Coexistence policies in cognitive radio

Mario Lopez Martinez   Supervisor: Juan Jose Alcaraz Espin

01 March 2015[*]

---

[*]First drafted on 28 November 2014

Contents

List of Figures

List of Tables

CHAPTER **1**

Introduction

Part I

Dynamic Spectrum Access

2

Response Surface Methodology for Efficient Spectrum Reuse in Cellular Networks

2.1 Introduction

In this chapter we move on from mechanisms that ensure the proper operation of opportunistic access to develop a full DSA framework particularized for cellular networks.

Approximately every decade, a new cellular access technology is developed and introduced in the market. However, because not all users upgrade their terminals at the same pace, the operators have to keep their legacy networks working, and the spectrum assigned to these old networks becomes gradually more and more underused.

One way to increase the spectrum efficiency is to allow the users of the newest networks to opportunistically access the spectrum of the legacy networks. Applying the concepts of cognitive radio [174], the terminals of the newest network would be the secondary users (SUs), and the terminals of the legacy network would be the primary users (PUs). The secondary access to the spectrum of the primary (legacy) network should not cause noticeable degradation to PU transmissions.

The operator owns and control both the primary and the secondary networks, and therefore can establish the rules for secondary access and monitor the impact of these rules on the performance of both SU and PU transmissions. However, it is more profitable for the operator *not making any modifications on the legacy network*, implying that the operation of the secondary network is *transparent* to the primary network.

In this chapter, we propose a semi-decentralized secondary access scheme allowing each SU to access a set of primary frequency bands using either temporal or spatial spectrum holes (opportunities). By giving more access options to each SU, this approach can outperform previous, more limited, mechanisms. We consider

that the SUs establish point-to-point connections among them (cognitive pairs) in an ad-hoc fashion.

To fully exploit its potential, we describe an on-line algorithm that, with very small computational and signaling overhead, allows the system to learn the optimal SU access policy in terms of capacity.

Related Work

Other works have proposed the combination of temporal and spatial sensing by the SUs [175], [176], [177], [178]. Works like [175] and [176] consider a single secondary transmitter and exploit information from spatial sensing to improve the performance of temporal sensing. The single transmitter model is also applied in [177] for vehicular networks. In [178] the capacity is optimized by randomizing the access strategies, but for a single PU, single SU scenario. However, the motivational scenario of our work comprises multiple secondary transmitters with multiple primary base stations. Thus, we must consider relevant features that are not captured by the single transmitter model, such as the inter-SU interference and the frequency reuse in a cellular structure.

In cellular networks, previous works like [179] and [180] have addressed spatial spectrum reuse by a secondary network. However, these works assume that the secondary users only scan one frequency. As pointed out by their authors, scanning all the frequencies would improve the performance. In contrast, we follow this latter approach, mixing it with the exploitation of temporal opportunities.

Contribution

Our contribution in this chapter is summarized as follows:

- We develop a semi-distributed mechanism for opportunistic spectrum access combining access over temporal and spatial opportunities, in which *all the spectrum of the system can be made available to each SU.*

- Our method is especially conceived for cellular networks, considering multiple PU transmitters within a cell structure. The system is evaluated in a realistic setting considering irregular cell shapes.

- The most important feature, 3) *the system is capable of learning the optimal probability distribution over the frequency bands of the cellular network* to maximize SU capacity. The learning algorithm applies the response surface methodology (RSM) [183], which is a novel and promising approach to address interference management problems.

In the following section we describe the system. Section 2.3 formulates the design problem and Section 2.4 presents the RSM algorithm to solve it. Finally, Sections 2.5 and 2.6 presents the numerical results and the conclusions of this work.

2.2   System description

The system considered comprises: a legacy cellular network (primary network), a secondary network establishing ad-hoc point-to-point links, and a secondary access controller (SAC) which monitors the system performance and broadcasts the operation parameters of the SU access strategy, with small signaling overhead, as we discuss in Section 2.4. The primary network contains base stations (PBSs) and primary users (PUs). Each PBS covers a certain geographical area (primary cell) and is assigned a frequency band different from its adjacent cells.

We assume a frequency reuse scheme of 7 frequency bands (reuse factor 7), denoted by $f_1, \ldots, f_7$. Nevertheless, the proposed method can be applied to other reuse factors as well. Each frequency band is divided into $2N$ orthogonal channels (N downlink and N uplink channels). Secondary access is constrained to downlink channels. Time is divided into equal duration time-slots, which is usual in most cellular systems. The data transmitted over a single PU channel in a time-slot is referred to as *packet*.

The secondary network consists of pairs of secondary users (SUs) entering and leaving the system in an ad-hoc fashion. This network model can characterize femtocells, terminals acting as relays, or any short-range transmission using available spectral resources of the legacy cellular network.

The SAC is associated to the network to which the SUs belong. In particular, we assume that the SUs are the users of a new generation cellular network. Because both networks (the new generation network and the legacy one) belong to the same operator, we consider that the SAC can retrieve some information from the legacy network.

The SUs can detect the power of the pilot tones of the neighboring PBSs. With this information (and possibly with the aid of the SAC) each SU can infer its position with respect to the surrounding cells and therefore be aware of the PBS power levels from each frequency band. Indeed, the SU does not need to estimate exactly these PBS power levels, it just needs to establish an ordering of the frequencies $f_1, \ldots, f_7$ from lower to higher PBS power level. For a generic SU, let $\boldsymbol{\phi} = (\phi_1, \ldots, \phi_7)$ be the vector of frequencies ordered in increasing received power, which clearly depends on the location of the SU. Note that ϕ_7 corresponds, in general, to the frequency band of the primary cell where the SU is located.

   Example. In Figure 2.1, any SU located in area A has $\phi_1 = f_1$ (similarly, any SU in area B has $\phi_1 = f_2$). But because each SU is closer to a different PBS, $\phi_7 = f_5$ for SU 1, and $\phi_7 = f_6$ for SU 2. These SUs have also different values of ϕ_2 and ϕ_4.

   When an SU transmits over any band ϕ_i, it may cause some interference to the PUs of the closest cells using this band (and the same channel within this band). In general, the level of SU interference caused at PU receivers is proportional to the ordering index i of the selected band ϕ_i, *i.e.* a single SU transmission over ϕ_1 causes generally less interference than an SU transmission over ϕ_2, and so on.

   In our system, the classic strategy of occupying exclusively *spatial opportunities* implies that each SU only tries to access over ϕ_1. However, what really matters
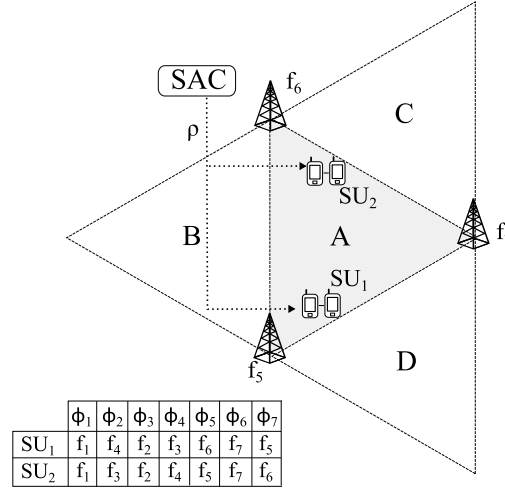
	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7
SU_1	f_1	f_4	f_2	f_3	f_6	f_7	f_5
SU_2	f_1	f_3	f_2	f_4	f_5	f_7	f_6

Figure 2.1: Example of the system with 2 SU pairs. Every SU in area A associates f_1 to ϕ_1. The remaining f_j-ϕ_i associations for each SU depend on how close the SU is to areas B, C or D. The SAC broadcasts a vector of operation parameters $\boldsymbol{\rho}$ to the SUs.

is the aggregate interference at the receivers. Note that, in accordance to the ad-hoc nature of the secondary network (small SU transmission range, low antenna heights, indoor locations sometimes) the SINR at the PU receivers can still be acceptable even if the interference from some SUs is a bit higher, *i.e.* if some SUs select other bands different from ϕ_1. The potential benefit of giving more frequency band options to the SUs is to decrease the inter-SU interference, increasing the capacity of the secondary network.

Besides, when an SU tries to access the band of a close PBS, *i.e.* a band associated to a higher interference power such as ϕ_7, the SU can perform *PU activity detection* on the channels within the band [174]. This activity detection allows the SU to detect free channels before starting transmission, and to stop SU transmission when detecting overlap with PU transmissions as our mechanism in chapter **??** does. The closer the SU is to the PBS, the more reliable is the PU activity detection and therefore the less impact on PU communication. The free channels in ϕ_7 are identified as *temporal opportunities*.

The typical strategies of using only spatial opportunities (ϕ_1 channels) or only temporal ones (ϕ_7 free channels) are not optimal as we show in Fig. 2.2. The achievable capacity for SUs using these strategies is limited, because of inter-SU interference and the limitation in the number of available channels when using temporal opportunities.

