Efficient Pricing Technique for Resource Allocation Problem in Uplink OFDM Cognitive Radio Networks

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***Abstract*— Cognitive radio (CR) has been proposed to solve the problem of spectrum underutilisation by opportunistically accessing unutilised bands. In this research, the problem of resource allocation in OFDM-CR networks has been examined. The main objective of this study, is to provide better control management for the interference to the primary user (PU) while maintain low complexity to the proposed algorithm. This objective has been secured by adopting pricing scheme to develop better power allocation algorithm with respect to the interference management. The performance of the proposed power allocation algorithm is tested for OFDM-based CRNs and has been compared to a number of related algorithms in the literature. The simulation results show excellent performance for the proposed algorithm compared to that algorithms presented in the literature with lower computational complexity, $O(NM)+O(N\log(N))$, compared to the optimal solution.**

Keywords: OFDM Cognitive radio, resource allocation, pricing theory.

I. INTRODUCTION

Various studies conducted by the Federal Communications Commission (FCC) have proven that the conventional spectrum allocation approach is becoming insufficient to address the rapid development of wireless communications technologies, and there is a call for the development of an open spectrum allocation methodology to compensate for spectrum underutilisation [1]. To meet this important demand in the wireless spectrum, dynamic spectrum access (DSA) and cognitive radio (CR) have been developed as innovative techniques to resolve the problems related to the fixed spectrum approach. OFDM technique, on the other hand, is seen as a promising candidate for cognitive radio networks (CRNs) due to its reliability and flexibility in allocating the available resources among CRs [2, 3]. In OFDM CRNs, the CR and PU band exist side by side, which results in mutual interference [4]. This interference is considered as a degradation factor that mainly affects the performance of primary network. The resource allocation problem in uplink non-cognitive radio networks has been widely examined, e.g.,[5, 6]. In OFDM-based CRNs, however, two different users exist side by side and simultaneously transmit, which results in mutual interference. Thus, the use of a conventional water-filling algorithm to allocate power is not sufficient, and an additional constraint must be defined in the optimisation problem to control the negative effects of the generated interference from CR to PU. The problem of resource allocation in the context of multicarrier CRNs based on supermarket theory has garnered much interest in the literature, see, for example,[7], and [8]. Moreover, pricing theory have been proven to provide efficient spectrum sharing among CRs and PUs because such technique define the interaction and competition among players[9]. Furthermore, pricing technique has been adopted to solve the problem of resource allocation in MC-CRNs as presented in [10-12]. In [10], a linear pricing scheme is proposed to manage not only the spectrum competition among CRs but also the correlation between the transmit power and assigned sub-channels for each CRs. Additionally, a distributed algorithm based on pricing technique is proposed to maximize the energy efficiency (EE) and maintain good quality-of-service (QoS) requirement for the PUs. A pricing approach in MC-distributed CRNs has been adopted in [11]. The pricing function is composed of two components: one component manages the interference among CRs, and the other component manages the negative effects from active CRs to the PU's sub-band. Unlike [10], the proposed algorithm in [11] is tested for convergence to the NE. Another market games has been considered in [12]. The most attractive component of this work, compared to other studies, is the adoption of the Colonel Blotto market game to model not only the problem of resource allocation in uplink scenario, but also in the downlink scenario as well.

In this paper, we consider more realistic uplink scenarios in OFDM-based CRNs by adopting a pricing scheme in the utility function. The main objective is to maximise the uplink capacity of the CRNs, respecting the interference limit to the PUs with a lower computational complexity compared to that in the optimal solution. Furthermore, the main contribution of this paper is that the pricing scheme is adopted to achieve two goals: (i) reducing the complexity of the optimisation problem (ii) and providing flexibility in managing the interference introduced to the Pus rather than increasing the revenue of the PUs as presented in [12] and [12].

The remainder of this paper is organised as follows. In Section II, the system model has been presented, including the OFDM-based CR, system setting and interference model. Section III, the problem formulation and the related constraints have been developed. The uplink market model based on the pricing scheme is illustrated in Section IV. The simulation results of the proposed market power allocation algorithm and a comparison study are provided in Section V. Finally, we conclude this paper in Section VI.

