Cooperative Spectrum Sharing Among Primary and Secondary Users in Cognitive Radio Networks

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ABSTRACT

In this paper, we present an idea of cooperative communication which can enhance the transmission opportunities for cognitive radio ad hoc networks. In this mechanism, primary and secondary users cooperate with each other for their own good. By cooperating with secondary users, primary users can save energy and transmission time without degrading the throughput. Secondary users can achieve more opportunities to access the channel by cooperating with primary users. It is a win-win situation for both primary and secondary users.

1. INTRODUCTION

Cognitive radio (CR) technology has been proposed as a new way to improve spectral efficiency of wireless networks. A CR network normally includes primary users (PUs) that are licensed to use the specific channel and secondary users (SUs) or cognitive users which are typically not licensed to utilize the channel. However, the cognitive radio technology allows SUs to access the free portions of licensed spectrum in opportunistic manner without causing any interference to PUs. Normally, SUs detect the spectrum holes (i.e., parts of the channel not being used by PUs) and access the channel [1]. However, as soon as the primary signal is detected, all SUs must defer their transmissions and find another spectrum holes since they are responsible for avoiding interference with PUs' transmission [2]. Thus, the availability of the channel is highly dependent on PU activities. If the spectrum usage of PUs on a channel is dense, there will be lack of opportunities for the SUs to access the channel.

In this paper, we provide a cooperative mechanism that enables SUs to access the channel even the PU activities are quite dense on it. In our proposed mechanism, first, SUs access the licensed channel in traditional way; detecting the spectrum holes and accessing the channel. When the PUs appear on the channel, SUs attempts to provide communication and create the spectrum holes. In other words, instead of finding and detecting the spectrum holes, we let the SUs create their own transmission opportunities when there are lacks of these. With PUs' Cooperation, SUs can create spectrum holes for CR network without causing any interference or without sacrificing the throughput of the primary network.

1.1 Background

In this section, we briefly introduce the Distributed Coordination Function (DCF) of IEEE 802.11 [3] which we exploit in our cooperative communication.

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DCF employs carrier sense multiple access with collision avoidance (CSMA/CA). In CSMA/CA, each station needs to sense the channel before data transmission and it is called physical sensing. Virtual sensing, also known as Network Allocation Vector (NAV), is also used to avoid collisions and hidden terminal problems. NAV is the channel reservation time for data transmission. Before data transmission begins between two stations (transmitter and receiver), they need to exchange request to send (RTS) and clear to send (CTS) packets. The packets, RTS and CTS, carry the information of the length of the data packet to be transmitted. Any other stations which overhear the RTS or CTS can update their NAVs which indicate the period of time in which the channel will remain busy. These neighbor stations can suitably delay future transmissions and it can avoid collisions. The basic procedure of DCF can be seen in Fig.1.

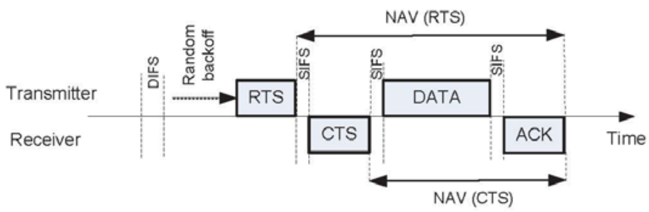

Fig.1 DCF of 802.11

The main goal of the proposed cooperative communication is to reduce the transmission time of PUs. After exchanging the control packets (the RTS and CTS), the channel is reserved for NAV which is the required period for direct data transmission. If this transmission time can be reduced by exploiting cooperative communication, SUs can access the channel in the remaining time. In the remaining time, SUs can access the channel exclusively because NAV guarantees that there will be no PU activity in this interval.

2. COOPERATIVE COMMUNICATION

2.1 System Model

We assume that both primary network and secondary network (or cognitive radio network) are constructed based on CSMA/CA and follow the principles of DCF of IEEE 802.11. Both networks share the same spectrum and users (PUs and SUs) are randomly distributed. We also assume that SUs can get the perfect channel sensing results [4] which means as soon as the PU appears on the channel, the presence of PU can be detected by SUs. The RTS and CTS of PUs can be overheard by SUs.

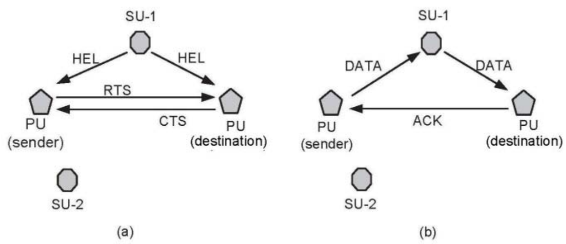

Fig. 2. (a) Control packets exchanges between PUs and the helper (SU), and (b) cooperative data transmission.

