Partial Cooperation for Spectrum Sharing in Cognitive Radio Network

Lok Man Law[1], Fen Hou[2], Jianwei Huang[1]
[1]Information Engineering Department, Chinese University of Hong Kong, {llm007, jwhuang}@ie.cuhk.edu.hk
[2]Ubiquitous Computing Research Lab, Macao Polytechnic Institute, fhou@ipm.edu.mo

***Abstract*— In this paper, we consider a cognitive radio network where secondary users may have different sets of available channels. We propose a partial cooperation scheme that captures the feature of incomplete channel availability information under spatial heterogeneity. It encourages cooperation among users in a group with the same priority channel, while allows contentions among users from different groups. We show that our proposed scheme achieves a good balance between the channel utilization and additional signaling overhead by comparing with no cooperation and full cooperation schemes. We further derive the lower bound of channel utilization of the proposed scheme by comparing it with a full cooperation scheme. Numerical results show that the average performance of the scheme can be more than two times better than the lower bound derived. In our simulations, the scheme is up to 15% better in channel utilization than the no cooperation scheme.**

I. Introduction

The Federal Communications Commission (FCC) report [1] and various field measurements have shown that many licensed radio spectrums are heavily under-utilized. Cognitive radio technology can improve the spectrum utilization by allowing secondary unlicensed users to sense and utilize the tentatively unoccupied spectrum, without affecting the normal communications of the primary licensed users.

In cognitive radio networks, *cooperation* can be very effective in improving the system performance. For example, cooperative spectrum sensing among secondary users can significantly improve the accuracy of detection for primary user and reduce the total sensing time (e.g., [2]–[4]). Cooperation between licensed primary users and secondary licensed users can help improve the performances of both sides (e.g., [5]–[7]). *In this paper, we focus on the issue of cooperation among secondary users in terms of spectrum sharing.* The key observation that motivates us in this study is that different secondary users may have different sets of channels, depending on their physical locations and activities of surrounding primary users. We study how the secondary users can efficiently share the spectrum with such *spatial heterogeneity*.

There are several existing results considering spectrum sharing with spatial heterogeneity. In [8], each user first discovers its neighbors and chooses a channel that covers the highest number of neighbors as the channel for coordination. An algorithm is proposed to make sure all users are connected with all of its neighbors through some local common channels. In [9], users form clusters with the existence of local common channels. In addition, some gateway nodes help to exchange information among different clusters. In both [8], [9], it was assumed that all users will eventually know the channel availability information of all users after the signaling exchange. This is, however, not always possible in practice.

Furthermore, extensive signaling exchange reduces transmission time and leads to a cost. Although benefits of various forms of cooperation have been extensively studied recently, the signaling overhead involved in the cooperation process is often neglected in the analysis. Few papers (e.g., [10]) considered the cost of coordination and control signaling when designing protocol for cooperative communications.

The key question we want to answer in this paper is as follows: *When is cooperation most beneficial for spectrum sharing in cognitive radio networks?* We will examine the tradeoff between the benefit of cooperation (e.g., better transmission coordination and collision avoidance) and the cost of cooperation (e.g., signaling overhead and reduced transmission time).

The key contribution of this paper is the design and analysis of a *partial cooperation scheme* which achieves the desirable tradeoff.

Our main results include:

- We propose a novel partial cooperation scheme that encourages *intra-group cooperations* to improve channel utilization and allows *inter-group contentions* to avoid excessive signaling overhead.
- We characterize the performance lower bound of the partial cooperation scheme, and numerically show that the average performance is often much better than the lower bound (e.g., more than two times better in our simulations).
- We show that the partial cooperation scheme shortens the time for signaling and reduces the message overhead comparing with a full cooperation scheme. The benefit is particularly significant for a large system with many channels and users.

The rest of the paper is organized as follows. The system model and the partial cooperation scheme are described in Sections II and III respectively. In Section IV, we compare the the proposed scheme with no cooperation scheme and full cooperation scheme in terms of the signaling overhead and channel utilization. We numerically compare the partial cooperation scheme with several other schemes in Section V.

This work is supported by the General Research Funds (Project Number 412509, 412710, and 412511) established under the University Grant Committee of the Hong Kong Special Administrative Region, China.

The conclusion and future work are given in Section VI.

II. The System Model

We consider a cognitive radio system with M primary users (PUs) and N secondary users (SUs). Each PU owns a licensed channel and has the exclusive priority to access its channel, while SUs are the opportunistic users who search for and utilize the spectrum holes (e.g., channels tentatively unused by PUs).

