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Distributed Routing, Relay Selection, and Spectrum Allocation in Cognitive and Cooperative Ad Hoc Networks

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***Abstract*—Throughput maximization is a key challenge in *cognitive radio ad hoc networks*, where the availability of local spectrum resources may change from time to time and hop-by-hop. To achieve this objective, cooperative transmission is a promising technique to increase the capacity of relay links by exploiting spatial diversity without multiple antennas at each node. This idea is particularly attractive in wireless environments due to the diverse channel quality and the limited energy and bandwidth resources. In this paper, decentralized and localized algorithms for joint dynamic routing, relay assignment, and spectrum allocation in a distributed and dynamic environment are proposed and studied. A cross-layer protocol to implement the joint routing, relay selection, and dynamic spectrum allocation algorithm is also introduced, and its performance is evaluated through simulation. Performance evaluation results show that the proposed protocol achieves much higher throughput than solutions that do not rely on cooperation.**

***Index Terms*—Cooperative communications, cognitive radio networks, dynamic spectrum allocation, routing, cross-layer design.**

I. Introduction

The need to wirelessly share high-quality multimedia content is driving the need for ever-increasing wireless transport capacity, which is however limited by the scarcity of the available spectrum. Cognitive radio networks [1], [2], [3], [4] have recently emerged as a promising technology to improve the utilization efficiency of the existing radio spectrum. Based on the reported evidence that static licensed spectrum allocation results in highly inefficient resource utilization, the cognitive radio paradigm prescribes the coexistence of licensed (or primary) and unlicensed (secondary or cognitive) radio nodes on the same portion of the spectrum. The main requirement is that the activity of secondary nodes should be transparent to the primary.

A key challenge in the design of cognitive radio networks is dynamic spectrum allocation, which enables wireless devices to opportunistically access portions of the spectrum as they become available. Consequently, techniques for dynamic spectrum allocation have received significant attention in the last few years, e.g., [5], [6], [7], [8], [9], [10], [11].

However, mainstream cognitive radio research has so far been focused on infrastructure-based networks, while the underlying root challenge of devising decentralized spectrum management mechanisms for infrastructure-less cognitive radio ad hoc networks is still substantially unaddressed. In cognitive radio networks with multi-hop communication requirements, the dynamic nature of the radio spectrum calls for a new approach to spectrum management, where the key networking functionalities, in particular routing and medium access control, closely interact and are jointly optimized with the spectrum management functionality. In fact, in a spatially distributed ad hoc network, spectrum occupancy is location-dependent. Therefore, in a multi-hop path the available spectrum bands may be different at each relay node. Hence, in multi-hop cognitive radio networks controlling the interaction between the routing, medium access, and the spectrum management functionalities is of fundamental importance. While cross-layer design principles have been extensively studied by the wireless networking research community in the recent past [12], [13], the availability of cognitive and frequency agile devices motivates research on new algorithms and models to study cross-layer interactions that involve spectrum management-related functionalities.

Within this context, this paper goes one step further and addresses techniques to leverage the *spatial diversity* that characterizes the wireless channel in cognitive radio ad hoc networks. Spatial diversity is traditionally exploited by using multiple transceiver antennas to effectively cope with fading in wireless channels. However, equipping a mobile device with multiple antennas may not be practical. The concept of *cooperative communications* has been hence proposed to achieve spatial diversity without requiring multiple transceiver antennas on the same node [14], [15], [16]. In cooperative communications, in their *virtual multiple-input single-output* (VMISO) variant, each node is equipped with a single antenna, and relies on the antennas of neighboring devices to achieve spatial diversity. There is a vast and growing literature on information theoretic and communication theory problems [17] in cooperative communications. The reader is referred to [18] and [19] and references therein for excellent surveys of the main results in this area. However, the common theme of most research in this field is to optimize physical layer performance measures (i.e., bit error rate and link outage probability) from a broad system perspective, without considering in much detail how cooperation interacts with higher layers of the protocol stack to improve network performance measures. For example, [20], [21] investigate the achievable rates and diversity gains

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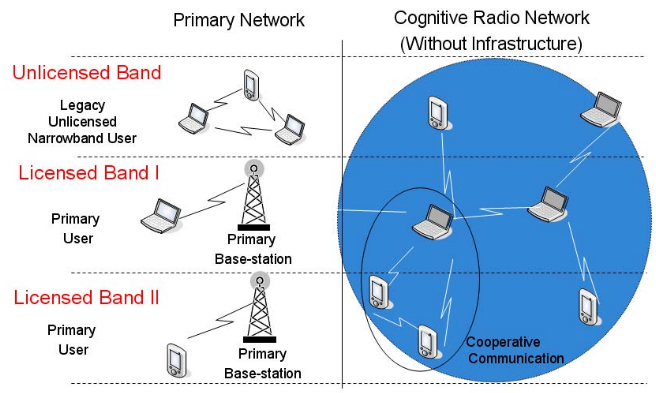


Fig. 1. Architecture of the proposed Cognitive Radio Ad Hoc Networks, and its coexistence with legacy narrowband unlicensed users and primary users.

of given cooperative schemes focusing on a single source and destination pair. Some initial promising work on networking aspects of cooperative communications includes studies on medium access control protocols to leverage cooperation [22], [16], cooperative routing [23], [24], [25], [26], optimal network-wide relay selection [27], and optimal stochastic control [28]. However, decentralized spectrum management with cooperative devices is a substantially unexplored area.

Figure 1 depicts the considered application scenarios. We consider an ad hoc network of devices endowed with wideband reconfigurable transceivers that communicate without an infrastructure and can potentially coexist with i) legacy narrowband unlicensed devices (e.g., IEEE 802.11, IEEE 802.15.4, Bluetooth transceivers), and ii) primary users operating on licensed portions of the spectrum. The main contributions of this paper are outlined as follows:

- **Distributed joint routing, relay selection, and dynamic spectrum allocation**. We formulate a joint routing, relay selection, and dynamic spectrum allocation problem. Given the centralized nature and high computational complexity of the problem, we study decentralized and localized algorithms for joint dynamic routing, relay assignment, and spectrum allocation that are designed to maximize the global objective function of the centralized problem. To the best of our knowledge, no existing algorithm attempts to jointly control the functionalities above under realistic interference models.
- **Uncoordinated spectrum management.** Unlike mainstream work on cognitive radio, we consider a distributed and dynamic environment. We study cooperative spectrum management mechanisms for infrastructure-less cognitive radio ad hoc networks.
- **Decentralized and localized decision making.** We propose algorithms that consider and leverage the unique characteristics of cognitive radio ad hoc networks including the availability of spectrum holes at a particular geographic location and their possible variability with time; furthermore, we study decentralized spectrum management with *cooperative devices*. In the proposed solution, each cognitive radio makes real-time decisions based on locally collected information. We propose a practical implementation of the proposed algorithm based on a medium access control strategy that relies on a common control channel and a frequency-agile data channel.

