Spread-spectrum Cognitive Networking: Distributed Channelization and Routing

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***Abstract*—We study a framework that captures the interdependencies between spreading channelization and routing for a secondary multi-hop cognitive radio network that operates cognitively to coexist with primary users. We consider interactions between dynamic routing and code-division channelization functionalities for cognitive radio networks. With this respect, we study the effect of joint routing, spreading code and power allocation on the network throughput. A solution for joint routing and spread-spectrum channelization is proposed as a localized approximation of the throughput-maximizing problem. Specifically, power and spreading code are allocated to guarantee the quality of service of the on-going primary and secondary transmissions, while the routing algorithm dynamically selects relays based on the network traffic dynamics and on the achievable data rates on different secondary links.**

***Index Terms* – Cognitive radio networks, routing, power allocation, code-channel allocation, cross-layer design.**

I. INTRODUCTION

Mainstream cognitive radio proposals focus on opportunistic access to the licensed spectrum where the primary users of the band are known a priori and this knowledge can be utilized to detect if the band is occupied by the known signal pattern. Quite the opposite, in the unlicensed band there are potentially many uncoordinated devices, and their signal waveforms and activation statistics are in general unknown. Moreover, in cognitive radio networks with multi-hop communication requirements, spectrum occupancy is location-dependent, and the receiver interference profile may, thus, vary at each relay node.

We therefore propose a new spread-spectrum management paradigm, in which spreading code and power are designed to occupy the entire available spectrum without generating harmful interference to active primary or secondary users. In this way, the secondary users share the licensed spectrum with the primary users to achieve frequency reuse. At the same time, the dynamic and location-dependent nature of the wireless environment calls for the development of routing algorithms that are aware of the interference profile at each potential relay.

The lack of established infrastructure and the wireless channel dynamics impose an unprecedented set of challenges over spread-spectrum cognitive ad hoc networks. First, secondary users should optimize the spreading code and power to avoid generating harmful interference to primary users. The challenges here arise from the assumption that the spreading codes of primary users are unknown to the secondary users. Second, the spectrum environment varies in time and space depending on the activities of primary users, interference, and fading. The optimal spectrum-spreading channelization may therefore be different at each hop in a multi-hop path. Furthermore, as new secondary links are formed and others vanish, and following network traffic dynamics, end-to-end data delivery paths among secondary nodes may frequently change. Therefore, controlling the interactions between routing and spread-spectrum channelization is of fundamental importance.

In this paper we consider interactions between dynamic routing and code-division channelization functionalities for cognitive radio ad hoc networks. With this respect, we study the effect of joint routing, spreading code optimization and power allocation on the network throughput. The throughput optimization is carried out dynamically by all secondary transmitters to continuously adapt to the changing spectrum environment and traffic arrival rates.

The remainder of this paper is organized as follows. In Section II, we review related work. In Section III, we introduce the system model. We formulate the problem in Section IV. In Section V we propose the distributed algorithm for joint routing and code-division channelization. In Section VI we present the details of the proposed algorithm for secondary power and spreading code allocation solution. The performance of the proposed distributed solution is evaluated in Section VI. A few concluding remarks are drawn in Section VII.

II. RELATED WORK

Since spectrum occupancy is location-dependent, the available spectrum bands in a multi-hop path may be different at each relay node. Therefore, one of the key challenges in the design of cognitive radio networks is joint routing and dynamic spectrum allocation. The authors in [9] proposed a routing algorithm based on a probabilistic estimation of the available capacity of every secondary link. A probability-based routing metric relies on the probability distribution of the primary user to secondary user interference over a given channel. This distribution accounts for the activities of primary users and their random deployment. In [11], the authors proposed a connectivity-driven routing algorithm, where paths are measured in terms of their degree of connectivity in a multi-hop cognitive radio network that is highly influenced by the primary user behavior. Route-stability-oriented routing is introduced in [10] based on the concept of route maintenance cost. The maintenance cost represents the effort needed or penalty paid to maintaining end-to-end connectivity. In [16], a distributed and localized algorithm for joint dynamic routing and spectrum allocation for ad hoc cognitive radio networks is proposed. The proposed algorithm jointly addresses routing and spectrum assignment with power control under the physical interference model. The reader is referred to [17] and references therein for an excellent survey of the main results in this area.

