# Link Scheduling and Channel Assignment in Multi-channel Cognitive Radio Networks: Spectrum Underlay Approach

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***Abstract*—In this paper, we investigate the performance of multi-channel cognitive radio networks (CRNs) by taking into consideration the problem of channel assignment and link scheduling. We assume that secondary nodes are equipped with multiple radios and can switch among multiple channels. How to allocate channels to links and how much power used on each channel to avoid mutual interference among secondary links are the key problem for such CRNs. We formulate the problem of channel assignment and link scheduling as a combinatorial optimization problem. Then, we propose a the optimal solution and show that it converges to maximum optimum in some iterations by using numerical results.**

## I. Introduction

Recently, cognitive radio [1] has been realized to be novel communication paradigm which can relax spectrum scarcity. Each node in CRNs is considered the smart wireless node which can switch and work on a different set of available frequency bands without being limited by the number of radio interfaces. The major issue of CRNs is how to effectively assign channels to links and allocate power per channel to improve spectral efficiency and obtain high overall throughput. Moreover, secondary links must align its interference to PU-Rx at acceptable target.

In CRNs, the spectrum opportunity of each link is expressed as the link capacity which they can achieve on channel assigned minus the cost they must pay to use that channel. To get high spectrum opportunity, links need performing channel assignment strategies and power control policy. More importantly, secondary links must cooperate together to achieve the totally perfect scheduling. In the literature, there are some studies of resource allocation for such CRNs. Shi [2] and [3] formulated the optimization problem of power and routing using the bandwidth-footprint-product (BFP) as an objective metric, aiming to minimize the interference footprint area on each channel. Thereby, the secondary nodes transmitting on the same bandwidth with suitable power levels which may not make interference to each other. A channel is allowed to use only if the secondary node senses that band idle and is not in the other node's interference range. Consequently, their proposed algorithms must keep track of the set of nodes fall in the transmission range and the set of nodes that can produce interference whenever the transmit power is changed at each node. Such solutions make the implementation of the local search algorithm [2] and the distributed optimization algorithm [3] become more complicated and unscalable.

In underlay fashion of spectrum sharing, secondary users's transmssion can make harmful interference to PU's reception. Most existing works [3], [4], and [5] applied Listen-Before-Talk (LBT) technique to detect the presence or absence of primary signals before channel access in order to avoid interfering with primary users (PU). However, the authors does not take the aggregate interference from multiple potential SUs's transmission into account at PU receivers. There will be no transmission from SUs while a PU system operating under full load can tolerate more interference. To address this shortcomings, we propose a optimization framework for link scheduling and spectrum assignment which mutual interference among secondary users are relaxed by protocol interference model while aggregate interference caused by them to primary links is limited below a acceptable threhold. Our objective is to allocate the less power to links close to PUs. Then, we seek a combination of link-band which their total weight is maximum.

## II. System Model and Problem Formulation

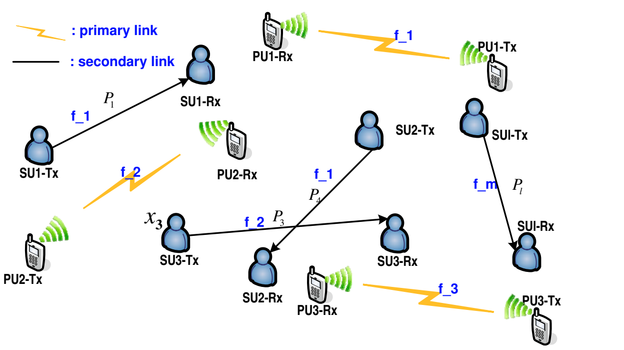


Fig. 1: Co-existence of SUs and PUs in CRNs

We consider MHCRNs modeled by the set of secondary links $\mathcal{L}$ as illustrated in Fig. 1. We assume that the whole spectrum is divided into a set of orthogonal frequency channels

