ROSA: Distributed Joint Routing and Dynamic Spectrum Allocation in Cognitive Radio Ad Hoc Networks

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ABSTRACT

Throughput maximization is one of the main challenges in cognitive radio ad hoc networks, where local spectrum resources may change from time to time and hop-by-hop. For this reason, a cross-layer opportunistic spectrum access and dynamic routing algorithm for cognitive radio networks is proposed, called ROSA (ROuting and Spectrum Allocation algorithm). Through local control actions, ROSA aims at maximizing the network throughput by performing joint routing, dynamic spectrum allocation, scheduling, and transmit power control.

Specifically, the algorithm dynamically allocates spectrum resources to maximize the capacity of links without generating harmful interference to other users while guaranteeing bounded BER for the receiver. In addition, the algorithm aims at maximizing the weighted sum of differential backlogs to stabilize the system by giving priority to higher-capacity links with high differential backlog. The proposed algorithm is distributed, computationally efficient, and with bounded BER guarantees.

ROSA is shown through discrete-event packet-level simulations to outperform baseline solutions leading to a high throughput, low delay, and fair bandwidth allocation.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless Communication*

General Terms

Algorithms, Design

Keywords

Cognitive Radio Networks, routing, dynamic spectrum allocation, cross-layer design

1. INTRODUCTION

Cognitive [1] radio networks [2] [19] have recently emerged as a promising technology to improve the utilization efficiency of the

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existing radio spectrum. In a cognitive radio network, users access the existing wireless spectrum opportunistically, without interfering with existing users. 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 access have received significant attention in the last two years, e.g., [5] [17] [27].

In addition to this, in cognitive radio networks with multi-hop communication requirements (e.g., cognitive radio ad hoc networks [1]), the dynamic nature of the radio spectrum calls for the development of novel spectrum-aware routing algorithms. In fact, spectrum occupancy is location-dependent, and therefore in a multi-hop path available spectrum bands may be different at each relay node. Hence, in multi-hop cognitive radio networks controlling the interaction between the routing 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, 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.

For the reasons above, in this paper we consider interactions between spectrum management and dynamic routing functionalities. With this respect, we propose a distributed algorithm that jointly solves the routing, dynamic spectrum assignment, scheduling and power allocation problems for multi-hop cognitive radio networks. The objective of the proposed algorithm is to allocate resources efficiently, distributively, and in a cross-layer fashion. For this reason, we focus on real-time and computationally efficient spectrum allocation and routing algorithms.

We further show how our algorithm can be interpreted as a distributed solution to a centralized cross-layer optimization problem. While the optimization problem is centralized and hard to solve, our algorithm is practically and distributively implementable and provides performance guarantees. We show how a cross-layer solution that solves routing and spectrum allocation jointly at each hop outperforms approaches where routes are selected independently of the spectrum assignment, with moderate computational complexity.

Our main contributions can be outlined as follows:

- We derive a distributed and localized algorithm for joint dynamic routing and spectrum allocation for multi-hop cognitive radio networks. To the best of our knowledge, this is the first algorithm to jointly solve routing and spectrum assignment with power control under the so-called physical interference model. The proposed algorithm considers and leverages the unique characteristics of cognitive radio including the availability of spectrum holes at a particular geographic location and their possible variability with time.

- Our proposed solution jointly considers routing, spectrum assignment, power allocation, and (potentially) congestion control in a distributed way. The proposed solution lets each cognitive radio make real-time decisions on spectrum and power allocation based on locally collected information. Nodes can adjust transmission power to maximize link capacity based on the assigned spectrum portion.

- We assume a richer physical layer model than previously considered in the related literature; we introduce a notion of "spectrum hole" that considers interference from neighboring secondary as well as primary users, and leverage it to optimize resource utilization at a low computational cost.

- We discuss details of a practical implementation of the proposed algorithm that relies on a dual radio with a common control channel and a frequency-agile data channel.

- We show how the proposed algorithm can be interpreted as a distributed and practical solution to a cross-layer optimal resource allocation problem, whose performance is close to the optimum with low computational complexity.

The remainder of this paper is organized as follows. In Section 2, we review related work on cognitive radio networks. In Section 3, we introduce the system model. In Section 4 we propose ROSA, our distributed algorithm for joint routing and dynamic spectrum allocation. Section 5 addresses implementation details. In Section 6 we show how ROSA can be interpreted as a distributed solution to a centralized cross-layer network utility maximization problem for cognitive radio ad hoc networks. Section 7 evaluates the performance of the algorithm. Finally, Section 8 concludes the paper.

2. RELATED WORK

Recent work has investigated algorithms and protocols for dynamic spectrum allocation in cognitive radio networks. Proposed approaches to assign spectrum can be broadly classified into *centralized* and *distributed* schemes. For example, the Dynamic Spectrum Access Protocol (DSAP) [3] is centralized, and thus requires a central controller to allocate spectrum. In contrast, we propose a distributed solution to let each cognitive radio make real-time decision on spectrum based on locally collected information. In [27], a distributed spectrum assignment algorithm is proposed, which aims at solving the spectrum allocation problem: which node should use how wide a spectrum-band at what center-frequency and for how long. Our work differs significantly from [27], which assumes mutually exclusive transmissions with zero interference tolerance.

Spectrum band auctions [10][28] have been proposed to allocate wireless spectrum resources, in which bidders obtain different spectrum channels to minimize the interference. In contrast, our proposed solution jointly considers spectrum allocation and routing in a cross-layer design fashion, since available spectrum bands may be different at each hop.