The system model is similar to [13] and is shown in Figure 1. A tower represents a PU (e.g., a television station). The primary channels are non-overleaping orthogonal channels with equal bandwidths. The mobile devices represent SUs located in an area partially covered by several PUs. Hence, it is possible for different SUs to see different available channels depending on their locations. The set of available channels for SU i is denoted by $\mathcal{S}_i \in \mathcal{M}$, where $\mathcal{M}$ is the set of all channels. The sets of available channels for all SUs is given by $\mathcal{S} = (\mathcal{S}_1, \cdots, \mathcal{S}_N) \in \mathcal{M} \times \cdots \times \mathcal{M}$. Figure 1 gives a concrete example, where PUs of all channels are active. SU A cannot use channel 3 as it is in the coverage area of PU 3, but can use channels 1 and 2, i.e., $\mathcal{S}_A = \{1, 2\}$. SU B is not in the coverage area of any PUs and thus can access all channels, i.e., $\mathcal{S}_B = \{1, 2, 3\}$.

To focus on the study of the impact of spatial heterogeneity, we assume that all available channels are identical for all SUs. Therefore, maximizing the total system throughput is equivalent to maximizing the total number of utilized channels. We will further generalize the study to channel heterogeneity in the future. We assume that SUs are close to each other, so that any two SUs having a common channel can communicate on that channel. If SUs can be far away from each other, they may not be within the interference range of each other. This leads to the interesting issue of spatial reuse, which will be studied in the future using a graph theoretical model. Once an SU is outside the coverage range of a PU, the SU can transmit on that PU's channel using low power without affecting the PU's normal communications. Moreover, we assume that each SU has a single radio transceiver that can communicate over only one channel at any time.

III. Partial Cooperation Scheme (PCS)

There are two facts that motivate us to study the partial cooperation scheme: (1) when all SUs know the complete channel availability information of each other, they can perfectly coordinate the channel access and achieve the maximum channel utilization; (2) obtaining complete channel availability information requires extensive information exchange among all SUs and reduce the time for transmission. Therefore, we aim to propose an algorithm that can strike a balance between channel utilization and the amount of signaling overhead.

A. Partial Cooperation Scheme (PCS)

We first explain two terminologies used in the PCS.

Definition 1 (Priority channel): An SU's priority channel is the one that the SU chooses to communicate with other SUs. Each SU uses its priority channel to exchange channel

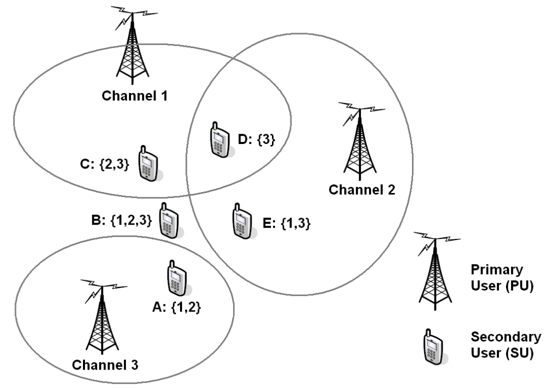

Fig. 1. A cognitive radio network with spatial heterogeneity.

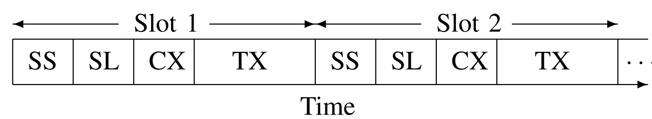

Fig. 2. The four phases in a time slot for the PCS. The meaning of notations are as follows: SS for sensing, SL for signaling, CX for contention, and TX for transmission.

availability information and form cooperative group with other SUs.

Definition 2 (Cooperative group): A group of SUs having the same priority channel form a cooperative group. Their common priority channel is also called the priority channel of the cooperative group. Note that each SU belongs to only one cooperative group since it has one priority channel.

Figure 2 illustrates how the PCS works. Here time is divided into discrete slots of equal lengths. Each time slot includes four phases: Sensing, Signaling, Contention, and Transmission, with details as follows.

- *Sensing (SS)*: Each SU senses channels sequentially for locally available ones and chooses a priority channel randomly from the set of available channels based on its sensing result independently from other SUs. A channel is available if the SU cannot detect a strong enough PU signal on this channel[1].
- *Signaling (SL)*: Each SU broadcasts its local channel availability information on its priority channel. SUs with the same priority channels form a group and exchange information[2]. The SU who first broadcasts on a particular priority channel becomes the leader of the corresponding group. The leader decides how SUs on the group access channels in the contention phase based on two simple rules: (i) it always chooses the group's priority channel

[1]This means that either the PU of that channel is not active, or the PU is active but the SU is far away from the PU. For detail discussions of various spectrum sensing mechanisms, see [11], [12].

