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Game-Theoretic Optimization of Common Control Channel Establishment for Spectrum Efficiency in Cognitive Small Cell Network

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Abstract

Cognitive small cell networks, consisting of macro-cells and small cells, are foreseen as a promising candidate solution to address 5G spectrum scarcity. Recently, many technological issues (such as spectrum sensing, spectrum sharing) related to cognitive small cell networks have been studied, but the common control channel (CCC) establishment problem has been ignored. CCC is an indispensable medium for control message exchange that could have a huge significant on transmitter-receiver handshake, channel access negotiation, topology change, and routing information updates, etc. Therefore, establishing CCC in cognitive small cell networks is a challenging problem. In this paper, we propose a potential game theory-based approach for CCC establishment in cognitive radio networks. We design a utility function and demonstrate that it is an exact potential game with a pure Nash equilibrium. To maintain the common control channel list (CCL), we develop a CCC update algorithm. The simulation results demonstrate that the proposed approach has good convergence. On the other hand, it exhibits good delay and overhead of all networks.

Keywords: *Cognitive small cell networks, Common control channel, potential game theory, Nash equilibrium*

1 Introduction

In recent years, the substantial increase in data traffic, the proliferation of devices, and the widespread adoption of 5G wireless communication networks have posed significant challenges for the allocation of spectrum resources [1]. Regrettably, certain spectrum bands experience congestion, while others remain underutilized. In the conventional static spectrum allocation approach, assigning spectrum to specific users or applications leads to increasing inefficiency, primarily due to the limited availability of spectrum resources.

In an attempt to address this challenge, cognitive radio technology was proposed. It is defined as a smart radio capable of sensing the environment, learning from historical information, make intelligent decisions, and adjusting is operational parameters [2]. These functionalities are generally achieved by two types of users: licensed spectrum users (referred to primary users or PUs) and unlicensed users (commonly known as cognitive radio users or secondary users, SUs). SUs can opportunistically access the spectrum when the licensed

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spectrum is unoccupied by PUS.

Cognitive small cell networks (CSCs) have acknowledged that activating cognitive capabilities in small cells [3] not only improves the energy efficiency of the small cell tier but also addresses the issue of spectrum underutilization in heterogeneous small cells [4]. Recently, numerous technological issues related to CSCs have been explored, encompassing spectrum sensing [5,6], spectrum allocation [7], and spectrum sharing [8]. CSCs can be viewed as a cooperative cognitive radio networks, with two distinct networks operating simultaneously. Coordinating dynamic spectrum access effectively requires a substantial amount of control messaging for coordination, cooperation, and collaboration among elements. The optimization of control messaging is attainable by selecting an appropriate Common Control Channel (CCC). The choice of CCC significantly influences the performance of spectrum sensing, spectrum sharing, and spectrum allocation, particularly in spectrum sharing, as all decisions and actions related to spectrum sharing are distributed through CCC. In other words, SUs can exchange fundamental control messages, including local sensing results, channel selection messages, data channel setup messages, spectrum handover messages, etc., through CCC. Within this context, the establishment of the CCC is a crucial issue.

The strategy for selecting the CCC differs from the approach used for channel selection in data transmission. In this paper, leveraging the inherent features of CR, we employ game theory [9] to establish the CCC. Game-theoretic approaches have found application in various wireless communication technologies, including cognitive radios. A game proposing a minimum connected weighted inner edge spanning tree (MWIEST) is introduced in [10]. In [11], the authors proposed a game theory-based approach for jointly optimizing the energy efficiency of resources in Cognitive Radio Networks (CRN). In [12], a spectrum sensing structure based on game theory is designed for energy-harvesting hybrid CRN to address complications, including finite sensing duration and interferences. In this paper, to establish the CCC with a game converging to a Nash equilibrium (NE), we employ the theory of potential games. Our contributions are summarized as follows:

1) We employ a potential game model to establish CCC for CSCs across multiple channels. We design a utility function that accounts for the impact of interference on CCC establishment. Furthermore, we demonstrate that a game incorporating this utility function qualifies as a potential game

2) We introduce the concepts of CCC delay and broadcasting. Additionally, we employ these concepts to access the performance of the proposed approach in terms of both delay and overload.