Some recent work has made initial steps in the direction of leveraging interactions between routing and spectrum allocation. In [24], each source node finds candidate paths based on Dynamic Source Routing (DSR) [14] and collects information on link connectivity and quality. For each candidate route, the algorithm finds all feasible spectrum assignment combinations and estimates the end-to-end throughput performance for each combination. Based on this computation, it selects the route and spectrum assignment with maximal throughput and schedules a conflict-free channel for this route.

The authors in [25] propose a layered graph model, where each layer corresponds to a channel, and find shortest paths based on the layered graph. Both [24] and [25] are channel-based solutions,

i.e., the available spectrum is divided into predefined channels, and devices are assigned opportunities to transmit on channels for a relatively long time scale. However, the time-varying nature of available links needs to be considered in cognitive radio networks since the available spectrum may change or vanish when licensed users enter the network. In addition, the algorithms in [24] and [25] are based on the so-called protocol model [12] in which two links either interfere destructively or do not interfere at all. Although simple, this model fails to capture the cumulative effect of interference. Conversely, our work assumes a richer interference model, which provides a comprehensive representation of radio interference. For example, it accounts for the fact that advanced transmission techniques such as code-division multiple access (CDMA) [21][20] allow concurrent co-located communications so that a message from node i to node j can be correctly received even if there is a concurrent transmission close to j.

Recent work has started investigating cross-layer optimizations for cognitive radio networks. In [13], Hou et al. formulated a cross-layer optimization problem for a network with cognitive radios, whose objective is to minimize the required network-wide radio spectrum resource needed to support traffic for a given set of user sessions. The problem is formulated as a mixed integer non-linear problem (MINLP), and a sequential fixing (SF) algorithm is developed where the integer variables are determined iteratively via a sequence of linear programs, which provides a near-optimal solution to the original problem. However, the work of [13] does not consider power control, which is addressed in our work.

In [6], a routing and spectrum assignment algorithm is proposed to achieve lower cumulative delay caused by channel switching, queueing and collisions. However, the algorithm is under the assumption that the node that has data to transmit knows the frequency band choice of every nodes along the route to destination, which requires global information. Conversely, our solution performs routing and spectrum assignment without global knowledge of the network state. Finally, in [15], Khalife et al. proposed a routing and spectrum selection algorithm for cognitive radio networks. The algorithm chooses the path that has the highest probability to satisfy the demands of secondary users in terms of capacity. The work in [15] does not cover the issues of scheduling and power control, which are addressed in our work in detail.

3. SYSTEM MODEL

We consider a cognitive radio network consisting of M primary users and N secondary users. Primary users are nodes holding licenses for specific spectrum bands, and can only occupy their assigned 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.

Let the multi-hop wireless network be modeled by a directed *connectivity* graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$, where $\mathcal{V} = \{v_1, ..., v_{N+M}\}$ is a finite set of wireless transceivers (nodes), with $|\mathcal{V}| = N + M$, and $(i, j) \in \mathcal{E}$ represent a unidirectional wireless link from node v_i to node v_j (referred to also as node i and node j, respectively, for simplicity). Nodes from the subset $\mathcal{PU} = \{v_1, ..., v_M\}$ are designated as primary users, and nodes from subset $\mathcal{SU} = \{v_{M+1}, ..., v_{M+N}\}$ are designated as secondary users. We assume $\mathcal{G}$ is link symmetric, i.e., if $(i, j) \in \mathcal{E}$, then $(j, i) \in \mathcal{E}$. Let $\mathcal{S}_i \triangleq \{j : (i, j) \in \mathcal{E}\}$ be the set of neighbors for node i.

We assume that all the secondary users are equipped with cognitive radios which consist of a reconfigurable transceiver and a scanner, similar for example to the KNOWS prototype from Microsoft [26]. The transceiver can tune to a set of contiguous frequency bands $[f, f + \Delta B]$, where ΔB is the bandwidth of the cognitive

radio. We keep the physical layer model general. However, we assume that multiple transmissions can concurrently occur in a frequency band, e.g., with different spreading codes. Among others, our physical layer model could represent orthogonal frequency division multiplexing (OFDM)-based transmission, which is based on a flexible subcarriers 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 low SINR regime [8][18].

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 $\{f_{min}, f_{min+1}, \cdots, f_{max-1}, f_{max}\}$, each of bandwidth w and identified by a discrete index. For example, the interval $[f_i, f_{i+\Delta f_i}]$ represents the (discrete) set of minibands selected by secondary user i between f_i and $f_{i+\Delta f_i}$, with bandwidth $w\Delta f_i$. Each secondary user that has packets to send contends for spectrum access on the 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.

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 $\lambda_i^s(t)$, 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 $\forall i \in \mathcal{SU}$, the queue is updated as follows:

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

4. JOINT ROUTING AND DYNAMIC SPECTRUM ALLOCATION

In this section, we present the distributed joint *ROuting and dynamic Spectrum Allocation* (ROSA) algorithm. To this aim, we introduce the notions of *spectrum utility* and *spectrum hole*. Opportunities to transmit are assigned based on the concept of *spectrum utility*, and routes are explored based on the presence of *spectrum holes* with the objective of maximizing the *spectrum utility*.

Our goal is to design a distributed cross-layer control scheme that allows secondary users to jointly control the routing, spectrum and power allocation functionalities to maximize the global spectrum utility. The scheme should be easy to implement and yield high throughput and low delay.