The rest of the paper is organized as follows. In Section II, we introduce the system model. In Section III we formulate the cross-layer optimization problem. In Section IV, we discuss link capacity maximization with and without cooperative relays. In Section V, we introduce the decentralized algorithm for joint routing, relay selection and dynamic spectrum allocation. Section VI discusses the cooperative MAC/routing protocol design and addresses implementation details. In Section VII we evaluate the performance of the proposed protocol. Finally, Section VIII concludes the paper.

II. System Model

We consider a cognitive radio network consisting of primary users and N secondary users. Primary users hold licenses for specific spectrum bands, and can only occupy their assigned portion of the spectrum. Since primary users are licensed users, they will be provided with a highly reliable communication environment whenever and wherever needed. Secondary users do not have any licensed spectrum and opportunistically send their data by utilizing idle primary spectrum.

We let $\mathcal{V} = \{v_1, ..., v_N\}$ represent a finite set of secondary users (also referred to as nodes), with $|\mathcal{V}| = N$. We assume that all the secondary users are equipped with cognitive radios that consist of a reconfigurable transceiver, which can tune to a set of contiguous frequency minibands, and a scanner, similar for example to the KNOWS prototype from Microsoft [29]. We keep the physical layer model general. Among others, the considered physical layer model can accurately represent orthogonal frequency division multiplexing (OFDM)-based transmission, which is based on a flexible subcarrier pool, and is thus a promising candidate technology for cognitive radio networks. Alternatively, the considered abstraction could model multi-channel time-hopping impulse radio ultra wide band system, in the low SINR regime [30], [31].

A. Channel Model

The available spectrum is assumed to be organized in two separate channels. A *common control channel* (CCC) is used by all secondary users for spectrum access negotiation, and is assumed to be time slotted. A *data channel* (DC) is used for data communication. The data channel consists of a set of discrete minibands $\{f_{min}, f_{min+1}, \cdots, f_{max-1}, f_{max}\}$, identified by a discrete index. The bandwidth of each miniband is w. For example, the interval $[f_i, f_{i+\Delta B}]$ represents the contiguous set of minibands selected by secondary user i between f_i and $f_{i+\Delta B}$, with bandwidth $w \cdot \Delta B$. Each secondary user that has packets to send contends for spectrum access on the fixed control channel f_{cc}, where $f_{cc} \notin [f_{min}, f_{max}]$. All secondary users in the network exchange local information on the common control channel. This is in line with the capabilities of existing prototypes for experimental evaluation of software defined and cognitive radio technology such as the USRP2/GNU radio suite [32], [33]. We let a binary vector $\mathbf{A}$ indicate activities of primary users on the data channel, i.e., $A(f) = 1$ indicates ongoing activity on miniband f, while $A(f) = 0$ indicates no primary activity on miniband f.

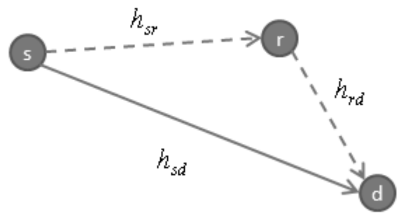


Fig. 2. Illustration of Cooperative Relaying Model.

B. Transmission Mode

Cooperative Relaying: Consider a simple cooperative relaying network as shown in Fig. 2. Relay node r decodes the received signal from source node s in the first time period, and forwards the data to destination node d in the second time period. The destination jointly decodes the signals received from source and relay, for example through maximal ratio combining [34]. Assuming the relay can fully decode the source message, the capacity of the cooperative link between s and d with relay r on a single miniband is given by [15]

$$C_{sd} = \frac{w}{2}\min\{\log_2(1+\mathrm{SINR}_{sr}), \log_2(1+\mathrm{SINR}_{sd}+\mathrm{SINR}_{rd})\} \tag{1}$$

where SINR_{sr}, SINR_{sd} and SINR_{rd} are the signal-to-interference-plus-noise power ratios (SINR) of links (s,r), (s,d) and (r,d), respectively. Considering multiple orthogonal frequencies (e.g., using OFDM), we can express the capacity of a cooperative link as

$$C_{sd}^{coop}(\mathbf{F},\mathbf{P_s},\mathbf{P_r}) = \frac{w}{2}\min\sum_{f\in\mathbf{F}}\left\{\log_2\left(1+\mathrm{SINR}_{sr}^{f}(p_s(f))\right), \log_2\left(1+\mathrm{SINR}_{sd}^{f}(p_s(f))+\mathrm{SINR}_{rd}^{f}(p_r(f))\right)\right\} \tag{2}$$

where $\mathbf{F}$ represents the contiguous set of minibands used by nodes s and r. Define $p_s(f)$ and $p_r(f)$ as the transmit power allocated at node s and r, respectively, on miniband f, and $\mathbf{P_s} = \{p_s(f)|f\in\mathbf{F}\}$ and $\mathbf{P_r} = \{p_r(f)|f\in\mathbf{F}\}$ as the vectors of allocated power at node s and r. Note that C_{sd}^{coop} is an increasing function of $\mathbf{P_s}$ and $\mathbf{P_r}$, which means that both source and relay node should transmit at the maximum power to achieve maximum capacity. In cognitive radio networks with decentralized control, different minibands may have different maximum allowed power limits, and such constraints are different for different nodes. Hence, the capacity of a link depends on an intertwined selection of relay node, spectrum, and power on different minibands.

