Performance Improvement of the Cognitive Radio Networks with User Cooperation

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Summary

The cognitive radio has been considered as a promising paradigm to achieve efficient spectrum usage by allowing the coexistence of the primary and cognitive radio networks. One fundamental challenge is to ensure the quality of service (QoS) of the primary link while maximizing the achievable transmission rate of the cognitive radio user. In this paper, we investigate the cooperation based spectrum access at the cognitive radio networks. If the QoS requirement is stringent, low power is allowed at the cognitive radio transmitter and hence the transmission rate is limited. It is beneficial that the cognitive radio user obtains cooperation from the surrounding cognitive radio users to increase the transmission rate. The best relay which provides the maximal transmission rate is selected for cooperation. The transmission rate performance is investigated under the peak and average interference temperature constraints. The simulation results show that the cognitive radio link transmission rate can be improved by cooperation, especially when the power of the direct link is limited. Under the average interference temperature constraint, the transmission rate is better than that under the peak interference temperature constraint, due to the power adaptation between the transmitter and relay. Higher gain can be obtained as the number of potential relays increases.

Key words:
Cognitive Radio, Cooperation, Interference Temperature, Power Allocation, Rate Maximization

1. Introduction

Cognitive radio is a new promising solution to improve the utilization of the limited spectral resources, which allows the primary and cognitive radio (secondary) networks to coexist and share the same spectrum [1], [2]. Traditionally, the cognitive radio users sense the radio environment in search of spectrum holes (the frequency band or time slot that is not being utilized by the primary users) to exploit transmission opportunities. As a fundamental requirement, the cognitive radio users should not create interference to the primary network during the process of both spectrum sensing and spectrum access [2]. Recently with the Federal Communications Commission's spectrum policy reform, a new metric referred to as the interference temperature has been proposed to quantify and manage the interference in a radio environment. It means that the cognitive radio users can access the licensed spectrum as long as the created interference to the primary user is below a threshold, i.e., the Quality of Service (QoS) of the primary users is not affected [3]. Therefore, the transmit power of the cognitive radio users is limited to guarantee the QoS of the primary user. However when the QoS requirement of the primary user is stringent, very low power level is allowed for the cognitive radio user and the throughput is limited.

Cooperative communication is increasingly regarded as a powerful technology to combat fading and improve link reliability [4]-[7]. And it also has great potential to be adopted in the cognitive radio networks [8]. Cooperative communication has been applied to enhance the reliability of spectrum sensing in the cognitive radio network [9]. The cognitive radio users may relay the received primary signal to each other for more reliable detection of the local primary activity. In [10], the cooperation based symbiotic architecture was proposed to support the coexistence of the primary and cognitive radio networks. The primary user can request cooperation to the cognitive radio users and allocate a channel time fraction to them as exchange. The achievable rate region for both the primary and cognitive radio users was presented in an information theoretic perspective assuming that the cognitive radio user can cooperate the primary transmission non-causally [11]. It is possible that the cooperative communication can also be applied in the data transmission among the cognitive radio users and this may face new challenges under the cognitive radio environment. However, no previous works addressed this application in detail and thus there is a strong need for a systematic study of the cooperative communications in the cognitive radio networks.

In this paper, the user cooperation is adopted in the cognitive radio networks and we investigate the maximal transmission rate of the cognitive radio link. During the cooperation based cognitive radio link transmission, both the cognitive radio transmitter and relay are required to satisfy the interference temperature of the primary link. Under the peak and average interference constraint, the transmit power is optimized to maximize the transmission rate. If the direct link of the cognitive radio user has low

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transmission rate, it can request cooperation from other users to improve the rate. Thus, the optimal transmission mode which provides the maximal rate is selected for data transmission. Simulation results show that the cooperation based link transmission can increase the transmission rate, especially when the interference temperature constraint is stringent. And under the average interference constraint, the maximal transmission rate is higher than that under the peak interference constraint, since the power adaptation between the cognitive radio transmitter and relay can be beneficial. As the number of potential relays increases, the achievable maximal transmission rate is also increased.

