Hindawi Publishing Corporation
EURASIP Journal on Advances in Signal Processing
Volume 2010, Article ID 528378, 13 pages
doi:10.1155/2010/528378

*Research Article*

# Computationally Efficient Power Allocation Algorithm in Multicarrier-Based Cognitive Radio Networks: OFDM and FBMC Systems

**Musbah Shaat and Faouzi Bader**

*Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Parc Mediterrani de la Tecnología (PMT), Avenida Carl Friedrich Gauss 7, Castelldefels, 08860 Barcelona, Spain*

Correspondence should be addressed to Musbah Shaat, musbah.shaat@cttc.es

Received 4 June 2009; Revised 19 October 2009; Accepted 23 December 2009

Academic Editor: Behrouz Farhang-Boroujeny



Cognitive Radio (CR) systems have been proposed to increase the spectrum utilization by opportunistically access the unused spectrum. Multicarrier communication systems are promising candidates for CR systems. Due to its high spectral efficiency, filter bank multicarrier (FBMC) can be considered as an alternative to conventional orthogonal frequency division multiplexing (OFDM) for transmission over the CR networks. This paper addresses the problem of resource allocation in multicarrier-based CR networks. The objective is to maximize the downlink capacity of the network under both total power and interference introduced to the primary users (PUs) constraints. The optimal solution has high computational complexity which makes it unsuitable for practical applications and hence a low complexity suboptimal solution is proposed. The proposed algorithm utilizes the spectrum holes in PUs bands as well as active PU bands. The performance of the proposed algorithm is investigated for OFDM and FBMC based CR systems. Simulation results illustrate that the proposed resource allocation algorithm with low computational complexity achieves near optimal performance and proves the efficiency of using FBMC in CR context.

## 1. Introduction

Federal Communications Commission (FCC) has reported that many licensed frequency bands are severely underutilized in both time and spatial domain [1]. Assigning frequency bands to specific users or service providers exclusively does not guarantee that the bands are being used efficiently all the time. Cognitive radio (CR) [2–4], which is an intelligent wireless communication system capable of learning from its radio environment and dynamically adjusting its transmission characteristics accordingly, is considered to be one of the possible solutions to solve the spectrum efficiency problem. By CR, a group of unlicensed users (referred to as secondary users (SUs)) can use the licensed frequency channels (spectrum holes) without causing a harmful interference to the licensed users (referred to as primary users (PUs)) and thus implement efficient reuse of the licensed channels.

Multicarrier communication systems have been suggested as a candidate for CR systems due to its flexibility to allocate resources between the different SUs. As the SU and PU bands may exist side by side and their access technologies may be different, the mutual interference between the two systems is considered as a limiting factor affects the performance of both networks. In [5], the mutual interference between PU and SU was studied. The mutual interference depends on the transmitted power as well as the spectral distance between PU and SU. Orthogonal frequency division multiplexing- (OFDM-) based CR system suffers from high interference to the PUs due to large sidelobes of its filter frequency response. The insertion of the cyclic prefix (CP) in each OFDM symbol decreases the system capacity. The leakage among the frequency subbands has a serious impact on the performance of FFT-based spectrum sensing, and in order to combat the leakage problem of OFDM, a very tight and hard synchronization implementation has to be imposed among the network nodes [6].

The filter bank multicarrier system (FBMC) does not require any CP extension and can overcome the spectral leakage problem by minimizing the sidelobes of each subcarrier and therefore lead to high efficiency (in terms of spectrum and interference) [6, 7]. Moreover, efficient use of filter banks for spectrum sensing when compared with the FFT-based preiodogram and the Thomson's multitaper (MT) spectrum sensing methods have been recently discussed in [6, 8].

The problem of resource allocation for conventional (noncognitive) multiuser multicarrier systems has been widely studied [9–12]. The maximum aggregated data rate in downlink can be obtained by assigning each subcarrier to the user with the highest signal-to-noise ratio (SNR) and then the optimal power allocation that maximizes the channel capacity is waterfilling on the subcarriers with a given total power constraint [9]. In cognitive radio systems, two types of users (SU and PU) and the mutual interference between them should be considered. The use of the power allocation based on conventional waterfilling algorithm is not always efficient. An additional constraint should be introduced due to the interference caused by the sidelobes in different subcarriers. The transmit power of each subcarrier should be adjusted according to the channel status and the location of the subcarrier with respect to the PU spectrum.

