Network Formation Game for Interference Minimization Routing in Cognitive Radio Mesh Networks

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Abstract. Cognitive radio (CR)-based wireless mesh networks (WMNs) provide a very suitable framework for secondary users' (SUs') transmissions. When designing routing techniques in CR-WMNs, we need to consider the aggregate interference from the SUs to PUs. Although the interference from a single SU that is outside the PUs' footprints is small, the aggregate interference from a great number of SUs transmitting at the same time may be significant, and this will greatly influence the PUs' performance. Therefore, in this paper, we develop a distributed routing algorithm using the network formation game to minimize the aggregate interference from the SUs to the PUs. The proposed distributed algorithm can avoid the problems in the centralized routing solution, such as the high computation complexity and high information-gathering delay. Simulation results show that the proposed framework can provide better routes in terms of interference to the PUs compared to the Dijkstra's shortest path algorithm, and the distributed solution shows near optimum compared to the upper bound.

1 Introduction

Cognitive radio (CR) is a revolutionary technology that allows secondary users (SUs) to occupy the idle licensed spectrum holes left by the primary users (PUs) [1]. CR-based wireless mesh networks (WMNs) is dynamically self-organized and self-configured, and the SUs (wireless mesh routers) have the capabilities to automatically establish and maintain the mesh connections among themselves avoiding the interference to the PUs [2–5].

Although there have been some work investigating routing problems in CR networks, few in the literatures consider the aggregate interference to the PUs from a large amount of SUs transmitting at the same time. Also the game theoretical approaches have been less investigated in the routing problems for the CR networks. In this paper, we focus on the development of routing algorithms for CR-WMNs to minimize the aggregate interference from the SUs to the PUs. Note that we are not considering the interference between different secondary nodes or between multiple paths, which has been well investigated in the idea

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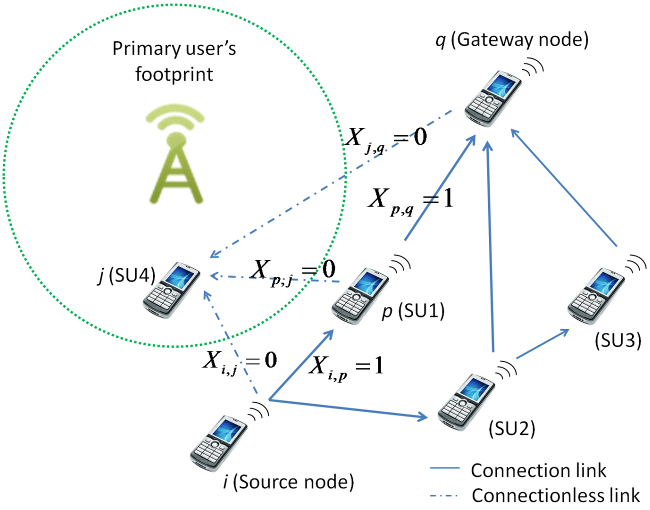

Fig. 1. Illustration of the CR-WMN model

of interference aware routing [6]. Instead, we are studying the aggregate interference from multiple SUs to the PUs in the CR networks. In CR-WMNs, the secondary mesh nodes equipped with CR functionalities must be out of PUs' footprint to avoid interference to the PUs, as long as they want to use the same channels as the PUs'. Although the interference from a single SU (that is outside the primary users' footprint) is small, the aggregated interference from a large number of SUs transmitting at the same time to the PUs can be significant, and the performance of the PUs can be greatly influence by this aggregate interference. We formulate the routing problem to minimize the aggregate interference from the SUs to the PUs. We develop a distributed algorithm using the network formation game framework and a myopic distributed algorithm [7]. From the simulation results, we can see that the proposed distributed algorithm can produce better routes in terms of interference to the PUs compared to Dijkstra's algorithm. Also the distributed solution shows near optimum compared to the upper bound.

The remainder of this paper is organized as follows. In Section 2, the CR-WMN model is introduced. In Section 3, we provide the formulation of the distributed routing algorithm. Section 4 presents the simulation results, and Section 5 concludes the paper.

