WIRELESS COMMUNICATIONS AND MOBILE COMPUTING
Wirel. Commun. Mob. Comput. 201X; **00**:2–26
DOI: 10.1002/wcm

Channel Assignment Schemes for Cooperative Spectrum Sensing in Multi-Channel Cognitive Radio Networks

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ABSTRACT

In this paper, channel assignment for spectrum sensing is studied in multi-channel cognitive radio networks to maximize the number of channels satisfying sensing performance (called available channels). Beginning with a nonlinear integer programming problem, we derive the upper bound of optimal value through many-to-many assignment problem and then propose three algorithms for both centralized and distributed scenarios. In centralized case, a heuristic scheme is proposed based on the signal-to-noise ratios (SNRs) over all primary channels (PCs). Then, a greedy scheme is proposed to reduce the reported information from the cognitive radios (CRs). In distributed case, a novel scheme with multi-round operation is designed following the coalitional game theory. In each round, each CR selects some PCs based on SNRs. Then, the CRs selecting the same channel play coalitional game and thereby multiple games are played concurrently over multiple channels. Finally, the best coalition for each channel is chosen among the formed coalitions to perform the cooperative spectrum sensing. The simulation results show that the proposed schemes can significantly increase the number of available channels.

KEYWORDS

Multi-channel cognitive radio networks, channel assignment, cooperative spectrum sensing, coalitional game, centralized scheme, distributed scheme

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1. INTRODUCTION

Recently, cognitive radio (CR) has been considered as a promising technology to overcome the under-utilization of the licensed spectrum in order to relief the stress on spectrum scarcity [1, 2]. A cognitive radio network (CRN) commonly consists of two kinds of users, i.e., primary users (PUs) and secondary users or cognitive radios (CRs). The PUs have higher priorities to access the licensed spectrum, called primary channels (PCs), while the CRs can only use the PCs opportunistically when PUs are absent. For CRNs, spectrum sensing, aiming at detecting the activity of PUs (i.e., presence or absence), plays a critical role in implementation and has attracted numerous research efforts [3, 4].

In the literature, the probabilities of miss-detection (i.e., an occupied PC is detected as vacant one) and false alarm (i.e., a vacant PC is detected as occupied one) are defined to describe the spectrum sensing performance. The former and the latter determine the interference to PUs and the degradation of the achievable performance of CRs (e.g., the utilization efficiency of the PCs or throughput), respectively. Thus, sensing algorithms should be developed to restrict both parameters over the sensed channel so that the performance of CRs can be improved with little harm to PUs. Due to the limitation of sensing performance, the channel fading and the potential hidden terminal problem, the channel sensing done by a single CR may not meet the required sensing performance, which results in a new technology, called cooperative spectrum sensing (CSS) [5, 6]. Specifically, in CSS, several CRs cooperate with each other to sense one channel simultaneously and with the aid of fusion center, a final decision is made based on all sensing results via fusion rules, such as OR-rule [6], AND-rule [7], or Counting-rule [8]. In the past, the majority of researches, in the field of CSS, focused on single-channel sensing. Although the sensing performance is guaranteed by CSS, sensing one PC by all CRs is ineffective to improve the performance of CRs. It is due to the fact that to avoid co-channel interference, all CRs cannot utilize such PC simultaneously. In practice, in multi-channel systems, each CR has

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DOI: 10.1002/wcm
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the capability of sensing multiple channels simultaneously. Thus, by employing CSS, it is important to detect more channels with satisfied sensing performance and then assign them to different CRs to avoid co-channel interference. In other words, suitably grouping CRs to sense different channels becomes necessary. For example, both [9] and [10] proposed that CRs should be allowed to sense part of system channels at the same time. However, the discussions therein were performed under an additive white Gaussian noise (AWGN) channel so that CSS was not considered. In [11], the authors studied how to maximize throughput of CRs for discrete and continuous sensing times in multi-channel CRNs, while, their scheme was designed for soft-decision fusion only. In addition, the details of channel assignments for sensing was not mentioned. In [12], sensor allocation and quantization schemes in multi-channel CRNs were considered in a centralized fashion. However, the assumptions of error-free reporting channels and assigning equal number of sensors to each PC may not be practical and reduce the number of PCs sensed. The works mentioned above belong to the narrow band spectrum sensing, where each sensed channel is sufficient narrow, and each CR cannot sense large range of frequency spectrum in the system. Recently, a new direction, named wide-band spectrum sensing, has drawn attention for multi-channel spectrum sensing [13]. In this filed, the number of PCs in the system matches to the number of channels each CR can sense. Thus, the researches are focused on designing detectors to improve the sensing performance and reduce the complexity [14, 15, 16]. However, in a real system, the number of PCs can be more than the number of channels each CR can sense. Therefore, assigning different channels to CRs for spectrum sensing becomes a practical issue which has not been covered by wide-band spectrum sensing yet.

In this paper, considering each CR can only sense small part of PCs in the system simultaneously, the channel assignment schemes are studied for cooperative spectrum sensing in both centralized and distributed fashions. First, the optimal scheme is modeled as a nonlinear integer programming problem to maximize the number of *available channels* in the system. Here, the *available channel* is defined as the one which satisfies sensing performance constraints on both false alarm and miss-detection probabilities. Then, since the original problem is proved to be NP-hard, its relaxed upper bound is derived by transferring it to a many-to-many assignment problem [17]. After that, novel algorithms are proposed for both centralized and distributed scenarios. In centralized case, a heuristic channel assignment scheme is first proposed. Specifically, each CR reports the primary signal-to-noise ratios (SNRs) over all PCs to secondary base station (SBS). Then, the SBS assigns channels one by one and each assignment follows three successive criteria: 1) the channel can be sensed by a minimum number of candidate coalitions, each of which includes a group of CRs sensing the same channel, 2) the coalition can sense a minimum number of channels, and 3) the coalition has the smallest miss-detection probability. In order to relief the requests that all CRs have to report SNRs over all channels, a second method, called greedy channel assignment scheme, is also introduced. In this scheme, the channel assignment for sensing follows the similar procedure as the heuristic one, but in each assignment, each CR only reports SNRs of carefully selected channels. In distributed case, coalitional game theory is introduced to figure out the best coalition formation for CSS. In particular, each CR selects K PCs at most, which have the largest SNRs among those not assigned for sensing. Then, for CRs selecting the same channel, a coalitional game is played till forming a stable coalitional structure. After that, each selected channel is assigned to the coalition with the best property in terms of miss-detection and false alarm probabilities. Such procedure is performed round by round till no channel can be assigned for sensing or each CR has been assigned K channels. Finally, the simulation results verifies that the number of *available channels* can be significantly improved by both centralized and distributed schemes.

In summary, the major contributions of this paper include: 1) The original nonlinear integer programming problem is approximated by a many-to-many assignment problem to derive the upper bound of the optimal value; 2) A new heuristic channel assignment scheme is proposed to increase the number of *available channels* with low computational complexity; 3) A new greedy channel assignment scheme is proposed to further decrease the communication overhead between SBS and CRs to achieve less congested and more energy efficient CRNs; 4) A distributed channel assignment scheme based on coalitional game theory is proposed in order to search the best coalition formation in non-infrastructure cognitive radio networks.

The rest of this paper is organized as follows. Section 2 describes the system model. In Section 3, the upper bound of the original optimal problem is derived by a many-to-many assignment problem. The proposed centralized and distributed channel assignment schemes are discussed in Sections 4 and 5, respectively. The simulation results are presented in Section 6, followed by conclusions in Section 7.

