A Multi-hop Cooperation based Routing Protocol in Cognitive Radio Networks

Journal:	*IEEE Transactions on Cognitive Communications and Networking*
Manuscript ID	TCCN-TPS-16-0068.R1
Manuscript Type:	Transactions Paper Submissions
Date Submitted by the Author:	04-Dec-2016
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Keyword:	Cognitive radio ad hoc networks, Routing, Cooperative systems, Simulation

A Multi-hop Cooperation based Routing Protocol in Cognitive Radio Networks

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***Abstract*—In this work, we consider a cognitive radio network where coexisting primary and secondary users explore cooperative diversity to experience improved quality of services. This goal driven collaboration model is formulated as an overlapping coalition formation game. Primary users' goal is defined in their payoff function in terms of throughput and end to end delay while secondary users' goal is incorporated into their payoff function in terms of transmission opportunities and power consumption. We analyze the complexity and stability concept of the game. Following the analysis of the game, we devise mcRoute, a routing algorithm that forms distributed multi-hop coalition based on their mutual interests. A primary user constructs its routing path in the form of a coalition with secondary users relaying its packet. A secondary user takes part in one or more coalitions by relaying corresponding primary packets and accessing their channels for its own transmission. We have discussed how this routing algorithm can be integrated with existing standards. We implemented the algorithm in ns-3 and analyzed the performance of the algorithm in terms of various metrics e.g. throughput, end to end delay, and packet loss.**

Keywords*—overlapping coalition game, cooperative diversity, routing protocol, payoff function

I. Introduction

The concept of cognitive radio network (CRN) has been incepted based on the principle that secondary users will detect idle spectrum through spectrum sensing and transmit their packets without the primary users' knowledge. Since its inception its application area has been broadened to explore its full potential. Among all models the research community has explored the cooperative diversity among primary and secondary users for improved network performance which is also referred to as cooperative cognitive radio network or CCRN([1]–[6]). Cooperative transmission brings a powerful means to combat channel fading, to achieve improved network capacity, and to provide efficient spectrum sharing among primary and secondary users. By exploiting cooperative diversity in this model, a primary user (PU) appoints a secondary user to relay its packets, and improves its throughput, and a secondary user (SU) increases channel access opportunities in return for its services. The success in single hop relay model motivates the researchers to study and explore the cooperation model in multi-hop communication [7]–[9].

In a multi-hop cooperation model, a primary user intends to establish a stable routing path to its destination by selecting multiple secondary users as intermediate relays. A secondary user, on the other hand, participates in one or more routing paths to ensure its transmission opportunities while limiting power consumption in relaying. Exploiting time and space diversity over multiple hops, this model can offer an innovative solution for transmission of $3G/4G$ cellular traffic through inter-carrier relaying communication [7]. The emerging technology of cognitive sensor networks with limited transmission range and longer lifetime expectation also advocates an efficient mechanism for relaying traffic [8]. On the other hand, cooperation among primary and secondary users eliminates the unintentional collision with PU transmission [9].

Although multi-hop cooperative relaying brings significant promises, we need to address several unique challenges to design the cooperation model and exploit its full benefits. The main challenge is to quantify the mutual interest of primary and secondary users into payoff function and incorporate it in their decision making. For example, while a secondary user as an intermediate relay may offer higher data rate, it also introduces delay in the same routing path. Therefore, a primary user's payoff must reflect the tradeoff between achievable throughput and path delay. On the other hand, unlike single hop relay model, a secondary user's cooperation benefit is defined not only by its own action but also by the action of other users in the routing path. Therefore, we must take into consideration the competition among the secondary users to meet their requirements. As a result, single hop relay based research ([1]–[5]) may not be optimal to multi-hop scenarios.

In this regard, few work [8], [9] address the multi-hop cooperative relay selection problem and design a cooperation model focusing on primary users' interest only. For example, Xue et al. [9] present a scheduling algorithm for a single primary transceiver pair whose routing path consists of fixed and predetermined secondary relay nodes. However, the competition among multiple primary source-destination pairs is not addressed and the consideration of fixed routing path make the cooperation model impractical. Although Li et al. [8] have considered multiple primary users in their work, the model becomes unstable when users have to deal with simultaneous requests. Also, a secondary user acts only in response to primary users' specific requests, and each one may cooperate with at most one primary user. This limitation prevents a secondary user from exploring its cooperative transmission opportunity. Furthermore, none of these models consider the interference between users in the network. Finally, we need to ensure the stability of the routing path and the scalability and complexity of the cooperation algorithm. An unscalable algorithm causes unstable routing path that leads to collision and packet loss, and the network output degrades significantly. Therefore, previously proposed framework do not represent the true potential of a multi-hop cooperation framework.

In this paper, we analyze the multi-hop cooperation framework and present $mcRoute$, a multi-hop cooperation-based relay selection and transmission scheduling algorithm addressing the issues discussed above. In contrast to the preliminary result[1] [10], this work adds (i) proof of the NP-completeness of the optimization problem and discussion on determination of the stability of the game (ii) integration of the protocol into existing standard explaining the protocol with flow charts and algorithms and (iii) finally, evaluation of the protocol by performing simulation in ns-3 with symmetric and asymmetric secondary users.

We consider coexisting primary and secondary users and analyze a multi-hop cooperation framework based on users' mutual interests. In this framework, we consider both primary and secondary users as 'active' participants, which actively adopt strategies to decide when and how to accept and offer cooperation from other users for improved system performance. This complex interaction and negotiation process is analyzed using an overlapping coalition formation game. The result from this analysis is then used to devise a cooperation based routing algorithm that handles simultaneous route discovery requests and ensures stable routing paths through coalition formation. Therefore, our network model is more general than others and exploits the full benefits of mutual cooperation.

The salient contributions of our work are summarized as follows.

- We formulate the multi-hop relay selection and routing problem as an overlapping coalition formation (OCF) game. Unlike existing approaches, this model involves active participation from both primary and secondary users where one secondary user can join more than one coalition. The user payoff functions in the game are defined reflecting their mutual interest on the cooperation. The NP-hardness and stability of the game are analyzed.
- We propose $mcRoute$, a cooperation based routing algorithm based on the properties of the OCF game. Each primary transmitter initiates a route discovery request. When a secondary user receives such requests, it coordinates between multiple requests and carefully sets its cooperation parameters to show its interest to join in coalitions. After exchanging messages between users, the routing paths are guaranteed to converge and packets are scheduled for transmission.
- Finally, we develop the proposed joint routing and scheduling algorithm and compare our algorithm with an existing work [8] and show that our algorithm performs better than existing one. We have integrated the routing protocol with the existing standard in ns-3. We have analyzed the performance of our proposed algorithm in terms of various performance metrics e.g. throughput, end to end delay, and packet loss.

[1]Preliminary result of this work has been published in 10th IEEE International Workshop on Wireless Mesh and Ad hoc Networks

II. Related Work

Various collaboration based techniques have been applied in the context of cognitive radio networks to ensure improved system performance. While the channel sensing techniques [11], [12], [13] and multi-hop opportunistic routing [14], [15] have been proposed based on collaboration between secondary users only, there is a growing interest to study the collaboration between primary and secondary users in cognitive radio networks. This cooperation based cognitive radio network opens opportunity for researchers to investigate the mutual benefits of both primary and secondary users.

To understand the cooperation framework among primary and secondary users, researchers have applied some key technology like game theory, back-pressure algorithm [1], [9] and so on. Stackelberg game is arguably one of the most cited game theory approaches used to explain the cooperation framework ([4], [16]). For example, Simeone et al. [16] proposed a cooperation model considering a single primary link sharing spectrum with a set of ad hoc networks of secondary nodes. They formulated outage probability as a Stackelberg game to maximize the quality of service in terms of transmission rate. Similarly, the cooperation framework-based optimization problem was analyzed using Stackelberg game in [3], [4]. Hyder et al. investigated a cooperation model to ensure reliable delivery of real-time packet [17]. However, all these work mainly focuses on single hop communication in time domain or frequency domain or both [1]–[6].

Nevertheless a cross-layer optimal scheduling algorithm was proposed in [9] for cooperative multi-hop CRNs. In this network, the secondary users cooperate with primary users to transmit in a multi-hop fashion, and the secondary users earn transmission opportunity in return. The analysis was developed to achieve optimal throughput for the primary users where the upper bound was derived. However, the analysis considers a fixed routing path between a pair of primary source and destination nodes. Li et al. [8] considers multi-hop cooperation among primary and secondary users in both time and frequency domain and investigates the cooperation opportunity for finding a stable routing path. Accordingly, the routing path construction problem is formulated as a network formation game, and utility and payoff functions are defined accordingly. Primary users sequentially construct routing paths through one or more secondary users. However, members of two separate routing path are mutually exclusive i.e. no secondary user can participate in more than one routing path, which limits the opportunity of secondary users to improve its winning probability. Therefore, it is important to study the cooperation behavior considering the strategic independence of primary and secondary users.

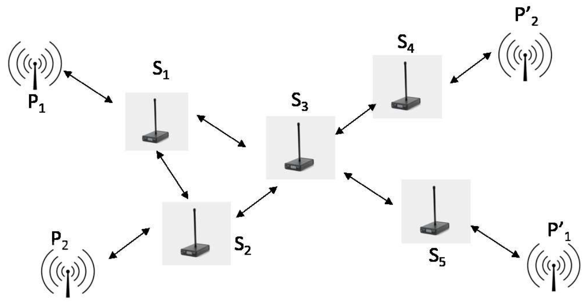


Fig. 1: Network model

III. System Model and Problem Formalization

In this section, we describe the network system model, and formulate our optimization problem using overlapping coalition formation game.

A. System Model

We consider a time slotted network consisting of m independent source-destination pairs of primary users. The set of primary transmitters is represented as $\mathcal{P} = \{P_1, \ldots P_m\}$ while the set of corresponding receivers is represented as $\mathcal{P}' = \{P'_1, \ldots P'_m\}$. We assume the coexistence of an ad hoc secondary network with n secondary transmitters in set $\mathcal{S} = \{S_1, \ldots, S_n\}$ and their corresponding receivers in set $\mathcal{S}' = \{S'_1, \ldots, S'_n\}$. Fig. 1 depicts a network scenario consisting of two pairs of primary source destination pairs (P_1, P'_1, P_2, P'_2) and five secondary users (S_1, S_2, S_3, S_4, and S_5).

We assume that each primary transmitter $P_i \in \mathcal{P}$ is allocated a subset of sub-carriers, and together they are referred to as 'sub-channel' for data transmission [8]. We consider that each sub-channel consists of an equal number of sub-carriers, thereby achieving equal bandwidth[2], B. Each secondary user $S_i \in \mathcal{S}$ can operate over any of the sub-channels of these primary users based on their cooperation agreement.

We assume that users engage in cooperative transmission [1], [2], [8] if it increases their mutual interest. In a cooperative transmission, a primary user exploits the diversity (offered by coexisting secondary users) to build a routing path leading to improved network throughput. Similarly, a secondary user participates in relaying primary traffic for transmission opportunities. This mutual interest is the basis of users' participation in resource sharing and building a multi-hop cooperation model.

B. Preliminaries

An overlapping coalition formation game is a special type of cooperative game where a single player can share its resources in multiple coalitions. This theory has been used to model collaborative spectrum sensing in cognitive radio networks [18], and interference management in small cell networks [19], among other scenarios. In the context of relay selection in $CCRN$, we adopt the overlapping coalition formation game to model and analyze the behavior of the framework. We present the properties of the overlapping coalition formation game in the following definitions.

[2]The model can be extended to users with variable bandwidth.

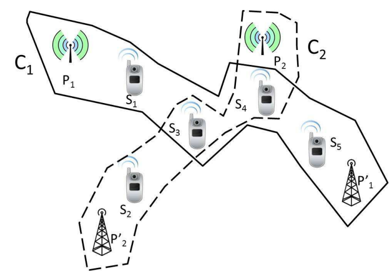


Fig. 2: Overlapping coalition example

1) OCF Game and Properties: An OCF game $G(\mathcal{N}, v)$ is represented with player set $\mathcal{N}$ where players share resources to form coalitions and a characteristic function v that defines the maximum payoff from each coalition [19]. The outcome of the OCF game is represented with a pair $(\mathcal{CS}, \mathbf{u})$ where $\mathcal{CS}$ represents the set of coalitions over $\mathcal{N}$ and $\mathbf{u}$ represents the payoff distributions among users. The main components of the game are defined as follows:

- **Coalition and Coalition Structure**: A coalition C_j is represented with a resource vector $\mathbf{r}^j = (r^j_1\ r^j_2 \ldots r^j_a)$ where r^j_i denotes the fraction of resource player i allocates to coalition C_j and $|\mathcal{N}| = a$. An overlapping coalition structure over $\mathcal{N}$, denoted as $\mathcal{CS}$, is defined as a set $\mathcal{CS} = \{C_1, \ldots, C_b\} = \{\mathbf{r}^1, \mathbf{r}^2, \ldots \mathbf{r}^b\}$ where b is the number of coalitions, $C_j \subset \mathcal{N}$ and $\cup_{j=1}^{b} C_j = \mathcal{N}$. The coalitions can be overlapping, and thus, the sets may not be disjoint. If $r^j_i = 0$, it means that user i does not belong to coalition C_j. $\mathcal{CS}_{\mathcal{N}}$ denotes the set of all possible coalition structures over $\mathcal{N}$. The characteristic function $v(C_j)$ denotes the value of a coalition C_j while the total valuation of a coalition structure is defined as $v(\mathcal{CS}) = \sum_{j=1}^{b} v(C_j)$. The superadditive cover of a characteristic function v is the mapping
$$v^*(C_j) = \sup_{\mathcal{CS} \in \mathcal{CS}_{\mathcal{N}}} \{v(\mathcal{CS}) | \sum_{C'_j \in \mathcal{CS}} C'_j \leq C_j\} \quad (1)$$
$v^*(C_j)$ calculates the maximum that the players in coalition C_j can earn given their resource contribution $\mathbf{r}^j$.
- **Payoff Distribution**: While the characteristic function v denotes the value of a coalition, the payment vector $\mathbf{u}^j$ specifies the payoff distribution to the members of each coalition $C_j \in \mathcal{CS}$. The payment vector of an individual coalition C_j can be represented as $u(C_j, \mathcal{CS}) = u(\mathbf{r}^j, \mathcal{CS}) = \mathbf{u}^j = [u^j_1\ u^j_2 \ldots u^j_a]$.
The payoff of an individual player i can be represented as a summation of payment from all the coalitions it has participated in. $u_i(\mathcal{CS}) = \sum_{j=1}^{b} u_i(C_j, \mathcal{CS}) = \sum_{j=1}^{b} u^j_i$. The payoff of a coalition is defined as the summation

of the payoff of all its members earned from joining the coalition.

- **Imputation**: An imputation for $\mathcal{CS}$ is a y tuple $\mathbf{u} = (\mathbf{u}^1 \dots \mathbf{u}^b)$ where $\mathbf{u}^i \in \mathbb{R}^a$ for $i = 1 \dots b$ such that
  - for every coalition $\mathbf{r}^j \in \mathcal{CS}$, $\sum_{j=1}^{b} u_i^j = v(\mathbf{r}^j)$ and $r_i^j = 0$ implies $u_i^j = 0$.
  - the total payoff of an agent i is at least as large as what he can achieve on his own $\sum_{j=1}^{b} u_i^j \geq v^*(\{i\})$.

  The set of all imputations for a coalition structure $\mathcal{CS}$ is denoted as $\mathcal{I}(\mathcal{CS})$. A pair $(\mathcal{CS}, \mathbf{u})$ is a feasible outcome if $\mathbf{u} \in \mathcal{I}(\mathcal{CS})$. The feasible outcome also implies a stable coalition structure.

2) Stability and Arbitration Function in OCF Games: If any subset of players can increase their payoffs by deviating from an outcome of the game and readjusting their resources the game becomes unstable. The arbitration function concept [20], [21] is introduced to analyze the stability of the OCF games. The arbitration function $\mathcal{A}(\mathcal{CS}, \mathbf{u}, \mathcal{Q})$ is a mapping that receives a feasible outcome $(\mathcal{CS}, \mathbf{u})$, a deviating set of players $\mathcal{Q} \subset \mathcal{N}$, and the deviation proposal of the set and outputs a number for each coalition C_j with supp$(C_j) \cap \mathcal{Q} \neq \emptyset$, supp$(C_j) \cap \{\mathcal{N} \setminus \mathcal{Q}\} \neq \emptyset$. This number represents how much of C_j's payoff the deviators in supp$(C_j) \cap \mathcal{Q}$ can keep if they deviate. The output will be dependent on the features of the game. Let us denote that $\mathcal{A}^*(\mathcal{CS}, \mathbf{u}, \mathcal{Q})$ represents the maximum a set of players $\mathcal{Q}$ can get when deviating from the outcome $(\mathcal{CS}, \mathbf{u})$. We conclude that an outcome $(\mathcal{CS}, \mathbf{u})$ belongs to $\mathcal{A}$-core if no player set $\mathcal{Q}$ can deviate so that each $i \in \mathcal{Q}$ can get more than $u_i(\mathcal{CS}, \mathbf{u})$. However, it has been shown that computing an $\mathcal{A}$-core outcome of an OCF game is NP-complete [20].

Chalkiadakis et al. in [22] presented three concepts of core in OCF games with respect to arbitration function – (1) the deviators receive nothing from the existing coalitions (known as c-core or conservative core), (2) the deviators receive the same from unaffected coalitions (known as r-core or refined core), and (3) the deviators receive the same payoff unless the non-deviators' payoff is affected (known as o-core or opportunistic core).

C. Formulation

We formulate the cooperative relay selection and scheduling problem as an OCF game, G = $(\mathcal{N}, v)$ where $\mathcal{N} = \mathcal{P} \cup \mathcal{S}$, and $|\mathcal{N}| = m + n$. We present the formulation into two steps - routing path construction as coalition formation and payoff distribution and transmission scheduling as resource sharing in an OCF game.