[2]We will explain how SUs exchange information on the same priority channel and resolve the contention between message passing in Section IV-A.

first, and then chooses other channels in the SUs' sets of available channels as much as possible, and (ii) only one SU from the same group can contend on a channel. The first rule tries to minimize the contention among groups (as different groups have different priority channels), and the second rule avoids contention among SUs within the same group. This rule simplifies the analysis but is not as restrictive as it seems. The key reason is that having more than one SU from the same cooperative group contending for the same channel will not increase the channel utilization. At the end of the signaling phase, each leader broadcasts its group members' choices of channels for contention of the next phase. Since SUs are divided into groups based on their priority channels, multiple groups can concurrently exchange signals on their corresponding priority channels without affecting each other.

- *Contention (CX)*: SUs from different groups compete to transmit on the channels through random access.[3] In the rest of the analysis, we will assume that no transmission collision will happen among users.
- *Transmission (TX)*: The winner of contention on each channel occupies the channel and transmits during the rest of the time slot.

We denote the cooperative group for channel i as $\mathcal{C}_i$, when there exists one or more SUs on channel i during the signaling phase. The sets of available channels for cooperative group $\mathcal{C}_i$ is given by $\mathcal{A}_{\mathcal{C}_i} = \bigcup_{u \in \mathcal{C}_i} \mathcal{S}_u$. The set of contending channels $\mathcal{X}_{\mathcal{C}_i} \subseteq \mathcal{A}_{\mathcal{C}_i}$ includes the channels selected by the leader of cooperative group $\mathcal{C}_i$ in the contention phase. Since each SU can access one channel at a time, we have $|\mathcal{X}_{\mathcal{C}_i}| \leq |\mathcal{C}_i|$ where $|\cdot|$ represents the cardinality of set.

B. Two Benchmark Schemes

Now, we describe the two benchmark schemes that are used for comparison.

1) No Cooperation Scheme: All SUs choose their channels to contend independently without any information exchange. After sensing, each SU contends immediately on one of its available channels.

2) Full Cooperation Scheme: All SUs know the channel availability information of all other SUs by iterative signal exchange on common channels. With complete information of the system, a central coordinator runs a maximum matching algorithm that leads to an optimal channel-SU assignment without contention.

C. Intuition of the PCS

In the PCS, SUs having the same priority channel cooperate, while SUs with different priority channels compete with each other. We illustrate some intuitions of the PCS with the following examples:

- The PCS can improve the channel utilization by reducing contention among users. Consider a simple two-SU system, where both SUs have the same set of available channels $\{1, 2\}$. Without cooperation, with 50% probability SUs would contend on the same channel. In contrast, if SUs exchange messages over the priority channel $\{1\}$, they can achieve good coordination and transmit on different channels.
- Since the PCS provides partial cooperation, it may not perform as well as full cooperation scheme. An example is that SU A has channels $\{1, 2\}$, SU B has channels $\{1, 3\}$, and SU C has channel $\{3\}$ only. In this case, SUs A and B can exchange channel availability information through channel 1, while SU C cannot share information with the other SUs as they belong to different priority groups. After the cooperation of SUs A and B, a possibility is that SUs A and B access channel 1 and 3, respectively. As a result, there is a contention between SU B and C on channel 3; while channel 2 is idle. This leads to a loss in channel utilization. Compared with the full cooperation scheme where all three channels are utilized (e.g., SU A on channel 2, SU B on channel 1, and SU C on channel 3), the PCS induces a loss of 1/3 in terms of channel utilization.

To summarize, the PCS can provide partial cooperation opportunities for SUs having the same priority channel, and thus can improve the channel utilization comparing with no cooperation scheme. Compared with the full cooperation scheme, the PCS has less signaling overhead at the expense of some performance loss.

IV. System Comparison

In order to observe how the PCS can strike a good balance between the benefit and cost of cooperation, we compare it with the two benchmark schemes in two aspects: the signaling overhead and the channel utilization of the system.

A. Overhead Comparison

Consider a cognitive radio network with M channels, N SUs, and a reservation-based channel access scheme for message exchange during the signaling period. Synchronization of SUs can be done by beacon messages sent by PUs.

Figure 3 illustrates the structure of signal exchange for the PCS. There are N mini slots for all N SUs to broadcast their channel availability information in turn at the beginning. Each SU only broadcasts its local channel availability information once on its priority channel. One more mini slot at the end of those N slots is needed for the leader (the first SU who broadcasts on a particular priority channel) of the group to broadcast the decision of channel contention for the next phase. Note that all cooperative groups conduct signaling exchange concurrently over their own priority channels. In the contention phase, SUs belonging to different cooperative groups try to compete with each other. Depending on the

[3] One possible random access scheme is based on the random countdown mechanism similar as in IEEE 802.11, where each SU chooses a random timer and will only transmit if it does not detect any active transmission on the channel when its timer expires. When the maximum value of the timer is large enough, having two SUs counting down to zero simultaneously happens with a close-to-zero probability. In other words, no collision will happen.

