Wideband PHY/MAC Bandwidth Aggregation Optimization For Cognitive Radios

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***Abstract*—Unlike conventional radios, cognitive radios are to use channel occupancy information measured at the PHY layer and conveyed to the MAC layer to select suitable frequency bands to communicate. Many existing PHY/MAC decision-making strategies, however, assume that the cognitive radio belongs to a particular radio network and its communication capabilities are limited to the protocols supported by that radio network. In this paper, we propose a cognitive radio PHY/MAC decision-making strategy that may simultaneously utilize multiple radio networks across a wide spectrum band. The whole spectrum range is assumed to be divided into several sub-bands in performing spectrum sensing. Each of the sub-bands may have an arbitrary bandwidth, depending on the spectrum sensing capability of the cognitive radio. In this paper, we derive an optimal *wideband* bandwidth aggregation (BAG) strategy for the energy and frequency efficient communication problem: a multi-objective optimization problem is formulated, one objective is the communication throughput of the mobile cognitive radio device and the other one is energy consumption of the device. The proposed multi-objective optimization problem takes into account the essential practical issues including imperfect spectrum sensing, time varying channel coefficients, hardware reconfiguration time delay, hardware reconfiguration power consumptions, and communication power consumptions. The optimal BAG strategy is solved using a combination of the *Hungarian* algorithm and convex optimization. In this paper, we show that by self-adjusting the weighting coefficients of two objectives, the cognitive radio may achieve autonomous operation. The formulation can also be easily extended to multi-objective problems that have more than two objectives.**

***Index Terms*—Cognitive radios, bandwidth aggregation, dynamic spectrum access (DSA).**

I. Introduction

Unlike conventional radios, cognitive radios (CR's) are expected to use channel occupancy information measured at the PHY layer and conveyed to the MAC layer in order to make decisions on choosing suitable frequency bands to communicate. Clearly, PHY/MAC cross-layer designs and optimization techniques are needed to better coordinate between these layers. The main objective of a cross-layer design is to improve the overall performance of a CR device in terms of communication throughput subjected to constraints such as interference to licensed radios and power consumption [1].

Many existing PHY/MAC algorithms assume that the CR in question belongs to a particular radio network and its communication capabilities are limited only to the protocols supported by that network (see e.g. [2], [3]). On the other hand, the National Broadband Plan (NBP) [4] is a policy document that was the culmination of almost a year's worth of study by the Federal Communications Commission (FCC) with inputs from industry and government agencies on how to formulate spectrum policies in order to facilitate broadband usage for the coming years. One of the main recommendations of the NBP is to free up 500 MHz of spectrum for broadband use in the next 10 years with 300 MHz being made available for mobile use in the next five years [4]. The plan proposes to achieve this goal in a number of ways: incentive auctions, repacking spectrum, and enabling innovative spectrum access models that take advantage of opportunistic spectrum access and cognitive techniques to better utilize the spectrum. The plan urges the FCC to initiate further proceedings on opportunistic spectrum access beyond the already completed TV white spaces proceedings. The Radiobot architecture proposed in [5] is in-line with above vision and envisions CR's that are not limited to a single radio network. Instead, a Radiobot considers all the communications opportunities across a wide radio frequency spectrum, including for instance, UHF TV-band communications, WiFi, Bluetooth, 3G, satellite communications, etc., at least in theory. As an example, a Radiobot may be operating in an environment where two radio networks are available for communications. The objective of this Radiobot may be to minimize delay. In this case, the Radiobot may decide to transmit over the two available networks by splitting its payload optimally, so as to minimize the end-to-end delay. However, these kind of wideband CR capabilities do rely on both state-of-the-art RF hardware front-end (such as wideband antennas, real-time reconfigurable antennas, etc.) and sophisticated signal processing techniques for spectrum sensing. The details on the hardware and software requirements for a Radiobot architecture were discussed in [5].

The simultaneous transmission over multiple radio interfaces by a single mobile terminal has been previously discussed in the literature under the term of the bandwidth aggregation (BAG) [6]–[11] (also known as channel aggregation), which aims at performing simultaneous use of multiple interfaces to improve transmission quality or throughput depending on specific architectural designs. A similar idea called Carrier aggregation (CA) can also be found in recent literature on the Third Generation Partnership Project Long Term Evolution-Advanced (3GPP LTE-A) [12]–[15]. In order to meet the technical requirements defined by the International Mobile Telecommunications Advanced (IMT-ADV), which targets achieving peak data rates up to 1 Gbps in downlink and 500 Mbps in uplink respectively, the 3GPP started the new study item in March 2008 for evolving from LTE towards LTE-A [12]. CA is one of the key features assumed in the LTE-A, in which mobile users can access a much wider transmission bandwidth up to 100 MHz compared with LTE Release 8 standard (up to 20 MHz) [12]. This is achieved by

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aggregating two or more individual component carriers (CCs) belonging to contiguous or non-contiguous frequency bands [12], essentially scheduling a mobile user on multiple CCs simultaneously.