1) Routing path Construction as Coalition Formation: The construction of routing path can be mapped to the coalition formation in an OCF game. Each primary transmitter $i \in \mathcal{P}$ starts the process, secondary users join the coalition if profitable, and a coalition C_i (i.e. a path between the primary transmitter and receiver) is formed. Thus, C_i represents the routing path starting with primary transmitter i, followed by one or more secondary transmitters from the set $\mathcal{N}$ based on their mutual needs - constructing a multi-hop routing path and creating transmission opportunities respectively.

For example, there are two coalitions formed in Fig. 2. The first primary transmitter-receiver pair (P_1, P_1') forms a coalition C_1 with four secondary users S_1, S_3, S_4, and S_5. This implies the packets from primary user P_1 follows this path $P_1 \rightarrow S_1 \rightarrow S_3 \rightarrow S_4 \rightarrow S_5 \rightarrow P_1'$. The second primary transmitter-receiver pair (P_2, P_2') forms another coalition C_2 with three secondary users S_2, S_3, and S_4. There are two secondary users (S_3, S_4) overlapping in both the coalitions.

2) Scheduling as Resource Sharing: The resource vector of a coalition C_j is denoted as $\mathbf{r}^j = [r_1^j \dots r_{(m+n)}^j]$ where the first m entries represent resource contribution from primary users and the next n entries represent contribution from secondary users. Considering a time slotted model, each user has maximum T time slots to either share with other users in its coalition or schedule its own transmission.

A primary user only contributes to its own coalition and the resource contribution by a primary user $i \in \mathcal{P}$ is the fraction of total number of time slots over which secondary users in its coalition are transmitting their own packets in its sub-channel,

$$r_i = r_i^i = \frac{1}{T} \sum_{t=1}^{T} \sum_{j \in C_i} \theta_{j \rightarrow j'}^i(t) \leq 1, \forall\ i \in \mathcal{P}. \tag{2}$$

Here, $\theta_{x \rightarrow y}^j(t)$ is an indicator function whose value can be $\{0, 1\}$. $\theta_{x \rightarrow y}^j(t) = 1$ implies that user x sends packet to user y at time t in coalition C_j where $x, y \in \mathcal{N}$, 0 means no transmission. If $y = x'$, user x sends packet directly to its corresponding destination.

A secondary user may contribute its timeslots to more than one coalitions. The resource contribution by a secondary user $i \in \mathcal{S}$ to a coalition C_j is the fraction of time slots over which it engages in receiving and relaying packets of the primary user $j \in \mathcal{P}$ of that coalition.

$$r_i^j = \frac{1}{T} \sum_{t=1}^{T} \left[\sum_{k \in C_j} \theta_{i \rightarrow k}^j(t) + \sum_{q \in C_j} \theta_{q \rightarrow i}^j(t) \right], \forall\ i \in \mathcal{S}. \tag{3}$$

In order to schedule users' transmission without interference, additional constraints must be satisfied. In general, any user $x \in \mathcal{N}$ cannot send to more than one user $y \in \mathcal{N}$. Also, it cannot receive from more than one user $y \in \mathcal{N}$ at the same time.

$$\sum_{j=1}^{m} \sum_{y \in C_j} \theta_{x \rightarrow y}^j(t) \leq 1, (x \in \mathcal{N}), \tag{4}$$

$$\sum_{j=1}^{m} \sum_{y \in C_j} \theta_{y \rightarrow x}^j(t) \leq 1, (x \in \mathcal{N}) \tag{5}$$

Also, a user $x \in \mathcal{N}$ cannot send and receive packet simultaneously at the same time slot t.

$$\sum_{j=1}^{m} \left[\sum_{y \in C_j} \theta_{x \rightarrow y}^j(t) + \sum_{y \in C_j} \theta_{y \rightarrow x}^j(t) \right] \leq 1. \tag{6}$$

Furthermore, all the scheduled transmissions must be interference free. So, while a user in a coalition is receiving a packet from another user in the same coalition, all other interfering users to that receiver in the same coalition cannot send any packet. Otherwise, the receiver will experience interference.

$$\theta^j_{x\to y}(t) + \sum_{z\in I_y}\sum_{q\in\mathcal{V}_z}\theta^j_{z\to q}(t) \leq 1. \tag{7}$$

Here, I_y represents the set of nodes interfering to users y's transmission while $\mathcal{V}_z$ represents the set of nodes within transmission range of user z. Note that, a user's interference range is usually longer than its transmission range.

D. Payoff of a Primary User

The primary user's goal is to increase throughput. Whereas relayed transmission increases data rate, too many hops may introduce significant delay. Therefore, the payoff function of a primary user should reflect the tradeoff between data rate and delay. Accordingly, the payoff of a primary user $i \in \mathcal{P}$ from a coalition C_i, $u^p_i(C_i, \mathcal{CS})$ is defined in terms of data rate profit $\Re_i(C_i)$ and path delay profit $\mathbb{D}_i(C_i)$ as

$$u^p_i(C_i, \mathcal{CS}) = \alpha\Re_i(C_i) + (1-\alpha)\mathbb{D}_i(C_i). \tag{8}$$

Here, the parameter α denotes a primary user's preference between throughput and delay in payoff calculation. For example, $\alpha = 1$ means that a primary user's only focus is to maximize throughput while $\alpha = 0$ means that the user is delay sensitive and aims to minimize delay.

Data Rate Profit: The data rate profit $\Re_i(C_i)$ of a primary user i in coalition C_i is calculated comparing cooperative transmission rate[3] $R_i(C_i)$ with $R_i(\{i\})$. $R_i(\{i\})$ denotes the effective transmission rate that the primary player i can achieve from direct transmission i.e. coalition has only one player. We can calculate $R_i(\{i\})$ directly from (10).

$$\Re_i(C_i) = \frac{R_i(C_i) - R_i(\{i\})}{R_i(\{i\})}. \tag{9}$$

We start our analysis with the calculation of data rate. We assume that the channel experiences white Gaussian noise, and the signal quality degrades due to path loss. The effective transmission rate R_{ij} from node i to node j is calculated following [23]. Thus, we calculate transmission rate over any link between two consecutive members in a coalition as follows:

$$R_{ij} = B\log_2\left(1 + \frac{W_{tx}G^i_tG^j_r(d_0/d^{ij})^{\gamma^{ij}}}{N^{ij}_0 B}\right) \tag{10}$$

where B, W_{tx}, G^i_t, G^j_r, and N^{ij}_0 denote the bandwidth, transmission power and transmitter gain of node i, receiver gain of node j, and power spectral density of noise between i and j respectively. Also, d is the distance between node i and node j, d_0 is the reference distance for the antenna far-field, and γ^{ij} is the path loss exponent between i and j. The overall packet transmission rate of a primary user from a coalition

[3] $R_i(C_i)$ and $R_i(\mathcal{CS})$ are the same for a primary user i

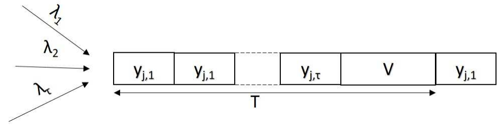


Fig. 3: M/G/1 Queueing Model with Vacation Period

is denoted as the minimum data rate of any of the links in that coalition (since nodes have to receive the packet first and then send it to the next one, the effective transmission rate is factored by $\frac{1}{2}$). Consequently, the effective transmission rate of a primary user i in a coalition C_i is defined as,

$$R_i(C_i) = \min\left(R_i(\{i\}), \frac{1}{2}\min_{\forall_{j,j+1\in C_i}}\left(R_{j,j+1}(C_i)\right)\right) \tag{11}$$

Here, $R_{j,j+1}(C_i)$ denotes the data rate between two consecutive members in the coalition C_i.

Delay Profit: The delay profit $\mathbb{D}_i(C_i)$ of a primary user i in coalition C_i is calculated as a ratio of delay improvement compared to delay from direct transmission.

$$\mathbb{D}_i(C_i) = \frac{D_i(\{i\}) - D_i(C_i)}{D_i(\{i\})}. \tag{12}$$

We assume that both the PUs and SUs generate traffic following a Poisson distribution. Authors in [24] modeled the Poisson traffic system with an $M/G/1$ queue and calculated end to end packet delay. We can use (13) to calculate the delay in direct transmission

$$D_i(\{i\}) = \frac{\lambda_i}{2\mu_i(\mu_i - \lambda_i)} + \frac{1}{\mu_i}. \tag{13}$$

Here, λ_i and μ_i denote the packet arrival rate (according to Poisson distribution) and packet transmission rate, respectively and for a stable system, $\lambda_i < \mu_i$.

The delay of the routing path is the summation of each link delay in the coalition.

$$D_i(C_i) = \sum_{j,j+1\in C_i} D_{j,j+1}(C_i). \tag{14}$$

where, $D_{j,j+1}(C_i)$ denotes the delay between two consecutive secondary users in the coalition C_i.

In relayed transmission, the secondary user receives packet from cooperating primary users at different rate in addition to its own traffic. Based on the cooperation, a secondary user first relays primary traffic and then sends its own packet. To determine the link delay $D_{j,j+1}(C_i)$ experienced by a primary packet, we use an $M/G/1$ queueing model with vacation period. In this queueing model, the server continues vacation until it finds at least one waiting unit upon return from vacation. In the context of relayed transmission, a secondary user relays primary traffic and takes 'vacation' to transmit its own packet (see Fig. 3). Let us assume that a secondary user j receives packets from τ different primary users at rates following Poisson distribution with $\lambda_1, \ldots, \lambda_\tau$ and offers relay service times $y_{j,1}, \ldots, y_{j,\tau}$ respectively. The service times are independent random variables drawn from a common distribution H_y and finite mean $\bar{y}$. The relayed transmission is followed by vacation time V which is a random variable with distribution $F(V)$ and finite mean $\bar{V}$. Using Cobham's well-known formula for the waiting time of an arbitrary arrival in the higher priority queue, we can calculate the mean delay $D_{j,j+1}(C_i)$ experienced by a packet of a primary user i from one secondary user j to another secondary user $j+1$ in the coalition C_i as follows [25]

$$D_{j,j+1}(C_i) = \frac{\lambda E(y^2)}{2(1-\lambda\bar{y})} + \frac{E(V^2)}{2\bar{V}}, \tag{15}$$

where, $\lambda = \lambda_1 + \ldots + \lambda_\tau$.

E. Payoff of a Secondary Player

The secondary user's goal is to ensure transmission opportunity in exchange for its relay services. At the same time, it wants to keep the power consumption to minimum. Accordingly, the payoff value of a secondary player j is defined in terms of the fraction of transmission period earned in return for relay period and power consumption in relaying. A secondary player's payoff is determined by the following equation:

$$u_j^s(C_i, \mathcal{CS}) = \frac{R_{jj'} \times \sum_{t=1}^{T} \theta^i_{j\to j'}(t)}{T \times \sum\limits_{k\in\mathcal{P}} \mathrm{w}_{j,k} \times r_j^k} \tag{16}$$

Here, $\theta^i_{j\to j'}(t)$ denotes that user j transmits to its destination using the sub-channel of primary user i in coalition S_i at time t, $R_{jj'}$ denotes the transmission rate between secondary transmitter j and secondary receiver j' which can be calculated using (10), r_j^k is already defined as resource allocated by j for coalition k, and $\mathrm{w}_{j,k}$ denotes the transmission power spent in relaying traffic from primary user k per time unit. As it can be seen from the payoff function, a secondary user can increase its payoff either by asking for more bandwidth time from the primary user or spending less power in relaying primary traffic.

F. Problem Statement

Given the set of primary players $\mathcal{P}$ and secondary players $\mathcal{S}$ and their corresponding resources $\mathbf{r}$, our goal is to allocate resources into m coalitions such that individual payoff is maximized while satisfying the routing and scheduling constraints mentioned in (2) - (7). Mathematically, we define the problem statement as follows:

$$\max_{\theta_{i\to j}} u_i^p, u_j^s \ \forall\ i,j \in \mathcal{P}\cup\mathcal{S} \tag{17}$$
$$\text{subject to (2) - (7)}$$

As mentioned, finding stable outcome in an unconstrained OCF game is NP-complete [20]. However in our model, each coalition must have only one primary user, and therefore, the optimization problem reduces to m-coalition OCF game. Also, without loss of generality, we assume that each user $i \in \mathcal{N}$ has w_i number of available timeslots to share with other users. So, we can interpret the model as a discrete OCF game and the characteristic function reduces to a mapping from $[0, w_1] \times [0, w_2] \times \cdots \times [0, w_{m+n}]$ to $\mathbb{R}$. Furthermore in our model, a deviated user does not get affected until its deviation does not cause payoff reduction to non-deviators. Therefore, we adopt the $o-core$ concept for stability analysis. Finally, the optimization problem is reduced to a discrete m-coalition OCF game with opportunistic arbitration function that can be solved to determine a stable outcome in polynomial time [26]. Since it is not practical to coordinate between all users in a large network, we develop a routing protocol based on distributed coalition formation in the next section.

IV. Cooperative Routing Protocol

In this section, we present *mcRoute*, a distributed cooperative routing protocol. Unlike traditional routing protocol, the participating users have different goals and often they are conflicting. Therefore, we need to take into consideration the conflict of interests while designing the routing protocol. We propose a three way message communication where primary and secondary users exchange cooperation information to build stable routing paths. There are three types of message defined in *mcRoute*. The first message is *coalition_join* request $C_i(i)$ that denotes a coalition request initiated by primary user i. The second message is *coalition_reply* request $C_i(j)$ which is a response from secondary user j to the initiating primary user i. The third message is *coalition_approval*, C_i which confirms secondary users in the selected routing path of primary user i.

To coordinate the message exchange, a primary user creates a virtual coalition agent referred to as 'PU agent' which is responsible for setup and maintenance of coalition with secondary users. Each primary user has only one virtual agent. On the other hand, the virtual coalition agent of a secondary user is referred to as an 'SU agent'. A secondary user may have multiple coalition agents (at most m), and all these agents of a secondary user coordinate and collaborate to form coalitions.

In *mcRoute*, the primary user i initiates a *coalition_join* request $C_i(i)$ to search for a more profitable path than the direct transmission. The message includes basic parameters e.g. direct transmission rate, traffic rate, and direct end to end delay in the message. The message is then sent to each user $j \in V_i$ where V_i denotes the set of secondary users within its transmission range. A primary user moves to a wait state to receive coalition offer from its neighbors. If no reply is received within a predefined time, the primary user continues transmitting directly to the destination. Otherwise, the primary user embraces the coalition offer that maximizes its payoff.

$$j^* = \arg\max_j u_i^p(C_i(j)) \tag{18}$$

Finally, the primary user sends a *coaltion_approval* C_i towards the selected secondary user j^*. The entire process of routing path construction continues until the convergence parameter β_d reduces below a predefined threshold ϵ (the update process of β_d is discussed later). The protocol is summarized in Algorithm 1.

An SU j receiving a *coalition_join* request $C_i(i)$ first checks whether the destination is reachable or not. Otherwise, it either drops the request from i (if it is not interested) or forwards it to its neighbor $k \in V_j$. Since a secondary user's success depends on other users on routing path, it takes its decision in two steps. First, it selects the one that offers the best coalition offer for the target primary user. Second, it combines its own cooperation terms to the selected offer considering its transmission requirement and prior commitment to other primary users. We explain the parameter selection mechanism in Sec. IV-A. The combined offer is then sent in the upstream direction as a coalition offer $coalition\_reply$, $C_i(j)$ from user j. When secondary user j receives $coalition\_approval$ C_i, it updates its routing table, schedules its packet for transmission, and forwards the packet in the downstream direction. The protocol is summarized in Algorithm 2.

Algorithm 1 *mcRoute*: PU agent of a primary user i

$C_i = \{i\}$, $u_i^p(C_i) = 0$
initiate a $coalition\_join$ request $C_i(i) = \{i\}$
repeat
  send $C_i(i)$ to each node $j \in V_i$
  receive $coalition\_reply$ $C_i(j)$ from each node $j \in V_i$
  select $j^* = \arg\max_j u_i^p(C_i(j))$
  if $u_i^p(C_i) < u_i^p(C_i(j^*))$ **then**
    select $C_i = C_i(j^*)$
    send the $coalition\_approval$ C_i to user j^*
  end if
  update β_d, add j^* as next hop, and update the routing table
  advance round d
until $\beta_d \geq \epsilon$

Algorithm 2 *mcRoute*: SU agent of a secondary user j

repeat
  for each $coalition\_join$ request $C_i(i)$ **do**
    initialize $C_i(j) = \{j\}$
    if destination is not reachable **then**
      forward the packet $C_i(i)$ to each node $k \in V_j$
      receive $coalition\_reply$ packet $C_i(j)$ from each node $k \in V_j$
      select $j^* = \arg\max_k u_i^p(C_i(k))$
      combine $C_i(j) = C_i(j*) \cup C_i(j)$
    end if
    calculate $u_j^s(C_i(j))$, $u_i^p(C_i(j))$ with its own offer
    send $coalition\_reply$ packet $C_i(j)$ in upstream and move to wait state
    if $coaltion\_approval$ C_i is received **then**
      forward the $coalition\_approval$ packet C_i in downstream
      update routing table
    end if
  end for
until no more $coalition\_join$ packet has been received

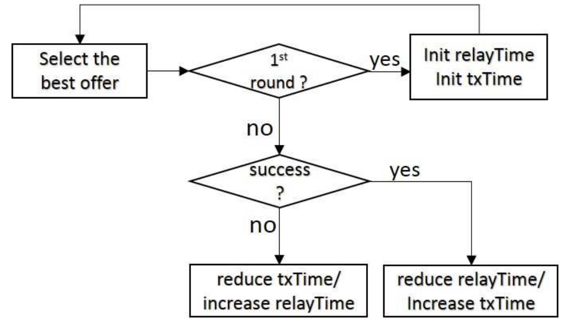


Fig. 4: Decision Flowchart of a Secondary User

A. *Coalition Offer and Payoff Calculation*

When a secondary user $j \in \mathcal{S}$ receives coalition proposals from its neighbors in response to a $coalition\_join$ $C_i(i)$, it selects the cooperation offer that provides the most profitable path for the initiating primary user $i \in \mathcal{P}$. Let us assume that the offer, $C_i(k)$ from user $k \in V_j$ is selected. The user j next selects two parameters as its cooperation terms to add into the chosen cooperation offer $C_i(k)$. The first parameter denotes the cycle time it allocates for relaying the corresponding primary user and the second parameter denotes the bandwidth time it requests from the coalition of primary user i.

