Relay Selection and Power Allocation with QoS Guranteed in Cognitive Radio Networks

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Abstract: In this paper, we consider the problem of joint relay selection and power allocation in a cognitive radio (CR) network, where a secondary user (SU) source communicates with a secondary access point (AP) assisted by a set of SU relays. Each SU in this set not only acts as a potential relay but also has its own quality of service (QoS) requirement. We propose an optimal scheme with QoS support. On the premise of meeting the minimum QoS requirements of all SUs, the goal of the proposed scheme is to maximize the weighted sum rate of the network. A closed-form solution for the optimal power allocation can be obtained by the Karush-Kuhn-Tucker (KKT) conditions.

1. Introduction

Future wireless communication networks envisage the challenge that the available spectrum is becoming increasingly scarce. The concept of Cognitive Radio (CR) [1] is the key technology towards efficient spectrum usage.

The usage of cooperative technique in CR networks was investigated in [2]-[4]. [2] demonstrated that cooperative transmission is a promising approach for improving the throughput of SUs. [3] developed power and channel allocation approaches that can improve the overall throughput. However, most of the existing relaying schemes do not consider the quality of service (QoS) requirement of the SU which acts as the relay. In fact, all SUs, including the one which acts as a relay, have different priorities and minimum QoS requirements. If the priorities and the rate requirements of the SU relays are ignored, the fairness of CR networks will not be guaranteed.

In our system model, both the relay and the source have their own QoS requirements. Our proposed scheme aims at maximizing the weighted sum rate of the network. We can formulate this joint problem as a nonlinear optimization problem and derive a closed-form solution.

2. System Description

Fig.1 Three-node cooperative system model

A three-node cooperative system model is shown in Fig.1. In this system, SU source s communicates with a secondary AP, assisted by SU relay i , $i=1,2,...,L$. SU i also transmits its own

data to the secondary AP. All the SUs in this scenario share the spectrum with a PU. The channels from SU s to the AP (CH0), SU s to SU i (CH1), and SU i to the AP occupy orthogonal spectrum bands for transmission. Thus, even if the spectrum band available for CH1 is available for CH2, SU i can also help SU s relay information to the AP [2]. We assume that CH0, CH1 occupy frequency band f_1 , and CH2, CH3 occupy another frequency band f_2 . The amplify-and-forward (AF) cooperation protocol is employed, and the AF cooperative transmission between SU s and SU i occurs in one frame which consists of two time slots.

In the first time slot, SU s broadcasts its own information to both the secondary AP and SU i . Then the received signal $Y_s^{AP}[1]$ at the AP is given by

$$Y_s^{AP}[1] = \sqrt{p_s[1]g_s^{AP}[1]}X_s[1] + Z_s^{AP}[1], \quad (1)$$

where $g_s^{AP}[1]$, $p_s[1]$, $X_s[1]$ and $Z_s^{AP}[1]$ are the channel gain from SU s to the AP, the transmission power of SU s , the transmitted data symbol of SU s , and the additive white Gaussian noise (AWGN) respectively in time slot 1. The received signal $Y_s^i[1]$ at SU i is given by

$$Y_s^i[1] = \sqrt{p_s[1]g_s^i[1]}X_s[1] + Z_s^i[1], \quad (2)$$

At the same time, SU i transmits its own information to the AP over CH2 and the received signal at the AP is

$$Y_i^{AP}[1] = \sqrt{p_i[1]g_i^{AP}[1]}X_i[1] + Z_i^{AP}[1]. \quad (3)$$

In the second time slot, SU i amplifies $Y_s^i[1]$ and relays it to the AP over CH3. The received signal at the AP is

$$Y_i^{AP}[2] = \sqrt{p_i[2]g_i^{AP}[2]}X_i[2] + Z_i^{AP}[2], \quad (4)$$

where $X_i[2] = Y_s^i[1]/|Y_s^i[1]|$ is the transmitted signal from SU i to the AP.

Assume the noises in different channels are independent and identically distributed (i.i.d.) with zero-mean and variance σ^2 . We can rewrite (4) as

$$Y_i^{AP}[2] = \frac{\sqrt{p_i[2]g_i^{AP}[2]}(\sqrt{p_s[1]g_s^i[1]}X_s[1] + Z_s^i[1])}{\sqrt{p_s[1]g_s^i[1] + \sigma^2}} + Z_i^{AP}[2], \quad (5)$$

Then the received signal-to-noise ratio (SNR) at the AP from the relay channel can be expressed as

$$\Gamma_{s,i}^R = \frac{p_s[1]g_s^i[1]p_i[2]g_i^{AP}[2]}{\sigma^2(p_s[1]g_s^i[1] + p_i[2]g_i^{AP}[2] + \sigma^2)}, \quad (6)$$

And the effective SNR of the AF cooperative channel of SU s helped by SU i is given by

$$\Gamma_{s,i}^{AF} = \Gamma_s^D + \Gamma_{s,i}^R, \quad (7)$$

where $\Gamma_s^D = p_s[1]g_s^{AP}[1]/\sigma^2$ is the SNR that results from the direct transmission from SU s to the AP in the first time slot.