Direct Transmission: When cooperative relaying nodes are not used, source node s transmits to destination node d in both time periods. The capacity of link (s,d) is

$$C_{sd}^{dirc}(\mathbf{F},\mathbf{P_s}) = \sum_{f\in\mathbf{F}} w\cdot\log_2\left(1+\mathrm{SINR}_{sd}^{f}(p_s(f))\right). \tag{3}$$

Note that the capacity of a cooperative link can be lower than that of the corresponding direct link (same source and destination with no relay).

Whether to relay or not to relay, and which is the optimal relay node are important decisions to maximize the capacity. In this paper, we develop algorithms for jointly selecting the next hop (routing), transmission mode (whether to relay or not), the relay node, and spectrum and power allocation for cooperative transmission.

C. Queueing Dynamics

Traffic flows are, in general, carried over multi-hop routes. Let the traffic demands consist of a set $\mathcal{S} = 1,2,\cdots,S$, where $S = |\mathcal{S}|$, of unicast sessions. Each session $s\in\mathcal{S}$ is characterized by a fixed source-destination node pair. We indicate the arrival rate of session s at node i as $\lambda_i^s(t)$ at time t, and with $\mathbf{\Lambda}$ the vector of arrival rates.

Each node maintains a separate queue for each session s for which it is either a source or an intermediate relay. At time slot t, define $Q_i^s(t)$ as the number of queued packets of session s waiting for transmission at secondary user i. Define $r_{ij}^s(t)$ as the transmission rate on link (i,j) for session s during time slot t, and $\mathbf{R}$ as the vector of rates. For $\forall i\in\mathcal{V}$, the queue is updated as follows:

$$Q_i^s(t+1) = \left[Q_i^s(t) + \sum_{k\in\mathcal{V},k\neq i} r_{ki}^s(t) - \sum_{l\in\mathcal{V},l\neq i} r_{il}^s(t) + \lambda_i^s(t)\right]^+.$$

We assume relay nodes forward packets to the destination node immediately after receiving the packets from the source node. The packets do not go into the queue as defined above.

III. Problem Formulation

Our stated goal is to design a distributed cross-layer control scheme to maximize the network throughput by jointly, dynamically, and distributively allocating (i) the next hop (routing), (ii) a cooperative relay, (iii) spectrum, i.e., minibands and power on each miniband, to be used at transmitter and relay of each network link. To achieve throughput optimality, the control strategy needs to adapt to the dynamics of available spectrum resources and network queueing under the constraints introduced by cognitive radio networks. A desirable solution should also let secondary users utilize dynamically the available spectrum to provide BER guarantees to both primary and secondary users. For this reason, an ideal throughput-optimal network controller should, at each decision period (e.g., time slot), find vectors $\mathbf{F_s}$, $\mathbf{F_r}$, $\mathbf{P_s}$, $\mathbf{P_r}$ for each link that maximize an appropriate *utility function*, as further specified later in this section. This is expressed by the problem below.

$$\mathbf{P1}: Maximize: \quad \sum_{i\in\mathcal{V}}\sum_{j\in\mathcal{V},j\neq i} U_{ij} \tag{4}$$

$$Subject\ to:$$

$$\sum_{s\in\mathcal{S}} r_{ij}^s \le C_{ij}, \quad \forall i\in\mathcal{V},\ \forall j\in\mathcal{V}\setminus i, \tag{5}$$

$$A(f)\cdot P_i(f) = 0, \quad \forall i\in\mathcal{V}, \forall f\in[f_{min}, f_{max}], \tag{6}$$

$$\mathrm{SINR}_j^f \ge \mathrm{SINR}^{th}(BER^*),\ \forall j\in\mathcal{V}, \forall f\in[f_{min}, f_{max}], \tag{7}$$

$$\sum_{f\in[f_i, f_{i+\Delta B}]} P_i(f) \le P^{Bgt},\ \forall i\in\mathcal{V}. \tag{8}$$

In the problem above, constraint (5) imposes that the total amount of traffic transported on link (i,j) be lower than the capacity of the physical link C_{ij}. Constraint (6) states that no transmission of secondary users is allowed if there is reception activity of primary users on that miniband. Constraint (7) imposes that secondary user transmissions should also satisfy a given BER performance, while sharing the spectrum with other secondary users. SINR^{th} denotes the SINR threshold to achieve a target bit error rate BER^*. Note that SINR_j^f denotes the SINR on miniband f of receiver j. In (8), P^{Bgt} represents a constraint on the total power for each device.

The *utility* U_{ij} for link (i, j) is defined as

$$U_{ij}(t) = C_{ij}(t) \cdot \left(Q_i^{s^*_{ij}}(t) - Q_j^{s^*_{ij}}(t) \right), \tag{9}$$

where
$$s^*_{ij} = \arg\max_s \left\{ Q_i^s - Q_j^s \right\}. \tag{10}$$

In (9), $C_{ij}(t)$ represents the achievable capacity for link (i, j) given the current spectrum condition at time t and the chosen transmission mode, while s^*_{ij} is the session with maximum differential backlog on link (i, j). The achievable capacity for cooperative and direct links under spectrum sharing constraints will be further discussed in Section IV-A.

The utility function is defined based on the principle of dynamic back-pressure, first introduced in [35]. It can be proven [36] that a control strategy that jointly assigns resources at the physical/link layers and routes to maximize the weighted sum of differential backlogs (with weights given by the achievable data rates on the link) as in (4) is throughput-optimal, in the sense that it is able to keep all network queues finite for any level of offered traffic within the network capacity region.

Therefore, ideally, a throughput-optimal policy would continuously (i.e., at each time slot) assign resources on each network link by solving problem $\mathbf{P1}$ to optimality. However, exact solution of $\mathbf{P1}$ requires global knowledge of all feasible rates and a centralized algorithm to solve a mixed integer nonlinear problem (NP-hard in general) such as $\mathbf{P1}$ on a time-slot basis. This is clearly unpractical for real-time decision making. This provides the rationale for our distributed algorithm, which is designed to provide an approximate solution to $\mathbf{P1}$ based on real-time distributed decisions driven by locally collected information. In addition, we show how the proposed distributed algorithm can be implemented in a practical protocol in Section VI. Note that, for the sake of simplicity, we will drop all time dependencies.