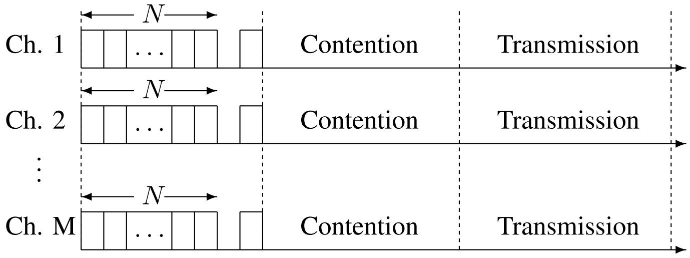

Fig. 3. Structure of message exchange in the PCS in one time slot.

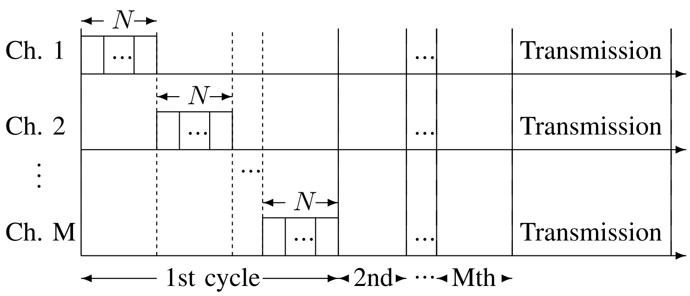

Fig. 4. Structure of message exchange in full cooperation scheme in one time slot.

choice of the multi-access scheme, the duration for contention varies. Afterwards, SU who wins in the contention can transmit on that channel and requires no more communication among SUs. Therefore, comparing with no cooperation scheme, the PCS only generates an extra of maximum $N + M$ messages for coordination, and the extra time for signaling will be $N+1$ mini slots.

The message exchange for full cooperation scheme is much more complicated. It usually includes neighbor discovery for SUs through a local common channel between them. Since there are multiple channels, the neighbor discovery phase may require SUs to send beacon message to each of its available channels. In general, it takes more than one iteration for all the SUs to get connected and completely exchange the channel availability information.

We simplify the structure of signal exchange for full cooperation scheme as shown in Figure 4. Since each SU can access only one channel a time, time should be perfectly adjusted so that SUs broadcast on different channels at different times. It takes a total of $N \times M$ mini slots for SUs to broadcast their channel availability information over all of their available channels once. In order to guarantee complete information exchange among the SUs, more than one cycle of message exchange is needed; M cycles are required in the worst case. An example with a total of 3 channels is given in Figure 5, where it takes 3 cycles for all SUs to completely exchange their channel availability information[4]. After having all SUs' channel availability information, we can run a centralized algorithm such as the bipartite matching algorithm to decide the

[4]In this example, SU D knows the information of SU C after the first cycle. It knows the information of SU B after the second cycle through SU C. Finally, it knows the channel information of SU A after the third cycle.

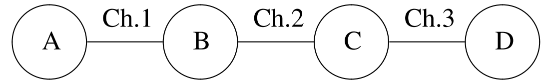

Fig. 5. An example of channel availabilities with number of channels $M = 3$ and 4 SUs. A node represents an SU, and a link represents a channel available to nodes connected to this link. In this figure, $\mathcal{S}_A = \{1\}, \mathcal{S}_B = \{1, 2\}, \mathcal{S}_C = \{2, 3\}$, and $\mathcal{S}_D = \{3\}$. Footnote 4 shows that it takes 3 cycles for all SUs to completely exchange their channel availability information.

optimal assignment without contention among users. Although contention period is omitted in the full cooperation scheme, the total time for signaling can be as much as $N \times M^2$ mini slots. The total number of messages generated for coordination is estimated by MN. One interpretation is that each of the N SUs generates M messages to broadcast its channel availability information on all channels. Although an SU may not have all the available channels, the broadcast message has to be relayed by some other SUs to the remaining channels, which generates the same number of overhead. Therefore, we can observe that the PCS generates less coordination messages and requires shorter signaling time than the full cooperation scheme. The reduction is more significant when the numbers of channels and SUs increase.

B. Channel Utilization Comparison

In the PCS, coordination of SUs allows them to explore channels other than the priority channels. Thus, we can be sure that the channel utilization in the PCS is no worse (and usually better) than no cooperation scheme. We are interested in the channel utilization of the PCS compared with full cooperation scheme, as a result of the tradeoff between complete channel availability information and signaling overhead. We first derive a lower bound of the channel utilization guaranteed by the PCS, and later show by numerical results that the performance of the PCS is usually better than this lower bound.

We first give the definition of several terminologies and use an example to illustrate the possible difference of channel utilization in the PCS and full cooperation scheme.

Definition 3 (Utilization, U): The total number of channels that are occupied (by at least one SU) in the transmission period.