Regarding PU degradation, note that the interference from the SUs using ϕ_7 or ϕ_6 may be very intense but, thanks to the PU activity detection in closer cells, it should be infrequent and last short periods of time (depending on the detection accuracy). On the other hand, the interference from the SUs using bands that usually do not allow PU activity detection (*e.g., ϕ_1 or ϕ_2*) will be sustained over time, but will be less intense (similar to the co-channel interference from other PBSs). To properly adjust the vector $\boldsymbol{\rho}$ we should combine the effects of these two
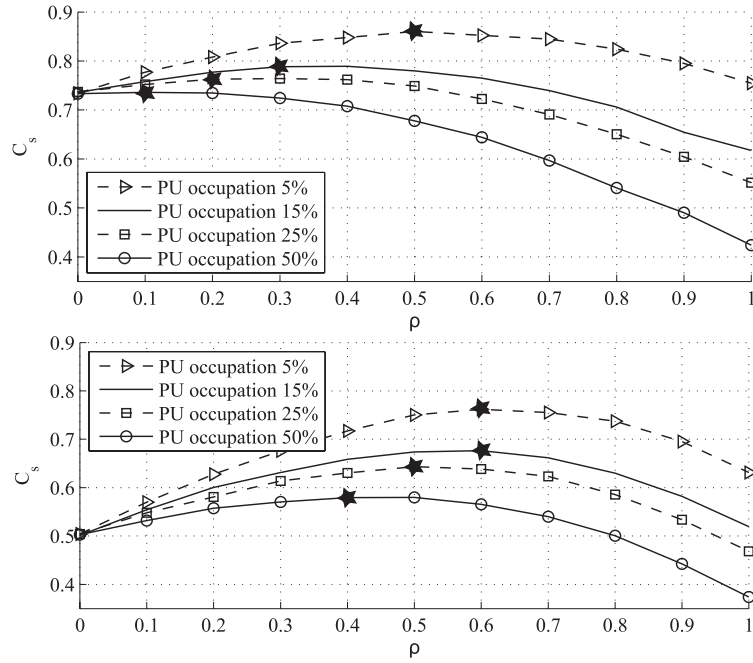
Figure 2.2: SU capacity versus ρ, the probability of using a temporal op-
portunity (and a spatial opportunity otherwise) under different PU traffic
intensities. The number of new SU cognitive pairs at each time slot is
generated by a binomial distribution characterized by 20 trials of 0.1 (top
figure) and 0.2 (bottom figure) probability each. The rest of this refer-
ence scenario is described in section 2.5. The stars indicate the optimum
SU capacity for each PU occupation.

types of interference into a single performance metric for the PUs: the probability
of correct packet reception per time-slot.

Let R be the number of bands that an SU can use. We define the R-dimensional
vector $\boldsymbol{\rho} = (\rho_1, \ldots, \rho_R)$, where ρ_i denotes the probability of using band ϕ_i, except
for ρ_R which always corresponds to the probability of using band ϕ_7 (pure temporal
access). Therefore, $0 \leq \rho_i \leq 1$ for $i = 1, \ldots, R$, and $\sum_{i=1}^{R} \rho_i = 1$. Let $\mathcal{P}$ denote
the set of R-dimensional vectors fulfilling these conditions.

The following steps summarize the **system operation**:

1. The SAC periodically updates the vector $\boldsymbol{\rho}$ and sends it to the SUs.[1]

2. Each SU builds its own $\boldsymbol{\phi}$ vector by scanning the PBS pilot tones on each
   frequency band. This vector only needs to be updated when the SU changes
   its location.

3. Before transmitting, an SU randomly selects one band, ϕ_i from its $\boldsymbol{\phi}$ vector,
   according to the probability distribution $\boldsymbol{\rho}$, i.e. $P(\text{select band } \phi_i) = \rho_i$.

---

[1]It is advisable to divide the system into relatively homogeneous regions in terms of PBS density,
traffic intensity and type of terrain, so that a suitable $\boldsymbol{\rho}$ can be found for each region.

4. If the SU is capable of detecting enough PBS power in ϕ_i to perform PU activity detection, then the SU tries to access over temporal opportunities, occupying only channels free of PU activity. Otherwise, the SU will access any channel with a sufficiently low SINR (considering also the interference from other SUs).

5. Periodically, the SAC retrieves information from both the primary and the secondary networks, particularly performance measures, which are taken into account to update vector $\boldsymbol{\rho}$.

This mechanism allows a semi-decentralized resource allocation. The SAC only needs to *announce* the vector $\boldsymbol{\rho}$ and retrieve small pieces of information measured at the terminals. The signaling overhead is therefore very low, especially compared to a centralized channel allocation by the SAC. If $\boldsymbol{\rho}$ is properly adjusted, the SUs will allocate themselves over the legacy spectrum, autonomously, efficiently, and with a low impact on the primary network. Moreover, $\boldsymbol{\rho}$ can be learned by the SAC with the RSM scheme explained in Section 2.4.

Next section formalizes the problem in terms of SU achieved capacity and PU probability of correct packet reception.

2.3   Problem Formulation

In this section we define the performance metrics for both the PUs and SUs and formulate the problem that the SAC needs to solve to determine the $\boldsymbol{\rho}$ vector.

Let us consider a secondary network with a given traffic intensity characterized by its arrival rate per area unit, and a random transmission time. As stated above, the vector $\boldsymbol{\rho}$ determines how the SUs distribute themselves over the available spectrum and the proportion of SUs using PU activity detection. In consequence, the SINR at each PU or SU receiver depends on $\boldsymbol{\rho}$. Let N_t^{SU} and N_t^{PU} denote the number of SUs and PUs in the system, respectively, at time-slot $t = 1, 2, \ldots$. The SINR over time at SU receiver $s \in \left\{1 \ldots N_t^{SU}\right\}$, is a discrete time stochastic process induced by $\boldsymbol{\rho}$, and denoted by $\Gamma_t^s(\boldsymbol{\rho})$. The expected normalized capacity per active SU pair is given by

$$C_s(\boldsymbol{\rho}) = E\left\{\lim_{T \to \infty} \frac{1}{T} \sum_{t=0}^{T} \sum_{s=1}^{N_t^{SU}} \frac{\log_2\left(1 + \Gamma_t^s(\boldsymbol{\rho})\right)}{N_t^{SU} C_{\max}^S}\right\} \qquad (2.1)$$

where $C_{\max}^S$ is the maximum achievable SU capacity per hertz. The expectation is taken over Γ_t^s and N_t^{SU}.[2] At a PU receiver, it is assumed that a data packet transmitted on time-slot t is correctly decoded if its SINR, Γ_t^{PU}, is greater than a given detection threshold, γ^{PU}. Then, the probability of correct detection at a PU

---

[2] Note that the traffic intensity in a cellular communication network varies during a day, but if it is observed during a smaller time window, *e.g.* 1 hour, the traffic arrival process can be considered stationary, with constant intensity.

is defined as

$$P_c(\boldsymbol{\rho}) = E \left\{ \lim_{T \to \infty} \frac{1}{T} \sum_{t=0}^{T} \sum_{j=1}^{N_t^{PU}} \frac{\mathbb{I}_{\left\{ \Gamma_t^j(\boldsymbol{\rho}) > \gamma^{PU} \right\}}}{N_t^{PU}} \right\} \tag{2.2}$$

where Γ_t^j refers to the SINR process at the j-th active PU, and $\mathbb{I}_{\{z\}}$ is an indicator function which equals 1 if condition z holds, and equals 0 otherwise.

Therefore, the objective of the SAC is to find ρ solving the following problem:

$$\begin{aligned} \max_{\boldsymbol{\rho}} \quad & C_s(\boldsymbol{\rho}) \\ \text{s.t.} \quad & P_c(\boldsymbol{\rho}) \geq P_{c,\min} \\ & \rho \in \mathcal{P} \end{aligned} \tag{2.3}$$

where $P_{c,\min}$ denotes the minimum acceptable P_c.

Finding an optimal $\boldsymbol{\rho}$ is a challenging task because the (multiple) SINR stochastic processes capture the interaction of a random number of randomly located terminals with fading effects among each pair of them. Moreover, these processes and the decision vector $\boldsymbol{\rho}$, take values from continuous spaces, and therefore conventional dynamic programming techniques result infeasible. The problem (2.3) is, in fact, a *stochastic optimization problem with stochastic constraints* [183]. As usual in this type of problems, the SAC has to dynamically *learn* an optimal $\boldsymbol{\rho}$. One feasible way to address it is by means of Surface Response Methods (RSM) [184]. However, the inclusion of stochastic constraints introduces high complexity in the formulation. In the following section we develop the particular case in which $P_{c,\min}$ is sufficiently low for condition $P_c(\boldsymbol{\rho}) \geq P_{c,\min}$ to hold at the optimal $\boldsymbol{\rho}$ (in numerical results, $P_c(\rho)$ at the optimal ρ is never less than 5% of the P_c obtained in absence of SU access). This allows us to remove the stochastic constraint regarding $P_c(\boldsymbol{\rho})$. We leave as future work the inclusion of constraints in the RSM formulation.

2.4 Response Surface Method (RSM) Algorithm

The aim of the algorithm is the maximization of the expected value of the average capacity function (2.1) on a closed convex feasible domain $\mathcal{P} \subset \mathbb{R}^R$ for the input vector ρ, that is, to find a ρ approximately solving

$$\max_{\boldsymbol{\rho} \in \mathcal{P}} C_s(\boldsymbol{\rho}) \tag{2.4}$$

RSM allows us to find an approximate solution to this problem by successively estimating the gradient of the objective function and using these estimations in stochastic gradient ascent steps. At each one of these steps, numbered by $n = 1, 2, \ldots$, the system generates one update of the input vector $\boldsymbol{\rho}_{(n)}$ according to the following expression:

$$\boldsymbol{\rho}_{(n+1)} = \boldsymbol{\rho}_{(n)} + \alpha_{(n)} \hat{\nabla} C_s(\boldsymbol{\rho}_{(n)}) \tag{2.5}$$

where $\hat{\nabla} C_s$ denotes the estimation of the gradient ∇C_s, and $\alpha_{(n)}$ is the step-size weighting factor. A standard condition for the selection of $\alpha_{(n)}$, assuring the convergence of $\boldsymbol{\rho}_{(n)}$ [183], is $\sum_{n=1}^{\infty} \alpha_{(n)} = \infty$, $\sum_{n=1}^{\infty} \alpha_{(n)}^2 < \infty$.