IV. Link Capacity Maximization Under Spectrum Sharing Constraints

In this section, we first derive the interference conditions under which multiple cognitive radio nodes can transmit simultaneously on the shared wireless medium (spectrum sharing constraints). Then, we discuss link capacity maximization for direct and cooperative links under the derived spectrum sharing constraints. These will constitute the building blocks for the distributed routing, relay selection, and spectrum allocation algorithm in Section V.

A. Spectrum Sharing Constraints

To share the spectrum, all network transmitters need to (i) satisfy receiver BER requirements, (ii) avoid interfering with ongoing communications.

Minimum Required Transmit Power

Let $\text{SINR}^{th}(BER^*)$ represent the minimum SINR that guarantees a target bit error rate BER^*, and $P_i(f)$ represent the transmit power of transmitter i on miniband f. The first constraint for link (i, j) can be expressed by

$$\frac{P_i(f) L_{ij} |h_{ij}|^2}{NI_j(f)} \geq \text{SINR}^{th}(BER^*), \tag{11}$$

where L_{ij} is path loss power attenuation, h_{ij} is the channel coefficient of link (i, j), and $NI_j(f)$ is the noise plus interference at receiver j on miniband f. The numerator represents the received power at receiver j.

Define $P_i^{min}(f)$ as the value of $P_i(f)$ for which (11) holds with equality. Thus, $P_i^{min}(f)$ is the minimum required transmit power of link (i, j) on miniband f. The constraint in (11) states that the SINR at receiver j needs to be above a certain threshold to allow receiver j to successfully decode the signal given its current noise and interference. For clarity, we use $P_{ij}^{min}(f)$ to denote the minimum required transmit power of transmitter i for receiver j.

Maximum Allowed Transmit Power

Let $P_i^{max}(f)$ denote the maximum allowed transmit power of transmitter i, $i \in \mathcal{V}$. If there is ongoing reception of primary user on miniband f, i.e., $A(f) = 1$, no transmission of i is allowed,

$$A(f) \cdot P_i^{max}(f) = 0, \quad \forall i \in \mathcal{V}, \forall f \in [f_{min}, f_{max}]. \tag{12}$$

In the following we will discuss $P_i^{max}(f)$ when there is no primary user's reception on f, i.e., $A(f) = 0$. Denote the interference on miniband f at a receiver k, $(k \in \mathcal{V}, k \neq j)$, as $NI_k(f) + \Delta I_{ik}(f)$, where $NI_k(f)$ represents noise plus interference at k before i's transmission, and $\Delta I_{ik}(f)$ represents the additional interference at k caused by i's transmission, i.e., $\Delta I_{ik}(f) = P_i(f) L_{ik} |h_{ik}|^2$.

The second constraint represents the fact that ongoing reception at node k should not be impaired by i's transmission. This can be expressed as

$$\frac{P_k^R(f)}{NI_k(f) + \Delta I_{ik}(f)} \geq \text{SINR}^{th}(BER^*), k \in \mathcal{V}, k \neq j, \tag{13}$$

where $P_k^R(f)$ represents the signal power being received at receiver k. Since this has to be true for every secondary receiver, the constraint can be written as

$$P_i(f) \leq \min_{k \in \mathcal{V}} \frac{\Delta I_k^{max}(f)}{L_{ik} |h_{ik}|^2} \tag{14}$$

where
$$\Delta I_k^{max}(f) = \frac{P_k^R(f)}{\text{SINR}^{th}(BER^*)} - NI_k(f), k \in \mathcal{V}. \tag{15}$$

The inequality in (14) states that the interference generated by i's transmission on each frequency should not exceed the threshold value that represents the maximum interference that can be tolerated by the most vulnerable of i's neighbors.

By combining (12) and (14), we obtain

$$P_i^{max}(f) \triangleq \begin{cases} 0, & A(f) = 1; \\ \min_{k \in \mathcal{V}} \frac{\Delta I_k^{max}(f)}{L_{ik} |h_{ik}|^2}, & A(f) = 0. \end{cases} \tag{16}$$

Hence, for link (i, j), node i's transmit power needs to be bounded on each frequency. The expressions in (11) and (16) define lower and upper bounds, respectively, on the transmit power for each frequency.

B. Distributed Spectrum and Power Allocation

In cognitive radio ad hoc networks the locally available spectrum resources may change from time to time. Hence, link capacities are time-varying and can be maximized through

(i) dynamic spectrum and power allocation (ii) choice of a cooperation strategy and a relay. In this section, we derive procedures to maximize the link capacities for direct and cooperative links. These procedures will then be used in the *distributed joint routing, relay selection, and spectrum allocation algorithm* in Section V. The objective is to assign a spectrum portion $\mathbf{F}_i$ (i.e., set of contiguous minibands) with corresponding transmit power $\mathbf{P}_i$ for node i, $\mathbf{F}_r$ with $\mathbf{P}_r$ for selected relay node $\mathcal{R}(i,j)$ to maximize the Shannon capacity for a given link (i,j), $C_{ij} = \max(C_{ij}^{coop}, C_{ij}^{dirc})$, where C_{ij}^{coop} and C_{ij}^{dirc} were defined in (2) and (3), respectively. For the case when transmitter i does not use a relay, we denote $\mathcal{R}(i,j) = \{\emptyset\}$, $\mathbf{F}_r = \{\emptyset\}$, $\mathbf{P}_r = \mathbf{0}$, and the capacity is the direct transmission capacity as defined in (3), i.e., $C_{ij} = C_{ij}^{dirc}$.