Recent work has also started investigating cross-layer optimizations for cognitive radio networks. In [12], 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. Shi et al. studied the joint optimization of power control, scheduling, and routing for a multi-hop cognitive radio network via a centralized approach [13] and a distributed approach [14]. In [14] the authors develop a distributed optimization algorithm with the objective of maximizing data rates for a set of user communication sessions.

Herein, we consider cognitive networks built around a primary code-division multiplexing (CDM) system. Unlike traditional frequency division operations where cognitive secondary users may transmit opportunistically in sensed spectrum holes/void only, cognitive code-division users may operate in parallel in frequency and time to a primary system as long as the induced spread-spectrum interference remains below a pre-defined acceptable threshold[1]. Power control under an "interference temperature" constraint (total secondary user disturbance power over primary band) was considered [18] in cognitive code-division systems, but no code-channel (signature) optimization was carried out for the secondary users. In contrast, in [19] a secondary code assignment scheme was presented to obtain the binary secondary signature by hard-limiting the code sequence that exhibits the minimum mean-square crosscorrelation with the primary received signal. Secondary code set of multiple secondary users was also constructed in an iterative way. Under interference-minimizing code assignments, bit rate and spreading factor adjustments for a secondary CDMA system were considered in [20]. A distributed algorithm for resource allocation of spectral bands, power, and data rates among multiple secondary users for multi-carrier CDMA systems was developed in [21].

[1]While early standardization and regulation discussions have begun [1], no conclusive "interference temperature" rules and agreements have been reached yet.

III. System model

We consider a primary spread-spectrum system with processing gain (code sequence length) L. Denote $\mathcal{PU}$ as the set of active primary communication links. Let (m,n) denote the link with transmitter m and receiver n. Note that link (m,n) is distinct from link (n,m). Each primary link is pre-assigned with an unique code sequence, i.e., $\mathbf{s}_{mn}$ for link (m,n). We let $\mathcal{N}=\{1,\cdots,N\}$ represent a finite set of secondary users (also referred to as nodes). Secondary users do not have any pre-assigned code sequence and opportunistically send their data by optimizing code sequence and power.

Traffic flows of secondary users are, in general, carried over multi-hop routes. Let the traffic demands consist of a set $\mathcal{D}=\{1,2,\cdots,D\}$ of unicast sessions. Each session $d\in\mathcal{D}$ is characterized by the destination node $d, d\in\mathcal{N}$ for the traffic. We indicate the arrival rate of session d at node i as $\mu_i^d(t)$ at time t. Each node maintains a separate queue for each session d for which it is either a source or an intermediate relay. At time slot t, define $Q_i^d(t)$ as the number of queued packets of session d waiting for transmission at secondary user i. Define $r_{ij}^d(t)$ (in packets/s) as the transmission rate on link (i,j) for session d during time slot t, and $\mathbf{R}$ as the vector of rates.

We recall that the secondary cognitive ad hoc network coexists with the primary system over the primary licensed band. After carrier demodulation, chip-matched filtering and sampling at the chip rate over the duration of a symbol (bit) period of L chips, the received signal at primary node k over the link of interest (l,k), denoted as $\mathbf{y}_{lk}^{(p)}$, can be represented as

$$\mathbf{y}_{lk}^{(p)} = \sqrt{E_l}L_{lk}\mathbf{s}_{lk}b_l + \sum_{\substack{(m,n)\in\mathcal{PU}\\(m,n)\neq(l,k)}} \sqrt{E_m}L_{mk}\mathbf{s}_{mn}b_m + \sum_{(u,v)\in\mathcal{SU}} \sqrt{E_u}L_{uk}\mathbf{c}_{uv}b_u + \mathbf{n}_k. \quad (1)$$