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$\mathcal{M}$, each of which with bandwidth $W$ is correspondingly licensed to one pair of PUs. Since the licensed channels are under-utilized by the corresponding PUs, secondary nodes can simultaneously transmit with PUs providing that the total interferences caused by them to PU-receivers are below the tolerable thresholds. However, for each licensed channel, the attainable capacity of each secondary link is totally different. We assume that pairs of PUs are are the mobile devices, hence spectrum opportunity for one SU on channel $m$ is varying in time depending on both its power and their behavior of the other SUs as follows:

$$O_l^m(\nu^m, h_l^m, P_l^m) = \log(1+\gamma_l^m P_l^m) - \nu^m P_l^m \|h_{l0}^m\|^2, \forall l, m. \quad (1)$$

where $P_l^m$ is the power which the link $l$ use to transmit its data on the channel $m$ at spectrum price $\nu^m$. $\gamma_l^m = K\frac{\|h_{ll}^m\|^2}{\eta_0+\|h_{l0}^m\|^2 P_0^m}$ is channel gain-to-interference ratio (CIR) of link $l$ on the channel $m$ and $h_{lk}^m$ is the channel gain between node $l$ and node $k$ on the channel $m$, generally. We use the special notation 0 to index the primary users (e.g, $P_0^m$ is the transmit power of PU-Tx $m$). Here constant $K = -\phi_1/\log(\phi_2 BER)$, where $\phi_1$ and $\phi_2$ are constants depending on the modulation method, coding scheme and bit-error rate (BER) [6].

To maintain its quality of service (QoS), the PU-Rx $m$ would require its interference level to stay below a certain threshold, denoted by $I_{th}^m$. Accordingly, the spectrum price $\nu^m, \forall m$ is set on the basis of balance between spectrum demand from SUs (i.e., $\sum_l \sum_m a_l^m P_l^m \|h_{l0}^m\|^2$) and the spectrum budget of the $m$th channel at each time slot. This constraints can be written as

$$\nu^m = C_m + \sum_{l=1}^{L}\sum_{m=1}^{M} a_l^m P_l^m \|h_{l0}^m\|^2 - I_{th}^m. \quad (2)$$

where $C_m$ is the flat price which pairs of SUs must pay whenever they join in cognitive radio networks. $\mathbf{a}_l = [a_l^1, a_l^2, ..., a_l^M]$ are the channel allocation indicator vector.

### A. Problem Formulation

Our objective is to maximize the overall throughput of SUs. The link scheduling and spectrum assignment problem with primary protection is mathematically expressed as following.

$$(\mathbf{P1}) \quad \max_{\mathbf{a},\mathbf{P}\geq 0} \sum_{l}^{L}\sum_{m}^{M} a_l^m O_l^m(\nu^m, h_l^m, P_l^m)$$

subject to

$$\sum_{l}^{L} a_l^m \leq 1, \quad \forall m, \quad (3)$$

$$\sum_{m}^{M} a_l^m P_l^m \leq P_l^{max}, \quad \forall l, \quad (4)$$

$$a_l^m \in \{0,1\} \quad \forall m, l. \quad (5)$$

The constraint in (4) states that each channel can only be assigned to at most one link. (4) is the upper bound of transmit power on each secondary link.

## III. Optimal Solution and Distributed Algorithm

The appearance of the binary variables $a_l^m$ to choose channel and the continuous variables $P_l^m$ force the optimization problem $\mathbf{P1}$ to belong to the class of Mixed Integer Nonlinear Programming (MINLP) [7]. The optimal solution is known to be NP-hard.

