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Second Order Suboptimal Power Allocation for MIMO-OFDM Based Cognitive Radio Systems

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Received June 30, 2013; revised December 20, 2013; revised May 3, 2014; accepted June 19, 2014; published August 29, 201

Abstract

This paper proposes an efficient and low complexity power-loading algorithm for MIMO-OFDM downlink based cognitive radio system that maximizes the sum rate of single secondary user (SU) under constraints on the tolerable interference thresholds between secondary user and primary user's frequency bands and the total transmission power. Our suboptimal algorithm is based on the 2nd order interference tracking and nulling mechanism to allocate transmission power of the subcarriers among SU's scheme. The performance of our proposed suboptimal scheme is compared with the performance of the classical power loading algorithms, e.g., water filling, 1st order interference tracking, nulling, and other suboptimal schemes. Numerical results show that our algorithm has low complexity but obtains a higher channel capacity than that of some previous suboptimal algorithms in some scenarios. We dedicate also that for a given interference threshold, the 2nd order interference tracking mechanism has dynamic number of nulling position instead fixed number of nulling position.

Keywords: Cognitive Radio, MIMO, OFDM, Power Allocation Optimization

A preliminary version of this paper appeared in ACM IMCOM (ICUIMC) 2013, January 17th – 19th 2013 Kota Kinabalu, Malaysia. This version provides a concrete analysis for the 2nd order interference tracking in MIMO system. Revised version supports analyzing the total throughput of Cognitive User coexist with different bandwidth of Primary User, where two scenarios of spectrum allocation are presented. This funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 102.02-2011.15.

http://dx.doi.org/10.3837/tiis.2014.08.004

1. Introduction

In the conventional wireless networks, the allocation of the frequency bands is constant. The entire frequency band is managed by a single committee (FCC). The spectrum allocated to licensed users, which are not occupied at all-time leads to the existence of spectrum hole or white space despite radio spectrum, is one of the most valuable resources for wireless communications. According to the report of FCC spectrum is extremely underutilized mostly due to the unreasonable command and control spectrum regulation [1,2]. Orthogonal Frequency Division Multiplexing (OFDM) based Cognitive Radio (CR) has been considered largely as a solution to improve the spectrum efficiency by exploiting unused spectrum dynamically [7]. A cognitive user can transmit in particular frequency bands that are not concurrently used by any primary users. Unlicensed users can temporally use these bands by using cognitive radio technology. As unlicensed users called secondary CR users uses unused spectrum, in many cases both CR and Primary User (PU) systems exist side-by-side band. In this system, CR users detect the white space of PU. The most important duty of the CR networks is to determine how the secondary users use these holes. Different strategies have thus been proposed for this problem, one of them is that after unused bands are recognized, CR users will arrange to transmit or receive in these bands but avoid interference to PU. The mutual interference is the limiting factors that reduce the performance of both networks.

OFDM, a popular technique in wireless communications with many advantages is a potential candidate for cognitive radio system. This is mainly due to its great flexibility in dynamically allocating the unused spectrum among secondary user. Another important feature of OFDM, which is ideally exploited for cognitive radio system, comes from inherent flexibility wherein individual subcarriers or subset of the subcarriers can carry different weight of power. Based on this aspect, multiple-input and multiple-output (MIMO) techniques is integrated into cognitive radio systems to increase the capacity. Multiple antennas are employed at both transmitter and receiver to exploit the spatial diversity that exists in a MIMO channel. In MIMO-OFDM based cognitive radio systems the CR coordinator should be determine the power, which are assigned to each CR subcarrier and transmit antenna to maximize the transmission throughput.

In order to come up with an effective spectrum-sensing algorithm, it requires considering the computational complexity of the power allocation procedure. Several suboptimal algorithms with low complexity have been proposed. This paper specifically addresses the 2nd order interference tracking mechanism at the suboptimizing total throughput of MIMO-OFDM of CR users under sum-power and interference constraints. The results of simulations of the proposed mechanism show a significant gain in transmission capacity with lower complexity than optimal allocation. The significant progress for channel capacity when using MIMO technique compared to SISO has been also presented clearly at the simulation results.

2. Related Work

There has been a number of works focusing on the system schemes and spectrum access aspects of CR systems. The power allocation problem for OFDM-based cognitive radio networks has been examined in [3], [5], where an optimal scheme, derived by Lagrangian formulation, is proposed to maximize the downlink capacity of the cognitive users while guaranteeing the interference introduced to the primary user should be lower than the specified threshold. For a given subchannel assignment, the standard convex optimization problem has complexity, which grows exponentially with the input size that generally has a complexity of $O((N+K)^3)$ where N and K are the number of subcarriers, and number of SU users, respectively [4]. In order to reduce the computational complexity, the problem is solved in two steps by many of the suboptimal algorithms [15]. It is important to mention that the CR coordinator should determine its possible transmission, this process, however, should be computationally simple and fast in order to catch up the changing of conditional parameters. High computational complexity may not be feasible in power-constrained systems. Thus, the requirement of suboptimal algorithms with low complexity is necessary. Several suboptimal methods with low complexity have been proposed to achieve as close as the performance of the optimal power allocation.

