An Efficient Guard-band-aware Multi-channel Spectrum Sharing Mechanism for Dynamic Access Networks

Haythem Bany Salameh
Dept. of Telecomm. Eng.
Yarmouk Univ., Irbid, Jordan

Marwan Krunz
Dept. of Electrical and Computer Eng.
Univ. of Arizona, Tucson, AZ

Dave Manzi
Raytheon Corporation
Tucson, AZ

***Abstract*—Spectrum sharing algorithms for cognitive radio networks (CRNs) are often designed ignoring adjacent-channel interference (i.e., no interference from neighboring CR transmissions operating on adjacent channels). In practice, such an assumption is unrealistic as guard bands are needed to prevent adjacent-channel interference. Introducing guard bands naturally constrains the effective use of the spectrum. In this work, we investigate the problem of assigning channels/powers to CR transmissions, while accounting for such a constraint. Specifically, we propose a novel *guard-band-aware* channel assignment scheme for CRNs. Our scheme reduces the number of required guard channels for a given transmission by exploiting the benefits of utilizing adjacent channels while considering already reserved guard channels. We analytically formulate the channel access problem as a joint power control and channel assignment optimization problem, with the objective of minimizing the required spectrum resource for a CR transmission. Because the optimization problem is found to be a binary linear program (BLP), which in general is known to be NP-hard, we present a near-optimal solution based on a sequential fixing procedure, where the binary variables are determined iteratively by solving a sequence of linear programs. Simulation results are provided, which verify the accuracy of our algorithm and demonstrate the significant gain achieved through guard-band-aware channel assignment.**

I. INTRODUCTION

The tremendous growth of wireless applications and services is straining the effectiveness of conventional static spectrum planning policies. Recent field studies conducted by the FCC and other agencies revealed vast temporal and geographical variations in the utilization of the licensed spectrum, ranging from 15% to 85% [1]. Such studies prompted regulators to push for a more efficient and adaptive spectrum allocation policy. As a result, the FCC has recently revised its regulations to allow for opportunistic (on demand) access to the spectrum. Cognitive radio (CR) is a technology that promises to offer such an opportunistic capability without noticeably affecting *primary radio* (PR) users. CRs are mainly characterized by their cognitive capability and reconfigurability. The cognitive capability provides spectrum awareness, whereas reconfigurability enables a CR user to dynamically adapt its operating parameters to the surrounding RF environment. In an environment where several licensed PR networks (PRNs) are operating, CR users that co-exist with PR users should frequently sense their operating channels for active PR signals to discover spectrum opportunities, and should vacate these channels if a PR signal is detected. Given the available spectrum opportunities at different CR users, a crucial challenge in this domain is how nodes in a CRN can cooperate to access the spectrum in order to efficiently utilize those opportunities while improving network throughput.

Motivation: Various channel assignment algorithms for CRNs have been proposed in the literature (e.g., [2]–[6]). Most of them were designed assuming no adjacent-channel interference (ACI), thus requiring ideal transmission filters. In practice, however, spectrum spill-over is common during signal filtering. To mitigate ACI and protect neighboring PR/CR reception, frequency separation between adjacent channels is needed. Such separation is referred to as a *guard channel* (or band). The imposition of guard bands adds a constraint on the effective use of the spectrum. Therefore, when assigning channels/powers to CR transmissions, it is necessary to consider the guard-band issue to improve spectrum utilization. Note that guard bands are not needed between contiguous channels that are assigned to the same transmission (we refer to a *contiguously* assigned set of channels as a *frequency block*). For every frequency block, one guard channel on each side of the block is needed.

Another aspect of previously proposed channel assignment mechanisms is that they are typically based on selecting the "best" channel, or set of channels, for a given transmission (e.g., [6]). In here, the *best* channel is the one that has the highest received SINR. We refer to this approach as the *greedy approach*. When the greedy approach is employed in a CRN, the number of required guard channels may significantly increase. This results in a higher blocking probability for CR transmissions, leading to a significant reduction in network throughput. To illustrate, consider a transmission that requires m data channels. Assume that the best found m channels are all non-contiguous, and one guard channel on each side of each channel is available. According to the greedy approach, the total number of required channels (data-plus-guard) is $m+2m=3m$. In general, if the m selected data channels are obtained from k non-contiguous frequency blocks, then the required number of channels is $m+2k$. Hence, an efficient channel assignment algorithm should try to minimize k (ideally, selecting $k=1$), which would minimize the number of guard channels per data channel.