II. SYSTEM AND INTERFERENCE MODEL

A hybrid CRNs in an underlay spectrum-sharing scenario has been considered in uplink manner. Figure 1 (a) shows an example of the network being investigated. Moreover, a single cell OFDM- CRN has been considered in this paper. The CRN consist of M CRs, denoted by $M = \{1,2,...,M\}$, sharing the licensed band with L PUs. An uplink transmission has been assumed in which the CRs are utilizing the vacant PU band opportunistically and communicating to their base station without causing interference to the owner of the spectrum. The whole spectrum band is divided into N subcarriers, denoted by $N = \{1,2,...,N\}$, with bandwidth represented by Δf. Moreover, The distribution of the frequency among CRs and PUs is supposed to be side by side frequency distribution as shown in Figure 1-b-. The frequency band named as $B_1^{PU}, B_2^{PU},..., B_L^{PU}$ have been utilized by the PUs and denoted as the active band while the rest of frequency bands represent the non-active band. The CR can utilize both active and non-active band if the generated interference to the PU does not exceed the predefined interference limit termed as (I_{th}). The channel gains of the links shown in Figure1-a- can be defined as follows, $g_{m-l,i}^c$ denote the channel gain of the interference link from m^{th} CR to the l^{th} PU on the i^{th} subcarrier where the superscripts (^{c}) refer to the CR. $y_{l-m,i}^p$ denote the channel gain of the interference link from the l^{th} PU's transmitter to the m^{th} CR over the i^{th} subcarrier where the superscripts (^{p}) refer to the PU. $h_{i,m}$ denotes the i^{th} subcarrier fading gain from the m^{th} user on the i^{th} subcarrier to the CRBS.

The critical issue that must be treated seriously in CRN is the generated interference from CR-to-PU. In order to achieve convenient coexistence between CR and PU, this interference must be well controlled to avoid the any degradation in the performance of the primary user network. Assuming that $\phi_i(f)$ is the power spectrum density of the i^{th} OFDM subcarrier which can be modeled according to

$$\phi_i(f) = p_{i,m} T \left(\frac{\sin \pi f T}{\pi f T} \right) \quad (1)$$

where, T is the OFDM symbol duration and $p_{i,m}$ is the total power produced by the m^{th} user on the i^{th} subcarrier. To be more specific, the interference induced by active CR to the PU can be defined as the integration of the power density spectrum of the i^{th} subcarrier across the l^{th}PU band as shown in (2).

$$I_{m,i}^{PU_l}(d_i^l, p_{i,m}) = P_{i,m}\Omega_{i,m}^l;\ \Omega_{i,m}^l = \int_{d_i - B_l/2}^{d_i + B_l/2} \left| g_{m-l,i}^c \right|^2 \phi_i(f) df \quad (2)$$

where, d_i^l is the distance between the i^{th} subcarrier and the l^{th} PU's spectrum band, $\Omega_{i,m}^l$ is the interference factor of the i^{th} subcarrier to the l^{th} PU's spectrum band and B_l is the PU's bandwidth band. In contrast, the interference power generated from the PU to the band of the CR can be defined as the integration of the PSD of the l^{th} PU across the i^{th} subcarrier as follows [7]:

$$I_{l,i}^{CR_m}(d_i^l, P_l^P) = \int_{d_i^l - \Delta f/2}^{d_i^l + \Delta f/2} \left| y_{l-m,i}^P \right|^2 \phi_l(f) df \quad (3)$$

where, $\phi_l(f)$ is the power spectrum density of the l^{th} PU signal.