Results in [5,6] show that the optimal solution of capacity can be achieved by water-filling policy. It means that more power should be allocated to the subcarrier, which has relatively better channel quality and is relatively far away from the PU's bands. We will refer to the capacity of this method as the benchmark of a cognitive radio system in comparison to others algorithms. The first simple suboptimal method of reducing the complexity is nulling the power at neighboring subcarriers towards PU's bands [3,5]. In this way we can limit the interference most from SU to PU's bands. In this method, subcarriers of SU neighbor PU's bands are eliminated from power allocation optimization and we can reduce the complexity of system. Nulling method still needs to solve optimization problem then the number of computation is a burden but its capacity performance is far from optimal solution. Uniform power loading is another solution, which has been presented in [5,6,13]. In this method, all subcarriers are assigned with the same power lever while keeping the interference to PU's bands lower than a threshold. Although it reduces significantly the complexity, this method has a very low performance. In [5], the authors have proposed suboptimal power loading algorithms to maximize downlink transmission capacity of CR system. This study suggested two suboptimal schemes (named scheme A and B) to reduce the numerical calculation.

It has been known that the far distance to PU's bands the less interference to it. In scheme A, authors assume that the interference from SU's subcarriers linearly decreases starting from the nearest neighbor subcarrier to PU's bands. Based on this assumption, the power will be allocated increasing by fix step to subcarriers of SU. We mention that this method is based on the first order of the interference tracking. In scheme B, the power allocated to subcarrier is chosen inversely proportional to its interference to PU's bands. Both schemes A and B do not need solve the optimization problem and save a lot of computation. However, the capacity performance of both schemes is much worse than the optimal solution. Based on the analysis in [8] about the mutual interference between PU and SU, sidelobe suppression methods are proposed in [9,13] to reduce the adjacent channel interference to PU's band. In these methods, the spectrum of SU's signal is modified in order to minimize the sidelobe, which causes the interference to the PU's bands. These methods distort the SU's signal can affect to the quality or spectrum efficiency of the cognitive systems. A max-min algorithm is proposed in [11] for sub-channel, bit and power allocation in a multiuser OFDM-based CR system. In this paper, the simulation result shows the improvement in system performance in comparison with case that uses guard bands to protect the active PU. The method in this paper requires the guard bands, which can reduce the overall capacity of cognitive system.

Motivated by the aforementioned challenging tasks and the interference model from previous studied such as [5], especially scheme A in [5] with linear tracking interference. In this paper, we propose a method, which is better in tracking the interference from SU to PU's bands by using second order function instead of linear function to allocate the power to subcarriers of SU. The analysis shows that our proposed method is much less complexity than the water filling or nulling algorithms because it does not require to solve the optimization problem. The simulation results prove that our proposed method outperforms previous methods such as scheme A and B in [5]. The capacity of proposed method can approach the optimal solution especially if the spectrum holes are symmetrical. It is obviously due to our power allocation is based on the symmetrical parabola.

3. System Descriptions and Problem Formulation

In this part, we will address the problem of maximization of the channel capacity of a cognitive radio system in condition of mutual interference with PU. The optimal solution of power allocation is derived by using water-filling policy. This solution will be used as the benchmark for others suboptimal algorithms.

We consider here the system with PU uses L licensed bands of frequencies. A single cognitive user uses N_T transmit and N_R receive antennas. They would like to use N free subcarriers from PU. Additionally, each CR's subcarrier has a bandwidth Δf ; the frequency B_l has been occupied by l-th Band of PU, respectively and the symbol duration is T_s .