Contributions: In this work, we consider the joint power control and channel assignment problem in multi-channel CRNs under the realistic assumption of non-ideal filters (i.e., guard bands are needed). Our goal is to improve network throughput by attempting to maximize spectrum efficiency. This is equivalent to minimizing the number of required guard channels for a given transmission, which can be achieved through a proper guard-band-aware channel assignment scheme. Our scheme exploits the benefits of synchronized contiguous multi-channel transmission while considering local spectrum opportunities, the already assigned guard channels, and the non-adjacency of channels assigned to neighboring CR users. According to this scheme, a CR user that intends to transmit has to account for *potential* future transmissions in its neighborhood. It does that by assigning to its transmission the set of channels that requires the minimum number of guard bands and that satisfies the rate demand. We propose two variants of the guard-band-aware channel assignment mechanism. The first variant is suitable for CRNs with a transmission technology that does not allow two neighboring CR transmissions to share the same guard channel (no guard-band reuse), while the other variant is for CRNs with a transmission technology that allows for guard-band reuse.

Organization: The rest of the paper is organized as follows. In Section II, we describe the system model, state the main design constraints, and formulate the channel/power assignment optimization problem. Section III introduces our proposed guard-band-aware channel assignment scheme. Simulation results and discussion are presented in Section IV. Finally, Section V gives concluding remarks.

II. MODELS AND PROBLEM FORMULATION

A. Network Model

We consider an ad hoc CRN that coexists geographically with L different PRNs. PR users are legacy radios that cannot be controlled by the CRN. The PRNs are licensed to operate over non-overlapping channels. For the ith PRN, its available bandwidth (B_i) is divided into C_i adjacent but non-overlapping frequency channels, each of Fourier bandwidth W (in Hz). Let M denote the total number of channels in the network; $M = \sum_{i=1}^{L} C_i$. CR users continuously scan the spectrum, identifying potential spectrum holes and opportunistically exploiting them for their transmissions. For a given physical-layer encoding scheme, we assume that the data rate of an idle channel is proportional to the channel bandwidth [7]. Accordingly, a bandwidth model that delivers 1 bit per 1 Hz is considered if the received SINR is greater than a given threshold (μ^*) [7]. Formally, for an idle channel $i \in M$, its transmission rate (R_i) is obtained according to the following rate-SINR relationship:

$$R_i = \begin{cases} W \text{ Mbps}, & \text{if SINR}^{(i)} \geq \mu^* \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

where SINR$^{(i)}$ denotes the received SINR over channel i.

Depending on PR/CR activities, a CR transmission may proceed over multiple contiguous or non-contiguous idle channels to avoid harmful interference to PR/CR users. This synchronized multi-channel transmission capability can be realized by using frequency division multiplexing (FDM) or discontinuous-orthogonal FDM (D-OFDM) technology [3]–[5].

1) FDM-based CRNs: In this case, each CR user is equipped with n_t half-duplex transceivers, $1 \leq n_t \leq M$, that can be used simultaneously. A CR user can transmit over an arbitrary segment of the available bandwidth by using tunable raised-cosine pulse filters, such that each frequency block is transmitted using one of the available transceivers. When a raised-cosine filter is used, the required number of guard channels depends on the number of channels in a frequency block and the rolloff factor of the raised-cosine filter (β). This β is a measure of the excess bandwidth of the filter. Formally, for a CR transmission that uses a block of m adjacent channels, the excess bandwidth on each side of the frequency block is $\Delta f = mW\frac{\beta}{2}$. Thus, a necessary and sufficient condition to mitigate ACI using only one guard channel of bandwidth W on each side of a frequency block is $\Delta f \leq W$, implying $m \leq \frac{2}{\beta}$. For practical values of m, β, and W, the above condition often holds. For example, with $\beta = 0.1$ and $W = 3$ MHz, $m \leq 20$ channels (i.e., a data rate of up to 60 Mbps). Accordingly, it is reasonable to assume that a guard-band of bandwidth W on each side of a frequency block is sufficient to protect the reception over that block. This means that two guard channels are needed to separate any two distinct blocks assigned to neighboring transmissions. This represents the case where a guard channel that is reserved for a CR transmission cannot be reused (shared) by another CR transmission.

2) D-OFDM-based CRNs: Under D-OFDM, a CR transmission can simultaneously proceed over multiple channels (contiguous or non-contagious) using a single half-duplex radio, where each channel consists of a distinct block of the same number of contiguous sub-carriers [3], [4]. In essence, this capability can be achieved through power allocation by assigning 0 powers to all sub-carriers of non-assigned/busy channels. For a given CR transmission and a set of assigned channels, all sub-carries belonging to the selected channels will be used for that transmission [3], [4]. It has been shown that only the nearest sub-carriers of a neighboring frequency block that is assigned to another transmission can be considered as a major source of interference to any demodulated sub-carrier [8]. Therefore, to prevent ACI, it is sufficient to assign one guard channel between any two blocks that are allocated to two different co-located CR transmissions, irrespective of the size of their blocks [9]. This represents the case where a reserved guard channel for a given CR user can be reused by other CR users.

It is worth mentioning that the available channel set for CR transmissions depends on whether a guard-band reuse is possible or not. In this paper, we investigate the problem of channel/power allocation for both cases.

