r^n = \overline{P_r^n}/n_0 W$ are the normalized transmitted powers for the IS user and the relay node in channel n where $\overline{P_s^n}, \overline{P_r^n}$ are actual transmitted powers in channel n, W is the bandwidth of each channel. The achievable data rate (7) is concave on the power and channel resource variables $\{P_s^n, P_r^n, t_1^n, t_2^n\}$ [17]. We note that this achievable data rate is larger than the sum data rates of independent DF relay scheme in each channel [17]. It is more convenient to reformulate the first term of (7) by

$$R_1 = \sum_{n=1}^{n} t_1^n \mathcal{C}\left(\frac{\kappa P_s^n \max\{g_1^n, g_3^n\}}{t_1^n}\right). \tag{8}$$

We first consider the case that the relay node's signal interferes the AH links. The optimal resource allocation for minimizing the expected overlap is formulated by a convex optimization problem (given the sensing result x^n)

$$\min \sum_{n=1}^{N} [\phi_{x^n,1}(t_1^n) + \phi_{x^n,2}(t_2^n)] \tag{9}$$

$$s.t.\ R_{DF} \geq R \tag{10}$$

$$\sum_{n=1}^{N} P_s^n \leq P_s^{max}, \sum_{n=1}^{N} P_r^n \leq P_r^{max} \tag{11}$$

$$(P_s^n, P_r^n, t_1^n, t_2^n) \in \mathcal{W}, \tag{12}$$

where $\mathcal{W} \doteq \{(P_s^n, P_r^n, t_1^n, t_2^n) | 0 \leq t_1^n, t_2^n \leq 1/2, P_r^n, P_s^n \geq 0, \forall n\}$, $P_s^{max} = \overline{P_s^{max}}/n_0 W$ and $P_r^{max} = \overline{P_r^{max}}/n_0 W$ are the normalized power constraints and $\overline{P_s^{max}}, \overline{P_r^{max}}$ are the maximal transmitted powers. Since the data rate of DF strategy R_{DF} is non-differentiable, we replace the constraint (10) by two separate inequality constraints

$$R_1 \geq R, R_2 \geq R, \tag{13}$$

where R_1, R_2 is defined in (7). The Lagrange of the equivalent problem (9), (11)-(13) is given by

$$\begin{aligned} &L(\zeta, \tau, \varepsilon, \eta; P_s^n, P_r^n, t_1^n, t_2^n) \\ &= \sum_{n=1}^{N} [\phi_{x^n,1}(t_1^n) + \phi_{x^n,2}(t_2^n)] + \zeta(R - R_1) + \tau(R - R_2) \\ &+ \varepsilon\left(\sum_{n=1}^{N} P_s^n - P_s^{max}\right) + \eta\left(\sum_{n=1}^{N} P_r^n - P_r^{max}\right), \end{aligned} \tag{14}$$

where $\zeta, \tau, \varepsilon, \eta$ are the dual variables. The dual function is the solution to the convex optimization problem

$$D(\zeta, \tau, \varepsilon, \eta) = \inf_{(P_s^n, P_r^n, t_1^n, t_2^n)\in\mathcal{W}} L(\zeta, \tau, \varepsilon, \eta; P_s^n, P_r^n, t_1^n, t_2^n). \tag{15}$$

The gradient of the dual function is given by

$$\begin{cases} \frac{\partial D}{\partial \zeta} = R - R_1, \\ \frac{\partial D}{\partial \tau} = R - R_2, \\ \frac{\partial D}{\partial \varepsilon} = \sum_{n=1}^{N} P_s^n - P_s^{max}, \\ \frac{\partial D}{\partial \eta} = \sum_{n=1}^{N} P_r^n - P_r^{max}. \end{cases} \tag{16}$$

The dual problem is defined by

$$\sup_{\zeta, \tau, \varepsilon, \eta \geq 0} D(\zeta, \tau, \varepsilon, \eta). \tag{17}$$

Following the duality theory, we first solve the problem (15) for fixed dual variables and then solve the dual problem (17).