In order to select these two parameters, the user checks the offers it made to other primary users. In the first round, it selects parameters for each coalition request proportional to the power consumption in relaying the corresponding primary traffic. Based on its success at previous rounds, a secondary user either (i) reduces its demand for transmission time (txTime) while relay time remains unchanged, (ii) requests more transmission time while relay time is unchanged. (iii) approves more relay time to the primary user with the request of the same unchanged transmission time, or (iv) reduces relay time with unchanged transmission time. A flowchart is added to explain the decision process of a secondary user in Fig. 4.

Finally, the cooperation offer of a secondary user is converted to a form that is understandable to a primary user that expects the offer in the form of cooperative data rate and end-to-end delay.Accordingly, an SU j calculates the payoff for primary user i using (11) as follows:

$$R_i(C_i(j)) = \min(R_{j,k}, R_i(C_i(k)).$$

The intermediate path delay (15) introduced by a secondary user j in a coalition S_i is as follows:

$$D_j(C_i) = \frac{\sum_{t=1}^{T}\sum_{x=1}^{m}\left(\theta^x_{j\rightarrow x}(t) + \theta^x_{x\rightarrow j}(t)\right) \times len}{\sum_{t=1}^{T}\theta^i_{j\rightarrow i}(t) \times R(C_i)}$$

$$D_i(C_i(j)) = D_i(C_i(k)) + D_j(C_i)$$

Here, len denotes the length of the packet. Also, the payoff of a secondary user j is calculated based on the resource sharing with the primary users using Eqn. 16.

B. Stability of Coalitions

In order to ensure stable coalitions, we control the search for coalition by two parameters. A primary user maintains a convergence parameter, β_p. The value of this parameter determines whether the user will initiate another round of route discovery or not. The initial value of the parameter is set to 1. After each round f, the user calculates the change in payoff over total rounds and if the value drops lower than the threshold (ϵ), the user stops the route discovery process. The value of ϵ is a system defined parameter. The parameter β_p at round f is calculated as follows:

$$\beta_p = \begin{cases} |\Delta u_f|/f & \text{if } f > 1 \\ 1 & \text{otherwise} \end{cases} \tag{19}$$

where Δu_f denotes the difference between user i's payoff at round f and at round $f-1$ which is upper bounded by the difference between optimal payoff in relayed transmission and payoff in direct transmission. As the number of round increases, β_f also decreases. If β_p reaches to a value below the threshold ϵ the primary user remains stable with its current coalition. Also, each secondary user cannot request transmission time lower than β_s. When a secondary user's request with minimum transmission time to a primary user fails, it stops participating in that coalition. Thus, the usage of β_p and β_s controls the convergence speed, and the routing paths become stable.

When users are on a stable routing path, the channel states may change that may reduce the payoff valuation of one or more users on the path. To avoid continuing on a less profitable path, all participants continuously monitor the payoff value. If the payoff drops significantly from the agreed one, the primary user may switch to direct transmission and initiate the search for the routing path while a secondary user may remove itself from the path and search for a new opportunity.

In the case of mobile secondary users, the stability of the routing path depends on their speed. If the users move too fast, the routing path becomes unstable. However, if the users are location aware, they can include their location information into the cooperation decision. We will investigate the performance of the routing protocol in future work.

When the users are on a stable routing path, the channel states may change that may reduce the payoff valuation of one or more users on the path. To avoid continuing on a less profitable path, all participants continuously monitor the payoff value. If the payoff drops significantly from the agreed one, the primary user may switch to direct transmission and initiate the search for the routing path while a secondary user may remove itself from the routing path and search for a new opportunity.

V. Numerical Simulation

In this section, we analyze the performance of coalition based multi-hop cooperative routing algorithm. We simulate a cognitive radio network located in an area of 5000m $\times$ 5000m. We deploy different number of primary source-destination pairs (5 to 10). Each primary source node is assigned a channel with 20KHz bandwidth. The transmission cycle time is normalized to one unit and a secondary user requires $1/10$th of its cycle time is for supporting its minimum rate requirement. In order to evaluate the impact of cooperation in the routing path selection, we vary the number of primary users, secondary users, and transmission power. The primary source and destination nodes are randomly and uniformly deployed in the network area. Secondary users are also randomly and uniformly deployed in the area so that each user has at least one neighbor. We have also made sure that each pair of primary source and destination node is connected, and there exists at least one path between primary source-destination pairs through secondary users. For each set of input configuration, we have generated as many as 50 sample scenarios and the statistics are recorded for each set. Finally, for statistical confidence, we take an average of results of all sets to represent the outcome of each scenario.

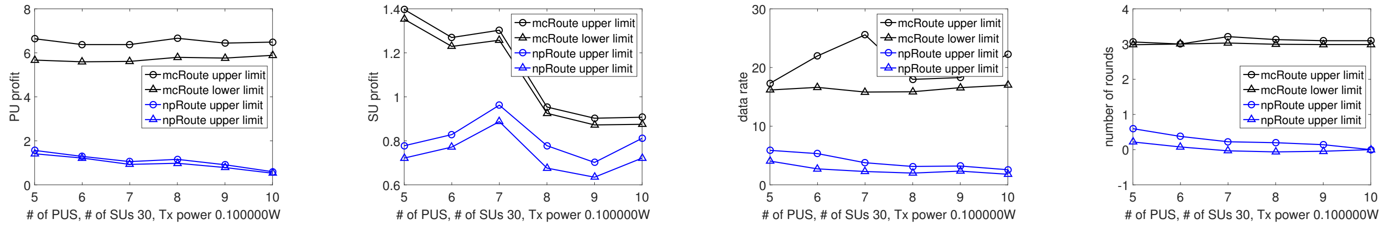
A. Performance Comparison with Prior Work

To compare with an existing algorithm, we implement a modified version of the algorithm proposed in [8]. We have chosen [8] over [9] since the latter one assumes fixed routing path. Unlike [8], in the modified version, a secondary user may receive simultaneous coalition requests from more than one primary user. A secondary user processes multiple concurrent cooperation requests, selects one of them randomly, and participates in routing path of only one primary user at a time. We refer to this algorithm as 'non-overlapping routing' in short 'npRoute'.

We calculate PU and SU profit (with 95% confidence interval) with the varying number of primary users while the transmission power is set to 0.1W and number of secondary users is set to 30. Fig. 5a and 5b show that the proposed cooperation algorithm achieves higher PU and SU payoff than those of npRoute. In mcRoute, PU profit stays almost constant with the increase in the number of PUs. This is because each primary user on average cooperates with the same number of secondary users and increasing number of primary users does not increase the average PU profit. On the other hand, SU profit decreases due to increasing competition among them. We also show in Fig. 5c that the cooperative data rate achieved through mcRoute is higher than npRoute. We also determine average number of rounds required to reach a stable path [18]. It also indicates the convergence speed of the algorithm. Fig. 5d shows that npRoute converges to a local maxima when it handles multiple cooperation offers simultaneously. On the other hand, mcRoute goes through few more rounds to achieve higher data rate and higher PU and SU payoff. Similarly, we also vary the number of secondary users and calculate PU and SU profit (with 95% confidence interval). mcRoute creates more cooperation opportunity for secondary users than npRoute and increases the number of secondary users involved in cooperation and their profits as well.

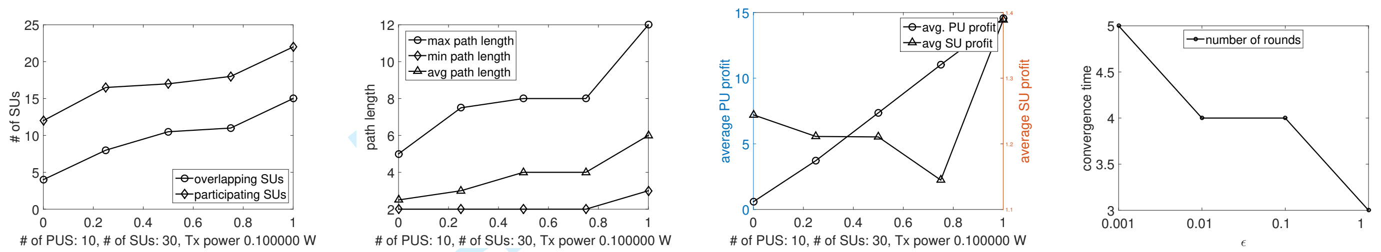
B. Results with Algorithm Parameters

We investigate the impact of changing two key parameters in relay selection and coalition formation. The first parameter α denotes the tradeoff between throughput and delay in the



(a) average PU profit (b) average SU profit (c) average data rate (d) number of rounds

Fig. 5: Comparison between mcRoute and npRoute [8]



(a) number of overlapping SUs vs. α (b) path length vs. α (c) profit vs. α (d) Convergence and stability

Fig. 6: Results with varying algorithm parameters

payoff of a primary user in Eqn. 8. We vary the value of α between 0 and 1 and record the change in user payoff, path length, and number of cooperating secondary users. The result is shown in Fig. 6. As the value of α reaches to 1, the primary user is more interested in increasing data rate and achievable throughput and ignoring the delay cost introduced by relaying secondary users. Therefore, number of participating secondary nodes (Fig. 6a) and path length (Fig. 6b) increases with the increase in value of α. This also increases PU profit almost linearly and opens more opportunity for secondary users to increase their payoff (Fig. 6c). The second parameter we consider here is the threshold ϵ that controls the number of iterations for the search of a stable routing path and the stability of the algorithm. Fig. 6d shows that more rounds are needed to reach stable coalitions with smaller values of ϵ. Thus, these two parameters control the cooperation opportunity and convergence speed of the routing paths.

VI. Integration to Existing Standards

In this section, we discuss how the proposed algorithm can be integrated to existing standards. We implement our protocol in widely used ns-3 network simulator [27] and present the performance of our proposed protocol in terms of throughput, end to end delay, packet loss and so on.

We have modified the `RReq` and `RRep` packet formats of `aodv` to incorporate few parameters of coalition request and coalition reply message. Also, we have added three timers in the proposed routing algorithm to prevent users from waiting indefinitely at different system states. First, `mcRouteTimer` specifies the maximum waiting time an agent should wait for coalition reply. This is true for both PUs and SUs. Second, `mcRouteApprovalTimer` specifies the maximum waiting time after sending/forwarding coalition approval from user agents (both at PU and SU). Third, `mcRouteReplySentTimer` defines the maximum waiting time after sending coalition reply from user agents (only at SU).

We have employed the 802.11 module that supports the medium access control (MAC) layers of IEEE 802.11a/b/e/n/p. In our simulation, we have used IEEE 802.11a to incorporate bit error rate, an important parameter of our protocol. From the perspective of MAC layer, there is no significant difference between PUs and SUs. Therefore, our proposed protocol works smoothly with the standard MAC protocol of IEEE 802.11a in our ns-3 simulation.

Next, we perform simulation and evaluate the characteristics of the proposed routing protocol in terms of different performance metrics. We consider both symmetric and asymmetric secondary users and vary the number of primary users, secondary users, power level to understand the impact of diversity in users' performance and overall network system.

A. Results with Symmetric SUs

In our first simulation settings, we assume all the secondary users are symmetric in their transmission and reception parameters. In this setting, we vary the number of PUs, the number of SUs, and the transmission power.

1) Results with Varying Number of PUs: We first vary the number of primary users from 5 to 10 pairs while the number of secondary users is fixed to 30. Also, the transmission power

(a) per PU throughput (b) per SU throughput (c) Avg hop counts

(d) Delay per packet for PUs (e) Delay per packet for SUs (f) Max hop counts

(g) Packet drop ratio for PUs (h) Packet drop ratio for SUs (i) Min hop counts

Fig. 7: Results with varying number of PUs, for symmetric SUs

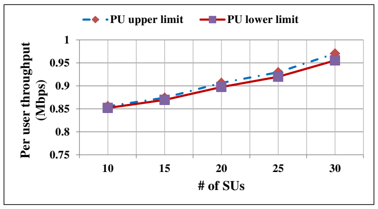
for each wireless node is set to $0.04W$. Fig. 7 shows the per user throughput, per packet end-to-end delay, and packet drop ratio for PUs and SUs as well as average, maximum, and minimum hop count for delivered packets. While per user throughput increases for both PUs and SUs with an increase in the number of PUs, (Fig. 7a, 7b), delay only increases for PUs (Fig. 7d). Consequently, packet drop ratio does not change that much for both PUs and SUs with the increase in the number of PUs (Fig. 7g, 7h). For hop counts, even though maximum and minimums are almost constant, average hop counts decreases up-to some level with the increase in number of PUs (Fig. 7c, 7f, 7i).

2) Results with Varying Number of SUs: We then vary the number of secondary users from 10 to 30 while the number of primary users is fixed to 5 pairs. Also, the transmission power for each wireless node is set to $0.04W$. Fig. 8 shows the per user throughput, per packet end-to-end delay, and packet drop ratio for PUs and SUs as well as average, maximum, and minimum hop count for delivered packets. While per user throughput increases for both PUs and SUs with an increase in the number of SUs, (Fig. 8a, 8b), delay only increases for SUs (Fig. 8e). Furthermore, packet drop ratio increases for both PUs and SUs with the increase in the number of SUs (Fig. 8g, 8h). For hop counts, other than the minimum, average as well as maximum hop counts increases with the increase in number of SUs (Fig. 8c, 8f, 8i).

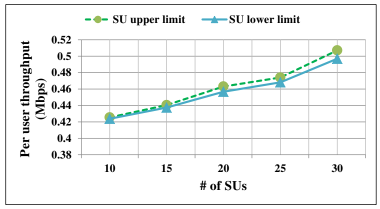
3) Results with Varying Transmission Power: Lastly, We vary the transmission power from 0.1W to 0.5W while the number of primary users is fixed to 5 pairs and the number of secondary users is fixed to 30. Fig. 9 shows the effect of transmission power on various performance metrics. In case of PUs, per user throughput as well as per packet delay initially decrease. However, it starts increasing with an increase in transmission power (Fig. 9a,9d). For SUs, delay increases before becoming constant (Fig. 9e). Also, average and maximum hop counts for delivered packets decreases with an increase in transmission power, as wireless nodes can cover more neighbors with high transmission power (Fig. 9c,9f).

B. Results with Asymmetric SUs

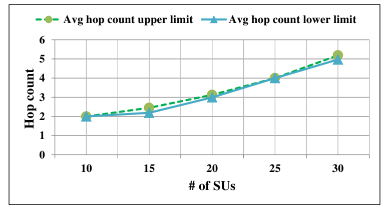
In our second simulation setting, we assume three different types of secondary users in the system model. These three types are different in their transmission and reception parameters. For the simplicity of making them asymmetric, we have



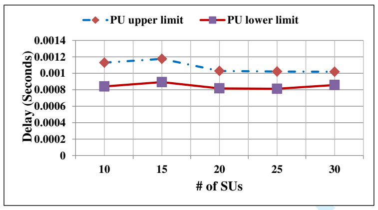
(a) per PU throughput



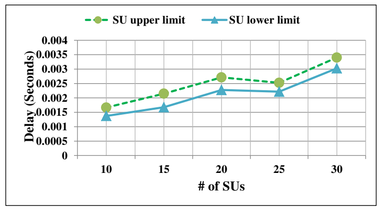
(b) per SU throughput



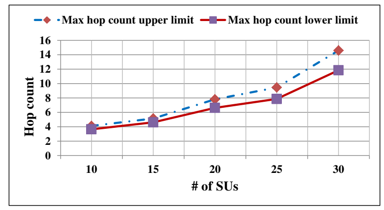
(c) Avg hop counts



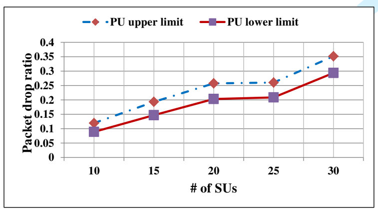
(d) Delay per packet for PUs



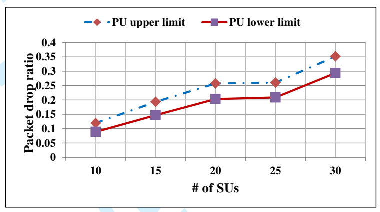
(e) Delay per packet for SUs



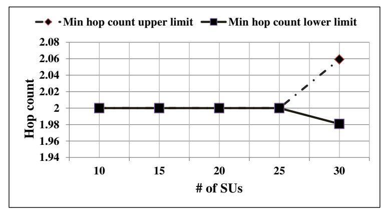
(f) Max hop counts



(g) Packet drop ratio for PUs



(h) Packet drop ratio for SUs



(i) Min hop counts

Fig. 8: Results with varying number of SUs, for symmetric SUs

chosen three different `TxGain/RxGain, (1, 2.5, 5)` for these different types of SUs. While selecting source and sink among SUs, we have connected similar type as source and sink, however, in a routing path, there could be different types of SUs. In this setting, we vary the number of PUs and the number of SUs to evaluate their impact on different performance metrics.