B. Design Constraints

For a given CR transmission, both the transmitter and receiver need to cooperatively select appropriate frequency channels and the transmission powers over these channels while meeting the following constraints:

1. *Half-duplex operation*: While transmitting, a CR user cannot receive/listen.
2. *Fixed rate per channel*: Each channel i can support a transmission rate W (in bps) if its received SINR is $\geq \mu^*$.
3. *Exclusive channel occupancy*: A selected data channel cannot be assigned to more than one transmission in the same neighborhood.
4. *Rate demand*: A CR transmission j has a rate demand $R_D(j) = m_j W$, where $m_j \leq M$ is the number of required data channels.
5. *Maximum transmit power*: For a CR transmission, the total transmit power (P_{tot}) over the selected channels is limited to $P_{\max}$.
6. *Guard-band reservation*: A guard channel cannot be used for CR data transmissions. As an example, in Figure 1, guard channels $\{1, 3, 5, 7, 9, 11, 14\}$ cannot be used for data transmissions.
7. *PR protection*: To protect PR receptions, an adjacent idle channel to a busy channel occupied by a PR user cannot be used for CR transmissions [10]. In Figure 1, channels $\{9, 11, 19\}$ cannot be used for CR transmissions. Note, however, these channels can be used as guard bands for CR transmissions.
8. *Guard-band reuse*: First, we consider the case where guard-band reuse in not allowed. In Section III-B2, we relax this constraint by considering the case of guard-band reuse.

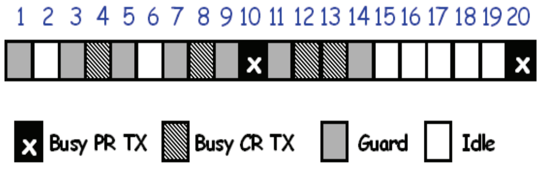


Fig. 1. Example that illustrates the impact of guard-band reuse.

C. Problem Statement and Formulation

It is well-known that the joint power control/channel assignment problem that aims at maximizing the overall network throughput in a multi-channel wireless packet network is a challenging optimization problem. In fact, even without considering the guard-band constraint, this problem is known to be NP-hard [11]. Worse yet, it requires perfect knowledge of the SINR at each CR receiver and the rate demands of all contending CR users. Hence, in this paper, we develop a suboptimal solution with low complexity and good spectrum utilization. Our scheme exploits guard-band awareness. The key idea behind it is to minimize the number of required guard channels for a given transmission while relying only on information provided by the two communicating users. If multiple solutions exist for our optimization problem, we seek the one that requires the least amount of total transmission power.

Let $\mathcal{I}_j$, $\mathcal{G}_j$, and $\mathcal{B}_j$ denote respectively the sets of idle, guard, and busy channels, as presently seen by the jth transmitter-receiver pair. Because our focus is on computing a feasible channel assignment $\Omega_j \subseteq \mathcal{I}_j$ for a given transmission j, the subscript j (i.e., the transmission index) is dropped in the rest of this paper to simplify the notation. Given the current status of all channels (i.e., $\mathcal{I}$, $\mathcal{G}$, and $\mathcal{B}$), the channel gain and measured interference over every channel $i \in \mathcal{I}$ along link j, the rate demand (m channels), and the SINR threshold μ^*, the receiver of the jth CR link can compute the minimum required power (P_i) for every idle channel $i \in \mathcal{I}$ such that the received SINR is $\geq \mu^*$. Using this fact, the channel assignment problem can be stated as follows:

$$\begin{aligned} \text{minimize}_{\{\Omega\}} & \left[k(\Omega) + \frac{P_{tot}(\Omega)}{P_{\max}}\right] \\ \text{s.t.} \quad & P_{tot}(\Omega) \overset{\text{def}}{=} \sum_{i\in\Omega} P_i \leq P_{\max} \\ & |\Omega| = m \end{aligned} \tag{2}$$

where k is the number of frequency blocks assigned to the jth link.

The second term in the objective function ensures that if multiple solutions exist for the problem in 2, the one with the least amount of total transmission power will be selected. Note that the first constraint in (2) ensures that $\frac{P_{tot}(\Omega)}{P_{\max}} \leq 1 \leq k(\Omega)$ for any feasible assignment Ω. So, for any two feasible assignment Ω_1 and Ω_2 with $k(\Omega_1) < k(\Omega_2)$, the above formulation will select Ω_1 over Ω_2, irrespective of P_{tot}.