2. SYSTEM MODEL

Consider a CRN consisting of M PUs and N CRs which are deployed randomly in a given geographic area. PUj ($\in \{1, \cdots, M\}$) indicates the PU using channel j. Both centralized and distributed setups are taken into account. In centralized setup, a SBS exists as a central controller, while in distributed setup, all CRs work in an ad hoc manner. In the system, each PU is assigned to one PC so that there are total M PCs available in the system. For the sake of hardware constraints and energy efficiency, each CR adopts energy detection as in [6] and the number of channels sensed by each CR at a time is limited to K $(K < M)$ [9]. Due to Rayleigh fading, the probabilities of miss-detection and false-alarm (i.e., $p_m^{i,j}$ and $p_f^{i,j}$) for CRi sensing channel j can be denoted, respectively, as [6]

$$p_m^{i,j} = 1 - [e^{-\frac{\lambda}{2}} \sum_{n=0}^{\tau-2} \frac{1}{n!} (\frac{\lambda}{2})^n + (\frac{1+\gamma_{i,j}}{\gamma_{i,j}})^{\tau-1} \times (e^{-\frac{\lambda}{2(1+\gamma_{i,j})}} - e^{-\frac{\lambda}{2}} \sum_{n=0}^{\tau-2} \frac{1}{n!} (\frac{\lambda\gamma_{i,j}}{2(1+\gamma_{i,j})})^n)], \quad (1)$$

$$p_f^{i,j} = \frac{\Gamma(\tau, \frac{\lambda}{2})}{\Gamma(\tau)}, \quad (2)$$

where $\gamma_{i,j}$, calculated by $\gamma_{i,j} = \frac{P_{PU} {d_{i,j}}^{-\alpha}}{N_0}$, is the average SNR of PCj measured at CRi [18]. Here, N_0 is the noise power, P_{PU} denotes the PU transmit power, $d_{i,j}$ represents the distance between CRi and PUj, and α is the path loss exponent. Thus, $P_{PU} {d_{i,j}}^{-\alpha}$ indicates the average signal strength received by CRi on PCj. $\Gamma(\cdot,\cdot)$ is the incomplete gamma function and $\Gamma(\cdot)$ is the gamma function. τ and λ are the time bandwidth product and the energy detection threshold, respectively. Without loss of generality, both are set to constant among CRs. Thus, $p_f^{i,j}$ in (2) is a constant for all CRs on each PC and we denote it as p_f for notation simplification.

In the system, CRs are first grouped in coalitions for CSS, each of which is assigned to sense one PC, with the aid of secondary base station (SBS) in centralized setup or collaboratively in distributed setup. Thus, each CR can belong to multiple coalitions, which sense different channels. Then, each CR senses the associated PCs and submits the sensing results through the dedicated control channel to fusion center (the SBS in centralized setup or the coalition head in distributed setup), where the final decision is made based on the fusion rule, such as OR-rule [6], AND-rule [7], or Counting-rule [8]. In CSS, the optimal fusion rule is different depending on the network deployment. For example, under the Rayleigh fading channel, some literatures verified that OR rule has better sensing performance than others [8, 19, 20]. Thus, per in several studies [6, 18], OR-rule is selected in this paper, i.e., the declaration of a vacant PC is made only if all CRs indicate it as vacant. However, other fusion rules can be also applied to the schemes proposed in this paper. We further let the reporting error rate, p_e, be the same for all CRs. Nevertheless, our scheme is also applicable for different reporting error rates. Let $\mathscr{C}_j$ be the coalition sensing PC j and $|\mathscr{C}_j|$ be the number of CRs in $\mathscr{C}_j$. Then, for centralized setup, the miss-detection and false alarm probabilities of CSS can be, respectively, calculated as [6]

$$Q_m^j = \prod_{i \in \mathscr{C}_j} [p_m^{i,j}(1-p_e) + (1-p_m^{i,j})p_e], \tag{3}$$

$$\begin{aligned} Q_f^j &= 1 - \prod_{i \in \mathscr{C}_j} [(1-p_f)(1-p_e) + p_f p_e] \\ &= 1 - [(1-p_f)(1-p_e) + p_f p_e]^{|\mathscr{C}_j|}. \end{aligned} \tag{4}$$

We can similarly derive the miss-detection and false alarm probabilities for distributed setup as

$$Q_m^{I,j} = p_m^{I,j} \prod_{i \in \mathscr{C}_j, i \neq I} [p_m^{i,j}(1-p_e) + (1-p_m^{i,j})p_e], \tag{5}$$

$$\begin{aligned} Q_f^{I,j} &= 1 - (1-p_f) \prod_{i \in \mathscr{C}_j, i \neq I} [(1-p_f)(1-p_e) + p_f p_e] \\ &= 1 - (1-p_f)[(1-p_f)(1-p_e) + p_f p_e]^{|\mathscr{C}_j|-1} \end{aligned} \tag{6}$$

where CRI denotes the coalition head. Apparently, the coalition head has an impact on $Q_m^{I,j}$. Thus, in order to optimize the sensing performance, the coalition head should be chosen to minimize $Q_m^{I,j}$, i.e., $I^* = \underset{I \in \mathscr{C}_j}{\text{argmin}} Q_m^{I,j}$ (for example, the selection can be done after each CR broadcasts its own p_m and p_f). Since the centralized and distributed scenarios are discussed separately, we use the same notations for both scenarios without introducing any confusion and then define $Q_m^j = Q_m^{I^*,j}$ and $Q_f^j = Q_f^{I^*,j}$.

Note that the difference between equation pairs of (3) and (4), and (5) and (6) comes from the fact that under distributed setup, the coalition head is unnecessary to report the sensing result. The constraints of Q_m^j and Q_f^j are defined as $Q_m^j < \overline{Q_m}$ and $Q_f^j < \overline{Q_f}$, where $\overline{Q_m}$ and $\overline{Q_f}$ are two predefined thresholds. Then, for the centralized scenario, according to Q_f^j in (4) and $Q_f^j < \overline{Q_f}$, we can have

$$|\mathscr{C}_j| < \frac{\ln(1 - \overline{Q_f})}{\ln[(1-p_f)(1-p_e) + p_f p_e]}. \tag{7}$$

Since $|\mathscr{C}_j|$ is an integer, the number of CRs in the coalition sensing PC j in the centralized scenario should satisfy

$$|\mathscr{C}_j| \leq \lfloor \frac{\ln(1 - \overline{Q_f})}{\ln[(1-p_f)(1-p_e) + p_f p_e]} \rfloor = Z_{max} \tag{8}$$

where $\lfloor\cdot\rfloor$ denotes the floor operation, and Z_{max} denotes the maximum number of CRs in each coalition for the centralized scenario. Similarly, according to (6) and $Q_f^j < \overline{Q_f}$, the number of CRs in the coalition sensing PC j in the distributed scenario should satisfy

$$|\mathscr{C}_j| \le \lfloor \frac{\ln(1-\overline{Q_f}) - \ln(1-p_f)}{\ln[(1-p_f)(1-p_e)+p_f p_e]} + 1 \rfloor = L_{max} \tag{9}$$

where L_{max} is the maximum number of CRs in each coalition for the distributed scenario. From the perspective of spectrum efficiency, the number of *available channels* should be maximized. Let $\mathscr{X} = (x_{ij})_{N\times M}$ be an allocation matrix where $x_{ij} = 1$ indicates that CRi senses channel j, otherwise $x_{ij} = 0$. Then, our objective can be formulated as a nonlinear optimization problem as

$$\max_{\mathscr{X}} \quad \sum_{j=1}^{M} \mathscr{U}_j(Q_m^j) \tag{10}$$

$$s.t. \quad \sum_{j=1}^{M} x_{ij} \le K, i \in \{1, \cdots, N\} \tag{11}$$

$$\sum_{i=1}^{N} x_{ij} \le L, j \in \{1, \cdots, M\} \tag{12}$$

$$x_{ij} \in \{0, 1\} \tag{13}$$

where $\mathscr{U}_j(Q_m^j)$ is an indicator function, i.e.,

$$\mathscr{U}_j(Q_m^j) = \begin{cases} 1, & Q_m^j < \overline{Q_m} \\ 0, & \text{otherwise.} \end{cases} \tag{14}$$