Let us discuss the computation of $\hat{\nabla} C_s$. Given $\rho_{(n)}$ at step n, we consider a subdomain $\mathcal{S}_{(n)}$ of the feasible domain $\mathcal{P}$ such that $\boldsymbol{\rho}_{(n)} \in \mathcal{S}_{(n)} \subset \mathcal{P}$. Note that $\rho_{(n)}$ is the point at which the estimate $\hat{\nabla} C_s$ must be computed. Therefore, we need to estimate the objective function $C_s(\rho_{(n)})$ on $\mathcal{S}_{(n)}$, by taking samples $y^{(i)}, i = 1, \ldots, p$, of the function. For this, we need a finite set of points $\boldsymbol{\rho}_{(n,i)}, i = 1, \ldots, p$, generally called *design points*, belonging to $\mathcal{S}_{(n)}$. These points are chosen by the decision maker (the SAC in our case), and can be, for example, random perturbations of $\boldsymbol{\rho}_{(n)}$, falling within $\mathcal{S}_{(n)}$.

Let $t_{(n)}$ denote the time-slot in which the update $\rho_{(n)}$ is obtained. Given the set of p decision points, the SAC can obtain samples $y^{(i)}$ by this simple procedure:

1. Determine p sampling instants $t_{(n,i)} = t_{(n)} + iT$ for $i = 1 \ldots p$, where T is a sufficiently long time period for measuring performance at the SUs.

2. At $t_{(n,i-1)}$ (where $t_{(n,0)} = t_{(n)}$), the SAC signals the design point $\boldsymbol{\rho}_{(n,i)}$ to the SUs, for $i = 1 \ldots p$.

3. At $t_{(n,i)}$, the SAC obtains the capacity samples from each active SU and averages them to obtain $y^{(i)}$.

Thus, the estimates can be expressed as:

$$y^{(i)} = \frac{1}{T} \sum_{k=t_{(n,i-1)}}^{t_{(n,i)}} \sum_{s=1}^{N_k^{SU}} \frac{\log_2 \left(1 + \Gamma_k^s(\boldsymbol{\rho}_{(n,i)}) \right)}{N_k^{SU} C_{\max}^S} \quad i = 1, 2, \ldots, p, \qquad (2.6)$$

Note that the stochastic ascent algorithm needs p periods of length T to upgrade $\boldsymbol{\rho}_{(n+1)}$.

The objective function C_s is then approximated on $S_{(n)}$ by a polynomial response surface model $\hat{C}_s(\boldsymbol{\rho}) = \hat{C}_s(\boldsymbol{\rho}|\beta_0, \beta_1 \ldots \beta_R)$. The coefficients β_j, are determined by least squares estimation. Therefore, the RSM-gradient estimator $\hat{\nabla} C_s(\boldsymbol{\rho}_{(n)})$ at $\boldsymbol{\rho}_{(n)}$ is defined by the gradient (with respect to $\boldsymbol{\rho}$)

$$\hat{\nabla} C_s(\boldsymbol{\rho}_{(n)}) = \nabla \hat{C}_s(\boldsymbol{\rho}_{(n)}). \qquad (2.7)$$

Thus, C_s is estimated on $S_{(n)}$ by the linear empirical model

$$\hat{C}_s(\boldsymbol{\rho}_{(n)}) = \beta_0 + \boldsymbol{\beta}_I^T (\boldsymbol{\rho} - \boldsymbol{\rho}_{(n)}) \qquad (2.8)$$

where

$$\boldsymbol{\beta}^T = (\beta_0, \boldsymbol{\beta}_I^T) = (\beta_0, \beta_1, \ldots, \beta_R)^T \qquad (2.9)$$

is the $(R + 1)$-vector of unknown coefficients of the linear model. Having samples $y^{(i)}$ of the function values $C_s(\boldsymbol{\rho}_{(n,i)})$ at the design points $\boldsymbol{\rho}_{(n,i)}, i = 1, \ldots, p$, in $S_{(n)}$, we can obtain, by least squares, the following estimate $\hat{\boldsymbol{\beta}}$ of $\boldsymbol{\beta}$:

$$\hat{\boldsymbol{\beta}} = (\mathbf{W}^T \mathbf{W})^{-1} \mathbf{W}^T \boldsymbol{y}. \qquad (2.10)$$

Here, the $p \times (R+1)$-matrix $\mathbf{W}$ and the p-dimensional vector $\mathbf{y}$ are defined by

$$
\mathbf{W} = \begin{pmatrix} 1 & \boldsymbol{\delta}^{(1)} \\ 1 & \boldsymbol{\delta}^{(2)} \\ \vdots & \vdots \\ 1 & \boldsymbol{\delta}^{(p)} \end{pmatrix}, \quad \mathbf{y} = \begin{pmatrix} y^{(1)} \\ y^{(2)} \\ \vdots \\ y^{(p)} \end{pmatrix} \tag{2.11}
$$

with $\boldsymbol{\delta}^{(i)} = \boldsymbol{\rho}_{(n,i)} - \boldsymbol{\rho}_{(n)}$, for $i = 1, 2, \ldots, p$. Note that $(\mathbf{W}^T\mathbf{W})$ in (2.10) is invertible whenever the columns of $\mathbf{W}$ are linearly independent, which can be easily guaranteed by a proper selection of the design points.

In case $C_s(\boldsymbol{\rho})$ is concave on $\mathcal{P}$, the RSM algorithm will approach the global optimum following the stochastic gradient ascent iterations (2.5) as it has been observed for $R \geq 2$ dimensions in the scenarios considered in the following Section.

2.5   Numerical Results

Evaluation Framework

This subsection describes the Monte-Carlo methodology and the scenario used to evaluate C_s. The primary network uses a 7-band frequency planning, as previously stated, with irregular shaped cells having an average radius $r = 700$ m. We consider pathloss and multipath fading. To compute the pathloss attenuation over distance, $A(d)$ (dB), we use the following piecewise dual-slope model [125]:

$$
A(d) = \begin{cases} K + 10\gamma_1 \log_{10}(d/d_0) & d_0 \leq d \leq d_c \\ K + 10\gamma_1 \log_{10}(d_c/d) + 10\gamma_2 \log_{10}(d/d_c) & d > d_c \end{cases} \tag{2.12}
$$

The critical distance d_c is notably smaller for SU transmission than for PBS transmissions, because the PBSs are located at high outdoor locations while SUs are, in general, located either indoors or at ground level. All the signals are assumed to experience Rayleigh fading.

The area used to generate random terminal locations is a 4.2 km × 4.8 km rectangle. We focus on the downlink channels of one frequency band. We consider an scenario in which the primary traffic intensity is low 0.16 Erlangs/km^2, so that the average occupation of the spectrum by the primary terminals is only 5%. In contrast, the SU traffic intensity, 27.5 Erlangs/km^2, is high in comparison.

In this case, the SU capacity is mostly determined by the inter-SU interference and the RSM algorithm is essentially performing *interference management* in the SU network. We also discuss the effect of higher PU spectrum occupation and a different SU traffic intensity.

According to the ad-hoc nature of the secondary network, the average SU link distance considered is 90 m. Table 2.1 summarizes the simulation parameters considered.

Parameter	Assigned value
Primary transmitters	
number of downlink channels, N	5
cell radius, r	700 m
average received power at PU	-78 dBm
SINR detection threshold at PU,γ^{PU}	-17 dB
baseline noise at PU $(N_0 + I_{PU})$	-110 dBm
Secondary transmitters	
average SU Tx power per channel	0.5 W
SU link distance	90 m
probability of PU activity detection	0.9
probability of overlap detection	0.8
Propagation parameters	
pathloss exponents, γ_1, γ_2	2.4, 4.2
propagation factor K	46.7 dB
critical distance for PBS transmission	$1.2r$ m
critical distance for SU transmission	100 m
RSM parameters	
dimensions of ρ,R	$1 \ldots 5$
measuring period T (in time-slots)	300
number of samples per step p	$3(2^{R-1} + 1)$

Table 2.1: Parameter setting of the reference scenario used in numerical evaluations

Convergence and Usage of the Frequency Bands

Let us consider the case of 3-dimensional ρ vectors, $R = 3$. In this case, the ρ vector of a particular SU is $\rho = (\rho_1, \rho_2, \rho_3)$, being ρ_3 the probability of trying to access the band ϕ_7 of the primary cell where the SU is in, and ρ_1 and ρ_2 the probabilities of accessing ϕ_1 and ϕ_2, the bands where the SU receives less PBS power. The SU can only perform PU activity detection on ϕ_7 channels, while the channels of the other bands are considered spatial opportunities. Fig. 2.3 shows the values of ρ_1 and ρ_2 (ρ_3 is simply $1 - \rho_1 - \rho_2$) over consecutive update steps $n = 1, 2, \ldots$. The initial vector is $\rho_{(0)} = (0, 0, 1)$. Although ρ_0 is a rather poor initial guess, we see that the RSM algorithm stabilizes after 20 iterations. The final value is $\rho = (0.29, 0.42, 0.29)$. Fig. 2.4 shows the estimated value of C_s as a function of ρ_1 and ρ_2. Consistently with the result obtained by RSM, the maximum values of C_s lie on the line $\rho_1 + \rho_2 = 0.7$.