The rest of this paper is organized as follows: Section 2 delineates the system model and related assumption. Subsequently, Section 3 outlies the design of the common control channel establishment games, confirming its classification as a potential game. Section 3 also includes the implementation details of the algorithm. Section 4 presents the simulation results. Finally, our work is concluded in Section 5.

2 System Model and Assumption

The system model addresses two-tier cellular networks comprising macro cells with macro base station (MBSs) and small cells with small cell base station (SBSs), potentially including femto BSs, pico BSs, or micro BSs, as illustrated in Figure1. (a). Macro-cells are constructed using lower and licensed bands to provide broader network coverage. SBSs are equipped with cognitive radio (CR) technology to identify licensed users in macro-cells and opportunistically utilize licensed bands when PUs are absent. Specifically, the SU determines available spectrum portions, detects PUs in licensed bands, selects the optimal channel, coordinates access with other SUs, and vacates the channel upon PU detection. To ensure shared communication of basic control messages among SUs, we presume the selection of an available channel with highest quality as the

CCC.

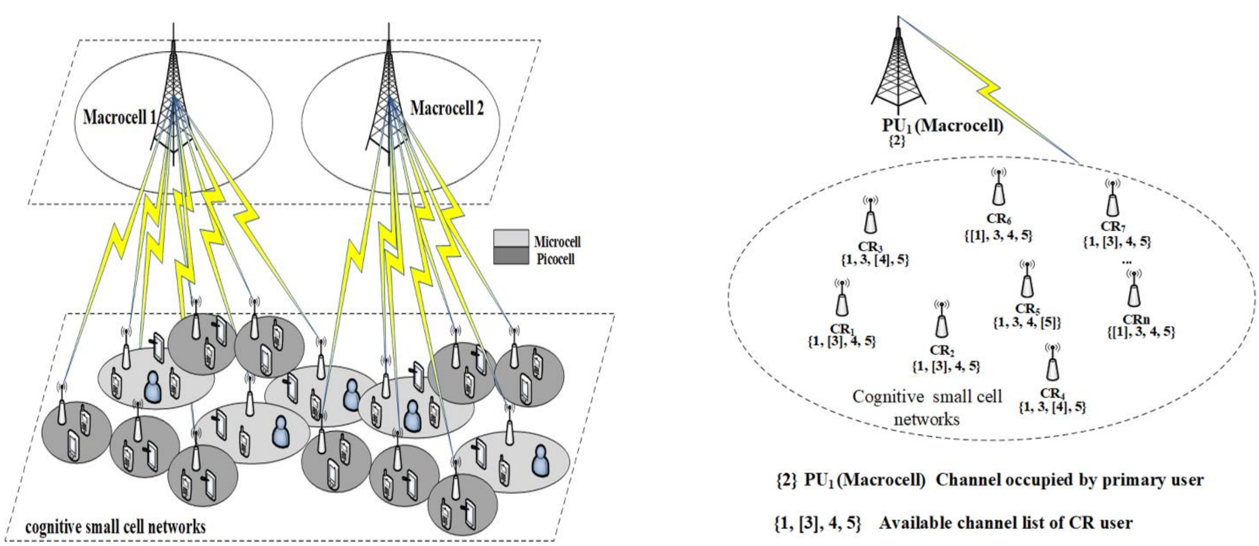
We assume a two-tier system where N SBSs and M MBSs share $C = \{1,2,...,c\}$channels. Additionally, there are α channels are occupied by PUs. Consequently, the allocated channels for SBSs are $K = \{1,2,...,k\} = (C - \alpha)$, satisfying the condition $K < N$. Each SU maintains an available channel list (ACL), as shown in Figure1. (b), with channel ID in square bracket indicating CCC selection.

Recognizing the significance of CCC, we propose selecting the channel with the least interference to PUs to serve as CCC. In general, the channel quality can be characterized by Signal-to-interference-ratio (SIR). In this paper, we address not only interference among SUs but also interference to PUs.

3 CCC Establishment Algorithm

3.1 Rethink Common Control Channel

In CSCs, a CCC can be allocated to either licensed or unlicensed band, with the allocation being temporary or permanent. As referred in [13], a CCC is channel allocated in portion of spectrum $[f_1, f_2]$ with channel bandwidth $b \in (f_2 - f_1)$ (3KHz $\leq f_1 < f_2 \leq 300G$Hz) during the time period$[t_1, t_2]$ $(0 < t_1 < t_2 < \infty)$. Consequently, a CCC within CR small cells may not always be unique and available; instead, it can be allocated to either licensed or unlicensed bands. Therefore, we focus on dynamically allocated CCCs in either licensed or unlicensed bands.