The Karush-Kuhn-Tucker (KKT) optimality conditions [19, Sec. 5.5.3] for $P_s^n, P_r^n, t_1^n, t_2^n$ are given by

$$-\frac{\zeta \max\{g_1^n, g_3^n\}}{1 + P_s^n \max\{g_1^n, g_3^n\}/t_1^n} - \frac{\tau g_3^n}{1 + P_s^n g_3^n / t_1^n} + \varepsilon = 0, \quad \text{if } P_s^n > 0, \tag{18}$$

$$-\frac{\tau g_2^n}{1 + P_r^n g_2^n / t_2^n} + \eta = 0, \quad \text{if } P_r^n > 0, \tag{19}$$

$$\begin{aligned} &\phi'_{x^n,1}(t_1^n) - \zeta f(P_s^n \max\{g_1^n, g_3^n\}/t_1^n) \\ &\quad - \tau f(P_s^n g_3^n / t_1^n) = 0, \quad \text{if } 0 < t_1^n < 1/2, \end{aligned} \tag{20}$$

$$\phi'_{x^n,2}(t_2^n) - \tau f(P_r^n g_2^n / t_2^n) = 0, \quad \text{if } 0 < t_2^n < 1/2. \tag{21}$$

where $f(x) = \log(1+x) - \frac{x}{1+x}$. Therefore, the optimal power allocation can be derived as

$$\begin{cases} P_s^n = t_1^n \left[\text{the larger root } x \text{ of (23)}\right]^\dagger, \\ P_r^n = t_2^n \left(\frac{\tau}{\eta} - \frac{1}{g_2^n}\right)^\dagger, \end{cases} \tag{22}$$

where $(\cdot)^\dagger = \max(\cdot, 0)$ and the root x is determined by

$$\frac{\zeta \max\{g_1^n, g_3^n\}}{1 + x \max\{g_1^n, g_3^n\}} + \frac{\tau g_3^n}{1 + x g_3^n} = \varepsilon, \tag{23}$$

which is equivalent with a quadratic equation.

The values of P_s^n, P_r^n cannot be derived now since the transmission time variables t_1^n, t_2^n are not known. However, we can get P_s^n/t_1^n and P_r^n/t_2^n from (22). By substituting the values of P_s^n/t_1^n and P_r^n/t_2^n into (20) and (21), respectively, we can obtain the transmission time t_1^n, t_2^n. When the sensing outcome is idle, the optimal values of t_1^n and t_2^n are given by

$$\begin{cases} t_1^n = \left[-\frac{1}{(\lambda+\mu)T} \log\left\{1 - \frac{\lambda+\mu}{\lambda}\left[\zeta f\left(\frac{P_s^n \max\{g_1^n, g_3^n\}}{t_1^n}\right) + \tau f\left(\frac{P_s^n g_3^n}{t_1^n}\right)\right]\right\}\right]_0^{1/2}, \\ t_2^n = \left[-\frac{1}{(\lambda+\mu)T} \log\left\{1 - \frac{\lambda+\mu}{\lambda}[\tau f(P_r^n g_2^n / t_2^n)]\right\} - \frac{1}{2}\right]_0^{1/2}. \end{cases} \tag{24}$$

where $[x]_0^y \doteq \min\{\max\{x, 0\}, y\}$ and $\log(x)$ is extended to take the value $-\infty$ for $x \in (-\infty, 0]$ (like [19, Sec. 3.1.2])

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[1] In this paper, we let $\kappa = 1$ to represent the theoretical maximal achievable rate. Other choices of κ include $\kappa = -1.5/\log(5\text{BER})$ for uncoded variable-rate MQAM with BER denoting the required bit-error rate [18].

hereafter to simplify the formulations. When the sensing outcome is busy, the optimal values of t_1^n and t_2^n are

$$\begin{cases} t_1^n = \Big[1/2 + \frac{1}{(\lambda+\mu)T}\log\Big\{\frac{\lambda+\mu}{\mu}\Big[\zeta f\Big(\frac{P_s^n\max\{g_1^n,g_3^n\}}{t_1^n}\Big) \\ \qquad\qquad\qquad +\tau f\Big(\frac{P_s^n g_3^n}{t_1^n}\Big)\Big] - \frac{\lambda}{\mu}\Big\}\Big]_0^{1/2}, \\ t_2^n = \Big[1+\frac{1}{(\lambda+\mu)T}\log\Big\{\frac{\lambda+\mu}{\mu}\left[\tau f(P_r^n g_2^n/t_2^n)\right] - \frac{\lambda}{\mu}\Big\}\Big]_0^{1/2}. \end{cases} \tag{25}$$

Now, we focus on the dual problem (17). Our previous discussion has shown that the optimal solution to (15) is unique, therefore the dual function $D(\zeta,\tau,\varepsilon,\eta)$ is continuous differentiable [20, Prop. 6.1.1]. Therefore, it is natural to utilize gradient projection method [20, Sec. 2.3] to solve (17) by choosing proper iterative stepsize.

