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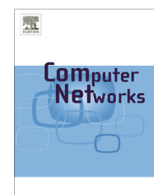
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Distributed resource allocation in cognitive and cooperative ad hoc networks through joint routing, relay selection and spectrum allocation [☆]

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ABSTRACT

Cooperative relaying and dynamic-spectrum-access/cognitive techniques are promising solutions to increase the capacity and reliability of wireless links by exploiting the spatial and frequency diversity of the wireless channel. Yet, the combined use of cooperative relaying and dynamic spectrum access in multi-hop networks with decentralized control is far from being well understood.

We study the problem of network throughput maximization in cognitive and cooperative ad hoc networks through joint optimization of routing, relay assignment and spectrum allocation. We derive a decentralized algorithm that solves the power and spectrum allocation problem for two common cooperative transmission schemes, decode-and-forward (DF) and amplify-and-forward (AF), based on convex optimization and arithmetic–geometric mean approximation techniques. We then propose and design a practical medium access control protocol in which the probability of accessing the channel for a given node depends on a local utility function determined as the solution of the joint routing, relay selection, and dynamic spectrum allocation problem. Therefore, the algorithm aims at maximizing the network throughput through local control actions and with localized information only.

Through discrete-event network simulations, we finally demonstrate that the protocol provides significant throughput gains with respect to baseline solutions.

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1. 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 [2,3] 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 and unbalanced resource utilization, the cognitive radio paradigm prescribes the coexistence of licensed (or primary) and unlicensed (secondary or cognitive) radio users on the same portion of the spectrum. A key challenge in the design of cognitive radio networks is then dynamic spectrum allocation, which enables wireless devices to

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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., [4–7].

However, mainstream cognitive radio research has mostly been focused on infrastructure-based networks, while the underlying root challenge of devising *decentralized spectrum management* mechanisms for infrastructure-less cognitive ad hoc networks is still substantially unaddressed. In cognitive 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 such as routing and medium access control, closely interact and are jointly optimized with the spectrum management functionality. Since in a spatially distributed ad hoc network spectrum occupancy is location-dependent the available spectrum bands may be different at each hop. Hence, controlling the interaction between the routing, medium access, and the spectrum management functionalities is of fundamental importance.

Within this context, we additionally consider techniques to leverage the *spatial diversity* that characterizes the wireless channel. Spatial diversity is traditionally exploited by using multiple transceiver antennas to effectively cope with channel fading. 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 [8–10]. 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 and communication theoretic problems in cooperative communications. The reader is referred to [11,12] 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 modeling in detail how cooperation interacts with higher layers of the protocol stack to improve network performance metrics. For example, [13–16] investigate the achievable rates and diversity gains 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 [17,10], cooperative routing [18–22], optimal network-wide relay selection [23,24], and optimal stochastic control [25]. However, decentralized spectrum management with cooperative devices is a substantially unexplored area.

In this paper, we consider an infrastructure-less ad hoc network (illustrated in Fig. 1) 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. We make the following contributions:

- *Uncoordinated spectrum management.* Unlike mainstream work on cognitive ad hoc networks, we consider a distributed and dynamic environment, and study the interactions between cooperation and spectrum management.
- *Distributed joint routing, relay selection, and dynamic spectrum allocation.* We formulate a joint routing, relay selection, and dynamic spectrum allocation problem, with the objective of maximizing the network throughput. Given the centralized nature and computational intractability 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.
- *Spectrum and power allocation algorithms for two common cooperative schemes.* We propose spectrum and power allocation algorithms for two alternative cooperative relaying schemes, decode-and-forward (DF) and amplify-and-forward (AF), which are building blocks of the distributed resource allocation algorithm. We compare the link capacity achievable by the two cooperative schemes, and show that DF outperforms AF in general.
- *Mapping local to global objectives through stochastic channel access.* We propose a practical implementation of the proposed algorithm based on a medium access control protocol that relies on a common control channel and a frequency-agile data channel. In the proposed medium access control protocol, the probability of accessing the channel, and therefore of having priority in reserving spectrum resources and relays, depends on a utility function determined as the local solution, for each individual node, of the joint routing, relay selection, and dynamic spectrum allocation problem. The protocol can be seen as a hybrid between traditional contention-based protocols and utility-based scheduled channel access schemes.

The rest of the paper is organized as follows. In Section 2, we review related work. In Section 3, we introduce the system model. In Section 4 we formulate the cross-layer optimization problem. In Section 5, we discuss link capacity maximization with and without cooperative relays. In Section 6, we introduce the decentralized algorithm for joint routing, relay selection and dynamic spectrum allocation. Section 7 discusses the cooperative MAC/routing protocol design and addresses implementation details. In Section 8 we evaluate the performance of the proposed protocol. Finally, Section 9 concludes the paper.

2. Related work

Cooperative transmission has mainly been addressed at the physical-layer, i.e., by studying the achievable rates or

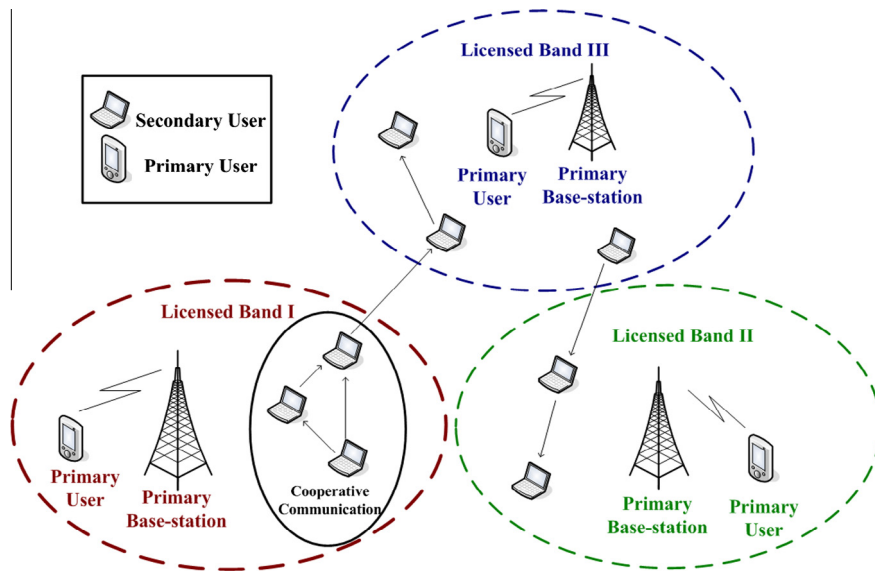


Fig. 1. Architecture of the proposed Cognitive Radio Ad Hoc Networks, and its coexistence with legacy narrowband unlicensed users and primary users.

diversity gains of given cooperative schemes [13–16]. Recent work has started investigating cooperative-transmission-aware routing and the relay node assignment problem.

In single-hop networks, the focus has mostly been on relay node selection between each source and destination pair. For example, Shi, Hou et al. [23] propose an optimal relay selection algorithm for multiple source–destination pairs such that the minimum capacity among all source–destination pairs is maximized. The algorithm achieves optimal relay assignment with polynomial-time complexity by using a “linear marking” mechanism that is able to achieve linear complexity at each iteration. In [26], the authors address the relay assignment problem to extend the coverage area. They show that cooperative transmission significantly outperforms direct transmission in terms of coverage area, transmit power, and spectral efficiency. Xue et al. [27] consider a system model where a relay node can be shared by multiple source–destination pairs. They propose an optimal algorithm that runs in polynomial time to solve the relay assignment problem with the objective of maximizing the total capacity of all source–destination pairs. Along with the proposed algorithm, the authors show that an optimal relay assignment preferably assigns a relay node to at most one source node to achieve the maximum total capacity even if multiple source–destination pairs are allowed to share a common relay node.