The rest of this paper is organized as follows. In Section 2 we first give an overview of the cognitive radio network and present the cooperation based cognitive radio link transmission. Section 3 analyzes the link quality and transmission rate maximization problem. In Section 4 we evaluate the transmission rate performance of the proposed scheme by means of simulations. In Section 5 we draw our conclusions.

2. System Model

In this section, we first give an overview of the cognitive radio networks. And then the cooperation based cognitive radio network is introduced.

2.1 Cognitive Radio

We consider a system model with coexistence of primary and secondary networks, as shown in Fig. 1. The primary network is assumed to be a Time Division Multiple Access (TDMA)-based cellular network. The primary base station (BS) transmits data to the primary users during different time slot. A secondary network without spectrum license lies in the range of the primary network, and the cognitive radio users are seeking transmission opportunities to access the secondary access point (AP).

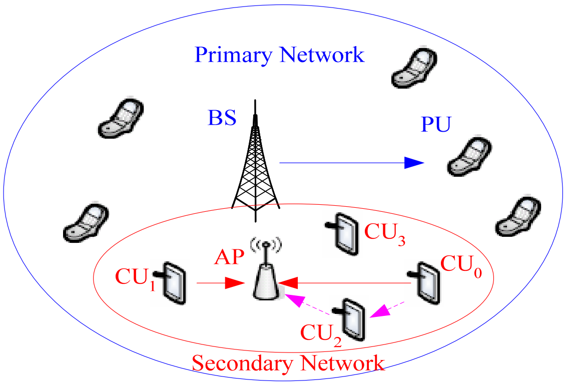

Fig. 1. System Model with Coexistence of Primary and Cognitive Radio Network

An important feature of the cognitive radio is that it is aware of the surrounding radio environment, e.g., the time slot allocation and user information in the primary network [2]. When BS transmits data to a primary user PU in a time slot, as shown in Fig. 1, CU_1 may utilize this time slot to transmit data to AP, under the constraint that the created interference to PU is less than the interference temperature. Note that AP also receives the primary signal from BS, which is the interference signal to the cognitive radio link. It is assumed that the primary interference signal received from BS can be perfectly cancelled at AP and the cognitive radio users, due to the cognitive radio features [2] [11]. It is evident that if a cognitive radio user is scheduled in a time slot, it would like to use the maximal allowed power to transmit its data, and accordingly to maximize the link throughput. However, when the interference constraint is stringent, the throughput is significantly limited due to the lower available transmit power at the cognitive radio user.

2.2 Cooperation Based Cognitive Radio

In this part we introduce the cooperation based cognitive radio network. The cooperation among the cognitive radio users is motivated by its high spectral efficiency in the power-limited region [6].

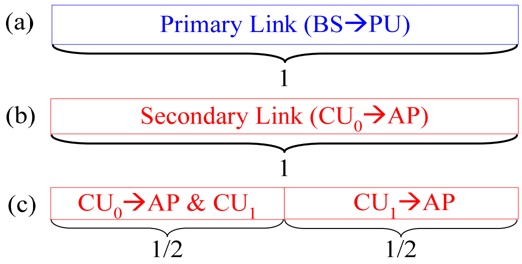

Fig. 2. Comparison of Time Slot Usage for (a) Primary Link, (b) Direct Cognitive Radio Link, and (c) Cooperation Based Cognitive Radio Link