Let us now consider the results for $R = 5$. The probability ρ_5 is now associated to ϕ_7, allowing PU activity detection, while $\rho_1 \ldots \rho_4$ are associated to $\phi_1 \ldots \phi_4$, where PU activity detection is assumed to be unfeasible. The initial ρ vector is $(0, 0, 0, 0, 1)$. Fig. 2.5 shows that, in this case, the convergence of RSM is as fast as with $R = 3$. Note that, as in the case of $R = 3$, the algorithm is not assigning ρ_1 the highest probability. The reason is that the algorithm aims to minimize inter
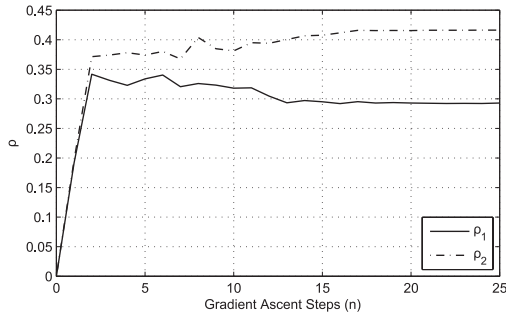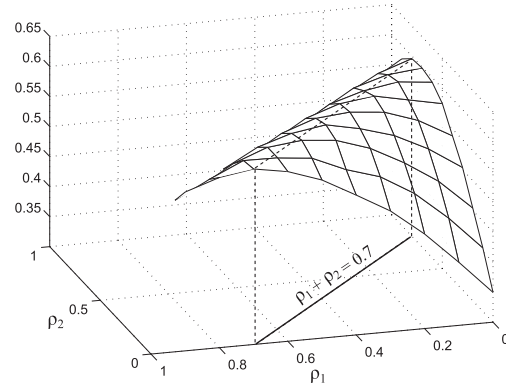
Figure 2.3: Consecutive RSM updates of ρ_1 and ρ_2.

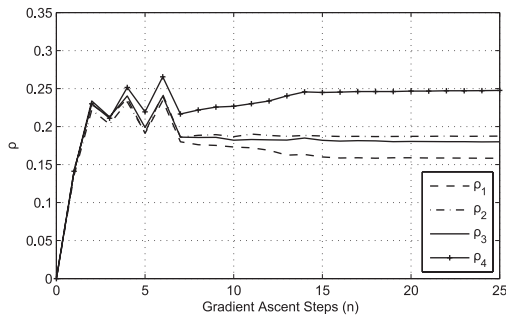Figure 2.4: Estimation of C_s over ρ_1 and ρ_2.

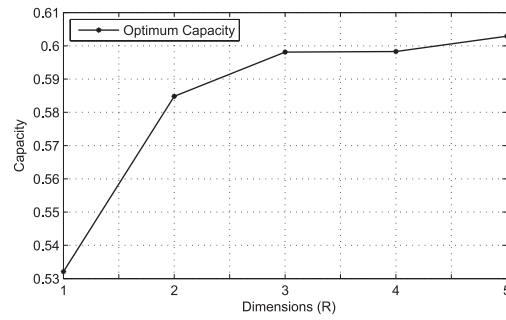Figure 2.5: Consecutive RSM updates of $\rho_1 \ldots \rho_4$.

Figure 2.6: Maximum SU capacity obtained with RSM versus the number of dimensions of ρ, R.

SU interference by separating the SU transmitters using the same band. Recall that in Fig. 2.1 all the SUs in triangular region A shared the same ϕ_1 but had different values for ϕ_2. The aggregated probability of using spatial opportunities is $\sum_{i=1}^{4} \rho_i = 0.77$, which is higher than in the $R = 3$ case. This result confirms the idea that, the more spectrum is available to each SU, the more spectrum the SU exploits. Having more spectrum options per SU (higher R) also allows the SU network to achieve a higher capacity, as illustrated by Fig. 2.6.

Effect of the Traffic Intensity

Fig. 2.7 shows the average SU capacity attained by the RSM algorithm with $R = 2$, versus the average spectrum usage by the PUs, for different SU traffic intensities. As expected, the more spectrum occupied by PU traffic, the smaller the achieved capacity. Similarly, more SU traffic implies less SU capacity. The reason of the reduction on the maximum achieved capacity is the increment of the aggregate interference power at the SU receivers, from both the PBSs and other SU pairs. Compared to the typical approach of exploiting only temporal opportunities, the benefit of using RSM is noticeable for every traffic situation. In all cases, the reduction of the probability of correct detection at the PU receivers (P_c) was less than 5%.
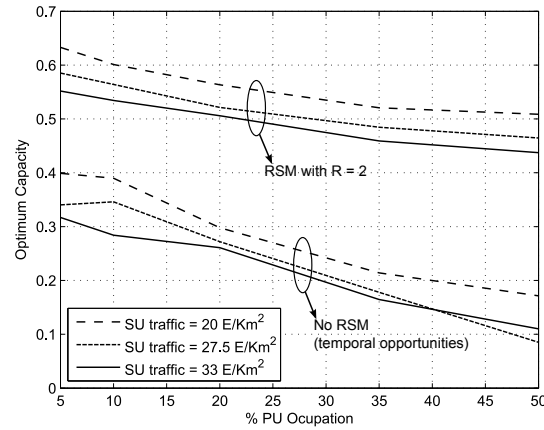
Figure 2.7: Maximum SU capacity obtained with RSM under different traffic intensities. For comparision, the figure also shows the capacity for a SU network exploiting only temporal opportunities (no RSM).

2.6 Conclusion

Motivated by the problem of spectrum reuse in cellular networks, we presented a semi-distributed mechanism allowing the secondary network to learn the most efficient spectrum access strategy. This mechanism exploits both spatial and temporal opportunities, and is especially effective for interference management in highly dense secondary networks. The learning approach is based on response surface methodology (RSM) which, according to our numerical results, improves notably the system capacity compared to usual strategies, and shows a fast convergence rate even when it is poorly initialized. Because of that, the system can adapt its control vector ρ to variations on the traffic intensity or user distribution. Surprisingly, to the best of our knowledge, the use of RSM on this framework had not been previously reported. Our future work is focused on incorporating performance constraints for the primary network in the RSM formulation.

Part II

Automated spectrum trading

Final conclusions

Bibliography

[1] FCC. (2002). Report of the spectrum efficiency working group. Techical report. FCC Spectrum Policy Task Force.

[2] Mitola, J., & Maguire, G. Q. (1999). Cognitive radio: making software radios more personal. *IEEE Personal Communications*, 6(4), 1318. doi:10.1109/98.788210

[3] Wang, B., & Liu, K. (2011). Advances in cognitive radio networks: A survey. *IEEE Selected Topics in Signal Processing*, 5(1), 523. doi:10.1109/JSTSP.2010.2093210

[4] Mayo, J. W., & Wallsten, S. (2010). Enabling efficient wireless communications: The role of secondary spectrum markets. *Information Economics and Policy*, 22(1), 6172. doi:10.1016/j.infoecopol.2009.12.005

[5] Yoon, H., Hwang, J., & Weiss, M. B. H. (2012). An analytic research on secondary-spectrum trading mechanisms based on technical and market changes. *Computer Networks*, 56(1), 319. doi:10.1016/j.comnet.2011.05.017

[6] Zhao, Y., Mao, S., Neel, J., & Reed, J. (2009). Performance evaluation of cognitive radios: Metrics, utility functions, and methodology. *Proceedings of the IEEE*, 97(4).

[7] Niyato, D., Hossain, E., & Han, Z. (2009). Dynamic spectrum access in IEEE 802.22-based cognitive wireless networks: a game theoretic model for competitive spectrum bidding and pricing. *IEEE Wireless Communications*, 16(2), 1623.

[8] Standard ECMA-392. (2009). MAC and PHY for Operation in TV White Space.

[9] Sun, C., & Tran, H.N., & Rahman, M. A., & Filin, S., & Alemseged, Y. D., & Villardi, G., & Harada, H. (2009). P802.19.1 Assumptions and Architecture

[10] IEEE 802.11 Working Group on Wireless Local Area Networks, `http://www.ieee802.org/11/` Accessed 10 July 2013

[11] IEEE P1900.5 Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications `https://ict-e3.eu/project/standardization/IEEE-SCC41.html` Accessed 10 July 2013

[12] Adler, J. (2012). Raging bulls: how Wall Street got addicted to light-speed trading. Wired.com. Retrieved from `http://www.wired.com/business/2012/08/ff_wallstreet_trading/all/` Accessed 15 June 2013

[13] Maharjan, S., Zhang, Y., & Gjessing, S. (2011). Economic approaches for cognitive radio networks: a survey. *Wireless Personal Communications*, 57(1), 3351. doi:10.1007/s11277-010-0005-9

[14] Hossain, E., Niyato, D., & Han, Z. (2009). *Dynamic spectrum access and management in cognitive radio networks*. Cambridge University Press.

[15] Niyato, D., & Hossain, E. (2008). Spectrum trading in cognitive radio networks: a market-equilibrium-based approach. *IEEE Wireless Communications*, (December), 7180.

[16] Niyato, D., & Hossain, E. (2008). Market-equilibrium, competitive, and cooperative pricing for spectrum sharing in cognitive radio networks: analysis and comparison. *IEEE Transactions on Wireless Communications*, 7(11), 42734283.