2 Cognitive Radio Wireless Mesh Network Model

In CR-WMNs, the wireless routers work as the SUs, which have the capabilities to sense the spectrum and access the idle spectrum holes left by the PUs. The SUs can employ the spectrum sensing techniques, such as radio identification based sensing or the spectral correlation algorithm, to detect the available spectrum left by the PUs [9]. We define $\mathcal{N}$ as the set of SUs in the CR-WMNs, and each router $i \in \mathcal{N}$. $\mathcal{E}$ is the set of direct links, and f_e represents the flow on direct link $e \in \mathcal{E}$. If two SUs are in each other's transmission range, we define the link between these two nodes as a direct link. Otherwise, the link is called indirect link, in which intermediate nodes along the link are required to relay packets. $c_{i,j}$ is defined as the capacity of direct link $e = (i, j)$, and it can be calculated using $c_{i,j} = W \log_2 \left(1 + \frac{P_i d_{i,j}^{-\alpha} h}{N_j + \Gamma}\right)$, where W represents the bandwidth, P_i is the transmission power of node i, $d_{i,j}$ is the distance between node i and j, α is path loss constant, and h is the channel response that can be defined as a circular symmetric complex Gaussian random variable. N_j and Γ represent AWGN noise and the interference from other nodes, respectively. We also define an indicator $X_{i,j}$, which is set to 1 only if the link $e = (i, j)$ is active. Fig. 1 illustrates the CR-WMN model, and we can see that the big circle represents the PU's footprint. Solid lines between SUs represent the links that are connected and dashed lines are the links that have no connections. If the licensed spectrum is occupied by the PU, secondary users, such as SU4, which are inside the PUs' footprint, are not allowed to access the spectrum. Therefore, we will have $X_{i,j} = 0$, $X_{p,j} = 0$, and $X_{j,q} = 0$. In contrast, if SUs are out of PU's footprint, such as SUs i, p, and q, they are allowed to access the spectrum, since the interference from single secondary user is sufficiently low. Consequently, we can have $X_{i,p} = 1$ and $X_{p,q} = 1$, showing that the SUs can access the spectrum because the SUs are out of the PU's footprint.

2.1 Routing with Minimum Aggregate Interference to the PUs in CR-WMNs

Single SU may produce sufficiently low interference to the PUs when the distance between itself and the primary users is sufficiently long. Nevertheless, when the number of the SUs increases, and a large amount of SUs are transmitting at the same time, the aggregate interference from the SUs to the PUs can be significant. We must design routing protocols in CR-WMNs to minimize this aggregate interference. The concept of interference temperature can be considered to model the interference level in CR-WMNs [8]. In this paper, we use the generalized interference temperature model T_I, i.e.,

$$T_I(f_c, B) = \frac{\mathcal{P}_I(f_c, B)}{kB}, \tag{1}$$

where $\mathcal{P}_I(f_c, B)$ is the average interference power in Watts centered at frequency f_c, covering a bandwidth of B in Hertz. Boltzmann's constant k is 1.38×10^{-23} Joules per Kelvin degree.

In the example shown in Fig. 1, the interference temperature level of SU2 is lower than that of SU1, considering the fact that SU1 is located closer than SU2 to the PU. When the SU i and SU q want to communicate with each other, we should choose the path of $i \rightarrow$ SU2 $\rightarrow q$ instead of $i \rightarrow$ SU1 $\rightarrow q$.

2.2 Transmission Range and Interference Range

The transmission power of SU i can be denoted as P_i. We define the channel gain between two secondary nodes i and j as $G_{i,j} = \beta d_{i,j}^{-\alpha}$, where α is the path loss constant, β is a constant related to antenna design, and d_{ij} is the distance between SU i and SU j. We define a threshold ρ_T. Only if the received power is higher than ρ_T, the data can be seen as successfully transmitted. We also assume that interference from a single secondary mesh node is sufficiently low when received power at the PUs is smaller than another threshold ρ_I. Therefore, the transmission range for a SU i can be calculated as $R_{T_i} = (\beta P_i/\rho_T)^{1/\alpha}$. In the same way, we can calculate the interference range for secondary node i as $R_{I_i} = (\beta P_i/\rho_I)^{1/\alpha}$.