Definition 4 (Utilization Ratio, $UR(N, M, \mathcal{S})$): Given the number of SUs N, the number of channels M, and the sets of available channels for all SUs $\mathcal{S} = (\mathcal{S}_1, \cdots, \mathcal{S}_N) \in \mathcal{M} \times \cdots \times \mathcal{M}$, the *Utilization Ratio* is defined as the ratio between the Utilization in the PCS (U_p) and that with full cooperation scheme (U_f),

$$UR(N, M, \mathcal{S}) = \frac{U_p(N, M, \mathcal{S})}{U_f(N, M, \mathcal{S})}.$$

Since the PCS cannot perform better than the full cooperation scheme, we have $UR \leq 1$.

Definition 5 (Lower bound of Utilization Ratio, UR_{LB}): Given the number of SUs N and the number of channels M, the lower bound of the Utilization Ratio is the worst possible Utilization Ratio over all possible sets of available channels

$\mathcal{S}$, i.e.,

$$UR_{LB}(N,M) = \min_{\mathcal{S}\in\mathcal{M}\times\cdots\times\mathcal{M}} UR(N,M,\mathcal{S}).$$

Example *1:* Consider a scenario with 4 SUs and the sets of available channels $\mathcal{S} = \{S_1, S_2, S_3, S_4\}$, where $S_1 = \{\underline{1}, 2, 3\}$, $S_2 = \{\underline{1}, 4\}$, $S_3 = \{1, \underline{2}, 4\}$, and $S_4 = \{\underline{2}, 3\}$. After the SUs randomly choose the priority channel (the underlined channel), we have two cooperative groups $\mathcal{C}_1 = \{1,2\}$ and $\mathcal{C}_2 = \{3,4\}$. The sets of available channels for the two cooperative groups are $A_{\mathcal{C}_1} = \{1,2,3,4\}$ and $A_{\mathcal{C}_2} = \{1,2,3,4\}$. In full cooperation scheme, all the channels are occupied when SU 1 chooses channel 1, SU 2 chooses channel 4, SU 3 chooses channel 2, SU 4 chooses channel 3. Hence, $U_f = 4$. In the PCS, a possible result is $X_{\mathcal{C}_1} = X_{\mathcal{C}_2} = \{1,2\}$ and $U_p = 2$. Therefore, $UR = \frac{2}{4} = \frac{1}{2}$.

From the above example, we observe that more overlapping in the set of contending channels for different cooperative groups leads to a lower Utilization Ratio. We will use this main idea to derive the lower bound of Utilization Ratio analytically.

Proposition 1: The Utilization in the PCS, U_p, is at least h when there are h cooperative groups.

Proof: As described in Section III, each cooperative group always chooses its priority channel for channel contention. As priority channels of different groups do not overlap, we prove the result. ■

Proposition 2: When there are N SUs and M channels, the Utilization is at most $\min(N,M)$.

Proof: When $N \leq M$, since each SU can access only one channel, the Utilization achieves the maximum N when each SU can transmit on a different channel. When $N > M$, apparently the Utilization will not be higher than the number of channels M. ■

Proposition 3: When there is only a single SU or a single channel, the Utilization Ratio equals to 1, i.e.,

- $UR(N,1) = UR_{LB}(N,1) = 1$;
- $UR(1,M) = UR_{LB}(1,M) = 1$.

Proposition 3 is straightforward to see.

Lemma 1: Given the number of SUs $N = r$, the number of channels $M = r$, and the Utilization in full cooperation scheme $U_f = r$ where r is a positive integer, the minimum Utilization in the PCS is q, where q is an integer satisfying $(q-1)^2 < r \leq q^2$. Thus, the lower bound of Utilization Ratio is

$$UR(r,r,\mathcal{S}^r) \geq \frac{q}{r},$$

where $\mathcal{S}^r$ is a set of available channels satisfying $U_f = r$.

Proof: According to Proposition 1, the Utilization in the PCS, U_p, is no less than the number of cooperative groups. Therefore, finding the minimum value of U_p is equivalent to finding the minimum number of cooperative groups such that channel utilization U_p equals to the number of cooperative groups. First, the channel utilization equals to the number of cooperative groups means that all SUs only contend on the priority channels (although SUs from one cooperative group may contend on the priority channel of another group). For example, we assume that the number of cooperative groups is q. That is, we have q priority channels. Therefore, the channel utilization U_p equals to q when all SUs contend for these q priority channels. With the condition $U_f = r$, it is possible for all SUs to access a different channel. This implies that a cooperative group with more than q SUs can access more than q channels, which leads to $U_p > q$. Thus, each cooperative group can accommodate a maximum number of q SUs such that the channel utilization U_p is still q. Therefore, given the number of cooperative groups q, the maximum number of SUs that leads to $U_p = q$ is q^2. If the number of SUs is larger than q^2, the minimum number of cooperative groups such that channel utilization U_p equals to the number of cooperative groups must be larger than q.