L is Z_{max} or L_{max} for centralized or distributed setup. The constraint in (11) means that CRi can sense K channels at most, and the inequation (12) indicates that each channel cannot be sensed by more than L CRs, which is equivalent to $Q_f^j < \overline{Q_f}$.

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DOI: 10.1002/wcm
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3. UPPER BOUND OF THE OPTIMIZATION PROBLEM

In the optimization problem of (10), the constraints of (11) and (12) can be further combined as $\mathbf{AX} \leq \mathbf{C}$, where $\mathbf{X} = [x_{11}, \cdots, x_{1M}, x_{21}, \cdots, x_{2M}, \cdots, x_{N1}, \cdots, x_{NM}]^T$ and $\mathbf{C} = [K, \cdots, K, L, \cdots, L]^T$ (N elements equal to K and M elements equal to L). $\mathbf{A}$ is a matrix with the format as

$$\mathbf{A} = \begin{bmatrix} \mathbf{A_1} & \mathbf{A_2} & \cdots & \mathbf{A_N} \\ \mathbf{I} & \mathbf{I} & \cdots & \mathbf{I} \end{bmatrix}_{(N+M)\times(N\times M)}, \tag{15}$$

where $\mathbf{A}_i$, $i \in \{1, \cdots, N\}$, is an $N \times M$ matrix with the elements in the i-th row equal to 1, and $\mathbf{I}$ is the identity matrix of size M. According to (3), if CR$_i$ does not sense PC$_j$, $x_{ij} = 0$ and it has no contribution to Q_m^j; otherwise, $x_{ij} = 1$. Thus, (3) can be rewritten as

$$Q_m^j = \prod_{i=1}^{N} [p_e + p_m^{i,j}(1 - 2p_e)]^{x_{ij}}, \tag{16}$$

which indicates that Q_m^j is a nonlinear function of $x_{ij}, i \in \{1, \cdots, N\}$. In this sense, the objective in (10) is a nonlinear function of $\mathbf{X}$, i.e., $f(\mathbf{X}) = \sum_{j=1}^{M} \mathscr{U}_j(Q_m^j)$. Thus, the original problem (10) is a typical nonlinear integer programming problem [21]. Since the discussions in [21, 22, 23, 24] demonstrate that solving such problem is difficult, we try to derive its upper bound, instead of the optimal value of problem (10).

First, a linear discrete function $g_j(x_{ij})$ is derived such that $\mathscr{U}_j(Q_m^j) < g_j(x_{ij})$. In (16), let $a_{ij} = p_e + p_m^{i,j}(1 - 2p_e)$. By applying natural logarithm, $Q_m^j < \overline{Q_m}$ in (14) can be written as

$$\ln(\prod_{i=1}^{N} a_{ij}^{x_{ij}}) < \ln \overline{Q_m} \tag{17}$$

$$\Rightarrow \sum_{i=1}^{N} \ln(a_{ij}^{x_{ij}}) < \ln \overline{Q_m} \tag{18}$$

$$\Rightarrow \textstyle\sum_{i=1}^{N} b_{ij}x_{ij} < \ln \overline{Q_m} \tag{19}$$

DOI: 10.1002/wcm

where $b_{ij} = \ln a_{ij}$. Since $\ln \overline{Q_m} < 0$, (19) can be rewritten as $\frac{\sum_{i=1}^{N} b_{ij} x_{ij}}{\ln \overline{Q_m}} > 1$. Meanwhile, because of $\mathscr{U}_j(Q_m^j) \leq 1$,

$$\mathscr{U}_j(Q_m^j) < \frac{\sum_{i=1}^{N} b_{ij} x_{ij}}{\ln \overline{Q_m}}. \tag{20}$$

Defining $g_j(x_{ij})$ as

$$g_j(x_{ij}) = \frac{\sum_{i=1}^{N} b_{ij} x_{ij}}{\ln \overline{Q_m}}, \tag{21}$$

the problem (10) can be bounded by the following optimization problem

$$\max_{\mathscr{X}} \quad \sum_{j=1}^{M} g_j(x_{ij}) \tag{22}$$

$$s.t. \quad \sum_{i=1}^{N} b_{ij} x_{ij} < \ln \overline{Q_m}, j \in \{1, \cdots, M\} \tag{23}$$

$$\sum_{j=1}^{M} x_{ij} \leq K, i \in \{1, \cdots, N\} \tag{24}$$

$$\sum_{i=1}^{N} x_{ij} \leq L, j \in \{1, \cdots, M\} \tag{25}$$

$$x_{ij} \in \{0, 1\}$$

where constraint (23) results from (18).

Moreover, according to (10), one possible assignment for sensing channel j, i.e., $\{x_{ij}\}, i \in \{1, \cdots, N\}$, can contribute 1 at most to the objective function. Thus, the $\frac{b_{ij}}{\ln \overline{Q_m}}$ in (21) is unnecessary to be larger than 1. Defining

$$f_{ij} = \begin{cases} \frac{b_{ij}}{\ln \overline{Q_m}}, & \frac{b_{ij}}{\ln \overline{Q_m}} < 1 \\ 1, & \text{otherwise} \end{cases} \tag{26}$$

and combining constraints (23) and (25), problem (22) can be further relaxed as

$$\max_{\mathscr{X}} \quad \sum_{j=1}^{M}\sum_{i=1}^{N} f_{ij}x_{ij} \tag{27}$$

$$s.t. \quad \sum_{i=1}^{N}(b_{ij}+1)x_{ij} < \ln\overline{Q_m} + L, j \in \{1,\cdots,M\} \tag{28}$$

$$\sum_{j=1}^{M} x_{ij} \le K, i \in \{1,\cdots,N\} \tag{29}$$

$$x_{ij} \in \{0,1\}.$$

By defining CR as an "agent" and a "task" to assign PC for spectrum sensing, problem (27) defines a many-to-many assignment (MMAP) problem [17]. Constraint (28) indicates that each "agent" can contribute its capacity of $a_{ij}+1$ to achieve the capacity limitation of the "task", i.e, $\ln\overline{Q_m}+L$, and constraint (29) denotes that each "agent" can be assigned to K "task" at most. Thus, in the defined MMAP problem, both "agent" and "task" have capacity limitation so that each "task" can be assigned to a limited number of agents, and each "agent" can contribute partial capacity to execute one task. In this paper, the method shown in [17] is adopted to solve the problem (27).

Since no algorithms with polynomial complexity exists for deriving the optimal solution of (10) due to its NP-hardness, new algorithms with low computational complexity should be proposed for the practical implementation.