### A. Optimal Solution

Since $O_l^m(\nu^m, h_l^m, P_l^m)$ is convex in $\boldsymbol{P}$, its first gradient is given by:

$$\frac{\partial O_l^m(\nu^m, h_l^m, P_l^m)}{\partial P_l^m} = \frac{\gamma_l^m}{1+\gamma_l^m P_l^m} - \nu^m \|h_{l0}^m\|^2. \quad (6)$$

By letting the first gradient $\frac{\partial O_l^m(\nu^m, h_l^m, P_l^m)}{\partial P_l^m}$ equals zero, we can obtain the optimal power for each link per channel by Karush-Kuhn-Tucker (KKT) conditions [7] as follows:

$$P_l^{m,(*)} = \min\Big\{ \max\Big\{\frac{1}{\nu_m \|h_{l0}^m\|^2} - \frac{1}{\gamma_l^m}, 0\Big\}, P_l^{max}\Big\} \quad (7)$$

We assume that the cognitive radio networks are a time-slotted networks, where the length of each slot is denoted by T. We also assume that the channels are constant for each time slot (i.e., block fading). Hence, at each time slot, spectrum opportunity will be maximum if the spectrum prices $\nu^m$ reach the flat price at the optimal powers $P_l^{m,(*)}$. This means

$$\nu^{m,(*)} = C \quad (8)$$

Then, the optimization problem $\mathbf{P1}$ is to schedule the link-band pairs satisfying (3) so that their total weight is maximum. In this paper, we use using Hungarian method [8] to solve Maximum Weighted Bipartite Matching problem on an $L \times M$ bipartite graph between L links and M channels where the weight of the edge is $O_l^m$.

### B. Numerical Results.

We consider a CRNs with 5 secondary nodes, 2 pairs of PUs randomly placed in area of $5m \times 5m$ and 4 flows. Each secondary link with a maximum transmit power of 26dBm can access both the licensed channels, baseband bandwidth of each is $125KHz$. For PUs, we require interference thresholds for the licensed band 1 and 2 are $4.4mW$, $72mW$, and $2.3mW$, respectively. Fig. 2 shows the interference powers caused by the secondary system converge to the target thresholds allowed by PU system. Fig. 3 illustrated the aggregated utility which is the sum of all spectrum opportunities. Hence, we can claim that our solution can converge to the optimum and can exploit the under-utilized spectrum of primary system.

## IV. Conclusion

In this paper, we proposed a novel scheme of link scheduling and channel assignment for cognitive radio networks considering the co-existence of the licensed and unlicensed users in underlay fashion. The resulting optimization problem can be optimally solved by KKT conditions and Hungarian method. The numerical results show our solution can reach the optimum in some iterations.

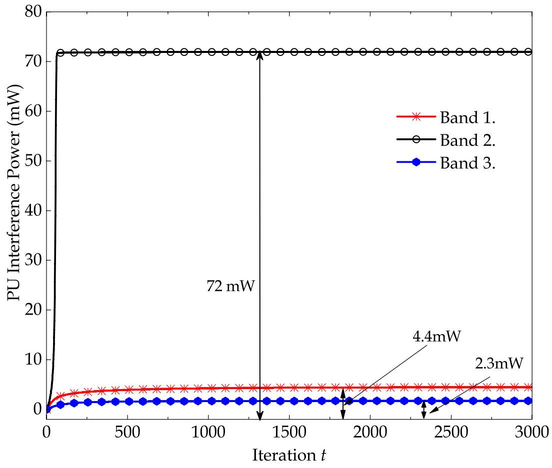


Fig. 2: Convergence of PU interference powers at BER $= 10^{-5}$.

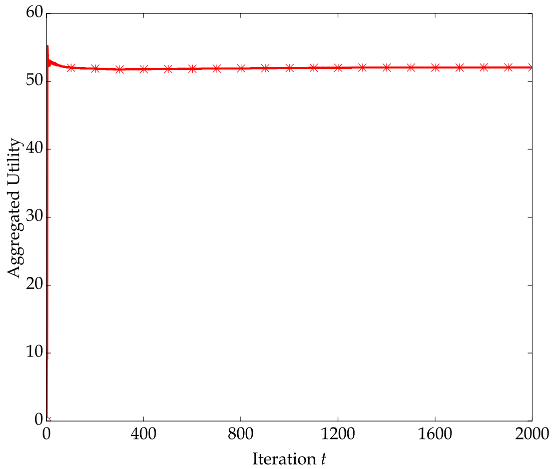


Fig. 3: Aggregated Utility of Algorithm

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