For $i = 0, \ldots, M+1$, let α_i be a binary variable that is defined as follows:

$$\alpha_i = \begin{cases} 1, & \text{if channel } i \in \Omega \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

We let $\alpha_0 \overset{\text{def}}{=} \alpha_{M+1} \overset{\text{def}}{=} 0$. By introducing the binary variables α_i, the number of non-adjacent frequency blocks for a given assignment Ω (i.e., $k(\Omega)$) can be written as:

$$k(\Omega) = \frac{1}{2}\sum_{i=1}^{M+1}(\alpha_i - \alpha_{i-1})^2. \tag{4}$$

Substituting (4) into (2), the optimization problem becomes:

$$\begin{aligned} \text{minimize}_{\{\alpha_i\}} & \left[\frac{1}{2}\sum_{i=1}^{M+1}(\alpha_i - \alpha_{i-1})^2 + \sum_{i=1}^{M}\frac{P_i}{P_{\max}}\alpha_i\right] \\ \text{s.t.} \quad & \sum_{i=1}^{M}\alpha_i = m \\ & \sum_{i=1}^{M}\alpha_i P_i \leq P_{\max}. \end{aligned} \tag{5}$$

For any channel $i \notin \mathcal{I}$, α_i is set to 0 a priori. An unavailable channel can be either an already reserved channel (for a PR or another CR transmission) or a channel that is adjacent to a busy channel (i.e., a guard channel). Note that the optimization problem in (5) is a binary quadratic program (BQP).

Proposition: The optimization problem in (5) can be transformed into a BLP with a linear objective and linear constraints.

Proof: The BQP Formulation in (5) can be easily transformed into BLP by introducing a new auxiliary variable z_i, $i = 1, \ldots, M+1$:

$$z_i \overset{\text{def}}{=} \begin{cases} 0, & \text{if channels } i \text{ and } i-1 \text{ have the same status,} \\ 1, & \text{otherwise.} \end{cases} \tag{6}$$

and adding the following constraints on z_i:

$$\begin{cases} z_i \geq \alpha_i - \alpha_{i-1}, \\ z_i \geq \alpha_{i-1} - \alpha_i. \end{cases} \tag{7}$$

According to (7), if channels i and $i-1$ have the same status, then $z_i = 0$. Otherwise, z_i must be at the same time greater than or equal -1 and 1. Thus, it will be 1.

With the introduction of z_i, the quadratic term in the objective function in (5) can be changed to $\frac{1}{2}\sum_{i=1}^{M+1} z_i$. This results in the following (equivalent) formulation to the original BQP problem in (5):

$$\begin{aligned} \text{minimize}_{\{\alpha_i, z_i\}} & \left[\frac{1}{2}\sum_{i=1}^{M+1} z_i + \sum_{i=1}^{M}\frac{P_i}{P_{\max}}\alpha_i\right] \\ \text{s.t.} \quad & \sum_{i=1}^{M}\alpha_i = m \\ & \sum_{i=1}^{M}\alpha_i P_i \leq P_{\max} \\ & \alpha_i - \alpha_{i-1} - z_i \leq 0, i \in \{1, \ldots, M+1\} \\ & -\alpha_i + \alpha_{i-1} - z_i \leq 0, i \in \{1, \ldots, M+1\}. \end{aligned} \tag{8}$$

It is clear that the optimization problem in (8) is a BLP.

III. CHANNEL ASSIGNMENT SCHEMES

In this section, we first present a greedy guard-band-unaware assignment scheme, whose simplicity and low processing overhead make it attractive for use in multi-channel systems [6]. However, this scheme results in a high blocking probability for data transmissions, leading to a reduction in network throughput. Hence, we propose a novel guard-band-aware spectrum sharing algorithm to improve the throughput performance of the CRN.

A. Greedy Algorithm

The greedy approach proceeds as follows. Given $\mathcal{I}, \mathcal{G}, \mathcal{B}$, the channel gains, the measured interference over every channel $i \in \mathcal{I}$ along the given CR link, and μ^*, the algorithm calculates the required power $P_i, \forall i \in \mathcal{I}$. The algorithm then sorts the idle channels in an increasing order of their P_i. Finally, The algorithm picks the first m channels from the top of the sorted list. If the total transmission power over the best m channels exceeds $P_{\max}$, then there is no feasible channel assignment.

Lemma 1: For a given CR transmission with a rate demand, if the greedy solution is infeasible, then there is no feasible channel assignment that can support the given rate demand.

B. Suboptimal Algorithm Based on Sequential Fixing

A BLP is a combinatorial problem. Its solution is, in general, NP-hard. There exist several methods for approximately solving BLP problems, including cutting plane methods, decomposition methods, and branch-and-bound methods [12]. However, the worst-case time complexity of such approximations is still exponential. Instead, we develop polynomial-time suboptimal algorithm by exploiting the special structure of the problem. Specifically, if we relax the binary constraints $\alpha_i \in \{0, 1\}$ and $z_i \in \{0, 1\}$ into real numbers in $[0, 1]$, then the resulting *linear relaxation* (LR) is solvable in polynomial time [13]. The main idea behind our fast solution is to fix the values of α_i sequentially through solving a series of relaxed LP problems, with at least one α_i finalized to a binary value in each iteration. Our suboptimal algorithm is called *sequential fixing LP (SFLP)*. Two variants of the SFLP algorithm are proposed. The first variant is suitable for CRNs with a transmission technology that does not allow for guard-band sharing, whereas the second one is for CRNs with a transmission technology that allows for guard-band sharing.