Recent work has also considered multi-hop cooperative networking. In [21], the authors study the minimum energy routing problem by exploiting cooperative gain. A dynamic programming based solution is proposed to find the route with minimum energy consumption. In [22], the authors study the problem of power allocation on a pre-selected route of links enhanced by cooperative relays to maximize the network lifetime. Yeh et al. [25] formulate and solve an optimal stochastic control problem with cooperative relays. In [10,19,20,18,24] the authors propose routing solutions with cooperative relaying. For example,

Lakshmanan and Sivakumar [18] investigate how cooperative relaying benefits translate into network level performance improvements. An adaptive routing protocol is proposed with algorithms to determine the choice of the number of cooperative transmitters such that the diversity gain and interference trade-off is appropriately leveraged; and the choice of the cooperation strategy such that the diversity gain is appropriately used for either an increase in the range or the rate of the links or both. In [24], Sharma and Hou study a joint problem of relay node assignment and multi-hop flow routing, with the objective to maximize the minimum rate among a set of concurrent sessions. The problem is formulated as a mixed integer linear programming and solved by using a branch-and-cut framework. In contrast, we study the problem of decentralized spectrum management with cooperative routing.

In the context of cognitive networks, Zhang et al. [28,29] demonstrate that cooperative transmissions can increase the network throughput by jointly exploiting spatial and spectrum diversity. Simeone et al. [30–32] propose a cooperative transmission scheme between primary and secondary users referred to as *spectrum leasing*, where secondary users relay the traffic on behalf of primary users in exchange for opportunities to transmit their own traffic. Leasing means that the primary users have an incentive (e.g., monetary rewards as leasing payments) to allow secondary users to access their licensed spectrum.

Recent work has also addressed spectrum-aware routing techniques in cognitive networks with multi-hop communication capabilities. Cesana et al. [33] provide an excellent overview of routing research on cognitive ad hoc networks. The survey identifies two main categories of solutions, i.e., approaches based on a global spectrum knowledge, and approaches that consider local spectrum knowledge only as obtained via distributed procedures and protocols.

Ekici et al. [34] propose a route-stability-oriented routing analysis, where a novel definition of route stability is introduced based on the notion of *route maintenance cost*. The maintenance cost represents the effort needed (or penalty paid) to maintain end-to-end connectivity. In [35], Chowdhury and Felice propose a routing protocol that discovers several paths from source to destination, which are then combined at the destination to form low-hop count paths. In case the operational path is affected by a new primary user activity, the protocol initiates a new partial route search through RREQ packets. A cross-layer opportunistic spectrum access and dynamic routing algorithm is introduced in [6], which can be interpreted as a distributed solution to a centralized cross-layer optimization problem. In contrast, in this paper we study the problem of decentralized joint routing and spectrum allocation by exploiting the benefits of cooperative relaying.

3. System model

We consider a cognitive ad hoc network consisting of primary and secondary users. Primary users hold licenses for specific spectrum bands, and can only occupy their assigned portion of the spectrum. Secondary users do not have any licensed spectrum and opportunistically send their data by utilizing idle primary spectrum. Let $\mathcal{N} = \{1, \dots, N\}$ represent a finite set of secondary users (also referred to as nodes). We assume that all the secondary users are equipped with cognitive radios that consist of a reconfigurable transceiver that can tune to a set of contiguous frequency minibands, and a scanner.

3.1. 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. A *data channel* (DC) is used for data communication. The data channel consists of a set of discrete minibands $\{f_{\min}, f_{\min+1}, \dots, f_{\max-1}, f_{\max}\}$, 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 $w \cdot \Delta B$, where ΔB is an integer. 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 [36,37]. Note that a dedicated frequency band is assigned as the CCC, which is always available to the secondary users so that they can constantly exchange information and update their observation of the neighboring nodes without interfering primary users. In this work, we focus on how to utilize the exchanged information for secondary users to optimize their resource allocation. There is extensive work

on how to design and realize CCC in cognitive radio networks. The readers are referred to [38] and the work therein for more details.

3.2. Transmission mode

Consider the cooperative relaying model shown in Fig. 2, with source node s , relay node r and destination node d . Considering multiple orthogonal frequencies, let \mathbf{f}_s represent the contiguous set of minibands used by both s and r . We define P_s^f and P_r^f as the transmit power allocated at node s and r , respectively, on miniband f , and $\mathbf{p}_s = \{P_s^f \mid f \in \mathbf{f}_s\}$ and $\mathbf{p}_r = \{P_r^f \mid f \in \mathbf{f}_s\}$ as the set of allocated power at node s and r . Let SINR_{sr}^f , SINR_{sd}^f and SINR_{rd}^f denote the signal-to-interference-plus-noise power ratios (SINR) on miniband f of links (s, r) , (s, d) and (r, d) , respectively. We have $\text{SINR}_{sr}^f(P_s^f) = \frac{P_s^f L_{sr}}{N_I^f}$, $\text{SINR}_{sd}^f(P_s^f) = \frac{P_s^f L_{sd}}{N_I^f}$, and $\text{SINR}_{rd}^f(P_r^f) = \frac{P_r^f L_{rd}}{N_I^f}$, where L_{sr} , L_{sd} and L_{rd} capture the effects of path-loss, shadowing and frequency nonselective fading of links (s, r) , (s, d) and (r, d) , respectively. N_I^f and N_I^f represent the noise plus interference on miniband f at node r and d , respectively. Note that N_I^f and N_I^f are not constant. Their values depend on other active transmissions. For example, $N_I^f = N_r^f + \sum_{k \in \mathcal{N}, k \neq s} P_k^f L_{kr}$, where N_r^f is the receiver noise on frequency f , and the expression $\sum_{k \in \mathcal{N}, k \neq s} P_k^f L_{kr}$ represents the sum of interferences from all neighboring transmissions at receiver r . Note that we are dropping all time dependencies.

We will consider two different cooperative schemes, i.e., *decode-and-forward* (DF) and *amplify-and-forward* (AF).

Decode-and-forward cooperative relaying: In the DF cooperative relaying scheme, relay r decodes the received signal from source s in the first time period, and forwards the data to destination d in the second time period. The destination jointly decodes the signals received from source and relay, for example through maximal ratio combining [39]. Assuming the relay can fully decode the source message, the capacity of the cooperative link between s and d with relay r is [9]

$$C_{sdr}^{DF}(\mathbf{f}_s, \mathbf{p}_s, \mathbf{p}_r) = \frac{w}{2} \min_{f \in \mathbf{f}_s} \left\{ \log_2 \left(1 + \text{SINR}_{sr}^f(P_s^f) \right), \log_2 \left(1 + \text{SINR}_{sd}^f(P_s^f) + \text{SINR}_{rd}^f(P_r^f) \right) \right\}. \quad (1)$$

Note that C_{sdr}^{DF} is an increasing function of \mathbf{p}_s and \mathbf{p}_r , which means that both source and relay node should

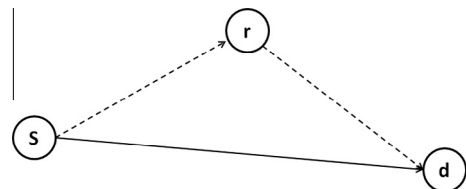


Fig. 2. Illustration of cooperative relaying model.

transmit at the maximum power to achieve maximum capacity. In spatially distributed cognitive networks with decentralized control, however, different minibands may have different maximum allowed power limits, and such constraints are different for different nodes as discussed in detail in Section V.A. Hence, the capacity of a link depends on the joint selection of relay node, spectrum, and power on different minibands.