We note that the superscript "p" in (1) denotes primary node. Similarly, let $\mathbf{y}_{ij}^{(s)}$ denote the secondary signal received at node j over the link of interest (i,j),

$$\mathbf{y}_{ij}^{(s)} = \sqrt{E_i}L_{ij}\mathbf{c}_{ij}b_i + \sum_{(m,n)\in\mathcal{PU}} \sqrt{E_m}L_{mj}\mathbf{s}_{mn}b_m + \sum_{\substack{(u,v)\in\mathcal{SU}\\(u,v)\neq(i,j)}} \sqrt{E_u}L_{uj}\mathbf{c}_{uv}b_u + \mathbf{n}_j, \quad (2)$$

where $E_l>0, b_l\in\{\pm 1\}$, and $\mathbf{s}_{lk}\in\mathbb{R}^L$, $\|\mathbf{s}_{lk}\|=1$, denote bit energy,information bit, and normalized signature vector of primary user l over primary link (l,k), $(l,k)\in\mathcal{PU}$, respectively; $E_i>0$, $b_i\in\{\pm 1\}$, and $\mathbf{c}_{ij}\in\mathbb{R}^L$, $\|\mathbf{c}_{ij}\|=1$, denote the bit energy, information bit, and normalized signature vector, respectively, of secondary user i over secondary link (i,j), $(i,j)\in\mathcal{SU}$, where $\mathcal{SU}$ is the set of active secondary links; L_{lk}, $(l,k)\in\mathcal{PU}$ and L_{ij}, $(i,j)\in\mathcal{SU}$ denote the path coefficients for primary link (l,k) and secondary link (i,j), respectively. $\mathbf{n}_k$ and $\mathbf{n}_j$ represent additive white Gaussian noise (AWGN) at primary node k and secondary node j, correspondingly, independent from each other with $\mathbf{0}$ mean and autocovariance matrix $\sigma^2\mathbf{I}$. We note that the superscript s in (2) denotes secondary node.

The linear filters at the primary and secondary receivers that exhibit maximum output SINR [22] can be found to be

$$\mathbf{w}_{maxSINR,lk} = c_1 \mathbf{A}_{lk}^{-1}\mathbf{s}_{lk},\ \ (l,k) \in \mathcal{PU},$$
$$\mathbf{w}_{maxSINR,ij} = c_2 \mathbf{A}_{ij}^{-1}\mathbf{c}_{ij},\ \ (i,j) \in \mathcal{SU},$$

where $\mathbf{A}_{lk} = E\{\mathbf{y}_{lk}^{(p)}\mathbf{y}_{lk}^{(p)T}\}$, $\mathbf{A}_{ij} = E\{\mathbf{y}_{ij}^{(s)}\mathbf{y}_{ij}^{(s)T}\}$, $c_1, c_2 > 0$.

In our cognitive radio setup, the normalized channel capacity $\frac{C_{ij}}{W}$ of secondary link (i,j) as a function of SINR_{ij} is given by

$$\frac{C_{ij}}{W} = \log_2(1 + \frac{C_{ij}}{W}\mathrm{SINR}_{ij}) \tag{3}$$

where C_{ij} is the channel capacity and W is the bandwidth of the primary licensed band. Given the fixed bandwidth W, the channel capacity C_{ij} can be optimized by (3) for any instantaneous value of SINR_{ij}.

Maximum output SINRs at the receiver end for link (l,k) and (i,j) are, respectively, given by

$$SINR_{lk} = L_{lk}^2 E_l \mathbf{s}_{lk}^T \mathbf{A}_{\setminus(l,k)}^{-1}\mathbf{s}_{lk},\ \ \forall (l,k) \in \mathcal{PU},$$
$$SINR_{ij} = L_{ij}^2 E_i \mathbf{s}_{ij}^T \mathbf{A}_{\setminus(i,j)}^{-1}\mathbf{s}_{ij},\ \ \forall (i,j) \in \mathcal{SU},$$

where $\mathbf{A}_{\setminus(l,k)}$ and $\mathbf{A}_{\setminus(i,j)}$ are the disturbance autocorrelation matrices at the receiver end for link (l,k) and (i,j), respectively, defined by