[17] Niyato, D., & Hossain, E. (2007). Hierarchical spectrum sharing in cognitive radio: a microeconomic approach. *IEEE Wireless Communications and Networking Conference, 2007.WCNC 2007.*, 38223826. doi:10.1109/WCNC.2007.699

[18] Niyato, D., & Hossain, E. (2007). Equilibrium and disequilibrium pricing for spectrum trading in cognitive radio: a control-theoretic approach. *IEEE Global Telecommunications Conference, 2007. GLOBECOM 07.*, 48524856. doi:10.1109/GLOCOM.2007.920

[19] Niyato, D., & Hossain, E. (2010). A microeconomic model for hierarchical bandwidth sharing in dynamic spectrum access networks. *IEEE Transactions on Computers*, 59(7), 865877.

[20] Xu, P., Kapoor, S., & Li, X. (2011). Market equilibria in spectrum trading with multi-regions and multi-channels. *IEEE Global Telecommunications Conference (GLOBECOM 2011)*, 2011, 04.

[21] Niyato, D., & Hossain, E. (2007). A game-theoretic approach to competitive spectrum sharing in cognitive radio networks. *IEEE Wireless Communications and Networking Conference*, 2007.WCNC 2007., 1620. doi:10.1109/WCNC.2007.9

[22] Mutlu, H., Alanyali, M., & Starobinski, D. (2008). Spot pricing of secondary spectrum usage in wireless cellular networks. *IEEE INFOCOM 2008. The 27th Conference on Computer Communications.*, 682690. doi:10.1109/INFOCOM.2008.118

[23] Wang, F., Krunz, M., & Cui, S. (2008). Price-based spectrum management in cognitive radio networks. *IEEE Journal of Selected Topics in Signal Processing*, 2(1), 7487. doi:10.1109/JSTSP.2007.914877

[24] Yu, H., Gao, L., Li, Z., Wang, X., & Hossain, E. (2010). Pricing for up-link power control in cognitive radio networks. *IEEE Transactions on Vehicular Technology*, 59(4), 17691778.

[25] Yang, L., Kim, H., Zhang, J., Chiang, M., & Tan, C. (2011). Pricing-based spectrum access control in cognitive radio networks with random access. *2011 Proceedings IEEE INFOCOM*, 22282236.

[26] Xu, D., Liu, X., & Han, Z. (2012). Decentralized bargain: a two-tier market for efficient and flexible dynamic spectrum access *IEEE Transactions on Mobile Computing*, 11. doi:10.1109/TMC.2012.130

[27] Huang, J., Berry, R. A., & Honig, M. L. (2006). Auction-based spectrum sharing. *Mobile Networks and Applications*, 11(3), 405418. doi:10.1007/s11036-006-5192-y

[28] Zhou, X., Gandhi, S., Suri, S., & Zheng, H. (2008). eBay in the Sky: strategy-proof wireless spectrum auctions. *Proceedings of the 14th ACM international conference on Mobile computing and networking . MobiCom 08*, 213.

[29] Huang, J., Han, Z., Chiang, M., & Poor, H. (2008). Auction-based resource allocation for cooperative communications. *IEEE Journal on Selected Areas in Communications*, 26(7), 12261237. doi:10.1109/JSAC.2008.080919

[30] Wang, X., Li, Z., Xu, P., Xu, Y., Gao, X., & Chen, H.-H. (2010). Spectrum sharing in cognitive radio networks–an auction-based approach. *IEEE transactions on systems, man, and cyberneticsPart B, Cybernetics*, 40(3), 58796. doi:10.1109/TSMCB.2009.2034630

[31] Gopinathan, A., Li, Z., & Wu, C. (2011). Strategyproof auctions for balancing social welfare and fairness in secondary spectrum markets. *2011 Proceedings IEEE INFOCOM*, 30203028. doi:10.1109/INFCOM.2011.5935145

[32] Zhu, Y., Li, B., & Li, Z. (2012). Truthful spectrum auction design for secondary networks. *2012 Proceedings IEEE INFOCOM*, 873881. doi:10.1109/INFCOM.2012.6195836

[33] Gandhi, S., Buragohain, C., Cao, L., Zheng, H., & Suri, S. (2008). Towards real-time dynamic spectrum auctions. *Computer Networks*, 52(4), 879897. doi:10.1016/j.comnet.2007.11.003

[34] Jayaweera, S. K., & Li, T. (2009). Dynamic spectrum leasing in cognitive radio networks via primary-secondary user power control games. *IEEE Transactions on Wireless Communications*, 8(6), 33003310. doi:10.1109/TWC.2009.081230

[35] Jayaweera, S. K., Vazquez-Vilar, G., & Mosquera, C. (2010). Dynamic spectrum leasing : a new paradigm for spectrum sharing in cognitive radio networks. *IEEE Transactions on Vehicular Technology*, 59(5), 23282339.

[36] Vazquez-Vilar, G., Mosquera, C., & Jayaweera, S. K. (2010). Primary user enters the game : performance of dynamic spectrum leasing in cognitive radio networks. *IEEE Transactions on Wireless Communications*, 9(12), 36253629.

[37] Duan, L., Gao, L., & Huang, J. (2011). Contract-based cooperative spectrum sharing. 2011 IEEE International Symposium on Dynamic Spectrum Access Networks, 399407.

[38] Ileri, O., Samardzija, D., & Mandayam, N. B. (2005). Demand responsive pricing and competitive spectrum allocation via a spectrum server. *2005 First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005.*, 194202.

[39] Xing, Y., Chandramouli, R., & Cordeiro, C. (2007). Price dynamics in competitive agile spectrum access markets. *IEEE Journal on Selected Areas in Communications*, 25(3), 613621. doi:10.1109/JSAC.2007.070411

[40] Niyato, D., & Hossain, E. (2008). Competitive pricing for spectrum sharing in cognitive radio networks: dynamic game, inefficiency of Nash equilibrium, and collusion. *IEEE Journal on Selected Areas in Communications*, 26(1), 192202.

[41] Jia, J., & Zhang, Q. (2008). Competitions and dynamics of duopoly wireless service providers in dynamic spectrum market. *Proceedings of the 9th ACM international symposium on Mobile ad hoc networking and computing. MobiHoc 08*, 313322.

[42] Maille, P., & Tuffin, B. (2009). Price war with partial spectrum sharing for competitive wireless service providers. *IEEE Global Telecommunications Conference, 2009. GLOBECOM 2009.*, 1-6.

[43] Duan, L., Huang, J., & Shou, B. (2010). Cognitive mobile virtual network operator: investment and pricing with supply uncertainty. *2010 Proceedings IEEE INFOCOM*, (February 2009).

[44] Duan, L., Huang, J., & Shou, B. (2010). Competition with dynamic spectrum leasing. *IEEE Symposium New Frontiers in Dynamic Spectrum Access Networks 2010*, 111.

[45] Duan, L., & Huang, JianweiShou, B. (2011). Duopoly competition in dynamic spectrum leasing and pricing. *IEEE Transactions On Mobile Computing*, 11(11), 17061719.

[46] Duan, L., Huang, J., & Shou, B. (2011). Investment and pricing with spectrum uncertainty: a cognitive operators perspective. *IEEE Transactions on Mobile Computing*, 10(11), 15901604.

[47] Zhu, K., Niyato, D., Wang, P., & Han, Z. (2012). Dynamic spectrum leasing and service selection in spectrum secondary market of cognitive radio networks. *IEEE Transactions on Wireless Communications*, 11(3), 11361145. doi:10.1109/TWC.2012.010312.110732

[48] Guijarro, L., Pla, V., Tuffin, B., Maille, P., & Vidal, J. R. (2011). Competition and bargaining in wireless networks with spectrum leasing. *2011 IEEE Global Telecommunications Conference (GLOBECOM 2011)*, 16.

[49] Min, A., Zhang, X., Choi, J., & Shin, K. G. (2012). Exploiting spectrum heterogeneity in dynamic spectrum market. *IEEE Transactions on Mobile Computing*, 11(12), 20202032.

[50] Kim, H., Choi, J., & Shin, K. G. (2011). Wi-Fi 2.0: price and quality competitions of duopoly cognitive radio wireless service providers with time-varying spectrum availability. *2011 Proceedings IEEE INFOCOM*, 24532461. doi:10.1109/INFCOM.2011.5935067

[51] Tan, Y., Sengupta, S., & Subbalakshmi, K. P. (2010). Competitive spectrum trading in dynamic spectrum access markets: a price war. *2010 IEEE Global Telecommunications Conference. GLOBECOM 2010*, 15. doi:10.1109/GLOCOM.2010.5683358

[52] Dixit, S., Periyalwar, S., & Yanikomeroglu, H. (2010). A competitive and dynamic pricing model for secondary users in infrastructure based networks. *2010 IEEE 72nd Vehicular Technology Conference Fall (VTC 2010-Fall)*, 15. doi:10.1109/VETECF.2010.5594326

[53] Levent-Levi, T. (2012). Will MVNOs live long and prosper? Amdocs blogs. Retrieved from `http://blogs.amdocs.com/voices/2012/06/04/what-do-i-want-for-my-22nd-birthday-my-own-mvno-please/` Accessed 10 May 2013.

[54] Wang, S., Xu, P., Xu, X., Tang, S., Li, X., & Liu, X. (2010). TODA: Truthful Online Double Auction for spectrum allocation in wireless networks. *2010 IEEE Symposium on New Frontiers in Dynamic Spectrum (DySPAN)*, 110. doi:10.1109/DYSPAN.2010.5457905

[55] Niyato, D., Hossain, E., & Han, Z. (2009). Dynamics of multiple-seller and multiple-buyer spectrum trading in cognitive radio networks: a game-theoretic modeling approach. *IEEE Transactions on Mobile Computing*, 8(8), 10091022.