(a) System Model **(b)The available channel lists of SU**

Figure 1. Network architecture and channel states

3.2 Common Control Channel Establishment Game

3.2.1 A Game Theoretic Formulation. In our system model, each SBS is considered as a player of the game, and we model the interactions among them as a cooperative Common Control Channel Establishment Game (CCCEG), which can be mathematically defined as $\Gamma := (N, (S_i)_{i \in N}, (U_i)_{i \in N})$. Na finite set of players. S_i is the set of strategies associated with player i. Formally, the strategy of $i$thplayer is $S_i = \{c_{i,1}, \ldots, c_{i,k}, \ldots c_{i,|k|}\}$, where $|k|$is the number of available channels, and $c_{i,k}$ is a binary value. If channel k is assigned to one of the players, $c_{i,k}$ is set to one. Otherwise, $c_{i,k}$ is set to zero. $S_{-i} = \{S_1, S_2, \ldots S_{i-1}, S_{i+1}, \ldots, S_N\}$ is specially defined as the strategy set chosen by all other players except player i for this model, steady-state conditions known as Nash equilibria (NE) are identified, where no player would rationally choose to deviate from their chosen action because the payoff of that condition is larger than they could achieve by deviating, i.e. $U_i(s^*) \geq U_i(s_i', s_{-i})(\forall s_i' \in s_i, \forall i \in N)$. That is, no player can benefit by deviating from its strategy if others do not change theirs. The CCC establishment algorithm reaching a stable state is the final goal of the game. However, due to the time-varying channel characteristics, ensuring the convergence of the CCC establishment algorithm is challenging in the general game model. Hence, to achieve CCCEG converging to a NE, we resort here to the theory of potential game. Potential games have useful properties and address the outcome efficiency issue and existence of NE [14]. Therefore, potential games have two inherent characteristics: 1) Every finite potential game possesses at least on pure strategy NE. 2) All NEs are either local or global maximizers of the utility function. For a potential game, there must be a potential function $\phi_i(s)(\forall s_i', s_i'' \in s_i)$ that is described as follows:

$$U_i(s_i', s_{-i}) - U_i(s_i'', s_{-i}) = \phi_i(s_i', s_{-i}) - \phi_i(s_i'', s_{-i}) \tag{1}$$

That is, the unilateral changes produced by the utility function of any game player can be accurately reflected by the potential function in the process.

3.2.2 Utility Function. In CCCEG, the utility function should characterize the preference of an SU for a channel. Considering that SUs are willing to cooperate to achieve a CCC, we impose that the utility function must account for both interferences perceived by the current SUs and the interference the SU is creating for neighboring SUs sharing the same channel. Given the importance of CCC, we propose that the channel with high quality (known as least interference) be selected as CCC. We introduce the Signal-to- interference- ratio (SIR) to characterize the channel quality. Hence, SIR measured at the receiver-jth SU associated with transmitter- $i$thSU can be expressed

$$SIR_{ij} = \frac{p_i(s_i)G_{ij}}{\sum_{j=1, j\neq i}^{N} p_j(s_j)G_{ij}(s_j, s_i) + \sigma^2} \tag{2}$$

$$\begin{cases} I(s_j, s_i) = 1, s_i = s_j \\ I(s_j, s_i) = 0, s_i \neq s_j \end{cases} \tag{3}$$

The formula (3) represents the interference function of ith SU considering its strategy. s_i and s_j are the CCC establishment strategies of SUs $i$and j. $p_i(s_i)$ and $p_j(s_j)$ denotes the transmission power of the $i$thSU and $i$thSU take strategy s_i and s_j, respectively. G_{ji} and G_{ij} represents the channel gain of receiver $j$and transmitter i. σ^2 denotes the receiver noise.

Considering that SUs are willing to cooperate to select a CCC with fairness, we impose that the utility function must account for interference perceived not only by the current SU but also by the particular user creating interference for neighboring users.