In [6] the authors proposed the Earliest Delivery Path First (EDPF) scheduling algorithm that partitions the traffic onto different interfaces such that the quality of service (QoS) requirements of the application are met. In [7] an adaptive medium access control (A-MAC) layer was proposed to address the heterogeneities posed by the next-generation (NG) wireless networks. The proposed A-MAC introduced a two-layered MAC framework that performs medium access to multiple networks without requiring any additional modifications in the existing network structures. In [8] the authors proposed a multi-path transmission control scheme combining BAG and packet scheduling for real-time streaming in a multi-path environment, in which the packet scheduling scheme was aimed at arranging the transmission sequence in order to effectively minimize the impact of packet reordering at the receiver. In [9], the authors investigated the BAG problem under certain practical limitations and cost issues such as switching delays and transmission delays, but without considering the power consumption. It is not realistic, however, to ignore the power consumption of the CR since it can be a crucial limitation for many radio devices operating on limited energy sources such as batteries. Moreover, the practical issue of time-varying channel coefficients was also not considered in [9]. In [10], the BAG problem was studied without considering hardware limitations, switching costs and delays, channel coefficients, and power consumptions. In [11], a spectrum assignment strategy was proposed to increase the BAG-aware access capacity and to decrease channel switching times. However, this was again obtained without considering essential practical issues such as power consumption and channel fading.

In this paper, we provide a general formulation for the BAG problem in wideband spectrum access, taking into account the essential practical issues and derive an optimal BAG strategy as the solution to a multi-objective optimization problem: one objective is the communication throughput of the mobile Radiobot device and the other one is the power consumption of the device. Note that, by self-adjusting coefficients used to give different priorities for each of the objectives, the Radiobot can achieve autonomous operations as envisioned in [5]. The proposed multi-objective optimization problem takes the following essential practical issues into account: imperfect spectrum sensing, time varying channel coefficients (caused by fading and shadowing), hardware reconfiguration time delay, hardware reconfiguration power consumption, and communication power consumptions.

The remainder of the paper is organized as follows: In Section II we introduce the system assumptions, our problem formulation and provide the solution to the multi-objective optimization problem. In Section III, the simulation results are provided and discussed. Finally, in Section IV we conclude by summarizing our results.

II. Problem Formulation

We assume that the spectrum range of interest is divided into N sub-bands, with labels $1, 2, \cdots, N$. We denote by f_n, B_n and T_n, respectively, the center-frequency, the bandwidth, and the sensing time length of the n-th sub-band. We assume that the maximum number of simultaneous transmissions that can be supported by the Radiobot is L.

We assume that spectrum sensing is performed in each sub-band in a pre-determined order. Let time sequence index $k = 0, 1, 2, \cdots$ denote the time instance at the end of the k-th spectrum sensing. We denote by i_k and j_k, respectively, for $1 \leq i_k, j_k \leq N$, the sub-band the Radiobot has just finished sensing on and the sub-band that is about to be sensed immediately at time k. We denote by $M_n(k)$ the number of detected idle channels in the n-th sub-band at time k. We index the m-th idle channel in the n-th sub-band by (n, m), where $1 \leq n \leq N$ and $1 \leq m \leq M_n(k)$. We assume that the Radiobot is free to choose to transmit on all the detected idle channels including the ones in the sub-band that is immediately going to be sensed by itself. This assumption is made based on the recent advances of the full duplex radio capability [16], which is based on RF interference cancellation algorithms. A diagram of the system operation is illustrated in Fig. 1.