Spectrum and Power Allocation for Direct Transmission: Maximizing the capacity of link (i,j) means selecting spectrum $\mathbf{F}_i$ and corresponding transmit power $P_i(f)$ that maximize the Shannon capacity under the spectrum sharing constraints introduced in (11) and (16) in Section IV-A.

$$\begin{aligned}
&\mathbf{P2.1}: Given: \quad (i,j),\ P_i^{max}(f),\ P_{ij}^{min}(f),\ P^{Bgt} \\
&\quad Find: \qquad \mathbf{F}_i,\ \mathbf{P}_i && (17)\\
&\quad Maximize: \qquad C_{ij}^{dirc} && (18)\\
&\quad Subject\ to: \\
&\qquad P_{ij}^{min}(f) \le P_i(f) \le P_i^{max}(f),\ \forall f \in \mathbf{F}_i; && (19)\\
&\qquad \sum_{f\in\mathbf{F}_i} P_i(f) \le P^{Bgt}. && (20)
\end{aligned}$$

Spectrum and Power Allocation for Cooperative Transmission: Consider the the cooperative transmission of link (i,j) with relay node $\mathcal{R}(i,j) = m$, where i,j and m correspond to nodes s, d and r shown in Fig. 2, respectively. In the spectrum and power allocation for cooperative transmission problem, power constraints should be satisfied not only at i but also at m.

$$\begin{aligned}
&\mathbf{P2.2}: Given: \quad (i,j), m,\ P_i^{max}(f),\ P_m^{max}(f),\ P^{Bgt} \\
&\quad Find: \qquad \mathbf{F}_i,\ \mathbf{F}_r, \mathbf{P}_i,\ \mathbf{P}_r && (21)\\
&\quad Maximize: \qquad C_{ij}^{coop} && (22)\\
&\quad Subject\ to: \\
&\qquad P_i(f) \le P_i^{max}(f),\ \forall\, f \in \mathbf{F}_i, && (23)\\
&\qquad P_m(f) \le P_m^{max}(f),\ \forall\, f \in \mathbf{F}_r, && (24)\\
&\qquad \mathbf{F}_i = \mathbf{F}_r, && (25)\\
&\qquad \sum_{f\in\mathbf{F}_i} P_i(f) \le P^{Bgt}, && (26)\\
&\qquad \sum_{f\in\mathbf{F}_r} P_m(f) \le P^{Bgt}. && (27)
\end{aligned}$$

In the problem above, for the sake of simplicity we impose through (25) that source and relay use the same spectrum. This can be easily removed, at the expense of computational complexity. For a given spectrum portion $\mathbf{F}_i$, problem $\mathbf{P2.2}$ is equivalent to the following problem.

$$\begin{aligned}
&\mathbf{P2.3}: Given: \quad \mathbf{F}_i, (i,j), m, P_i^{max}(f), P_m^{max}(f), P^{Bgt} \\
&\quad Find: \qquad z, \mathbf{P}_i,\ \mathbf{P}_r \\
&\quad Maximize: \qquad z \\
&\quad Subject\ to: \\
&\qquad z - \frac{w}{2}\sum_{f\in\mathbf{F}_i} \log_2(1+\mathrm{SINR}_{im}^f(P_i(f))) \le 0; && (28)
\end{aligned}$$

$$z - \frac{w}{2}\sum_{f\in\mathbf{F}_i} \log_2(1+\mathrm{SINR}_{ij}^f(P_i(f)) + \mathrm{SINR}_{mj}^f(P_m(f))) \le 0; \quad (29)$$

and constraints (23) - (27).

Problem $\mathbf{P2.3}$ is a convex optimization problem, because (i) the objective function of $\mathbf{P2.3}$ and constraints (23) - (27) are all affine functions of the problem variables $z, \mathbf{P}_i,\ \mathbf{P}_r$, (ii) the inequality constraint functions (28) and (29) are twice differentiable, and their Hessians are negative semidefinite. Clearly, problem $\mathbf{P2.1}$ is also a convex optimization problem for a given $\mathbf{F}_i$. Thus, for given spectrum $\mathbf{F}_i$, both problems can be solved efficiently in polynomial time by using interior point methods [37], [38].

Algorithm 1 Spectrum and Power Allocation Algorithm.

Given link (i,j), relay candidate m, $C_{ij}^* = 0$
for each $[f_l, f_{l+\Delta B}] \in [f_{min}, f_{max}]$ **do**
  Derive $\mathbf{P}_i$ by solving problem $\mathbf{P2.1}$ over $[f_l, f_{l+\Delta B}]$
  if $C_{ij}^{dirc} > C_{ij}^*$ **then**
    $C_{ij}^* = C_{ij}^{dirc}$
    $[\mathbf{F}_i^*, \mathbf{F}_r^*, \mathbf{P}_i^*, \mathbf{P}_r^*] = [[f_l, f_{l+\Delta B}], \emptyset, \mathbf{P}_i, \mathbf{0}]$
    $\mathcal{R}(i,j) = \emptyset$
  end if
  Derive $\mathbf{P}_i, \mathbf{P}_r$ by solving $\mathbf{P2.3}$ over $[f_l, f_{l+\Delta B}]$
  if $C_{ij}^{coop} > C_{ij}^*$ **then**
    $C_{ij}^* = C_{ij}^{coop}$
    $[\mathbf{F}_i^*, \mathbf{F}_r^*, \mathbf{P}_i^*, \mathbf{P}_r^*] = [[f_l, f_{l+\Delta B}], [f_l, f_{l+\Delta B}], \mathbf{P}_i, \mathbf{P}_r]$
    $\mathcal{R}(i,j) = m$
  end if
end for
Return solution as $[\mathbf{F}_i^*, \mathbf{F}_r^*, \mathbf{P}_i^*, \mathbf{P}_r^*, C_{ij}^*, \mathcal{R}(i,j)]$

V. Distributed Routing, Relay Selection, and Spectrum Allocation

In this section, we introduce a distributed algorithm, designed to provide an approximate solution to $\mathbf{P1}$ based on real-time distributed decisions driven by locally collected information.

A. Spectrum and Power Allocation Algorithm

We start by introducing the spectrum and power allocation algorithm executed in a distributed fashion at each secondary user to maximize the link capacity given the current spectrum condition. Note that a sender may not always use a relay node, because cooperative transmission may lead to a lower capacity than direct transmission. This fact underlines the significance of transmission mode selection, because different relay nodes may lead to different capacities due to the channel coefficients h_{sr}, h_{sd} in Fig. 2. Moreover, the available spectrum and the corresponding allowed transmit power at different relay nodes may be different in the spectrum-agile network, which influences the achievable capacity as well. Therefore, relay node selection with spectrum allocation in cooperative communications is essential to maximize link capacity.

The joint spectrum and power allocation Algorithm 1 is performed to find optimal spectrum and power allocation for given link (i, j) and relay candidate m.