Amplify-and-forward cooperative relaying: In the AF cooperative relaying scheme, cooperative relay node r receives and amplifies (but does not decode) the signal from source node s in the first time period, and forwards the signal to destination node d in the second time period. The destination jointly decodes the two copies of the signal from two different paths, thereby increasing the probability of correct detection. We can express the capacity of a AF cooperative link between s and d with relay r as [9]

$$C_{sdr}^{AF}(\mathbf{f}_s, \mathbf{p}_s, \mathbf{p}_r) = \frac{w}{2} \sum_{f \in \mathcal{F}_s} \log_2 \left(1 + \text{SINR}_{sd}^f(P_s^f) + \frac{\text{SINR}_{sr}^f(P_s^f) \cdot \text{SINR}_{rd}^f(P_r^f)}{\text{SINR}_{sr}^f(P_s^f) + \text{SINR}_{rd}^f(P_r^f) + 1} \right). \quad (2)$$

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

$$C_{sd}^{DIR}(\mathbf{f}_s, \mathbf{p}_s) = \sum_{f \in \mathcal{F}_s} w \cdot \log_2 \left(1 + \text{SINR}_{sd}^f(P_s^f) \right). \quad (3)$$

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). In this work, we assume the channel state information (CSI) and the time-varying interference introduced by primary users is available at the receivers. Channel estimation and data detection for cooperative communications has been studied for AF schemes in [40–43], and for DF schemes in [44,45]. There is rich work in time-varying interference sensing in cognitive radio system such as [46–48]. We believe the estimation problem is orthogonal to our problem and addressed in those papers. We do not look into the problem of channel state information estimation in this work.

3.3. Queueing dynamics

Traffic flows are, in general, carried over multi-hop routes. Let the traffic demands consist of a set $\mathcal{S} = \{1, 2, \dots, S\}$ of unicast sessions. Each session $s \in \mathcal{S}$ is characterized by a fixed source–destination node pair, and it can have source and destination at any of the \mathcal{S} nodes. We indicate the arrival rate of session s at node i as $\lambda_i^s(t)$ at time t .

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 , we define $Q_i^s(t)$ as the number of queued bits of session s waiting for transmission at secondary user i . We define $r_{ij}^s(t)$ as the transmission rate on link (i, j) for session s during time slot t , which is limited by

the link capacity. For $\forall i \in \mathcal{N}$, the queue is updated as follows:

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

We assume that relay nodes forward packets to the destination node immediately after receiving the packets from the source node, i.e., packets are not enqueued at relay nodes.

4. Problem formulation

Let binary matrix \mathbf{E} indicate active links of secondary users on the data channel, i.e., $E_{ij} = 1$ indicates that link (i, j) is active, while $E_{ij} = 0$ indicates the link is not active. Let $\mathbf{E}^V = \{E^V(f) \mid f \in [f_{\min}, f_{\max}]\}$ represent activities of primary users (input to the problem), i.e., $E^V(f) = 1$ indicates active primary users' reception on miniband f , and $E^V(f) = 0$ indicates no primary users' reception on f .

We define $\mathbf{A} = \{A_{ij}^k \mid i, j, k \in \mathcal{N}\}$ as the global AF cooperative relay selection variable. Specifically,

$$A_{ij}^k = \begin{cases} 1 & \text{if node } k \text{ is selected as an AF relay for link } (i, j), \\ 0 & \text{otherwise.} \end{cases} \quad (4)$$

Similarly, define $\mathbf{B} = \{B_{ij}^k \mid i, j, k \in \mathcal{N}\}$ as the global DF cooperative relay selection variable,

$$B_{ij}^k = \begin{cases} 1 & \text{if node } k \text{ is selected as an DF relay for link } (i, j), \\ 0 & \text{otherwise.} \end{cases} \quad (5)$$

Note that binary variable E_{ij} indicates whether or not the link (i, j) is active in the routing solution, while A_{ij}^k and B_{ij}^k indicate cooperative relay selection for (i, j) . We may assign a AF or DF relay node to link (i, j) only if it is active, i.e., $E_{ij} = 1$. Otherwise, no cooperative relay should be assigned to (i, j) . This constraint can be expressed as

$$E_{ij} - \sum_{\substack{k \in \mathcal{N} \\ k \neq ij}} A_{ij}^k - \sum_{\substack{k \in \mathcal{N} \\ k \neq ij}} B_{ij}^k \geq 0, \quad \forall i, j \in \mathcal{N}, i \neq j. \quad (6)$$

In addition, we assume that each node can be used as either next hop or cooperative relay at most once at the same time. This can be expressed as

$$\sum_{\substack{i \in \mathcal{N} \\ i \neq jk}} \sum_{\substack{j \in \mathcal{N} \\ j \neq k}} A_{ij}^k + \sum_{\substack{i \in \mathcal{N} \\ i \neq jk}} \sum_{\substack{j \in \mathcal{N} \\ j \neq k}} B_{ij}^k + \sum_{\substack{l \in \mathcal{N} \\ l \neq k}} E_{lk} + \sum_{\substack{l \in \mathcal{N} \\ l \neq k}} E_{kl} \leq 1, \quad \forall k \in \mathcal{N}. \quad (7)$$

Then, the capacity of link (i, j) can be expressed as

$$C_{ij} = \left(1 - \sum_{\substack{k \in \mathcal{N} \\ k \neq ij}} A_{ij}^k - \sum_{\substack{k \in \mathcal{N} \\ k \neq ij}} B_{ij}^k \right) C_{ij}^{DIR}(\mathbf{f}_i, \mathbf{p}_i) + \sum_{\substack{k \in \mathcal{N} \\ k \neq ij}} A_{ij}^k C_{ijk}^{AF}(\mathbf{f}_i, \mathbf{p}_i, \mathbf{p}_k) + \sum_{\substack{k \in \mathcal{N} \\ k \neq ij}} B_{ij}^k C_{ijk}^{DF}(\mathbf{f}_i, \mathbf{p}_i, \mathbf{p}_k), \quad \forall i, j \in \mathcal{N}, i \neq j. \quad (8)$$

We define utility U_{ij} of link (i, j) as

$$U_{ij}(t) = C_{ij}(t) \cdot \left[Q_i^{s_{ij}^s}(t) - Q_j^{s_{ij}^s}(t) \right]^+, \quad (9)$$

where

$$s_{ij}^s = \arg \max_s \{ Q_i^s(t) - Q_j^s(t) \}. \quad (10)$$

In (9), $C_{ij}(t)$ represents the achievable capacity for link (i, j) as defined in (8) given the current spectrum condition at time t and the chosen transmission mode, while s_{ij}^s 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 5.1.

The utility function is defined based on the principle of dynamic back-pressure, first introduced in [49]. It can be proven [50] 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 (11) 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.

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 ad hoc 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 \mathbf{E} , \mathbf{A} , \mathbf{B} , global spectrum and power allocation $\mathbf{F} = \{\mathbf{f}_i \mid i \in \mathcal{N}\}$ and $\mathbf{P} = \{\mathbf{p}_i \mid i \in \mathcal{N}\}$, that maximize a sum of utility functions. This is formally expressed by the problem below.

P1 : Find : $\mathbf{F}, \mathbf{P}, \mathbf{E}, \mathbf{A}, \mathbf{B}$

$$\text{Maximize : } \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{N}, j \neq i} U_{ij} \cdot E_{ij} \quad (11)$$

Subject to :

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

$$\text{SINR}_{ij}^f \geq \text{SINR}^{\text{th}}(\text{BER}^*) \cdot E_{ij}, \quad \forall i, j \in \mathcal{N}, \forall f \in \mathbf{f}_i, \quad (13)$$

$$\sum_{f \in \mathbf{f}_i} P_i^f \leq P_i^{\text{Bgt}}, \quad \forall i \in \mathcal{N}, \quad (14)$$

$$\mathbf{f}_i \subset [f_{\min}, f_{\max}], \quad \forall i \in \mathcal{N}, \quad (6)-(7). \quad (15)$$

In the problem above, constraint (12) states that no transmission of secondary users is allowed if there is a reception activity of primary users on that miniband.

Intuitively, the more active the primary users are (i.e., occupying their licensed frequency bands), the less available spectrum the secondary users can access. Constraint (13) 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^* . In (14), P_i^{Bgt} represents a constraint on the total power for each device.