4.1 Spectrum Utility

The control channel is assumed to be time slotted. At each time slot for which node i is backlogged and not already transmitting, node i can evaluate the spectrum utility for link (i, j), defined as

$$U_{ij}(t) = c_{ij}(t) \cdot \left(Q_i^{s^*}(t) - Q_j^{s^*}(t) \right), \tag{1}$$

where s^* is the session with maximal differential backlog on link (i, j). Note that, for the sake of simplicity, we will drop all time dependencies in the following. Note also that the notion of spectrum utility is defined for a specific link (i, j). In the expression above, $c_{ij}(t)$ represents the achievable capacity for link (i, j) given the current spectrum condition, and is defined as

$$c_{ij}(f, P_i(f)) \triangleq \sum_{f \in [f_i, f_{i+\Delta f_i}]} w \cdot log_2 \left[1 + \frac{P_i(f)L_{ij}(f)G}{N_j(f) + I_j(f)} \right]. \tag{2}$$

In (2), G is the processing gain, e.g., length of the spreading code, and $L_{ij}(f)$ is the transmission loss from i to j. $P_i(f)$ represents the transmit power of i on frequency f. $I_j(f)$ represents interference at j. Finally, $N_j(f)$ is the receiver noise on frequency f. The achievable values of c_{ij} depend on i) the scheduling policy; ii) dynamic spectrum allocation policy, i.e., spectrum selection vector $\mathbf{F} = [f_i, f_{i+\Delta f_i}]$, $\forall i \in \mathcal{SU}$, and power allocation vector $\mathbf{P} = [P_i(f)]$, $\forall i \in \mathcal{SU}, \forall f$. The notion of spectrum utility can be thought of as a *differential backlog*, inspired by dynamic resource allocation policies that react to the difference $(Q_i^s - Q_j^s)$ of queue backlogs for a given session [9][11][22], weighted with dynamic spectrum availability information.

A desirable solution should dynamically utilize the available spectrum and power efficiently to provide BER guarantees for both primary and secondary users. Denote $SINR_{PU}^{th}$ and $SINR_{SU}^{th}$ as the signal-to-interference-plus-noise power ratio (SINR) thresholds to achieve a target bit error rate BER_{PU}^* for primary users and BER_{SU}^* for secondary users, respectively. Thus, at each time slot the global objective is to find global vectors $\mathbf{R}$, $\mathbf{F}$, $\mathbf{P}$ that maximize the sum of spectrum utilities over the activated links, under given BER and power constraints. This is expressed by the problem below.

$$\begin{aligned} \mathbf{P1}: Given: & \quad BER_{SU}^*, BER_{PU}^*, \mathcal{G}(\mathcal{V}, \mathcal{E}), P^{Bgt}, Q_i^s \\ Find: & \quad \mathbf{R}, \mathbf{F}, \mathbf{P} \\ Maximize: & \quad \sum_{i \in \mathcal{SU}} \sum_{j \in \mathcal{SU}, j \neq i} U_{ij} \quad\quad (3) \\ Subject\ to: & \end{aligned}$$

$$\sum_{s \in \mathcal{S}} r_{ij}^s \leq c_{ij}, \quad \forall i \in \mathcal{SU}, \forall j \in \mathcal{SU} \setminus i \tag{4}$$

$$SINR_k \geq SINR_{PU}^{th}(BER_{PU}^*), \quad \forall k \in \mathcal{PU}, \forall f \tag{5}$$

$$SINR_l \geq SINR_{SU}^{th}(BER_{SU}^*), \quad \forall l \in \mathcal{SU}, \forall f \tag{6}$$

$$\sum_{f \in [f_i, f_{i+\Delta f_i}]} P_i(f) \leq P_i^{Bgt}, \quad \forall i \in \mathcal{SU} \tag{7}$$

In the problem above, constraint (4) imposes that the total amount of traffic transported on link (i, j) is lower than the capacity of the physical link. Constraint (5) states that the target BER of primary users should be guaranteed irrespective of the secondary users' presence. Constraint (6) imposes that secondary user transmissions should also satisfy a given BER performance, while sharing the spectrum with other secondary users. In (7), P_i^{Bgt} represents the instantaneous power available at the cognitive radio.

Solving the problem above requires global knowledge of feasible rates, is centralized and its complexity is worst-case exponential. This provides the motivation for our distributed algorithm, whose objective is to maximize (3) under the constraints introduced by cognitive radio networks in a distributed fashion. In addition, we show how the distributed algorithm can be implemented in a practical protocol. In the following, we first introduce a rigorous notion of spectrum hole (Section 4.2). Then, in Section 4.3 we outline the algorithm for spectrum and power allocation executed in a distributed fashion at each secondary user. Finally, we present the core ROSA algorithm in Section 4.4.

4.2 Spectrum Holes

In this section, we provide a rigorous definition of the notion of spectrum hole. We indicate a miniband by simply referring to its

central frequency. For frequency f, secondary user i needs to (1) satisfy the BER requirement when it transmits to secondary user j and (2) avoid interfering with ongoing communications of nodes $l \in \mathcal{S}_i$. The first constraint can be expressed by

$$\frac{P_i(f) \cdot L_{ij}(f) \cdot G}{N_j(f) + \sum_{k \in \mathcal{S}_j, k \neq i} P_k(f) L_{kj}(f)} \geq SINR_{SU}^{th}(BER_{SU}^*), i, j \in \mathcal{SU}. \tag{8}$$

The second constraint represents the fact that communication for a node $l \in \mathcal{S}_i$ is not impaired by i's transmission. We can also indicate interference at node $l \in \mathcal{S}_i, l \neq j$ as $NI_l(f) + \Delta I_{il}(f)$, where $NI_l(f)$ represents noise plus interference at l before i's transmission, and $\Delta I_{il}(f)$ represents the additional interference caused at l by i's transmission, i.e., $P_i(f) L_{il}(f)$. This can be expressed as

$$\frac{P_l^R(f)}{NI_l(f) + \Delta I_{il}(f)} \geq SINR^{th}(BER^*), l \in \mathcal{S}_i, l \neq j, \tag{9}$$

where $P_l^R(f)$ represents the signal power being received at receiver l. Since this has to be true for every node in the neighborhood of i, the constraint can be written as

$$P_i(f) \leq \min_{l \in \mathcal{S}_i} \frac{\Delta I_l^{max}}{L_{il}(f)} \triangleq P_i^{max}(f) \tag{10}$$

where

$$\Delta I_l^{max}(f) = \begin{cases} \frac{P_l^R(f)}{SINR_{PU}^{th}(BER_{PU}^*)} - NI_l(f), & l \in \mathcal{PU}, \\[2mm] \frac{P_l^R(f)}{SINR_{SU}^{th}(BER_{SU}^*)} - NI_l(f), & l \in \mathcal{SU}. \end{cases} \tag{11}$$