B. Distributed Joint Routing and Relay Selection Algorithm

Denote $\mathcal{N}^s(i)$ as the set of feasible next hops for the backlogged session s at node i, i.e., the set of neighbors with positive advance towards the destination of session s. Node m has *positive advance* with respect to i iff m is closer to the destination of session s than i [39]. Every backlogged node i, once it senses an idle common control channel, performs the distributed joint routing and relay selection algorithm (Algorithm 2).

Algorithm 2 Distributed Joint Routing and Relay Selection Algorithm.

At backlogged node i, $U_{ij} = 0$
for each backlogged session s **do**
  for $j \in \mathcal{N}^s(i)$ **do**
    for $m \in \mathcal{N}^s(i)$ **do**
      Calculate $[\mathbf{F}_i, \mathbf{F}_r, \mathbf{P}_i, \mathbf{P}_r, C_{ij}, \mathcal{R}(i,j)]$ by using Algorithm 1
      if $C_{ij} \cdot (Q_i^s - Q_j^s) > U_{ij}$ **then**
        $U_{ij} = C_{ij} \cdot (Q_i^s - Q_j^s)$
        $[\mathbf{F}_i^*, \mathbf{F}_r^*, \mathbf{P}_i^*, \mathbf{P}_r^*] = [\mathbf{F}_i, \mathbf{F}_r, \mathbf{P}_i, \mathbf{P}_r]$
        $[s^*, j^*] = [s, j]$
        $[\mathcal{R}^*(i, j^*)] = [\mathcal{R}(i,j)]$
      end if
    end for
  end for
end for
Set contention window $CW_i = \Phi(U_{ij})$
Generate backoff counter $BC_i \in [1, 2^{CW_i - 1}]$
Return $[s^*, j^*, \mathcal{R}^*(i,j^*), \mathbf{F}_i^*, \mathbf{F}_r^*, \mathbf{P}_i^*, \mathbf{P}_r^*, BC_i, U_{ij}]$

Algorithm 2 calculates the next hop opportunistically depending on queueing and spectrum dynamics, according to the utility function in (9). At every backlogged node, the next hop is selected with the objective of maximizing (9). The combination of next hops leads to a multi-hop path. The multi-hop path discovery terminates when the destination is selected as the next hop. If the destination is in the transmission range of the transmitter (either a source or an intermediate hop for that session), the differential backlog between the transmitter and the destination is no less than the differential backlogs between the transmitter and any other nodes, because the queue length of the destination is zero. Hence, the destination has a higher probability of being selected as next hop than any other neighboring node of the transmitter. Note that the transmitter may still select a node other than the destination as the next hop even if the destination is in the transmission range. This can happen, for example, if there is no available miniband between transmitter and destination, or if the interference on the minibands at that time is very high, which results in low link capacity between the transmitter and the destination.

Once spectrum selection, power allocation, scheduled session, next hop (with relay node if cooperative transmission is selected) have been determined by executing Algorithm 2, i.e. $[s^*, j^*, \mathcal{R}(i,j), \mathbf{F}_i, \mathbf{F}_r, \mathbf{P}_i, \mathbf{P}_r]$, the probability of accessing the medium is calculated based on the value of U_{ij}. Nodes with higher U_{ij} will get a higher probability of accessing the medium and transmit. Note that U_{ij} is an increasing function of $(Q_i^s - Q_j^s)$, i.e., links with higher differential backlog may have larger U_{ij} , thus have higher probability of being scheduled for transmission.

This probability is implemented by varying the size of the contention window at the MAC layer. The transmitting node i generates a backoff counter BC_i chosen randomly (with a uniform distribution) within the interval $[1, 2^{CW-1}]$, where CW_i is the contention window of transmitter i, whose value is a decreasing function $\Phi()$ of the utility U_{ij} as below

$$CW_i = -\alpha \cdot \frac{U_{ij}}{\sum_{k \in \mathcal{N}_i, k, l \in \mathcal{V}} U_{kl}} + \beta, \;\; \alpha > 0, \beta > 0 \qquad (30)$$

where $\sum_{k \in \mathcal{N}_i, k, l \in \mathcal{V}} U_{kl}$ represents the total utility of the neighboring competing nodes. Scalars α and β can be designed for specific network size and active sessions injected into the network to reduce collision. Note that sender i collects its neighbors utility values by overhearing control packets (shown in Figure 4) on the CCC as discussed in Section VI.

With this mechanism, heavily backlogged queues with more spectrum resources are given higher probability of transmission. For a node i that just has completed transmission on the data channel, the value of $\mathbf{Q}_i$ becomes smaller, which results in a reduced value of U_{ij}, which consequently leads to a lager size of the contention window. In this way, the node's level of priority in accessing spectrum resources is implicitly reduced, which, in turn, improves fairness. Differential backlog-aware routing can reduce the probability of forwarding data through a congested node. A large queue size at an intermediate node is interpreted as an indicator that the path going through that node is congested and should be avoided, while a small queue size at an intermediate node indicates low congestion on the path going through that node. According to the proposed routing algorithm, nodes with a smaller queue size have a higher probability of being selected as next hop. On the other hand, according to our proposed medium access control mechanism as discussed later, links with larger differential backlogs have smaller contention window size, and thus have higher probability of accessing the channel and consequently have higher priority in reserving resources. In this way, congestion is mitigated by the proposed routing and medium access control strategy.

VI. Distributed Protocol Design

The main challenge in implementing the distributed dynamic resource allocation and routing algorithm is to let nodes learn information about the environment to make real-time decisions on routing, relay selection, spectrum, and power allocation. One possible way to learn about the environment is to rely on extensive spectrum sensing. However, conventional CSMA/CA mechanisms cannot meet the challenging

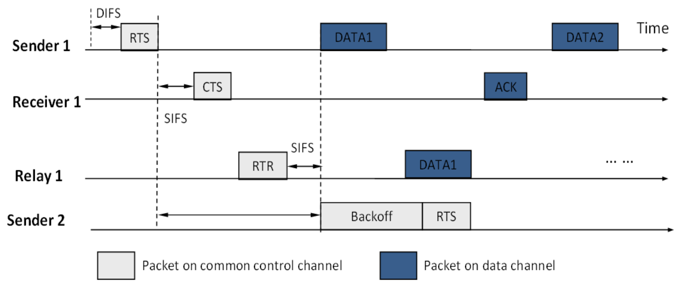


Fig. 3. Medium Access Control for Cooperative Transmissions.

radio sensitivity requirements and wideband frequency agility needed in cognitive radio networks.