If the maximal allowed transmit power of a cognitive radio user is limited due to the interference constraint of the primary user, its link has low throughput. For example in Fig. 1, CU_0 is close to the primary receiver PU, its link with AP may not have high throughput due to the limited transmit power. It may be possible and beneficial that CU_0 can request the surrounding cognitive radio users to assist its data transmission. As shown in Fig. 1, CU_2 is selected to assist the link transmission of CU_0. Generally the half-duplex mode is supported at the cognitive radio user terminal, i.e., it can not transmit and receive signal in the same frequency band at the same time [4] [5]. Thus, the cognitive radio transmitter and relay may use orthogonal time slot (or time fraction) to transmit the data. Fig. 2 illustrates the time slot usage for the primary link, direct cognitive radio link, and cooperation based cognitive radio links. For the direct cognitive radio link, it occupies the whole time slot which is used by the primary link. However for the cooperation based cognitive radio link, as illustrated in Fig. 2 (c), the original primary time slot should be divided by two equal time fractions. In the first time fraction, the cognitive radio transmitter sends it data to AP and the selected relay, and then in the second time fraction the relay retransmits the signal to AP. Finally AP can combine the signals of two time fraction to detect the data. The amplify-and-forward (AF) mode cooperation is considered at the cognitive radio relays, i.e., the relay amplifies and retransmits the received signal in the first time fraction [4] [5].

3. Rate Maximization for the Cognitive Radio Network

In this section, the SNR and transmission rate are analyzed for both direct and cooperation based secondary links, with both peak interference temperature constraint and average interference temperature constraint.

3.1 Link SNR Analysis

The channel model for the primary and secondary links is illustrated in Fig. 3. Assume that BS transmits the primary data x_p to PU with a fixed power P_{BS} during one time slot ($E[|x_p|^2]=1$). The cognitive radio user CU$_0$ wants to utilize this time slot to transmit its data x_c to AP ($E[|x_c|^2]=1$). Note here that the transmit power of each transmitter is assumed to be constant during its transmission time. The channels of all links are modeled as independent complex Gaussian random variables, which account for path loss, shadowing and fading channel gain, and are invariant within each time slot. The additive white Gaussian noise (AWGN) at all receivers has the same power of N.

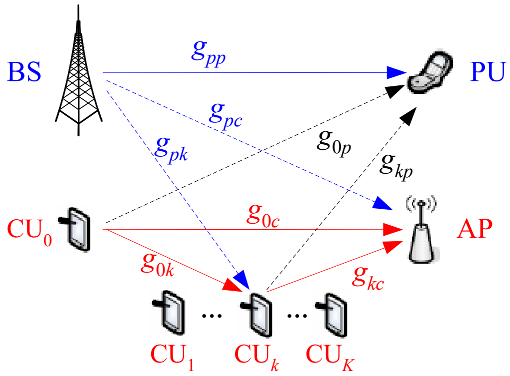

Fig. 3. Channel Model for Primary and Secondary Links

If CU$_0$ directly transmits its data to AP, the received signal at AP can be written as

$$y_{0c} = \sqrt{P_0}\, g_{0c} x_c + \sqrt{P_{BS}}\, g_{pc} x_p + n_c, \qquad (1)$$

where P_0 is the transmit power of CU$_0$, g_{0c} and g_{pc} denote the channel gain of link CU$_0$-AP and BS-AP respectively, and n_c is the noise at AP. As described in Section 2.1, the primary signal received at AP can be perfectly cancelled. The signal-to-noise ratio (SNR) of the direct link CU$_0$-AP can be written as

$$SNR_0 = \frac{P_0 G_{0c}}{N}, \qquad (2)$$

where $G_{0c}=E[|g_{0c}|^2]$ is the power gain of the link CU$_0$-AP, and similar definition can also be applied to other links.

If the cooperation is considered for the secondary link, CU$_0$ transmits its data to the cognitive radio relay and AP in the first time fraction. As shown in Fig. 3, assume that K ($K \geq 1$) potential cognitive radio users exist around CU$_0$ and the k-th ($1 \leq k \leq K$) user CU$_k$ is selected as a relay. If CU$_0$ uses the same transmit power P_0, the SNR at AP is same as in Eq. (2). And the received signal at the k-th relay can be written as

$$y_{0k} = \sqrt{P_0}\, g_{0k} x_c + \sqrt{P_{BS}}\, g_{pk} x_p + n_k, \qquad (3)$$

where g_{0k} and g_{pk} respectively denote the channel gain of link CU$_0$-CU$_k$ and BS-CU$_k$, and n_k is the noise at CU$_k$. The primary signal part is first detected and cancelled, and then the remaining signal is amplified and retransmitted. Thus, the transmitted signal at the k-th relay in the second time fraction can be written as