2.2 Secondary Users Supportive Cooperative Communication

First, SUs detect the spectrum holes which occur when the PUs are absent and access the channel in normal mode. This is one of the traditional ways of accessing the channel in CR networks and a bench of research works has been out. Therefore, we are going to emphasize on how to operate in cooperative mode. When the PU activity is detected, SUs defer all transmissions and try to detect the RTS and CTS of PUs in order to provide the cooperative communication.

When a PU wants to initiate data transmission, it attempts to transmit RTS to the destination (receiver) by following the principles of DCF. If the target destination station receives the RTS, it will reply the CTS after SIFS. After the RTS and CTS have been exchanged between two stations, the channel is reserved for upcoming data communication and other PUs that overhear the control packets update the NAVs and defer their transmissions. Moreover, any SU which overhears RTS or CTS or both synchronizes the NAVs with PUs' ones.

If a SU overhears both RTS and CTS, if it is appropriate to be a helper (which implies it satisfies all criteria to be a helper), it will broadcast helper (HEL) message, with probability P_h, to PU sender and receiver after waiting modified-SIFS (MSIFS). The M-SIFS is shorter than the SIFS which is used by PUs. The reason of using M-SIFS is to make sure that PU sender receives the HEL message before transmitting the data packet to PU receiver. In the HEL message, SU integrates its address and the maximum transmission rates it can support. If the sender is willing to collaborate, it will transmit the data packet to helper SU with the proposed transmission rate. Then, the helper SU forwards the data packet to destination with maximum transmission rate. The PU receiver replies the ACK to the sender directly. The basic procedure of cooperative communication can be seen in Fig.2. After the ACK has been sent to sender, which implies that data transmission of PUs has finished, SUs can access the channel till NAVs go to zero since all SUs follow the principle of DCF and synchronize their NAVs with PUs' ones. For example, suppose the length of data packet is L and x ms are required for transmission. So, the channel is going to be reserved for x ms (which is equal to NAV). If this data packet with length L can be transmitted within y ms by cooperating with PUs and SUs, and if $y < x$, in the remaining time, $x-y$ ms, the channel can be used for CR (secondary) network. The benefit of cooperative communications can be seen in Fig.3.

2.3 Helper Selection

Selecting the appropriate helper is vital in this cooperative communication since it is responsible to create the transmission opportunities for CR network. If a SU overhears both RTS (from PU sender) and CTS (from destination), it realizes that it is lying somewhere in between the sender and destination of upcoming data transmission. SU receives the RTS and CTS with received power levels SNR_{RTS} and SNR_{CTS}, respectively. Then, it checks its position by

$$1-\beta \le \frac{SNR_{RTS}}{SNR_{CTS}} \le 1+\beta\ , \qquad (1)$$

where β is predefined threshold. If β is small and (1) is satisfied, the SU is very likely to be lying in the middle of sender and receiver. Then, it can support cooperative communication with higher data rates than direct transmission since the data rate of wireless communication is distance dependent [5]. SU estimates the transmission time of cooperative communication which is

$$T_{coop} = \frac{Data_L}{R_{sh}} + \frac{Data_L}{R_{hd}}\ , \qquad (2)$$

where R_{sh} and R_{hd} are the transmission rates from source (sender) to helper (itself) and helper to destination, respectively. $Data_L$ represents the data packet with length L and the direct transmission time is

$$T_{dir} = \frac{Data_L}{R_{sd}}\ , \qquad (3)$$

where R_{sd} is the direct transmission rate from source to destination. Then, SU checks whether it can reduce the data transmission time of PUs with the maximum transmission rates it can support as,

$$T_{coop} < T_{dir}\ . \qquad (4)$$

If condition (1) and (4) are satisfied, SU will broadcast the *HEL* message with probability P_h.

3. PERFORMANCE EVALUATION

3.1 Transmission Opportunities

In general, SUs are allowed to use only free potions of the channel in the cognitive radio networks. We can refer these free potions of channel as transmission opportunities for CR network. The transmission opportunities occur when the PUs do not use the channel. An example of PU activities on a channel can be seen in Fig.3. In normal situation (without cooperating with PUs), the average transmission opportunities for SUs is

$$E[T_O^n] = \frac{E[PU_{free}]}{E[PU_{active}]+E[PU_{free}]}\ , \qquad (5)$$

where $E[PU_{active}]$ refers to the average PU occupied periods and $E[PU_{free}]$ represents the average idle periods of a channel. However, as discussed above, these transmission opportunities could be enhanced by providing cooperative communication. A candidate helper transmits HEL with the probability P_h. Therefore, the probability of successful HEL message transmission will be $P_s = P_h(1-P_h)^{m-1}$, where m is the number of candidate helpers and $(1-P_h)^{m-1}$ implies no other candidate helper transmits the HEL message. The transmission opportunities that SUs can achieve by cooperating with PUs can be estimated as $T_O = T_{dir} - T_{coop}$. The expected transmission opportunities by cooperating with PUs is,