Therefore, the first utility function $U_i^1(s_i, s_{-i})$ can be expressed as:

$$U_i^1(s_{i,}s_{-i}) = -\sum_{j=1, j\neq i}^{N} p_j(s_j)G_{ij}I(s_j, s_i) - \sum_{j=1, j\neq i}^{N} p_i(s_i)G_{ji}I(s_i, s_j) \tag{4}$$

Additionally, we assume that the available channel with highest channel quality will be selected as CCC. Accordingly, we adopt the Signal-to-Interference-plus-Noise Radio (SINR) as a metric for assessing channel quality. Following Shannon's formulation, the capacity of the CCC is expressed by formula (5),

$$Q_i(s_i) = B * log_2\big(1 + SINR_i(s_i)\big) = B * log_2\big(1 + p_i(s_i) * \frac{G_i(s_i)}{(\sigma^2 + I(s_{i,} s_{-i})))}\tag{5}$$

Where $B$is bandwidth of channel, $G_i(s_i)$ is the channel gain: $I(s_{i,}s_{-i})$ is the accumulated interference introduced by other SUs expect i.

The expression for the second utility function is:

$$U_i^2(s_i, s_{-i}) = \sum_{j=1, j\neq 1}^{N} I\big(s_i = s_j\big)\, Q_i(s_i)\tag{6}$$

Therefore, the global utility function of the ith SU is expressed as:

$$U_i(s_i, s_{-i}) = \lambda U_i^2(s_i, s_{-i}) + \mu(1 - \lambda) U_i^1(s_i, s_{-i})\tag{7}$$

As illustrated in formula (5), the utility function contains two criteria. The initial criterion represents the shared interest of multiple players, where each SU aims to utilize a channel commonly available and of high quality to the other SUs as the control channel. The second criterion addresses system interference. Specifically, each SU seeks to use a channel with minimal interference from neighboring SUs. The parameter $\lambda \in [0,1]$ determines the relative weights of the two criteria in the utility function. $\mu$is a correction factor.

3.2.3 Potential Game Formulation and Equilibrium Convergence. A characteristic of a potential game is the existence of a potential function that exactly reflects any unilateral change in the utility function of any player. In any potential game where players take actions sequentially, convergence occurs towards a pure strategy Nash equilibrium, maximizing the potential function.

In the context of our previously formulated joint interference with a global utility function $U_i(s_i, s_{-i})$, a potential function is defined as follows:

$$\phi_i(S) = \phi(s_i, s_{-i}) = \phi_i(s_i', s_{-i}) - \phi_i(s_i'', s_{-i})\tag{8}$$

Assuming a play i changes its strategy from channel $k$to l, the formulation (8) can be expressed as follows:

$$U_i(l, s_{-i}) - U_i(k, s_{-i}) = \lambda\big(U_i^2(l, s_{-i}) - U_i^2(k, s_{-i})\big) + u(1 - \lambda)(U_i^1(l, s_{-i}) - U_i^1(k, s_{-i}))\tag{9}$$

In [15], the authors have established the validity of formula (8). In this context, our focus is solely on verifying the truth of formula (8). Furthermore, we only demonstrate the $U_i^2(s_i, s_{-i})$ that it also validates formula (1). Suppose there is a potential function of the game is defined as formula (6) as $U_i^2(s_i, s_{-i}) = \sum_{j=1, j\neq 1}^{N} I\big(s_i = s_j\big)\, Q_i(s_i)$, where all $i \in \{1,2, \dots, N\}$. The player i changes its strategy from $s_i = k$ to $s_i = l$, then $\phi_i(s_i, s_{-i}) = \phi_i(l, s_{-i}) - \phi_i(k, s_{-i}) = \sum_{j=1, j\neq i}^{N} \Big(I\big(s_j = l\big) - I\big(s_j = k\big)\big(Q_i(l) - Q_i(k)\big)\Big)$. According to formula, we can define a matrix $\mathbf{A}_{NXN}$ as the indictor matrix. If the indicator $I\big(s_i = s_j\big) = 1$ for i, j, the element $\mathbf{A}_{ij}$=1. When the strategy of player i is changed from $s_i = k$ to $s_i = l$, that means, the i th row and i th column of $\mathbf{A}$ change. Hence, the accumulated change in the i th row is $\sum_{j=1}^{i-1} \Big(I\big(l = s_j\big) - I\big(k = s_j\big)\Big)$, and the accumulated change in the ith column is $\sum_{w=i+1}^{N-1}\big(I(s_m = l) - I(s_m = k)\big)$. Therefore, $\phi_i(l, s_{-i}) - \phi_i(k, s_{-i}) = \sum_{j=1, j\neq i}^{N} \Big(I\big(s_j = l\big) - I\big(s_j = k\big)\big(Q_i(l) - Q_i(k)\big)\Big)$. In this context, we have