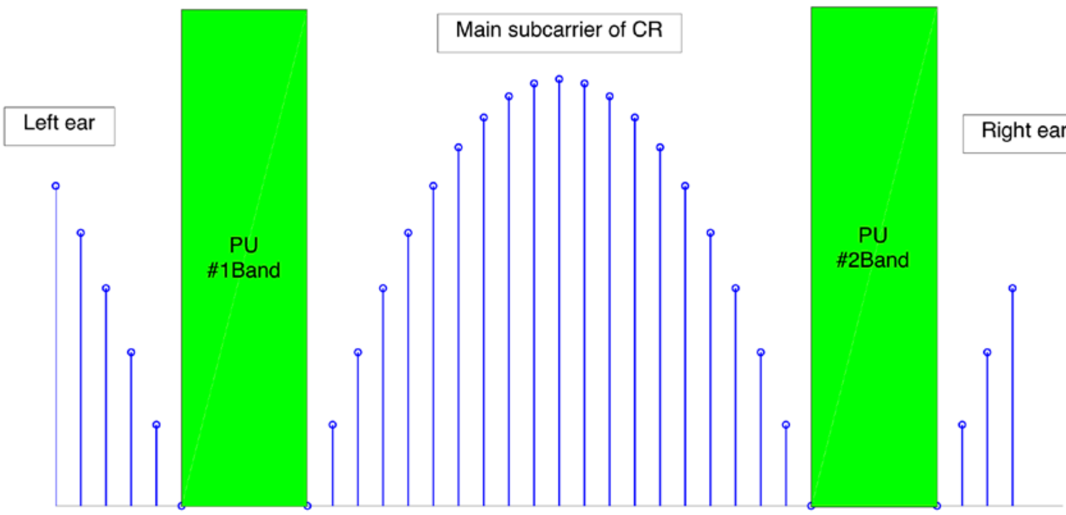

Fig. 1. Spectrum allocation scenario

3.1 Interference introduced by CR signal to PU users

Assume that Φ_i is the power spectrum density (PSD) of the i-th subcarrier, then Φ_i can be expressed as:

$$\Phi_i(f) = P_i T_s \left(\frac{\sin(\pi f T_s)}{\pi f T_s} \right)^2, \tag{1}$$

where P_i is the transmission power of *i*-th OFDM subcarrier, T_s is the symbol duration. The interference from *i*-th subcarrier, antenna n_t of CR user to PU's bands is the integration of this subcarrier spectrum density across the *i*-th PU band. This interference can be expressed as:

$$\begin{aligned} I_{i,n_t}^l(d_i^l, P_{i,n_t}^l) &= \left| h_{i,l,n_t}^{sp} \right|^2 P_{i,n_t}^l T_s \int_{d_{i,l}-B_l/2}^{d_{i,l}+B_l/2} \left(\frac{\sin(\pi f T_s)}{\pi f T_s} \right)^2 df \\ &= P_{i,n_t}^l K_{i,n_t}^l, \end{aligned} \tag{2}$$

where d_i^l is spectrum distance between CR's *i*-th subcarrier and the center frequency of *l*-th PU band, B_l is the bandwidth of *l*-th PU's band, P_{i,n_t}^l represents the transmission power *i*-th subcarrier, n_t transmit antenna of CR user, h_{i,l,n_t}^{sp} denotes channel gain between CR transmitter and PU receiver. The interference from *i*-th subcarrier to PU is therefore the total interference over N_T transmit antennas, which can be presented as:

$$\begin{aligned} I_i^l(d_i^l, P_{i,n_t}^l) &= \sum_{n_t=1}^{N_T} I_{i,n_t}^l(d_i^l, P_{i,n_t}^l) \\ &= \sum_{n_t=1}^{N_T} P_{i,n_t}^l K_{i,n_t}^l \end{aligned} \tag{3}$$

3.2 Interference introduced from PU to CR users

In the PU side, the power spectrum density of the PU signal after M-fast Fourier transforms (FFT) can be expressed as:

$$E\{I_N(\omega)\} = \int_{-\pi}^{\pi} \Phi_{PU}(e^{j\omega}) \left(\frac{\sin(\omega-\psi)M/2}{\sin(\omega-\psi)/2} \right) d\psi, \tag{4}$$

where ω is the frequency normalized to the sampling frequency, $\Phi_{PU}(e^{j\omega})$ is the power spectrum density of PU signal. The interference introduced by *l*-th PU signal to the CR's *i*-th subcarrier and n_r receive antenna will be calculated by integrating the PU power spectrum density across the bandwidth of *i*-th subcarrier as follows:

$$J_{i,n_r}^l(d_{i,n_r}^l, P_{PU}^l) = \left| h_{i,l,n_r}^{ps} \right|^2 \int_{d_{i,l}-B_l/2}^{d_{i,l}+B_l/2} E\{I_N(\omega)\} d\omega, \tag{5}$$

where h_{i,l,n_t}^{ps} is channel gain between PU transmitter and CR receiver and P_{PU}^l denotes transmission power of *l*-th PU signal. The interference introduced by *l*-th PU signal to the CR's *i*-th subcarrier is thereby found with

$$J_{i,n_r}^{l}(d_{i,n_t}^{l}, P_{PU}^{l}) = \sum_{n_r=1}^{N_R} J_{i,n_r}^{l}(d_{i,n_r}^{l}, P_{PU}^{l}). \tag{6}$$