As an alternative, we propose a cooperative MAC for cognitive radio networks (CoCogMAC), which aims at providing nodes with accurate spectrum information based on a combination of physical sensing and of local exchange of information. Scanner-equipped cognitive radios can detect primary user transmissions by sensing the data channel. In addition, CoCogMAC combines scanning results and information from control packets exchanged on the control channel that contain info about transmissions and power used on different minibands.

CoCogMAC uses a three-way handshaking among the source, destination and relay. The three-way handshaking is carried out via exchange of Request-to-Send (RTS), Clear-to-Send (CTS) and Relay- Ready-to-Relay (RTR) frames among the source, destination and the selected relay. Similar to the IEEE 802.11 two-way RTS and CTS handshake, backlogged nodes contend for spectrum access on the *common control channel* (CCC). However, CoCogMAC's three-way handshake is substantially different from the RTS and CTS handshake used in IEEE 802.11. All control packets have different structure and functions. Here, we enhance the RTS/CTS packets and introduce RTR packet to announce the spectrum reservation and transmit power to the neighboring nodes. Each node makes adaptive decisions based on the overheard RTS/CTS/RTR packets. Fig. 3 illustrates this operation.

The sender informs the receiver and relay of the selected frequency interval using an RTS packet. On receiving the RTS packet, the receiver responds by using a CTS packet after the Short Inter-Frame Space (SIFS) and tunes its transceiver for data transmission on the frequency specified in the RTS packet. The selected relay will send out an RTR packet after receiving the RTS and CTS packets. The RTR packet is used to announce the spectrum reservation and transmit power to the relay's neighbors and inform the receiver of the presence of the relay. Once RTS/CTS/RTR are successfully exchanged, sender, relay, and receiver tune their transceivers to the selected spectrum portion. Before transmitting, they sense the selected spectrum and, if it is idle, the sender begins data transmission without further delay. Note that it is possible that the sender, relay or the receiver finds the selected spectrum busy just before data transmission. This can be caused by the presence of primary users, or by conflicting reservations caused by losses of control packets. In this case, the node gives up the selected spectrum,

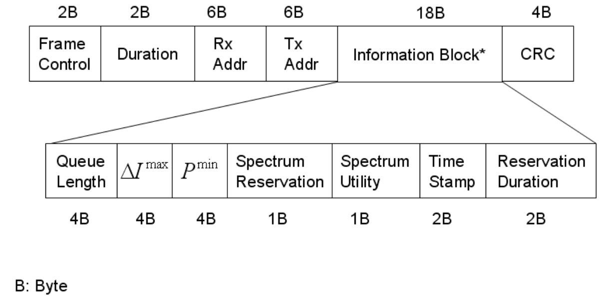


Fig. 4. Control Packet Format.

and goes back to the control channel for further negotiation. During the RTS/CTS/RTR exchange, if the sender-selected spectrum can not be entirely used, i.e., the receiver just sensed the presence of a primary user, the receiver will not respond with a CTS. This is also true for the relay node. The sender will go back to the control channel for further negotiation once the waiting-for-CTS timer expires and the RTS retransmission limit is reached.

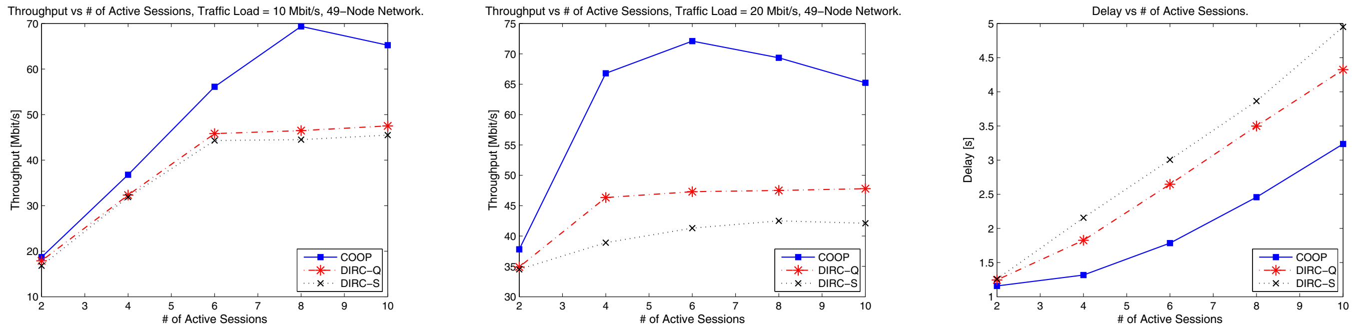
Note that CoCogMAC is significantly different from CoopMAC [22] in the following aspects: (i) different from CoopMAC, CoCogMAC enables collaborative spectrum sensing and spectrum reservation in cognitive radio ad hoc networks by exchanging control packets on the common control channel; (ii) unlike CoopMAC, CoCogMAC is an adaptive distributed channel access control scheme. CoCogMAC employs a dynamic contention window size as discussed in Section V to opportunistically give priority in spectrum reservation to links with higher capacity and larger differential backlog.

VII. Performance Evaluation

In this section, we analyze the performance of the proposed algorithm (referred to as COOP) in a multi-hop cognitive radio network. To evaluate COOP, we have developed an object-oriented packet-level discrete-event simulator, which models in detail all layers of the communication protocol stack as described in this paper. We would like to emphasize that our simulator is a packet-level simulator (similar to ns-2), which is however interfaced with the CVX modeling language [40] to solve at simulation time the resource allocation optimization problems discussed in Section V. Hence, we simulate in detail the network behavior based on the distributed decision making as it results from numerical optimization. Therefore, the results presented in this section are based on an accurate protocol simulation, and are not mere numerical results derived from the analytical model.