$$\phi_i(l, s_{-i}) - \phi(k, s_{-i}) = U_i(l, s_i) - U_i(k, s_{-i})\tag{10}$$

Hence, the game Γ is considered an exact potential game. In a potential game Γ, each player adjusting its strategy individually results in a proportional change in both its utility and the global potential function. Players update their strategies to maximize individual utility, while the potential function ultimately converges to a local maximum. At this moment, the potential game reaches a pure Nash equilibrium, a defining characteristic of potential games being the presence of a unique Nash equilibrium.

3.3 Algorithm Implementation

3.3.1 CCCEG Implementation. For each SU, it performs local spectrum sensing, determines available channels, and constructs an available channel list (ACL) [16]. Subsequently, the SU selects the channel with highest channel quality from (ACL) as CCC and encapsulates specific information (such as channel ID, channel quality) in a message named Hello Message. Afterward, the SU chooses the channel with the highest quality from (ACL) as CCC. The Hello Message is broadcast to one-hop neighboring SUs through CCC. Following a period Γ, SUs recalculate their utility using formula (7) and choose a channel with maximum utility as CCC. Additionally, SUs will re-encapsulate the Hello Message with updated information on the re-selected CCC and broadcast it in the next period $T+1$

The common control channel establishment algorithm for SU is presented as follows:

STEP 1: Initialization

For ith SU

1-1: Performs local spectrum sensing

1-2: Constructs its ACL_i according to $Q_i(s_i)$ monotonically decreasing order.

1-3: Selects a channel k with the highest $Q_i(k)$ from ACL_i, broadcast Hello message composed of $Q_i(k)$ on channel k

STEP 2: One period of game theory

2-1: During a broadcasting period T, $i$thSU receives all Hello messages and count t the number of Hello messages on c1hannels in ACL_i. That is, $\mathrm{counter}_k := \mathrm{counter}_k + 1$

2-2: The end of a broadcasting period T, ith SU calculates channel quality of each channel in ACL_i by utility function. A channel with the highest channel quality ($Q_i(k)$) is selected and broadcasted in the next period $T+1$.

STEP 3: Game End

3-1: After the specified iteration by the proposed algorithm, if all SUs receive Hello messages from the same channel, that channel can be considered as a CCC. Otherwise, the process returns to STEP 2. Regarding the algorithm described above, the primary focus lies in ACL update and utility function design. Detailed explanations of ACL update and utility function design will be provided in the following sections.

3.3.2 Available Channel List Update. In the aforementioned algorithm, it is imperative that the channel with the highest channel quality from the ACL be promptly assigned as the new common control channel when a PU occupies this channel. Consequently, ACL updates facilitate CCC recovery from PU activities.

Each SU constructs and maintains an ACL for periodic broadcast to its neighbors and dynamic CCC selection. Typically, the ACL is a list of channels commonly available to at least one neighbor. The order of the list is determined by channel quality $Q_i(k)$. All channels within the ACL are arranged in monotonically decreasing order based on $Q_i(k)$.

Each SU has the capability to update its ACL through periodic local spectrum sensing. In this scenario, the update is essential for two scenarios: 1) new PU- occupied channels should be removed from the ACL and 2) addition of newly sensed available channels into ACL. Apart from updating the ACL with local spectrum sensing information, SUs also update their ACLs upon receiving an ACL from a neighbor. Following the ACL update of a CR user with neighbor's ACL information, available channels shared with its neighbors persist in the ACL.

The pseudo code of a SU i's ACL_i update algorithm as follows

STEP1: ACL_i update with SU i's local spectrum sensing

1-1: SU $i$performs local spectrum sensing, initial $\mathrm{ACL}_i = 0$

If channel k is occupied by PU, then channel k removed from the ACL_i,

If channel k is a newly sensed available channel, then channel k is add to the ACL_i, and notify its neighbors.