$$x_k = \sqrt{\frac{P_k}{P_0 G_{0k} + N}} \left(\sqrt{P_0}\, g_{0k} x_c + n_k \right), \qquad (4)$$

where P_k is the transmit power of CU$_k$. The received signal at AP during the second time fraction can be written as

$$y_{kc} = g_{kc} x_k + \sqrt{P_{BS}}\, g_{pc} x_p + n_c, \qquad (5)$$

where g_{kc} denotes the channel gain of link CU$_k$-AP. The primary signal part can also be cancelled at AP. Then the SNR of the cooperative link CU$_k$-AP can be written as

$$SNR_k = \frac{P_0 G_{0k} P_k G_{kc}}{N(P_0 G_{0k} + P_k G_{kc} + N)}. \qquad (6)$$

It is assumed that the direct secondary signal from CU$_0$ in the first time fraction and the forwarded signal from the k-th cognitive radio user in the second time fraction can be perfectly combined at AP. Thus, the combined SNR can be written as

$$SNR_{Com,k} = \frac{P_0 G_{0c}}{N} + \frac{P_0 G_{0k} P_k G_{kc}}{N(P_0 G_{0k} + P_k G_{kc} + N)}. \quad (7)$$

3.2 SNR Maximization

It is evident that both the cognitive radio transmitter and AP want to maximize the link SNR and hence maximize the transmission rate; no matter the direct cognitive radio link or cooperation based link is employed.

If the direct cognitive radio link is considered, the SNR maximization problem can be formulated by

$$\text{Maximize} \quad SNR_0 = \frac{P_0 G_{0c}}{N}, \quad (8)$$

$$\text{Subject to} \quad P_0 \geq 0, \quad P_0 G_{0p} \leq I_p, \quad (9)$$

where I_p is the interference temperature constraint of PU. It is noted that Eq. (9) can be considered as not only the peak interference temperature constraint but also average interference temperature constraint. It is optimal that CU_0 uses its maximum power $P_0^*=I_p/G_{0p}$ to transmit the data and hence to maximize its transmission rate.

If the cognitive radio link is cooperated by the k-th user, the SNR maximization problem can be written as

$$\text{Max} \quad SNR_{Com.k} = \frac{P_0 G_{0c}}{N} + \frac{P_0 G_{0k} P_k G_{kc}}{N(P_0 G_{0k} + P_k G_{kc} + N)}, \quad (10)$$

$$\text{Subject to} \quad \begin{array}{l} P_0 \geq 0, \quad P_0 G_{0p} \leq I_p; \\ P_k \geq 0, \quad P_k G_{kp} \leq I_p, \end{array} \quad (11)$$

$$\text{or} \quad P_0 \geq 0, P_k \geq 0, \frac{P_0 G_{0p}}{2} + \frac{P_k G_{kp}}{2} \leq I_p, \quad (12)$$

where Eqs. (11) and (12) respectively denote the peak and average interference temperature constraint.

We first consider the peak interference constraint. It is observed that $SNR_{Com,k}$ is an increasing function of both P_0 and P_k. Thus, it is optimal that both CU_0 and CU_k use the maximum power for transmission, which can be expressed as

$$P_0^* = \frac{I_p}{G_{0p}}, \quad P_k^* = \frac{I_p}{G_{kp}}. \quad (13)$$

With the average interference constraint, the SNR maximization problem can be solved following the method of Lagrange multipliers [12]. We take the partial derivative of Eq. (12) as follows

$$\frac{\partial}{\partial P} \left(\begin{array}{l} \frac{P_0 G_{0c}}{N} + \frac{P_0 G_{0k} P_k G_{kc}}{N(P_0 G_{0k} + P_k G_{kc} + N)} \\ -\lambda \left(P_0 G_{0p} + P_k G_{kp} - 2 I_p \right) \end{array} \right) = 0 \quad (14)$$

where P can be replaced by P_0 and P_k, and λ is the Lagrange multiplier.