4. CENTRALIZED CHANNEL ASSIGNMENT SCHEMES

In this section, the channel assignment is considered in the centralized setup where a central fusion center, e.g. SBS, exists. A heuristic scheme is proposed first based on full SNR information from CRs. Then, a greedy scheme is developed to reduce the signaling overhead.

4.1. Heuristic channel assignment scheme

The development of the heuristic scheme is based on the following observations:

1) Since each CR can only sense limited number of channels, the coalitions with fewer CRs should be formed first so that more CRs can be left to sense other channels after each assignment. That is, the coalitions with smaller numbers of CRs should be assigned channel first.

2) When allocating channels among coalitions with same number of CRs, the channels with more candidate coalitions have large chance to be allocated. Accordingly, the channels with fewer candidates should be assigned first.

3) Different coalitions can sense different number of channels. Hence, the coalition which senses the minimum number of channels should be assigned first when a channel is to be allocated among multiple coalitions.

With the observations above, a heuristic scheme is proposed, as shown in **Algorithm 1**, by considering each CR reports SNRs of all PCs to SBS.

In **Algorithm 1**, a reference table is defined with the following data in each row:

- *CH_Seq*: PC's sequence number;
- *Max_Co*: the maximum number of candidate coalitions for PC *CH_Seq*;
- *Co_Seq*: the sequence number of the coalition which can be assigned to PC *CH_Seq*;
- *Max_CH*: the maximum number of channels which can be sensed by coalition *Co_Seq*;
- Q_m: the miss-detection probability if PC *CH_Seq* is sensed by coalition *Co_Seq*.

For example, the row with (2, 7, 3, 6, 0.05) indicates that among 7 candidate coalitions of channel 2, coalition 3 can sense 6 channels and Q_m is 0.05 if it is assigned to sense channel 2. In the core part of **Algorithm 1**, the coalition with one CR only is assigned channel first. For each loop, function FormRefTab, illustrated by **Function 1**, is used to form the reference table, and function AssgCH, as shown in **Function 2**, is implemented for channel assignment based on the generated reference table. Specifically, function FormRefTab defines three successive sorting processes: 1) sorting the channels by the ascending order of the maximum number of candidate coalitions (i.e., the value of *Max_Co*); 2) for each channel, sorting the candidate coalitions by the ascending order of the maximum number of channels which can be sensed by such coalition (i.e., the value of *Max_CH*); 3) sorting rows with the same values of *Max_Co* and *Max_CH* by the ascending order of Q_m to improve Q_m of the system. After that, function ASSGCH is implemented to assign the channel in the first row of the reference table to the coalition in the same row. Thus, such procedure ensures that the channel with the minimum number of candidate coalitions is allocated to a coalition sensing the minimum number of channels and with the smallest Q_m. To further understand this algorithm, an example is shown in Table I. In the table, three (i.e., coalitions 1, 2, and 3) and six candidate coalitions (i.e., coalitions 2, 3, 4, 5, 6, and 7) can be assigned to sense channels 3 and 5, respectively. Thus, according to the first sorting process, the rows for channel 3 are at the top of this table, i.e., channel 3 should be assigned to a coalition first. After that, since the candidate coalitions 1 and 2 have the smallest number of channels for sensing, the rows corresponding to these two coalitions for channel 3 are at the top of table, based on the second sorting process. Finally, by applying the third sorting process via Q_m, the first row indicates that channel 3 should be assigned to coalition 2 since such assignment provides the smallest Q_m. Accordingly, after applying **Function 2** to Table I, channel 3 is allocated to coalition 2. Moreover, the rows related to channel 3, i.e., rows 1-3, and the row corresponding to coalition 2, i.e., row 4, are deleted. Following similar assignment principle, the channel assignment continues from row 5 and the implementation of **Function 2** ends when no row is left.

The complexity of **Algorithm 1** is determined by the size of the reference table, which is reduced significantly with the algorithm continuing. The reason is that after each main loop, some channels have been assigned to some coalitions for sensing (i.e., the rows with those channels or coalitions are deleted from the table) and some CRs may have been allocated K channels (i.e., the rows with coalitions including those CRs are deleted from the table).

Algorithm 1 Heuristic channel assignment scheme

Initialization:

- Generate the matrix $\Pi = (\pi_{ij})_{N \times M}$ based on the reported SNRs on all PCs from each CR. Here, π_{ij} is the SNR of PCj measured by CRi;
- Generate the initial allocation matrix $\mathscr{X}$ where each element equals to 0.

Main loop:

for z (number of CRs in the coalition)$= 1 : Z_{max}$ **do**

  RefTab=FORMREFTAB(Π, $\mathscr{X}$, z, $\overline{Q_m}$, $\overline{Q_f}$)

  $\mathscr{X}$=ASSGCH(**RefTab**, $\mathscr{X}$)

end for

Output: $\mathscr{X}$

Function 1 Heuristic channel assignment scheme-FORMREFTAB

function FORMREFTAB(Π, $\mathscr{X}$, z, $\overline{Q_m}$, $\overline{Q_f}$)

1. Formulate all possible coalitions with z CRs by the rest CRs which are not assigned K channels and designate each of them a sequence number.
2. Generate a reference table **RefTab** by all possible combinations of the channels, *CH_Seq*s, and coalitions, *Co_Seq*s, which includes the following information in corresponding columns.

CH_Seq	*Max_Co*	*Co_Seq*	*Max_CH*	Q_m

   In each row, if the channel is assigned to the corresponding coalition, the constrains to Q_m and Q_f can be satisfied (i.e., $Q_m < \overline{Q_m}$, $Q_f < \overline{Q_f}$).
3. Sort **RefTab** through three following processes:
   - Sort rows by the ascending order of *Max_Co*;
   - For each channel, sort rows with the same *Max_Co* by the ascending order of *Max_CH*;
   - For the rows with the same values of *Max_Co* and *Max_CH*, sort them by the ascending order of Q_m.

  return RefTab

end function

Function 2 Heuristic channel assignment scheme-ASSGCH

function ASSGCH(**RefTab**, $\mathscr{X}$)

  while the number of rows in the reference table$\neq 0$ **do**

- The channel in the first row is assigned to the corresponding coalition and the corresponding element of $\mathscr{X}$ is set to 1;
- Delete the rows with the assigned channel or with the assigned coalition or with the coalitions including CRs assigned K channels.
- Update the number of rows.

  end while

  return $\mathscr{X}$

end function

Finally, after **Algorithm 1** is stopped running, the final assignment results are broadcast to all CRs by SBS.

Algorithm 2 The greedy channel assignment scheme (one round)

1: **Initialization:**
- $\mathcal{N}_g$ (the set of unassigned channels);
- $\{k_i^g\}, i = \{1, \cdots, N\}$ (the number of channels assigned to CRi)

2: **One round operation:**
- CRi reports $K - k_i^g$ SNRs corresponding to channels which have the highest SNR values among those in $\mathcal{N}_g$;
- SBS implements **Algorithm 1** based on the received information;
- SBS broadcasts the channel assignment result;
- For each CR, $\mathcal{N}_g$ and $\{k_i^g\}$ are updated to $\mathcal{N}_{g+1}$ and $\{k_i^{g+1}\}$, $i = \{1, \cdots, N\}$, respectively.

4.2. Greedy channel assignment scheme

The heuristic scheme introduces huge signaling overhead since each CR has to report SNRs over all PCs to SBS. However, considering each CR can sense K channels at most, the majority of reported SNRs are useless for the channel assignment. Thus, the overhead can be reduced through reporting SNRs of PCs selectively.