[56] Gao, L., Xu, Y., & Wang, X. (2011). MAP : Multiauctioneer Progressive auction for dynamic spectrum access. *IEEE Transactions on Mobile Computing*, 10(8), 11441161.

[57] Zhou, X., & Zheng, H. (2009). TRUST : a general framework for truthful double spectrum auctions. *IEEE INFOCOM 2009*, 9991007.

[58] Xu, H., Jin, J., & Li, B. (2010). A secondary market for spectrum. *2010 Proceedings IEEE INFOCOM*, 15. doi:10.1109/INFCOM.2010.5462277

[59] Jia, J., Zhang, Q., Zhang, Q., & Liu, M. (2009). Revenue generation for truthful spectrum auction in dynamic spectrum access. In *Proceedings of the*

tenth ACM international symposium on Mobile ad hoc networking and computing (pp. 312).

[60] Sengupta, S., Chatterjee, M., & Ganguly, S. (2007). An economic framework for spectrum allocation and service pricing with competitive wireless service providers. *2007 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, 8998. doi:10.1109/DYSPAN.2007.19

[61] Sengupta, S., & Chatterjee, M. (2009). An economic framework for dynamic spectrum access and service pricing. *IEEE/ACM Transactions on Networking*, 17(4), 12001213.

[62] Kasbekar, G. S., & Sarkar, S. (2010). Spectrum auction framework for access allocation in cognitive radio networks. *IEEE/ACM Transactions on Networking*, 18(6), 18411854. doi:10.1109/TNET.2010.2051453

[63] Ji, Z., & Liu, K. J. R. (2008). Multi-stage pricing game for collusion-resistant dynamic spectrum allocation. *IEEE Journal on Selected Areas in Communications*, 26(1), 182191. doi:10.1109/JSAC.2008.080116

[64] Courcoubetis, C., & Weber, R. (2003). *Pricing communication networks: economics, technology and modelling*. Wiley.

[65] Yu, F. R. (2011). *Cognitive radio mobile ad hoc networks*. Springer.

[66] Liu, K., & Wang, B. (2010). *Cognitive radio networking and security: A game-theoretic view*. New York: Cambridge University Press.

[67] Hardin, G. (1968). The Tragedy of the Commons. *Science*, 162(3859), 12431248.

[68] Domenico, A. De, Strinati, E. C., & Di Benedetto, M.-G. (2012). A survey on MAC strategies for cognitive radio networks. *IEEE Communications Surveys Tutorials*, 14(1), 2144.

[69] Zhu, H., Pandana, C., & Liu, K. J. R. (2007). Distributive opportunistic spectrum access for cognitive radio using correlated equilibrium and no-regret learning. *IEEE Wireless Communications and Networking Conference, 2007.WCNC 2007.*, 1115.

[70] Maskery, M., Krishnamurthy, V., & Zhao, Q. (2009). Decentralized dynamic spectrum access for cognitive radios: cooperative design of a non-cooperative game. *IEEE Transactions on Communications*, 57(2), 459469.

[71] Myerson, R. B. (199). *Game theory: analysis of conflict*. Harvard University Press.

[72] Shen, S., Lin, X., & Lok, T. M. (2013). Dynamic Spectrum Leasing under uncertainty: A stochastic variational inequality approach. *2013 IEEE Wireless Communications and Networking Conference (WCNC)*, 727732. doi:10.1109/WCNC.2013.6554653

[73] Zhang, Y., Niyato, D., Wang, P., & Hossain, E. (2012). Auction-based resource allocation in cognitive radio systems. IEEE Communications Magazine, 50(11), 108120. doi:10.1109/MCOM.2012.6353690

[74] Yan, Y., Huang, J., & Wang, J. (2012). Dynamic bargaining for relay-based cooperative spectrum sharing. *IEEE Journal on Selected Areas in Communications*, (August), 14801493.

[75] Pan, M., Liang, S., Xiong, H., Chen, J., & Li, G. (2006). A novel bargaining based dynamic spectrum management scheme in reconfigurable systems. In *2006 International Conference on Systems and Networks Communications (ICSNC06)* (Vol. 00, pp. 5454). IEEE. doi:10.1109/ICSNC.2006.10

[76] Ji, Z., & Liu, K. J. R. (2006). WSN03-3: Dynamic pricing approach for spectrum allocation in wireless networks with selfish users. In *IEEE Globecom 2006* (pp. 15). IEEE. doi:10.1109/GLOCOM.2006.939

[77] Gao, L., Huang, J., & Shou B. (2013). An integrated contract and auction design for secondary spectrum trading. *IEEE Journal on Selected Areas in Communications*, (March), 581592.

[78] Vidal, J. R., Pla, V., Guijarro, L., & Martinez-Bauset, J. (2013). Dynamic spectrum sharing in cognitive radio networks using truthful mechanisms and virtual currency. *Ad Hoc Networks*, 11(6), 18581873. doi:10.1016/j.adhoc.2013.04.010

[79] Kim, S. (2013). A repeated Bayesian auction game for cognitive radio spectrum sharing scheme. *Computer Communications*, 36(8), 939946. doi:10.1016/j.comcom.2013.02.003

[80] Lee, K., Simeone, O., Chae, C.-B., & Kang, J. (2011). Spectrum leasing via cooperation for enhanced physical-layer secrecy. In *2011 IEEE International Conference on Communications (ICC)* (pp. 15). IEEE. doi:10.1109/icc.2011.5963501

[81] Elias, J., & Martignon, F. (2013). Joint operator pricing and network selection game in cognitive radio networks: equilibrium, system dynamics and price of anarchy. *IEEE Transactions on Vehicular Technology*, 62(9), 45764589.

[82] Galla, T., & Farmer, J. D. (2013). Complex dynamics in learning complicated games. *Proceedings of the National Academy of Sciences of the United States of America*, 110(4), 12326. doi:10.1073/pnas.1109672110

[83] Yan, Y., Huang, J., Zhong, X., Zhao, M., & Wang, J. (2011). Sequential bargaining in cooperative spectrum sharing: incomplete information with reputation effect. In *2011 IEEE Global Telecommunications Conference - GLOBECOM 2011* (pp. 15). IEEE. doi:10.1109/GLOCOM.2011.6134516

[84] F. Pantisano, *et. al.*, "Spectrum leasing as an incentive towards uplink macro-cell and femtocell cooperation," *IEEE J. Select. Areas Commun.*, vol.30, no.3, pp.617-30, Apr. 2012.

[85] Yi, Y., Zhang, J., Zhang, Q., Jiang, T., & Zhang, J. (2010), "Cooperative communication-aware spectrum leasing in cognitive radio networks," *2010 IEEE Symposium on New Frontiers in Dynamic Spectrum*, Apr. 2010.

[86] Zhang, Z., Long, K., & Wang, J. (2013). Self-organization paradigms and optimization approaches for cognitive radio technologies: a survey. *IEEE Wireless Communications*, (April), 3642.

[87] Akkarajitsakul, K., Hossain, E., Niyato, D., & Kim, D. I. (2011). Game theoretic approaches for multiple access in wireless networks: a survey. *IEEE Communications Surveys & Tutorials*, 13(3), 372395. doi:10.1109/SURV.2011.122310.000119

[88] 1. Shoham, Y., Powers, R., & Grenager, T. (2007). If multi-agent learning is the answer, what is the question? *Artificial Intelligence*, 171(7), 365377. doi:10.1016/j.artint.2006.02.006

[89] T. M. Valletti, "Spectrum trading," *Telecommunications Policy*, vol. 25, no. 10-11, pp. 655–670, Oct. 2001.

[90] E. A. Jorswieck, L. Badia, T. Fahldieck, E. Karipidis, and J. Luo, "Spectrum sharing improves the network efficiency for cellular operators," *IEEE Commun. Mag.*, vol. 52, no. 3, pp. 129–136, Dec. 2013.

[91] Q. Zhao and B. Sadler, "A survey of dynamic spectrum access," *IEEE Signal Process. Mag.*, vol. 24, no. 3, pp. 79–89, May 2007.

[92] M. López-Martínez, J. J. Alcaraz, J. Vales-Alonso, and J. Garcia-Haro, "Automated spectrum trading mechanisms: Understanding the big picture," *Wireless Networks*, pp. 1–24, 2014, to be published.

[93] O. Simeone, I. Stanojev, S. Savazzi, U. Spagnolini, and R. Pickholtz, "Spectrum leasing to cooperating secondary ad hoc networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 203–213, Jan. 2008.

[94] J. Zhang and Q. Zhang, "Stackelberg game for utility-based cooperative cognitive radio networks," in *Proceedings of the 10th ACM International Symposium on Mobile Ad Hoc Networking and Computing, (MobiHoc)*, 2009, pp. 23–31.

[95] G. Zhang, K. Yang, J. Song, and Y. Li, "Fair and efficient spectrum splitting for unlicensed secondary users in cooperative cognitive radio networks," *Wireless Personal Communications*, vol. 71, no. 1, pp. 299–316, Aug. 2012.

[96] M. López-Martínez, J. J. Alcaraz, L. Badia, and M. Zorzi, "Multi-armed bandits with dependent arms for cooperative spectrum sharing," in *IEEE International Conference on Communications ICC*, 2015, to be published.