Let q be the minimum number of cooperative groups such that channel utilization U_p equals to the number of cooperative groups. Given the number of SUs $N = r$ and the number of channel $M = r$, q satisfies $(q-1)^2 < r \leq q^2$. If the number of SUs r is larger than q^2, it is possible to find a number larger than q to be the minimum number of cooperative groups such that channel utilization U_p equals to the number of cooperative groups. If the r is less than $(q-1)^2$, it is possible to find a number less than q to be the minimum number of cooperative groups such that the channel utilization U_p equals to the number of cooperative groups. Therefore, given the number of SUs $N = r$ and the number of channel $M = r$, we can find an integer number q satisfying $(q-1)^2 < r \leq q^2$, and the minimum channel utilization $U_p(N = r, M = r, S^r)$ is q. Since the channel utilization of full cooperation is $U_f = r$, we have a lower bound of the Utilization Ratio $UR(r,r,S_r) \geq q/r$. ■

TABLE I

THE LOWER BOUND OF THE PCS WITH DIFFERENT FULL COOPERATION METRIC AS STATED IN LEMMA 1

$U_f = r$	1	2	3	4	5	6	7	8	9	10	11
q	1	2	2	2	3	3	3	3	3	4	4
$UR(r,r,\mathcal{S}^r)$	1	1	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{3}{5}$	$\frac{1}{2}$	$\frac{3}{7}$	$\frac{3}{8}$	$\frac{1}{3}$	$\frac{2}{5}$	$\frac{4}{11}$

Table I illustrates the lower bound given in Lemma 1 for the values of $U_f = 1$ to 11.

Lemma 2: For all sets of available channels $\mathcal{S}^r$ that lead to $U_f = r$, we have

$$UR(N,M,\mathcal{S}^r) \geq UR(r,r,\mathcal{S}^r) \geq \frac{q}{r},$$

for any values of $N, M \geq r$.

Proof: Since $U_f = r$, the maximum number of utilized channels is r. That is, at most r out of M channels are utilized. Therefore, the system with $M \geq r$ channels is equivalent to a system with only r channels when computing the lower bound of the Utilization Ratio. Similarly, when the number of SUs $N \geq r$, the excess SUs on a channel do not change the number of cooperative groups. In finding the lower bound of Utilization Ratio, we can simply consider a system with the same number of SUs and channels, where each of the r SUs transmits on a different channel in the optimal case of the full cooperation scheme. ■

Based on the above lower bound result for a specific value

TABLE II

UR LOW BOUND AS STATED IN THEOREM 1

$\min(N, M)$	1	2	3	4	5	6	7	8	9	10	11
UR_{LB}	1	1	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{3}{7}$	$\frac{3}{8}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$

$U_f = r$, we can further compute the lower bound of general values of N and M, where N is the number of SUs and M is the number of channels.

Theorem 1: Given the number of SUs N and number of channels M, $UR_{LB}(N, M) = \min_{1 \leq r \leq \min(N,M)} UR_r$.

Proof: Given N and M, we know that the Utilization in full cooperation scheme falls in the range of $1 \leq U_f \leq \min(N, M)$. With the result from Lemma 1 and 2, we only have to compare the lower bound of different given values of U_f and find the minimum among those. ∎

Example 2: For a network scenario with $M > N = 4$, we can have four possible Utilizations in full cooperation scheme, i.e., $U_f = 1, 2, 3$, or 4. Note that here the U_f is upper bounded by the number of SUs N according to Proposition 2. Therefore, the possible set of lower bounds of Utilization Ratio for the PCS is $\{1, 1, \frac{2}{3}, \frac{1}{2}\}$ (by checking Table I). Then the lower bound of Utilization Ratio the scheme is $\min(1, 1, \frac{2}{3}, \frac{1}{2}) = \frac{1}{2}$.

The lower bounds of Utilization Ratio for a system with given N and M are listed in Table II.

V. NUMERICAL RESULTS

We have shown that the PCS has a higher channel utilization than the no cooperation scheme and have derived the lower bound of the channel utilization compared with the full cooperation scheme. In this section, we numerically show how the PCS performs in general.

In the simulation, we assume that the channel availability for each SU follows a Markovian On-Off model with the parameter α and β, where α and β are the probabilities that the channel transits from the state "On" to "Off" and from "Off" to "On", respectively. The state "On" represents that the channel is not available for the SU, while "Off" represents that the channel is available for it. For each parameter setting of α and β (ranges between 0.1 and 0.5), the number of channel M, and the number of SUs N, we repeat the simulation 1000 times with different random seeds and calculate the average value for the Utilization Ratio.

Figure 6 shows the performance of the three schemes: full cooperation scheme, PCS, and no cooperation scheme, with the number of channels $M = 10$. It shows that full cooperation scheme achieves the highest expected Utilization. The PCS is better than the no cooperation scheme, with the maximum performance gap as 15% when $N = 10$. This gap becomes larger when N increases from zero to M, as contention among SUs increases accordingly. The gap becomes smaller when there are significantly more SUs than channels, so that most channels are utilized even with random access from SUs.