The constraint in (8) states that the SINR at receiver j needs to be above a certain threshold, which means the power received at receiver j on frequency f needs be sufficiently high to allow receiver j to successfully decode the signal given its current noise and interferences. The constraint in (10) 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 $l \in \mathcal{S}_i, l \neq j$. Hence, i's transmit power needs to be bounded on each frequency. Constraint in (8) represents a lower bound and constraint in (10) represents an upper bound on the transmit power for each frequency. By combing constraints (8) and (10), we define a control variable $S_{ij}(f)$ for link (i, j) and frequency f as

$$S_{ij}(f) = P_i^{max}(f) - P_i^{min}(f), \tag{12}$$

where $P_i^{max}(f)$ is defined in (10) and $P_i^{min}(f)$ is the value of $P_i(f)$ for which equality in (8) holds.

In cognitive radio networks, available spectrum holes should provide users with limited interference level spectrum bands to satisfy user requirements, and power limitations to enable spectrum sharing without harmful interference. Hence, to capture these characteristic of the available spectrum holes, we introduce the following definition.

DEFINITION 1. *A spectrum hole for link (i, j) is a set of contiguous minibands where $S_{ij}(f) \geq 0$.*

4.3 Spectrum and Power Allocation

In this section we present 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.

In cognitive radio networks local spectrum resource and transmit power allocation may change from time to time, hence link capacity is time-varying and can be maximized through spectrum and power allocation. Maximizing the capacity of link (i, j) means selecting

spectrum $[f_i, f_{i+\Delta f_i}]$ and corresponding transmit power $P_i(f)$ that maximize the Shannon capacity within the spectrum holes.

$$\begin{aligned} \textbf{P2} : Given: \quad & P_k \ \forall k \in \mathcal{S}_i, k \neq i, \ L_{ij} \ \forall (i, j) \in \mathcal{E} \\ Find: \quad & [f_i, f_{i+\Delta f_i}], \ P_i(f) \\ Maximize: \quad & c_{ij} \quad (13) \\ Subject \ to: \end{aligned}$$

$$c_{ij} = \sum_{f \in [f_i, f_{i+\Delta f_i}]} w \cdot log_2 \left[1 + \frac{P_i(f) L_{ij}(f) G}{N_j(f) + I_j(f)} \right]; \tag{14}$$

$$P_i^{min}(f) \leq P_i(f) \leq P_i^{max}(f) \ \forall \ f \in [f_i, f_{i+\Delta f_i}]; \tag{15}$$

$$\sum_{f \in [f_i, f_{i+\Delta f_i}]} P_i(f) \leq P_i^{Bgt}. \tag{16}$$

The objective of the problem above is to find a spectrum hole with maximal capacity, given spectrum condition and hardware limitations of the cognitive radio. Note that (14) represents the capacity of link (i, j), constraint (15) imposes the presence of a spectrum hole, and (16) indicates the hardware restrictions.

For a fixed contiguous set of minibands $[f_i, f_{i+\Delta f_i}]$, we can obtain a solution to the problem above by relaxing constraints (15) and (16). Hence, we can express the dual objective function as

$$g(\mathbf{P_i}, \mathbf{\Upsilon}) = \sum_{f \in [f_i, f_{i+\Delta f_i}]} w \cdot log_2 \left[1 + \frac{P_i(f) L_{ij}(f) G}{N_j(f) + I_j(f)} \right] +$$

$$+ \sum_{f \in [f_i, f_{i+\Delta f_i}]} [v_{min}^f(P_i^{min,f} - P_i(f)) + v_{max}^f(P_i(f) - P_i^{max,f})] +$$

$$+ v^{BGT} \left(\sum_{f \in [f_i, f_{i+\Delta f_i}]} P_i(f) - P_i^{BGT} \right), \tag{17}$$

where

$$\mathbf{\Upsilon} = [v_{min}^{f_i} v_{min}^{f_{i+1}} \cdots v_{min}^{f_{i+\Delta f_i}} v_{max}^{f_i} v_{max}^{f_{i+1}} \cdots v_{max}^{f_{i+\Delta f_i}} v^{BGT}] \tag{18}$$

is the vector of Lagrange multipliers, $\mathbf{\Upsilon} \succeq 0$.