1) Results with Varying Number of PUs: For asymmetric SUs, we first vary the number of primary users from 5 to 10 pairs while the number of secondary users is fixed to 30. Fig. 10 shows the effect of the asymmetric SUs with an increase in the number of PUs in various performance metrics. Similar to symmetric SUs, the per user throughput increases for both PUs and SUs (Fig. 10a,10b) but delay increases for both PUs (Fig. 7d) and SUs (Fig. 10e), while in case of symmetric SUs, delay only increased in case of PUs (Fig. 7d). Also, packet drop ratio shows similar results for both PUs and SUs (Fig. 10g, 10h). However, average hop counts become constant in the asymmetric case (Fig. 10c), which is significantly different (much higher) from symmetric case (Fig. 7c). Moreover, maximum hop counts of asymmetric SUs (Fig. 10f) are also significantly lower than that of symmetric SUs (Fig. 7f).

2) Results with Varying Number of SUs: Lastly, we vary the number of secondary users from 15 to 30 (different from symmetric SUs, as we have 3 different types of SUs, we vary with an increment of 3) while the number of primary users is fixed to 5 pairs. The results are depicted in Fig. 11. Interestingly, the results throughput, delay, and packet drop ratio is comparable with symmetric case (Fig. 8), which suggests that our approach does not relay on the symmetric property of the SUs. However, for hop counts, the maximum and average hop count significantly falls in asymmetric case (Fig. 11c, 11f).

VII. Conclusion

In this paper, we explore the cooperation based collaboration model in cognitive radio network. In this regard, we formulate the route selection problem as an overlapping coalition formation game where secondary users actively participate in multiple routing paths. A PU's payoff is defined as a combination of data rate profit and path delay. An SU's payoff is defined as bit per energy spent in relaying. Based on the payoff functions defined in an OCF game, we devise a

(a) per PU throughput (b) per SU throughput (c) Avg hop counts

(d) Delay per packet for PUs (e) Delay per packet for SUs (f) Max hop counts

(g) Packet drop ratio for PUs (h) Packet drop ratio for SUs (i) Min hop counts

Fig. 9: Results with varying transmission power, for symmetric SUs

distributed multi-hop routing and scheduling protocol. Both primary and secondary users go through rounds of exchanging messages and negotiating on cooperation terms to build stable routing paths. We compare our algorithm with an existing work and the simulation results show that our approach outperforms the existing work in terms of PU and SU profit. We have implemented the routing protocol on top of an existing routing protocol and made changes to incorporate it into existing standard. We also present the performance of the routing protocol with varying different parameters e.g. throughput, end to end delay, packet loss. Furthermore, our algorithm provides stable routing paths that is also verified through simulation. In this paper, we consider single path routing between each primary source destination pair. We will investigate the impact of cooperative behavior in the case of multi-path routing and possible cooperation strategy with secondary users in future work.

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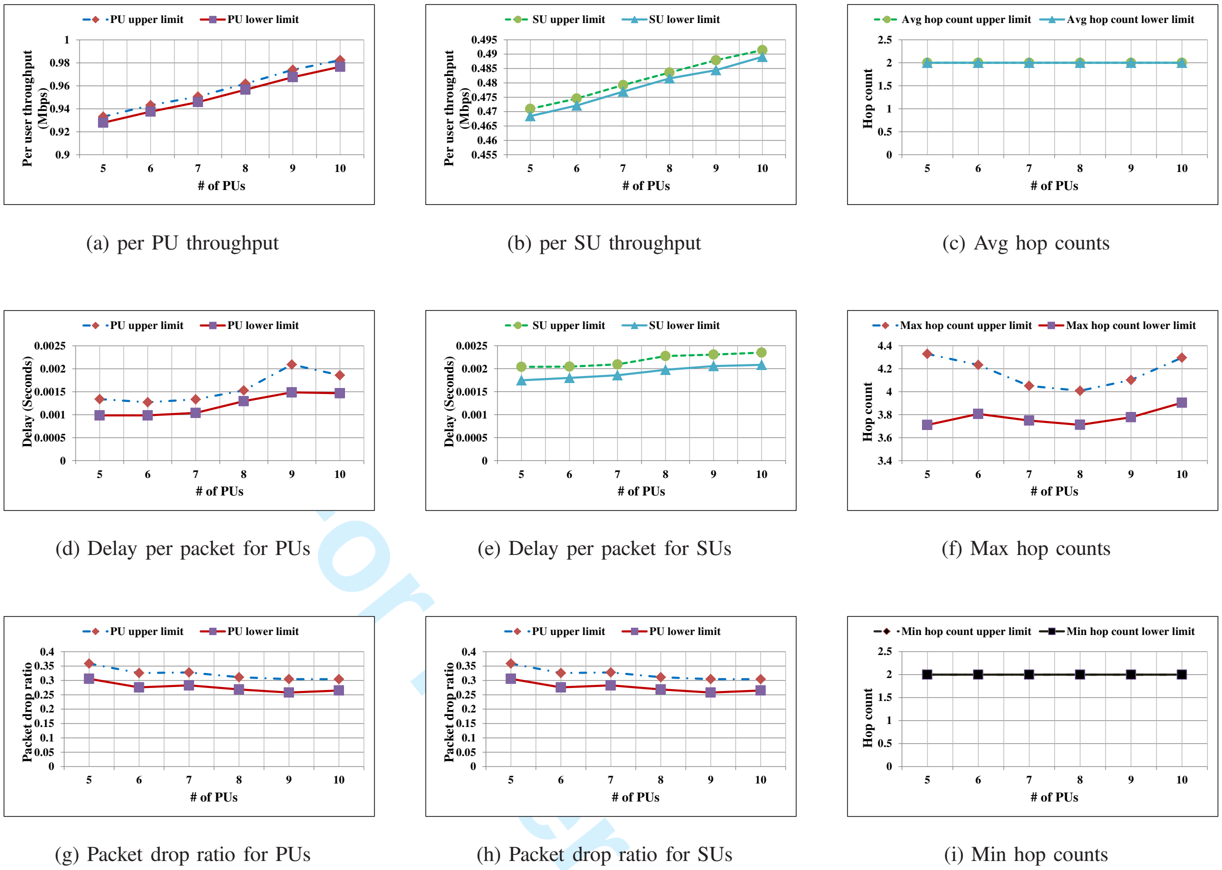

(a) per PU throughput (b) per SU throughput (c) Avg hop counts

(d) Delay per packet for PUs (e) Delay per packet for SUs (f) Max hop counts

(g) Packet drop ratio for PUs (h) Packet drop ratio for SUs (i) Min hop counts

Fig. 10: Results with varying number of PUs, for asymmetric SUs

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(a) per PU throughput

(b) per SU throughput

(c) Avg hop counts

(d) Delay per packet for PUs

(e) Delay per packet for SUs

(f) Max hop counts

(g) Packet drop ratio for PUs

(h) Packet drop ratio for SUs

(i) Min hop counts

Fig. 11: Results with varying number of asymmetric SUs

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A Multi-hop Cooperation based Routing Protocol in Cognitive Radio Networks

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Abstract

In this work, we consider a cognitive radio network where coexisting primary and secondary users explore cooperative diversity to experience improved quality of services. This goal driven collaboration model is formulated as an overlapping coalition formation game. Primary users' goal is defined in their payoff function in terms of throughput and end to end delay while secondary users' goal is incorporated into their payoff function in terms of transmission opportunities and power consumption. We analyze the complexity and stability concept of the game. Following the analysis of the game, we devise mcRoute, a routing algorithm that forms distributed multi-hop coalition based on their mutual interests. A primary user constructs its routing path in the form of a coalition with secondary users relaying its packet. A secondary user takes part in one or more coalitions by relaying corresponding primary packets and accessing their channels for its own transmission. We have discussed how this routing algorithm can be integrated with existing standards. We implemented the algorithm in ns-3 and analyzed the performance of the algorithm in terms of various metrics e.g. throughput, end to end delay, and packet loss.

Keywords

overlapping coalition game, cooperative diversity, routing protocol, payoff function

I. Introduction

The concept of cognitive radio network (CRN) has been incepted based on the principle that secondary users will detect idle spectrum through spectrum sensing and transmit their packets without the primary users' knowledge. Since its inception its application area has been broadened to explore its full potential. Among all models the research community has explored the cooperative diversity among primary and secondary users for improved network performance which is also referred to as cooperative cognitive radio network or CCRN([1]–[6]). Cooperative transmission brings a powerful means to combat channel fading, to achieve improved network capacity, and to provide efficient spectrum sharing among primary and secondary users. By exploiting cooperative diversity in this model, a primary user (PU) appoints a secondary user to relay its packets, and improves its throughput, and a secondary user (SU) increases channel access opportunities in return for its services. The success in single hop relay model motivates the researchers to study and explore the cooperation model in multi-hop communication [7]–[9].

In a multi-hop cooperation model, a primary user intends to establish a stable routing path to its destination by selecting multiple secondary users as intermediate relays. A secondary user, on the other hand, participates in one or more routing paths to ensure its transmission opportunities while limiting power consumption in relaying. Exploiting time and space diversity over multiple hops, this model can offer an innovative solution for transmission of $3G/4G$ cellular traffic through inter-carrier relaying communication [7]. The emerging technology of cognitive sensor networks with limited transmission range and longer lifetime expectation also advocates an efficient mechanism for relaying traffic [8]. On the other hand, cooperation among primary and secondary users eliminates the unintentional collision with PU transmission [9].

Although multi-hop cooperative relaying brings significant promises, we need to address several unique challenges to design the cooperation model and exploit its full benefits. The main challenge is to quantify the mutual interest of primary and secondary users into payoff function and incorporate it in their decision making. For example, while a secondary user as an intermediate relay may offer higher data rate, it also introduces delay in the same routing path. Therefore, a primary user's payoff must reflect the tradeoff between achievable throughput and path delay. On the other hand, unlike single hop relay model, a secondary user's cooperation benefit is defined not only by its own action but also by the action of other users in the routing path. Therefore, we must take into consideration the competition among the secondary users to meet their requirements. As a result, single hop relay based research ([1]–[5]) may not be optimal to multi-hop scenarios.

In this regard, few work [8], [9] address the multi-hop cooperative relay selection problem and design a cooperation model focusing on primary users' interest only. For example, Xue et al. [9] present a scheduling algorithm for a single primary transceiver pair whose routing path consists of fixed and predetermined secondary relay nodes. However, the competition among multiple primary source-destination pairs is not addressed and the consideration of fixed routing path make the cooperation model impractical. Although Li et al. [8] have considered multiple primary users in their work, the model becomes unstable when users have to deal with simultaneous requests. Also, a secondary user acts only in response to primary users' specific requests, and each one may cooperate with at most one primary user. This limitation prevents a secondary user from exploring its cooperative transmission opportunity. Furthermore, none of these models consider the interference between users in the network. Finally, we need to ensure the stability of the routing path and the scalability and complexity of the cooperation algorithm. An unscalable algorithm causes unstable routing path that leads to collision and packet loss, and the network output degrades significantly. Therefore, previously proposed framework do not represent the true potential of a multi-hop cooperation framework.

In this paper, we analyze the multi-hop cooperation framework and present $mcRoute$, a multi-hop cooperation-based relay selection and transmission scheduling algorithm addressing the issues discussed above. In contrast to the preliminary result[1] [10], this work adds (i) proof of the NP-completeness of the optimization problem and discussion on determination of the stability of the game (ii) integration of the protocol into existing standard explaining the protocol with flow charts and algorithms and (iii) finally, evaluation of the protocol by performing simulation in ns-3 with symmetric and asymmetric secondary users.

We consider coexisting primary and secondary users and analyze a multi-hop cooperation framework based on users' mutual interests. In this framework, we consider both primary and secondary users as 'active' participants, which actively adopt strategies to decide when and how to accept and offer cooperation from other users for improved system performance. This complex interaction and negotiation process is analyzed using an overlapping coalition formation game. The result from this analysis is then used to devise a cooperation based routing algorithm that handles simultaneous route discovery requests and ensures stable routing paths through coalition formation. Therefore, our network model is more general than others and exploits the full benefits of mutual cooperation.

The salient contributions of our work are summarized as follows.

- We formulate the multi-hop relay selection and routing problem as an overlapping coalition formation (OCF) game. Unlike existing approaches, this model involves active participation from both primary and secondary users where one secondary user can join more than one coalition. The user payoff

[1]Preliminary result of this work has been published in 10th IEEE International Workshop on Wireless Mesh and Ad hoc Networks

functions in the game are defined reflecting their mutual interest on the cooperation. The NP-hardness and stability of the game are analyzed.

- We propose $mcRoute$, a cooperation based routing algorithm based on the properties of the OCF game. Each primary transmitter initiates a route discovery request. When a secondary user receives such requests, it coordinates between multiple requests and carefully sets its cooperation parameters to show its interest to join in coalitions. After exchanging messages between users, the routing paths are guaranteed to converge and packets are scheduled for transmission.
- Finally, we develop the proposed joint routing and scheduling algorithm and compare our algorithm with an existing work [8] and show that our algorithm performs better than existing one. We have integrated the routing protocol with the existing standard in ns-3. We have analyzed the performance of our proposed algorithm in terms of various performance metrics e.g. throughput, end to end delay, and packet loss.

II. Related Work

Various collaboration based techniques have been applied in the context of cognitive radio networks to ensure improved system performance. While the channel sensing techniques [11], [12], [13] and multi-hop opportunistic routing [14], [15] have been proposed based on collaboration between secondary users only, there is a growing interest to study the collaboration between primary and secondary users in cognitive radio networks. This cooperation based cognitive radio network opens opportunity for researchers to investigate the mutual benefits of both primary and secondary users.

To understand the cooperation framework among primary and secondary users, researchers have applied some key technology like game theory, back-pressure algorithm [1], [9] and so on. Stackelberg game is arguably one of the most cited game theory approaches used to explain the cooperation framework ([4], [16]). For example, Simeone et al. [16] proposed a cooperation model considering a single primary link sharing spectrum with a set of ad hoc networks of secondary nodes. They formulated outage probability as a Stackelberg game to maximize the quality of service in terms of transmission rate. Similarly, the cooperation framework-based optimization problem was analyzed using Stackelberg game in [3], [4]. Hyder et al. investigated a cooperation model to ensure reliable delivery of real-time packet [17]. However, all these work mainly focuses on single hop communication in time domain or frequency domain or both [1]–[6].

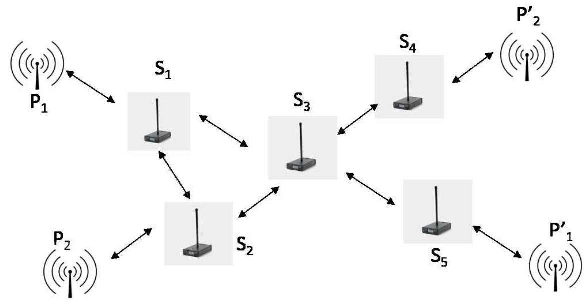


Fig. 1: Network model

Nevertheless a cross-layer optimal scheduling algorithm was proposed in [9] for cooperative multi-hop CRNs. In this network, the secondary users cooperate with primary users to transmit in a multi-hop fashion, and the secondary users earn transmission opportunity in return. The analysis was developed to achieve optimal throughput for the primary users where the upper bound was derived. However, the analysis considers a fixed routing path between a pair of primary source and destination nodes. Li et al. [8] considers multi-hop cooperation among primary and secondary users in both time and frequency domain and investigates the cooperation opportunity for finding a stable routing path. Accordingly, the routing path construction problem is formulated as a network formation game, and utility and payoff functions are defined accordingly. Primary users sequentially construct routing paths through one or more secondary users. However, members of two separate routing path are mutually exclusive i.e. no secondary user can participate in more than one routing path, which limits the opportunity of secondary users to improve its winning probability. Therefore, it is important to study the cooperation behavior considering the strategic independence of primary and secondary users.

III. System Model and Problem Formalization

In this section, we describe the network system model, and formulate our optimization problem using overlapping coalition formation game.

A. System Model

We consider a time slotted network consisting of m independent source-destination pairs of primary users. The set of primary transmitters is represented as $\mathcal{P} = \{P_1, \ldots P_m\}$ while the set of corresponding receivers is represented as $\mathcal{P}' = \{P'_1, \ldots P'_m\}$. We assume the coexistence of an ad hoc secondary network with n secondary transmitters in set $\mathcal{S} = \{S_1, \ldots, S_n\}$ and their corresponding receivers in set $\mathcal{S}' = \{S'_1, \ldots, S'_n\}$.

Fig. 1 depicts a network scenario consisting of two pairs of primary source destination pairs (P_1, P_1', P_2, P_2') and five secondary users (S_1, S_2, S_3, S_4, and S_5).

We assume that each primary transmitter $P_i \in \mathcal{P}$ is allocated a subset of sub-carriers, and together they are referred to as 'sub-channel' for data transmission [8]. We consider that each sub-channel consists of an equal number of sub-carriers, thereby achieving equal bandwidth[2], B. Each secondary user $S_i \in \mathcal{S}$ can operate over any of the sub-channels of these primary users based on their cooperation agreement.

We assume that users engage in cooperative transmission [1], [2], [8] if it increases their mutual interest. In a cooperative transmission, a primary user exploits the diversity (offered by coexisting secondary users) to build a routing path leading to improved network throughput. Similarly, a secondary user participates in relaying primary traffic for transmission opportunities. This mutual interest is the basis of users' participation in resource sharing and building a multi-hop cooperation model.

B. Preliminaries

An overlapping coalition formation game is a special type of cooperative game where a single player can share its resources in multiple coalitions. This theory has been used to model collaborative spectrum sensing in cognitive radio networks [18], and interference management in small cell networks [19], among other scenarios. In the context of relay selection in $CCRN$, we adopt the overlapping coalition formation game to model and analyze the behavior of the framework. We present the properties of the overlapping coalition formation game in the following definitions.