3 Distributed Routing Algorithm Using Network Formation Game

In this section, we propose a distributed routing algorithm for CR-WMNs using the network formation game. Compared to the centralized routing solution, which may cause problems such as the high cost for building the centralized coordinate nodes, high information-gathering delay, and system breakdown caused by the possible failures in the centralized nodes, the network formation based distributed routing algorithm can significantly reduce the system overhead and the computation complexity.

3.1 Game Formulation

Network formation games provide a suitable framework to model the interactions among the SUs in CR-WMNs when they are trying to form the routes [7]. Network formation game constitute the problems that involve a number of players interacting with each other in order to form a suitable graph that connects them. Depending on the objectives and incentives of the players in the network formation game, we can form a final network graph G based the interactions between the players and their decisions. Therefore, we can model the routing problem in CR-WMNs as a network formation game, and SUs are players. The result of the game will be a directed graph $G(\mathbb{N}, \mathbb{E})$. $\mathbb{N} = \{1, ..., N\}$ is defined as the set of all secondary nodes, and $\mathbb{E}$ denotes the set of edges between the SUs.

Definition 1. *A path between two SUs i and j in G can be defined as a sequence of SUs i_1,...,i_K such that $i_1 = i$, $i_K = j$, and each directed link $(i_k, i_{k+1}) \in G$ for each $k \in \{1, \ldots, K-1\}$. We denote $\mathbb{V}_i$ as the set of all paths from SU i to the destination of SU i, denoted as $\mathcal{D}_i$, and thus $|\mathbb{V}_i|$ represents the number of paths from SU i to destination $\mathcal{D}_i$.*

Convention 1: Each destination $\mathcal{D}_i$ is connected to its source through at least one path. Therefore, we can have $|\mathbb{V}_i| \geq 1$, $\forall i \in \mathcal{N}$.

We need to define the strategy for each player in the game. The strategy of SU i is to select the link that it wants to form from its strategy space, which can be defined as the SUs in $\mathbb{N}$ that SU i is able to and wants to connect to. We want to set a rule that player i cannot connect to player j which is already connected to i. This means that if a link $(j,i) \in G$, then link (i,j) cannot be in G. Formally, for a current network graph G, let $\mathbb{A}_i = \{j \in \mathbb{N}\backslash\{i\} | (j,i) \in G\}$ be the set of nodes from which node i accepted a link (j,i), and $\mathbb{S}_i = \{(i,j) | j \in \mathbb{N}\backslash(\{i\} \bigcup \mathbb{A}_i)\}$ as the set of links corresponding to the nodes with whom node i wants to connect. Consequently, the strategy of player i is to select the link $s_i \in \mathbb{S}_i$ that it wants to form by choosing the player that it wants to connect to.

3.2 Utility

The players try to make decisions for utility maximization. Given a network graph G and a selected strategy s_i for any player $i \in \mathcal{N}$, the utility of player i can be expressed as

$$u_i(G) = -B_e^1 B_e^2 \frac{f_{i,i_{nexthop}}}{c_{i,i_{nexthop}}} \times T_{I_i}, \tag{2}$$

where B_e^1 and B_e^2 are the barrier functions, T_{I_i} is node i's interference temperature, $f_{i,i_{nexthop}}$ is the flow on the edge between node i and its next hop, and $c_{i,i_{nexthop}}$ represents the capacity of the same edge.