According to (1), (2), (3), and (4), the channels with large SNRs can be sensed with small Q_m and Q_f. Consequently, to improve sensing performance, each CR prefers to being assigned channels with large SNRs for sensing, which inspires us to propose a greedy scheme, as shown in **Algorithm 2**. In particular, at the beginning of one round implementation (e.g., round g), the set of unassigned channels is $\mathcal{N}_g$. Given CRi has been assigned k_i^g channels for sensing, it only reports $K - k_i^g$ SNRs corresponding to the channels with the highest SNR values among the unassigned ones. Note that since different CRs may have different SNRs for the same channel, the reported SNRs from different CRs may correspond to different channels. After that, SBS can implement **Algorithm 1** based on the received SNRs with fairly small size of the reference table. Through **Algorithm 2**, the number of SNRs reported by each CR is reduced round by round, and the CRs which are assigned K channels are excluded for further SNR reporting. Hence, the communication overhead is reduced significantly, which is verified by the simulation results in Section 6.

5. DISTRIBUTED CHANNEL ASSIGNMENT SCHEME

In this section, the scenario without SBS is considered so that the channel assignment has to be implemented distributively. Inspired by the coalitional game theory, a distributed channel assignment scheme is proposed to increase the number of *available channels*.

5.1. Multi-channel coalitional game

In [25], a coalitional game is described by two key elements: player set $\mathcal{N}$ and coalition function v which designates each coalition a real number (i.e., coalition value). Such game aims at formulating a coalition structure including multiple coalitions so that the summation of all coalition values is maximized. Accordingly, in our system, for channel j, the game can be played among all CRs with the coalition function $v_j(\mathcal{S})$, where $\mathcal{S}$ is a coalition (i.e., a set of CRs sensing channel j). Define $Q^j_{m,\mathcal{S}}$ and $Q^j_{f,\mathcal{S}}$ be the probabilities of miss-detection and false-alarm, respectively, which are achieved by CRs in coalition $\mathcal{S}$ over channel j. The optimization problem (10) indicates that channel j can be available if $Q^j_{m,\mathcal{S}}$ and $Q^j_{f,\mathcal{S}}$ are smaller than the corresponding constraints. Thus, in such coalitional game, maximizing the summation of $v_j(\mathcal{S})$ determines that $v_j(\mathcal{S})$ should be a decreasing function of $Q^j_{m,\mathcal{S}}$ and $Q^j_{f,\mathcal{S}}$. As an example, we define

$$v_j(\mathcal{S}) = 1 - C_m(Q^j_{m,\mathcal{S}}) - C_f(Q^j_{f,\mathcal{S}}) \tag{30}$$

where $C_m(Q^j_{m,\mathcal{S}})$ and $C_f(Q^j_{f,\mathcal{S}})$ are increasing functions of $Q^j_{m,\mathcal{S}}$ and $Q^j_{f,\mathcal{S}}$, respectively. The formations of both functions can be defined by considering the following two cases:

Case 1. $Q^j_{m,\mathcal{S}} < \overline{Q_m}$ and $Q^j_{f,\mathcal{S}} < \overline{Q_f}$

Eqn. (14) indicates that reducing $Q^j_{m,\mathcal{S}}$ and $Q^j_{f,\mathcal{S}}$ would not change the value of $\mathscr{U}_j(Q^j_m)$ if $Q^j_{m,\mathcal{S}} < \overline{Q_m}$ and $Q^j_{f,\mathcal{S}} < \overline{Q_f}$. However, the derived $Q^j_{m,\mathcal{S}}$ and $Q^j_{f,\mathcal{S}}$ may have indirect impact to our objective, i.e., maximizing the number of *available channels*. In particular, from (3) and (4), $Q^j_{f,\mathcal{S}}$ decreases with the reduction of the number CRs in $\mathcal{S}$, while $Q^j_{m,\mathcal{S}}$ is opposite. To achieve our objective, the coalition should include CRs as small as possible so that more

CRs are left to sense other channels. In this sense, reducing $Q^j_{f,\mathcal{S}}$ is more important than reducing $Q^j_{m,\mathcal{S}}$. Therefore, $C_f(Q^j_{f,\mathcal{S}})$ should dominate $C_m(Q^j_{m,\mathcal{S}})$, i.e.,

$$\min_{Q^j_{f,\mathcal{S}}<\overline{Q_f},\mathcal{S}\in\Xi_j} C_f(Q^j_{f,\mathcal{S}}) > \max_{Q^j_{m,\mathcal{S}}<\overline{Q_m},\mathcal{S}\in\Xi_j} C_m(Q^j_{m,\mathcal{S}}) \tag{31}$$

where Ξ_j denotes the set of coalitions over channel j. In other words, the impact of $Q^j_{m,\mathcal{S}}$ to $v_j(\mathcal{S})$ is considered only for the coalitions with the same $Q^j_{f,\mathcal{S}}$.

Case 2. $Q^j_{m,\mathcal{S}} \geq \overline{Q_f}$ or $Q^j_{f,\mathcal{S}} \geq \overline{Q_m}$

This case is not desirable for our objective. Thus, $C_m(Q^j_{m,\mathcal{S}})$ and $C_f(Q^j_{f,\mathcal{S}})$ should tend to infinity.

By jointly considering both cases, a logarithmic barrier penalty function is a good choice to define $C_m(Q^j_{m,\mathcal{S}})$ and $C_f(Q^j_{f,\mathcal{S}})$, i.e.,

$$C_m(Q^j_{m,\mathcal{S}}) = \begin{cases} -(\overline{Q_m})^\beta \log(1-(\frac{Q^j_{m,\mathcal{S}}}{\overline{Q_m}})^\beta), & Q^j_{m,\mathcal{S}} < \overline{Q_m} \\ +\infty, & \text{otherwise.} \end{cases} \tag{32}$$

$$C_f(Q^j_{f,\mathcal{S}}) = \begin{cases} -\log(1-\frac{Q^j_{f,\mathcal{S}}}{\overline{Q_f}}), & Q^j_{f,\mathcal{S}} < \overline{Q_f} \\ +\infty, & \text{otherwise.} \end{cases} \tag{33}$$

where β is a coefficient guaranteeing (31).

According to (4), $Q^j_{f,\mathcal{S}}$ increases with the number of CRs in $\mathcal{S}$. Hence, $\min C_f(Q^j_{f,\mathcal{S}})$ is determined by the false-alarm probability of a single CR, i.e., $C_f(p^{i,j}_f)$. Then, we have

$$\min_{Q^j_{f,\mathcal{S}}<\overline{Q_f},\mathcal{S}\in\Xi_j} C_f(Q^j_{f,\mathcal{S}}) = \min_{i\in\{1,\cdots,N\},p^{i,j}_f<\overline{Q_f}} C_f(p^{i,j}_f). \tag{34}$$

For the right-hand side of (31), although it requires to derive all possible coalitions over channel j, $\min_{Q^j_{f,\mathcal{S}}<\overline{Q_f},\mathcal{S}\in\Xi_j} C_f(Q^j_{f,\mathcal{S}}) \gg C_m(Q^j_{m,\mathcal{S}})$ can be guaranteed in most cases by setting $\beta \geq 2$.