3.3 Transmission capacity of OFDM-based CR system

The problem is addressed that the CR coordinator needs to determine the position and power which are assigned to each CR user to maximize the total transmission rate of CR user while considering the interference between CR users and from PU to CR user and vice versa. It is assumed that a full Tx and Rx channel state information (CSI) of all the users (both primary and secondary) in this work are considered. The capacity can be announced as

$$C = \underbrace{\max}_{P_{i,n_t} \geq 0} \left\{ \sum_{i=1}^{N} \Delta f \log_2 \left(I_{n_r} + \frac{H P_i H^H}{N_T(\sigma^2 + \sum_{l=1}^{L} J_i^l)} \right) \right\} \tag{7}$$

s.t.

$$\sum_{l=1}^{L} \sum_{i=1}^{N} \sum_{n_t=1}^{N_T} I_i^l(d_i^l, P_{i,n_t}^l) \leq I_{th} \tag{8}$$

$$P_{i,n_t}^l \geq 0 \quad \text{for } \forall i = 1,..., N; n_t = 1,..., N_T \tag{9}$$

$$\sum_{i=1}^{N} \sum_{n_t=1}^{N_T} P_{i,n_t} \leq P_{th} \tag{10}$$

Where C denotes the transmission capacity of the CR user, N represents the total number of OFDM subcarriers; I_{th} and P_{th} are the maximum interference threshold which can be accepted by L PU users and the limit power. σ^2 is the power of Additive white Gaussian noise (AWGN), Δf is the bandwidth of each subcarrier. $P_i = \mathrm{diag}([P_{i,1},..., P_{i,N_T}])$, where P_{i,n_t} represents the transmission power of *i*-th subcarrier, n_t transmit antenna of CR user. H is an $N_T \times N_R$ matrix at subcarrier *i*-th of CR user denoted by:

$$H_{n_r,n_t}^{(i)} = \begin{pmatrix} h_{1,1}^{(i)} & \cdots & h_{1,n_t}^{(i)} \\ \vdots & \ddots & \vdots \\ h_{n_r,1}^{(i)} & \cdots & h_{n_r,n_t}^{(i)} \end{pmatrix} \tag{11}$$

Note that above optimization problem is convex, i.e., the Karush-Kuhn-Tucker (KKT) condition is sufficient. The problems at the optimizing total throughput of MIMO-OFDM is convex and the maximization of the sum-rate of CR user under a sum-power and interference constraint. We reconsider the problem which has been announced in Eq. (8), (9) and (10). This optimization can be solved by fulfilling the KKT conditions with Lagrangian multipliers λ (.). We construct the following Lagrangian function as follows:

$$L(P_{i,n_t}^{*l},\lambda_1,\lambda_2)=\sum_{i=1}^{N}\Delta f\log_2\left(I_{n_r}+\frac{HP_iH^H}{N_T(\sigma^2+\sum_{l=1}^{L}J_i^l)}\right)-\lambda_1\left(\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T}P_{i,n_t}^{*l}K_{i,n_t}-I_{th}\right)-\lambda_2\left(\sum_{i=1}^{N}\sum_{n_t=1}^{N_T}P_{i,n_t}^{*l}-P_{th}\right) \quad (12)$$

The KKT conditions for the optimization problem in above thus read as

$$\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T}P_{i,n_t}^{*l}K_{i,n_t}-I_{th}\leq 0 \quad (13)$$

$$\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T}P_{i,n_t}^{*l}K_{i,n_t}-I_{th}\leq 0 \quad (14)$$

$$\lambda_1\left(\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T}P_{i,n_t}^{*l}K_{i,n_t}-I_{th}\right)=0 \quad (15)$$

$$\lambda_2\left(\sum_{i=1}^{N}\sum_{n_t=1}^{N_T}P_{i,n_t}^{*l}-P_{th}\right)=0 \quad (16)$$

$$\frac{\partial L\left(P_{i,n_t}^{*l},\lambda_1,\lambda_2\right)}{\partial P_{i,n_t}^{*l}}=0,\quad \lambda_1,\lambda_2\geq 0 \quad (17)$$

After we have fulfilled the KKT conditions, we obtain [5]

$$P_{i,n_t}^{*l}=\max\left\{0,\frac{\Delta f\ln 2}{\lambda_1\sum_{l=1}^{L}\sum_{n_t=1}^{N_T}K_{i,n_t}^{l}+\lambda_2}-\frac{\sigma^2+\sum_{l=1}^{L}\sum_{n_r=1}^{N_R}J_{i,n_r}^{l}}{\left\|H_i\right\|^2}\right\} \quad (18)$$

Replacing the optimal power P_{i,n_t}^{*l} into Eq. (15, 16), solving these equations, we can obtain two parameters λ_1,λ_2 . We could recognize that the power allocation in Eq. (18) is a water-filling policy. More power is given to the subcarrier, which has relatively better channel quality and less interference. The optimal capacity is derived by replacing the power P_{i,n_t}^{*l} in Eq. (18) to Eq. (7). This is the upper limit of capacity for others suboptimal algorithms.