$$\mathbf{A}_{\setminus(l,k)} \triangleq \sum_{\substack{(m,n)\in\mathcal{PU}\\(m,n)\neq(l,k)}} L_{mk}^2 E_m \mathbf{s}_{mn}\mathbf{s}_{mn}^T + \sum_{(u,v)\in\mathcal{SU}} L_{uk}^2 E_u \mathbf{c}_{uv}\mathbf{c}_{uv}^T + \sigma^2\mathbf{I},$$
$$\mathbf{A}_{\setminus(i,j)} \triangleq \sum_{(m,n)\in\mathcal{PU}} L_{mj}^2 E_m \mathbf{s}_{mn}\mathbf{s}_{mn}^T + \sum_{\substack{(u,v)\in\mathcal{SU}\\(u,v)\neq(i,j)}} L_{uj}^2 E_u \mathbf{c}_{uv}\mathbf{c}_{uv}^T + \sigma^2\mathbf{I}.$$

IV. Problem formulation

Our goal is to design a distributed cross-layer control algorithm to maximize the secondary network throughput by jointly and dynamically allocating routes, code sequence and transmit power for each secondary link along the path. Denote $\mathcal{SU}(t)$ as the set of secondary links chosen for activation during time slot t, $\mathbf{c}(t) = \{\mathbf{c}_{ij}(t) : (i,j) \in \mathcal{SU}(t)\}$ and $\mathbf{E}(t) = \{\mathbf{E}_i(t) : (i,j) \in \mathcal{SU}(t)\}$ as the sets of code sequences and power allocation decisions for every active secondary link. An ideal throughput-optimal network controller should, at each decision period (i.e. time slot t), find $\mathcal{SU}(t)$, $\mathbf{c}(t)$, and $\mathbf{E}(t)$ to maximize

$$\sum_{i\in\mathcal{SU}}\sum_{j\in\mathcal{SU}, j\neq i} C_{ij}(\mathbf{c}(t), \mathbf{E}(t)) \cdot \Delta Q_{ij}(t), \tag{4}$$

where $\Delta Q_{ij}(t) = \max_{d\in\mathcal{D}} \left[Q_i^d(t) - Q_j^d(t)\right]^+$. The transmission rates are then given by

$$r_{ij}^d(t) = \begin{cases} C_{ij}(\mathbf{c}(t), \mathbf{E}(t)) & \text{if } d = d_{ij}^*(t) \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

where $d_{ij}^*(t) = \arg\max_{d\in\mathcal{D}} \left\{Q_i^d(t) - Q_j^d(t)\right\}$.

The objective function (4) is defined based on the principle of dynamic back-pressure, first introduced in [2]. It can be proven [3] 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) achieves throughput optimality, in the sense that it is able to keep all network queues finite for any level of offered traffic within the network capacity region. Moreover, a desirable solution should enable secondary users to dynamically utilize the available spectrum resource in the code domain to provide SINR guarantees for both primary and secondary users. The problem can be expressed as

$$\begin{aligned}
&\mathbf{P1} : Find: && \mathcal{SU}(t),\ \mathbf{E}(t),\ \mathbf{c}(t)\\
&Maximize: && \sum_{i\in\mathcal{SU}}\sum_{j\in\mathcal{SU}} C_{ij}(\mathbf{c}(t), \mathbf{E}(t)) \cdot \Delta Q_{ij}(t)\\
&Subject\ to: && \\
& && \mathrm{SINR}_{mn} \geq \mathrm{SINR}_{PU}^{th},\ \ \forall (m,n) \in \mathcal{PU},\\
& && \mathrm{SINR}_{ij} \geq \mathrm{SINR}_{SU}^{th},\ \ \forall (i,j) \in \mathcal{SU}(t),\\
& && \mathbf{c}_{ij}(t)^T\mathbf{c}_{ij}(t) = 1,\ E_i \leq E_{max},\ \ \forall (i,j) \in \mathcal{SU}(t).
\end{aligned}$$

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

In the following sections, we first discuss the decentralized solution for joint routing and code-division channelization in Section V. Then, we present in detail our power and spreading code allocation algorithm to maximize the SINR for secondary links in Section VI.