Therefore, ideally, a throughput-optimal policy would continuously (i.e., at each time slot) assign resources on each network link by solving problem **P1** to optimality. However, exact solution of **P1** requires global knowledge of all feasible rates and a centralized algorithm to solve a mixed integer non-linear problem (NP-hard in general) such as **P1** on a time-slot basis. This is clearly unpractical for real-time decision making. The problem above can be solved rather efficiently (but, certainly not in real time) through a combination of branch and bound and convex relaxation techniques, similar to the algorithm that we proposed in [51]. However, this is outside the scope of this paper. The main difficulty in solving problem **P1** is that the capacity region, which captures all possible routing, scheduling, and resource allocation strategies, has no easy representation in terms of the power constraints at the individual links or nodes in general. It has been shown that the complexity of this family of schedule problems is worst-case exponential [52]. The fastest algorithms we know for them are all exponential, not substantially better than an exhaustive search, and the problem is NP-hard [52]. Here, based on the formulation above, we derive distributed and localized best-response algorithms designed to achieve an approximate solution to **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 7. Note that, for the sake of simplicity, we will drop all time dependencies.

In the following sections, we first propose the physical layer resource allocation solution for link capacity maximization problem in Section 5. Then we present our distributed joint routing, relay selection and spectrum allocation algorithm with the objective of maximizing local utilities in Section 6.B. A stochastic channel access mechanism is then proposed in Section 6.C to map local to global objective we aim to maximize in **P1**.

5. Link capacity maximization under spectrum sharing constraints

In this section, we first derive the interference conditions under which multiple 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 discussed in Section 6.

5.1. Spectrum sharing constraints

All network transmitters need to (i) satisfy receiver BER requirements, (ii) avoid interfering with ongoing communications.

5.1.1. Minimum required transmit power

Let $\text{SINR}^t h(\text{BER}^*)$ 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

$$\frac{P_i^f L_{ij}}{\text{NI}_j^f} \geq \text{SINR}^{\text{th}}(\text{BER}^*), \quad (16)$$

where L_{ij} captures the effects of path-loss, shadowing and frequency nonselective fading of link (i, j) , and NI_j^f represents the noise plus interference at receiver j on miniband f . The numerator represents the received power at receiver j .

We define $P_i^{\text{min},f}$ as the value of P_i^f for which (16) holds with equality. Thus, $P_i^{\text{min},f}$ is the minimum required transmit power of link (i, j) on miniband f . The constraint in (16) 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 $P_{ij}^{\text{min},f}$ to denote the minimum required transmit power of transmitter i for receiver j .

5.1.2. Maximum allowed transmit power

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

$$E^V(f) \cdot P_i^{\text{max},f} = 0, \quad \forall i \in \mathcal{N}, \forall f \in [f_{\text{min}}, f_{\text{max}}]. \quad (17)$$

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

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

$$\frac{P_k^{\text{R},f}}{\text{NI}_k^f + \Delta I_{ik}^f} \geq \text{SINR}^{\text{th}}(\text{BER}^*), \quad k \in \mathcal{N}, k \neq i, k \neq j, \quad (18)$$

where $P_k^{\text{R},f}$ represents the signal power being received on miniband f at receiver k , and j is the intended receiver of transmitter i in link (i, j) . Since this has to be true for every secondary receiver, the constraint can be written as

$$P_i^f \leq \min_{k \in \mathcal{N}} \frac{\Delta I_k^{\text{max},f}}{L_{ik}} \quad (19)$$

where

$$\Delta I_k^{\text{max},f} = \frac{P_k^{\text{R},f}}{\text{SINR}^{\text{th}}(\text{BER}^*)} - \text{NI}_k^f, \quad k \in \mathcal{N}. \quad (20)$$

The inequality in (19) 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 (17) and (19), we obtain

$$P_i^{\text{max},f} \triangleq \begin{cases} 0, & E^V(f) = 1; \\ \min_{k \in \mathcal{N}} \frac{\Delta I_k^{\text{max},f}}{L_{ik}}, & E^V(f) = 0. \end{cases} \quad (21)$$

Hence, for link (i, j) , node i 's transmit power needs to be bounded on each miniband. The expressions in (16) and (21) define lower and upper bounds, respectively, on the transmit power for each frequency.

5.2. Distributed spectrum and power allocation

In cognitive 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 algorithms 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 6.

The objective here is to find a spectrum portion \mathbf{f}_i (i.e., set of contiguous minibands) with corresponding transmit power \mathbf{p}_i for node i , and \mathbf{p}_k for relay candidate k (i.e., $A_{ij}^k = 1$, or $B_{ij}^k = 1$) to maximize the link capacity as defined in (8). For the case when transmitter i does not use relay k (i.e., $\sum_k A_{ij}^k + \sum_k B_{ij}^k = 0$), we assign $\mathbf{p}_k = \mathbf{0}$.

5.2.1. 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 as defined in (3) under the spectrum sharing constraints introduced in (16) and (21) in Section 5.1.

P2.1 : Given : $P_i^{\text{max},f}$, $P_{ij}^{\text{min},f}$, P^{Bgt}

Find : \mathbf{f}_i , \mathbf{p}_i

Maximize : C_{ij}^{DIR}

Subject to :

$$P_{ij}^{\text{min},f} \leq P_i^f \leq P_i^{\text{max},f}, \quad \forall f \in \mathbf{f}_i,$$

$$\sum_{f \in \mathbf{f}_i} P_i^f \leq P^{\text{Bgt}},$$

$$\mathbf{f}_i \subset [f_{\text{min}}, f_{\text{max}}].$$

5.2.2. Decode-and-forward relaying

Consider the DF cooperative transmission of link (i, j) with relay node k (i.e., $B_{ij}^k = 1$), power constraints should be satisfied not only at i but also at k .

P2.2 : Given : $P_i^{max,f}, P_k^{max,f}, P_{ij}^{min,f}, P_{ik}^{min,f}, P^{Bgt}$

Find : $\mathbf{f}_i, \mathbf{p}_i, \mathbf{p}_k$

Maximize : C_{ijk}^{DF}

Subject to :

$$P_{ij}^{min,f} \leq P_i^f \leq P_i^{max,f}, \quad \forall f \in \mathbf{f}_i, \quad (22)$$

$$P_{ik}^{min,f} \leq P_i^f, \quad \forall f \in \mathbf{f}_i, \quad (23)$$

$$P_k^f \leq P_k^{max,f}, \quad \forall f \in \mathbf{f}_i, \quad (24)$$

$$\sum_{f \in \mathbf{f}_i} P_i^f \leq P^{Bgt}, \quad (25)$$

$$\sum_{f \in \mathbf{f}_i} P_k^f \leq P^{Bgt}, \quad (26)$$

$$\mathbf{f}_i \subset [f_{min}, f_{max}]. \quad (27)$$

For a given spectrum portion \mathbf{f}_i , problem **P2.2** is equivalent to the following problem.

P2.3 : Given : $\mathbf{f}_i, P_i^{max,f}, P_k^{max,f}, P_{ij}^{min,f}, P_{ik}^{min,f}, P^{Bgt}$

Find : $z, \mathbf{p}_i, \mathbf{p}_k$

Maximize : z

Subject to :

$$z - \frac{w}{2} \sum_{f \in \mathbf{f}_i} \log_2(1 + \text{SINR}_{ik}^f(P_i^f)) \leq 0; \quad (28)$$

$$z - \frac{w}{2} \sum_{f \in \mathbf{f}_i} \log_2(1 + \text{SINR}_{ij}^f(P_i^f) + \text{SINR}_{kj}^f(P_k^f)) \leq 0; \quad (29)$$

and constraints (22)–(27).

(22)–(27). The main difficulty in solving the problem in the AF case is introduced by the fact that the objective function, C_{ijk}^{AF} , is a function of three SINRs that can not be converted into a concave function. This makes the problems NP-hard as discussed later. In the following, we propose an approximation algorithm to solve the power allocation problem for given a spectrum \mathbf{f}_i .

We first define a monomial as a function $g : \mathbf{R}_{++}^n \rightarrow \mathbf{R}$:

$$g(\mathbf{x}) = d x_1^{a^{(1)}} x_2^{a^{(2)}} \dots x_n^{a^{(n)}}, \quad (31)$$

where the constant $d \geq 0$ and the exponential constants $a^{(j)} \in \mathbf{R}, j = 1, 2, \dots, n$. A sum of monomials, i.e., a function of the form

$$g(\mathbf{x}) = \sum_{m=1}^M d_m x_1^{a_m^{(1)}} x_2^{a_m^{(2)}} \dots x_n^{a_m^{(n)}}, \quad (32)$$

where $d_m \geq 0, m = 1, 2, \dots, M$, is called a posynomial.