1-2 Reorder ACL_i by monotonically decreasing order of $Q(k)(k \in \mathrm{ACL}_i)$

STEP 2: ACL_i update with neighbor j's ACL_j

2-1 If receiving a notification (ACL_j,) from neighbor j then

SU i generate a list of shared channels from $\mathrm{ACL}_i$and ACL_j

$$\mathrm{ACL}_i \leftarrow \mathrm{ACL}_i \cap \mathrm{ACL}_j$$

2-2 Reorder ACL_i with monotonically decreasing order of quality of channel $Q(k)(k \in \mathrm{ACL}_i)$

4 Simulation Results

In this section, simulation experiments are conduced to evaluate the performance of the CCCEG algorithm. The network configuration parameters are presented in Table 1

Table 1. Parameters Setting

Simulation area	300mx300m
The number of small cells	3
Maximum transmission power of $i$thSU	10W
SU transmission range	25m
The index of channel	1,2,3,4,5,6,7,8,9,10
Number of primary users	10
λ	0.5

4.1 Convergence of Utility Function j

Figure 2 illustrates the utility function for CCC establishment between SUs i and their neighbor using the proposed approach. The numerals on the x-axis and y-axis represent the available channels for SU i and j. Given that neighboring SUs typically experience homogeneous channel availability in cognitive small cell networks, each SU can independently compile a similar list of available channels. Consequently, SUs i and

j can collectively choose a channel with the highest channel quality as a CCC (as depicted by the points at the peak of the utility).

Figure 3 illustrates the convergence of the proposed method based on a potential game. As depicted in the figure, it is evident that the proposed method converges after 90 seconds. Specifically, a channel with the maximum channel quality is select as the CCC after this duration. The figure highlights the high convergence speed of the proposed method.

Figures 4 and 5 illustrate the establishment of CCC among 3 SUs with 4 and 10 available channels, respectively. In the case with 4 available channels, the proposed method converges after 8 iterations, as demonstrated in the figure. For the latter case, convergence is achieved after 10 iterations. Therefore, the proposed method exhibits strong convergence. In other words, CCC can be well-established by the proposed method.

4.2 Comparison

4.2.1 CCC Delay. We assume that SUs i transmit control information to a neighbor j on CCC l . The maximum achievable rate of the control information transmission is given by:

$$R_k^j = B \log\left(1 + \frac{P_i|G_{ij}|^2}{N_0 B + I_k^j}\right) \tag{11}$$

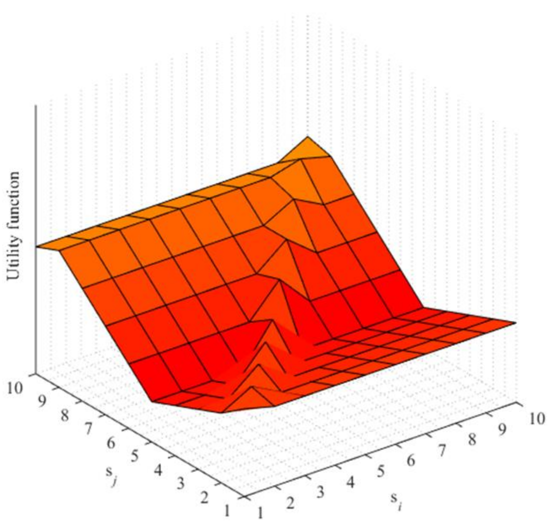


Figure 2. Utility function for CCC establishment

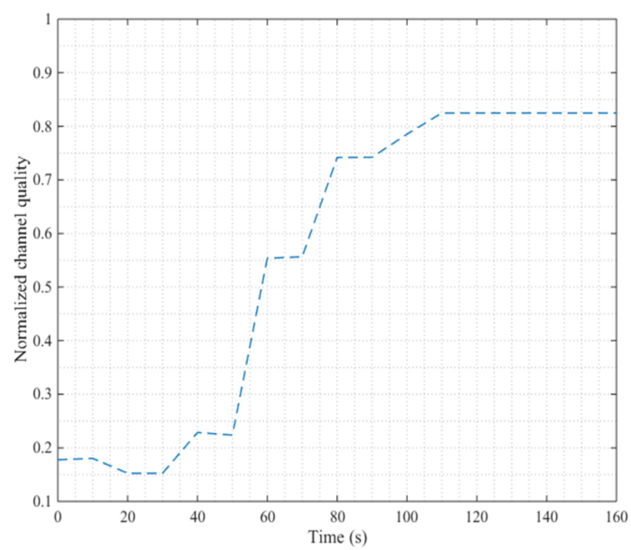


Figure 3. Convergence of proposed method

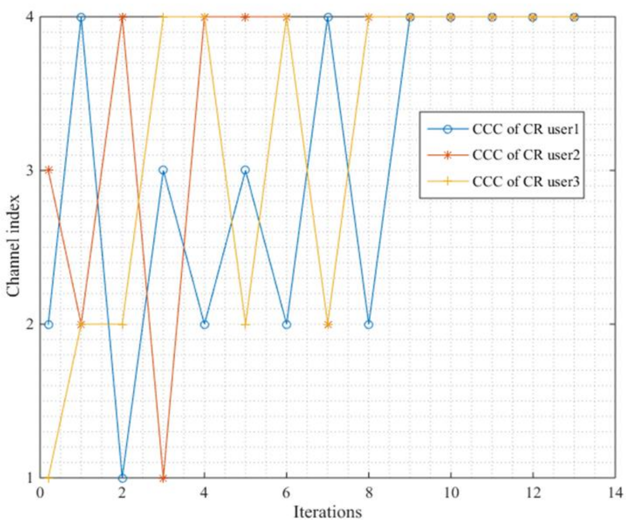


Figure 4. CCC is established (M=4, N=3)

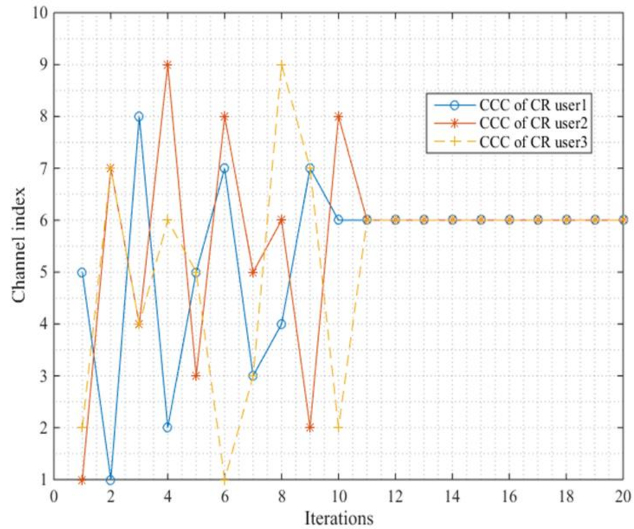


Figure 5. CCC is established (M=10, N=3)

Where B represents channel bandwidth, P_i is transmit power of SU i on CCC k, G_{ij} is the channel gain between SUs i and j, N_O is the power spectral density of additive white Gaussian noise, and I_k^j is the accumulated interference power of PU transmit signals observed by SU j on CCC l. If SUs i has N_j neighbors within its transmission range, all of N_j neighbors within its transmission range can turn CCC to channel k. Therefore, the maximum achievable throughput in SU i's transmission range can be expressed as $R_k = \min\{R_{k,j}^j = 1,2,\ldots,N_j\}$ since throughput is constrained by the rate of the weakest link (where the interference power I_i^j is the largest, and channel gain h_{ij} is the smallest). Additionally, we assume the control message is of length D bits, the transmission delay of CCC l is D/R_l. We denote the average control message transmission delay as E (CCC delay).

Figure 6 illustrates the comparison of the average control message transmission delay, denoted as E (CCC delay) between the proposed method and Group-based CCC method discussed in [17]. The figure demonstrates that the E values for both the proposed method and the Group-based CCC method increase as the size of the control packet increases. Notably, the E of the proposed method is less than the method referred in [17], attributed to its selection of the channel with the highest channel quality (specifically, the highest channel capacity) as CCC.