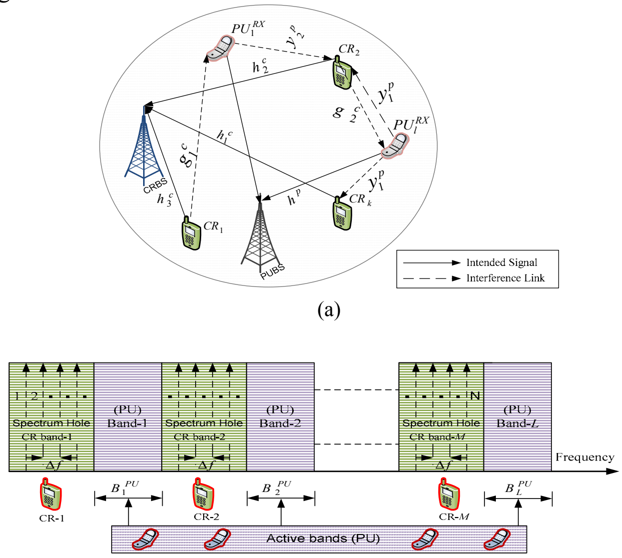

Fig.1. System model: (a) coexistence among PUs and CRs, (b) frequency distribution of the active and non-active primary bands.

II. PROBLEM FORMULATION

The best way to avoid the interference problem in CRN can be achieved by introducing concrete interference and power constraints. Moreover, adopting pricing scheme is an attractive method to maintain good performance in the primary network. Assuming that I_{th} represent the maximum tolerable interference by the PU and $\widetilde{P}_m$ is the maximum power budget constraint for the m^{th} CR. Without loss of generality, $\widetilde{P}_m$ is assumed to be constant for all CRs in the network. Let $s_{i,m}$ to be the binary indicator for the subcarrier allocation, $s_{i,m} = 1$ if and only if the given subcarrier is belong to the m^{th} user and $s_{i,m} = 0$, otherwise. Following the above mentioned assumptions, the interference constraints can be defined as follows:

$$\sum_{m=1}^{M} \sum_{i=1}^{N} s_{i,m} p_{i,m} \Omega_{i,m}^l \le I_{th}, \forall l \in \{1,2,..., L\} \quad (4)$$

Furthermore, the transmission power for CRs must be less than the maximum local power budget of each CR ($\widetilde{P}_m$). Hence, the total power constraint for the m^{th} CR can be represented according to (5).

$$\sum_{i=1}^{N} s_{i,m} p_{i,m} \le \widetilde{P}_m, \qquad \forall m \tag{5}$$

Following the assumptions, the signal-to-interference-plus noise ratio, abbreviated as SINR, for the i^{th} subcarrier can be formulated according to

$$\gamma_i^m = \frac{p_{i,m} \left|h_{i,m}\right|^2}{\delta_{AWGN} + \sum_{l=1}^{L} I_{l,i}^{CR_m}} = \frac{p_{i,m} \left|h_{i,m}\right|^2}{I^{Tot}} \tag{6}$$

The total interference denoted by I_i^{Tot} can be formed as follows:

$$I^{Tot} = \delta_{AWGN} + \sum_{l=1}^{L} I_{l,i}^{CR_m} \tag{7}$$

where, δ_{AWGN} is the mean variance of the additive white Gaussian noise (AWGN) and $I_{l,i}^{CR_m}$ is the interference introduced by the l^{th} PU to the m^{th} CR on the i^{th} subcarrier. Additionally, the Interference component from the PU-to-CR ($I_{l,i}^{CR_m}$) is assumed to be the superposition of large number of independent random variable components, i.e. $\sum_{l=1}^{L} I_{l,i}^{CR_m}$. Thus, the interference component ($I_{l,i}^{CR_m}$) can be modeled as AWGN by adopting the central limit theorem. Consequently, by considering equation (6), the transmission rate of the i^{th} subcarrier utilized by the m^{th} CR can be formulated according to

$$R_i^m = \Delta f \log_2(1+\gamma_i^m). \tag{8}$$

Hence, the resource allocation problem in the uplink OFDM-CRN can mathematically be formulated as in (P.1).