A solution to problem P2 is obtained as described in Algorithm 1. The algorithm provides a dual-based iterative solution to the problem. Specifically, for a given spectrum window between frequency f_i and $f_{i+\Delta f_i}$, at each iteration t the algorithm assigns power $P_i^t(f)$ sequentially for each frequency as in (20) (see following page). Equation (20) is obtained by setting $\frac{dg(\mathbf{P_i}, \mathbf{\Upsilon})}{dP_i(f)} = 0$. Then, Lagrange multipliers are updated following a gradient descent algorithm. In Algorithm 1, Δ^{th} represents a target precision, while ϵ is a small constant used in the gradient stepsize $\frac{1+\epsilon}{t+\epsilon}$. Finally, $\mathbf{\Gamma}(\mathbf{t})$ represents a suitable gradient at step t, i.e.,

$$\mathbf{\Gamma}(\mathbf{t}) = [(P_i^{min,f_i} - P_i^{t-1}(f_i)) \cdots (P_i^{min,f_{i+\Delta f_i}} - P_i^{t-1}(f_{i+\Delta f_i})$$

$$(-P_i^{max,f_i} + P_i^{t-1}(f_i)) \cdots (+P_i^{max,f_{i+\Delta f_i}} - P_i^{t-1}(f_{i+\Delta f_i}))$$

$$\left(\sum_{f=f_i}^{f_{i+\Delta f_i}} P_i^{t-1}(f) - P_i^{BGT} \right)]. \tag{19}$$

4.4 Distributed Routing and Dynamic Spectrum Allocation Algorithm

We now present the cross-layer ROuting and dynamic Spectrum Allocation algorithm (ROSA), which aims at maximizing throughput through joint opportunistic routing, dynamic spectrum allocation and transmit power control, while performing scheduling in a distributed way.

Every backlogged node i, once it senses an idle common control channel, performs the following joint routing and scheduling algorithm:

$$P_i^t(f) = \frac{wL_{ig}G - (N_i(f) + \sum_{k \in \mathcal{S}_j, k \neq i} P_k(f)L_{kj}(f))(v^{BGT,t} - v_f^{min,t} + v_f^{max,t})log_e 2}{L_{ij}G(v^{BGT,t} - v_f^{min,t} + v_f^{max,t})log_e 2} \qquad (20)$$

Algorithm 1 Spectrum and Power Allocation

1: $t = 1, \ \Delta = \infty, \ c_{ij} = 0$
2: **for** $f_i \in [f_{min}, \cdots, f_{max-\Delta f_i}]$ **do**
3:     **while** $\Delta > \Delta^{th}$ **do**
4:       $t = t + 1$
5:       **for** $f \in [f_i, \cdots, f_{i+\Delta f_i}]$ **do**
6:         Assign $P_i^t(f)$ as in (20)
7:       **end for**
8:       Update Lagrange Multipliers

$$\mathbf{\Upsilon(t)} = [\mathbf{\Upsilon(t-1)} + \frac{1+\epsilon}{t+\epsilon}\mathbf{\Gamma(t)}]^+ \qquad (21)$$

9:       $\Delta = |\mathbf{\Upsilon(t)} - \mathbf{\Upsilon(t-1)}|_2$
10:    **end while**
11:    Calculate c_{temp} as in (14)
12:    **if** $c_{temp} > c_{ij}$ **then**
13:       $c_{ij} = c_{temp}$
14:       $[f_i^*, \mathbf{P_i^*}] = [f_i, \mathbf{P_i}]$
15:    **end if**
16: **end for**
17: Return solution as $[f_i^*, \mathbf{P_i^*}, c_{ij}]$

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1. Find the set of feasible next hops $\{n_1^s, n_2^s, ..., n_k^s\}$ for the backlogged session s, which are neighbors with positive advance towards the destination of s. Node n has *positive advance* with respect to i iff n is closer to the destination than i. Calculate c_{ij} for each link (i, j), where $j \in \{n_1^s, n_2^s, ..., n_k^s\}$, using Algorithm 1.

2. Schedule s^* with next hop j^* such that
$$(s^*, j^*) = \arg\max(U_{ij}^s). \qquad (22)$$
Note that U_{ij}^s defined in (1) depends on both the capacity and the differential backlog of link (i, j). Hence, routing is performed in such a way that lightly backlogged queues with more spectrum resource receive most of the traffic.

3. Once spectrum selection, power allocation and next hop are determined, the probability of accessing the medium is calculated based on the value of U_{ij}^s. Nodes with higher U_{ij}^s will get a higher probability of accessing the medium and transmit. Note that U_{ij}^s defined in (1) is an increasing function of $(Q_i^s - Q_j^s)$, i.e., links with higher differential backlog may have higher spectrum utility, thus have higher probability of being scheduled for transmission.

This probability is implemented through the contention window at MAC layer. The transmitting node generates a backoff counter chosen uniformly from the range $[0, 2^{CW-1}]$, where CW is the contention window, whose value decreases when U_{ij}^s increases. With this mechanism, heavily backlogged queues with more spectrum resources are given higher probability of transmission.

5. COLLABORATIVE VIRTUAL SENSING

As discussed earlier, we assume that each node is equipped with two transceivers, one of which is a reconfigurable transceiver that can dynamically adjust its waveform and bandwidth for data transmission. [2] The other is a conventional transceiver employed on the

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[2]Implementations of ROSA that rely on a single transceiver are also possible, for example by letting the reconfigurable transceivers periodically tune to the common control channel to exchange control information. This is the subject of ongoing research.

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common control channel. Handshakes on the CCC are conducted in parallel with data transmissions on the data channel.

The main challenge in implementing ROSA is to let nodes learn about the environment to make distributed decisions on routing, spectrum, and power allocation with bounded interference. One possible way to learn about the environment is to rely on extensive spectrum sensing. However, conventional CSMA/CA mechanisms cannot meet the challenging radio sensitivity requirements and wideband frequency agility needed in cognitive radio networks. A cognitive radio device should have the capability of scanning a wideband spectrum and obtaining the information about the statistics of the spectrum environment. In addition, RF and signal processing techniques have been considered for spectrum feature detection [4]. The performance of these techniques is limited by the received signal strength, which may be severely degraded because of multipath fading and shadowing [4].

As an alternative, we propose a new scheme called *Collaborative Virtual Sensing* (CVS), 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 users transmissions by sensing the data channel. In addition, collaborative virtual sensing is achieved by combining scanning results and information from control packets exchanged on the control channel that contain info about transmissions and power used on different minibands.