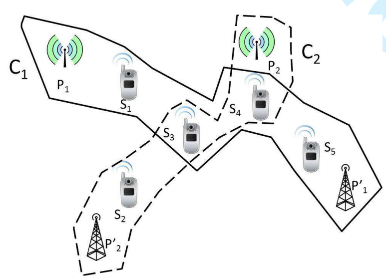


Fig. 2: Overlapping coalition example

1) OCF Game and Properties: An OCF game $G(\mathcal{N}, v)$ is represented with player set $\mathcal{N}$ where players share resources to form coalitions and a characteristic function v that defines the maximum payoff from each coalition [19]. The outcome of the OCF game is represented with a pair $(\mathcal{CS}, \mathbf{u})$ where $\mathcal{CS}$ represents

[2]The model can be extended to users with variable bandwidth.

the set of coalitions over $\mathcal{N}$ and $\mathbf{u}$ represents the payoff distributions among users. The main components of the game are defined as follows:

- **Coalition and Coalition Structure**: A coalition C_j is represented with a resource vector $\mathbf{r}^j = (r_1^j\ r_2^j \ldots r_a^j)$ where r_i^j denotes the fraction of resource player i allocates to coalition C_j and $|\mathcal{N}| = a$. An overlapping coalition structure over $\mathcal{N}$, denoted as $\mathcal{CS}$, is defined as a set $\mathcal{CS} = \{C_1, \ldots, C_b\} = \{\mathbf{r}^1, \mathbf{r}^2, \ldots \mathbf{r}^b\}$ where b is the number of coalitions, $C_j \subset \mathcal{N}$ and $\cup_{j=1}^b C_j = \mathcal{N}$. The coalitions can be overlapping, and thus, the sets may not be disjoint. If $r_i^j = 0$, it means that user i does not belong to coalition C_j. $\mathcal{CS}_\mathcal{N}$ denotes the set of all possible coalition structures over $\mathcal{N}$. The characteristic function $v(C_j)$ denotes the value of a coalition C_j while the total valuation of a coalition structure is defined as $v(\mathcal{CS}) = \sum_{j=1}^b v(C_j)$. The superadditive cover of a characteristic function v is the mapping

$$v^*(C_j) = \sup_{\mathcal{CS} \in \mathcal{CS}_\mathcal{N}} \{v(\mathcal{CS}) | \sum_{C'_j \in \mathcal{CS}} C'_j \leq C_j\} \tag{1}$$

$v^*(C_j)$ calculates the maximum that the players in coalition C_j can earn given their resource contribution $\mathbf{r}^j$.

- **Payoff Distribution**: While the characteristic function v denotes the value of a coalition, the payment vector $\mathbf{u}^j$ specifies the payoff distribution to the members of each coalition $C_j \in \mathcal{CS}$. The payment vector of an individual coalition C_j can be represented as $u(C_j, \mathcal{CS}) = u(\mathbf{r}^j, \mathcal{CS}) = \mathbf{u}^j = [u_1^j\ u_2^j \ldots u_a^j]$. The payoff of an individual player i can be represented as a summation of payment from all the coalitions it has participated in. $u_i(\mathcal{CS}) = \sum_{j=1}^b u_i(C_j, \mathcal{CS}) = \sum_{j=1}^b u_i^j$. The payoff of a coalition is defined as the summation of the payoff of all its members earned from joining the coalition.
- **Imputation**: An imputation for $\mathcal{CS}$ is a y tuple $\mathbf{u} = (\mathbf{u}^1 \ldots \mathbf{u}^b)$ where $\mathbf{u}^i \in \mathbb{R}^a$ for $i = 1 \ldots b$ such that
  - for every coalition $\mathbf{r}^j \in \mathcal{CS}$, $\sum_{j=1}^b u_i^j = v(\mathbf{r}^j)$ and $r_i^j = 0$ implies $u_i^j = 0$.
  - the total payoff of an agent i is at least as large as what he can achieve on his own $\sum_{j=1}^b u_i^j \geq v^*(\{i\})$.

  The set of all imputations for a coalition structure $\mathcal{CS}$ is denoted as $\mathcal{I}(\mathcal{CS})$. A pair $(\mathcal{CS}, \mathbf{u})$ is a feasible outcome if $\mathbf{u} \in \mathcal{I}(\mathcal{CS})$. The feasible outcome also implies a stable coalition structure.

2) Stability and Arbitration Function in OCF Games: If any subset of players can increase their payoffs by deviating from an outcome of the game and readjusting their resources the game becomes unstable. The arbitration function concept [20], [21] is introduced to analyze the stability of the OCF games. The arbitration function $\mathcal{A}(\mathcal{CS}, \mathbf{u}, \mathcal{Q})$ is a mapping that receives a feasible outcome $(\mathcal{CS}, \mathbf{u})$, a deviating set of players $\mathcal{Q} \subset \mathcal{N}$, and the deviation proposal of the set and outputs a number for each coalition C_j with supp(C_j) $\cap$ $\mathcal{Q} \neq \emptyset$, supp($C_j$) $\cap$ $\{\mathcal{N} \setminus \mathcal{Q}\} \neq \emptyset$. This number represents how much of C_j's payoff the deviators in supp(C_j) $\cap$ $\mathcal{Q}$ can keep if they deviate. The output will be dependent on the features of the game. Let us denote that $\mathcal{A}^*(\mathcal{CS}, \mathbf{u}, \mathcal{Q})$ represents the maximum a set of players $\mathcal{Q}$ can get when deviating from the outcome $(\mathcal{CS}, \mathbf{u})$. We conclude that an outcome $(\mathcal{CS}, \mathbf{u})$ belongs to $\mathcal{A}$-core if no player set $\mathcal{Q}$ can deviate so that each $i \in \mathcal{Q}$ can get more than $u_i(\mathcal{CS}, \mathbf{u})$. However, it has been shown that computing an $\mathcal{A}$-core outcome of an OCF game is NP-complete [20].

Chalkiadakis et al. in [22] presented three concepts of core in OCF games with respect to arbitration function – (1) the deviators receive nothing from the existing coalitions (known as c-core or conservative core), (2) the deviators receive the same from unaffected coalitions (known as r-core or refined core), and (3) the deviators receive the same payoff unless the non-deviators' payoff is affected (known as o-core or opportunistic core).

C. Formulation

We formulate the cooperative relay selection and scheduling problem as an OCF game, G = $(\mathcal{N}, v)$ where $\mathcal{N} = \mathcal{P} \cup \mathcal{S}$, and $|\mathcal{N}| = m + n$. We present the formulation into two steps - routing path construction as coalition formation and payoff distribution and transmission scheduling as resource sharing in an OCF game.

1) Routing path Construction as Coalition Formation: The construction of routing path can be mapped to the coalition formation in an OCF game. Each primary transmitter $i \in \mathcal{P}$ starts the process, secondary users join the coalition if profitable, and a coalition C_i (i.e. a path between the primary transmitter and receiver) is formed. Thus, C_i represents the routing path starting with primary transmitter i, followed by one or more secondary transmitters from the set $\mathcal{N}$ based on their mutual needs - constructing a multi-hop routing path and creating transmission opportunities respectively.

For example, there are two coalitions formed in Fig. 2. The first primary transmitter-receiver pair (P_1, P_1') forms a coalition C_1 with four secondary users S_1, S_3, S_4, and S_5. This implies the packets from primary user P_1 follows this path $P_1 \rightarrow S_1 \rightarrow S_3 \rightarrow S_4 \rightarrow S_5 \rightarrow P_1'$. The second primary transmitter-receiver pair (P_2, P_2') forms another coalition C_2 with three secondary users S_2, S_3, and S_4. There are two secondary users (S_3, S_4) overlapping in both the coalitions.

2) Scheduling as Resource Sharing: The resource vector of a coalition C_j is denoted as $\mathbf{r}^j = [r_1^j \dots r_{(m+n)}^j]$ where the first m entries represent resource contribution from primary users and the next n entries represent contribution from secondary users. Considering a time slotted model, each user has maximum T time slots to either share with other users in its coalition or schedule its own transmission.

A primary user only contributes to its own coalition and the resource contribution by a primary user $i \in \mathcal{P}$ is the fraction of total number of time slots over which secondary users in its coalition are transmitting their own packets in its sub-channel,

$$r_i = r_i^i = \frac{1}{T}\sum_{t=1}^{T}\sum_{j\in C_i}\theta^i_{j\to j'}(t) \le 1, \forall\ i \in \mathcal{P}. \tag{2}$$

Here, $\theta^j_{x\to y}(t)$ is an indicator function whose value can be $\{0,1\}$. $\theta^j_{x\to y}(t) = 1$ implies that user x sends packet to user y at time t in coalition C_j where $x, y \in \mathcal{N}$, 0 means no transmission. If $y = x'$, user x sends packet directly to its corresponding destination.

A secondary user may contribute its timeslots to more than one coalitions. The resource contribution by a secondary user $i \in \mathcal{S}$ to a coalition C_j is the fraction of time slots over which it engages in receiving and relaying packets of the primary user $j \in \mathcal{P}$ of that coalition.

$$r_i^j = \frac{1}{T}\sum_{t=1}^{T}\left[\sum_{k\in C_j}\theta^j_{i\to k}(t) + \sum_{q\in C_j}\theta^j_{q\to i}(t)\right], \forall\ i \in \mathcal{S}. \tag{3}$$

In order to schedule users' transmission without interference, additional constraints must be satisfied. In general, any user $x \in \mathcal{N}$ cannot send to more than one user $y \in \mathcal{N}$. Also, it cannot receive from more than one user $y \in \mathcal{N}$ at the same time.

$$\sum_{j=1}^{m}\sum_{y\in C_j}\theta^j_{x\to y}(t) \le 1, (x \in \mathcal{N}), \tag{4}$$

$$\sum_{j=1}^{m}\sum_{y\in C_j}\theta^j_{y\to x}(t) \le 1, (x \in \mathcal{N}) \tag{5}$$

Also, a user $x \in \mathcal{N}$ cannot send and receive packet simultaneously at the same time slot t.

$$\sum_{j=1}^{m}\left[\sum_{y\in C_j}\theta^j_{x\to y}(t) + \sum_{y\in C_j}\theta^j_{y\to x}(t)\right] \le 1. \tag{6}$$

Furthermore, all the scheduled transmissions must be interference free. So, while a user in a coalition is receiving a packet from another user in the same coalition, all other interfering users to that receiver in the same coalition cannot send any packet. Otherwise, the receiver will experience interference.

$$\theta^j_{x\to y}(t) + \sum_{z\in I_y}\sum_{q\in\mathcal{V}_z}\theta^j_{z\to q}(t) \leq 1. \tag{7}$$

Here, I_y represents the set of nodes interfering to users y's transmission while $\mathcal{V}_z$ represents the set of nodes within transmission range of user z. Note that, a user's interference range is usually longer than its transmission range.

D. Payoff of a Primary User

The primary user's goal is to increase throughput. Whereas relayed transmission increases data rate, too many hops may introduce significant delay. Therefore, the payoff function of a primary user should reflect the tradeoff between data rate and delay. Accordingly, the payoff of a primary user $i \in \mathcal{P}$ from a coalition C_i, $u^p_i(C_i, \mathcal{CS})$ is defined in terms of data rate profit $\Re_i(C_i)$ and path delay profit $\mathbb{D}_i(C_i)$ as

$$u^p_i(C_i, \mathcal{CS}) = \alpha\Re_i(C_i) + (1-\alpha)\mathbb{D}_i(C_i). \tag{8}$$

Here, the parameter α denotes a primary user's preference between throughput and delay in payoff calculation. For example, $\alpha = 1$ means that a primary user's only focus is to maximize throughput while $\alpha = 0$ means that the user is delay sensitive and aims to minimize delay.

Data Rate Profit: The data rate profit $\Re_i(C_i)$ of a primary user i in coalition C_i is calculated comparing cooperative transmission rate[3] $R_i(C_i)$ with $R_i(\{i\})$. $R_i(\{i\})$ denotes the effective transmission rate that the primary player i can achieve from direct transmission i.e. coalition has only one player. We can calculate $R_i(\{i\})$ directly from (10).

$$\Re_i(C_i) = \frac{R_i(C_i) - R_i(\{i\})}{R_i(\{i\})}. \tag{9}$$

We start our analysis with the calculation of data rate. We assume that the channel experiences white Gaussian noise, and the signal quality degrades due to path loss. The effective transmission rate R_{ij} from node i to node j is calculated following [23]. Thus, we calculate transmission rate over any link between two consecutive members in a coalition as follows:

$$R_{ij} = B\log_2\left(1 + \frac{W_{tx}G^i_tG^j_r(d_0/d^{ij})^{\gamma^{ij}}}{N^{ij}_0 B}\right) \tag{10}$$

[3] $R_i(C_i)$ and $R_i(\mathcal{CS})$ are the same for a primary user i

where B, W_{tx}, G_t^i, G_r^j, and N_0^{ij} denote the bandwidth, transmission power and transmitter gain of node i, receiver gain of node j, and power spectral density of noise between i and j respectively. Also, d is the distance between node i and node j, d_0 is the reference distance for the antenna far-field, and γ^{ij} is the path loss exponent between i and j. The overall packet transmission rate of a primary user from a coalition is denoted as the minimum data rate of any of the links in that coalition (since nodes have to receive the packet first and then send it to the next one, the effective transmission rate is factored by $\frac{1}{2}$). Consequently, the effective transmission rate of a primary user i in a coalition C_i is defined as,

$$R_i(C_i) = \min\left(R_i(\{i\}), \frac{1}{2}\min_{\forall_{j,j+1\in C_i}}\left(R_{j,j+1}\left(C_i\right)\right)\right) \tag{11}$$

Here, $R_{j,j+1}\left(C_i\right)$ denotes the data rate between two consecutive members in the coalition C_i.

Delay Profit: The delay profit $\mathbb{D}_i(C_i)$ of a primary user i in coalition C_i is calculated as a ratio of delay improvement compared to delay from direct transmission.

$$\mathbb{D}_i(C_i) = \frac{D_i(\{i\}) - D_i(C_i)}{D_i(\{i\})}. \tag{12}$$

We assume that both the PUs and SUs generate traffic following a Poisson distribution. Authors in [24] modeled the Poisson traffic system with an $M/G/1$ queue and calculated end to end packet delay. We can use (13) to calculate the delay in direct transmission

$$D_i(\{i\}) = \frac{\lambda_i}{2\mu_i(\mu_i - \lambda_i)} + \frac{1}{\mu_i}. \tag{13}$$

Here, λ_i and μ_i denote the packet arrival rate (according to Poisson distribution) and packet transmission rate, respectively and for a stable system, $\lambda_i < \mu_i$.

The delay of the routing path is the summation of each link delay in the coalition.

$$D_i(C_i) = \sum_{j,j+1\in C_i} D_{j,j+1}(C_i). \tag{14}$$

where, $D_{j,j+1}(C_i)$ denotes the delay between two consecutive secondary users in the coalition C_i.

In relayed transmission, the secondary user receives packet from cooperating primary users at different rate in addition to its own traffic. Based on the cooperation, a secondary user first relays primary traffic and then sends its own packet. To determine the link delay $D_{j,j+1}(C_i)$ experienced by a primary packet, we use an $M/G/1$ queueing model with vacation period. In this queueing model, the server continues vacation

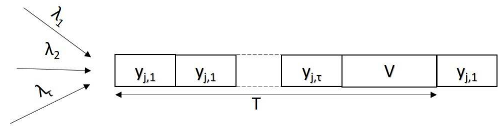


Fig. 3: M/G/1 Queueing Model with Vacation Period

until it finds at least one waiting unit upon return from vacation. In the context of relayed transmission, a secondary user relays primary traffic and takes 'vacation' to transmit its own packet (see Fig. 3). Let us assume that a secondary user j receives packets from τ different primary users at rates following Poisson distribution with $\lambda_1, \ldots, \lambda_\tau$ and offers relay service times $y_{j,1}, \ldots, y_{j,\tau}$ respectively. The service times are independent random variables drawn from a common distribution H_y and finite mean $\bar{y}$. The relayed transmission is followed by vacation time V which is a random variable with distribution $F(V)$ and finite mean $\bar{V}$. Using Cobham's well-known formula for the waiting time of an arbitrary arrival in the higher priority queue, we can calculate the mean delay $D_{j,j+1}(C_i)$ experienced by a packet of a primary user i from one secondary user j to another secondary user $j+1$ in the coalition C_i as follows [25]

$$D_{j,j+1}(C_i) = \frac{\lambda E(y^2)}{2(1-\lambda\bar{y})} + \frac{E(V^2)}{2\bar{V}}, \tag{15}$$

where, $\lambda = \lambda_1 + \ldots + \lambda_\tau$.

E. Payoff of a Secondary Player

The secondary user's goal is to ensure transmission opportunity in exchange for its relay services. At the same time, it wants to keep the power consumption to minimum. Accordingly, the payoff value of a secondary player j is defined in terms of the fraction of transmission period earned in return for relay period and power consumption in relaying. A secondary player's payoff is determined by the following equation:

$$u_j^s(C_i, \mathcal{CS}) = \frac{R_{jj'} \times \sum_{t=1}^{T} \theta^i_{j\to j'}(t)}{T \times \sum\limits_{k\in\mathcal{P}} \mathrm{w}_{j,k} \times r_j^k} \tag{16}$$

Here, $\theta^i_{j\to j'}(t)$ denotes that user j transmits to its destination using the sub-channel of primary user i in coalition S_i at time t, $R_{jj'}$ denotes the transmission rate between secondary transmitter j and secondary receiver j' which can be calculated using (10), r_j^k is already defined as resource allocated by j for coalition k, and $\mathrm{w}_{j,k}$ denotes the transmission power spent in relaying traffic from primary user k per time unit. As it can be seen from the payoff function, a secondary user can increase its payoff either by asking for more bandwidth time from the primary user or spending less power in relaying primary traffic.