$$\text{P.1} : \max_{p_i^m} (R_i^m),$$

s.t.,

$$\begin{cases} C1 : s_{i,m} \in \{0,1\}, \quad \forall i, m, \\ C2 : \sum_{m=1}^{M} s_{i,m} \le 1, \quad \forall i, \\ C3 : \sum_{m=1}^{M} \sum_{i=1}^{N} s_{i,m} p_{i,m} \Omega_{i,m}^{l} \le I_{th}, \forall l \in \{1,2,..., L\}, \\ C4 : \sum_{i=1}^{N} s_{i,m} p_{i,m} \le \widetilde{P}_m, \quad \forall m \\ C5 : p_{i,m} \ge \overline{P}_m, \quad \forall i, m \end{cases} \tag{P4.1}$$

where, $\widetilde{P}_m$ denotes the maximum power budget for the m^{th} CR and L denote the number of active PU bands. Generally speaking, the optimization problem in (P.1) deals with both binary variables and continuous variables and resulted in a mix optimization problem, which is NP hard problem. Furthermore, achieving the optimal solution requires high computational complexity in such optimization problem. In the following section, a convenient solution to (P.1) is provided by adopting pricing technique in order to relax some constraint to simplify the solution of the optimization problem and to reduce the computational complexity as well.

IV. UPLINK MARKET MODEL

A common solution to RA problem is solved it via two stages, subcarrier allocation stage and Uplink-Market power allocation stage (**UMPA**).

A. Subcarrier Allocation Algorithm

To obtain an efficient subcarrier allocation in uplink CRN, the algorithm should allocate the subcarriers to CRs considering per-CR power constraint, channel quality for each user and interference constraint which more complicated compared to that in the classical uplink scenario. In this context, the subcarrier allocation algorithm proposed in [4] is adopted in this work. Note that, compared to [4], the subcarriers allocation problem in this work is solved without rate constraints for the CRs. Hence, there is no restriction in allocating the subcarriers to any of CRs.

Algorithm 1: Subcarriers Allocation

1) Preliminary step: in this step, the following assumption is made as follows
   a) Assuming that I_{th}^* is the interference introduced to the PUN and it is divided uniformly among the available subcarrier [7].
   b) Following the above assumption, the maximum amount of interference, denoted by $I_{Uniform}^*$, can be formulated as follow $I_{Uniform}^* = \frac{I_{th}^*}{N}$ [4].
   c) By referring to equation 2, the maximum power that can be assigned to the i^{th} subcarrier when it is assigned to the m^{th} CR is formulated according to, $P_{i,m}^{\max} = \frac{I_{Uniform}^*}{\Omega_{i,m}^{l*}}$.
2) Definition step: the following sets can be defined as follows
   a) C: unassigned subcarrier set.
   b) A_m: include the subcarriers that allocated to the m^{th} CR with powers equal to the maximum power $P_{i,m}^{\max}$.
   c) B_m: include the subcarriers that allocated to the m^{th} CR with powers equal to the average power.
   d) Average Power: the average power is the remaining power for the m^{th} CR after assigning the powers to the subcarriers in the set A_m divided among the subcarriers in the set B_m, that is $P_m^{avg} = \frac{\widetilde{P}_m - \sum_{x \in A_m} P_{x,m}^{\max}}{|B_m|}$
3) Assigning procedure: assuming primarily that set A_m and B_m are empty sets then to allocate a given subcarrier, let say i^*, the following procedure is performed as follows
   a) Evaluate the $P_{Test} = \frac{\widetilde{P}_m - \sum_{r \in A_m} P_{r,m}^{\max}}{|B_m| + 1}$
      - Check:
      - if $P_{Test} \ge P_{i^*,m}^{\max}$
      - let $A_m^* = A_m^* \cup \{i^*\}$, and $B_m^* = B_m$
      - else let $B_m^* = B_m^* \cup \{i^*\}$, and $A_m^* = A_m$.