However, the gradient projection method can be quite slow for this problem. To explain this, the contour of the dual function with respect to τ,η for fixed τ and ε is provided in Fig. 2, where the gradient direction on the variables τ,η is orthogonal to the contour. We can find that the gradient direction is almost orthogonal to the direction that leads to the minimum, like the discussion about gradient method in [20, pp. 25-26]. This problem becomes more serious as the rate constraint R decreases. The scenario of Fig. 2 can be explained as follows: η is in the denominator of the first term of P_r^n's expression, a small change of η may cause a large change of P_r^n and also a large change of $\frac{\partial D}{\partial \eta}$, while $\frac{\partial D}{\partial \tau}$ varies much slower.

To address the convergent difficulty of gradient projection method, we propose to use a layered iterative algorithm. More specifically, we first fix ζ,τ and solve

$$h(\zeta,\tau) = \sup_{\varepsilon,\eta\geq 0} D(\zeta,\tau,\varepsilon,\eta) \tag{26}$$

and then solve

$$\sup_{\zeta,\tau\geq 0} h(\zeta,\tau). \tag{27}$$

Since ε is only related with P_s^n and t_1^n and η is only related with P_r^n and t_2^n, the optimal values of ε and η in problem (26) are irrelated for fixed ζ,τ. We use bisection method to get the optimal ε and η separately, by which problem (26) is solved.

However, the problem (27) has two variables. It can not be solved by bisection method as in [2]-[3]. The convex analysis theory has showed that the gradient of $h(\zeta,\tau)$ is still given by the first two formulas in (16) at the optimal solution of (26) [21, pp. 192-193]. Thus, the gradient projection method of (27) is given as

$$\begin{cases} \zeta(k+1) = [\zeta(k) + \alpha(R - R_1)]^\dagger, \\ \tau(k+1) = [\tau(k) + \alpha(R - R_2)]^\dagger, \end{cases} \tag{28}$$

where α is chosen according to *Armijo Rule* [20, pp. 29-31]. The convergence of above duality based algorithm is provided in [22].

In fact, this algorithm has a nice and interesting explanation in the dual theory, which is given by the following statement

Lemma 1: The function $h(\zeta,\tau)$ is the dual function of the equivalent problem (9), (11)-(13) with respect to the constraints in (13).

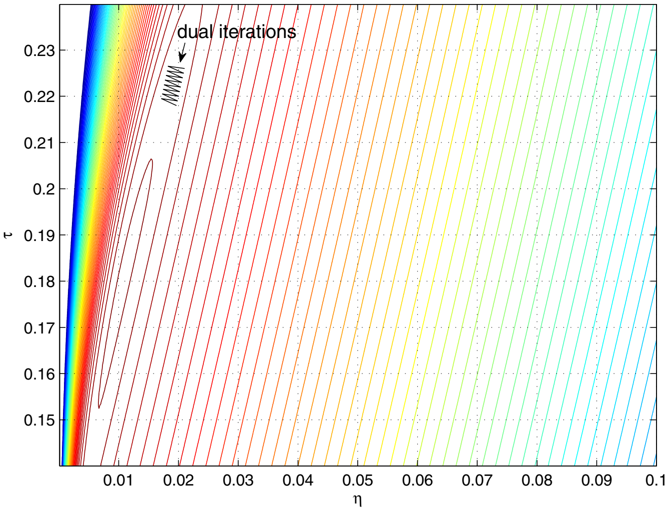

Fig. 2. The contour of the dual function with respect to τ,η for fixed ζ,ε.

The proof of Lemma 1 is given in [22]. Therefore, *this algorithm changes the dual problem (17) which has convergent difficulty to another dual problem (27) which can be solved quickly by gradient projection method.*

If the relay node does not interfere AH links, the object function in (9) is replaced by $\sum_{n=1}^{N}\phi_{x^n,1}(t_1^n)$ and the optimal value of t_2^n is simply 1/2. The values of P_s^n, P_r^n, t_1^n are still given by (22)-(25). The layered iterative algorithm still applies.

IV. NUMERICAL RESULTS

This section presents numerical results for the proposed relay-assisted scheme and compares it with the relay free scheme given in [2]-[3]. The results are obtained for a single AH band overlapping with $N = 5$ IS channels. The parameters of CTMC are $\lambda = \mu = 1s^{-1}$, and the channels of the three IS links (user-to-relay, relay-to-BS, user-to-BS) satisfy i.i.d. Rayleigh distribution and block fading. The average transmitted SNRs of IS user and relay node are assumed to be $\frac{\overline{P_s^{max}}}{Nn_0W} = \frac{\overline{P_r^{max}}}{Nn_0W}$ =35dB. The locations of the three nodes are assumed as shown in Fig. 3 and the path-loss factor is 4.

