Power-Optimized Cooperative Spectrum Sensing in Cognitive Radio Networks Using Bandit Processes

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***Abstract*—Power saving and management is a critical aspect of cooperative spectrum sensing in cognitive radio networks, in which a group of secondary cognitive radio nodes share the task of spectrum sensing in order to detect gaps in the spectral bands temporally or spatially not utilized by primary transceivers, facilitating dynamic allocation of physical layer and networking resources that finds application to emergency networks and the military, among others. We show how the problem of power-optimized cooperative spectrum sensing can be cast to a monotonic class of restless bandit processes and present analysis and computationally efficient solutions. Our numerical results verify the effectiveness of the proposed power-optimized spectrum sensing scheme.**

***Index Terms*—Cognitive radio networks, cooperative spectrum sensing, energy efficiency, network lifetime**

I. Introduction

The secondary spectrum access paradigm promises to significantly improve the utilization of the scarce radio spectrum. The enabling technology to realize such secondary spectrum access is cognitive radio (CR), envisioned by Mitola over a decade ago [1]. There has been extensive investigation of CR networks (CRNs) in the literature to date, ranging from theoretical performance bounds to more practical aspects of CRN deployment. Furthermore, several standardization efforts, including IEEE 802.22, are underway to facilitate commercial products [2].

Power constraints are a concern in CRNs. For instance, the task of spectrum sensing [10]—i.e., finding the best spectrum for communication in terms of interference, throughput, and fairness—is a very important module in making CRs feasible and certainly requires enough power at each CR node to run complex hardware and cope with high sampling rates, high resolution analog-to-digital converters (ADCs) with large dynamic range, and high speed signal processors [5].

Although power conservation has been extensively studied in the literature, most notably in the context of wireless sensor networks (WSNs), this topic seldom has been considered for CRNs. There are two major phases of power consumption by CRs that make the issue of power management in CRNs uniquely different from legacy systems such as cellular or sensor networks. First, the spectrum-sensing-and-decision making phase, including the required signaling and message passing to facilitate cooperative sensing, requires allocating portions of power to each CR. Second, the actual communication phase and, similar to the previous case, its associated signaling, will consume a considerable portion of a given CR's power.

Chen *et al.* [13] derived a general formula for the lifetime of WSNs and, accordingly, proposed a MAC protocol, relying on channel state information and residual energy information of individual users. In [9], aiming at investigating how CRs can be more energy efficient than conventional radios, the impact of various parameters on energy consumption in *ad hoc* wireless local area networks (WLANs) has been studied. Investigating the physical layer (e.g., modulation, coding, power amplification, and radiated power) for CR energy consumption reduction is studied in [11].

With respect to energy efficiency in wireless *ad hoc* CR spectrum access, Gao *et al.* [12] propose minimizing the energy consumption per bit over all selected subcarriers in an OFDMA system by solving a constrained optimization problem that considers desired data rate, maximal power, and interference limits.

One of the approaches toward energy efficiency, widely deployed in WSNs, is network synchronization and scheduling for duty-cycling (e.g., by Halkes *et al.* [7]), where some sensors are made non-active while others are active.

While there have been numerous resource allocation studies dealing with optimal transmission power management in CRNs [3], [4], there are very few works addressing the processing power consumption, which is essential in realizing CR communications. As mentioned above, of particular interest in our analysis are the power requirements associated with the task of CR spectrum sensing.

In this paper, we present a power-optimized scheme for collaborative spectrum sensing among a group of secondary CR nodes. We aim at achieving the optimal strategy for node scheduling in the MAC layer using a constrained optimization formulation, where the objective function is CRN lifetime and constraints relate to the power states and power transition probabilities of secondary CR nodes. We show how proper secondary CRs can be chosen to perform spectrum sensing in each time slot to maximize the CRN lifetime. Modeling the problem using a restless bandit representation allows us to develop structured results that provide useful insight into optimal operation of CRNs.

The remainder of this paper is organized as follows: problem formulation and the solution are addressed in Section II.

Section III contains the numerical results from simulations and Section IV concludes the paper.

II. Problem Statement

Consider a CRN setting where spectrum sensing is distributed among a group of secondary CR nodes.[1] There are n secondary CR nodes. In terms of available power, each node i can be in one of K states, namely, $\mathcal{S}_i = \{\mathfrak{P}_1^i, \ldots, \mathfrak{P}_K^i\}$. There is a set of transition probabilities $q^i(k,j)$ associated with each state $\mathfrak{P}_k^i \in \mathcal{S}_i$. No reward is associated with a node that is not active in a time slot, i.e., that is not performing any sensing task.