To better understand the performance loss of the PCS comparing with the full cooperation scheme, we plot a graph with the Utilization Ratio in Figure 7 with $M = 10$. For

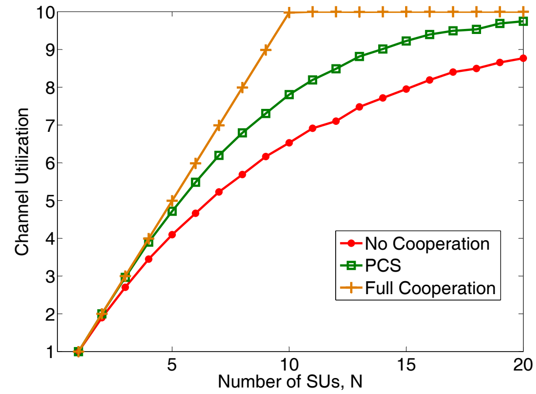

Fig. 6. The expected channel utilization under different schemes with number of channels, $M = 10$.

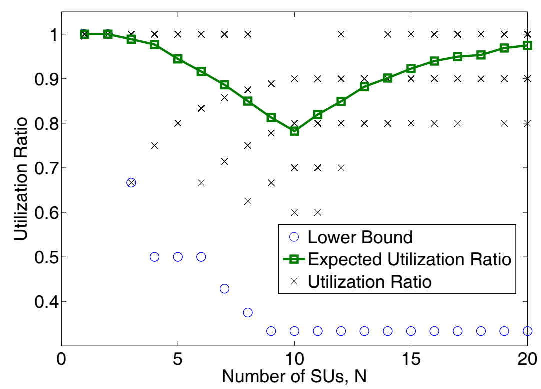

Fig. 7. The expected Utilization Ratio of the PCS with number of channels, $M = 10$. We run 1000 simulations for each value of number of SUs, N and the instants of Utilization Ratio are marked by the crosses. The circle indicates the lower bound of Utilization Ratio computed analytically in Section IV-B. The curve of expected Utilization Ratio is higher than the lower bound.

each value of number of SUs, N, we run 1000 simulations to compute the Utilization Ratio as marked by the crosses. We observe that the Utilization Ratios for different values of N are higher than the lower bounds we obtained analytically in Theorem 1 ($\frac{1}{3}$ for $\min(N, M) = 10$), which are marked as the circles in the graphs. For a fixed value of $M = 10$, the worst possible ratio happens when $N = 10$, which is consistent with Lemma 2. When $N > M$, an increasing number of users N results in a higher Utilization Ratio. The average Utilization Ratio is 85% in Figure 7, which is more than two times of the lower bound derived in Theorem 1. There is a large difference between the expected Utilization Ratio and the lower bound computed because the worst case occurs less frequent.

From the above, we can see that the PCS can attain more than 80% of the Utilization in full cooperation scheme by an additional signaling phase for exchanging information on available channels among SUs. One may question: *Is it better to have more channel availability information by forming*

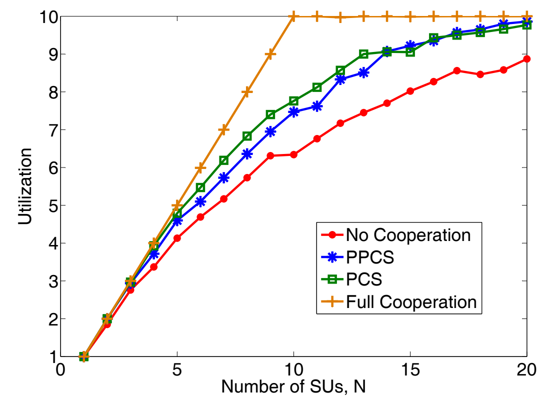

Fig. 8. The expected channel utilization under different schemes with number of channels, $M = 10$.

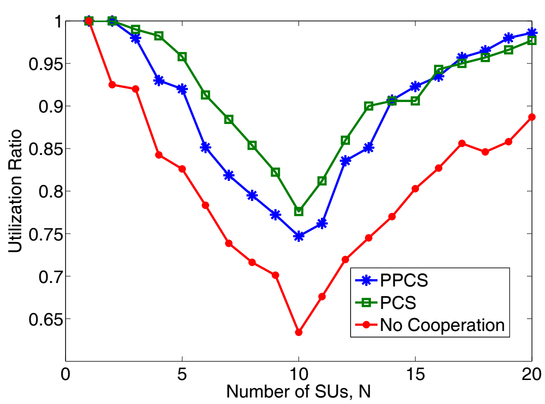

Fig. 9. The expected Utilization Ratio with number of channels, $M = 10$.

larger cooperative groups? To see how the size of cooperative groups affect the channel utilization, we present a variation of the PCS, the priority-based partial cooperation scheme (PPCS).