F. Problem Statement

Given the set of primary players $\mathcal{P}$ and secondary players $\mathcal{S}$ and their corresponding resources $\mathbf{r}$, our goal is to allocate resources into m coalitions such that individual payoff is maximized while satisfying the routing and scheduling constraints mentioned in (2) - (7). Mathematically, we define the problem statement as follows:

$$\max_{\theta_{i\to j}} u_i^p, u_j^s \;\forall\; i, j \in \mathcal{P} \cup \mathcal{S} \tag{17}$$
$$\text{subject to (2) - (7)}$$

As mentioned, finding stable outcome in an unconstrained OCF game is NP-complete [20]. However in our model, each coalition must have only one primary user, and therefore, the optimization problem reduces to m-coalition OCF game. Also, without loss of generality, we assume that each user $i \in \mathcal{N}$ has w_i number of available timeslots to share with other users. So, we can interpret the model as a discrete OCF game and the characteristic function reduces to a mapping from $[0, w_1] \times [0, w_2] \times \cdots \times [0, w_{m+n}]$ to $\mathbb{R}$. Furthermore in our model, a deviated user does not get affected until its deviation does not cause payoff reduction to non-deviators. Therefore, we adopt the $o-core$ concept for stability analysis. Finally, the optimization problem is reduced to a discrete m-coalition OCF game with opportunistic arbitration function that can be solved to determine a stable outcome in polynomial time [26]. Since it is not practical to coordinate between all users in a large network, we develop a routing protocol based on distributed coalition formation in the next section.

IV. Cooperative Routing Protocol

In this section, we present $mcRoute$, a distributed cooperative routing protocol. Unlike traditional routing protocol, the participating users have different goals and often they are conflicting. Therefore, we need to take into consideration the conflict of interests while designing the routing protocol. We propose a three way message communication where primary and secondary users exchange cooperation information to build stable routing paths. There are three types of message defined in $mcRoute$. The first message is $coalition\_join$ request $C_i(i)$ that denotes a coalition request initiated by primary user i. The second message is $coalition\_reply$ request $C_i(j)$ which is a response from secondary user j to the initiating primary user i.

The third message is $coalition\_approval$, C_i which confirms secondary users in the selected routing path of primary user i.

To coordinate the message exchange, a primary user creates a virtual coalition agent referred to as 'PU agent' which is responsible for setup and maintenance of coalition with secondary users. Each primary user has only one virtual agent. On the other hand, the virtual coalition agent of a secondary user is referred to as an 'SU agent'. A secondary user may have multiple coalition agents (at most m), and all these agents of a secondary user coordinate and collaborate to form coalitions.

In $mcRoute$, the primary user i initiates a $coalition\_join$ request $C_i(i)$ to search for a more profitable path than the direct transmission. The message includes basic parameters e.g. direct transmission rate, traffic rate, and direct end to end delay in the message. The message is then sent to each user $j \in V_i$ where V_i denotes the set of secondary users within its transmission range. A primary user moves to a wait state to receive coalition offer from its neighbors. If no reply is received within a predefined time, the primary user continues transmitting directly to the destination. Otherwise, the primary user embraces the coalition offer that maximizes its payoff.

$$j^* = \arg\max_j \; u_i^p(C_i(j)) \tag{18}$$

Finally, the primary user sends a $coaltion\_approval$ C_i towards the selected secondary user j^*. The entire process of routing path construction continues until the convergence parameter β_d reduces below a predefined threshold ϵ (the update process of β_d is discussed later). The protocol is summarized in Algorithm 1.

An SU j receiving a $coalition\_join$ request $C_i(i)$ first checks whether the destination is reachable or not. Otherwise, it either drops the request from i (if it is not interested) or forwards it to its neighbor $k \in V_j$. Since a secondary user's success depends on other users on routing path, it takes its decision in two steps. First, it selects the one that offers the best coalition offer for the target primary user. Second, it combines its own cooperation terms to the selected offer considering its transmission requirement and prior commitment to other primary users. We explain the parameter selection mechanism in Sec. IV-A. The combined offer is then sent in the upstream direction as a coalition offer $coalition\_reply$, $C_i(j)$ from user j. When secondary user j receives $coalition\_approval$ C_i, it updates its routing table, schedules its packet for transmission, and forwards the packet in the downstream direction. The protocol is summarized in Algorithm 2.

Algorithm 1 *mcRoute*: PU agent of a primary user i

$C_i = \{i\}$, $u_i^p(C_i) = 0$
initiate a *coalition_join* request $C_i(i) = \{i\}$
repeat
  send $C_i(i)$ to each node $j \in V_i$
  receive *coalition_reply* $C_i(j)$ from each node $j \in V_i$
  select $j^* = \arg\max_j u_i^p(C_i(j))$
  if $u_i^p(C_i) < u_i^p(C_i(j^*))$ **then**
    select $C_i = C_i(j^*)$
    send the *coalition_approval* C_i to user j^*
  end if
  update β_d, add j^* as next hop, and update the routing table
  advance round d
until $\beta_d \geq \epsilon$

Algorithm 2 *mcRoute*: SU agent of a secondary user j

repeat
  for each *coalition_join* request $C_i(i)$ **do**
    initialize $C_i(j) = \{j\}$
    if destination is not reachable **then**
      forward the packet $C_i(i)$ to each node $k \in V_j$
      receive *coalition_reply* packet $C_i(j)$ from each node $k \in V_j$
      select $j^* = \arg\max_k u_i^p(C_i(k))$
      combine $C_i(j) = C_i(j*) \cup C_i(j)$
    end if
    calculate $u_j^s(C_i(j))$, $u_i^p(C_i(j))$ with its own offer
    send *coalition_reply* packet $C_i(j)$ in upstream and move to wait state
    if *coaltion_approval* C_i is received **then**
      forward the *coalition_approval* packet C_i in downstream
      update routing table
    end if
  end for
until no more *coalition_join* packet has been received

A. *Coalition Offer and Payoff Calculation*

When a secondary user $j \in \mathcal{S}$ receives coalition proposals from its neighbors in response to a *coalition_join* $C_i(i)$, it selects the cooperation offer that provides the most profitable path for the initiating primary user $i \in \mathcal{P}$. Let us assume that the offer, $C_i(k)$ from user $k \in V_j$ is selected. The user j next selects two parameters as its cooperation terms to add into the chosen cooperation offer $C_i(k)$. The first parameter denotes the cycle time it allocates for relaying the corresponding primary user and the second parameter denotes the bandwidth time it requests from the coalition of primary user i.

In order to select these two parameters, the user checks the offers it made to other primary users. In

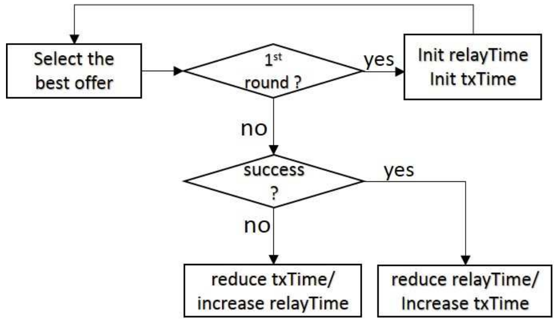


Fig. 4: Decision Flowchart of a Secondary User

the first round, it selects parameters for each coalition request proportional to the power consumption in relaying the corresponding primary traffic. Based on its success at previous rounds, a secondary user either (i) reduces its demand for transmission time (txTime) while relay time remains unchanged, (ii) requests more transmission time while relay time is unchanged. (iii) approves more relay time to the primary user with the request of the same unchanged transmission time, or (iv) reduces relay time with unchanged transmission time. A flowchart is added to explain the decision process of a secondary user in Fig. 4.

Finally, the cooperation offer of a secondary user is converted to a form that is understandable to a primary user that expects the offer in the form of cooperative data rate and end-to-end delay.Accordingly, an SU j calculates the payoff for primary user i using (11) as follows:

$$R_i(C_i(j)) = \min(R_{j,k}, R_i(C_i(k)).$$

The intermediate path delay (15) introduced by a secondary user j in a coalition S_i is as follows:

$$D_j(C_i) = \frac{\sum_{t=1}^{T}\sum_{x=1}^{m}\left(\theta^x_{j\to x}(t) + \theta^x_{x\to j}(t)\right) \times len}{\sum_{t=1}^{T}\theta^i_{j\to i}(t) \times R(C_i)}$$

$$D_i(C_i(j)) = D_i(C_i(k)) + D_j(C_i)$$

Here, len denotes the length of the packet. Also, the payoff of a secondary user j is calculated based on the resource sharing with the primary users using Eqn. 16.

B. Stability of Coalitions

In order to ensure stable coalitions, we control the search for coalition by two parameters. A primary user maintains a convergence parameter, β_p. The value of this parameter determines whether the user will initiate another round of route discovery or not. The initial value of the parameter is set to 1. After each round f, the user calculates the change in payoff over total rounds and if the value drops lower than the threshold (ϵ), the user stops the route discovery process. The value of ϵ is a system defined parameter. The parameter β_p at round f is calculated as follows:

$$\beta_p = \begin{cases} |\Delta u_f|/f & \text{if } f > 1 \\ 1 & \text{otherwise} \end{cases} \tag{19}$$

where Δu_f denotes the difference between user i's payoff at round f and at round $f-1$ which is upper bounded by the difference between optimal payoff in relayed transmission and payoff in direct transmission. As the number of round increases, β_f also decreases. If β_p reaches to a value below the threshold ϵ the primary user remains stable with its current coalition. Also, each secondary user cannot request transmission time lower than β_s. When a secondary user's request with minimum transmission time to a primary user fails, it stops participating in that coalition. Thus, the usage of β_p and β_s controls the convergence speed, and the routing paths become stable.

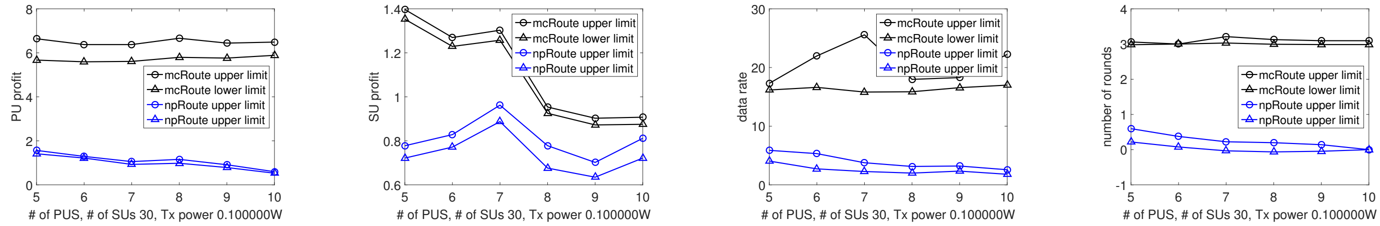
When users are on a stable routing path, the channel states may change that may reduce the payoff valuation of one or more users on the path. To avoid continuing on a less profitable path, all participants continuously monitor the payoff value. If the payoff drops significantly from the agreed one, the primary user may switch to direct transmission and initiate the search for the routing path while a secondary user may remove itself from the path and search for a new opportunity.

In the case of mobile secondary users, the stability of the routing path depends on their speed. If the users move too fast, the routing path becomes unstable. However, if the users are location aware, they can include their location information into the cooperation decision. We will investigate the performance of the routing protocol in future work.

When the users are on a stable routing path, the channel states may change that may reduce the payoff valuation of one or more users on the path. To avoid continuing on a less profitable path, all participants continuously monitor the payoff value. If the payoff drops significantly from the agreed one, the primary user may switch to direct transmission and initiate the search for the routing path while a secondary user may remove itself from the routing path and search for a new opportunity.

V. Numerical Simulation

In this section, we analyze the performance of coalition based multi-hop cooperative routing algorithm. We simulate a cognitive radio network located in an area of $5000\text{m} \times 5000\text{m}$. We deploy different number



(a) average PU profit (b) average SU profit (c) average data rate (d) number of rounds

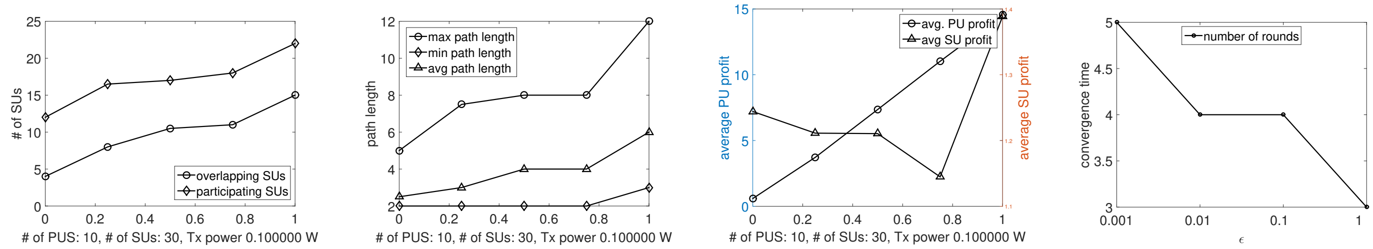
Fig. 5: Comparison between mcRoute and npRoute [8]

of primary source-destination pairs (5 to 10). Each primary source node is assigned a channel with 20KHz bandwidth. The transmission cycle time is normalized to one unit and a secondary user requires $1/10$th of its cycle time is for supporting its minimum rate requirement. In order to evaluate the impact of cooperation in the routing path selection, we vary the number of primary users, secondary users, and transmission power. The primary source and destination nodes are randomly and uniformly deployed in the network area. Secondary users are also randomly and uniformly deployed in the area so that each user has at least one neighbor. We have also made sure that each pair of primary source and destination node is connected, and there exists at least one path between primary source-destination pairs through secondary users. For each set of input configuration, we have generated as many as 50 sample scenarios and the statistics are recorded for each set. Finally, for statistical confidence, we take an average of results of all sets to represent the outcome of each scenario.

A. *Performance Comparison with Prior Work*

To compare with an existing algorithm, we implement a modified version of the algorithm proposed in [8]. We have chosen [8] over [9] since the latter one assumes fixed routing path. Unlike [8], in the modified version, a secondary user may receive simultaneous coalition requests from more than one primary user. A secondary user processes multiple concurrent cooperation requests, selects one of them randomly, and participates in routing path of only one primary user at a time. We refer to this algorithm as ‘non-overlapping routing’ in short ‘npRoute’.

We calculate PU and SU profit (with 95% confidence interval) with the varying number of primary users while the transmission power is set to 0.1W and number of secondary users is set to 30. Fig. 5a and 5b show that the proposed cooperation algorithm achieves higher PU and SU payoff than those of npRoute. In mcRoute, PU profit stays almost constant with the increase in the number of PUs. This is because



(a) number of overlapping SUs vs. α (b) path length vs. α (c) profit vs. α (d) Convergence and stability

Fig. 6: Results with varying algorithm parameters

each primary user on average cooperates with the same number of secondary users and increasing number of primary users does not increase the average PU profit. On the other hand, SU profit decreases due to increasing competition among them. We also show in Fig. 5c that the cooperative data rate achieved through mcRoute is higher than npRoute. We also determine average number of rounds required to reach a stable path [18]. It also indicates the convergence speed of the algorithm. Fig. 5d shows that npRoute converges to a local maxima when it handles multiple cooperation offers simultaneously. On the other hand, mcRoute goes through few more rounds to achieve higher data rate and higher PU and SU payoff. Similarly, we also vary the number of secondary users and calculate PU and SU profit (with 95% confidence interval). mcRoute creates more cooperation opportunity for secondary users than npRoute and increases the number of secondary users involved in cooperation and their profits as well.

B. Results with Algorithm Parameters

We investigate the impact of changing two key parameters in relay selection and coalition formation. The first parameter α denotes the tradeoff between throughput and delay in the payoff of a primary user in Eqn. 8. We vary the value of α between 0 and 1 and record the change in user payoff, path length, and number of cooperating secondary users. The result is shown in Fig. 6. As the value of α reaches to 1, the primary user is more interested in increasing data rate and achievable throughput and ignoring the delay cost introduced by relaying secondary users. Therefore, number of participating secondary nodes (Fig. 6a) and path length (Fig. 6b) increases with the increase in value of α. This also increases PU profit almost linearly and opens more opportunity for secondary users to increase their payoff (Fig. 6c). The second parameter we consider here is the threshold ϵ that controls the number of iterations for the search of a stable routing path and the stability of the algorithm. Fig. 6d shows that more rounds are needed to reach stable coalitions with smaller values of ϵ. Thus, these two parameters control the cooperation opportunity and convergence speed of the routing paths.

VI. Integration to Existing Standards

In this section, we discuss how the proposed algorithm can be integrated to existing standards. We implement our protocol in widely used ns-3 network simulator [27] and present the performance of our proposed protocol in terms of throughput, end to end delay, packet loss and so on.

We have modified the `RReq` and `RRep` packet formats of `aodv` to incorporate few parameters of coalition request and coalition reply message. Also, we have added three timers in the proposed routing algorithm to prevent users from waiting indefinitely at different system states. First, `mcRouteTimer` specifies the maximum waiting time an agent should wait for coalition reply. This is true for both PUs and SUs. Second, `mcRouteApprovalTimer` specifies the maximum waiting time after sending/forwarding coalition approval from user agents (both at PU and SU). Third, `mcRouteReplySentTimer` defines the maximum waiting time after sending coalition reply from user agents (only at SU).