V. Joint Routing and Code-Division Channelization

We now present the decentralized joint routing and code-division channelization solution.

In the proposed solution, backlogged nodes i first maximize their local objective function $C_{ij} \cdot \Delta Q_{ij}$ over all feasible next hops j by optimizing $\mathbf{c}_{ij}$ and E_i based on locally collected spectrum information - details are given in what follows. Then, in case of channel access contention, each node will access the channel with a probability that is a monotonically increasing function of its local utility. We now describe the details of the proposed solution. Every backlogged node i performs the following algorithm:

1) Find the set of feasible next hops $\{n_1^d, n_2^d, \cdots, n_k^d\}$ for the backlogged session d, which are neighbors with positive advance towards the destination of d. We say

node j has *positive advance* with respect to i iff j is closer to the destination d than i.

2) For each candidate next hop $j \in \{n_1^d, n_2^d, \cdots, n_k^d\}$, maximize link capacity C_{ij} by optimizing $\mathbf{c}_{ij}$ and E_i, using the algorithm proposed in the following Section.
3) Schedule the session d^* with next hop j^* with maximal $C_{ij} \cdot \Delta Q_{ij}$. Hence, routing is performed in such a way that lightly backlogged nodes with higher link capacity receive most of the traffic.
4) Once the next hop and corresponding code sequence and power allocation have been determined, the probability of accessing the medium is calculated based on the value of $C_{ij} \cdot \Delta Q_{ij}$. Nodes with higher $C_{ij} \cdot \Delta Q_{ij}$ will have a higher probability of accessing the medium and transmit. Note that links with higher differential backlog may have higher spectrum utility, and thus have higher probability of being scheduled for transmission. This 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 $\Phi()$ of $C_{ij} \cdot \Delta Q_{ij}$ as below

$$CW_i = -\theta_1 \cdot \frac{C_{ij} \cdot \Delta Q_{ij}}{\sum_{k \in \mathcal{N}_i, k, l \in \mathcal{V}} (C_{kl} \cdot \Delta Q_{kl})} + \theta_2, \quad (6)$$

where $\theta_1 > 0, \theta_2 > 0$ and the denominator represents the objective value of neighboring competing nodes. Note that sender i collects the utility values of its neighbors by overhearing control packets coded by a common spreading code.

The algorithm calculates the next hop j opportunistically depending on queueing and spectrum dynamics, according to the objective function $C_{ij} \cdot \Delta Q_{ij}$. The combination of opportunistically selected 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. With this scheme, lightly-congested nodes (as indicated by a smaller differential backlog) have a higher probability of being selected as intermediate relays. Links with larger differential backlogs result in smaller contention window size at the medium access control, and therefore have higher probability of accessing the channel to reserve resources. Ultimately, heavily backlogged nodes with potential high-data rate opportunities to transmit have a higher probability of accessing the channel.

The algorithm is implemented through a MAC protocol that uses a three-way handshake between source and destination. The three-way handshake is carried out via exchange of Request-to-Send(RTS), Clear-to-Send(CTS) and Data Transmission reServation(DTS) packets. Backlogged nodes contend for spectrum access on a common control channel that operates in parallel to the data channel using a common spreading code. Each node makes adaptive decisions based on local information collected via RTS/CTS/DTS packets coded with a common spreading code. The DTS packet is used to announce the information on spreading code and transmit power allocation to neighbors.

VI. A Secondary Power and Spreading Code Allocation Solution

We now consider the spread-spectrum channelization problem, which plays a key role in our spectrum management framework. As mentioned at step 2 of the algorithm in the previous section, we propose a design of power and spreading code allocation scheme in this section. We attempt to dynamically and adaptively design digital waveforms that span the whole licensed spectrum band to maximize the capacity of the secondary link without causing harmful interference to existing users (what we refer to as spread-spectrum channelization).