Note that with the noise plus interference NI_j^f at receiver j on miniband f we have

$$\text{SINR}_{ij}^f(P_i^f) = \frac{P_i^f L_{ij}}{NI_j^f},$$

which is a monomial in P_i^f . Similarly, SINR_{ik}^f and SINR_{kj}^f are monomials of P_i^f and P_k^f , respectively. The link capacity in (2) for given spectrum \mathbf{f}_i can be expressed as in (30), where g_f and h_f are both posynomials, since monomials (i.e., $\text{SINR}_{ij}^f, \text{SINR}_{ik}^f$, and SINR_{kj}^f) are closed under multiplication.

We can then express the objective of the power allocation problem for given \mathbf{f}_i as $\max \frac{w}{2} \sum_{f \in \mathbf{f}_i} \log_2 \frac{g_f}{h_f}$, which is

$$C_{ijk}^{AF}(\mathbf{p}_i, \mathbf{p}_k) = \frac{w}{2} \sum_{f \in \mathbf{f}_i} \log_2 \frac{\text{SINR}_{ij}^f + \text{SINR}_{kj}^f + 1 + \text{SINR}_{ij}^f \cdot \text{SINR}_{ik}^f + \text{SINR}_{ij}^f \cdot \text{SINR}_{kj}^f + \text{SINR}_{ik}^f + \text{SINR}_{ik}^f \cdot \text{SINR}_{kj}^f}{\text{SINR}_{ik}^f + \text{SINR}_{kj}^f + 1} \quad (30)$$

$$\triangleq \frac{w}{2} \sum_{f \in \mathbf{f}_i} \log_2 \frac{g_f(\mathbf{p}_i, \mathbf{p}_k)}{h_f(\mathbf{p}_i, \mathbf{p}_k)}$$

Problem **P2.3** is a convex optimization problem, because (i) the objective function of **P2.3** and constraints (22)–(27) are all affine functions of the problem variables $z, \mathbf{p}_i, \mathbf{p}_k$, (ii) the inequality constraint functions (28) and (29) are twice differentiable, and their Hessians are negative semidefinite. Clearly, problem **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 [53,54].

5.2.3. Amplify-and-forward relaying

Similarly, spectrum and power should be allocated to maximize the link capacity C_{ijk}^{AF} under constraints

equivalent to $\max \log_2 \prod_{f \in \mathbf{f}_i} \left(\frac{g_f}{h_f} \right)$, which is in turn equivalent to $\min \prod_{f \in \mathbf{f}_i} \left(\frac{h_f}{g_f} \right)$. We define $g \triangleq \prod_{f \in \mathbf{f}_i} g_f$. Then, g is a posynomial since each g_f is a posynomial and the product of posynomials is again a posynomial. Similarly, we have another posynomial $h \triangleq \prod_{f \in \mathbf{f}_i} h_f$ as the denominator. Then, the problem can be expressed as

P2.4 : Given : $\mathbf{f}_i, P_i^{max,f}, P_k^{max,f}, P_{ij}^{min,f}, P^{Bgt}$

Find : $\mathbf{p}_i, \mathbf{p}_k$

$$\text{Minimize : } \frac{h(\mathbf{p}_i, \mathbf{p}_k)}{g(\mathbf{p}_i, \mathbf{p}_k)} \quad (33)$$

Subject to :

$$P_{ij}^{\min,f} \leq P_i^f \leq P_i^{\max,f}, \quad \forall f \in \mathbf{f}_i, \quad (34)$$

$$P_k^f \leq P_k^{\max,f}, \quad \forall f \in \mathbf{f}_i, \quad (35)$$

$$\sum_{f \in \mathbf{f}_i} P_i^f \leq P_i^{\text{Bgt}}, \quad (36)$$

$$\sum_{f \in \mathbf{f}_i} P_k^f \leq P_k^{\text{Bgt}}, \quad (37)$$

where the objective is a ratio between two posynomials, and all the constraints are affine functions. Minimizing a ratio between two posynomials is a nonlinear and nonconvex problem and in general an NP-hard problem [55]. Here, we provide an approximation algorithm to solve it.

1. Set an initial feasible power vector \mathbf{p}_i^0 , \mathbf{p}_k^0 , and $n = 1$.
2. Compute for each term in g_f with \mathbf{p}_i^{n-1} and \mathbf{p}_k^{n-1} ,

$$\alpha_f^m = \frac{u_f^m(\mathbf{p}_i^{n-1}, \mathbf{p}_k^{n-1})}{g_f(\mathbf{p}_i^{n-1}, \mathbf{p}_k^{n-1})}, \quad (38)$$

where u_f^m is the m th term in g_f .

3. Approximate g_f with a monomial \tilde{g}_f using α_f^m ,

$$\tilde{g}_f(\mathbf{p}_i, \mathbf{p}_k) = \prod_m \left(\frac{u_f^m(\mathbf{p}_i, \mathbf{p}_k)}{\alpha_f^m} \right)^{\alpha_f^m}. \quad (39)$$

In steps (2) and (3), we approximate g_f with \tilde{g}_f using the arithmetic–geometric mean approximation, which enables the algorithm to be provably convergent to a point satisfying the necessary optimality Karush–Kuhn–Tucker (KKT) conditions of the original problem. It is also observed through extensive numerical experiments that the convergence point is often the globally optimal solution.

4. Solve the approximated ratio using interior point methods,

$$(\mathbf{p}_i^n, \mathbf{p}_k^n) = \arg \min \frac{\prod_{f \in \mathbf{f}_i} (h_f(\mathbf{p}_i, \mathbf{p}_k))}{\prod_{f \in \mathbf{f}_i} (\tilde{g}_f(\mathbf{p}_i, \mathbf{p}_k))}.$$

By approximating the denominator g_f with a monomial \tilde{g}_f , but leaving the numerator h_f as a posynomial, the objective function (33) is converted into a posynomial, since posynomials can be divided by monomials with the result still a posynomial.

5. $n = n + 1$, and go to step (2) until convergence, i.e., $\|(\mathbf{p}_i^n, \mathbf{p}_k^n) - (\mathbf{p}_i^{n-1}, \mathbf{p}_k^{n-1})\| \leq \epsilon$ where ϵ is the error tolerance for exit condition, return solution as $(\mathbf{p}_i^n, \mathbf{p}_k^n)$.

Proposition 1. Consider the approximation of a ratio of posynomials $\frac{h}{g}$ with $\frac{\tilde{h}}{\tilde{g}}$ where \tilde{g} is the monomial approximation of g using the arithmetic–geometric mean approximation as in (38) and (39). The solutions of this series of approximations converge to a point satisfying the necessary optimality KKT conditions of the original problem.

Proof. See Appendix A. \square

The proposed algorithm uses existing research on successive approximation and the arithmetic–mean–geometric–mean inequality [56]. Algorithm 1 shows the spectrum and power allocation algorithm for given link (i, j) and relay candidate k .

Algorithm 1. Spectrum and Power Allocation Algorithm.