1) SFLP-based Channel Assignment with No Guard-band Reuse: In the first iteration of the assignment scheme, we relax the binary constraints by allowing α_i's and z_i's to take real values in $[0, 1]$. For an unavailable (guard or busy) channel $i \notin \mathcal{I}$, we set $\alpha_i = 0$ (i.e., cannot be assigned to a new CR transmission). We also set $\alpha_i = 0$ for any idle channel that is adjacent to a busy channel occupied by a PR user or to an already allocated guard channel. We refer to the resulting formulation as $\text{LR}^{(1)}$, which must have a feasible solution if the original BLP has a feasible solution (i.e., if $\text{LR}^{(1)}$ problem is infeasible, then there is no feasible assignment). The solution to $\text{LR}^{(1)}$ provides a lower bound on the optimal solution to (8), because the feasibility region of the BLP is a subset of that of $\text{LR}^{(1)}$. However, the solution of $\text{LR}^{(1)}$ is, in general, not a feasible solution to the original BLP problem, because α_i's and z_i's can now take values between 0 and 1. Among all newly obtained real-valued α_i's, we then set the one that has the largest value to 1. Then, at iteration $i, i = 2, \dots m$, the algorithm proceeds as follows:

i. The algorithm relaxes all unfixed α_i's and all z_i's to real values in $[0, 1]$.

ii. The algorithm checks the feasibility region of the new LR, called $\text{LR}^{(i)}$. If this region is empty, this means the fixing in the $(i-1)$th iteration was not correct. Thus, we flip the value of the last fixed variable to 0 and update $\text{LR}^{(i)}$. Note that the revised $\text{LR}^{(i)}$ problem must be feasible (see Lemma 3).

iii. The algorithm solves the resulting LR program ($\text{LR}^{(i)}$), whose variables do not include those that have been fixed after the execution of $\text{LR}^{(i-1)}$.

iv. The algorithm chooses the largest α_i and fix it to 1.

v. The process is repeated until a total of m α_i's are set to 1 (feasible assignment) or all α_i's are fixed and no feasible channel assignment can be found.

2) SFLP-based Channel Assignment with Guard-band Reuse: Now, we consider the case in which guard-band reuse is allowed. Recall that, to improve spectrum efficiency, the number of introduced guard channels should be minimized. When guard-band sharing is not allowed, minimizing the number of frequency blocks is equivalent to minimizing the number of newly introduced guard channels. However, when guard-band reuse is allowed, the number of introduced guard channels is minimized by attempting to reuse existing guard channels (introduce no new guard channels) and at the same time minimize the number of frequency blocks required for a given transmission. To achieve 100% efficiency in the guard-band overhead, we should select frequency blocks that do not introduce additional guard channels (i.e., already has a guard channel on each side and can reuse it). To illustrate, consider the channel status table in Figure 1. Suppose that a prospective CR transmission requires 2 data channels. Assume that any possible combination of two idle channels is power-feasible (i.e., $P_{tot} \leq P_{\max}$). Also assume that channels 16 and 17 require the minimum P_{tot} among all possible combinations of two adjacent channels. According to the SFLP algorithm proposed in Section III-B1, channels 16 and 17 will be selected. This assignment introduces 2 additional guard channels (50% spectrum efficiency). However, when guard-band reuse is allowed, by selecting channels 2 and 6, no additional guard channels will be introduced, leading to 100% spectrum efficiency. We now modify the SFLP algorithm to incorporate the feasibility of guard-band reuse.

In the first iteration, we relax the binary constraints by allowing α_i's and z_i's to take real values in $[0, 1]$. For a busy channel $i \in \mathcal{B}$ (occupied by PR or CR user), we set $\alpha_i = 0$. We also set $\alpha_i = 0$ for all channels that are adjacent to a busy channel occupied by a PR user. For a guard channel $i \in \mathcal{G}$, we set $\alpha_i = 1$. By setting $\alpha_i = 1, \forall i \in \mathcal{G}$, our algorithm will prefer frequency blocks that already have guard channels reserved by neighboring transmissions. Note that because $\alpha_i, \forall i \in \mathcal{G}$ is set to 1, the constraint on the number of selected channels in the original BLP (i.e., $\sum_{i=1}^{M} \alpha_i = m$) should be updated as follow: $\sum_{i=1}^{M} \alpha_i = m + |\mathcal{G}|$. We refer to the resulting formulation as $\text{LR}^{(1)}$, which must have a feasible solution if the modified BLP has a feasible solution. Among all α_i's of the optimal solution of $\text{LR}^{(1)}$, we set the one that has the largest value to 1. Then, for the subsequent iterations ($i = 2, \dots m$), the same algorithm used for SFLP with no guard-band reuse is used to compute a feasible channel/power assignment. In the rest of this paper, we refer to the channel assignment mechanism that uses the original (modified) SFLP algorithm as SFLP (SFLP-GR).