For simplicity of notation, let

$$\begin{aligned} a &= G_{0k} G_{kp} - G_{0p} G_{kc}; \\ b &= 2 G_{kc} I_p + G_{kp} N; \\ c &= G_{0c} a^2 - G_{0p} G_{0k} G_{kc} a; \\ d &= G_{0c} ab - G_{0p} G_{0k} G_{kc} b; \\ e &= G_{0c} b^2 + 2 G_{0k} G_{kc} I_p b; \end{aligned} \quad (15)$$

and the optimal power allocation of P_0^* and P_k^* can be calculated as

$$P_0^* = \frac{-d \pm \sqrt{d^2 - ce}}{c}; \quad P_k^* = \frac{2 I_p - P_0^* G_{0p}}{G_{kp}}. \quad (16)$$

3.3 Transmission Rate Maximization

If a cognitive radio user wants to send data to AP, AP can estimate both the direct link quality and cooperation based link quality, assuming that the instantaneous channel state information (CSI) is available at AP. The cognitive radio user aims to transmit data with highest rate during a time slot.

The maximal transmission rate can be obtained in the following steps:

1) Calculate the maximal transmission rate of the direct link

$$R_0^* = \log_2 \left(1 + SNR_0^*(P_0^*) \right); \quad (17)$$

2) Consider the cooperation based cognitive radio link, calculate individual maximal rate for each potential relay

$$R_k^* = \frac{1}{2} \log_2 \left(1 + SNR_{Com,k}^*(P_0^*, P_k^*) \right); \quad (18)$$

where ½ is due to the usage of two time fractions, and P_0^* and P_k^* can be obtained from Eqs. (13) and (16), respectively for the peak and average interference constraint.

3) Select relay k^* which gives the largest rate, i.e.,

$$k^* = \arg\max R_k^* \qquad (19)$$

and the corresponding rate is denoted by $R_{k^*}{}^*$.

4) Select the optimal transmission mode to maximize the transmission rate, i.e., if $R_0^* \geq R_{k^*}{}^*$, consider the direct transmission; otherwise, consider the cooperation based transmission from the best relay k^*.

Thus, AP may send the control message to the cognitive radio user to indicate the transmission mode selection and power allocations. It is noted that this kind of protocol has been successfully applied in the cooperative networks and can also be directly applied in the cooperation based cognitive radio networks [7].

4. Simulation Results

In this section, simulation results are presented to illustrate the performance of the proposed scheme in this paper.

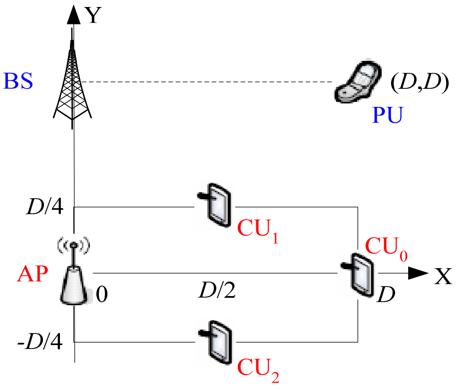

Fig. 4. Simulation Model

A two-dimension distribution model is considered as the simulation model, as shown in Fig. 4. The cognitive radio network AP, cognitive radio transmitter CU_0, and primary receiver PU are located at coordinates (0, 0), (D, 0) and (D, D), respectively. The path loss model with a path loss coefficient $\alpha = 3$ is considered. The AWGN at all the receivers (PU, AP and all CUs) has the same power of N. The interference temperature constraint is illustrated by the interference-to-noise ratio (INR) at PU.