ROSA's medium access control logic is illustrated in Fig. 1. Similar to the IEEE 802.11 two-way RTS (request-to-send) and CTS (clear-to-send) handshake, backlogged nodes contend for spectrum access on the *common control channel* (CCC). In particular, backlogged nodes must first sense an idle control channel for a time period of Distributed Inter-Frame Spacing (DIFS), and then generate a backoff counter. The values of backoff counter are determined under the objective that nodes with higher spectrum utility should have a higher channel access probability. As discussed in Section 4.4, the backoff counter is chosen randomly (with a uniform distribution) within the interval $[0, 2^{CW-1}]$, where CW represents the contention window, whose value is a decreasing function $\Phi()$ of the spectrum utility. The function $\Phi()$ must be designed carefully to minimize the collision rate and provide high channel utilization. Different choices of Φ lead to different system performance in terms of fairness, overall throughput, and delay.

The sender informs the receiver of the selected frequency interval $[f_i, f_{i+\Delta f}]$ 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. As in [27], an additional control packet, DTS (Data Transmission reServation), is needed for the transmitter to announce the spectrum reservation and transmit power to its neighbors. Here, we modify the RTS/CTS/DTS packets and include channel allocation information to allow the nodes to make adaptive decisions. By actively collecting RTS, CTS, and DTS packets transmitted on the CCC, each node learns the spectrum environment and queue information of its neighborhood.

Once RTS/CTS/DTS are successfully exchanged, sender 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 or the receiver find the selected spectrum busy just before data transmission. This can be caused by the presence of primary users, or by conflicting reservations caused by
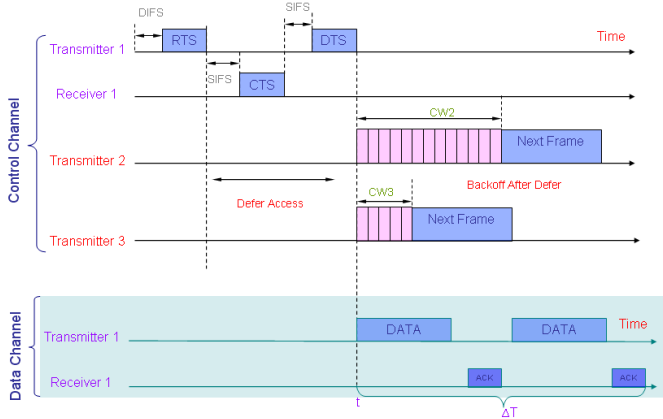
Figure 1: ROSA's Medium Access Control.

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/DTS exchange, if the sender's selected spectrum can not be entirely used, i.e. the receiver just sensed a primary user's presence, the receiver will not send a CTS. 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 achieved. If data are successfully received, an ACK will be sent by the receiver. The transaction is considered completed after the ACK is successfully received.

6. INTERPRETATION OF ROSA AS A NUM SOLVER

In this section, we show how ROSA can be interpreted as a distributed dual-based solution to a cross-layer network utility maximization problem for cognitive radio ad hoc networks under the system model described in the previous sections. A joint congestion control, routing, and dynamic spectrum allocation problem for cognitive radio networks can be formulated as follows.

$$\mathbf{P3} : Given: \quad BER_{SU}^*, BER_{PU}^*, \mathcal{G}(\mathcal{V}, \mathcal{E}), P^{Bgt}$$
$$Find: \quad \mathbf{\Lambda}, \mathbf{R}, \mathbf{C}$$
$$Maximize: \quad \sum_{i \in \mathcal{SU}} \sum_{s \in \mathcal{S}} U_i(\lambda_i^s); \quad (23)$$
$$Subject\ to:$$
$$\lambda_i^s + \sum_{k \in \mathcal{SU}, k \neq i} r_{ki}^s = \sum_{l \in \mathcal{SU}, l \neq i} r_{il}^s, \quad \forall i \in \mathcal{SU}, \forall s \in \mathcal{S} \quad (24)$$

$$\sum_{s \in \mathcal{S}} r_{ij}^s \leq c_{ij}, \quad \forall i \in \mathcal{SU}, \forall j \in \mathcal{SU} \setminus i \quad (25)$$

where

$$c_{ij} \triangleq \sum_{f \in [f_i, f_{i+\Delta f_i}]} w \cdot log_2 \left[1 + \frac{P_i(f) L_{ij}(f) G}{N_j(f) + I_j(f)} \right] \quad (26)$$

$$\sum_{f \in [f_i, f_{i+\Delta f_i}]} P_i(f) \leq P_i^{Bgt} \quad (27)$$

$$SINR_k \geq SINR_{PU}^{th}(BER_{PU}^*), \quad \forall k \in \mathcal{PU}, \forall f \quad (28)$$

$$SINR_l \geq SINR_{SU}^{th}(BER_{SU}^*), \quad \forall l \in \mathcal{SU}, \forall f \quad (29)$$

In the problem above, the objective is to maximize a sum of utility functions $U_i(\lambda_i^s)$, which are assumed to be smooth, increasing, concave, and dependent on local rate at node i only [7]. Constraint (24) expresses conservation of flows through the routing variables r_{ij}^s, which represent the traffic from session s that is being transported on link (i, j). Finally, constraint (25) imposes that the total amount of traffic transported on link (i, j) is lower than the capacity of the physical link. Note that if $\mathbf{C}$ is the feasible set of the physical rates, values of $c_{ij} \in Co(\mathbf{C})$, i.e., they are constrained to be

be within the convex hull of the feasible rate region [11][16]. The achievable values of c_{ij} depend on i) the scheduling policy; ii) allocation of resources at the physical layer, as expressed by constraints (26), (27), (28) and (29).