In coalitional game, two coalition structures with different collections of coalitions, e.g., $\mathcal{T}=\{\mathcal{T}_1,\cdots,\mathcal{T}_s\}$ and $\mathcal{R}=\{\mathcal{R}_1,\cdots,\mathcal{R}_t\}$, can be compared based on a *comparison relation* $\triangleright$. Here, $\mathcal{T}$ and $\mathcal{R}$ are formed by the same set of players, i.e., $\bigcup_{a=1}^s \mathcal{T}_a$=$\bigcup_{b=1}^t \mathcal{R}_b$, where $\mathcal{T}_a$ or $\mathcal{R}_b$ is one coalition. In this paper, the *Pareto order* is applied as the *comparison relation*, and the detailed definition can be referred to [25].

Till now, a N-player coalitional game is formed over channel j. Similarly, in the multi-channel system, the same game can be played over each channel. However, N players over each channel results in huge interaction overhead. Actually, since the number of channels sensed by each CR is limited to K, each CR is unnecessary to join the game over each channel. Considering the sensing performance is determined by the SNR value, each CR can select the first K channels with the highest SNRs to play the coalitional game so that the number of players on each channel is reduced. Through this method, CRs selecting the same channel can play the game according to the merge-and-split rule [26] till each player has no incentive to leave its coalition, i.e., the formed coalition structure is $\mathbb{D}_{hp}$-stable [18]. After that, multiple coalitions are formed over each channel. However, to maximize the number of *available channels*, it is enough to assign each channel to one coalition for sensing. In this sense, such coalition should be the one with the highest coalition value among all coalitions in the structure since it involves the fewest CRs to achieve the best sensing performance. To find this coalition for each channel, the coalition heads of all coalitions in the final structure can interact with each other after the game, and the details will be described later.

5.2. Distributed scheme

One round implementation of the multi-channel coalitional game results in that some CRs are assigned some channels for sensing. Thus, to achieve the objective in (10), such game should be played round by round till each CR is assigned K channels for sensing or no channel can be assigned. In this paper, such multi-round operation is called distributed channel assignment scheme, and one round implementation is summarized in **Algorithm 3**. An example with 6 CRs and 8 channels is shown in Tables II and III. In Table II, each column represents the channels sorted by the descending order of the SNRs measured at the

Algorithm 3 Distributed channel assignment scheme (one round)

1: **Initialization** (the beginning of round g operation)**:**
- $\mathcal{G}_g$ (The set of unassigned channels);
- $\{k_i^g\}, i = \{1, \cdots, N\}$ (The number of channels assigned to CRi)

2: **One round operation:**
- Step 1: CRi chooses $K - k_i^g$ channels with the highest SNRs among those in $\mathcal{G}_g$;
- Step 2: The multi-channel coalitional game is played following merge-and-split rule among CRs selecting the same channel;
- Step 3: Each selected channel is assigned to the coalition with the highest value in the formed coalition structure on it;
- Step 4: Update $\mathcal{G}_g$ and $\{k_i^g\}$ to $\mathcal{G}_{g+1}$ and $\{k_i^{g+1}\}$, $i = \{1, \cdots, N\}$, respectively.

corresponding CR. For example, CR 1 has the highest SNR on channel 3 and the lowest SNR on channel 5. The procedure of applying **Algorithm 3** is as follows.

- Initially, the set of unassigned channels in the first round, i.e., $\mathcal{G}_1$, is $\{1, 2, \cdots, 8\}$, and the number of channels assigned to each CR is 0, i.e., $k_i^1 = 0, i = \{1, \cdots, 6\}$.
- Considering each CR can sense 3 channels at most, i.e., $K = 3$, in Step 1 of the first round, the channels selected by each CR are listed on rows 2 to 4 in Table II.
- After that, in Step 2, the CRs selecting the same channel plays the coalitional game through merge-and-split rule. As shown in Table III, the second and third columns represent the CRs selecting the channel in the first column and the coalitions formed by merge-and-split rule, respectively. For instance, on channel 1, 5 CRs play the coalitional game and two coalitions, i.e., (CR1, CR6) and (CR2, CR4, CR5), are formed with different coalition values.
- According to Step 3, each channel is assigned to the coalition with the highest value, which is highlighted by boldface in the third column of Table III, e.g., channel 1 is assigned to coalition (CR1, CR6) for sensing.
- After step 3, channels 7 and 8 are left for the assignment in the next round, i.e, $\mathcal{G}_2 = \{7, 8\}$, and certain number of channels are assigned to each CR for sensing, e.g., CR1 is assigned channels 1 and 2 (i.e., $k_1^2 = 2$) and it can be assigned one more channel for sensing in the next round.

Furthermore, **Algorithm 3** indicates three requirements: 1) $\mathcal{G}_g$ should be known to each CR at the beginning of each round; 2) one coalition should be selected among all coalitions formed over one selected channel; 3) each CR should know the end of one round operation to start the next round. To meet all these requirements, the interaction among CRs is needed. However, from perspective of reducing the signaling overhead, such interaction can be performed among coalition heads only. It is because each coalition head can gather information from all CRs in the coalitions, which includes

- the assigned channels which are used to derive $\mathcal{G}_g$;
- the coalition value which are used for coalition selection;
- whether CRs in the coalition have incentive to leave such coalition or not, which is used for determining the end of one round operation;

The information above can be exchanged through the multi-hop network formed by the coalition heads. Since the detailed procedure is out of scope of this paper and several efficient methods for multi-hop communication have been proposed in the previous studies, such as [27], we omit it here.

6. SIMULATION RESULTS

In this section, the simulation is carried out for a multi-channel cognitive radio network consisting of 50 PUs (each PU uses one channel) and 6 CRs in a 2Km×2Km square area. The parameters for calculations in (1) and (2) are $P_{PU} = 0.05\text{W}$, $N_0 = -90\text{dBm}$, $\alpha = 3$, $\tau = 5$, $p_f = 0.01$. Other parameters are set as $p_e = 0.01$, $\overline{Q_m} = 0.05$, $\overline{Q_f} = 0.1$ and $\beta = 2$. Each CR can sense 6 channels at most, i.e., $K = 6$. Each simulation result is derived by averaging over 200 samples. In the following, the proposed heuristic channel assignment scheme in subsection 4.1 and the distributed scheme in subsection 5.2 are compared with the upper bound in (27) first. After that, the simulation results for centralized and distributed scenarios are presented separately.

DOI: 10.1002/wcm
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6.1. Centralized schemes vs. distributed scheme

In this subsection, a unified scenario is used to fairly compare three schemes. A SBS with coverage radius of 1Km is located at the center of the square area. PUs and CRs are randomly distributed in the square area and SBS's coverage area, respectively. The upper bound indicated by (27) is derived by CPLEX using A Mathematical Programming Language (AMPL) codes [28]. Fig. 1 illustrates the comparison results among two centralized schemes (i.e., heuristic scheme and greedy scheme) and the distributed scheme. The x-axis and y-axis represents K and the ratio of the average number of the *available channels* to the upper bound, respectively. In the figure, three curves decrease with the increase of K. It is because the deviation from the upper bound to the optimal value of (10) increases with the increment of K. Specifically, in (27), the constraint (28) relaxes $Q_m^j < \overline{Q_m}$ (or constraint (23)) so that $\sum_{i=1}^{N} f_{ij}x_{ij}$ may be larger than 1, while $\mathscr{U}_j(Q_m^j)$ in the original problem (10) can be 1 at most. Moreover, the number of assignments resulting in such case increases when K becomes large. Nevertheless, Fig. 1 shows that the ratio achieved by the heuristic scheme is larger than 0.95. Since the optimal number of the *available channels* is larger than that achieved by the heuristic scheme and smaller than the upper bound, we can conclude that the upper bound derived in this paper is close to the optimal value and the average number of the *available channels* through the heuristic scheme are close to the optimal value. In addition, it is observed that both greedy scheme and distributed scheme are less optimal than the heuristical one because these two schemes can not utilize all the information (i.e., SNRs for all PCs) to form coalitions. Moreover, the number of *available channels* derived by the distributed scheme is larger than that obtained by the greedy one. It is due to the fact that the former can achieve better sensing performance (i.e., smaller probabilities of miss-detection and false alarm) than the latter. Specifically, in distributed scheme, the sensing result reporting, impacted by p_e, is not applied to the coalition head. However, in greedy scheme, each CR in the coalition has to report the sensing result to the SBS. Thus, for the coalition with same set of CRs, equations (3) to (6) indicate that the distributed scheme can achieve smaller Q_m and Q_f than the greedy one.