When a node is not assigned the spectrum sensing task, it can take this as an opportunity to replenish its power resources. This can be modeled using a monotonically non-decreasing function of time $f_k^i(t) \in [0,1]$. When the node is activated for sensing after t time slots, its power level has either evolved to $\mathfrak{P}_j^i \neq \mathfrak{P}_k^i$ with probability $q^i(k,j)f_k^i(t)$ or remained at the same level $\mathfrak{P}_k^i$ with probability $1 - \sum_{j \neq k} q^i(k,j)$.

In each time slot, activation of node i gives a reward r_k^i proportional to the amount of power available in that node. We can assume power level transitions for different secondary nodes to be independent of each other. Non-activity of a node implies no power reduction for that node, i.e.,

$$f_k^i(t) \leq f_k^i(t+1) \ \forall t.$$

Assuming that, at each time slot, one secondary CR is selected to perform the spectrum-sensing task, our goal is to find a policy to select nodes so that the infinite horizon time-average reward is maximized with power-level constraints in mind.

Next, we explain how the optimal policy can be deduced and what conditions reduce the computational complexity of this approach, making it more suitable for practical applications.

A. Solution

Using Whittle's linear program (LP) formulation approach [6]:

$$\text{Maximize} \sum_{i=1}^{n} \sum_{\mathfrak{P}_k^i \in \mathcal{S}_i} \sum_{t \geq 1} r_k^i x_{kt}^i, \tag{1}$$

subject to

$$\sum_{i=1}^{n} \sum_{\mathfrak{P}_k^i \in \mathcal{S}_i} \sum_{t \geq 1} x_{kt}^i \leq 1, \tag{2}$$

$$\sum_{k \in \mathcal{S}_i} \sum (x_{kt}^i + y_{kt}^i) \leq 1, \quad \forall i = 1, 2, \ldots, n, \tag{3}$$

$$x_{kt+1}^i + y_{kt+1}^i = y_{kt}^i, \quad \forall i, k \in \mathcal{S}_i, \tag{4}$$

$$\sum_{t \geq 2} x_{kt}^i + \sum_{\substack{j \in \mathcal{S}_i \\ j \neq k}} \sum_{t \geq 1} [(x_{jt}^i q^i(j,k) f_j^i(t) - x_{kt}^i q^i(k,j) f_k^i(t))] = y_{k1}^i, \ \forall i, k \in \mathcal{S}_i, \tag{5}$$

and

$$x_{kt}^i, y_{kt}^i \in [0,1], \quad \forall i, k \in \mathcal{S}_i, t \geq 1, \tag{6}$$

where x_{kt}^i and y_{kt}^i represent the probabilities that secondary node i with power level equal to $\mathfrak{P}_k$ is selected or not selected again after t time slots since the last time it did spectrum sensing.

Rewriting the above LP to remove dependency of the CRN lifetime upon y_{kt}^i variables [8] gives:

$$\text{Maximize} \sum_{i=1}^{n} \sum_{\mathfrak{P}_k^i \in \mathcal{S}_i} \sum_{t \geq 1} r_k^i x_{kt}^i, \tag{7}$$

subject to

$$\sum_{i=1}^{n} \sum_{\mathfrak{P}_k^i \in \mathcal{S}_i} \sum x_{kt}^i \leq 1, \tag{8}$$

$$\sum_{k \in \mathcal{S}_i} \sum (t x_{kt}^i) \leq 1, \quad \forall i, \tag{9}$$

$$\sum_{\substack{j \in \mathcal{S}_i \\ j \neq k}} \sum_{t \geq 1} x_{kt}^i q^i(k,j) f_k^i(t) = \sum_{\substack{j \in \mathcal{S}_i \\ j \neq k}} \sum_{t \geq 1} x_{jt}^i q^i(j,k) f_j^i(t), \tag{10}$$

and

$$x_{kt}^i \geq 0. \tag{11}$$

For brevity, power level $\mathfrak{P}_k^i$ is simply denoted by k in the above equations.

The above optimization problem is computationally not efficient. On the other hand, if the monotonically non-decreasing functions f_i are piece-wise linear, a poly-time solution can be achieved [8]. In other words, for secondary CRi and state $\mathfrak{P}_k \in \mathcal{S}_i$, if time slots are denoted by $\{t_1, t_2, \ldots, t_m\}$, then for two consecutive time slots $t_1 < t_2$ in the interval $t \in (t_1, t_2)$, the value of f_k^i is

$$f_k^i(t) = \frac{(t_2 - t_1) f_k^i(t_1) + (t - t_1) f_k^i(t_2)}{t_2 - t_1} \tag{12}$$

and $f_k^i(t) = f_k^i(t_m)$ for $t \geq t_m$.