In [17], a semi-Markov model was proposed to describe the channel state switching based on measurements of a WLAN in the $2.4-2.475$ GHz ISM band, in which the sojourn time of idle periods was shown to fit a generalized Pareto distribution (GDP) [18] having a probability density function (pdf)

$$f(t \mid s, \sigma, \theta) = \begin{cases} \frac{1}{\sigma}\left(1 + s\frac{(t-\theta)}{\sigma}\right)^{-1-1/s} & \text{, for } s \neq 0 \\ \frac{1}{\sigma}\exp\left(-\frac{(t-\theta)}{\sigma}\right) & \text{, for } s = 0 \end{cases} \quad (1)$$

with the domain $\theta \leq t < +\infty$ for $s \geq 0$ and $\theta \leq t \leq \theta - \sigma/s$ for $s < 0$, where s is the shape parameter, $\sigma > 0$ is the scale parameter, and θ is the location parameter [18]. Note that when $s = 0$, (1) reduces to an exponential distribution. In [19], an Maximum Likelihood (ML) estimator for the sojourn time (both idle and busy) distribution was proposed. The estimation of the sojourn times with time-varying distributions was also discussed in [19]. In this paper, however, we do not investigate the details of the estimation of the sojourn time distributions. We denote by $F^I_{n,m}(t)$ and $F^B_{n,m}(t)$, in general, the cumulative density functions (cdf's) of the idle period and busy period respectively, of channel (n, m), with

$$F^I_{n,m}(t) = \int_0^t f^I_{n,m}(\tau)d\tau, \quad \text{and } F^B_{n,m}(t) = \int_0^t f^B_{n,m}(\tau)d\tau$$

where $f^I_{n,m}(t)$ and $f^B_{n,m}(t)$ are the probability density functions (pdf's) of the idle period and busy period respectively.

The transmission rate on an idle channel (n, m) at time instance k can be defined as

$$r_{n,m,k} = B_{n,m,k} \log_2\left(1 + \frac{h^2_{n,m,k} P_{n,m,k}}{B_{n,m,k} N_0}\right) \text{ bits/s}, \quad (2)$$

where $B_{n,m,k}$ is the bandwidth of the channel (n, m) at time k, with $1 \leq m \leq M_n(k)$. We denote by $h_{n,m,k}$ and $P_{n,m,k}$, respectively, the channel coefficient and the transmit power with the constraint $0 \leq P_{n,m,k} \leq \bar{P}$, and N_0 is the single-sided noise power spectral density level. Note that, one can obtain the knowledge of the channel coefficients by performing the pilot-assisted transmission (PAT) training periodically or before each transmission [20], [21]. In this paper, we assume that only the distributions of the channel coefficients are known *a priori*.

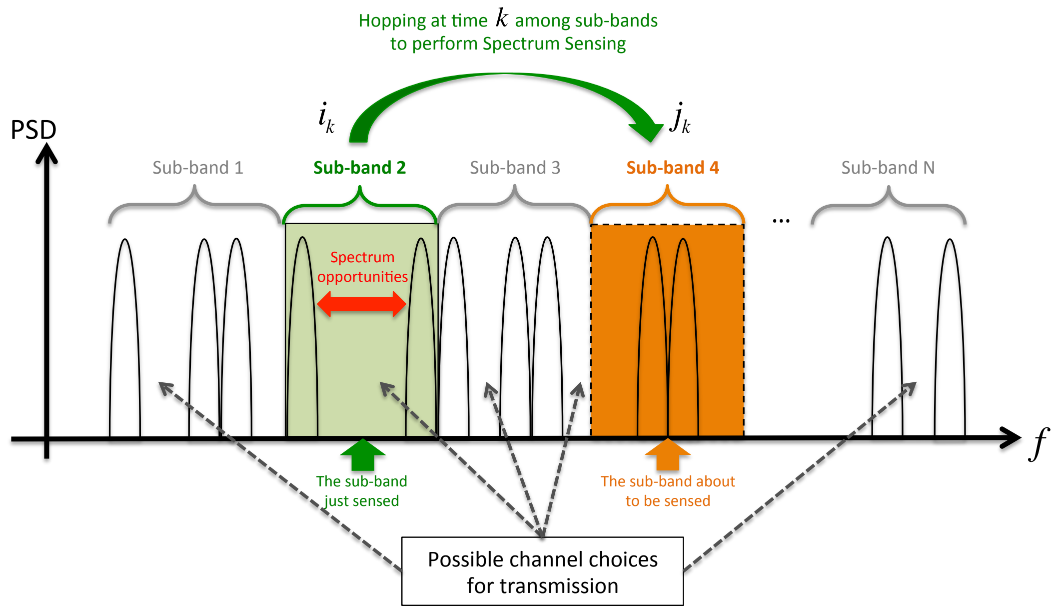

Fig. 1: A diagram of the system operation with N number of sub-bands.