We first consider a scenario to examine the benefit of the cooperation based transmission for the cognitive radio link. For simplicity the fading channel is not considered here. As illustrated in Fig. 4, two potential cognitive radio relays, CU_1 and CU_2, are located at coordinates (D/2, D/4) and (D/2, -D/4) respectively. Fig. 5 shows the transmission rate performance for the direct link and cooperation based link. It is observed that the higher gain can be obtained from cooperation at lower INR, i.e., when the interference temperature constraint is stringent. The cooperation from CU_2 can provide more gain than CU_1, since it is farther to PU and higher transmit power can be allowed. It is noted that if there is no interference constraint, both CU_1 and CU_2 can provide same cooperation gain, since their links to CU_0 and AP are same. The achievable rate under the peak interference temperature constraint is higher than that under the average interference temperature constraint, due to the power adaptation between the transmitter and relay.

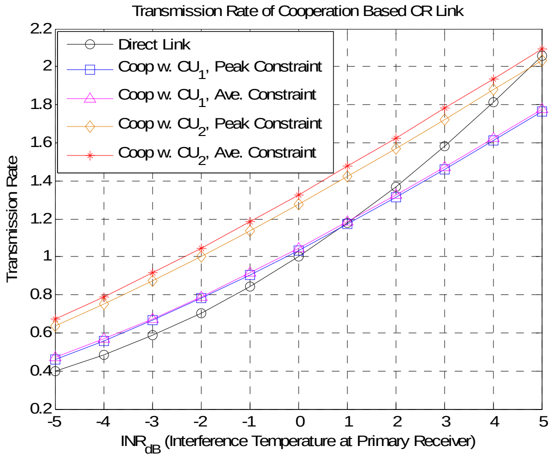

Fig. 5. Comparison of Direct Link and Cooperation Based Link

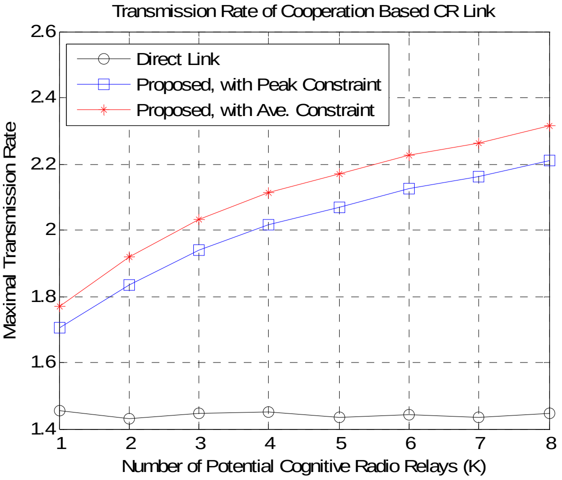

Fig. 6. Transmission Rate v.s. Number of Potential Cognitive Radio Relays

Now we consider the impact of number of potential cognitive radio relays. For example, K potential cognitive radio relays are randomly located within the rectangular area which is determined by the coordinates (0, -D/4), (D, -D/4), (0, D/4) and (D, D/4), as shown in Fig. 4. An INR value of 0dB is considered for the interference temperature constraint. And here we additionally consider the Rayleigh fading channel. Given the number of potential cognitive radio relays, the achievable maximal transmission rate is investigated, averaged over different relay distributions and fading channel realizations. Fig. 6 shows the average maximal transmission rate performance with different number of potential cognitive radio users, in both peak and average interference temperature constraint cases. As the number of potential cognitive radio relays increases, the probability that the relays can obtain high transmit power and high cooperation gain increases. Thus, the best relay also has high probability to provide better performance as the number of cognitive relays increases. With a single relay, the transmission rate increases by 17.3% and 22.5% compared to the direct transmission, respectively under the peak and average interference temperature constraint. With eight potential relays, the transmission rate increases by 51.7% and 58.6%, under the peak and average interference temperature constraint.

5. Conclusion

In this paper, we applied user cooperation in the cognitive radio networks. If a cognitive radio transmitter encounters stringent interference temperature constraint to the primary user, user cooperation is beneficial. The best relay can be selected from the users which can create less interference to the primary user and provide higher cooperation gain to the cognitive radio link. With the average interference temperature constraint, the achievable transmission rate is higher than the peak interference temperature constraint case due to power adaptation between the transmitter and relay. And higher transmission rate can be obtained as the number of potential relays increases.

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