Due to the burden of computation for optimal solution including eigenvalues calculation and sort algorithm [14], a low complexity suboptimal algorithm by tracking the interference and parabola power allocation is proposed in the next part to cope with this problem.

4. Suboptimal Scheme

In this section, we propose a suboptimal algorithm to estimate CR's average power, denoted by $\overline{P}$. Based on $\overline{P}$, a 2nd order interference-tracking algorithm to allocate power at CR's subcarriers will be presented. To fully exploit the total capacity of the cognitive radio system, the transmitters must transmit their signal with transmission power P_{i,n_t}^{l} inversely proportional with K_{i,n_t}^{l} [7]. In [5], the allocated power P_{i,n_t}^{l} should be assigned to a subcarrier linearly depends on the distance between it selves and the neighboring PU's bands. It can be understood that the distance d_i from *i*-th subcarrier to PU represents K_{i,n_t}^{l}. However, as this method bases only on one parameter d_i it affects negatively on the system performance. We present here a method for improving total capacity of CR users based on two parameters: the distance d_i and the CR's average power $\overline{P}$. With this approach the system performance improves with negligible increment of complexity.

4.1 CR's average transmission power

In this part, we describe how to estimate CR's average transmission power $\overline{P}$. Suppose that is the transmission power P_{i,n_t}^{l} of *i*-th subcarrier, antenna n_t, Eq. (13) can be expressed as:

$$\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T} P_{i,n_t}^{l} K_{i,n_t}^{l} = I_{th} \tag{19}$$

By taking Cauchy-Schwarz's inequality we obtain:

$$\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T} P_{i,n_t}^{l} K_{i,n_t}^{l} \le \sqrt{\left(\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T}\left(P_{i,n_t}^{l}\right)^2\right)\left(\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T}(K_{i,n_t}^{l})^2\right)} \tag{20}$$

In addition, we have

$$\begin{cases} \sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T}\left(P_{i,n_t}^{l}\right)^2 \le \left(\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T} P_{i,n_t}^{l}\right)^2 \\ \sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T}\left(K_{i,n_t}^{l}\right)^2 \le \left(\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T} K_{i,n_t}^{l}\right)^2 \end{cases} \tag{21}$$

Equality holds in both inequations (20) and (21), if and only if $P_{i,n_t}^{l} = 0$ and $K_{i,n_t}^{l} = 0$. This condition is not tallied with our realistic system. However, that is a close inequality. Because the subcarrier is far from PU's bands causes almost zero interfere to PU. Moreover, the neighboring subcarriers of PU's bands have always zero power transmission. Substituting (21) and (20) to equation (11), leads to

$$\begin{aligned}\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T} P_{i,n_t}^{l} K_{i,n_t}^{l} &\le \sqrt{\left(\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T} P_{i,n_t}^{l}\right)^2 \left(\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T} K_{i,n_t}^{l}\right)^2} \\ &\le \left(\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T} P_{i,n_t}^{l}\right)\left(\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T} K_{i,n_t}^{l}\right) \\ &\le LNN_T \overline{P}\left(\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T} K_{i,n_t}^{l}\right)\end{aligned} \tag{22}$$

The inequation in (22) can alternatively be written as:

$$\overline{P} \ge \frac{I_{th}}{LNN_T\left(\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T} K_{i,n_t}^{l}\right)} \tag{23}$$

Eq. (23) represents the lowest limitation of CR's average power $\overline{P}$. In order to estimate the highest limitation of $\overline{P}$, we consider

$$\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T} P_{i,n_t}^{l} K_{i,n_t}^{l} \ge K_{\min}\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t=1}^{N_T} P_{i,n_t}^{l} \tag{24}$$

Note that the left-hand side of Eq. (24) is I_{th} and the right-hand side of Eq. (24) is $K_{\min} LNN_T \overline{P}$, so we obtain

$$I_{th} \ge LNN_T K_{\min} \overline{P} \tag{25}$$

Or in other form

$$\overline{P} \le \frac{I_{th}}{LNN_T K_{\min}} \tag{26}$$

Denote $\alpha = \dfrac{I_{th}}{LNN_T\left(\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{n_t}^{N_T} K_{i,n_t}^{l}\right)}$ and $\beta = \dfrac{I_{th}}{LNN_T K_{\min}}$, we determine approximately the range of CR's average transmission power $\alpha \le \overline{P} \le \beta$ for each transmit antenna.