b) Rate calculation: Calculate the amount of increment in the data rate when the subcarrier i^* is allocated to the m^{th} CR according to

$$\nabla_m = R_m^n - R_m^o = R(m, A_m^*, B_m^*) - R(m, A_m, B_m), \quad (9)$$

where, the superscripts (n) and (o) refers to the new and old rate respectively and $R(m, A_m^*, B_m^*)$ and $R(m, A_m, B_m)$ can be determined as follows:

$$R(m, A_m, B_m) = \sum_{i\in A_m} R_i(P_m^{\max}, h_{i,m}) + \sum_{i\in B_m} R_i(P_m^{avg}, h_{i,m}) \quad (10)$$

Note that $R_i(P_{i,m}, h_{i,m})$ is calculated using equation (8).

c) Find m^* fulfilling $m^* = \arg\max_m(\nabla_m)$, set the subcarrier indicator to one i.e., $s_{i^*,m} = 1$, and update set A and B as follows: $A_{m^*} = A_{m^*}^*$ and $B_{m^*} = B_{m^*}^*$

4) Subcarriers update: take out the subcarrier i^* from the C set and repeat the above mentioned steps till reach to empty C set.

B. Uplink Market Power Allocation (***UMPA***)

In the first stage, the subcarriers are allocated to the CR users. That means, the binary values of the subcarrier indicators ($s_{i,m}$) is known. Therefore, the problem of resource allocation can be viewed virtually as a single user optimization problem. In the power allocation sub-problem, however, the pricing technique is adopted from market theory to put more simplification to the optimization problem defined in (P.1). Thus, the interference constraint in (P.1) is neglected and letting the pricing scheme control the interference generated to PUs. Thus, the uplink market power allocation can be defined as follows:

$$\textbf{UMPA}\left\langle M, \{a_i^{\text{ction}}\}, \{S^c(\bullet)\}\right\rangle$$

where, $M = \{1,2,...,M\}$ is a finite set of decision makers; $\{a_i^{\text{ction}}\}$ is the action space, which include power to subcarrier allocation; and $S^c(\bullet)$ is the surplus function or utility function, where the superscript (^{c}) refers to CR. Let assume that the power strategy for CRs in each subcarrier is compact convex set bounded by minimum and maximum power budget denoted by $\hat{P}_{i,m} = [\overline{P}_m, \widetilde{P}_m]$. Hence, the strategy space can be defined as follows

$$\hat{P}_{i,m} = \left\{ \boldsymbol{P}_{i,m} : \sum_{i=1}^{N} p_{i,m} \le \widetilde{P}_m,\ \overline{P}_m \le p_{i,m} \le \widetilde{P}_m, \forall i \in N \right\} \quad (11)$$

1. Design of Surplus Function and Uplink Power Algorithm

The common surplus function in the market theory is the transmission rate. Moreover, the surplus function can be chosen as a function of the action chosen by player m on the i^{th} subcarrier, and the actions chosen by all of the players in the game except those of player m, which can be formulated as follows

$$S_{i,m}^c(\boldsymbol{p_{i,m}}, \boldsymbol{p_{-i,m}}) = \sum_{i=1}^{N} \log_2\left(1 + \frac{\gamma_i^m}{I_i^{Tot}}\right) - p_i^m \sum_{l=1}^{L} \alpha_l \Omega_{i,m}^l \quad (12)$$

where $S_m^c(\bullet)$ is the surplus function for m^{th} CR, in which α_l is the pricing controlling factor. Consequently, pricing scheme is adopting to reduce the complexity of (P.1) by relaxing the interference constraint, i.e., ($C3$). Thus, (P4.1) can be rewritten as follows:

$$\text{P.2} : \max_{\hat{p}_{i,m}} (S_{i,m}^c),$$

s.t.

$$\begin{cases} C1: \sum_{i\in N_m} \hat{p}_{i,m} \le \widetilde{P}_m, & \forall m \\ C2: \hat{p}_{i,m} \ge \overline{P}_m, & \forall i \end{cases} \quad (\text{P.2})$$

where, m in $\hat{p}_{i,m}$ denotes to the CR who's already given the subcarrier i, i.e., $s_{i,m} = 1$ and N_m refers the set of subcarriers assigned to the m^{th} CR. The defined problem P.2 is convex problem in which the optimal solution can be derived easily. Moreover, the existence of the Nash equilibrium (NE) in the market model is omitted due to the page limit, and the existence of the NE can be easily derived similar to [13].