Recall that the allowed maximum number of simultaneous transmission is L, and we use the notation $(n_{l,k}, m_{l,k})$, for $l = \{1, \cdots, L\}$ to denote the channel being selected at time k for the l-th transmission. We may use the $L \times 3$ matrix $\mathbf{A}_k$ to denote the action of the Radiobot at time k:

$$\mathbf{A}_k = \begin{bmatrix} n_{1,k} & m_{1,k} & P_{1,k} \\ \vdots & \vdots & \vdots \\ n_{L,k} & m_{L,k} & P_{L,k} \end{bmatrix}. \tag{3}$$

When $(n_{l,k-1}, m_{l,k-1}) \neq (n_{l,k}, m_{l,k})$, we say that the l-th transmission performed a frequency hopping. When $n_{l,k-1} \neq n_{l,k}$, we denote by the constants Δ_t and Δ_p the incurred time delay and power consumption for the hardware reconfiguration, respectively, and denote by the constants δ_t and δ_p the incurred time delay and power consumption respectively when $n_{l,k-1} = n_{l,k}$ but $m_{l,k-1} \neq m_{l,k}$. We assume that $\Delta_t > \delta_t$ and $\Delta_p > \delta_p$, since switching channels from one sub-band to another may generally involve much more complicated RF hardware reconfigurations compared to the case of switching within a sub-band.

Thus, given $(n_{l,k-1}, m_{l,k-1})$ and $(n_{l,k}, m_{l,k})$, the time delay incurred on the l-th transmission can be expressed as

$$\begin{aligned} \tau_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1}) \;&=\; \Delta_t \mathcal{I}_{\{n_{l,k-1} \neq n_{l,k}\}} \\ &\quad + \delta_t \mathcal{I}_{\{n_{l,k-1} = n_{l,k}, m_{l,k-1} \neq m_{l,k}\}}, \end{aligned} \tag{4}$$

and the power consumption overhead incurred on the l-th communication hardware can be expressed as

$$\begin{aligned} p_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1}) \;&=\; \Delta_p \mathcal{I}_{\{n_{l,k-1} \neq n_{l,k}\}} \\ &\quad + \delta_p \mathcal{I}_{\{n_{l,k-1} = n_{l,k}, m_{l,k-1} \neq m_{l,k}\}}, \end{aligned} \tag{5}$$

where $\mathcal{I}_{\{E\}}$ is the indicator function of event E such that

$$\mathcal{I}_{\{E\}} = \begin{cases} 1\,, & \text{if } E \text{ is true} \\ 0\,, & \text{if } E \text{ is not true} \end{cases}. \tag{6}$$

We assume that there are always data to be transmitted and the Radiobot assumes that a primary user is interfering its communication if several packets are sent wihtout receiving any ACK, and therefore, stops its transmission on a channel. Let us denote by τ_s the amount of time needed before it stops transmission. We define a multi-objective problem: high communication throughput, and low transmission energy consumption. The throughput $G_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1})$ on the channel $(n_{l,k}, m_{l,k})$ from time k to $k+1$ is given by (7), where $t_{k,n}$ denotes the amount of time that has passed since the end of the last sensing on the n-th sub-band at time instance k, $T^I_{n,m,k}$ denotes the random variable of the idle sojourn time of the channel (n, m), and T_{j_k} denotes the sensing time duration for the j_k-th subband. The events C, D, and E are defined in (8), (9), and (10), respectively.

The total expected throughput of the Radiobot from time k to $k+1$ can be given as in (11), where

$$\begin{aligned} & p_I^{(n_{l,k}, m_{l,k})} = \mathbb{E}\{\mathcal{I}_{\{E\}}\} \\ = \;& \Pr\{\text{channel } (n_{l,k}, m_{l,k}) \text{ is idle, given it is detected idle}\} \end{aligned}$$

denotes the posteriori probability of channel $(n_{l,k}, m_{l,k})$ being idle, and $\mathbb{E}_H\{r_{n_{l,k}, m_{l,k}, k}\}$ can be given as in (12).