4.2 Second order interference tracking algorithm

We assume that P_{i,n_t}^{l} has parabola's characteristics. A parabola equation is given by a standard form

$$y(x) = a_1 x^2 + a_2 x + a_3 \tag{27}$$

We consider a coordinate system with the horizontal axis is subcarrier number and the vertical axis is power transmission of *i*-th subcarrier. To determine $[a_1, a_2, a_3]$ we assume that CR's 1st and *N*-th subcarriers are null subcarriers (Nulling algorithm). The integration of CR's power over N subcarriers is equal with multiplication of $\overline{P}$ and *N*. Let us take a look at the system depicted in **Fig. 1**. We have thereby

$$\begin{cases} a_1\left(N_1+B_1\right)^2 + a_2(N_1+B_1) + a_3 = 0 \\ a_1\left(N+N_1+B_1\right)^2 + a_2(N+N_1+B_1) + a_3 = 0 \\ \int_0^{N_1} y(x+N_1-N)dx + \int_{N_1+B_1}^{N_2} y(x)dx + \int_{N_2+B_2}^{N+B_1+B_2} y(x)dx = N\overline{P} \end{cases} \tag{28}$$

Per each value of $\overline{P}$ we have a set of $[a_1, a_2, a_3]$ and those sets create a set of parabolas. The interval of $\overline{P}$ is determined in Eq. (23) and (26). So we can allocate our CR transmission power between two parabolas by setting $\overline{P}$ corresponding to α and β. This allocation algorithm is a remarkable attention of the form of optimal solution. The curve of optimal transmission power may not have parabolic characteristics, but inequations above show that the most of optimal results will be appear within the range of two parabolas with $\overline{P}$ corresponds to α and β values. The aim of the next step is to bring the form of suboptimal curve close to optimal curve. After determining two parabolas denoted by $\Gamma_1(x)$ and $\Gamma_N(x)$ corresponding to α and β, we determine two peaks value of those parabolas denoted by $P_{\max}$ and $P_{\min}$. We divide the range $[P_{\min}, P_{\max}]$ into $N_m = N_2 - N_1 - B_l$ equal section ΔP and denote $\Gamma_n(x)$ the parabola, which has the peak value of $P_{\max} - n\Delta P$. The free spectrum between two PU's bands has N_m free subcarriers. The transmission power assigned to the center subcarrier is accurate to $\Gamma_1(N_m/2)$. We follow this process to determine further transmission power assigned to *i*-th subcarrier. This proposed algorithm could be applied also for two "ear" of PU's Bands depicted in **Fig. 2** and mathematically presented as follows

$$P_{N_m/2\pm i} = \Gamma_i(N_m/2 \pm i) \text{ for } i \in \left[N_1+B_1, ..., N_2\right] \tag{29}$$

The left ear is assigned as

$$P_i = P_{N_2-N_1+i} \quad \text{for } i \in \left[0, ..., N_1\right] \tag{30}$$

The right ear has transmission power equal to

$$P_{N_2+B_2+i} = P_{N_1+B_1+i} \quad \text{for } i \in \left[N_2+B_2, ..., N\right] \tag{31}$$

However, this process will be stopped until one of two additional constraints Eq. (14) or $n \in [0, ..., N/2]$ is fulfilled, where n denotes the index of $\Gamma_n(x)$. Eq. (14) can be fulfilled before all subcarriers are used for transmitting. It means that the number of nulling is not a constant in this proposed algorithm. In other words, we have proposed a 2nd order interference-tracking algorithm with dynamic Nulling.

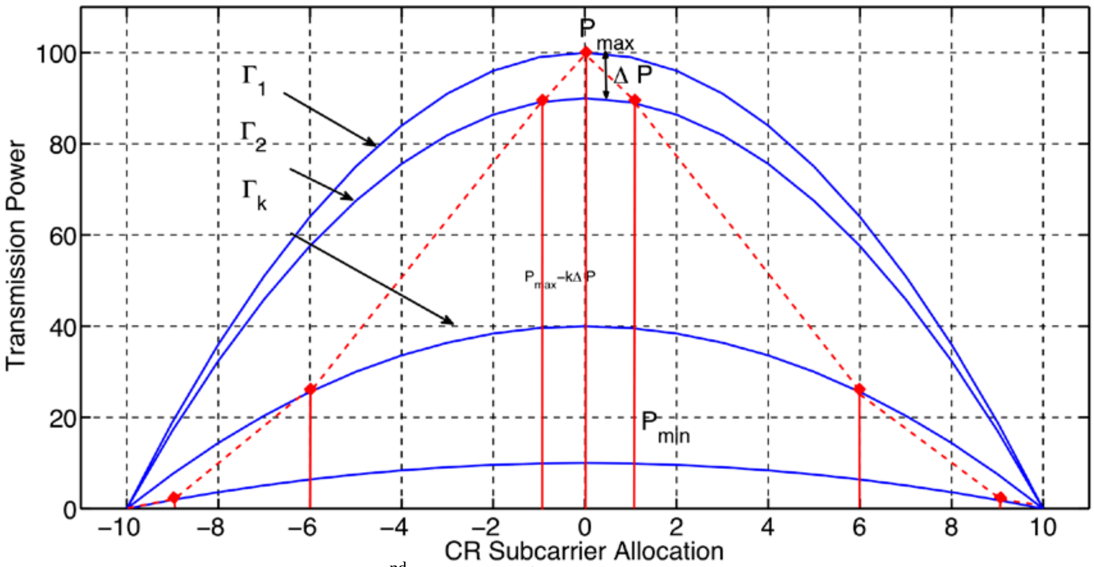

Fig. 2. 2nd order interference tracking algorithm

5. Simulation Results

For comparison purpose, a numerical simulator is developed in Matlab. The simulation results are presented in this section.