-
- 1: Given link (i, j) , relay candidate k
 - 2: Set $C_{ij}^* = 0$, $A_{ij}^k = 0$, $B_{ij}^k = 0$
 - 3: **for each** $[f_l, f_{l+\Delta B}] \in [f_{\min}, f_{\max}]$ **do**
 - 4: Derive \mathbf{p}_i by solving problem **P2.1** over $[f_l, f_{l+\Delta B}]$
 - 5: **if** $C_{ij}^{\text{DIR}} > C_{ij}^*$ **then**
 - 6: $C_{ij}^* = C_{ij}^{\text{DIR}}$
 - 7: $[\mathbf{f}_i^*, \mathbf{p}_i^*, \mathbf{p}_k^*] = [[f_l, f_{l+\Delta B}], \mathbf{p}_i, \mathbf{0}]$
 - 8: $A_{ij}^k = 0$, $B_{ij}^k = 0$
 - 9: **end if**
 - 10: Derive $\mathbf{p}_i, \mathbf{p}_k$ by solving **P2.3** over $[f_l, f_{l+\Delta B}]$
 - 11: **if** $C_{ijk}^{\text{DF}} > C_{ij}^*$ **then**
 - 12: $C_{ij}^* = C_{ijk}^{\text{DF}}$
 - 13: $[\mathbf{f}_i^*, \mathbf{p}_i^*, \mathbf{p}_k^*] = [[f_l, f_{l+\Delta B}], \mathbf{p}_i, \mathbf{p}_k]$
 - 14: $A_{ij}^k = 0$, $B_{ij}^k = 1$
 - 15: **end if**
 - 16: Derive $\mathbf{p}_i, \mathbf{p}_k$ by solving **P2.4** over $[f_l, f_{l+\Delta B}]$
 - 17: **if** $C_{ijk}^{\text{AF}} > C_{ij}^*$ **then**
 - 18: $C_{ij}^* = C_{ijk}^{\text{AF}}$
 - 19: $[\mathbf{f}_i^*, \mathbf{p}_i^*, \mathbf{p}_k^*] = [[f_l, f_{l+\Delta B}], \mathbf{p}_i, \mathbf{p}_k]$
 - 20: $A_{ij}^k = 1$, $B_{ij}^k = 0$
 - 21: **end if**
 - 22: **end for**
 - 23: Return solution as $[\mathbf{f}_i^*, \mathbf{p}_i^*, \mathbf{p}_k^*, C_{ij}^*, A_{ij}^k, B_{ij}^k]$
-

6. COOP: distributed routing, relay selection, and spectrum allocation

In this section, we introduce a distributed algorithm, named COOP, which is designed to provide an approximate solution to **P1** based on real-time distributed decisions driven by locally collected information.

6.1. 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 L_{sr} , L_{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.

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 .

6.2. 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 [57]. 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.

```

1: At backlogged node  $i$ ,  $U_{ij} = 0$ 
2: for each backlogged session  $s \in \mathcal{S}$  do
3:   for  $j \in \mathcal{N}^s(i)$  do
4:     for  $k \in \mathcal{N}^s(i)$  do
5:       Calculate  $[\mathbf{f}_i, \mathbf{p}_i, \mathbf{p}_k, C_{ij}, A_{ij}^k, B_{ij}^k]$  using Algorithm
1
6:       if  $C_{ij} \cdot (Q_i^s - Q_j^s) > U_{ij}$  then
7:          $U_{ij} = C_{ij} \cdot (Q_i^s - Q_j^s)$ 
8:          $[\mathbf{f}_i^*, \mathbf{p}_i^*, \mathbf{p}_k^*] = [\mathbf{f}_i, \mathbf{p}_i, \mathbf{p}_k]$ 
9:          $[s^*, j^*] = [s, j]$ 
10:       end if
11:     end for
12:   end for
13: end for
14: Set contention window  $CW_i = \Phi(U_{ij})$ 
15: Generate backoff counter  $BC_i \in [1, 2^{CW_i-1}]$ 

```

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. Note that loop-freeness is considered and ensured in our proposed solution. Specifically, the set of next hop candidates is restricted to the neighbors that are estimated to be closer to the destination than the transmitting node. This avoids loops but packets may get stuck at nodes with broken forward links.

6.3. Mapping local to global objectives through stochastic channel access

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. $[s^*, j^*, \mathbf{A}(i, j^*), \mathbf{B}(i, j^*), \mathbf{f}_i^*, \mathbf{p}_i^*, \mathbf{p}_k^*]$, 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 $[1, 2^{CW_i-1}]$, where CW_i is the contention window of transmitter i , whose value is a decreasing function $\Phi(\cdot)$ of the utility U_{ij} as below

$$CW_i = -\alpha \cdot \frac{U_{ij}}{\sum_{k \in \mathcal{N}_i, k, l \in \mathcal{N}} U_{kl}} + \beta, \alpha > 0, \beta > 0 \quad (40)$$

where $\sum_{k \in \mathcal{N}_i, k, l \in \mathcal{N}} U_{kl}$ 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 on the CCC as discussed in Section 7.

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 Q_i becomes smaller, which results in a reduced value of U_{ij} , which consequently leads to a larger 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

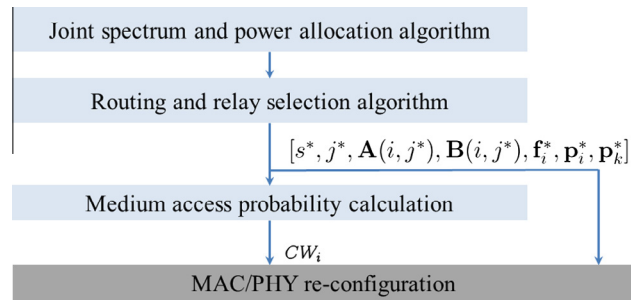


Fig. 3. COOP Illustration.

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.

We summarized the algorithms we proposed in this section in Fig. 3. As illustrated in the figure, the physical layer resource allocation algorithm is executed first to solve the link capacity maximization problem in Section 5. Then joint routing and relay selection algorithm is executed to solve the local utility optimization problem. Finally, a channel access mechanism is employed to map local to global objective we aim to maximize in problem P1.

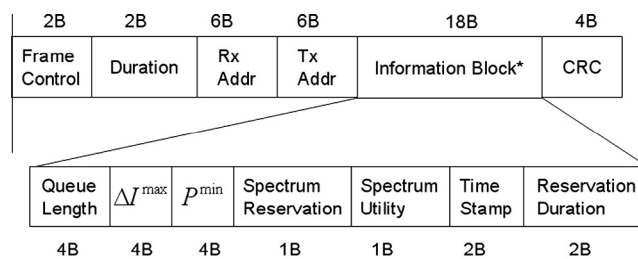
Our proposed algorithm is based on a randomized controller that assigns opportunities to transmit based on the current relative value of spectrum utility, defined in (9), for competing nodes. Links with larger differential backlog and higher link capacity will have a higher utility, and hence have higher probability of being scheduled for transmission. The basic idea behind this operation is to adapt the transmitters' contention aggressiveness as a function of sum utilities we aim to maximize in P1. When the product of differential backlog and link capacity becomes large, the transmitter becomes aggressive in the contention for channel access. The larger utility value decreases its contention window size thus increases its

probability to access the channel as compared to competing nodes.

7. Distributed protocol design

In this section, we propose and discuss a cooperative MAC for cognitive ad hoc 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 (shown in Fig. 4) exchanged on the control channel that contain information about transmissions and power used on different minibands as well as information on relays. As illustrated in Fig. 4, 4 bytes of queue size information and 14 bytes of spectrum information are introduced as additional overhead in our proposed solution, which is certainly allowable compared to the benefits in terms of throughput gains.

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



B: Byte

Fig. 4. Control packet format.

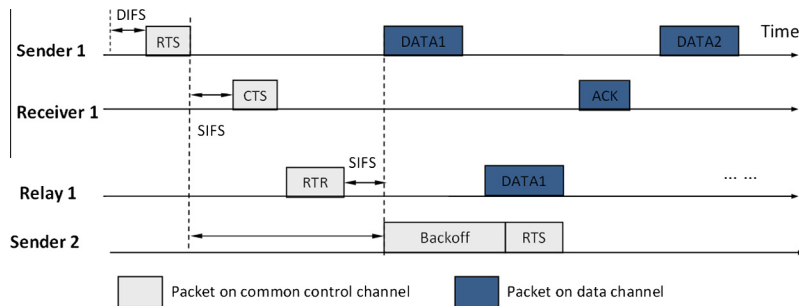


Fig. 5. Medium access control for cooperative transmissions.

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. 5 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, 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 [17] in the following aspects: (i) different from

CoopMAC, CoCogMAC enables collaborative spectrum sensing and spectrum reservation in cognitive 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 6 to opportunistically give priority in spectrum reservation to links with higher capacity and larger differential backlog.