6.2. Centralized scenario

In the simulation, the unified scenario defined in subsection 6.1 is reused. Fig. 2 illustrates the average number of SNRs reported by each CR in greedy channel assignment scheme. It is observed that such number is much smaller than that in the heuristic scheme, which is the number of PCs. Although Fig. 1 indicates that the heuristic scheme obtains more *available channels* than the greedy one, the significant reduction of communication overhead demonstrates that the greedy one outperforms the heuristic one by considering the performance and overhead jointly. In this sense, the following discussions are focused on the greedy scheme.

Firstly, the greedy channel assignment scheme is further compared with the traditional scheme [29], where the first K channels with the highest SNRs are selected by each CR for CSS. Fig. 3 gives the average numbers of *available channels* achieved by both schemes. In the figure, the greedy scheme outperforms the traditional one, and the achieved gain increases with K.

Secondly, the sensing performance of the greedy channel assignment scheme is studied in terms of the average $Q_f^{I,j}$ and $Q_m^{I,j}$, denoted as average Q_f and Q_m, respectively. Fig. 4 presents average Q_f vs. K. According to this figure, the greedy scheme significantly decreases the average Q_f compared to that in the traditional scheme. The average Q_m vs. K is shown in Fig. 5. It is seen that the greedy scheme derives larger average Q_m than the traditional scheme. The reason is that in the proposed scheme, the coalition can be formed as long as the Q_m^j satisfies the corresponding constraint $\overline{Q_m}$. However, in the traditional scheme, the channels selected by each CR are always those with the highest SNR, which results in more CRs sensing one channel, i.e., smaller Q_m^j.

Thirdly, the greedy channel assignment scheme is studied with respect to α in Fig. 6. In the figure, α is set to 2.5 and 3, respectively, with $P_e = 0.01$. Two curves indicate that the number of *available channels* decreases with the increment of α significantly. It is due to that the large α causes more signal attenuation, which results in more number of CRs to sense one channel.

6.3. Distributed scenario

In the distributed scenario, since SBS is not required, all PUs and CRs are distributed randomly in the square area. The traditional scheme used in centralized scenario is the comparison benchmark. Moreover, in each formed coalition, one CR is selected as coalition head. Fig. 7 presents the average number of *available channels* via K. In the figure, the proposed scheme can greatly increase the number of *available channels*. The reason is that the proposed scheme assigns the channel to the best coalition for sensing and CRs in different coalitions sense different channels. However, in the traditional scheme, a channel is sensed by all CRs selecting it even the required sensing performance can be achieved through less number of CRs. In addition, Fig. 7 indicates that the curve slope of the proposed scheme decreases with the increment of K. It can be explained that with large K, the **Algorithm 3** may be implemented with more rounds than the case for small K. Thus, the SNRs of the remaining unassigned channels become worse after each round, which results in that the the number of CRs sensing one channel increases and the number of assigned channels decreases.

7. CONCLUSIONS

In this paper, channel assignment schemes for spectrum sensing have been discussed in multi-channel cognitive radio networks. In the beginning, a nonlinear integer programming problem is formulated and then the performance upper bound is derived by approximation. After that, new centralized and distributed channel assignment schemes have been proposed.

The centralized schemes consist of two implementation options with different signalling overhead, while the proposed distributed scheme solves the multiple channel assignment problem based on coalitional game theory. The simulation results demonstrate that the proposed schemes increase the number of *available channels* significantly compared to the counterparts, and reach near optimal performance.

ACKNOWLEDGEMENTS

This work is supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada IRC, Discovery Grants and the Opening Project (2011KF08) of Key Laboratory of Cognitive Radio and Information Processing (Guilin University of Electronic Technology), Ministry of Education.

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Table I. An example of heuristic channel assignment scheme

CH_Seq	*Max_Co*	*Co_Seq*	*Max_CH*	Q_m
3	3	2	2	0.01
3	3	1	2	0.02
3	3	3	3	0.01
5	6	2	2	0.02
5	6	3	3	0.01
5	6	5	4	0.02
5	6	4	4	0.01
5	6	7	4	0.02
5	6	6	5	0.01
...	...	...	...	...

Table II. Channels sorted by SNRs over each CR

CR1	CR2	CR3	CR4	CR5	CR6
3	1	4	4	5	1
1	6	3	1	1	3
2	5	5	2	3	6
7	8	6	3	2	7
6	5	1	6	8	5
5	4	4	7	6	6

Table III. Multi-channel coalitional game

Channel	CRs playing coalitional game	Coalitions
1	CR1&CR2&CR4&CR5&CR6	**(CR1&CR6)**,(CR2&CR4&CR5)
2	CR1&CR4	**(CR1&CR4)**
3	CR1&CR3&CR5&CR6	(CR1&CR6), **(CR3&CR5)**
4	CR3&CR4	**(CR3&CR4)**
5	CR2&CR3&CR5	**(CR2&CR3&CR5)**
6	CR2&CR6	**(CR2&CR6)**

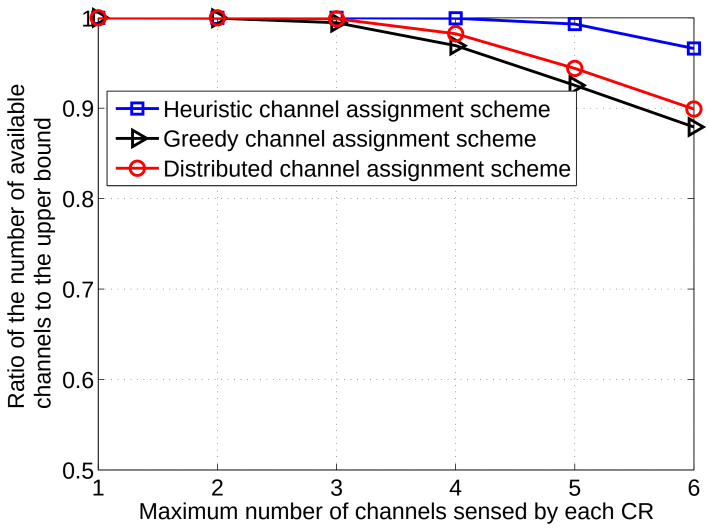

Figure 1. Heuristic channel assignment scheme vs. distributed channel assignment scheme.