[97] P. Auer, N. Cesa-Bianchi, and P. Fischer, "Finite-time analysis of the multi-armed bandit problem," *Machine learning*, vol. 47, no. 2-3, pp. 235–256, 2002.

[98] J. Gittins, K. Glazebrook, and R. Weber, *Multi-armed Bandit Allocation Indices.* West Sussex, UK: Wiley, 2011.

[99] X. Feng, G. Sun, X. Gan, F. Yang, and X. Tian, "Cooperative spectrum sharing in cognitive radio networks: A distributed matching approach," *IEEE Trans. Commun.*, vol. 62, no. 8, pp. 2651–2644, Aug. 2014.

[100] L. Duan, L. Gao, and J. Huang, "Cooperative spectrum sharing: A contract-based approach," *IEEE Trans. Mobile Comput.*, vol. 13, no. 1, pp. 174–187, Jan. 2014.

[101] Y. Yan, J. Huang, and J. Wang, "Dynamic bargaining for relay-based cooperative spectrum sharing," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 8, pp. 1480–1493, Aug. 2013.

[102] Y. Yi, J. Zhang, Q. Zhang, T. Jiang, and J. Zhang, in *IEEE Symposium on New Frontiers in Dynamic Spectrum (DySPAN 2010)*, 2010, pp. 1–11.

[103] X. Yuan, Y. Shi, Y. T. Hou, W. Lou, and S. Kompella, "UPS: A united cooperative paradigm for primary and secondary networks," in *IEEE 10th International Conference on Mobile Ad-Hoc and Sensor Systems*, 2013, pp. 78–85.

[104] T. Nadkar, V. Thumar, G. Shenoy, A. Mehta, U. B. Desai, and S. N. Merchant, "A cross-layer framework for symbiotic relaying in cognitive radio networks," in *IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, May 2011, pp. 498–509.

[105] Y. Han, S. H. Ting, and A. Pandharipande, *IEEE Trans. Wireless Commun.*, vol. 9, no. 9, pp. 2914–2923, Sep. 2010.

[106] D. Li, Y. Xu, X. Wang, and M. Guizani, "Coalitional game theoretic approach for secondary spectrum access in cooperative cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 3, pp. 844–856, Mar. 2011.

[107] D. Niyato and E. Hossain, "Market-equilibrium, competitive, and cooperative pricing for spectrum sharing in cognitive radio networks: Analysis and comparison," *IEEE Trans. Wireless Commun.*, vol. 7, no. 11, pp. 4273–4283, Nov. 2008.

[108] S. Jayaweera, M. Bkassiny, and K. A. Avery, "Asymmetric cooperative communications based spectrum leasing via auctions in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 8, pp. 2716–2724, 2011.

[109] J. Alcaraz and M. van der Schaar, "Coalitional games with intervention: Application to spectrum leasing in cognitive radio," *IEEE Trans. Wireless Commun.*, vol. PP, no. 99, pp. 1–1, 2014.

[110] J. Huang, "Market mechanisms for cooperative spectrum trading with incomplete network information," *IEEE Commun. Mag.*, vol. 51, no. 10, pp. 201–207, Oct. 2013.

[111] A. Calvo-Armengol, "On bargaining partner selection when communication is restricted," *International Journal of Game Theory*, vol. 30, no. 4, pp. 503–515, Jan. 2002.

[112] T. T. Tran and H. Y. Kong, "Exploitation of diversity in cooperative spectrum sharing with the four-way relaying af transmission," *Wireless Personal Communications*, vol. 77, no. 4, pp. 2959–2980, Aug. 2014.

[113] D. B. Brown and J. E. Smith, "Optimal Sequential Exploration: Bandits, Clairvoyants, and Wildcats," *Operations Research*, vol. 61, no. 3, pp. 644–665, Jun. 2013.

[114] S. Pandey, D. Chakrabarti, and D. Agarwal, "Multi-armed bandit problems with dependent arms," in *ICML Proceedings of the 24th International Conference on Machine learning*, 2007, pp. 721–728.

[115] P. Si, H. Ji, F. R. Yu, and V. C. M. Leung, "Optimal cooperative internetwork spectrum sharing for cognitive radio systems with spectrum pooling," *IEEE Trans. Veh. Technol.*, vol. 59, no. 4, pp. 1760–1768, May 2010.

[116] M. Bkassiny, Y. Li, and S. K. Jayaweera, "A survey on machine-learning techniques in cognitive radios," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 3, pp. 1136–1159, Oct. 2013.

[117] L. Gavrilovska, V. Atanasovski, I. Macaluso, and L. A. Dasilva, "Learning and reasoning in cognitive radio networks," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 4, pp. 1761–1777, Mar. 2013.

[118] C. Shao, H. Roh, and W. Lee, "Aspiration level-based strategy dynamics on the coexistence of spectrum cooperation and leasing," *IEEE Communications Letters*, vol. 18, no. 1, pp. 70–73, Jan. 2014.

[119] A. Goldsmith, S. Jafar Ali, I. Maric, and S. Srinivasa, "Breaking spectrum gridlock with cognitive radios : An information theoretic perspective," *Proc. IEEE*, vol. 97, no. 5, pp. 894 − 914, May 2009.

[120] J. N. Laneman and G. W. Wornell, "An efficient protocol for realizing distributed spatial diversity in wireless ad-hoc networks," in *Proc. of ARL Fed-Lab Symposium on Advanced Telecommunications and Information Distribution*, Washington, DC, 2001, pp. 294–.

[121] D. Bertsekas, *Dynamic Programming and Optimal Control.* Nashua, NH: Athena Scientific, 2000.

[122] P. Whittle, "Multi-armed bandits and the gittins index," *Journal of the Royal Statistical Society. Series B (Methodological)*, vol. 42, no. 2, pp. 143–149, 1980.

[123] S. Gass and T. Saaty, "The computational algorithm for the parametric objective function," *Naval Research Logistics*, vol. 2, no. 1-2, pp. 39–45, Mar. 1955.

[124] J. Vermorel and M. Mohri, "Multi-armed bandit algorithms and empirical evaluation," in *Machine Learning: ECML*, 2005, pp. 437–448.

[125] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.

[126] P. Pawelczak, *et. al.*, "Performance Analysis of Multichannel Medium Access Control Algorithms for Opportunistic Spectrum Access," *Vehicular Technology, IEEE Transactions on* , vol.58, no.6, pp.3014-3031, July 2009.

[127] A. De Domenico, E. Calvanese Strinati and M.G. Di Benedetto, "A Survey on MAC Strategies for Cognitive Radio Networks," *Communications Surveys & Tutorials, IEEE* , vol. 14, no. 1, pp. 21-44, 2012.

[128] J. Jia, Q. Zhang, X. Shen, "HC-MAC: A Hardware-Constrained Cognitive MAC for Efficient Spectrum Management," *Selected Areas in Communications, IEEE Journal on* , vol.26, no.1, pp.106-117, Jan. 2008.

[129] L. Gao, X. Wang, Y. Xu and Q. Zhang, "Spectrum trading in cognitive radio networks: a contract-theoretic modeling approach," *IEEE J. Selected Areas in Comm.*, 2011.

[130] J.P. Vasseur, M. Pickavet, and P. Demeester. "Network recovery: Protection and Restoration of Optical, SONET-SDH, IP, and MPLS." Morgan Kaufmann, 2004.

[131] R. Ramjee, R. Nagarajan, and D. Towsley. "On optimal call admission control in cellular networks," *IEEE INFOCOM*, 1996.

[132] J. Vazquez-Avila, F.A. Cruz-Perez and L. Ortigoza-Guerrero, "Performance analysis of fractional guard channel policies in mobile cellular networks," *IEEE Transactions on Wireless Communications*, vol. 5, no.2, Feb. 2006.

[133] Y.-C., Liang, K.-C. Chen, G.Y. Li, and P. Mhnen, "Cognitive radio networking and communications: An overview," *IEEE Trans. Veh. Technol.* vol. 60, no. 7, pp. 3386-3407, Sept. 2011.

[134] B. Wang, and K.J. Ray Liu, "Advances in cognitive radio networks: A survey," *IEEE Journal of Selected Topics in Signal Processing*, vol. 5n no. 1 pp. 5-23, Feb. 2011.

[135] X. Zhu, L. Shen, and T.-S.P. Yum., "Analysis of cognitive radio spectrum access with optimal channel reservation," *IEEE Comm. Letters*, vol. 11, no. 4, 304-306, Apr. 2011.

[136] J. Martinez-Bauset, V. Pla, D. Pacheco-Paramo, "Comments on "analysis of cognitive radio spectrum access with optimal channel reservation"," *IEEE Comm. Letters*, vol.13, no.10, pp.739, Oct. 2009.

[137] W. Ahmed, J. Gao, H. Suraweera, M. Faulkner, "Comments on "analysis of cognitive radio spectrum access with optimal channel reservation"," *IEEE Transactions on Wireless Communications*, vol.8, no.9, pp. 4488-4491, Sept. 2009.

[138] Lai, Jin, Ren Ping Liu, Eryk Dutkiewicz, and Rein Vesilo, "Optimal Channel Reservation in Cooperative Cognitive Radio Networks," in *IEEE 73rd Vehicular Technology Conference (VTC Spring)*, pp. 1-6, 2011.

[139] P.K. Tang, Y.H. Chew, L.C. Ong, M.K.Haldar, "Performance of secondary radios in spectrum sharing with prioritized primary access," in *Military Communications Conference, 2006*, IEEE MILCOM 2006, pp. 1-7. 2006.