Without loss of generality, we use unit channel bandwidth to facilitate our discussion, the achievable rates of SU i and SU s are

$$R_i(p_i[1]) = \frac{1}{2} \log_2 \left(1 + \frac{p_i[1]g_i^{AP}[1]}{\sigma^2} \right), R_s(p_s[1], p_i[2]) = \frac{1}{2} \log_2 (1 + \Gamma_{s,i}^{AF}) \quad (8)$$

respectively. The coefficient 1/2 in (8) is due to the fact that the transmission time of a SU will occupy two time slots.

Considering that a SU is not only power limited but also energy limited in practical networks, we assume that there is a frame energy constraint. Therefore, the transmission powers of SU i and SU s must satisfy

$$p_i[1], p_i[2] \leq p_i^{\max}, \frac{p_i[1]T}{2} + \frac{p_i[2]T}{2} \leq E_i^{\max} \text{ and } p_s[1] \leq p_s^{\max}, \frac{p_s[1]T}{2} \leq E_s^{\max}, \quad (9)$$

where $p_i^{\max}$ and $p_s^{\max}$ are the maximum transmission power allowed by SU i and SU s , respectively, $E_i^{\max}$ and $E_s^{\max}$ are the frame energy constraints, and T is the length of each transmission frame. To make linear inequality constraints (9) effective and reasonable, let $E_i^{\max} = K p_i^{\max} T$, $K \in [1/2, 1]$ and $p_s^{\max} = 2E_s^{\max}/T$.

On the other hand, to prevent SUs from causing severe interference to the PU, the transmission powers must also satisfy

$$p_i[1]g_i^{PU}[1], p_i[2]g_i^{PU}[2], p_s[1]g_s^{PU}[1] \leq I \quad (10)$$

where I is acceptable interference power of the PU.

As mentioned in Section I, diverse QoS for SUs with different minimum transmission rate requirements should be supported in cognitive radio networks, so the achievable rates of SU i and SU s must satisfy

$$R_i(p_i[1]) \geq R_i^{\text{th}}, R_s(p_s[1], p_i[2]) \geq R_s^{\text{th}} \quad (11)$$

where R_i^{th} and R_s^{th} are the minimum rate requirements of SU i and SU s , respectively.

Here we consider maximizing the weighted sum rate of the three-node cooperative network, where weights are used to take different priorities of SUs into consideration. Then the network utility using SU i as the relay can be expressed as

$$T_i(p_s[1], p_i[1], p_i[2]) = w_s R_s(p_s[1], p_i[2]) + w_i R_i(p_i[1]) \quad (12)$$

where w_i and w_s are the weights of SU i and SU s .

3. Algorithm Development

In this section, we develop an optimal relay selection and power allocation scheme with QoS support for cooperative CR networks.

From the analysis above, the problem of relay selection and power allocation can be formulated as

$$(p_s^*[1], p_i^*[1], p_i^*[2]) = \arg \max_{p_s[1], p_i[1], p_i[2]} T_i(p_s[1], p_i[1], p_i[2]), \quad (13a)$$

$$i^* = \arg \max_i T_i(p_s^*[1], p_i^*[1], p_i^*[2]), \quad (13b)$$

subject to

$$h_{i,1} = p_i[1] - \min(p_i^{\max}, I/g_i^{PU}[1]) \leq 0, \quad h_{i,2} = p_i[2] - \min(p_i^{\max}, I/g_i^{PU}[2]) \leq 0, \quad h_{i,3} = p_i[1] + p_i[2] - 2E_i^{\max}/T \leq 0, \\ h_{i,4} = R_i^{\text{th}} - R_i(p_i[1]) \leq 0, h_{i,5} = R_s^{\text{th}} - R_s(p_s[1], p_i[2]) \leq 0, h_{i,6} = p_s[1] - \min(p_s^{\max}, I/g_s^{PU}[1]) \leq 0,$$

where $h_{i,1}, h_{i,2}, h_{i,3}, h_{i,4}, h_{i,5}, h_{i,6}$ are the constraint functions.

Noticing that T_i is a monotonically increasing function of $p_s[1]$, the optimal transmission power

of SU s is $p_s^*[1] = \min(p_s^{\max}, I/g_s^{PU}[1])$.

Substituting $p_s^*[1]$ into (13a), (13) is a joint optimization over the relay indexes and the transmission powers of the relay. However, this optimization can be performed in two steps: first over the transmission powers and then over the relay indexes. Accordingly, for a specific SU i selected from the potential relay set Ω , first we verify whether the corresponding feasible region of problem (13a) determined by $p_i[1] \geq 0$, $p_i[2] \geq 0$ and $h_{i,m} \leq 0$ for $m=1,2,3,4,5$ is empty or not. If the feasible region is not empty, we solve the problem (13a) for relay index i with respect to transmission powers.

It is quite obvious that $-R_i(x)$ is a convex function and we can prove that $-R_s(p_s^*[1], x)$ is also convex.