The energy consumption $E_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1})$ on the channel $(n_{l,k}, m_{l,k})$ from time k to $k+1$ can be given as in (13), where event $F = E^C$ is the complement of event E. The total expected energy consumption of the Radiobot from time k to $k+1$ is then given by (14). The optimization problem of achieving transmission throughput and low energy consumption can then be expressed as follows:

$$\begin{aligned} \text{maximize} \quad & \alpha_1 \mathbb{E}\{G_k(\mathbf{A}_k, \mathbf{A}_{k-1})\} - \alpha_2 \mathbb{E}\{E_k(\mathbf{A}_k, \mathbf{A}_{k-1})\} \\ \text{subject to} \quad & (n_{l,k}, m_{l,k}) \neq (n_{l',k}, m_{l',k}) \ \forall\, l, l' \in \{1, \cdots, L\}, \\ & \text{and } 0 \leq P_{l,k} \leq \bar{P}, \ \forall\, l \in \{1, \cdots, L\}, \end{aligned}$$

where $\alpha_1 \geq 0$ and $\alpha_2 \geq 0$ are the priority coefficients for the transmission throughput and the energy consumption

$$
\begin{aligned}
& G_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1}) \\
= \; & \left[\left(T^I_{n_{l,k},m_{l,k},k} - t_{k,n_{l,k}} - \tau_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1})\right) r_{n_{l,k},m_{l,k},k}\mathcal{I}_{\{C\}} + \left(T_{j_k} - \tau_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1})\right) r_{n_{l,k},m_{l,k},k}\mathcal{I}_{\{D\}}\right]\mathcal{I}_{\{E\}} \\
= \; & r_{n_{l,k},m_{l,k},k}\left[\left(T^I_{n_{l,k},m_{l,k},k} - t_{k,n_{l,k}} - \tau_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1})\right)\mathcal{I}_{\{C\}} + \left(T_{j_k} - \tau_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1})\right)\mathcal{I}_{\{D\}}\right]\mathcal{I}_{\{E\}} \qquad (7)
\end{aligned}
$$

$$
\begin{aligned}
C &= \left\{0 < \left(T^I_{n_{l,k},m_{l,k},k} - t_{k,n_{l,k}} - \tau_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1})\right) < \left(T_{j_k} - \tau_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1})\right)\right\} \\
&= \left\{t_{k,n_{l,k}} + \tau_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1}) < T^I_{n_{l,k},m_{l,k},k} < t_{k,n_{l,k}} + T_{j_k}\right\} \qquad (8) \\
D &= \left\{T^I_{n_{l,k},m_{l,k},k} \geq t_{k,n_{l,k}} + T_{j_k}\right\} \qquad (9) \\
E &= \left\{\text{channel } (n_{l,k}, m_{l,k}) \text{ is indeed idle, given it is detected idle}\right\} \qquad (10)
\end{aligned}
$$

$$
\begin{aligned}
& \mathbb{E}\left\{G_k(\mathbf{A}_k, \mathbf{A}_{k-1})\right\} = \sum_{l=1}^{L} \mathbb{E}\left\{G_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1})\right\} \\
= \; & \sum_{l=1}^{L} \mathbb{E}_H\{r_{n_{l,k},m_{l,k},k}\} p_I^{(n_{l,k},m_{l,k})} \left[\int_{t_{k,n_{l,k}}+\tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})}^{t_{k,n_{l,k}}+T_{j_k}} \tau f^I_{n_{l,k},m_{l,k}}(\tau)d\tau + \left(T_{j_k} - \tau_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1})\right)\int_{t_{k,n_{l,k}}+T_{j_k}}^{\infty} f^I_{n_{l,k},m_{l,k}}(\tau)d\tau \right. \\
& \left. - \left(t_{k,n_{l,k}} + \tau_{l,k}(\mathbf{A}_k, \mathbf{A}_{k-1})\right)\int_{t_{k,n_{l,k}}+\tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})}^{t_{k,n_{l,k}}+T_{j_k}} f^I_{n_{l,k},m_{l,k}}(\tau)d\tau\right] \qquad (11)
\end{aligned}
$$

$$
\mathbb{E}_H\{r_{n_{l,k},m_{l,k},k}\} = \int_{-\infty}^{\infty} B_{n_{l,k},m_{l,k},k}\log_2\left(1 + \frac{h^2 P_{n_{l,k},m_{l,k},k}}{B_{n_{l,k},m_{l,k},k}N_0}\right) f_{H_{n_{l,k},m_{l,k},k}}(h)dh \qquad (12)
$$

respectively. The optimization problem can equivalently be expressed as follows:

$$
\mathbf{A}^*_k = \arg\max_{\mathbf{A}_k} \sum_{l=1}^{L} R_{l,k}\left(\mathbf{A}_k, \mathbf{A}_{k-1}\right) \qquad (15)
$$

subject to $(n_{l,k}, m_{l,k}) \neq (n_{l',k}, m_{l',k}) \; \forall \; l, l' \in \{1, \cdots, L\}$,
and $0 \leq P_{l,k} \leq \bar{P}, \; \forall \; l \in \{1, \cdots, L\}$,

where $R_{l,k}\left(\mathbf{A}_k, \mathbf{A}_{k-1}\right)$ in (15) denotes the reward function of l-th transmission and is given in (16). The quantity $J_{l,k}\left(\mathbf{A}_k, \mathbf{A}_{k-1}\right)$ in (16) is defined in (17).