By taking a duality approach, the Lagrange dual function of **P3** can be obtained by relaxing constraint (24) through Lagrange multipliers $\mathbf{Q} = [Q_i^s]$, with $i \in \mathcal{SU}$ and $s \in \mathcal{S}$.

$$L(\mathbf{Q}) = \max_{\mathbf{\Lambda}} \left\{ \sum_{i \in \mathcal{SU}} \sum_{s \in \mathcal{S}} (U_i(\lambda_i^s) - Q_i^s \lambda_i^s) \right\} +$$
$$\max_{\mathbf{R}, \mathbf{C}} \left\{ \sum_{i \in \mathcal{SU}} \sum_{j \in \mathcal{SU}, j \neq i} \sum_{s \in \mathcal{S}} r_{ij}^s \left(Q_i^s - Q_j^s \right) \right\}, \quad (30)$$

where variables indicating data rates are still constrained to be $c_{ij} \in Co(\mathbf{C})$, and where $\mathbf{C}$ is defined by constraints (26)- (29).

In the above decomposition, the first term of (30) represents the congestion control functionality (which can be carried out independently), while the second term represents routing, scheduling, and physical rate allocation. Let $\mathbf{\Lambda}^*(\mathbf{Q}), \mathbf{R}^*(\mathbf{Q}), \mathbf{C}^*(\mathbf{Q})$ be the vectors of optimum values for a given set of Lagrange multipliers $\mathbf{Q}$. While $\lambda_i^{s,*}(\mathbf{Q})$ can be computed locally at each source i of session s, $\mathbf{R}^*(\mathbf{Q}), \mathbf{C}^*(\mathbf{Q})$ require global knowledge and centralized algorithms.

To solve the above problem, the following actions need to be performed at each time slot t:

- Update the congestion control variables. For each session s and for each source node i:
$$\lambda_i^s(t) = \sup_{\lambda_i^s} \{ U_i(\lambda_i^s) - Q_i^s \lambda_i^s \} \quad (31)$$

- Scheduling and Routing. For each link (i, j), choose the session that maximizes the differential backlog between transmitter and receiver:
$$s_{ij}^* = \arg \max_s \{ Q_i^s - Q_j^s \} \quad (32)$$

Then, set $r_{ij}^{s_{ij}^*}(t) = c_{ij}(t)$. Assign link rates $c_{ij}(t)$ to maximize the weighted sum of the link rates of the network, where the weights correspond to differential backlogs:

$$\mathbf{C}(t) = \arg \max_{\mathbf{C}} \left\{ \sum_{i \in \mathcal{SU}} \sum_{j \in \mathcal{SU}, j \neq i} c_{ij} \left(Q_i^{s_{ij}^*} - Q_j^{s_{ij}^*} \right) \right\} \quad (33)$$

Note that the maximization above is analogous to the dynamic backpressure algorithm in [11][23].

- Update Lagrange multipliers (queues) as

$$\left[Q_i^s(t) + \epsilon \left(\sum_{k \in \mathcal{SU}, k \neq i} r_{ki}^s(t) - \sum_{l \in \mathcal{SU}, l \neq i} r_{il}^s(t) + \lambda_i^s(t) \right) \right]^+ \quad (34)$$

Note that the Lagrange function is always convex, and thus the multipliers can be computed using a subgradient algorithm. A subgradient for a given vector of Lagrange multipliers is the vector consisting of all multiplicative terms in the Lagrange function, which are the results of the maximization above. Hence, the Lagrange multipliers are computed using an iterative algorithm which updates them based on the value of the local subgradient. When $\epsilon = 1$, the Lagrange multipliers behave like real queues. However, ϵ needs to be small for the algorithm to converge to the global optimum.

Clearly, the bottleneck of the above solution lies in the routing and scheduling component in (33). Solving (33) requires global knowledge of feasible rates, is centralized and its complexity is worst-case exponential. Exact distributed solution of (33) is thus infeasible. However, it can be shown that the closer a policy gets to maximizing (33), the closer the policy gets to the capacity region of the

	Scenario 1	Scenario 2
Area	6000m x 6000m	6000m x 6000m
Number of Nodes	49	49
Data Channel Bandwidth	54-72 MHz	54-72 MHz
Bandwidth per Mini-band (for Data Channel)	2 MHz	2 MHz
Bandwidth Usable by Cognitive Radios (for Data Channel)	2/4/6 MHz	2/4/6 MHz
Bandwidth of Control Channel	2 MHz	2 MHz
Packet Size	2500 bytes	2500 bytes
Packet Interval	0.001 s	0.001 s
Data Rate Injected into the Network	2 Mbit/s	0.1/ 0.2/ 0.5/ 1/ 2/ 4/ 6/ 8 Mbit/s
Number of Active Sessions	2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24	4

Table 1: PARAMETERS OF THE MODEL USED FOR SIMULATIONS.

network [11]. This provides the rationale for our distributed algorithm, whose objective is to maximize (33) under the constraints expressed by (27), together with (28) and (29) for cognitive radio ad hoc networks.