Since $-R_i(x)$ and $-R_s(p_s^*[1], x)$ are both convex functions, $-T_i$ and nonlinear inequality constraint functions $h_{i,4}$ and $h_{i,5}$ are convex. (13a) is then a convex optimization problem, so the Karush-Kuhn-Tucker (KKT) conditions are both necessary and sufficient for this problem.

Using the Lagrange multiplier method [5], the Lagrange function for (13a) is given by

$$L(p_i[1], p_i[2], \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5) = -\left(w_s R_s(p_s^*[1], p_i[2]) + w_i R_i(p_i[1])\right) + \sum_{m=1}^5 \lambda_m h_{i,m}, \quad (14)$$

where $\lambda_m, m=1,2,3,4,5$ are the introduced Lagrange multipliers. By taking the partial derivative of L with $p_i[1]$, $p_i[2]$ and λ_m , and according to the KKT conditions, we obtain

$$\lambda_m h_{i,m} = 0, \lambda_m \geq 0, \frac{\partial L}{\partial p_i[1]} = 0, \frac{\partial L}{\partial p_i[2]} = 0, \quad (15)$$

Now, we define the following variables:

$$H = p_s^*[1]g_s^i[1] + \sigma^2, J = p_s^*[1]g_s^{AP}[1] + \sigma^2 \text{ and } K = \frac{p_s^*[1]g_s^i[1]g_i^{AP}[2](p_s^*[1]g_s^i[1] + \sigma^2)(w_s + \lambda_5)}{2(\lambda_2 + \lambda_3)\ln 2}.$$

Solving the equations (17), we obtain the following closed-form optimal solution

$$p_i[1] = \left[\frac{w_i + \lambda_4}{2(\lambda_1 + \lambda_3)\ln 2} - \frac{\sigma^2}{g_i^{AP}[1]} \right]^+, \quad p_i[2] = \left[-\frac{H(H + 2J - \sigma^2)}{2(H + J - \sigma^2)g_i^{AP}[2]} + \frac{\sqrt{H^2(H - \sigma^2)^2 + 4K(H + J - \sigma^2)}}{2(H + J - \sigma^2)g_i^{AP}[2]} \right]^+, \quad (16)$$

where $[x]^+ = \max(x, 0)$. Using the iterative algorithm, $p_i[1]$, $p_i[2]$ are updated using (17) while the λ_m can be obtain using the sub-gradient method in each step given by

$$\lambda_1^{n+1} = \left[\lambda_1^n + \alpha^n (p_i^n[1] - \min(p_i^{\max}, I/g_i^{PU}[1])) \right]^+, \quad (17a)$$

$$\lambda_2^{n+1} = \left[\lambda_2^n + \alpha^n (p_i^n[2] - \min(p_i^{\max}, I/g_i^{PU}[2])) \right]^+, \quad (17b)$$

$$\lambda_3^{n+1} = \left[\lambda_3^n + \alpha^n (p_i^n[1] + p_i^n[2] - 2E_i^{\max}/T) \right]^+, \quad (17c)$$

$$\lambda_4^{n+1} = \left[\lambda_4^n + \alpha^n (R_i^{th} - R_i(p_i^n[1])) \right]^+, \quad (17d)$$

$$\lambda_5^{n+1} = \left[\lambda_5^n + \alpha^n (R_s^{th} - R_s(p_s^*[1], p_i^n[2])) \right]^+, \quad (17e)$$

where α^n is a small positive step size for the n^{th} iteration. With appropriate step sizes, the iterations are proved to be convergent [6]. Once λ_m are obtained, we can get the optimal power allocation $p_i^*[1]$, $p_i^*[2]$ and corresponding T_i^* when the i^{th} SU relay is selected. Repeating the above procedures at all SU relays in the set Ω , we can find the relay with the maximum weighted sum rate.

4. Simulation Results

In this section, we present simulation results. In the simulation, the potential SU relays in set $\mathcal{Q}$ are uniformly located between SU s and the secondary AP. We consider a system with $L=10$ relays

First, we compare the performance of the proposed scheme in terms of weighted sum rate (i.e. system throughput) with respect to the maximum transmission power of SU relay, $p_i^{\max}$. As observed in Fig.2, the proposed scheme results in better system throughput compared to the other schemes.

Fig.3 presents the achievable rate of SU relay versus $p_i^{\max}$. We can see that the proposed scheme achieves 60% and 25% rate gain of SU relay over the random relay selection with EPA and the best relay selection with EPA. It is obvious that the minimum transmission rate requirement of SU relay is well guaranteed in the proposed scheme but not met in the other schemes, especially in low $p_i^{\max}$ region.

Fig.2 The weighted sum rate of the system versus the maximum transmission power of relay

Fig.3 The relay rate versus the maximum transmission power of relay

5. Conclusion

We proposed an optimal scheme for joint relay selection and power allocation with QoS support in CR networks. The proposed scheme maximizes the weighted sum rate of the network under constraints on transmission power and energy, and supports QoS requirements of both the source and the relay. It also ensures sufficient protection of PUs from unacceptable interference. A close-form solution for the optimal power allocation between the source and the relay was obtained. Simulation results demonstrated the advantage of the proposed algorithm over comparing schemes.

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