Wang et al. in [13] proposed an iterative partitioned single user waterfilling algorithm. The algorithm aims to maximize the capacity of the CR system under the total power constraint with the consideration of the per subcarrier power constraint caused by the PUs interference limit. The per subcarrier power constraint is evaluated based on the pathloss factor between the CR transmitter and the PU protection area. The mutual interference between the SU and PU was not considered. In [14, 15], the authors proposed an optimal and two suboptimal power loading schemes using the Lagrange formulation. These loading schemes maximize the downlink transmission capacity of the CR system while keeping the interference induced to only one PU below a prespecified interference threshold without the consideration of the total power constraint. In [16], an algorithm called *RC algorithm* was presented for multiuser resource allocation in OFDM-based CR systems. This algorithm uses a greedy approach for subcarrier and power allocations by successively assigning bits, one at a time, based on minimum SU power and minimum interference to PUs. The algorithm has a high computational complexity and a limited performance in comparison with the optimal solution. In [17], a low complexity suboptimal solution is proposed. The algorithm initially assumes that the maximum power that can be allocated to each subcarrier is equal to the power found by the conventional waterfilling and then modifies these values by applying a power reduction algorithm in order to satisfy the interference constraints. Experimental results like [18] emphasize the need of low interference constraints where this algorithm has a limited performance. Moreover, the nontransmission of the data over the subcarriers below the waterfilling level or the deactivated subcarriers due to the power reduction algorithm decreases the overall capacity of the CR system. In [19], we give some preliminary research results for resource allocation in OFDM-based CR systems. This preliminary work considers a simple model with one PU. The performance of the algorithm was not compared with neither the optimal nor the existed suboptimal algorithms.

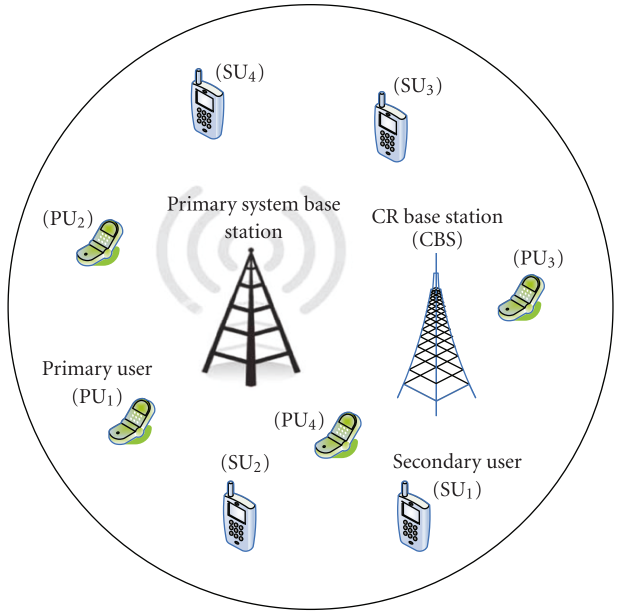


Figure 1: Cognitive Radio Network.

In this paper, considering more realistic scenario with several primary user interference constraints, a computationally efficient resource allocation algorithm in multicarrier-based CR systems is proposed. The proposed algorithm maximizes the downlink capacity of the CR system under both total power and interference induced to the PUs constraints. The CR system can use the nonactive and active PU bands as long as the total power and the different interference constraints are satisfied. The simulation results demonstrate that the proposed solution is very close to the optimal solution with a good reduction in the computational complexity. Moreover, the proposed algorithm outperforms the previously presented algorithms in the literature. The efficiency of using FBMC in CR systems is investigated and compared to OFDM-based CR systems. The rest of this paper is organized as follows. Section 2 gives the system model while Section 3 formulates the problem. The proposed algorithm is presented in Section 4. Selected numerical results are presented in Section 5. Finally, Section 6 concludes the paper.

## 2. System Model

In this paper, the downlink scenario will be considered. As shown in Figure 1, the CR system coexists with the PUs radio in the same geographical location. The cognitive base station (CBS) transmits to its SUs and causes interference to the PUs. Moreover, the PUs base station interferes with the SUs. The CR system's frequency spectrum is divided into $N$

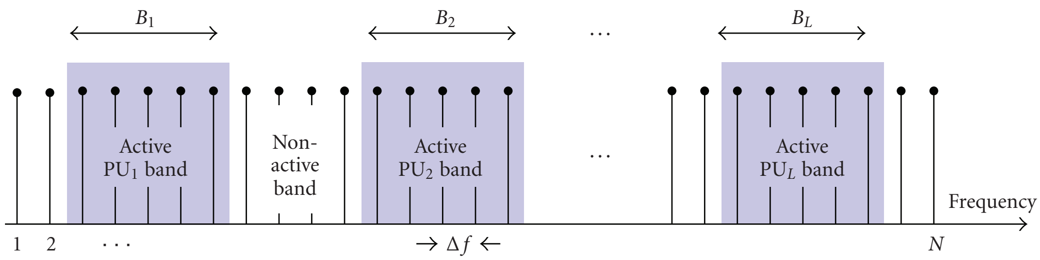


Figure 2: Frequency distribution of the active and nonactive primary bands.

subcarriers each having a $\Delta f$ bandwidth. The side by side frequency distribution of the PUs and SUs will be assumed (see Figure 2). The frequency bands $B_1, B_2, \ldots, B_L$ have been occupied by the PUs (active PU bands) while the other bands represent the nonactive PU bands. Its assumed that the CR system can use the nonactive and active PU bands provided that the total interference introduced to the $l^{th}$ PU band does not exceed $I^l_{th}$ where $I^l_{th} = T^l_{th} B_l$ denotes that the maximum interference power that can be tolerated by the $PU_l$ and $T^l_{th}$ is the interference temperature limit for $PU_l$.