We know that the flow on each edge should be smaller than the link capacity, which means $f_e \leq c_e, \forall e \in \mathcal{E}$. In addition, the outgoing flow should be equal to the sum of incoming flow and generated traffic. Therefore, we can have $l_j + \sum_{e=(i,j)\in\mathcal{E}} f_e = \sum_{e=(j,i)\in\mathcal{E}} f_e$, where l_j represents the generated traffic of secondary node j. This is the flow conservation constraint. We assume that that l_j consists of only generated traffic if there is no incoming traffic from wired Internet. Therefore, the barrier functions that consider the above two constraints can be defined as

$$B_e^1 = \left(\sum \frac{1}{1 - \frac{f_e}{c_e} + \varepsilon_1} \right)^{\kappa_1}, \tag{3}$$

and

$$B_e^2 = \left(\sum \frac{1}{1 - \frac{l_j + \sum_{e \in E} f_e}{\sum_e f_e} + \varepsilon_2} \right)^{\kappa_2}, \tag{4}$$

where ε_1 and ε_2 are two small dummy constants so that the denominators are not zero. κ_1 and κ_2 are set to be great than 0 in order to weight different constraints. When the constraints are almost not met, the values of the constraint functions will be large. Therefore, in the proposed utility function, the interference to the PUs are protected by the barrier functions to ensure that the two constraints are satisfied.

3.3 Proposed Algorithm for Network Formation Game

Now we will start to design an algorithm of interaction to form the network graph considering the utility function. When SU i plays a strategy $s_i \in \mathbb{S}_i$ and all other SUs keep their strategies $s_{-i} = [s_1, ..., s_{i-1}, s_{i+1}, ..., s_M]$, we can have graph $G_{s_i,s_{-i}}$. For each player i, it want to select strategy $s_i = (i, j) \in \mathbb{S}_i$ which can maximize its utility. We can define the best response for any player as:

Definition 2. *A strategy* $s_i^* \in \mathbb{S}_i$ *is a best response for a player* $i \in \mathbb{N}$ *if* $u_i(G_{s_i^*,s_{-i}}) \geq u_i(G_{s_i,s_{-i}})$, $\forall s_i \in \mathbb{S}_i$. *Therefore, given that the other nodes maintain their strategies, the best response for player i is to choose the strategy that maximizes its utility.*

Subsequently, a distributed formation of the network graph is proposed in this paper. We assume that network is dense enough. We also consider that each node is myopic, which means that each player only considers the current state of the network. When they want to improve their utilities, they do not consider the future evolution of the network. In this paper, we propose a myopic network formation algorithm consisting of two phases: a fair prioritization phase and a network formation phase. In the fair prioritization phase, we develop a priority function that assigns a priority to each node. In the network formation phase, the players interact to select the next hop to this destination by increasing priority.

In the fair prioritization phase, the node with a higher interference to the PUs is assigned a higher priority. The objective of the prioritization is to make the SUs that produce high interference to the PUs have an advantage in the selection of their path towards their destinations. Therefore, those players can have a larger chance to improve their performances because they are allowed to select their partners with a larger space of strategies. In addition, we need to mention that we can also use other priority functions. In fact, in the simulation results, we use a random priority function for a general case.

In the myopic network formation phase, the secondary nodes start to select their strategies based on the priorities defined in the fair prioritization phase. Given the current network graph resulting from the strategies of the other players, player i plays its best response $s_i^* \in \mathbb{S}_i$ in order to maximize its utility at each round. Every node replaces its current link to the destination with another link that maximizes its utility, and therefore, the best response action is a link replace operation. In order to find the best response, each node engages in pairwise negotiations with the other nodes. Once the negotiations are completed, the node can select the strategy that maximizes its payoff. Finally a graph $G^\sharp$ will be formed after convergence in which no player can improve its utility by changing the best response.

Definition 3. *A network graph G in which no player i can improve its utility by a unilateral change in its strategy* $s_i \in \mathbb{S}_i$ *is a Nash network.*

From the definition above, we can see that when the links chosen by each node are the best responses, a Nash network is formed. In Nash network, no node is able to improve its utility by unilaterally changing its current strategy, which