Lemma 2: If the greedy solution in Section III-A is feasible, then the original BLP and the corresponding LR (i.e., $\text{LR}^{(1)}$) have feasible solutions (see [14] for the proof).

Lemma 3: The updated $\text{LR}^{(i)}$ problem in Step (ii) must be feasible (refer to our technical report [14] for the proof).

Theorem 1: The SFLP algorithm can determine a feasible or no feasible solution in no more than $\max\{m, |\mathcal{I}|\}$ iterations (see [14] for the proof).

Based on Theorem 1, it is easy to show that the time complexity of the proposed SFLP algorithm is bounded by the complexity of the LR solver times $\max\{m, |\mathcal{I}|\}$. Because an LR solver (LP solver) has a polynomial complexity, the complexity of our sequential fixing algorithm is also polynomial. Our simulations show that in most cases our algorithm requires m iterations to find a feasible assignment. In addition, the performance gap between the SFLP and the optimal solution (obtained through an exhausted search) is shown to be very small (below 5%), and in most cases it is zero. We also provide a lower bound on the optimal BLP solution, which is the solution to $\text{LR}^{(1)}$ in the first iteration. Our simulations show that this bound is typically loose.

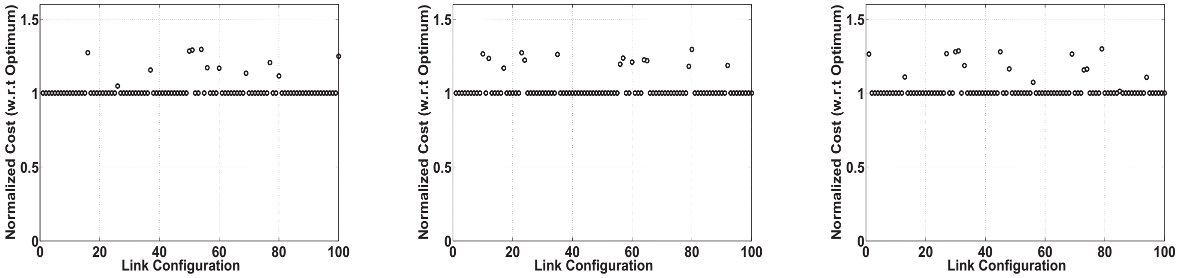
IV. PERFORMANCE EVALUATION

A. Simulation Setup

We consider N CR links in a 100 meter × 100 meter area. We assume that there are $M = 21$ channels, each licensed to one PRN. CR users can opportunistically access the 21 channels. Each channel has 1 MHz of bandwidth. The carrier frequency of the ith PRN is $f_i = 900 + i$ MHz, for $i = 1, \dots M$. We set μ^* to 0.63 for all channels. The status of a PR signal is modeled as a 2-state Markov model that alternates between IDLE and BUSY states. A BUSY (IDLE) state indicates that some (no) PR user is transmitting over the given channel. For channel i, denote the average IDLE and BUSY durations of the PR signal by λ_i and μ_i, respectively. At a given time, the ith PR channel is busy with probability $P_B^{(i)} = \frac{\lambda_i}{\lambda_i + \mu_i}$. We set $\mu_i = 100$ ms and $\lambda_i = \lambda, \forall i \in \{1, \dots, M\}$. Accordingly, $P_B^{(i)} = P_B, \forall i$. We consider a Rayleigh fading model to describe the channel gain between any two users. We set $P_{\max}$ to 1 W and the thermal noise power density to 10^{-21} W/Hz for all channels.

B. Results

1) Link-level Simulations: First, we use MATLAB simulations to empirically verify the validity of our SFLP algorithm and highlight its advantages. We consider a single CR link, and investigate the performance of the SFLP algorithm as a function of various system parameters. The simulation results are presented for 100 "link configurations" (i.e., optimization



(a) Low activity ($P_B = 0.1$, average = 1.0287, variance = 0.0059)

(b) Moderate activity ($P_B = 0.4$, average = 1.0425, variance = 0.0074)

(c) High activity ($P_B = 0.7$, average = 1.0291, variance = 0.0052)