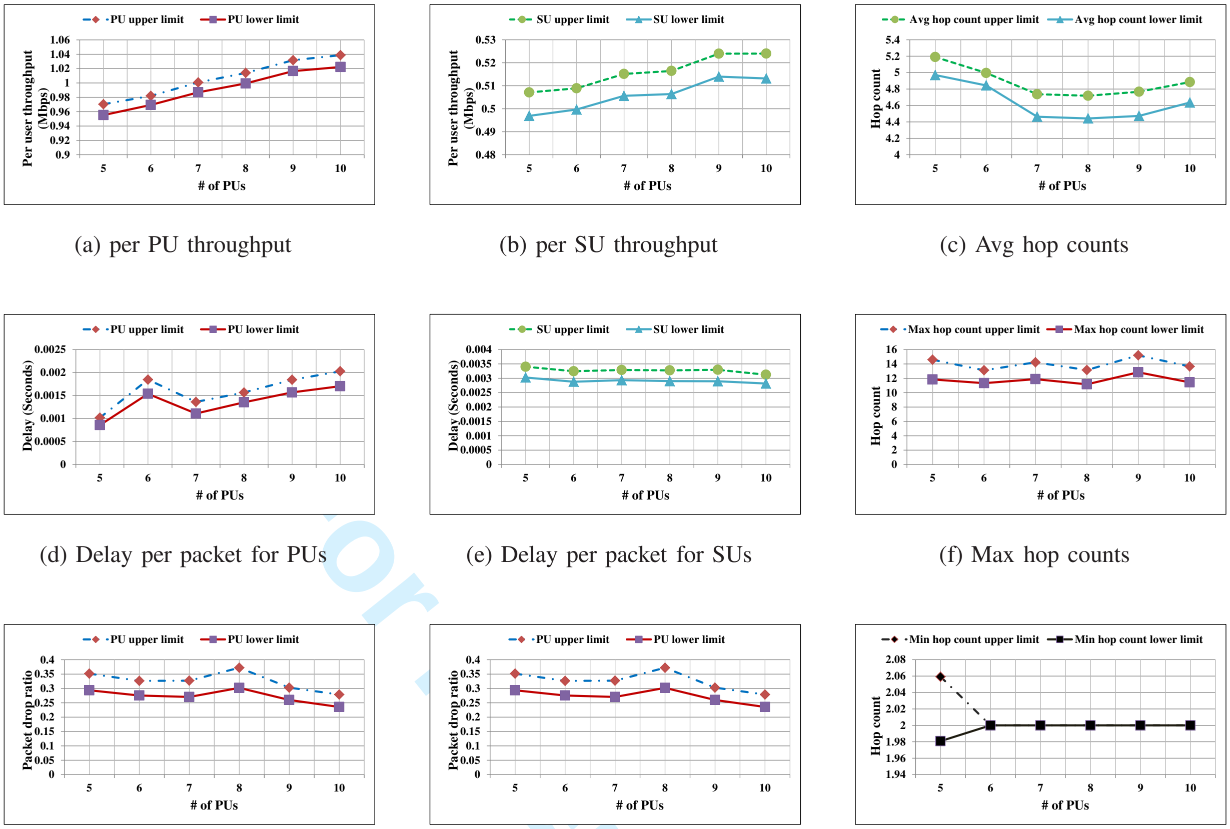
We have employed the 802.11 module that supports the medium access control (MAC) layers of IEEE 802.11a/b/e/n/p. In our simulation, we have used IEEE 802.11a to incorporate bit error rate, an important parameter of our protocol. From the perspective of MAC layer, there is no significant difference between PUs and SUs. Therefore, our proposed protocol works smoothly with the standard MAC protocol of IEEE 802.11a in our ns-3 simulation.

Next, we perform simulation and evaluate the characteristics of the proposed routing protocol in terms of different performance metrics. We consider both symmetric and asymmetric secondary users and vary the number of primary users, secondary users, power level to understand the impact of diversity in users' performance and overall network system.

A. *Results with Symmetric SUs*

In our first simulation settings, we assume all the secondary users are symmetric in their transmission and reception parameters. In this setting, we vary the number of PUs, the number of SUs, and the transmission power.

1) Results with Varying Number of PUs: We first vary the number of primary users from 5 to 10 pairs while the number of secondary users is fixed to 30. Also, the transmission power for each wireless node is set to $0.04W$. Fig. 7 shows the per user throughput, per packet end-to-end delay, and packet drop ratio for



(a) per PU throughput (b) per SU throughput (c) Avg hop counts

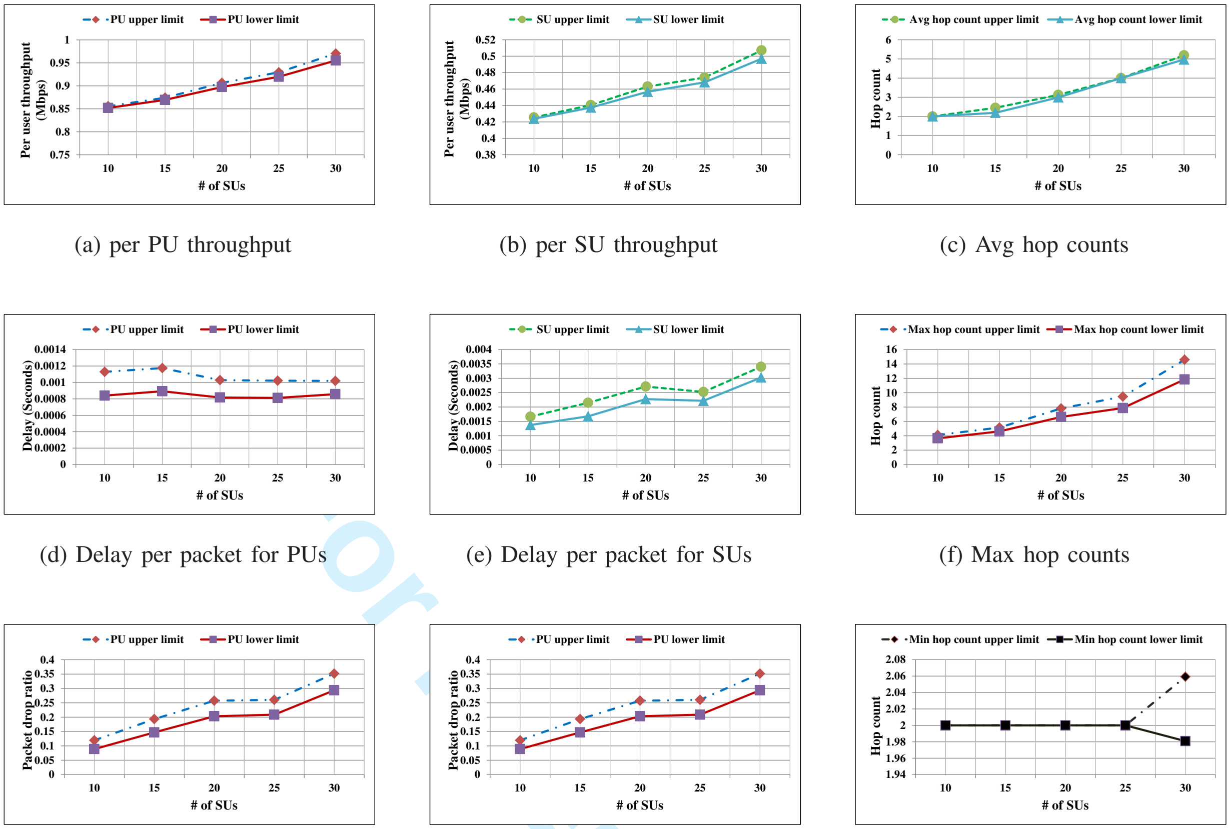
(d) Delay per packet for PUs (e) Delay per packet for SUs (f) Max hop counts

(g) Packet drop ratio for PUs (h) Packet drop ratio for SUs (i) Min hop counts

Fig. 7: Results with varying number of PUs, for symmetric SUs

PUs and SUs as well as average, maximum, and minimum hop count for delivered packets. While per user throughput increases for both PUs and SUs with an increase in the number of PUs, (Fig. 7a, 7b), delay only increases for PUs (Fig. 7d). Consequently, packet drop ratio does not change that much for both PUs and SUs with the increase in the number of PUs (Fig. 7g, 7h). For hop counts, even though maximum and minimums are almost constant, average hop counts decreases up-to some level with the increase in number of PUs (Fig. 7c, 7f, 7i).

2) Results with Varying Number of SUs: We then vary the number of secondary users from 10 to 30 while the number of primary users is fixed to 5 pairs. Also, the transmission power for each wireless node is set to $0.04W$. Fig. 8 shows the per user throughput, per packet end-to-end delay, and packet drop ratio for PUs and SUs as well as average, maximum, and minimum hop count for delivered packets. While per user throughput increases for both PUs and SUs with an increase in the number of SUs, (Fig. 8a, 8b), delay only increases for SUs (Fig. 8e). Furthermore, packet drop ratio increases for both PUs and SUs with the



(a) per PU throughput (b) per SU throughput (c) Avg hop counts

(d) Delay per packet for PUs (e) Delay per packet for SUs (f) Max hop counts

(g) Packet drop ratio for PUs (h) Packet drop ratio for SUs (i) Min hop counts

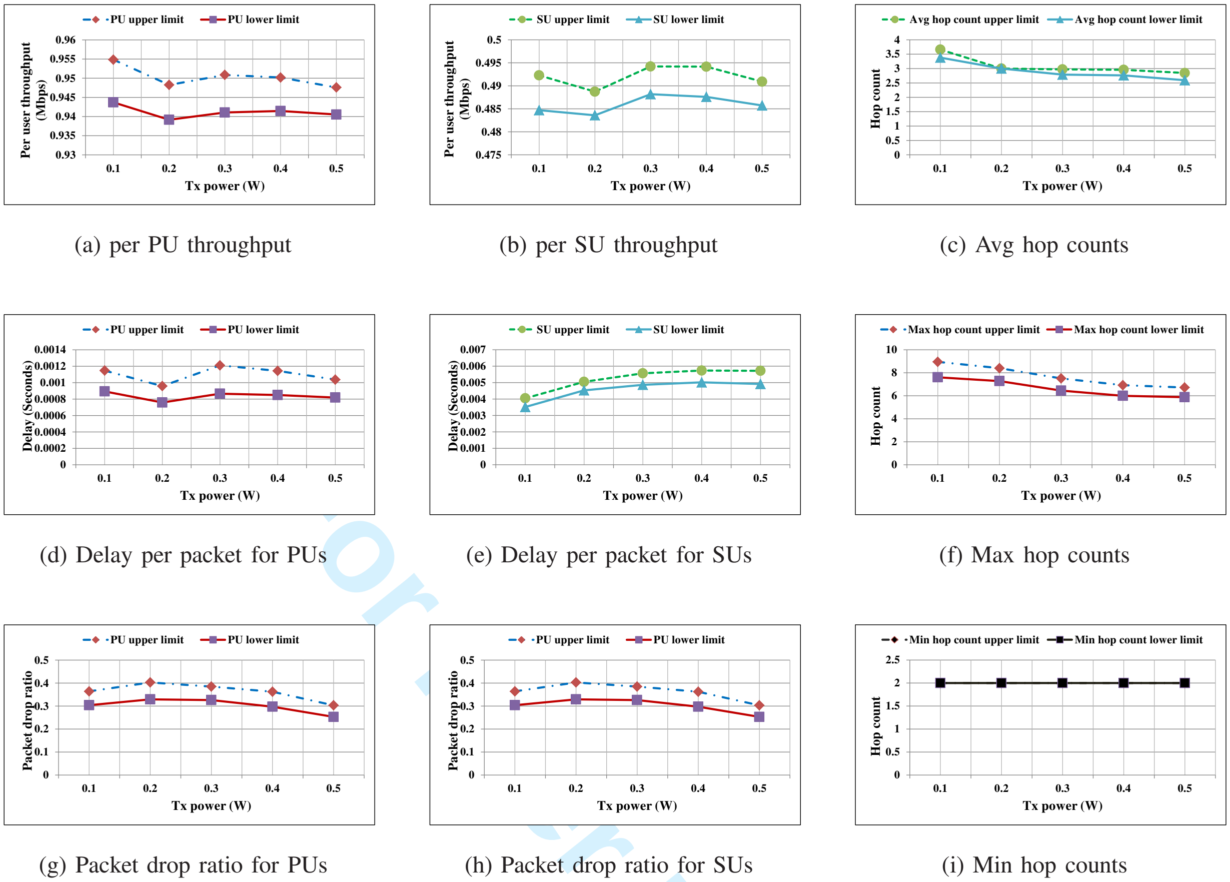
Fig. 8: Results with varying number of SUs, for symmetric SUs

increase in the number of SUs (Fig. 8g, 8h). For hop counts, other than the minimum, average as well as maximum hop counts increases with the increase in number of SUs (Fig. 8c, 8f, 8i).

3) Results with Varying Transmission Power: Lastly, We vary the transmission power from 0.1W to 0.5W while the number of primary users is fixed to 5 pairs and the number of secondary users is fixed to 30. Fig. 9 shows the effect of transmission power on various performance metrics. In case of PUs, per user throughput as well as per packet delay initially decrease. However, it starts increasing with an increase in transmission power (Fig. 9a,9d). For SUs, delay increases before becoming constant (Fig. 9e). Also, average and maximum hop counts for delivered packets decreases with an increase in transmission power, as wireless nodes can cover more neighbors with high transmission power (Fig. 9c,9f).

B. Results with Asymmetric SUs

In our second simulation setting, we assume three different types of secondary users in the system model. These three types are different in their transmission and reception parameters. For the simplicity of making



(a) per PU throughput (b) per SU throughput (c) Avg hop counts

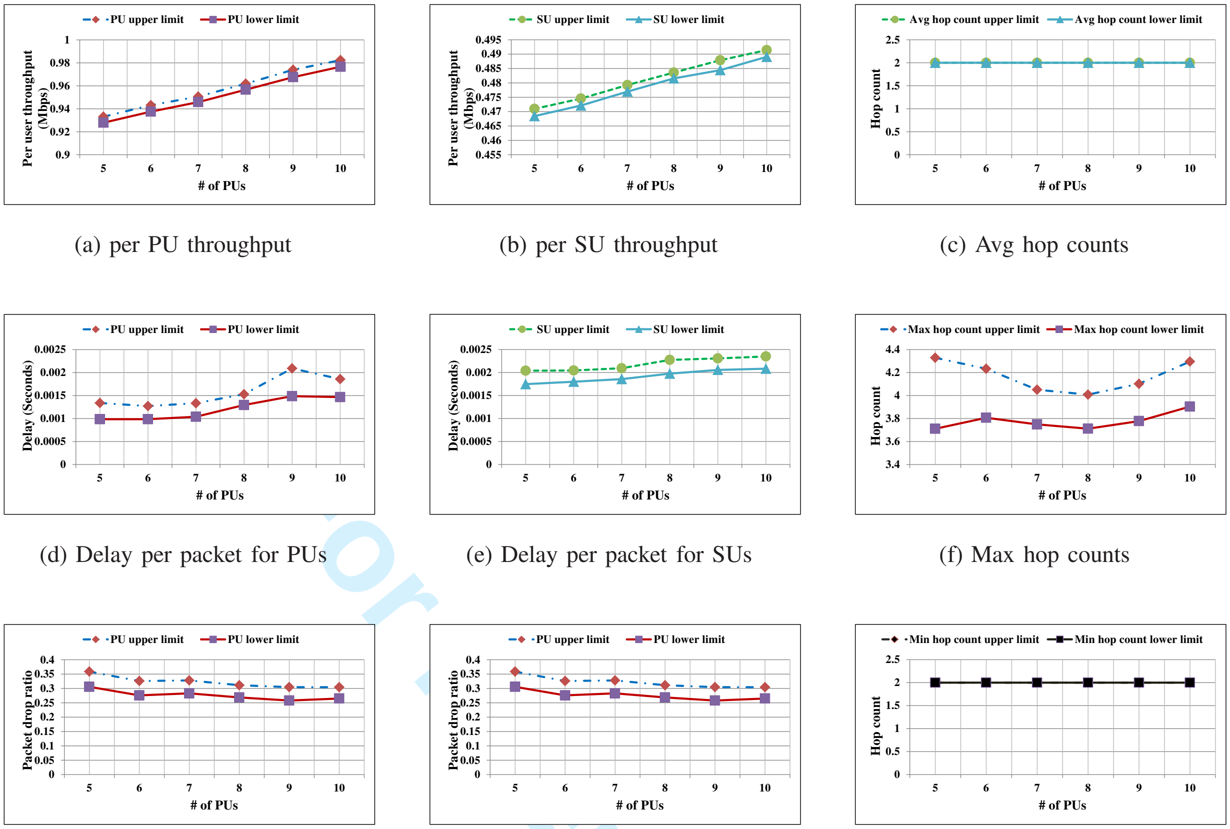
(d) Delay per packet for PUs (e) Delay per packet for SUs (f) Max hop counts

(g) Packet drop ratio for PUs (h) Packet drop ratio for SUs (i) Min hop counts

Fig. 9: Results with varying transmission power, for symmetric SUs

them asymmetric, we have chosen three different `TxGain/RxGain, (1, 2.5, 5)` for these different types of SUs. While selecting source and sink among SUs, we have connected similar type as source and sink, however, in a routing path, there could be different types of SUs. In this setting, we vary the number of PUs and the number of SUs to evaluate their impact on different performance metrics.