The optimal power algorithm in the uplink scenario can be derived according to the following proposition.

***Proposition* 1**: If the power is allocated to subcarriers by maximizing (P.2), then the optimal power strategy across the subcarriers is formulated as follows:

$$\hat{p}_{i,m} = \left[\frac{1}{\sum_{m=1}^{M} \beta^{user} + \sum_{l=1}^{L} \alpha_l \Omega_{i,m}^l} - \frac{I^{total}}{|h_{i,m}|^2} \right]^+ \quad (13)$$

Proof: the Lagrange method has been adopted to derive the optimal solution to the constrained optimization problem in (P.2). Hence, the Lagrange function can be defined as follows:

$$\Gamma(\hat{p}_{i,m}) = \sum_{i=1}^{N} \log_2\left(1 + \frac{\hat{p}_{i,m}|h_{i,m}|^2}{I^{Tot}}\right) - \hat{p}_{i,m} \sum_{l=1}^{L} \alpha_l \Omega_{i,m}^l - \sum_{m=1}^{M} \beta_m \left(\sum_{i=1}^{N} \hat{p}_{i,m} - \widetilde{P} \right) + \sum_{i=1}^{N} \hat{p}_{i,m} \lambda_i$$

where, the Karush-Kuhn-Tucker (K.T.T) conditions can be written as follows:

$$\hat{p}_{i,m} \ge \overline{P},\ \forall i \in \{1,2,...,N\}, \quad \beta_m \ge 0,\ \forall m \in \{1,2,...,M\},$$
$$\lambda_i \ge 0, \quad \beta_i \hat{p}_{i,m} = 0,\ \forall i \in \{1,2,...,N\}, \text{ and } \sum_{m=1}^{M} \beta_m(\hat{p}_{i,m} - \widetilde{P}) = 0, \quad (14)$$

where, β and λ are the non-negative Lagrange multipliers. The optimal power algorithm can be derived by taking the partial derivative of (16) with respect to $\hat{p}_{i,m}$, and equating the result to zero. This gives,

$$\hat{p}_{i,m} = \left[\frac{1}{\sum_{m=1}^{M} \beta_m + \sum_{l=1}^{L} \alpha_l \Omega_{i,m}^l} - \frac{I^{Tot}}{|h_{i,m}|^2} \right]^+ \quad (15)$$

where $[\bullet]^+ = \max(0,\bullet)$. The optimal power strategy presented in (15) comes with single Lagrange multiplier compared to two Lagrange multipliers in a number of related studies in the literature [4, 7]. Therefore, the computational complexity of the proposed algorithm is minimized compared to that in the optimal solution, which is one of the achievements behind adopting the pricing mechanism in this work. Note that the Lagrange multiplier (β_m) in the uplink scenario is derived for each CR user in the network because of the availability of per-user power constraints in the uplink scenario. Therefore, the Lagrange multiplier can solved by substituting (15) in the per-CR power constraints, i.e., $C1: \sum_{i=1}^{N} \hat{p}_{i,m} \le \tilde{P}_m$ in (P.2). This gives,

$$\beta^{user} = \frac{m|N|}{\psi_l \left(\tilde{P}_m + \sum_{i=1}^{N} \frac{I^{Tot}}{|h_{i,m}|^2} \right)} - \frac{\sum_{l=1}^{L} \alpha_l \Omega^{avg}}{m} \quad (16)$$

Accordingly, the optimal power strategy algorithm can be reformulated by considering (16), that is

$$\hat{p}_{i,m} = \left[\frac{1}{\sum_{m=1}^{M} \beta^{user} + \sum_{l=1}^{L} \alpha_l \Omega_{i,m}^{l}} - \frac{I^{Tot}}{|h_{i,m}|^2} \right]^+ \quad (17)$$

■

Following the above derivations and analysis, the uplink market power algorithm (**UMPA**) is proposed as shown in Algorithm 2.