[140] G. Wu, P.Ren, and Q. Du, "Recall-Based Dynamic Spectrum Auction with the Protection of Primary Users," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 10 pp. 2070-2081, 2012.

[141] E. Biglieri, et. al., "Principles of Cognitive Radio," Cambridge University Press, 2012.

[142] Chen Sun; G.P. Villardi, Zhou Lan, Y.D. Alemseged, H.N. Tran, H. Harada, "Optimizing the Coexistence Performance of Secondary-User Networks Under Primary-User Constraints for Dynamic Spectrum Access," *IEEE Trans. Veh. Technol.*, vol.61, no.8, pp.3665-3676, Oct. 2012.

[143] H. Kim. and K.G. Shin, "Efficient Discovery of Spectrum Opportunities with MAC-Layer Sensing in Cognitive Radio Networks," *Mobile Computing, IEEE Transactions on* , vol.7, no.5, pp.533-545, May 2008.

[144] W. Gabran, P. Pawelczak and D. Cabric, "Throughput and Collision Analysis of Multichannel Multistage Spectrum Sensing Algorithms," *Vehicular Technology, IEEE Transactions on* , vol.60, no.7, pp.3309-3323, Sept. 2011.

[145] H. T. Cheng, H. Shan and W. Zhuang; , "Stopping Rule-Driven Channel Access in Multi-Channel Cognitive Radio Networks," *2011 IEEE International Conference on Communications (ICC)*, pp.1-6, 5-9 June 2011.

[146] E. Jung and X. Liu, "Opportunistic Spectrum Access in Multiple-Primary-User Environments Under the Packet Collision Constraint," *Networking, IEEE/ACM Transactions on* , *in press* doi: 10.1109/TNET.2011.2164933.

[147] Q. Zhao, L. Tong, A. Swami and Y. Chen, "Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework," *Selected Areas in Communications, IEEE Journal on* , vol.25, no.3, pp.589-600, April 2007.

[148] S. Huang, X. Liu and Z. Ding, "Optimal Transmission Strategies for Dynamic Spectrum Access in Cognitive Radio Networks," *Mobile Computing, IEEE Transactions on* , vol.8, no.12, pp.1636-1648, Dec. 2009.

[149] S. Huang, X. Liu and Z. Ding, "Opportunistic Spectrum Access in Cognitive Radio Networks," *in Proc. IEEE INFOCOM 2008*, pp.1427-1435, 13-18 April 2008.

[150] J. Park, P. Pawelczak, and D. Cabric, "Performance of Joint Spectrum Sensing and MAC Algorithms for Multichannel Opportunistic Spectrum Access Ad Hoc Networks," *IEEE Transactions on Mobile Computing*, *in press* doi: 10.1109/TMC.2010.186

[151] Li, Yang, et al. "Optimal Myopic Sensing and Dynamic Spectrum Access in Cognitive Radio Networks with Low-Complexity Implementations," Wireless Communications, IEEE Transactions on 11.7 (2012): 2412-2423.

[152] W.S. Jeon, J.A. Han, and D. G. Jeong, "A novel MAC scheme for multichannel cognitive radio ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 11, no. 6, pp. 922-934, June 2012.

[153] D. Xu, E.J. Dan, and X. Liu, "Efficient and Fair Bandwidth Allocation in Multichannel Cognitive Radio Networks," *IEEE Transactions on Mobile Computing*, vol. 11, no.8, pp. 1372-1385, Aug. 2012.

[154] W. Rhee and J. M. Cioffi, "Increase in capacity of multiuser OFDM system using dynamic subchannel allocation," *in Proc. IEEE VTC*, vol. 2, pp. 1085-1089, May 2000.

[155] S. Sadr, A. Anpalagan and K. Raahemifar, "Radio Resource Allocation Algorithms for the Downlink of Multiuser OFDM Communication Systems," *IEEE Communications Surveys & Tutorials*, Vol. 11, No. 3, 2009.

[156] X. Gelabert, O. Sallent, J. Prez-Romero, and R. Agust, "Flexible Spectrum Access for Opportunistic Secondary Operation in Cognitive Radio Networks," *IEEE Transactions on Communications*, vol. 59, no. 10, pp. 2659-2664, Oct. 2011.

[157] L. Jiao, F.Y. Li, and V. Pla., "Modeling and Performance Analysis of Channel Assembling in Multichannel Cognitive Radio Networks With Spectrum Adaptation," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 6, pp. 2686-2697, Jul. 2012.

[158] S. Tang and B. L. Mark, "Modelling and analysis of opportunistic spectrum sharing with unreliable spectrum sensing," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 1934-1943, Apr. 2009.

[159] D. Bertsekas, J. Tsitsiklis, "Introduction to Probability, 2nd Edition" Athenea Scientific, 2008.

[160] Solomon, H. "Geometric Probability," Philadelphia, PA: SIAM, 1978.

[161] P. Paweczak, *et. al,* "Quality of service assessment of opportunistic spectrum access: A medium access control approach," *IEEE Wireless Commun.*, vol. 15, no. 5, pp. 20-29, Oct. 2008.

[162] M. L. Puterman,*Markov Decision Processes: Discrete Stochastic Dynamic Programming.* Wiley-Interscience, Mar. 2005.

[163] D. Bolch, *et. al.,* 2006. *Queueing Networks and Markov Chains : Modeling and Performance Evaluation With Computer Science Applications* (2nd Edition). Wiley-Interscience.

[164] M. Masonta, M. Mzyece, N. Ntlatlapa, "Spectrum Decision in Cognitive Radio Networks: A Survey," *Communications Surveys & Tutorials, IEEE* , vol.PP, no.99, pp.1-20, 0 doi: 10.1109/SURV.2012.111412.00160.

[165] Q. C. Zhao, S. Geirhofer, L. Tong, and B. M. Sadler, "Opportunistic spectrum access via periodic channel sensing," *IEEE Trans. Signal Process.*, vol. 56, no. 2, pp. 785-796, Feb. 2008.

[166] Q. Zhao, L. Tong, A. Swami, and Y. Chen, "Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: a POMDP framework," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 3, pp. 589-600, Apr. 2007.

[167] Y. C. Liang, Y. H. Zeng, E. Peh, and A. T. Hoang, "Sensing-throughput tradeoff for cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, pp. 1326-1336, Apr. 2008.

[168] X. W. Zhou, J. Ma, G. Y. Li, Y. H. Kwon, and A. C. K. Soong, "Probability-based optimization of inter-sensing duration and power control in cognitive radio," *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 4922-4927, Apr. 2009.

[169] W. Y. Lee and I. F. Akyildiz, "Optimal spectrum sensing framework for cognitive radio network," IEEE Trans. Wireless Commun., vol. 7, no. 10, pp. 3845-3857, Oct. 2008.

[170] J. Zhang, L. Qi, H. Zhu, "Optimization of MAC Frame Structure for Opportunistic Spectrum Access," *Wireless Communications, IEEE Transactions on* , vol.11, no.6, pp.2036-2045, June 2012.

[171] E. Jung, X. Liu, "Opportunistic Spectrum Access in Multiple-Primary-User Environments Under the Packet Collision Constraint," *Networking, IEEE/ACM Transactions on* , vol.20, no.2, pp.501-514, April 2012.

[172]

[173]

[174] E. Biglieri et.al., *Principles of Cognitive Radio*, Cambridge University Press, 2013.

[175] D. Tuan, B.L. Mark, "Joint spatial-temporal spectrum sensing for cognitive radio networks," , *IEEE Transactions on Vehicular Technology*, vol.59, no.7, pp.3480,3490, Sept. 2010

[176] Q. Wu et.al., "Spatial-Temporal Opportunity Detection for Spectrum-Heterogeneous Cognitive Radio Networks: Two-Dimensional Sensing," *IEEE Trans. on Wireless Commun.*, vol.12, no.2, pp.516-526, Feb. 2013.

[177] D. Guoru, et.al., "Joint exploration and exploitation of spatial-temporal spectrum hole for cognitive vehicle radios," *2011 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC)*, pp.1-4, Sep. 2011.

[178] M. G. Khoshkholgh, K. Navaie, and H. Yanikomeroglu, "Access strategies for spectrum sharing in fading environment: overlay, underlay and mixed," *IEEE Trans. Mobile Comput.*, vol. 9, no. 12, pp. 1780-1793, Dec. 2010.

[179] E. G. Larsson, M. Skoglund, "Cognitive radio in a frequency-planned environment: some basic limits," *IEEE Transactions on Wireless Communications*, vol.7, no.12, pp.4800-06, Dec. 2008.

[180] E. Axell, E.G. Larsson, D. Danev, "Capacity considerations for uncoordinated communication in geographical spectrum holes," *Physical Communication*, vol. 2, no.1, pp- 3-9, Mar. 2009.

[181] J. J. Alcaraz, J. A. Ayala-Romero, M. Lopez-Martinez, J. Vales-Alonso, "Combining Dual Tesselation and Temporal Access for Spectrum Reuse in Cellular Systems", *11th International Symposium on Wireless Communication Systems*, Aug. 2014.

[182] A. Goldsmith, *Wireless Communications*, Cambridge University Press, 2005.

[183] K. Marti, *Stochastic Optimization Methods*, Springer-Verlag, Berlin-Heidelberg, 2008.

[184] E. Angn et.al., *Response surface methodology with stochastic constraints for expensive simulation*, Journal of the Operational Research Society, 60 (6) (2009), pp. 735-746.