4.2.2 Overhead. The overhead of proposed method is predominantly influence by the broadcast of *Hello* message to neighbors for maintaining CCLs. Thus, the broadcast rate plays a pivotal role in determining the associated overhead of the proposed method. Conversely, the CCL update and broadcast depend on PU activities and the broadcast rate of neighbors. Assuming that the SU i has N_j neighbors, where neighbor $j(j = 1,2,..,N_j)$ broadcasts its CCL with the rate r_j. We define a broadcast rate r_{br} as the percentage of HELLO message broadcasted over all received messages of its CCL with the rate r_j. This broadcast rate r_{br} is expressed as the percentage of HELLO message broadcasted over all received message at SUs, as follows:

$$r_{br} = \frac{N_{Hel}}{N_{tot}} \tag{12}$$

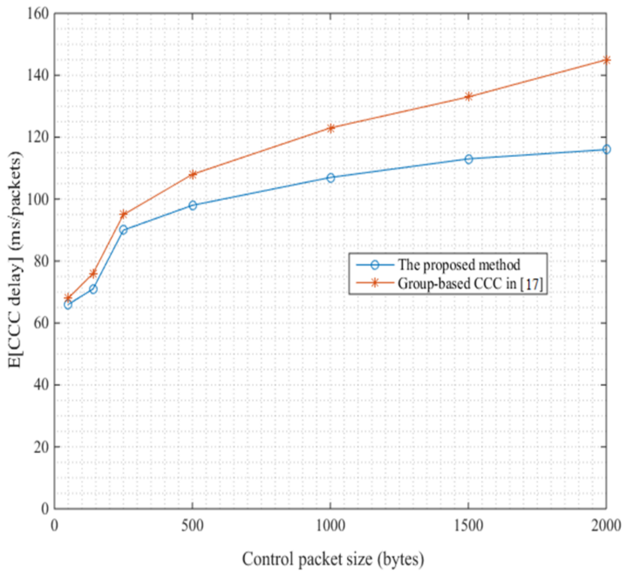


Figure 6. Comparison of CCC delay

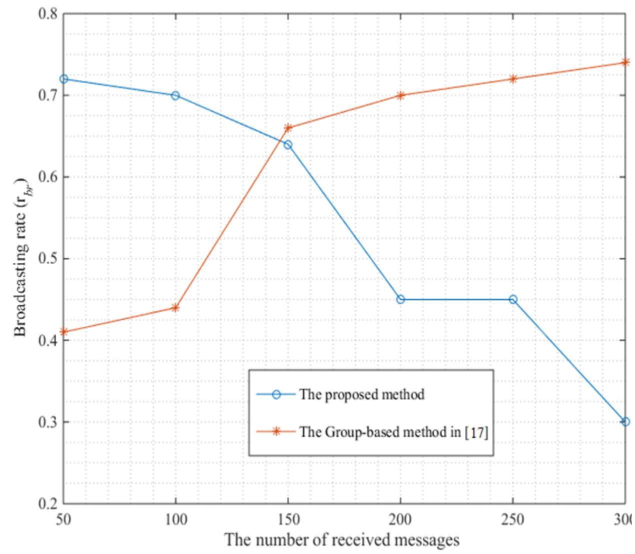


Figure 7. Comparison of broadcasting rate

Here, N_{Hel} represents the number of currently sent HELLO message by SUs, and N_{tot} is the total number of received message at CR user.

Figure 7 illustrates the comparison of broadcasting rate between our proposed method and the Group-based method described in [17]. The broadcasting rate of our proposed method is initially high but diminishes with all received messages as the utility function gradually converges. In other words, fewer Hello messages are need to broadcast for CCL updates in our proposed method. However, the method referred in [17] still requires more Hello message to maintain CCL, particularly for SUs referred to as gateways, which play an essential role for exchanging CCLs from different groups. Consequently, the proposed method incurs less overhead compare to the method in [17].

5 Conclusion

In this paper, we propose a game theory-based approach for establishing a common control channel in cognitive small cells. We modeled the common control establishment problem as game, designed a utility function, and demonstrated this game is a potential game. Each SU serves as a game player and selects an available channel with the highest channel quality as common control channel using its strategy. The utility of each SU reflects not only its own benefit but also the common interest of other SUs. The simulation results demonstrate that the proposed game theory-based algorithm for common control channel establishment exhibits better convergence. The performance of the proposed approach surpasses that of the group-based approach in terms of common control channel delay and overall network overhead.

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