Algorithm 2: **U**plink **M**arket **P**ower **A**llocation (**UMPA**)

1: Initialization step: $N, M, \tilde{P}_m, \overline{P}_m, \alpha_l, \Omega_{i,m}^{l}, I^{Tot}$
2: Set the value of α_l, such that the interference constraint is respected.
3: Call Pricing-Based Water-filling:
- Find β_m according to (16)
- Set, $\hat{p}_{i,m}$ according to (17)

4: Declare the power $\hat{p}_{i,m}$.
5: end

V. SIMULATION RESULTS AND COMPLEXITY ANALYSIS

A. Simulation Results

The simulations are implemented according to the system model shown in Fig. 1. The multicarrier networks consist of $M = 5$, and the total number of subcarriers is assumed to be $N = 32$. The values of $\Delta f, \tilde{P}, I_{th}^1 = I_{th}^2$ and $B_1^{PU} = B_2^{PU}$ are assumed to be 0.3125 MHz, 1 W, 1 mW and 10 MHz, respectively. The thermal noise is assumed to be 10^{-6}. The subcarrier fading gains h and g are assumed to be the outcome of independent, identically distributed (i.i.d) Rayleigh distributed random variables with unity mean. Furthermore, the channel gains are assumed to be perfectly known by the CRBS. In addition, all the results have been compiled over 1000 iterations. For fair comparison with the related studies [4, 14], two active PU bands are assumed with two interference constraints, that is L=2, $B_1^{PU} = B_2^{PU}$ and $I_{th}^1 = I_{th}^2$. The simulation model is as depicted in Figure 2.

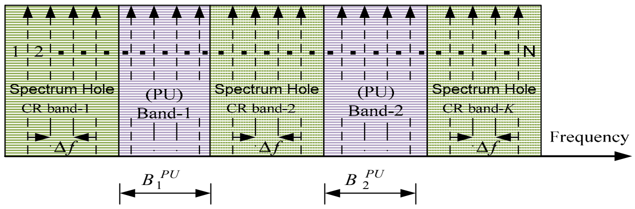

Fig.2.Simulation model in Uplink OFDM-CRNs

Figure 3 shows the average sum rate of the CRN versus different defined interference constraints related to defined thresholds, $I_{th}^1 = I_{th}^2$. It can be noted that the sum rate increases when the interference threshold increases. This is because each CR, in this case, has the flexibility in assigning more power on its own subcarriers. Additionally, the performance of the **UMPA** algorithm outperforms Wang-algorithm and approaches to the PI-algorithm.

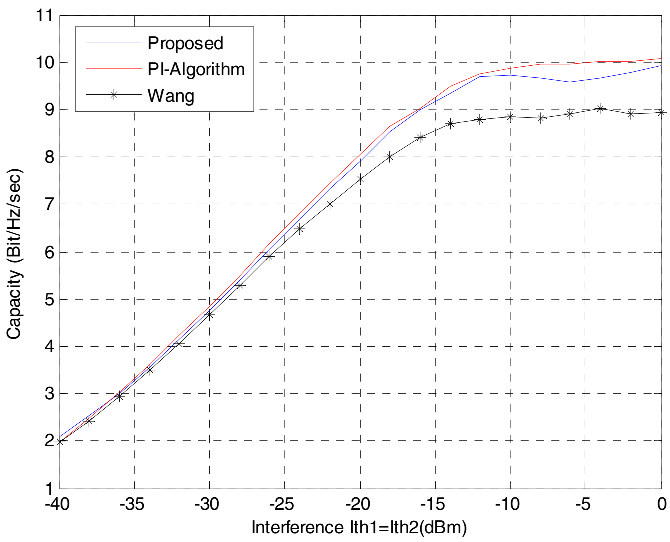

Figure 3 Achieved capacity vs. interference threshold

The net interference generated to the PUs using **UMPA**, PI-algorithms and Wang-algorithm with $I_{th}^1 = I_{th}^2$ is plotted in Figure 4 and Figure 5 respectively. It can be observed that the net interference produced by the proposed **UMPA** algorithm satisfies the pre-defined interference constraints in both bands, i.e., B_1^{PU} and B_2^{PU} . Moreover, it can be noted that the proposed algorithm shows more flexibility in interference management compared to reference algorithms because of adopting the pricing scheme which can play an important role in terms of respecting the interference constraint.