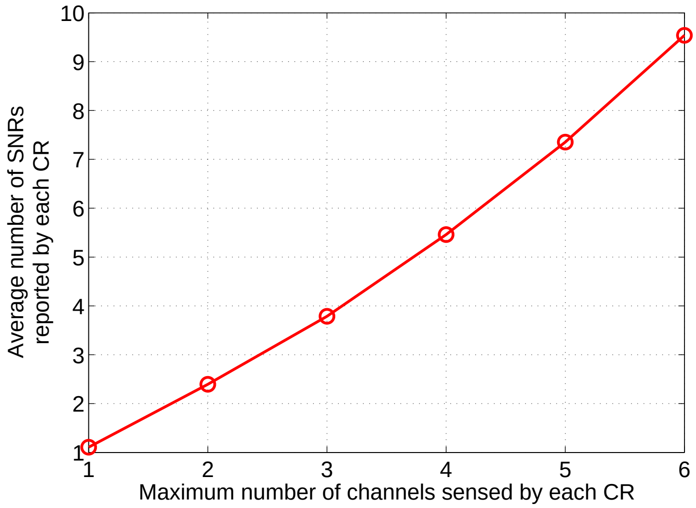

Figure 2. Average number of SNRs reported by each CR.

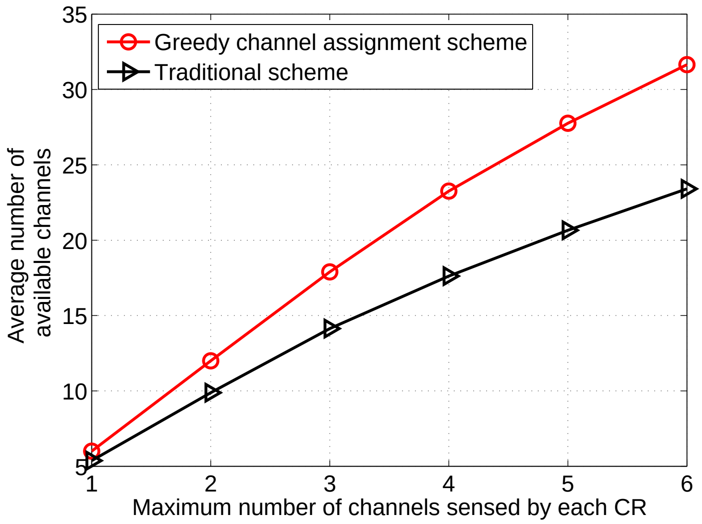

Figure 3. Average number of available channels for centralized scenario.

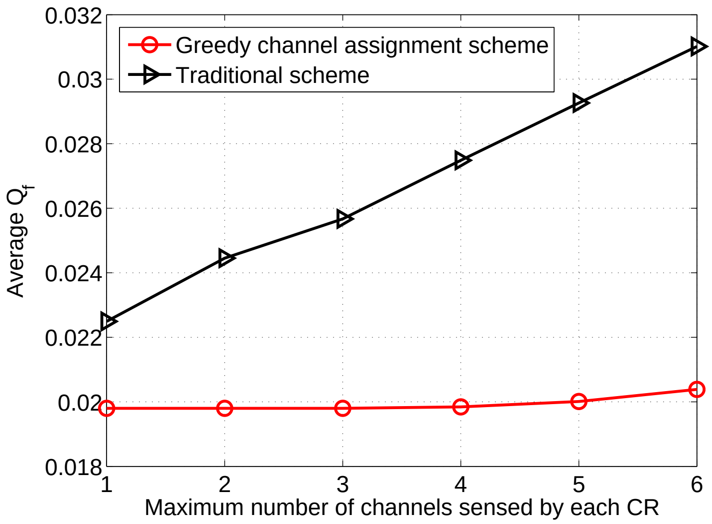

Figure 4. The average Q_f of the greedy channel assignment scheme.

Wirel. Commun. Mob. Comput. 201X; **00**:2–26
DOI: 10.1002/wcm
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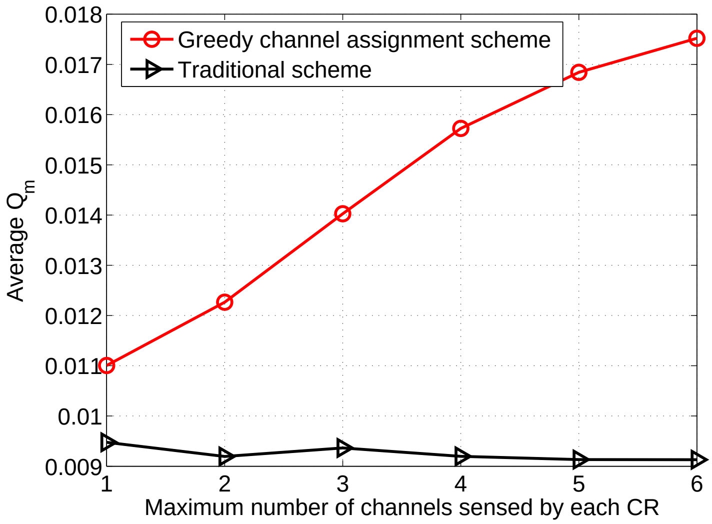

Figure 5. The average Q_m of the greedy channel assignment scheme.

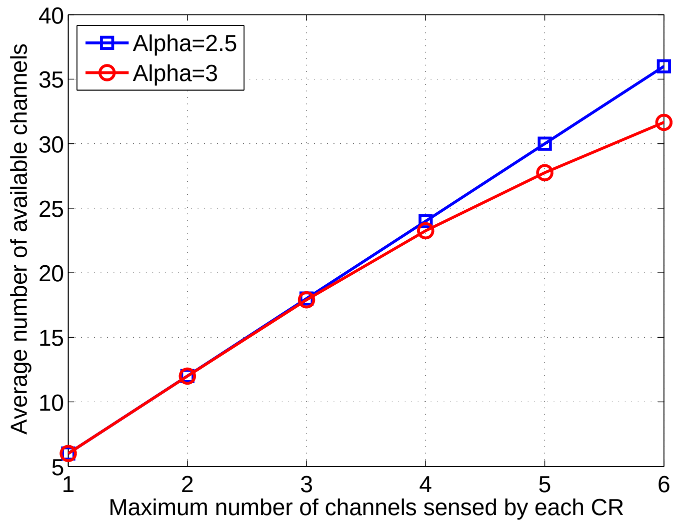

Figure 6. The performance of greedy channel assignment scheme via α.

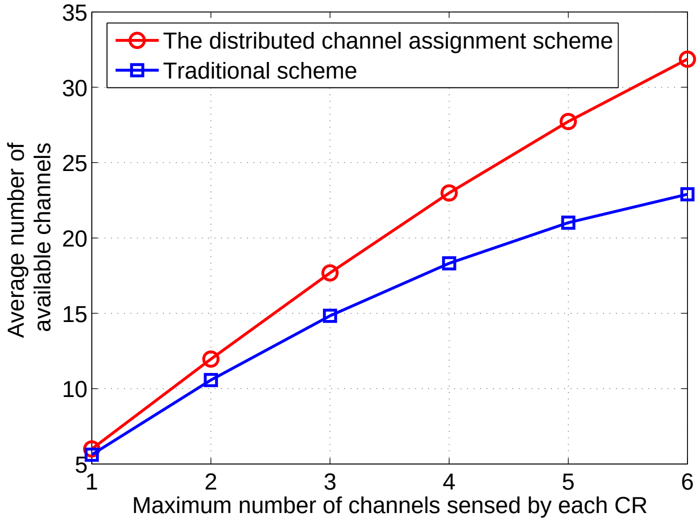

Figure 7. Average number of available channels for distributed scenario.