In this work, we assume a separate channel as the control channel for the handshake of secondary users. We assume this control channel is different from the set of frequency-agile data channels, and is not affected by primary user activities. Recent work also study channel rendezvous [63,64] to migrate the unpredictable changes, where SUs hop among the available channels until they find each other in any of the available channels. Then, SUs determine (via spectrum sensing) which channels are available and attempt to establish a link on one of those channels for handshake.

8. Performance evaluation

8.1. The impact of transmission strategies on single link performance

In this section, we study the impact of relay node location and transmission strategies on the performance of direct and cooperative communications in terms of link capacity. We study the topology depicted in Fig. 6.

Fig. 7 shows the impact of relay node location and transmission strategies on link capacity, where the noise power is set to $0.5 \mu\text{W}$ for all nodes. As shown in the figures, the performance of cooperative transmission depends on the location of the relay node. DF cooperative

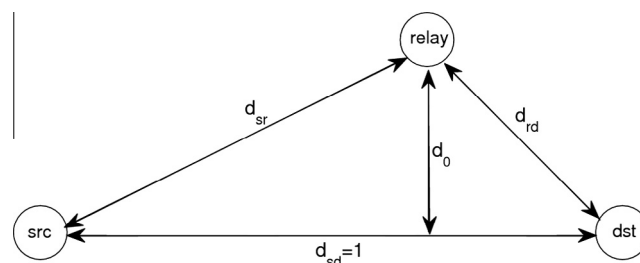


Fig. 6. Transmission topology.

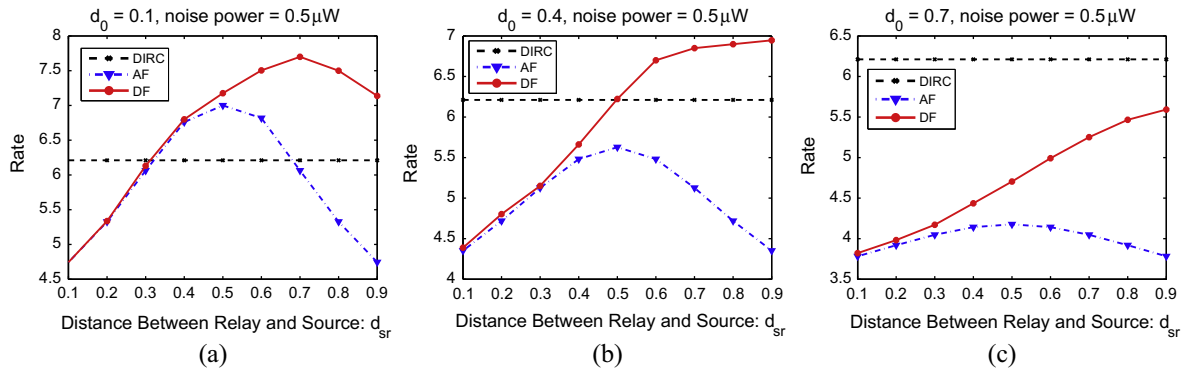


Fig. 7. Impact of relay node location and transmission strategies on the performance of link capacity, with noise power $0.5 \mu\text{W}$.

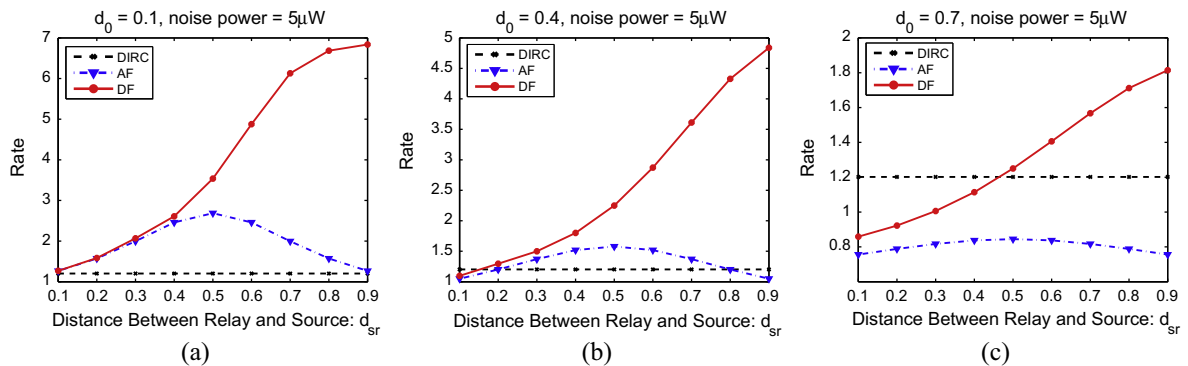


Fig. 8. Impact of relay node location and transmission strategies on the performance of link capacity, with noise power $5 \mu\text{W}$.

transmission outperforms AF in general. In addition, cooperative transmission is not always better than direct transmission, especially when the relay node is far away from both source and destination as shown in Fig. 7(c).

We then increase the noise power to $5 \mu\text{W}$. As shown in Fig. 8(a) and (b), cooperative transmissions achieve an overall higher rate compared to direct transmission, and the performance gain obtained by DF is more visible as the relay node gets closer to the destination node.

8.2. Network performance evaluation

In this section, we analyze the performance of the proposed solution described in Section 6 (referred to as COOP) in a multi-hop cognitive ad hoc 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 [65] to solve at simulation time the resource allocation optimization problems discussed in Section 6. 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. 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 Mbit/s for a 1 MHz band. The algorithms proposed in the paper are generic with all options of DF, AF and direct transmission mode as described in Algorithm 1. In our simulation scenario DF outperforms AF in general as shown in Section VIII-A, thus we consider DF as cooperative transmission option in our simulations based on these observations.

We first compare the performance of COOP with two alternative schemes, which both 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 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 54–60 MHz, a portion of the TV

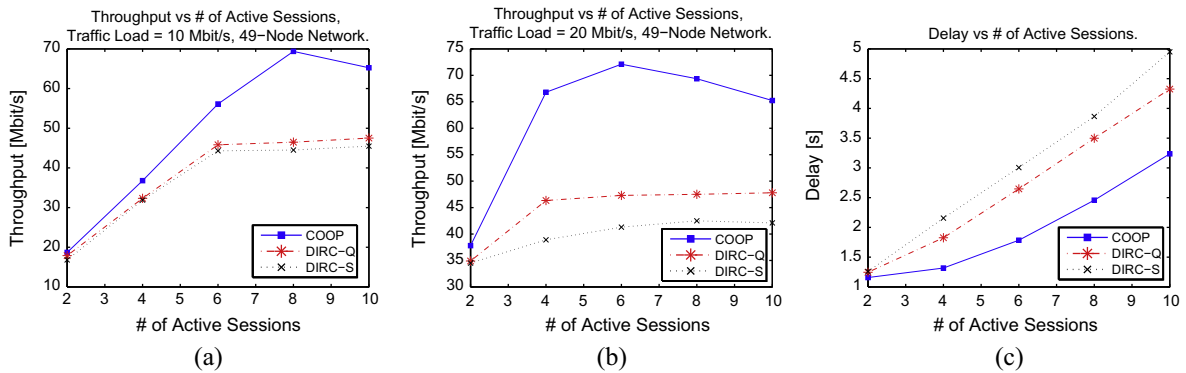


Fig. 9. (a) Throughput with 10 Mbit/s load per session; (b) throughput with 20 Mbit/s load per session; (c) delay with 20 Mbit/s load per session.