5.1 Simulation Parameters

We assume that CR system has 20 subcarriers to operate in 2 bands of PU systems, which have the different bandwidths in two scenarios. The first scenario is that PU's bands are equal. In this scenario, corresponding to PU's interference distribution CR left ear (see **Fig. 1**) is assigned subcarrier from 0 to 4, CR main spectrum uses subcarrier from 6 to 19, CR right ear uses subcarrier from 21 to 25. And the second scenario is that one band is much larger than the other band. In this scenario, subcarrier from 0 to 5 belong to CR left ear, CR main spectrum uses subcarrier corresponding to from 6 to 19, CR right ear uses subcarrier from 21 to 25. Second PU's band in this scenario is five times larger than the first band. We assume the OFDM duration T_s is 3.2μs and Δf has the value of 0.3125MHz. The value of σ^2 is assumed to be 10^{-3} W. The value of amplitude P_{PU} is assumed to be 1W. The channel gains h_{i,l,n_t}^{ps}, h_{i,l,n_t}^{ss} and h_{i,l,n_t}^{sp} are simulated to be ideal with an average channel power gain of 0 dB. The interference threshold I_{th} is the multiple of noise power and varies from $2 \times \sigma^2$ to $10 \times \sigma^2$.

The suboptimal Scheme A is based on the step size of the power profile. While allocating power using Scheme A for particular CR user subcarriers, the power P_i is distributed as follows [5]

$$P_{i,n_t}^{lA} = \left(\frac{N}{L} + 1 - i\right) P \tag{32}$$

Where N represents the number of subcarriers, L is denotes number of PU's bands and P is a constant, which can be determined by replacing Eq. (30) into Eq. (13). Here, suboptimal Scheme A in implemented with two cases of Nulling, namely, the one-nulling and two-nulling cases. This procedure implies that for a given interference threshold, more power can be allocated to the far apart subcarriers than to the neighboring subcarriers so that the neighboring subcarriers are allocated to zero power. In the Scheme B, the step size is taken to be inversely proportional to K_{i,n_t}^{l}. Hence, the power of i-th subcarrier can be written as [5]

$$P_{i,n_t}^{lB} = \frac{P}{K_{i,n_t}^{l}} \tag{33}$$

Fig. 3 shows the maximum total capacity of the CR user versus the interference imposed on PU's bands for SISO and MIMO system under first scenario and different suboptimal methods. According to results in Fig. 3, in comparison with the conventional water filling our proposed algorithm delivers a very good performance in both SISO and MIMO system. The reason is that we do not only avoid to assign power at subcarriers nearby PU's bands but we have also assigned more power to subcarrier far from PU's bands position and brought the assignment strategy in close form with optimal solution.