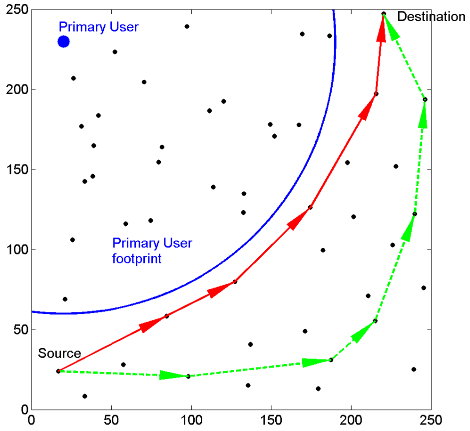

Fig. 2. A simulation result showing the network routing using distributed algorithm in a 250-by-250 meter area

means that the nodes are in a Nash equilibrium. Consequently, we can have $u_i(G_{s_i^*,s_{-i}}) \geq u_i(G_{s_i,s_{-i}})$, $\forall s_i \in \breve{\mathbb{S}}_i$, for any $i \in \mathcal{N}$.

Theorem 1. *In the game with finitely many nodes, there exists a Nash network* $G^\sharp$.

After solving the network formation algorithm and obtaining the whole network topology, the source node may have several choices to the destination, as defined in Convention 1. However, if we select a route that is very far away from the primary users, which may provide significantly low interference to the primary users, we may have large delay along this route. Therefore, we need a tradeoff between the cumulative delay and the aggregate interference. In order to make sure that the interference to the PUs is low enough without increasing much delay, we will select a route based on the constraint:

$$D_{total} \leq D_\tau, \tag{5}$$

where D_{total} represents the total delay along the route, and D_τ is the threshold. Note that for different source and destination pairs, we may have different values for the delay threshold. Given the constraint in Eq. (5), the source will then select the route with the lowest aggregate interference to the PUs.

4 Simulation Results and Discussions

In this section, we present the simulation results for the network formation game based distributed routing algorithm for CR-WMNs. We consider that the nodes are deployed in a 250-by-250 meter area. The value of path loss constant is 2.

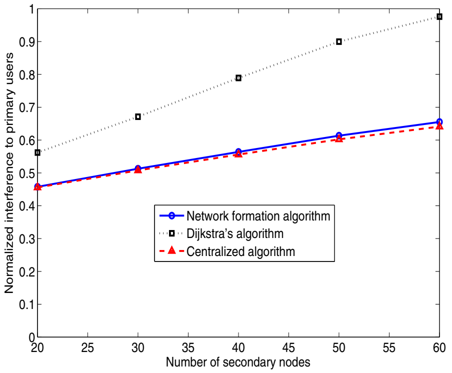

Fig. 3. Number of secondary nodes vs. interference

We assume that link capacities only depend on the distance between the two players to simplify the problem. The data rate is 48 Mbps within the distance of 32m , 36 Mbps within 37m, 24 Mbps within 45m, 18 Mbps within 60m, 12 Mbps within 69m, 9 Mbps within 77m, and 6 Mbps within 90m [11]. The maximum interference range R_I is 180m, and the maximum transmission range R_T is 90m. The number of the nodes in the network may change, and we consider random topologies for the simulation. We generate a data set of 1,000 for the simulation. For every data set, the generated traffic by the node, the locations of the gateway are randomly generated and defined.

Fig. 2 shows the simulation results for the proposed distributed routing algorithm. We use a random priority in the fair prioritization phase for a general case. The big dot represents a PU with the sector area as the PU's footprint. The other dots are 50 SUs and those SUs that are inside the PU's footprint are forced to turn off because the spectrum is occupied by the PU. We also define the source and destination nodes in Fig. 2. After applying the proposed distributed interference minimization routing algorithm, we can get the route shown as the dashed arrows. If we use the Dijkstra's shortest path algorithm that does not consider the aggregate interference to the PU, the solid route is achieved. In these two routes, the interference temperature values to the primary user are 1.6195 and 1.3354, respectively. Clearly, the solid route produces higher interference to the PU than the dashed route, since the nodes in the solid route are closer to the PU.