1) Results with Varying Number of PUs: For asymmetric SUs, we first vary the number of primary users from 5 to 10 pairs while the number of secondary users is fixed to 30. Fig. 10 shows the effect of the asymmetric SUs with an increase in the number of PUs in various performance metrics. Similar to symmetric SUs, the per user throughput increases for both PUs and SUs (Fig. 10a,10b) but delay increases for both PUs (Fig. 7d) and SUs (Fig. 10e), while in case of symmetric SUs, delay only increased in case of PUs (Fig. 7d). Also, packet drop ratio shows similar results for both PUs and SUs (Fig. 10g, 10h). However, average hop counts become constant in the asymmetric case (Fig. 10c), which is significantly different (much higher) from symmetric case (Fig. 7c). Moreover, maximum hop counts of asymmetric SUs



(a) per PU throughput (b) per SU throughput (c) Avg hop counts

(d) Delay per packet for PUs (e) Delay per packet for SUs (f) Max hop counts

(g) Packet drop ratio for PUs (h) Packet drop ratio for SUs (i) Min hop counts

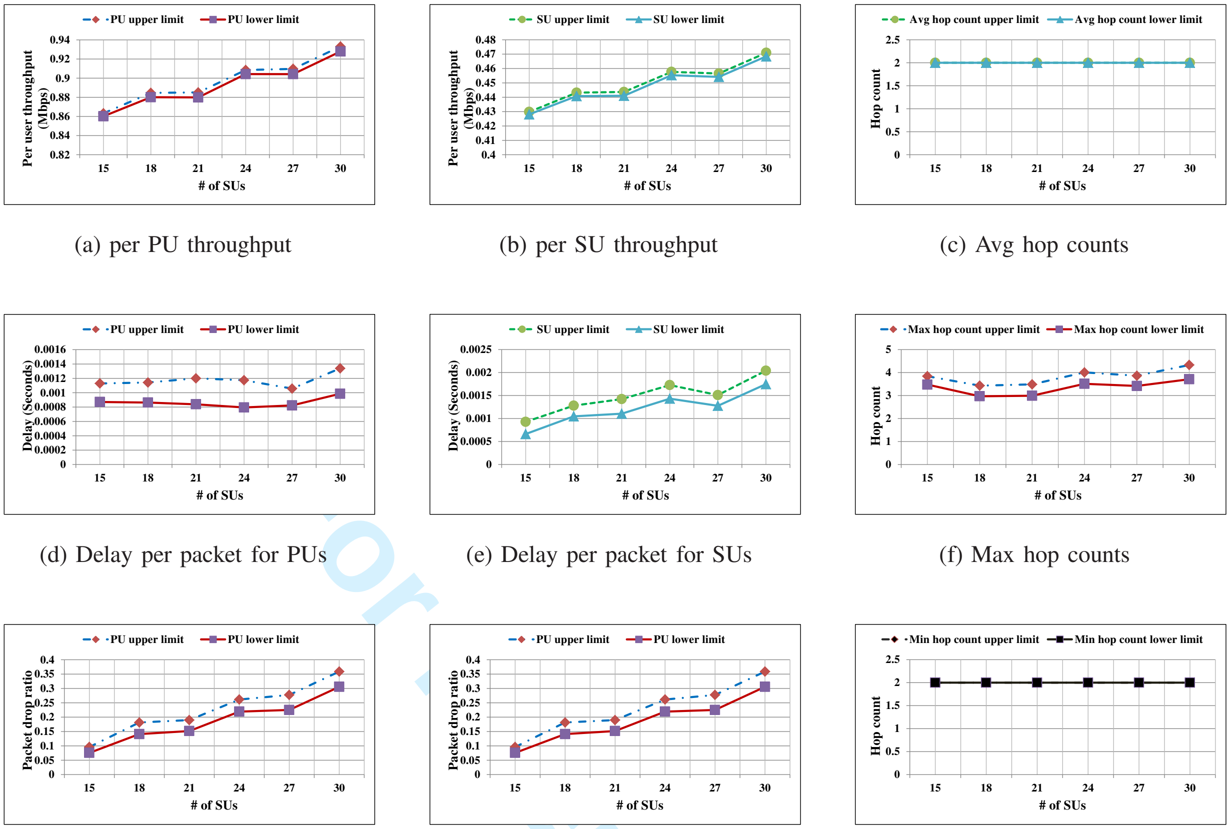
Fig. 10: Results with varying number of PUs, for asymmetric SUs

(Fig. 10f) are also significantly lower than that of symmetric SUs (Fig. 7f).

2) Results with Varying Number of SUs: Lastly, we vary the number of secondary users from 15 to 30 (different from symmetric SUs, as we have 3 different types of SUs, we vary with an increment of 3) while the number of primary users is fixed to 5 pairs. The results are depicted in Fig. 11. Interestingly, the results throughput, delay, and packet drop ratio is comparable with symmetric case (Fig. 8), which suggests that our approach does not relay on the symmetric property of the SUs. However, for hop counts, the maximum and average hop count significantly falls in asymmetric case (Fig. 11c, 11f).

VII. Conclusion

In this paper, we explore the cooperation based collaboration model in cognitive radio network. In this regard, we formulate the route selection problem as an overlapping coalition formation game where secondary users actively participate in multiple routing paths. A PU's payoff is defined as a combination of data rate profit and path delay. An SU's payoff is defined as bit per energy spent in relaying. Based on



(a) per PU throughput (b) per SU throughput (c) Avg hop counts

(d) Delay per packet for PUs (e) Delay per packet for SUs (f) Max hop counts

(g) Packet drop ratio for PUs (h) Packet drop ratio for SUs (i) Min hop counts

Fig. 11: Results with varying number of asymmetric SUs

the payoff functions defined in an OCF game, we devise a distributed multi-hop routing and scheduling protocol. Both primary and secondary users go through rounds of exchanging messages and negotiating on cooperation terms to build stable routing paths. We compare our algorithm with an existing work and the simulation results show that our approach outperforms the existing work in terms of PU and SU profit. We have implemented the routing protocol on top of an existing routing protocol and made changes to incorporate it into existing standard. We also present the performance of the routing protocol with varying different parameters e.g. throughput, end to end delay, packet loss. Furthermore, our algorithm provides stable routing paths that is also verified through simulation. In this paper, we consider single path routing between each primary source destination pair. We will investigate the impact of cooperative behavior in the case of multi-path routing and possible cooperation strategy with secondary users in future work.

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We would like to thank all the reviewers for their valuable comments. For convenience, we have answered the reviewers' comments as follows.

Reviewer 1:

1) It seems that the proposed method can only be applied to static CRNs. The authors should clarify it and should at least discuss how mobility will affect its performance.

   Answer: Yes, we have only considered static CRNs. We have added a brief discussion on how mobility will affect its performance in Section IV (2nd last paragraph).

2) End-to-end throughput and delay, and packet loss ratio are commonly used metrics for performance evaluation of ad-hoc routing algorithms and protocols. However, in the simulation, the authors used a different set of metrics. This should be justified. Is it possible to present some simulation results in terms of the above metrics.

   Answer: We have generated results for end to end throughput, delay, packet loss with varying number of primary, secondary users, and transmission power. The results are presented in Section VI Fig. 7 - 11

3) Scheduling has been addressed in the paper too. However, it is not clear how the proposed protocol can work with a standard MAC protocol.

   Answer: In our simulation using ns-3, we have employed the 802.11 module that supports the medium access control (MAC) layers of IEEE 802.11a/b/e/n/p. In our simulation, we have used IEEE 802.11a to incorporate bit error rate, an important parameter of our protocol. For the simplicity of our simulation, we have differentiated secondary users (SUs) from primary users (SUs) using different IP ranges. From the perspective of MAC layer, there is no significant difference between PUs and SUs. Therefore, our proposed protocol worked smoothly with the standard MAC protocol of IEEE 802.11a in our ns-3 simulation. This paragraph is also added in Section VI 3rd paragraph.

4) There are a few errors and typos in the paper. For example,
   a) Sometimes, "the" is not needed, e.g., page 1 "the participating secondary users" and "the primary and secondary users".
   b) Page 3: "are defined reflecting" -> to reflect
   c) Page 4, "The set of primary transmitters is" -> are
   d) Page 4, "dedicated for"->to
   e) Proofread is needed.

Answer: In addition to these fixes, we have gone through the paper and made changes wherever needed.

Reviewer 2:

1) The authors seem to assume that there is no interference at all along the entire multi-hop paths. This assumption is rather restrictive, especially in a cognitive radio network. The authors must explicitly account for interference between SUs/PUs, as appropriate.

   Answer: We have considered interference among PUs and SUs. In our discrete event simulation setting in ns-3, we have installed wifi-interfaces in all nodes that communicate over a 6-Mbps wifi channel. Therefore, PUs and SUs interfere with each other within their transmission-reception range. In contrast to general settings of cognitive radio network, where SUs backoff at the presence of nearby PUs, we have permitted those SUs to be present on this channel. That is because, among such SUs one of them can be selected as the next hop relay for the nearby active PU. Moreover, we have installed 802.11 MAC layer to all the devices irrespective of PUs and SUs to maneuver any contention for the channel.

2) It is not clear how time is factored into the formulation. Do coalitions form once and never change? Do you adapt to time changes? Does the system change over time? Does the activity pattern of PUs change? These issues must be properly analyzed.

   Answer: We have considered that users are sharing time as their resources. For a primary user sharing time means it refrains from transmitting and lets secondary users in its coalition to transmit. For a secondary user sharing time means it engages in receiving and forwarding packets of a primary user in its coalition.

   The coalition will change if the contribution from any member drops from its agreed one. At this point, the primary user initiates the coalition formation request (route_request) again and the entire process continues. This discussion is also added in Section IV last paragraph.

3) Is the game of transferable or nontransferable utility?

   Answer: The game is of nontransferable utility. We have followed the analysis in the paper [21][22] .

4) More details on the derivation of (14) are needed.

   Answer: The M/G/1 queueing model with vacation period is explained along with a detailed description on the equation in Section III-D

5) What is the physical meaning of (15)?

Answer: Eqn(15) denotes the number of bits a secondary user can transmit for each unit of power spent in relaying primary traffics. This reflects the secondary tradeoff in terms of throughput and energy consumption.

6) The stability analysis in Section III.E is very weak. There are numerous solid stability notions for overlapping coalition games (such as core-based stability) that are more formal and more suitable to analyze from a game theory perspective. The current stability notion is rather artificial and incoherent with the game formulation. More realistic stability notions are needed along with thorough analysis on convergence of coalition formation to such stable solutions.

   Answer: We have added a brief summary of core concept in terms of OCF game based on the analysis in the paper. We then showed that the problem is NP-hard and can be achieved stability. Section III-B and III-F discussed the time complexity and stability of the problem

7) In Fig. 8 (d), how is the convergence time measured? How does this relate to the wireless network dynamics, such as the coherence time of the channel?

   Answer: Convergence is measured in terms of number of rounds i.e. number of times a primary user initiates route search request before settling down. Since the optimization problem is a NP-Hard problem, we have used convergence parameters (one for each user) to control the exploration of better routing paths. We have made sure that as iteration increases, the value converges and the users stop exploring.

8) The abstract of the paper must be completely rewritten. It currently reads like a literature review, not an abstract.

   Answer: We have modified the abstract reflecting changes to the entire writeup.

Reviewer 3:

1) The novelty of the work as compared to the conference paper [19] needs to be clearly highlighted in the introduction section as part of the contributions and a statement on the footnote of the 1st page stating that this work has been presented in .... needs to be added.

   Answer: We have modified Introduction to clearly state the differences between the conference version and the current journal version. We have also added the footnote as suggested. Introduction is changed clearly mentioning the difference with the conference version (Section 1, page 3, 2nd paragraph)

2) To achieve sufficient novelty compared to conference publications, the authors needs to address the following points (listed in the PDF at the last page): (i) The authors needs to address the complexity of their proposed algorithm formally and compare it to previous

methods, (ii) A formal mathematical analysis of stability and convergence needs to addressed with bounds on the controlling parameters, (iii) The discussion on NP-completeness needs to provide more detailed and more solid argument on why and how.

Answer: We have provided a stability analysis and proof of NP-completeness in Section III-B and III-F.

3) More practical justification and/or motivation needs to be provided to explain the framework on cognitive radio where the primary is actually involved with the secondary users rather than the classical case where the secondary is typically transparent to primary network. Maybe reference to standards development as well as suitable practical applications would suffice.

   Answer: The aforementioned paragraph has been modified. Few references to existing work have been added.

4) The authors in page 2 refer to single hop relaying in cognitive as being not extendable to multi-hop cases which is not convincing. They might be non-optimal but still can be extended.

   Answer: The aforementioned statement has been modified.

5) The original scope of paper title/abstract/introduction is general while the system model is specific to OFDMA system. Either the former needs to change or the latter to be coherent with the former.

   Answer: This model can be applicable to any system, so wording has been changed.

6) In page 4 lines 41 and 47, it is not clear whether different PUs use orthogonal sub-channels and whether SUs can work on more than one sub-channel simultaneously or only switch from one to another as needed.

   Answer: Yes, different PUs use orthogonal sub-channels. SUs also can work on more than one sub-channel simultaneously based on the cooperation agreement. SUs can combine the sub-channels and transmit over them.

7) There are in several places confusion between sub-carriers and sub-channels as per the definition in the system model.

   Answer: We have gone through paper and corrected the notation as needed.

8) There are confusions between "bandwidth time" and "transmission time" in several places and not clear what is the difference.

Answer: They are same. We have removed bandwidth time and made it consistent.

9) Page 6 line 1, is it a list, a set or a tuple? Based on the description is should be a set.

Answer: Yes, it is set. We have also simplified few syntaxes to avoid confusion.

10) Fig. 1 doesn't correspond to the text describing it and needs to be modified.

Answer: The description of Fig. 1 is added in the paper.

11) In equation (10) as well as simulation results, it is assumed that all SUs are symmetric in all their parameters. This is quite impractical and makes the system almost trivial.

Answer: The proposed system does not rely on the symmetric properties of the SUs. The SUs can be different in terms of their properties. In our simulation, we have used symmetric SUs as well as asymmetric SUs to recognize the impact of diversity in secondary users. Results are shown in Fig 7-11.

Generally, we have considered that all SUs are symmetric in all their parameters. However, to show that our proposed approach does not rely of the symmetric property of SUs we have conducted another extra set of simulations where we assume three different types of secondary users. These three types are different in their transmission and reception parameters. For the simplicity of making them asymmetric, we have chosen three different TxGain/RxGain, (1, 2.5, 5) for these different types of SUs. In this setting, we vary the number of PUs and the number of SUs to evaluate their impact on different performance metrics. From this set of experiment results it has been found that, the per user throughput, end-to-end delay as well as packet drop ratio for the case of asymmetric SUs are very much comparable with that of symmetric SUs.

12) The justification for M/G/1 model usage is not provided. Moreover, the system queueing model needs a figure to represent the description provided in page 10.

Answer: The M/G/1 queueing model has been explained. A figure is added to visualize the model (Fig. 3).

13) Why the PU payoff is additive with tunable parameter while the SU payoff is multiplicative without a tuning parameter? You need to justify these payoff functions and why they are different in format?

Answer: Since PU and SU have different goals, their payoff function is also different. While PU's focus is on the balance between throughput and delay SU's focus is to balance between spectrum access and power consumption.

14) There are several undefined parameters such as \beta and concepts such as "agent". Please, define in the proper place.

    Answer: The β is defined as convergence parameter. The value of β regulates the primary user's participation in cooperative transmission. At the end of each iteration, the value of β is set. The term agent is used to differentiate a virtual entity from a physical entity. Their definitions are clarified.

15) Section III-D needs a flowchart/pseudocode/time-sequence diagram to clarify the described algorithm.

    Answer: We have added a flowchart (Fig. 4) to clarify the decision process of a secondary user.

16) The algorithm in III-D doesn't show any optimization or greediness on SU payoff, all choices of primary and secondary among offered coalitions are solely based on PU payoff. This contradicts the objectives of the originally defined problem. Either some clarification is needed or the original problem needs to change.

    Answer: There are two parts in a secondary user's decision. First, it needs to select which coalition it wants to join, and second, what it should demand from that coalition. In the first case, a secondary user selects the best offer from the perspective of the cooperating primary user. Second, it tunes its transmission time and relay time based on its own preference.

17) Page 16, line 38, it is not clear how the power is calculated and whether it is adaptive or fixed power, and if fixed power, then it shouldn't be a factor at all since its SU invariant.

    Answer:
    We have performed two sets of simulations. First for symmetric SUs and then for asymmetric SUs. In the case of asymmetric SUs, we have installed three different types of SUs. They are different based on their transmission and reception power range. That simulation results show that our proposed approach is not SU invariant.
    Also, in the case of symmetric SUs we have given each SU the same transmission and reception power settings. However, we have also varied this same amount of power to see the effect of the transmission power range in our proposed approach on different performance metrics.

18) Since the objective is a routing protocol, it should fit existing routing standards such as TCP/IP routing rather than having its own packet formats and methodology. In other words, it should only be that it alters the metrics used in TCP/IP routing to achieve the desired objectives using the described methods. Can you elaborate on how can this be achieved and provide a description for implementing it in the paper?

Answer: We have added section VI to discuss the adaptation of our routing algorithm with the existing routing standards. While we use the existing standards, we have also recommended a few extensions that will be needed to apply the routing algorithm. For example, we need to include few timers and additional fields in the routing packet.

To simulate the proposed algorithm, we implemented our protocol on the top of existing standard aodv routing protocol in the aodv module of ns-3. For example, we have modified the RReq and RRep packet formats of aodv to incorporate our Coalition Request and Coalition Reply format. Also, to implement the algorithm, we had to add several timers in the proposed routing protocol.

19) In the results sections in many comments on figures (e.g. is page 21 line 21), the described behaviour in the text doesn't fit what the curves in the corresponding figure shows. This is repeated all-over the results and needs to be fixed either by further simulation or by modifying the text and the arguments/conclusions.

Answer: We have implemented the algorithm in ns-3 and generated new results with varying different network parameters. We have explained the performance of the algorithm in terms of different metrics e.g. throughput, end to end delay, packet loss rate (Fig 7 - 11).

20) There are many editorial issues with the paper in terms of the organization, English and punctuation. All marked in the paper attached.

Answer: All the comments have been addressed.