In the PPCS, a fixed priority order of channels for signaling phase is announced. One example is that low frequency channels are more preferable than high frequency channels. Each SU uses the lowest frequency channel among its set of available channels as the priority channel. With this policy, SUs have a higher chance to form groups and exchange the channel availability information. After signaling phase, the leader of each cooperative group will broadcast the assignment that leads to maximum matching as in the PCS, and the contention phase follows.

We can see the performance of the PPCS in both the channel utilization and Utilization Ratio in Figure 8 and 9. As shown in the figures, the PPCS achieves higher channel utilization than no cooperation scheme, and its performance is almost the same as the PCS. From the system point of view, larger cooperative groups cannot improve the channel utilization when the channels are identical. Therefore, the PCS is more preferable than the PPCS as it does not require the prior agreement of a priority order.

VI. Conclusion and Future Work

In this paper, we propose a partial cooperation scheme (PCS) that encourages cooperation of SUs with the same priority channel, and allows contention of SUs from different cooperative groups. We compare the PCS with the full cooperation scheme and no cooperation scheme in two aspects: channel utilization and signaling overhead. We derive the lower bound on the Utilization Ratio, which indicates the performance guaranteed by the PCS with the reduction of signaling overhead. Later, we show by simulation results that the PCS in general performs (much) better than the lower bound. In our simulations, the performance of PCS can be more than two times better than the lower bound derived. Finally, we show that a fixed priority order for all SUs is not essential to achieve the benefits of partial cooperation.

One possible extension is to apply the PCS to networks with heterogeneous channels, and evaluates its performance with full cooperation and no cooperation schemes. Another direction is to consider spatial reuse which may increase the system throughput.

References

[1] FCC, "Spectrum Policy Task Force," ET Docket 02-135, Nov. 2002.

[2] S. Mishra, A. Sahai, and R. Brodersen, "Cooperative sensing among cognitive radios," *IEEE ICC*, pp. 1658-1663, 2006.

[3] J. Unnikrishnan and V. V. Veeravalli, "Cooperative sensing for primary detection in cognitive radio," *IEEE Journal of Selected Topics in Signal Processing*, vol. 2, no. 1, pp. 18-27, 2008.

[4] K. B. Letaief and W. Zhang, "Cooperative communications for cognitive radio networks," *Proceedings of the IEEE*, vol. 97, no. 5, pp. 878-893, 2009.

[5] O. Simeone, I. Stanojev, S. Savazzi, Y. Bar-Ness, U. Spagnolini, and R. Pickholtz, "Spectrum leasing to cooperating secondary ad hoc networks," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, pp. 203-213, Jan 2008.

[6] J. Zhang, Q. Zhang, "Stackelberg Game for Utility-Based Cooperative Cognitive Radio Networks," *ACM MobiHoc*, New Orleans, USA, May 2009.

[7] L. Duan, L. Gao, and J. Huang, "Contract-based Cooperative Spectrum Sharing," *IEEE Dynamic Spectrum Access Networks (DySPAN)*, Aachen, Germany, 2011.

[8] J. Zhao, H. Zheng, G.-H. Yang, "Distributed coordination in dynamic spectrum allocation networks," *Proceedings of the IEEE DySPAN*, pp. 259-268, 2005.

[9] T. Chen, H. Zhang, G.M. Maggio, I. Chlamtac, "CogMesh: a clusterbased cognitive radio network,"*Proceedings of the IEEE DySPAN*, April 2007, pp. 168-178.

[10] J. Yackoski, L. Zhang, B. Gui, C. Shen, and L. Cimini, "Networking with cooperative communications: holistic design and realistic evaluation," *IEEE Communications Magazine*, vol. 47, no. 8, pp. 113-119, 2009.

[11] T. Ycek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Communications Surveys & Tutorials*, vol. 11, no. 1, pp. 116-160, 2009.

[12] Y. Zeng, Y. Liang, A. T. Hoang, and R. Zhang, "A review on spectrum sensing for cognitive radio: Challenges and solutions," *EURASIP J. Adv. Signal Process.*, vol. 2010, pp. 1-15, 2010.

[13] J. Jia, J. Zhang, and Q. Zhang, "Cooperative Relay for Cognitive Radio Networks," *IEEE INFOCOM*, 2009.

[14] C. Doerr, D. Grunwald, D. Sicker, "Dynamic control channel management in presence of spectrum heterogeneity," *IEEE Military Communications Conference, MILCOM 2008*, pp. 1-8, 2008.

[15] C. Corderio and K. Challapali, "C-MAC: a cognitive MAC protocol for multichannel wireless networks," *Proc. IEEE Symposium on New Frontiers in Dynamic Spectrum Access networks*, April 2007.