Now we compare the performance between the proposed distributed algorithm and the upper bound. The upper bound can be achieved using the centralized routing algorithm proposed in [12]. Fig. 3 shows the simulation results about the interference comparison with different numbers of the SUs. ε_1, ε_2 are both set to be 1.5, and $\kappa 1$, $\kappa 2$ are 0.01. We choose small κ values to avoid the cost function changing too fast. Delay threshold is set to be twice the delay if using the Dijkstra's algorithm. The solid line represents the simulated performance of the distributed network formation algorithm. The dashed line is the centralized

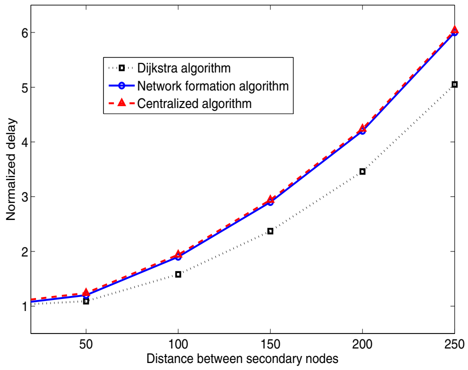

Fig. 4. Distance between secondary nodes vs. delay

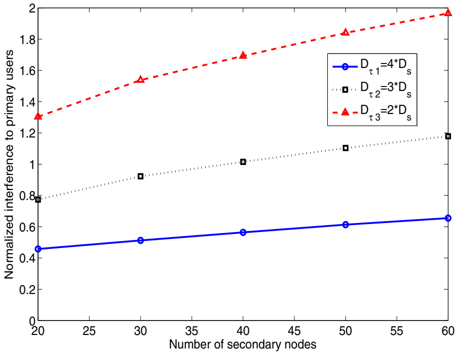

Fig. 5. Comparison of aggregate interference given different delay thresholds

solution, and it performs better than the distributed approach as expected. The distributed solution shows near optimum compared with the centralized interference minimization solution, producing about 1.0098 time the interference from the centralized algorithm. This means that it is 99.02% efficient compared to the upper bound. The black dashed line is the result using the Dijkstra's algorithm without considering the aggregate interference to the PUs. We can find that it produces the highest interference in the three solutions. Moreover, with the increasing number of SUs, interference to the PUs increases in Fig. 3. Note that the reason that we only compare the proposed algorithms with the Dijkstra's shortest path algorithm is that most other existing routing algorithms for CR networks do not consider the aggregate interference to the PUs.

Fig. 4 shows the comparison of delay between the proposed distributed algorithm and the upper bound. For simplicity, the delay is defined as the number of hops. We can find that with the increasing of the distance between SUs, the total delay will increase, which is consistent with the results in Fig. 3. In addition, the centralized algorithm provides slightly higher delay than the distributed network formation algorithm since the network formation algorithm provides slightly higher interference than the centralized algorithm. Moreover, the Dijkstra's algorithm performs the best since it does not consider the aggregate interference to the PUs, and always finds the shortest path.

If we do not set a delay threshold shown in Eq. (5) in a large area with a significantly large amount of SUs, the route will be very long with large delay, although the aggregate interference to the PUs is decreased. This is not acceptable and we need to use delay threshold to constrain the route. In Fig. 5, we show the performance comparison between different delay thresholds using the distributed network formation algorithm. D_s represents the delay of the route between the source and destination using the Dijkstra's algorithm. We can find in Fig. 5 that higher delay threshold provides longer path with lower aggregate interference to the primary user. With a higher delay threshold, although the path we find is longer with more secondary nodes and farther away from the primary user, the aggregate interference decreases exponentially with distance, which is much faster than the linear increasing of number of nodes on the route.

5 Conclusion

In this paper, we develop a distributed routing algorithm using network formation game in CR-WMNs. In CR-WMNs, although the interference from a single SU to the PUs is small, aggregate interference from a large number of SUs that are transmitting at the same time can be significant, which will influence the PUs' performance. Therefore, we develop a distributed routing algorithm using the network formation game framework to minimize the aggregate interference to the PUs, which is practically implementable. Simulation results shows that the proposed scheme finds better routes in terms of interference to the PUs compared to the shortest path scheme. We also compare the performance of the distributed optimization algorithm with an upper bound and validate it efficiency, and the distributed solution shows near optimum compared to the centralized solution, providing 99.02% efficiency of the upper bound.

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