The optimal solution of $\mathbf{A}^*_k$ in (15) can be solved using a combination of the *Hungarian* algorithm [22] and a convex optimization procedure, by separating the problem of channel selection and the problem of power allocation in each transmission. The separation is valid since the objective function in (15) is in the form of a summation of rewards on each transmission link and the power constraints on each transmission link are decoupled, i.e. not a joint total constraint, such that a choice of transmission power for any transmission link does not affect the choice of any other transmission links.

First, for a given channel allocation $(n_{l,k}, m_{l,k})$ of the l-th transmission, the optimal transmission power $P^*_{l,k}|_{(n_{l,k},m_{l,k})}$ can be found as

$$
P^*_{l,k}|_{(n_{l,k},m_{l,k})} = \arg\max_{P_{l,k}} \; R_{l,k}\left(\mathbf{A}_k, \mathbf{A}_{k-1}\right). \qquad (18)
$$

Since it can be shown that $R_{l,k}\left(\mathbf{A}_k, \mathbf{A}_{k-1}\right)$ is a concave function, we have $P^*_{l,k}|_{(n_{l,k},m_{l,k})} = P^{\triangle}_{l,k}$, if $P^{\triangle}_{l,k}$ is the solution of

$$
\frac{dR_{l,k}\left(\mathbf{A}_k, \mathbf{A}_{k-1}\right)}{dP_{l,k}} = 0 \qquad (19)
$$

such that $0 < P^{\triangle}_{l,k} < \bar{P}$. Otherwise, if such a solution can not be found, we have

$$
P^*_{l,k}|_{(n_{l,k},m_{l,k})} = \arg\max_{P_{l,k}\in\{0,\bar{P}\}} \; R_{l,k}\left(\mathbf{A}_k, \mathbf{A}_{k-1}\right). \qquad (20)
$$

Note that the solution $P_{l,k}$ to (19) can be shown to equivalently satisfy

$$
\int_{-\infty}^{\infty} \frac{h^2 f_{H_{n_{l,k},m_{l,k},k}}(h)}{B_{n_{l,k},m_{l,k},k}N_0 + h^2 P_{l,k}} dh - \frac{\alpha_2(\tau_s/p_I^{(n_{l,k},m_{l,k})} + J_{l,k}\left(\mathbf{A}_k, \mathbf{A}_{k-1}\right) - \tau_s)}{\alpha_1 J_{l,k}\left(\mathbf{A}_k, \mathbf{A}_{k-1}\right) B_{n_{l,k},m_{l,k},k}\log_2(e)} = 0.
$$

Second, the channel assignment problem can be represented by a weighted bipartite graph[1], where the detected idle channels and the L number of transmissions constitute the two disjoint sets of vertices, and the edge weight between the channel $(n_{l,k}, m_{l,k})$ and l-th transmission is $R_{l,k}\left(\mathbf{A}_k, \mathbf{A}_{k-1}\right)|_{P_{l,k}=P^*_{l,k}|_{(n_{l,k},m_{l,k})}}$.

The problem of assigning the channels to the L transmissions is a special case of the Hitchcock problem [23], and it can be solved by the Hungarian algorithm [22]. The Hungarian algorithm solves the weighted matching problem

[1]A bipartite graph is a graph whose vertices belong to two disjoint sets, such that every vertex is connected to at most one vertex from the other set.