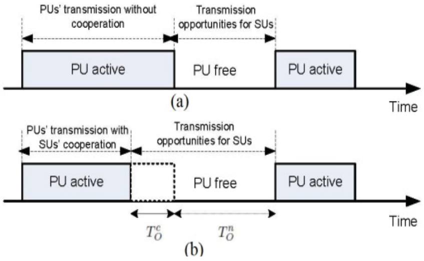

Fig.3. Benefit of cooperative communication and transmission opportunities for SUs (a) without cooperation and (b) with cooperation

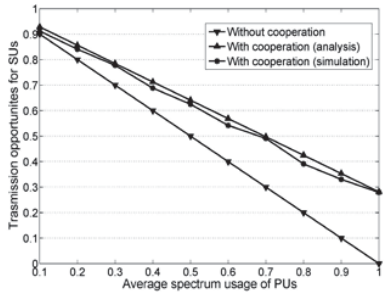

Fig. 4. Transmission opportunities for CR network against PU activities

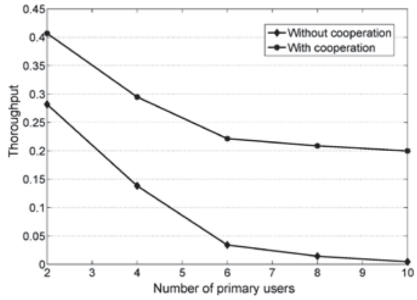

Fig. 5. Throughput of secondary network against number of PUs

$$E[T_O^c] = \frac{P_s \sum T_O}{E[PU_{active}] + E[PU_{free}]} . \quad (6)$$

Then, the total expected transmission opportunities for CR network is going to be,

$$E[T_O^t] = E[T_O^c] + E[T_O^n] \quad (7)$$

For better understanding the benefits of cooperative communication, we have run simulations. In the simulations, 10 PUs and 10 SUs are randomly deployed. The data packets size is assigned as 2048 bytes and the control packets sizes are set to be 38 bytes. For the data transmission, we use R_{sd}= 9 Mbps and $R_{sh} = R_{hd} = 36$ Mbps. The values, $P_h = 0.5$ and $\beta = 0.2$, are used and all control packets are sent with minimum transmission rate which is 1 Mbps.

As we described in (5), the availability of the channel is highly dependent on primary user activities. The transmission opportunities for SUs are inversely proportional to the PU activities. The more PUs use the channel, the less transmission opportunities SUs have. However, as shown in the Fig.3 and Fig.4, we can enhance the chance of accessing the channel for SUs by cooperating with PUs. Obviously, it can enhance the throughput of CR network since it has more channel accessing time.

3.2 Throughput

The secondary network is constructed based on DCF of 802.11. Thus, we directly apply some results of [3] to evaluate the throughput of secondary system. In [3], the throughput (S) is defined as the ratio of time the channel is used to successful transmit the data payload and it is described as,

$$S = \frac{E[N_{success}]}{T_{total}}, \quad (8)$$

where, $E[N_{success}]$ is the average number of data packets successfully transmitted and, according to (5), $T_{total} = E[PU_{active}] + E[PU_{free}]$. Suppose each SU transmits a data packet with probability τ, the probability that there is at least one transmission is $P_{trs} = 1 - (1-\tau)^n$, where, n is the number of SUs. Then, the probability of a successful packet transmission is going to be $P_{sus} = \frac{n\tau(1-\tau)^{n-1}}{P_{trs}}$.

Then, we can describe the average number of successful data transmissions as $N_{success} = P_{sus} P_{trs} E[N]$. Let S_c and S_n be the normalized throughputs of secondary network that achieve by with and without cooperating with PUs, respectively. Then, we obtain $S_c = \frac{P_{sus} P_{trs} E[N^c]}{T_{total} R_c}$ and $S_n = \frac{P_{sus} P_{trs} E[N^n]}{T_{total} R_n}$. Here, $E[N]$ refers to the average number of packets transmitted within transmission opportunities. Suppose, $E[l]$ is the average required time for a packet transmission, $E[N]$ can be derived as $E[N_c] = P_s \frac{\sum T_O}{E[l]}$ and $E[N_n] = P_s \frac{E[PU_{free}]}{E[l]}$. Then, the total throughput of secondary network simply becomes

$$S = S_n + S_c . \quad (9)$$

We ran simulation by setting $R_n = 2Mbps$ and $R_c = 11Mbps$ to evaluate the throughput. Other simulation parameters are similar as [3]. Fig.5 represents throughput of secondary network with and without cooperating with PUs. When the number of PUs increases, SUs have less opportunity to access the channel and it degrades the throughput. However, as shown in Fig.5, SUs can enhance the throughput by cooperating with PUs as cooperative communication creates some transmission opportunities for CR networks.

4. CONCLUSION

We have presented a cooperative communication mechanism that can be used for CR ad hoc networks. In the proposed mechanism, SUs can create the transmission opportunities for CR network without degrading the throughputs of the PUs. It might deviate from the principles of CR network, which is to find the spectrum holes and access the channel, but it obviously can enhance the spectrum efficiency.

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