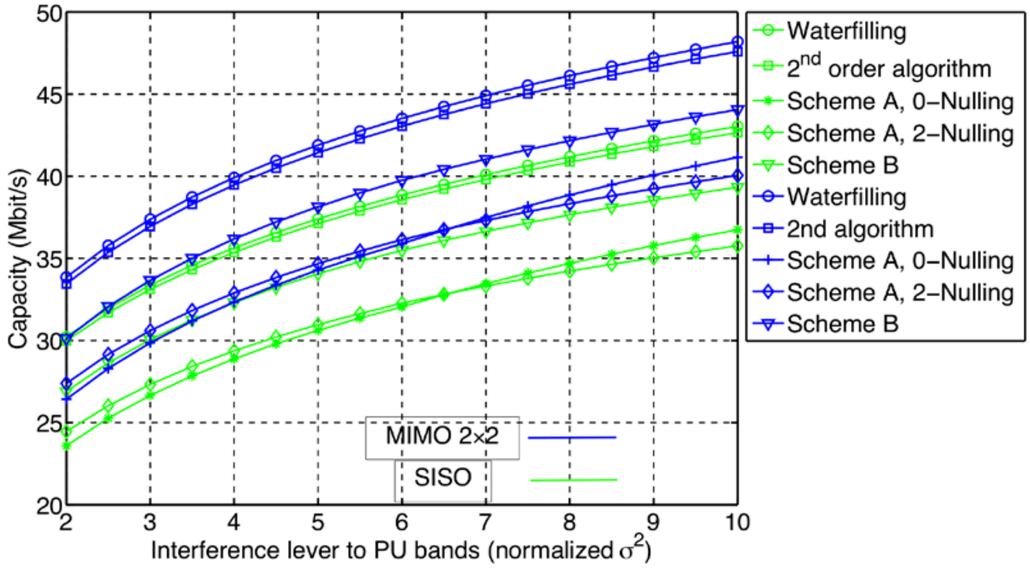

Fig. 3. Total Capacity of CR user in SISO and MIMO mode, 2 PU's Bandwidth equal

Moreover, in the comparison between two cases of Nulling of Scheme A, it can be concluded that it does not always help to improve system performance by fixing the number of nulling subcarriers. Not only that the sum rate of 0-Nulling is even better then 2-Nulling when the channel is ideal at I_{th} > 7mW. So we do not consider further nulling scenarios when simulating for Scheme B. Scheme B approach provides more flexibility in adaptively adjusting the transmit power in to each subcarrier than that of Scheme A. That why the performance of Scheme B in both **Fig. 3** and **Fig. 4** is better than Scheme A by nearly 5 Mbit/s with interference lever equal $5\sigma^2$. Above simulated algorithms allocate power by using the specified functions (linear and parabola) instead of sorting and eigenvalues calculating in optimal algorithm. Then they have almost the same low complexity.

Fig. 3 shows the capacity of MIMO CR system improves significantly in comparison with SISO. The improvement comes not only from the space diversity but also from the effectiveness of power allocation per transmit antenna. **Fig. 4** shows the simulation results for the case that one PU's band is much larger than the other band. The condition **is given aim to** make the form of the power allocation does not have symmetry characteristic any more. This will **affect mostly** to the results of two algorithms Scheme A and the proposed 2^{nd} order algorithm because these methods exploit the symmetrical power allocation.

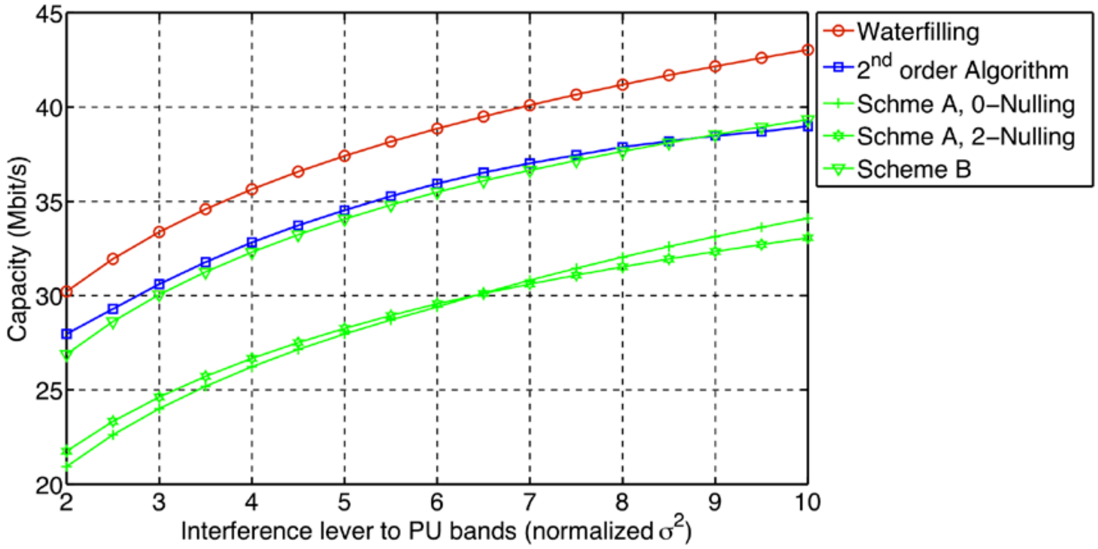

Fig. 4. Total Capacity of CR user in SISO mode, 2 PU's Bandwidth unequal

It shows that the capacity increases when the interference to PU is tolerated. Two cases of Scheme A provide lowest performance. Obviously, the performance of Scheme A and 2^{nd} order algorithm in this scenario is worse than in the first scenario. Scheme B shows that this method is hardly affected by difference bandwidth of PU's bands.

6. Simulation Results

In this paper, we have presented a scheme for suboptimal power allocation on subcarriers to maximize the total sum rate of secondary users. The results show that the CR's capacity is significantly improved and approaches the optimal scheme. Our investigation based on the dynamic nulling mechanism and 2^{nd} order interference tracking algorithm achieve higher transmission throughput in comparing with several previous suboptimal schemes. We have also investigated the power-loading scheme for the Cognitive Radio Networks utilizing the MIMO considering full Tx and Rx CSI of all the users. Numerical results show that space diversity gain has been fully exploited in the MIMO system. CR's transmission throughput could be reached closer to optimal scheme if the value of CR's transmission average power is better estimated.

7. Acknowledgement

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 102.02-2011.15.

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