In order for a cognitive radio network to efficiently share the licensed band with the primary network, the secondary transmitter is to maximize the secondary SINR of link (i, j) at its receiver end under the condition that the SINR QoS of all primary users and ongoing secondary users is guaranteed. We first assume that the secondary link (i, j) is activated with the transmission bit energy E_i and (normalized) signature vector $\mathbf{c}_{ij}$. In this spirit, our objective is to find the pair $(E_i, \mathbf{c}_{ij})$ that maximizes $SINR_{ij}$ under the constraints that $SINR_{lk}$, $\forall (l, k) \in \mathcal{PU}$, and $SINR_{uv}$, $\forall (u, v) \in \mathcal{SU} - \{(i, j)\}$, are all above the prescribed thresholds $SINR_{PU}^{th}$ and $SINR_{SU}^{th}$, respectively, i.e.

$$\begin{aligned} \mathbf{P2}: \ (E_i, \mathbf{c}_{ij})^{opt} &= \underset{E_i > 0, \mathbf{c}_{ij} \in \mathbb{R}^L}{\arg\max} \ E_i \mathbf{c}_{ij}^T \mathbf{A}_{\backslash (i,j)}^{-1} \mathbf{c}_{ij} \\ \text{s.t. } & E_l L_{lk}^2 \mathbf{s}_{lk}^T \mathbf{A}_{\backslash (l,k)}^{-1} \mathbf{s}_{lk} \geq SINR_{PU}^{th}, \quad \forall (l, k) \in \mathcal{PU}, \\ E_u L_{uv}^2 \mathbf{c}_{uv}^T \mathbf{A}_{\backslash (u,v)}^{-1} \mathbf{c}_{uv} &\geq SINR_{SU}^{th}, \ \forall (u, v) \in \mathcal{SU} - \{(i, j)\}, \\ & \mathbf{c}_{ij}^T \mathbf{c}_{ij} = 1, \ E_i \leq E_{max} \end{aligned}$$

where E_{max} denotes the maximum allowable bit energy for the secondary user.

The optimization task of maximizing a quadratic objective function ($\mathbf{A}_{\backslash (i,j)}^{-1}$ is positive definite) subject to the constraints in $\mathbf{P2}$ is, unfortunately, a non-convex NP-hard optimization problem. Using the matrix inversion lemma twice, the optimization problem $\mathbf{P2}$ can be rewritten as

$$\mathbf{P3}: \ (E_i, \mathbf{c}_{ij})^{opt} = \underset{E_i > 0, \mathbf{c}_{ij} \in \mathbb{R}^L}{\arg\max} \ E_i \mathbf{c}_{ij}^T \mathbf{A}_{\backslash (i,j)}^{-1} \mathbf{c}_{ij} \quad (7)$$

$$\text{s.t.} \quad E_i \mathbf{c}_{ij}^T \mathbf{B}_{lk} \mathbf{c}_{ij} - \beta_{lk} \leq 0, \forall (l, k) \in \mathcal{PU}, \quad (8)$$

$$E_i \mathbf{c}_{ij}^T \mathbf{B}_{uv} \mathbf{c}_{ij} - \beta_{uv} \leq 0, \forall (u, v) \in \mathcal{SU} - \{(i, j)\}, \quad (9)$$

$$E_i \leq E_{max}, \quad (10)$$

$$\mathbf{c}_{ij}^T \mathbf{c}_{ij} = 1 \quad (11)$$

where

$$\beta_{lk} \triangleq \mathbf{s}_{lk}^T \mathbf{A}_{lk\setminus(i,j)}^{-1} \mathbf{s}_{lk} - \frac{SINR_{PU}^{th}}{E_l L_{lk}^2 + SINR_{PU}^{th} E_l L_{lk}^2}, \quad \forall (l,k) \in \mathcal{PU}, \tag{12}$$

$$\beta_{uv} \triangleq \mathbf{c}_{uv}^T \mathbf{A}_{uv\setminus(i,j)}^{-1} \mathbf{c}_{uv} - \frac{SINR_{SU}^{th}}{E_u L_{uv}^2 + SINR_{SU}^{th} E_u L_{uv}^2}, \quad \forall (u,v) \in \mathcal{SU} - \{(i,j)\}, \tag{13}$$