B. Computational Complexity

The complexity of the subcarrier allocation stage can be determined based on the total number of users (M) and subcarriers (N). Therefore, every subcarrier requires no more than M calculations to be allocated to one CR user and then, the complexity of the first stage is $O(NM)$. Furthermore, the interference constraint and the related Lagrange multiplier are omitted by adopting pricing scheme. Then, the proposed **UMPA** algorithm requires one operation of priced-based water-filling algorithm. Hence, the computational complexity for the proposed power allocation algorithm is equal to the computational complexity of the classical water-filling algorithm, that is $O(N\log(N))$. As a result, the total computational complexity is equal to the summation of the complexity of the two stages. Thus, the total complexity is $O(NM)+O(N\log(N))$. Compared to the optimal scheme, the proposed algorithm has much lower computational complexity because the optimal scheme requires (M^N) iterations to assign subcarriers to the available users and the overall complexity is $O(N^3M^N)$.

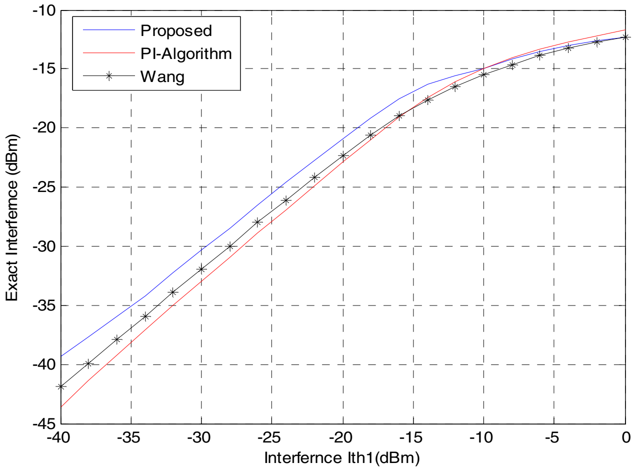

Figure 4 Interference to the PU vs. interference threshold

VI. CONCLUSION

In this paper, we have proposed a market-based uplink power allocation method in an underlay cognitive radio network termed as **UMPA**. The pricing scheme has been adopted from market theory to provide flexibility in distributing the power budget to the available subcarriers. Hence, the CRs can utilise all allowable interference produced by the PU. Moreover, the proposed algorithm offers good capacity compared to the previously tested algorithm in the context of OFDM-CRNs. Furthermore, the computational complexity of the proposed algorithm is reduced to $O(NM)+O(N\log(N))$ compared to $O(N^3M^N)$ in the optimal solution, which makes the proposed algorithm more suitable for practical implementation.

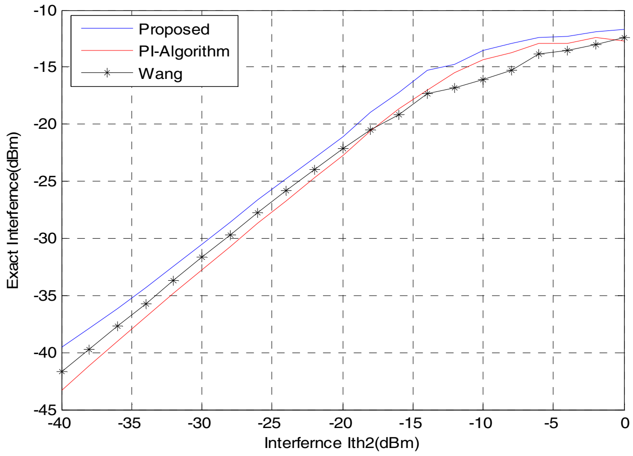

Figure 5. Interference to the PU vs. interference threshold

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