$$
\begin{aligned}
& E_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1}) \\
= \ & \Big\{P_{l,k}\Big[\Big(T^I_{n_{l,k},m_{l,k},k} - t_{k,n_{l,k}} - \tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})\Big)\mathfrak{I}_{\{C\}} + \left(T_{j_k} - \tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})\right)\mathfrak{I}_{\{D\}}\Big] + p_{l,k}\left(\mathbf{A}_k,\mathbf{A}_{k-1}\right)\tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})\Big\}\mathfrak{I}_{\{E\}} \\
& + P_{l,k}\tau_s\mathfrak{I}_{\{F\}} \quad (13)
\end{aligned}
$$

$$
\begin{aligned}
& \mathbb{E}\left\{E_k(\mathbf{A}_k,\mathbf{A}_{k-1})\right\} = \sum_{l=1}^{L}\mathbb{E}\left\{E_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})\right\} \\
= \ & \sum_{l=1}^{L} p_I^{(n_{l,k},m_{l,k})}\Bigg\{P_{l,k}\Bigg[\int_{t_{k,n_{l,k}}+\tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})}^{t_{k,n_{l,k}}+T_{j_k}} \tau f^I_{n_{l,k},m_{l,k}}(\tau)d\tau - \Big(t_{k,n_{l,k}} + \tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})\Big)\int_{t_{k,n_{l,k}}+\tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})}^{t_{k,n_{l,k}}+T_{j_k}} f^I_{n_{l,k},m_{l,k}}(\tau)d\tau \\
& + \left(T_{j_k} - \tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})\right)\int_{t_{k,n_{l,k}}+T_{j_k}}^{\infty} f^I_{n_{l,k},m_{l,k}}(\tau)d\tau\Bigg] + p_{l,k}\left(\mathbf{A}_k,\mathbf{A}_{k-1}\right)\tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})\Bigg\} + (1 - p_I^{(n_{l,k},m_{l,k})})P_{l,k}\tau_s \quad (14)
\end{aligned}
$$

$$
\begin{aligned}
R_{l,k}\left(\mathbf{A}_k,\mathbf{A}_{k-1}\right) \ = \ & p_I^{(n_{l,k},m_{l,k})}\Big[\Big(\alpha_1\mathbb{E}_H\{r_{n_{l,k},m_{l,k},k}\} - \alpha_2 P_{l,k}\Big)J_{l,k}\left(\mathbf{A}_k,\mathbf{A}_{k-1}\right) - \alpha_2 p_{l,k}\left(\mathbf{A}_k,\mathbf{A}_{k-1}\right)\tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})\Big] \\
& -(1 - p_I^{(n_{l,k},m_{l,k})})\alpha_2 P_{l,k}\tau_s \quad (16)
\end{aligned}
$$

$$
\begin{aligned}
J_{l,k}\left(\mathbf{A}_k,\mathbf{A}_{k-1}\right) = \ & \Bigg[\int_{t_{k,n_{l,k}}+\tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})}^{t_{k,n_{l,k}}+T_{j_k}} \tau f^I_{n_{l,k},m_{l,k}}(\tau)d\tau - \Big(t_{k,n_{l,k}} + \tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})\Big)\int_{t_{k,n_{l,k}}+\tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})}^{t_{k,n_{l,k}}+T_{j_k}} f^I_{n_{l,k},m_{l,k}}(\tau)d\tau \\
& + \left(T_{j_k} - \tau_{l,k}(\mathbf{A}_k,\mathbf{A}_{k-1})\right)\int_{t_{k,n_{l,k}}+T_{j_k}}^{\infty} f^I_{n_{l,k},m_{l,k}}(\tau)d\tau\Bigg] \quad (17)
\end{aligned}
$$

for a complete bipartite graph. A complete bipartite graph has the same number of elements in both sets, but according to [23], we can always assume that a bipartite graph is complete by setting the weights of the missing edges to be equal to 0, and still get the optimal solution for the bipartite graph by applying this modification [24]. The goal is to find the optimal matching between the elements of the two sets so that we maximize the sum of the weights of the matching edges.

The bipartite graph illustrating the channel assignment problem with M number of detected channels and $L \leq M$ transmissions is shown in Fig. 2

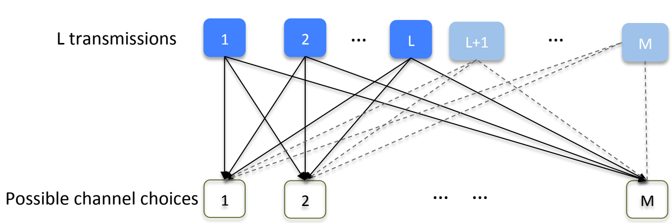

Fig. 2: An Illustration of the bipartite graph representation of the channel assignment problem with M number of channels and L number of transmissions. The dashed edges have weight of 0.