The expected overlap of relay-assisted cognitive coexistence scheme and relay free scheme are compared in Fig. 4 for one randomly generated channel fading state. It shows that the relay-assisted IS system can produce less interference and/or achieve a higher QoS level. If the relay node does not interfere the AH links, the performance is even better. Moreover, when IS rate constraint exceeds the capacity of relay free scheme a little, the relay-assisted scheme is still feasible since it has larger maximal achievable rate. Our numerical results show that 20-200 gradient projection iterations are required for our algorithm to converge.

The proposed relay-assisted scheme mainly benefits from superior communication ability. It is important to consider the chance that the relay-assisted scheme has larger achievable rate. The outage probability curves of achievable data rate for relay free scheme and R_1, R_2, R_{DF} for relay-assisted scheme are therefore depicted in Fig. 5. We can see that R_{DF} has a good opportunity to be larger than the achievable

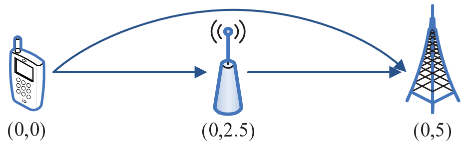

Fig. 3. The locations of IS user, relay node and the BS.

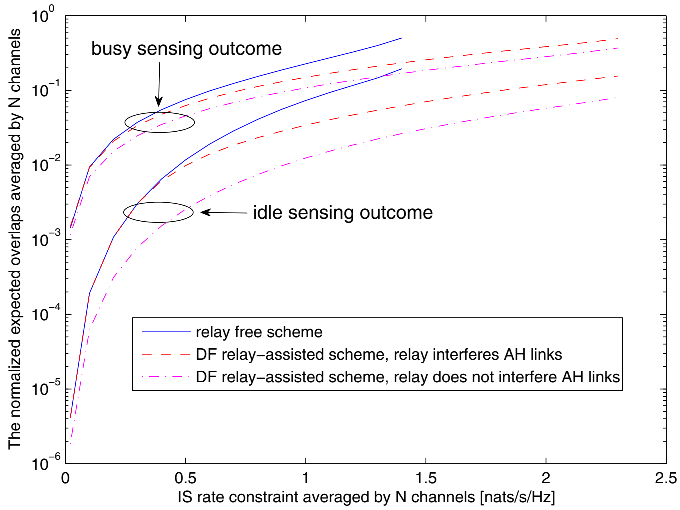

Fig. 4. The total expected overlap of relay-assisted cognitive coexistence scheme and relay-free scheme.

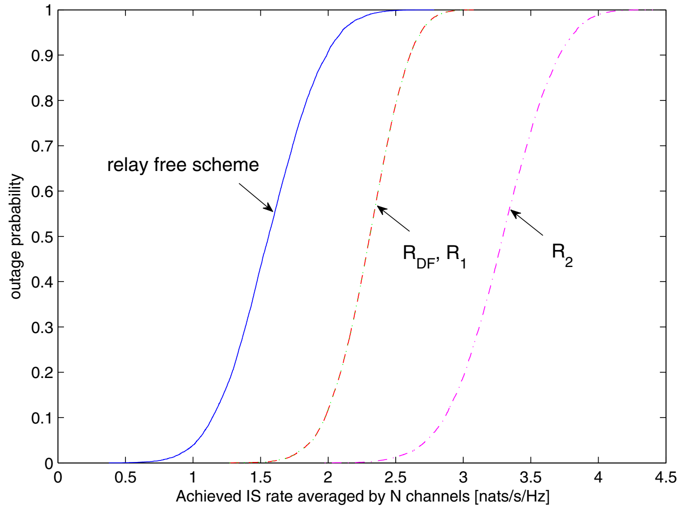

Fig. 5. Outage probability curves of relay-assisted scheme and relay free scheme.

data rate of relay free scheme. If the user-to-BS link further suffers from shadowing or penetration loss, this opportunity can be even larger. Moreover, since $R_{DF} = \min\{R_1, R_2\}$, the redundant communication ability for the hop with larger achievable rate (e.g. the second hop with achievable rate R_2 in our simulations) can be also used to mitigate interference.

V. CONCLUSIONS

This paper has introduced a relay-assisted cognitive coexistence scheme, in which the relay-assisted IS system senses and predicts these ad-hoc links' behaviors, and then allocates its transmission time and power adaptively such that the expected overlap with the ad-hoc links is minimized. Since the relay-assisted scheme has superior communication ability, it can produce less interference and/or achieve a higher QoS level than the relay free scheme.

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