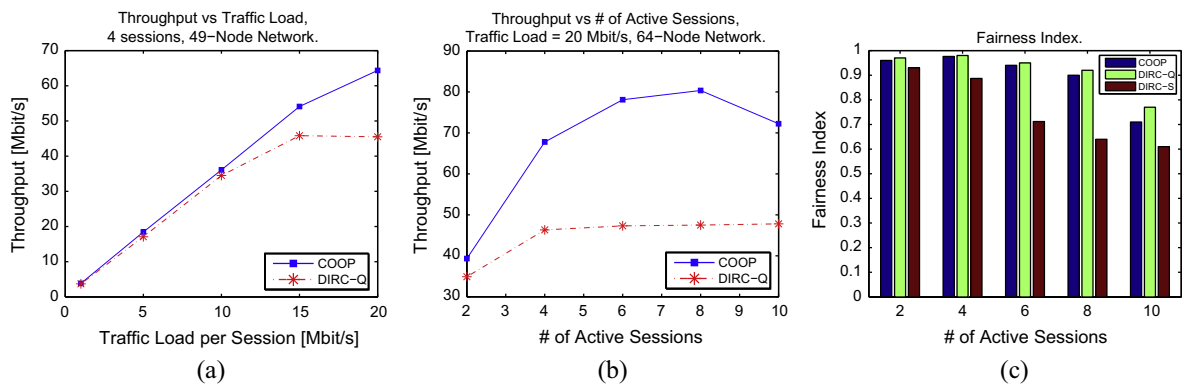


Fig. 10. (a) Impact of traffic load on throughput; (b) throughput with 20 Mbit/s load per session, 64-node network; (c) fairness index.

band that secondary users are allowed to use when there is no licensed (primary) user operating on it. We restrict the bandwidth usable by cognitive radios to be 3 MHz. The bandwidth of the CCC is 2 MHz. The duration of a time slot on the CCC is set to 20 μ s. Parameters α and β in (40) 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.

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). Fig. 9(a) and (b) show the impact of the number of sessions injected into the network on the throughput performance. The traffic load per session is 10 Mbit/s and 20 Mbit/s. When the traffic load is low, i.e., 10 Mbit/s, DIRC-Q and DIRC-S obtain similar throughput performance. However, with higher traffic load, i.e., 20 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.

Fig. 9(c) shows the delay performance for the three solutions with traffic load 20 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. Fig. 10(a) illustrates the network throughput as the traffic load per flow varies from 1 Mbit/s to 20 Mbit/s. As the per session load increases over 10 Mbit/s, the improvement obtained by COOP is more visible by opportunisticly exploiting spatial diversity.

Figs. 9(b) and 10(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. Fig. 10(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.

9. Conclusion

We studied and proposed decentralized and localized algorithms for joint dynamic routing, relay selection, and spectrum allocation in cooperative cognitive 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.

Appendix A. Proof of Proposition 1

To prove this proposition, we first show that the approximation has several properties. Then we use the properties to prove the proposition.

1. $\frac{h(\mathbf{x})}{g(\mathbf{x})} \leq \frac{h(\mathbf{x})}{\tilde{g}(\mathbf{x})}$ for all \mathbf{x} .

Recall that we first approximate the posynomial $g_f(\mathbf{x}) = \sum_m u_f^m(\mathbf{x})$ with monomial $\tilde{g}_f(\mathbf{x}) = \prod_m \left(\frac{u_f^m(\mathbf{x})}{\alpha_i^m} \right)^{\alpha_i^m}$.

Then $g = \prod_f g_f$ is approximated with monomial $\tilde{g} = \prod_f \tilde{g}_f$ since monomials are closed under multiplication. In such a way, we approximate $\frac{h(\mathbf{x})}{g(\mathbf{x})}$ with $\frac{h(\mathbf{x})}{\tilde{g}(\mathbf{x})}$. Thus, the arithmetic–geometric mean inequality

$$g_f(\mathbf{x}) \geq \tilde{g}_f(\mathbf{x}) = \prod_i \left(\frac{u_i(\mathbf{x})}{\alpha_i} \right)^{\alpha_i} \text{ leads to } \frac{h(\mathbf{x})}{g(\mathbf{x})} \leq \frac{h(\mathbf{x})}{\tilde{g}(\mathbf{x})}.$$

2. $\frac{h(\mathbf{x}^*)}{g(\mathbf{x}^*)} = \frac{h(\mathbf{x}^*)}{\tilde{g}(\mathbf{x}^*)}$ where \mathbf{x}^* is the optimal solution of the approximated problem in the previous iteration.

Since $\alpha_i^m = \frac{u_i^m(\mathbf{x}^*)}{g(\mathbf{x}^*)}$, $\forall m$ for any fixed positive \mathbf{x}^* , then $\tilde{g}_f(\mathbf{x}^*) = g_f(\mathbf{x}^*)$, and thus $\tilde{g}(\mathbf{x}^*) = g(\mathbf{x}^*)$.

3. $\nabla \frac{h(\mathbf{x}^*)}{g(\mathbf{x}^*)} = \nabla \frac{h(\mathbf{x}^*)}{\tilde{g}(\mathbf{x}^*)}$.

This property can be easily verified by taking derivatives of $\frac{h(\mathbf{x})}{g(\mathbf{x})}$ and $\frac{h(\mathbf{x})}{\tilde{g}(\mathbf{x})}$.

Now, based on the three properties above, without loss of generality, we can express the original nonconvex problem **P2.4** as

$$\begin{aligned} \mathbf{P3} \quad & \text{minimize : } z \\ & \text{subject to : } \frac{h(\mathbf{x})}{g(\mathbf{x})} - z \leq 0 \\ & f_i(\mathbf{x}) \leq 0, i = 1, \dots, b, 4 \end{aligned} \quad (\text{A.1})$$

where the original objective function is moved to the constraint $\frac{h(\mathbf{x})}{g(\mathbf{x})} - z \leq 0$ by introducing the auxiliary scalar variable z . Constraints $f_i(\mathbf{x}) \leq 0$, $i = 1, \dots, 4$, represent the

inequality constraints (34)–(37), and $f_i(\mathbf{x})$ are affine functions.

Since $\frac{h(\mathbf{x})}{g(\mathbf{x})} - z \leq 0$ is convex, the approximated problem of **P3** can be solved optimally by \mathbf{x}^* and z^* . So there exist dual optimal $\lambda^* \in \mathbf{R}^{k+1}$, together with \mathbf{x}^* and z^* , which satisfy the KKT conditions:

$$\nabla z^* + \sum_{i=1}^k \lambda_i^* \nabla f_i(\mathbf{x}^*) + \lambda_0^* \nabla \left(\frac{h(\mathbf{x}^*)}{\tilde{g}(\mathbf{x}^*)} - z^* \right) = 0, \quad (\text{A.2})$$

$$\lambda_i^* \geq 0, i = 0, \dots, 4, \quad (\text{A.3})$$

$$\lambda_i^* f_i(\mathbf{x}^*) = 0, i = 1, \dots, 4, \quad (\text{A.4})$$

$$\lambda_0^* \left(\frac{h(\mathbf{x}^*)}{\tilde{g}(\mathbf{x}^*)} - z^* \right) = 0. \quad (\text{A.5})$$

According to Properties (2) and (3), $\frac{h(\mathbf{x}^*)}{g(\mathbf{x}^*)}$ and $\nabla \frac{h(\mathbf{x}^*)}{g(\mathbf{x}^*)}$ can be replaced by $\frac{h(\mathbf{x}^*)}{\tilde{g}(\mathbf{x}^*)}$ and $\nabla \frac{h(\mathbf{x}^*)}{\tilde{g}(\mathbf{x}^*)}$, respectively. Thus, we have

$$\nabla z^* + \sum_{i=1}^k \lambda_i^* \nabla f_i(\mathbf{x}^*) + \lambda_0^* \nabla \left(\frac{h(\mathbf{x}^*)}{\tilde{g}(\mathbf{x}^*)} - z^* \right) = 0, \quad (\text{A.6})$$

$$\lambda_i^* \geq 0, i = 0, \dots, 4, \quad (\text{A.7})$$

$$\lambda_i^* f_i(\mathbf{x}^*) = 0, i = 1, \dots, 4, \quad (\text{A.8})$$

$$\lambda_0^* \left(\frac{h(\mathbf{x}^*)}{\tilde{g}(\mathbf{x}^*)} - z^* \right) = 0. \quad (\text{A.9})$$

Therefore, the KKT conditions of the original problem are satisfied.

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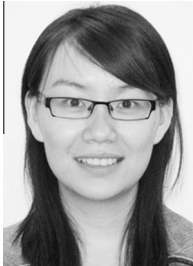
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