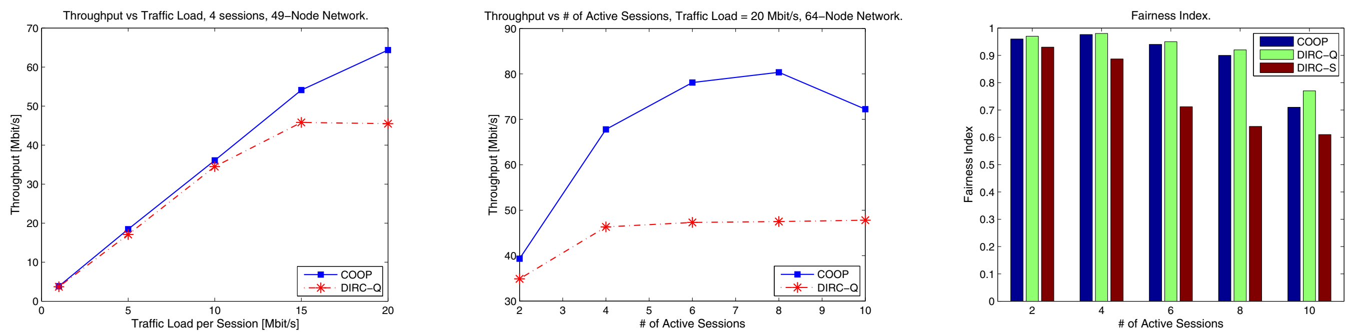
For simulation purposes, we map the Shannon capacity to physical data rates as follows. Since the relation between BER and SINR varies with different modulation schemes, we consider the class of M-QAM [41]. Specifically, we consider BPSK, QPSK, 16-QAM and 64-QAM as the modulation set. The transmitter compares the expected SINR with a set of pre-defined thresholds to choose the best modulation scheme. The data rate for BPSK is $2\,\mathrm{Mbit/s}$ for a $1\,\mathrm{MHz}$ miniband.

We first compare the performance of COOP with two alternative schemes, both of which rely on the same knowledge of the environment as COOP. In particular, we consider DIRC-Q as the solution where routing with dynamic spectrum allocation is based on the same utility as COOP but with



(a) (b) (c)

Fig. 5. (a): Throughput with $10\,\mathrm{Mbit/s}$ load per session; (b): Throughput with $20\,\mathrm{Mbit/s}$ load per session; (c): Delay with $20\,\mathrm{Mbit/s}$ load per session.



(a) (b) (c)

Fig. 6. (a): Impact of traffic load on throughput; (b): Throughput with $20\,\mathrm{Mbit/s}$ load per session, 64-node network; (c): Fairness Index.

direct transmission only, and to routing with dynamic spectrum allocation (DIRC-S) as the solution where routing with direct transmission is based on shortest path without considering differential backlog.

Considering a grid topology of 49 nodes, we initiate sessions between randomly selected but disjoint source-destination pairs. Sessions are CBR sources. We set the available spectrum to be $54\,\mathrm{MHz}$ - $60\,\mathrm{MHz}$, a portion of the TV band that secondary users are allowed to use when there is no licensed (primary) user operating on it [42]. We restrict the bandwidth usable by cognitive radios to be $3\mathrm{MHz}$. The bandwidth of the CCC is $2\,\mathrm{MHz}$. The duration of a time slot on the CCC is set to 20 microseconds. Parameters α and β in (30) are set to 5 and 10 respectively. A larger CW can reduce the collision rate but may lead to lower utilization of the control channel caused by backoff. These values are implicitly optimized based on the network size in the simulation. Rayleigh fading channel is used and the path loss exponent is set to two.

We compare the three solutions by varying the number of sessions injected into the network and plot the network throughput (sum of individual session throughput). Figures 5(a) and 5(b) show the impact of the number of sessions injected into the network on the throughput performance. The traffic load per session is $10\,\mathrm{Mbit/s}$ and $20\,\mathrm{Mbit/s}$. When the traffic load is low, i.e., $10\,\mathrm{Mbit/s}$, DIRC-Q and DIRC-S obtain similar throughput performance. However, with higher traffic load, i.e., $20\,\mathrm{Mbit/s}$, COOP and DIRC-Q perform much better than DIRC-S since DIRC-S restricts packets forwarding to the receiver that is closest to the destination, even if the link capacity is very low or the receiver is heavily congested. In contrast, COOP and DIRC-Q, by considering both the link capacity and the differential backlog, are more flexible and may route packets along paths that temporarily take them farther from the destination, especially if these paths eventually lead to links that have higher capacity and/or that are not as heavily utilized by other traffic. Moreover, as shown in both figures, the throughput achieved by COOP is the highest due to the spatial diversity gain exploited by COOP.

Figure 5(c) shows the delay performance for the three solutions with traffic load $20\,\mathrm{Mbit/s}$ per session. In general, the delay performance gaps among the three solutions grow as the number of sessions increases.

We now concentrate on the comparison between COOP and DIRC-Q. Figure 6(a) illustrates the network throughput as the traffic load per flow varies from $1\,\mathrm{Mbit/s}$ to $20\,\mathrm{Mbit/s}$. As the per-session load increases over $10\,\mathrm{Mbit/s}$, the improvement obtained by COOP is more visible by opportunistically exploiting spatial diversity.

Figures 5(b) and 6(b) show the impact of varying number of sessions when the number of nodes deployed in the network is 64 and 49, respectively. In general, with the same traffic load, the 64-node network achieves a better performance since the available diversity is higher than that of 49-node network. The throughput first increases as the number of sessions increases. After a certain point, the throughput starts decreasing. As shown in the two figures, the throughput of the 64-node network decreases later than that of 49-node network, since the achievable spatial diversity is less in the latter. Figure 6(c) shows Jain's fairness index, calculated as $(\sum r_s)^2/S{*}\sum(r_s)^2$, where r_s is the throughput of session s, and S is the total number of active sessions. As shown in the figure, the overall fairness among competing sessions is improved by COOP and DIRC-Q by considering the differential backlog.

VIII. Conclusions

We studied and proposed decentralized and localized algorithms for joint dynamic routing, relay selection, and spectrum allocation in cooperative cognitive radio ad hoc networks. We have shown how the proposed distributed algorithms lead to increased throughput with respect to non-cooperative strategies. The discussion in this paper leaves several open issues for further research. First, we will aim at deriving a theoretical lower bound on the performance of the proposed algorithm. Furthermore, we will evaluate the performance of the algorithm in conjunction with a congestion control module. Finally, we will implement the proposed algorithm on an testbed based on URSP2 [32] and GNU Radio [33].

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