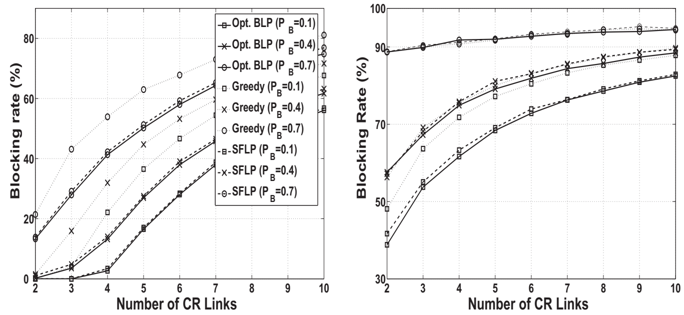
Fig. 2. Normalized cost of the SFLP solution relative to the optimal solution ($m = 4$).

instances) that can produce feasible solutions. For each configuration, the source-destination distance is randomly generated, the fading process $\xi^{(i)}$ is exponentially distributed $\forall i$, and the status of a PR channel is determined according to the 2-state Markov model described before. The SFLP algorithm is used to determine the channel assignment and cost function (number of frequency blocks plus the normalized total transmit power). We compare these results with the lower bound (the solution for LR$^{(1)}$), the optimal solution, and the greedy solution.

For $m = 4$ and for three different values of P_B (0.1, 0.4, and 0.7), Figure 2 shows the normalized cost of the SFLP algorithm, relative to the optimal cost obtained through exhaustive search for 100 link configurations. In most cases, the SFLP solution is identical to the optimal solution. Other results (shown in [14]) indicate that for various settings of the design parameters, the mean and variance of the normalized cost are ≤ 1.04 and ≤ 0.007, respectively. Hence, the SFLP algorithm achieves a near-optimal solution.

2) Network-level Simulations: To study the performance in a multi-user environment, we conduct simulation experiments using CSIM (a C-based discrete-event simulation package [15]). We use the same simulation setup described in Section IV-A, but we vary N. To resolve channel contention between CR pairs, in our simulations, we adopt the CSMA/CA-based CRN MAC protocol proposed in [6]. This protocol uses contention-based handshaking, whose objectives are: (1) conducting and announcing the channel assignment, (2) prompting the transmitter and the receiver to tune to the agreed on channels before transmission commences, and (3) ensuring non-overlapping local channel occupancy between CR users. Each CR sender generates 2-KB data packets and requires m data channels. The time is divided into slots, each corresponding to the transmission of one packet at a rate of m Mbps. We assume that there is always a packet to transmit for each CR user. The locations of the CR transmitters and receivers are randomly assigned within the simulation region. In any given slot, the PR activity over a given channel is determined according to the 2-states Markov model described earlier. Our performance metrics include: (1) network throughput, (2) CR blocking rate, and (3) average energy consumption for successfully transmitting one data packet (E_p). The CR blocking rate is defined as the percentage of packets that are blocked due to the unavailability of a feasible channel assignment. Our results are based on the average of 25 randomly generated topologies, with a simulation time of 10000 time slots for each topology.

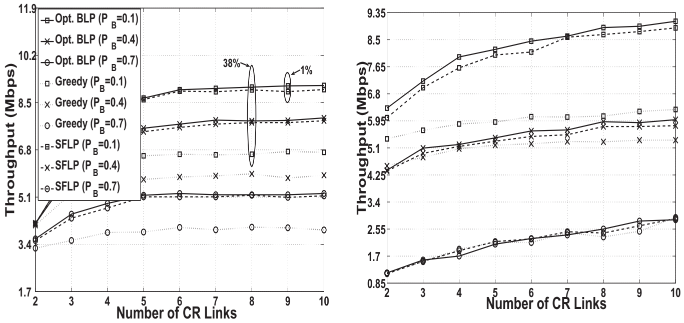
Channel Assignment with No Guard-band Reuse: We first simulate a CRN where no guard-band reuse is allowed. Our SFLP scheme is compared with two other channel assignment schemes: an optimal scheme (uses exhaustive search) and the greedy scheme. We study the throughput performance as a function of N, m, and P_B. Figures 3 and 4 show that the SFLP algorithm significantly reduces the packet blocking rate and improves the overall throughput by up to 38% compared with the greedy approach for various settings of the design parameters. In all cases, the SFLP solution is within 5% of the optimal one. Figure 4 reveals that the throughput gain of SFLP over the greedy approach is smaller at larger P_B. This is expected since the larger the value of P_B, the lower the chances of finding contiguous channels. This increases the number of required guard channels, and consequently reduces the throughput gain. Note that for large values of m and P_B, all schemes achieve comparable throughput performance. In Figure 5, we investigate the impact of various channel assignment strategies on E_p (the performance in terms of E_p under SFLP is comparable to the one for the optimal solution. Thus, for clarity, Figure 5 does not show the E_p of SFLP). It is clear that



(a) $m = 2$

(b) $m = 5$

Fig. 3. Blocking rate vs. N for different P_B (without guard-band reuse).