This assumption can hold in CR systems for power resource replenishment, because first, if time slots are close enough, recharging for each node can be interpolated by a linear function given two consecutive values and, second, due to the fact that energy values of CR nodes at only discrete points in time are important.

By solving (7) using $f_k^i(t)$ as in (12), the selection of CR nodes in each time slot leads to optimized lifetime of the CRN with respect to available energy.

III. Analytical Results

We carried out simulations for the linear program presented in Section II. The power level transition probabilities $q(j,k)$ were generated randomly such that transition probabilities for each state to others including itself sum to unity. The piece-wise linear monotonically increasing escape functions $f_k^i(t)$ were generated by random slopes for every CR node at different time intervals.

[1]Notation in this section is based primarily on that found in [8].

At each time step, the most promising secondary CR, i.e., the one assumed to have the highest amount of power, was selected. The total lifetime of the CRN associated with the sum of the powers of chosen nodes was compared with a random selection scheme. The Monte–Carlo technique was used in all simulation scenarios.

The number of secondary CRs and sensing slots can represent an orthogonal frequency division multiple access or OFDMA-based CR system that decides how to sense the channel in consideration of the various types of primary users and physical properties of the OFDMA as investigated by Jeong *et al.* [14].

Figure 1 depicts the available power in each selected CR at every time slot using the proposed method and random selection for the total number of secondary nodes equal to 10 and total sensing time of 20 slots. As is evident in this figure, our method dominates the random method in the majority of time slots, resulting in greater total network lifetime.

Figures 2 and 3 show how our deployed scheme outperforms random selection of CR nodes in terms of total CRN lifetime, defined to be directly proportional to power levels of selected CRs. The total number of available secondary CRs was fixed to 30 in Figure 2, whereas in Figure 3 optimization was performed over 40 time slots.

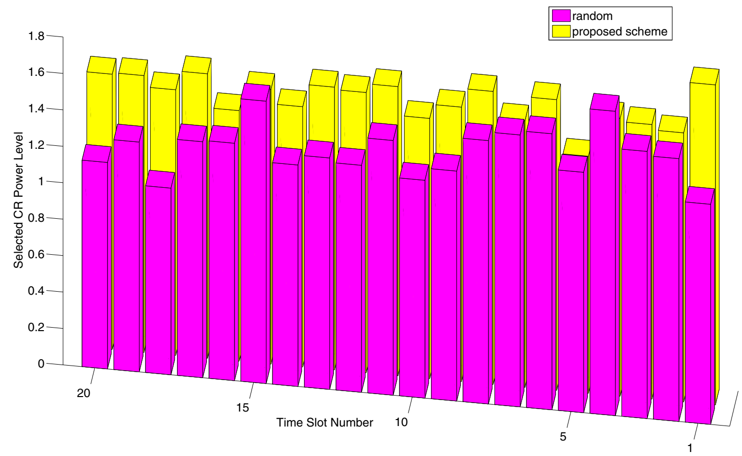

Fig. 1. Power-level comparisons for every single selected sensing CR using random and the proposed node selection methods.

IV. Conclusion

We addressed prolonging the lifetime of a CRN network for the case of shared spectrum sensing once at each time slot. By formulating the problem within the restless bandit processes, where the power level of resting CRs can change according to a monotonic function over time, we came up with an optimal policy for selecting CR nodes to undertake spectrum sensing in each time slot. To make it more suitable for real-time applications, the problem was solved in a less complex way by piece-wise-linear approximations for the pattern of changes in the energy level of nodes over discrete points in time. Simulation results verified the effectiveness of our technique in increasing total network lifetime. Though energy efficiency in spectrum sensing was specifically considered here, the same approach can be applied to similar CR and WSN problems.