$$\mathbf{B}_{lk} \triangleq L_{ik}^2 \mathbf{A}_{lk\setminus(i,j)}^{-1} \mathbf{s}_{lk} \mathbf{s}_{lk}^T \mathbf{A}_{lk\setminus(i,j)}^{-1} - \beta_{lk} L_{ik}^2 \mathbf{A}_{lk\setminus(i,j)}^{-1}, \tag{14}$$

$$\mathbf{B}_{uv} \triangleq L_{iv}^2 \mathbf{A}_{uv\setminus(i,j)}^{-1} \mathbf{c}_{uv} \mathbf{c}_{uv}^T \mathbf{A}_{uv\setminus(i,j)}^{-1} - \beta_{uv} L_{iv}^2 \mathbf{A}_{uv\setminus(i,j)}^{-1}. \tag{15}$$

Now we propose a realizable suboptimum solution of the NP-hard problem $\mathbf{P2}$. Specifically, we first draw an L-dimensional uniformly distributed vector on the unit hypersphere $\mathbf{c}_{ij}^{(1)} \in \mathbb{R}^L$, $\|\mathbf{c}_{ij}^{(1)}\| = 1$. Then, conditioned on $\mathbf{c}_{ij}^{(1)}$, the transmission bit energy $E_i^{(1)}$ is optimized to make all constraints satisfied with at least one of SINR QoS and power budget constraints hold at equality. Repeat the above procedure P times, then we collect a sequence of feasible solution pairs $(E_i^{(p)}, \mathbf{c}_{ij}^{(p)}), p = 1, \ldots, P$. Among the feasible pairs, we choose the one with the maximum $E_i \mathbf{c}_{ij}^T \mathbf{A}_{\setminus(i,j)}^{-1} \mathbf{c}_{ij}$ objective function value. Our proposed scheme is summarized in Algorithm 1.

Algorithm 1 Cognitive Code-division Channelization.
Inputs: $SINR_{PU}^{th}, SINR_{SU}^{th} > 0$.

if $\beta_{lk} \geq 0, \forall (l,k) \in \mathcal{PU}$ and $\beta_{uv} \geq 0, \forall (u,v) \in \mathcal{SU} - \{(i,j)\}$ **then**
  for $p = 1, 2, \ldots, P$ **do**
    Draw $\mathbf{c}_{ij}^{(p)}$ from a uniform distribution over the unit hypersphere.
    Optimize $E_i^{(p)}$ such that $(E_i^{(p)}, \mathbf{c}_{ij}^{(p)})$ satisfies all constraints of $\mathbf{P3}$ with at least one of (8), (9), (10) hold at "=".
  end for
  $(E_i, \mathbf{c}_{ij}) \leftarrow (E_i^{(p)}, \mathbf{c}_{ij}^{(p)})$ with the maximum value of (7).
else
  No feasible solution by assigning $E_i \leftarrow 0$ and $\mathbf{c}_{ij} \leftarrow \mathbf{0}$
end if
Return the link design $(E_i, \mathbf{c}_{ij})$ as candidate for transmission.

VII. Performance Evaluation

In this section, we evaluate the performance of our proposed solution in a multi-hop cognitive radio network. We have developed an object-oriented packet-level discrete-event simulator, which models in detail all layers of the communication protocol stack, including routing, medium access control and spread-spectrum channelization as described in this paper.

A grid topology of 49 secondary nodes and 14 active primary links is deployed in a 5000 m $\times$ 5000 m area. The spreading code length is set to 16 for both primary and secondary users. Active primary links use pre-assigned code sequences as described in the previous section. We initiate CBR traffic sessions between randomly selected but disjoint source-destination pairs among the 49 nodes. Parameters θ_1 and θ_2 in (6) are set to 5 and 10, respectively. Rayleigh fading channel is used and the path loss exponent is set to four.