III. SIMULATION RESULTS

To illustrate the performance of the proposed wideband BAG solution, a simulation was first carried out under the following conditions: 1) maximum number of simultaneous transmissions of the Radiobot is $L = 2$; 2) number of sub-bands $N = 3$; 3) number of channels in each sub-band are 2, 3, and 3, respectively, and each of these channels have bandwidths 22, 22, 40, 40, 40, 36, 36, and 36MHz respectively; 4) the sojourn time of idle and busy periods are all exponentially distributed with a common idle sojourn time mean of 0.3ms and a common busy sojourn time mean of 0.6ms [17]; 5) $\bar{P} = 1$ Watt, and $\tau_s = 0.2$ms. The transmission throughput of the Radiobot as a function of the probability of idle state detection, in a time period of 100ms is shown in Fig. 3. As shown in Fig. 3, we see that the first case with $\alpha_1 = 1$ and $\alpha_2 = 0.2$ results in more transmission throughput compared to the second case with $\alpha_1 = 1$ and $\alpha_2 = 5$, as expected. This is due to the fact that the power consumption was considered more critical in the second case by setting a higher value for α_2.

With the same radio environment setup, in Fig. 4, we show the performance comparison for the following two cases: 1) $L = 2$ and $\alpha_1 = 1$; 2) $L = 1$ and $\alpha_1 = 1$, in terms of the data throughput as a function of α_2, in a time period of 1000ms. The probability of idle state detection was set to be 0.8. We observe that in the first case, the Radiobot is able to perform $L = 2$ number of simultaneous transmissions, resulting in a higher data throughput compared to the second case with only one supported transmission. We can also see that as the α_2 increases, the data throughput drops to conserve energy as expected.

IV. CONCLUSIONS

We proposed an optimal wideband bandwidth aggregation strategy as the solution to a multi-objective optimization

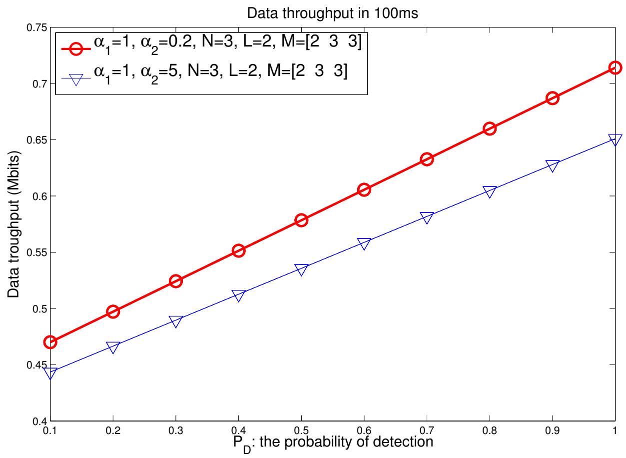

Fig. 3: Achieved throughput as a function of the probability of detection of idle channels in two cases: 1) $\alpha_1 = 1$, $\alpha_2 = 0.2$; and 2) $\alpha_1 = 1$, $\alpha_2 = 5$.

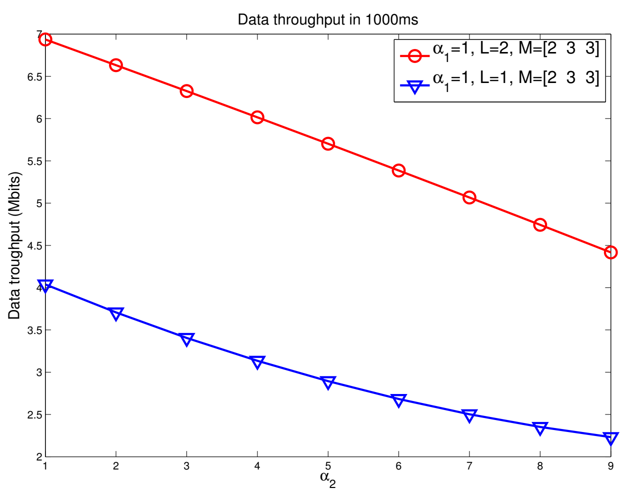

Fig. 4: Achieved throughput as a function of the α_2 in two cases: 1) $L = 2$, $\alpha_1 = 1$; and 2) $L = 1$, $\alpha_1 = 1$.

problem: one objective is the communication throughput of the mobile cognitive radio device and the other one is power consumption of the device. The optimal bandwidth aggregation strategy was derived taking into account practical issues including imperfect spectrum sensing, channel fading, hardware reconfiguration time delay and power consumption, and communication power consumptions. Moreover, we analyzed and verified the performance of the proposed strategy through simulations.

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