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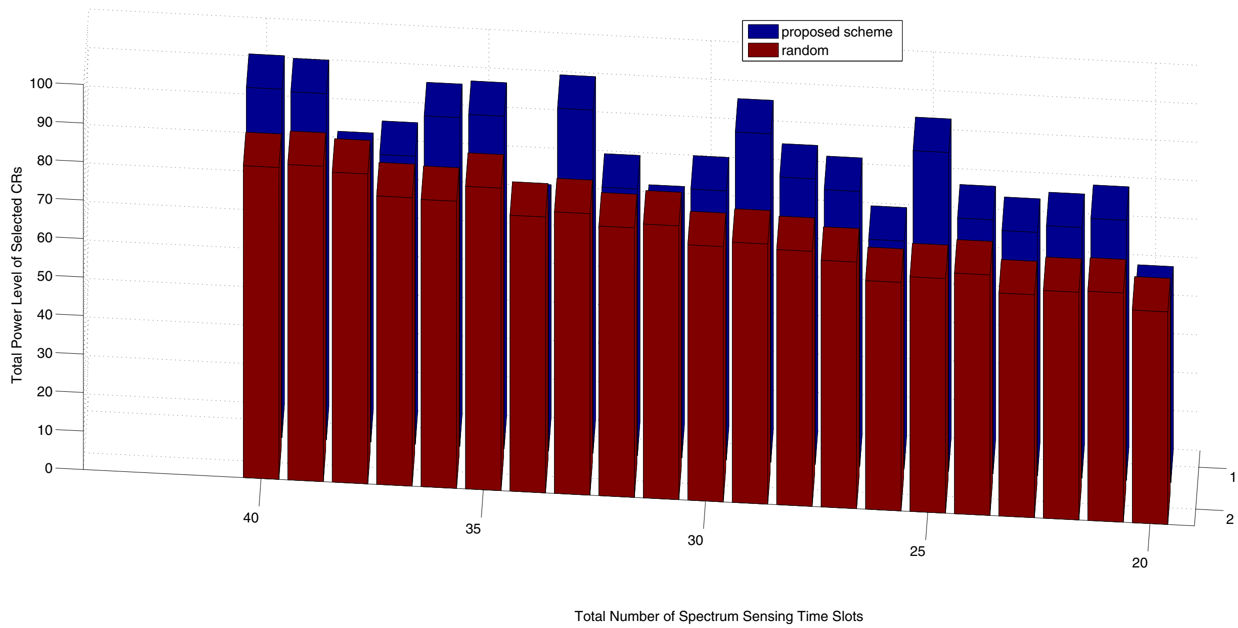

Fig. 2. Power-level comparison of the proposed sensing CR selection method with random selection for various numbers of total time slots.

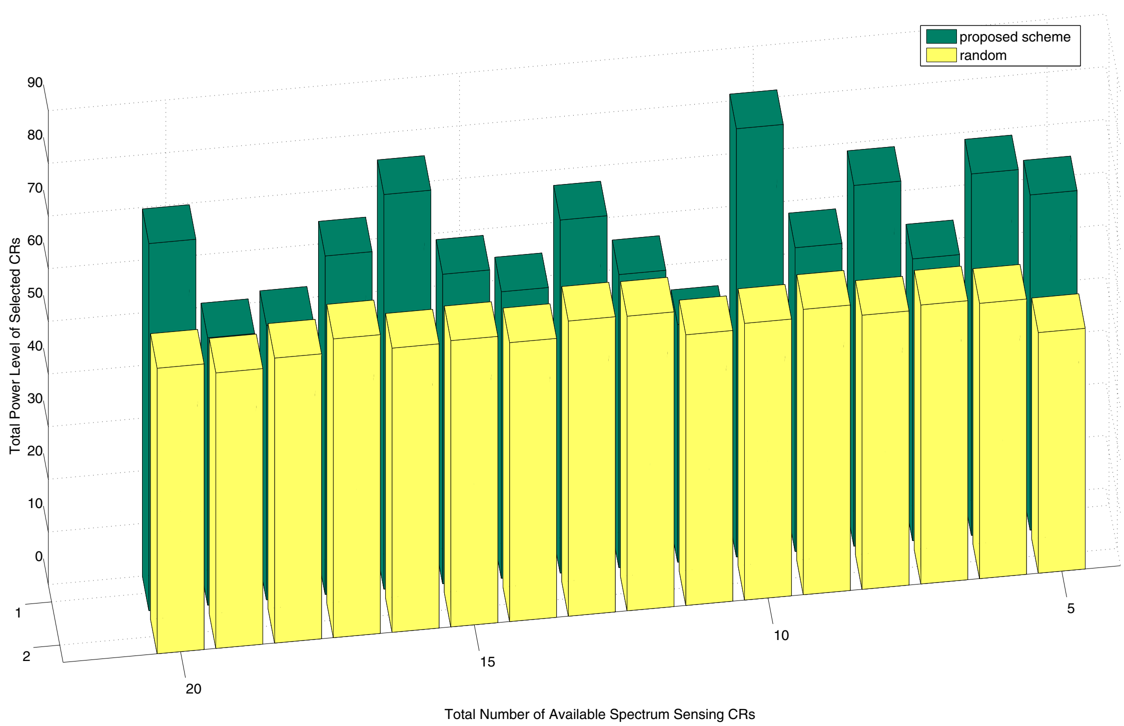

Fig. 3. Power-level comparison of the proposed sensing CR selection method with random selection for various numbers of available secondary CR nodes.