We compare the performance of our proposed solution, referred as BP-RCA, with SP-RCA, where routing is based on the shortest path with random code assignment. We vary the number of sessions injected into the network and plot the network throughput (sum of individual session throughputs). Figures 1 and 2 show the impact of the number of sessions injected into the network on the network throughput. The traffic load per session is set to 2 Mbit/s and 4 Mbit/s. As shown in both figures, BP-RCA achieves higher throughput than SP-RCA, since SP-RCA restricts packets forwarding to the receiver that is the closest to the destination, even if the

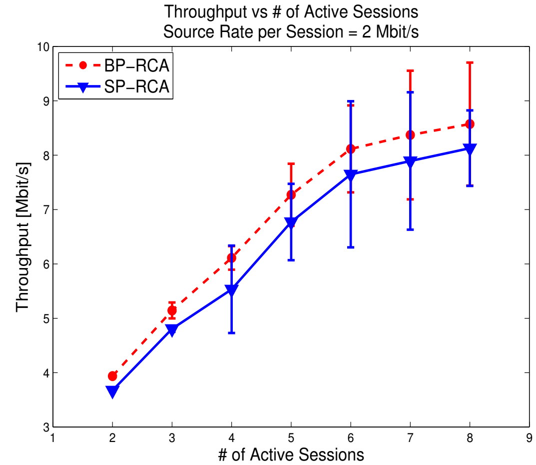

Fig. 1. Throughput vs. Number of Active Sessions.

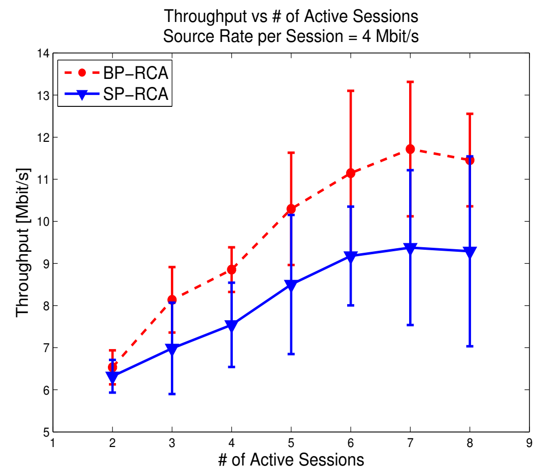

Fig. 2. Throughput vs. Number of Active Sessions.

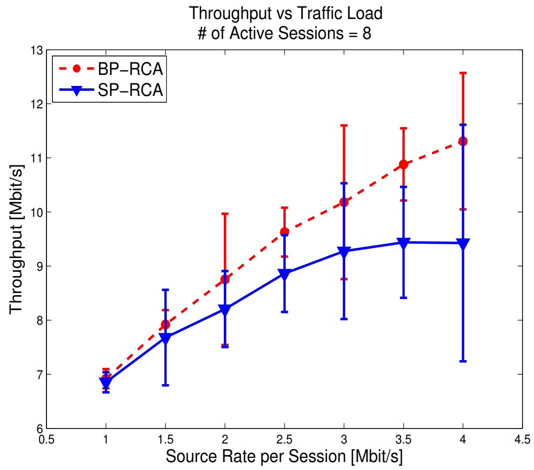

Fig. 3. Throughput vs. Traffic Load Sessions.

link capacity is very low or the receiver is heavily congested.

Figure 3 shows the impact of source data rate per session on the performance of throughput. We increase the traffic load per session from 1 Mbit/s to 4 Mbit/s. As shown in Fig. 3, the improvement obtained by BP-RCA is more visible when the traffic load increases.

VII. Conclusions

We studied and proposed a decentralized algorithm for joint dynamic routing and code-division channelization in cognitive radio ad hoc networks. We considered the general problem of maximizing the network throughput through joint routing and spread-spectrum channelization. We proposed an algorithm that can be seen as a distributed localized approximation of the throughput-maximizing policy. The proposed algorithm requires solution of a code-division channelization problem as the search for the secondary amplitude, code transmission pair that maximizes the secondary link output SINR subject to the condition that all primary signal output SINR values are maintained above a given SINR-QoS threshold value. The formulated constrained optimization problem is non-convex and NP-hard in the code vector dimension. Simulation results show that the proposed joint routing and spread-spectrum channelization.

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