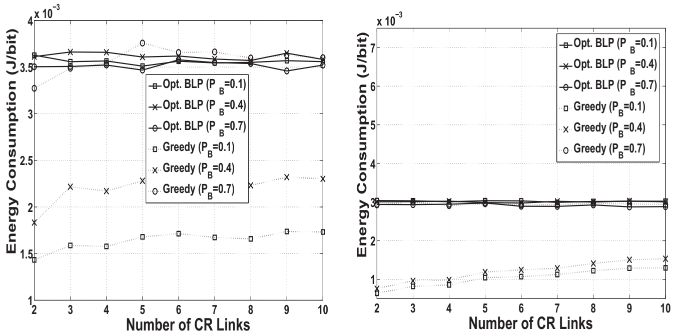


(a) $m = 2$

(b) $m = 5$

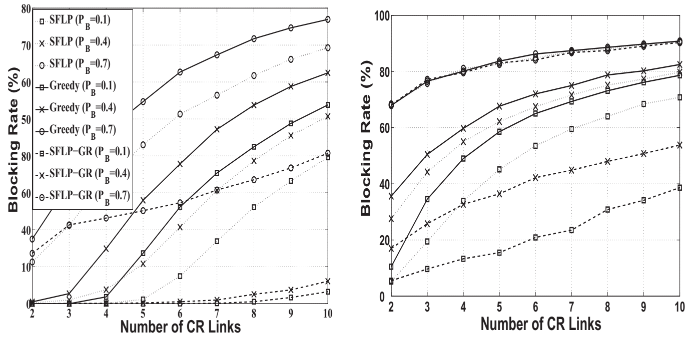
Fig. 4. Network throughput vs. N for different values of P_B and m.

the greedy approach performs better in terms of E_p (because the greedy approach always selects channels of high qualities). Thus, the throughput advantage of SFLP comes at the expense of additional energy consumption.



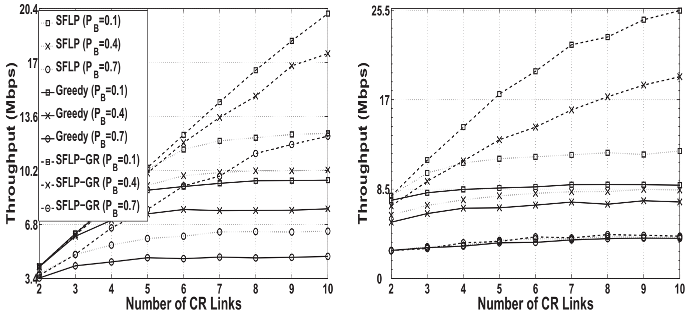
(a) $m = 2$ (b) $m = 5$

Fig. 5. Energy consumption vs. N for different values of P_B and m.



(a) $m = 2$ (b) $m = 4$

Fig. 6. Blocking rate vs. N.



(a) $m = 2$ (b) $m = 4$

Fig. 7. Throughput vs. N (similar behavior for other m was observed).

Channel Assignment with Guard-band Reuse: We now consider a CRN where guard-band reuse is allowed. Our proposed scheme (SFLP-GR) is compared with two other assignment schemes: the original SFLP (which tries to minimize the number of frequency blocks) and the greedy scheme. We adapt the operation of both schemes such that a guard channel can be reused (i.e., an idle channel that is adjacent to an already assigned guard channel can be used for CR data transmissions). We first study the throughput performance. Figures 6-7 show that SFLP-GR significantly outperforms the other schemes. SFLP-GR reduces the CR blocking rate and improves the overall throughput by up to 180% compared with the greedy approach and 110% compared with the SFLP algorithm. This improvement is mostly attributed to the proper channel assignment, which attempts to reuse already allocated guard channels. Consequently, our scheme preserves more channels for future CR transmissions, leading to an increase in the number of simultaneous transmissions. Similar to the case of no guard-band reuse, we observe that the achieved throughput is smaller at larger values of P_B and m. Finally, similar trends in terms of E_p to the no guard-band reuse case are observed.

V. CONCLUSIONS

In this paper, we proposed an opportunistic guard-band-aware channel assignment for CRNs. Our scheme improves the CRN throughput through cooperative channel assignment, taking into consideration the guard-band constraint. The proposed channel assignment mechanism reduces the number of required guard channels for a given transmission by assigning adjacent channels as much as possible to that transmission, which significantly improves spectrum efficiency and network throughput. We first formulated the channel access as a joint power control and channel assignment optimization problem, with the objective of minimizing the required spectrum for a given transmission. We showed that this problem can be formulated as a BLP. Because of its non-polynomial time complexity, we presented a near-optimal algorithm to solve this problem based on a sequential fixing procedure, where the binary variables are determined iteratively by solving a sequence of LPs. Simulation results verified the accuracy of our algorithm. We compared the performance of our scheme with that of a reference (greedy) scheme. We showed that our scheme achieves up to a 180% increase in throughput over the greedy scheme, with manageable processing overhead.

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