7. PERFORMANCE EVALUATION

In this section, we analyze the performance of ROSA in a multi-hop cognitive radio network, and compare it to the performance of other schemes. We concentrate on evaluating network throughput, delay, and fairness. To evaluate ROSA, we developed an object-oriented packet-level discrete-event simulator, which implements the features described in this paper.
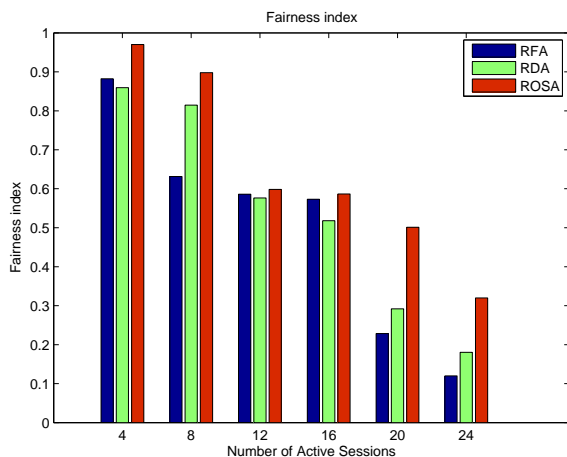
In all simulation scenarios, we considered a common set of parameters, which is reported in Table 1. A grid topology of 49 nodes is deployed, in a $6000\,\mathrm{m}$ x $6000\,\mathrm{m}$ area. We initiate sessions between randomly selected but disjoint source-destination pairs. Sessions are CBR sources with a data rate of $2\,\mathrm{Mbit/s}$ each. We set the available spectrum to be $54\,\mathrm{MHz}$ - $72\,\mathrm{MHz}$. We restrict the bandwidth usable by cognitive radios to be 2, 4 and $6\,\mathrm{MHz}$. The bandwidth of the CCC is $2\,\mathrm{MHz}$.

We compare the performance of ROSA with two alternative schemes. In particular, we consider Routing with Fixed Allocation (RFA) as the solution where routing is based on differential backlog (as in Section 4) with pre-defined channel and transmit power, and to Routing with Dynamic Allocation (RDA) as the solution where routing is based on shortest path with dynamic channel selection and power allocation without considering differential backlog.

We compare against the three solutions by varying the number of sessions injected into the network and plot the network throughput (sum of individual session throughput) in Fig. 2(a), which shows that ROSA outperforms RFA and RDA. When there are a few active sessions, e.g., 2 or 4, ROSA, RDA and RFA obtain similar throughput performance. However, with more active sessions, ROSA and RDA perform much better than RFA since they use the best among possible spectrum allocations and routes adaptively. The improvement obtained by ROSA is more visible when the number of active sessions grows large. In fact, ROSA achieves higher network throughput than RDA when there are more than 10 active sessions in the network.

Fig. 2(b) shows the delay performance for the three solutions. RFA, on average, delivers a larger delay than the other two solutions. The above delay performance gap grows as the number of sessions increases. As shown in Fig. 2(b), ROSA provides very low and stable delay performance as the number of sessions increases. ROSA and RDA yield almost the same delay performance.

Fig. 2(c) shows the impact of source data rate per session on the performance of throughput. We evaluate the throughput as the traffic load per session increases from $100\,\mathrm{Kbit/s}$ to $8\,\mathrm{Mbit/s}$. As

Figure 3: Fairness Index.

shown in Fig. 2(c), the throughput achieved by ROSA increases linearly as the load per session increases. As the load increases, ROSA obtains a significant throughput gain.

Figure 3 shows Jain's fairness index, calculated as $(\sum r_i)^2 / n * \sum (r_i)^2$, where r_i is the throughput of session i, and n is the total number of active sessions. As shown in the figure, the overall fairness among competing sessions is improved by ROSA using prioritized channel access scheme. When the sessions are dynamic, the protocol is supposed to be stable since the algorithm adaptively adjusts channel selection and power allocation according to the current transmissions.

8. CONCLUSIONS

We proposed, discussed and analyzed ROSA, a distributed algorithm for joint opportunistic routing and dynamic spectrum access in multi-hop cognitive radio networks. ROSA was derived by decomposing a cross-layer network utility maximization problem formulated under the constraints of cognitive radio networks. As discussed in Section 6, a congestion control module that interacts with the other functionalities can also be easily integrated based on it. Through discrete-event simulation, ROSA was shown to outperform simpler solutions. Future work will aim at deriving a theoretical lower bound on the performance of ROSA, studying an efficient single-radio implementation of the algorithm, and evaluating the performance of the algorithm in conjunction with a congestion control module. In addition, we are currently implementing ROSA on GNU radio and Universal Software Radio Peripheral (USRP2).

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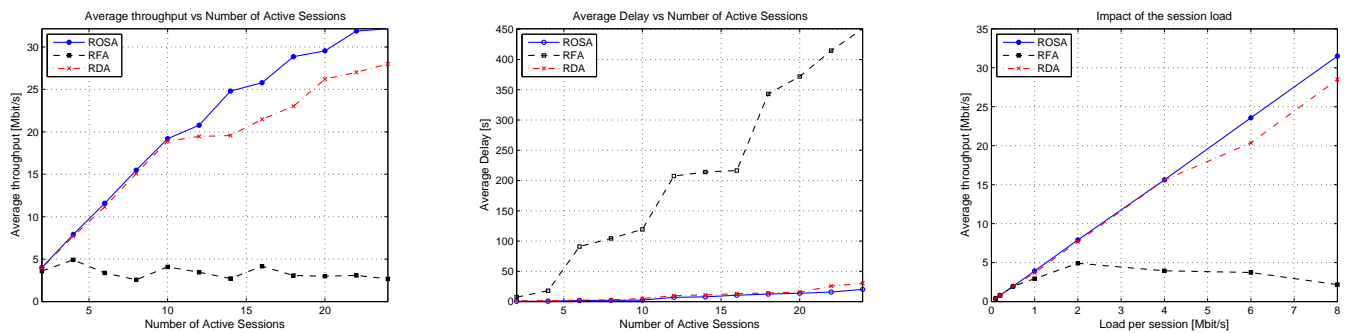
Figure 2: (a): Average throughput vs number of active sessions; (b): Delay vs number of active sessions; (c): Impact of Source Data Rate per Session on Throughput.

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