The interference introduced by the $i^{th}$ subcarrier to $l^{th}$ PU, $I^l_i(d_i, P_i)$, is the integration of the power spectrum density (PSD), $\Phi_i$, of the $i^{th}$ subcarrier across the $l^{th}$ PU band, $B_l$, and can be expressed as [5]

$$I^l_i(d_i, P_i) = \int_{di-B_l/2}^{di+B_l/2} \left| g^l_i \right|^2 \Phi_i(f) df = P_i \Omega^l_i, \tag{1}$$

where $P_i$ is the total transmit power emitted by the $i^{th}$ subcarrier and $d_i$ is the spectral distance between the $i^{th}$ subcarrier and the $l^{th}$ PU band. $g^l_i$ denotes the channel gain between the $i^{th}$ subcarrier and the $l^{th}$ PU. $\Omega^l_i$ denotes the interference factor of the $i^{th}$ subcarrier.

The interference power introduced by the $l^{th}$ PU signal into the band of the $i^{th}$ subcarrier is [5]

$$J^l_i(d_i, P_{PU_l}) = \int_{di-\Delta f/2}^{di+\Delta f/2} \left| y^l_i \right|^2 \psi_l\left(e^{j\omega}\right) d\omega, \tag{2}$$

where $\psi_l(e^{j\omega})$ is the power spectrum density of the $PU_l$ signal and $y^l_i$ is the channel gain between the $i^{th}$ subcarrier and $l^{th}$ PU signal. The PSD expression, $\Phi_i$, depends on the used multicarrier technique. The OFDM and FBMC PSDs are described in the following subsections.

*2.1. OFDM System and Its PSD.* The OFDM symbol is formed by taking the inverse discrete Fourier transform (IDFT) to a set of complex input symbols $\{X_k\}$ and adding a cyclic prefix. This can be written mathematically as

$$x(n) = \sum_k \sum_{w \in Z} X_{k,w} g_T(n - wT) e^{j2\pi(n-wT-C)k/N}, \tag{3}$$

where $\{k\}$ is the set of data subcarrier indices and is a subset of the set $\{0, 1, \ldots, N-1\}$, $N$ is the IDFT size, $C$ is the length of the cyclic prefix in number of samples, and $T = C + N$ is the length of the OFDM symbol in number of samples. $g_T$ denotes the pulse shape, while $w$ denotes the $w^{th}$ OFDM symbol.

Following the derivation of the PSD for general baseband signal given in [20], it can be shown that the OFDM PSD is

$$\Phi_{\text{OFDM}}(f) = \frac{\sigma_x^2}{T} \sum_k \left| G_T\left(f - \frac{k}{N}\right) \right|^2, \tag{4}$$

where $G_T(f)$ is the Fourier transform of $g_T(n)$, and $\sigma_x^2$ is the variance of the zero mean (symmetrical constellation) and uncorrelated input symbols. The assumption of the uncorrelated input symbols can be justified because of coding and interleaving in practical symbols [21].

$g_T(n)$ can be chosen as

$$g_T(n) = \begin{cases} 1, & n = 0, 1, \ldots, T-1, \\ 0, & \text{otherwise}, \end{cases} \tag{5}$$

and hence its Fourier transform is

$$\left| G_T(f) \right|^2 = T + 2 \sum_{r=1}^{T-1} (T - r) \cos(2\pi f r). \tag{6}$$

*2.2. FBMC System and Its PSD.* Each subcarrier in FBMC system is modulated with a staggered QAM (offset QAM) [22]. The basic idea is to transmit real-valued symbols instead of transmitting complex-valued ones. Due to this time staggering of the in-phase and quadrature components of the symbols, orthogonality is achieved between adjacent subcarriers. The modulator and the demodulator are implemented using the synthesis and analysis filter banks. The filters in the synthesis and analysis filter bank are obtained by frequency shifts of a single prototype filter. Figure 3 depicts the structure of the synthesis and analysis filter bank at the transmitter and receiver in FBMC-based multicarrier systems.

The FBMC, also called OQAM/OFDM, signal can be written mathematically as [23]

$$x(n) = \sum_k \sum_{w \in Z} a_{k,w} h(n - w\tau_o) e^{j2\pi(k/N)n} e^{j\phi_{k,w}}, \tag{7}$$

where $\{k\}$ is the set of subcarrier indices, $h$ is the pulse shape, $\phi_{k,w}$ is an additional phase term, and $\tau_o$ is FBMC symbol duration. $a_{k,w}$ are the real symbols obtained from the complex QAM symbols having a zero mean and variance

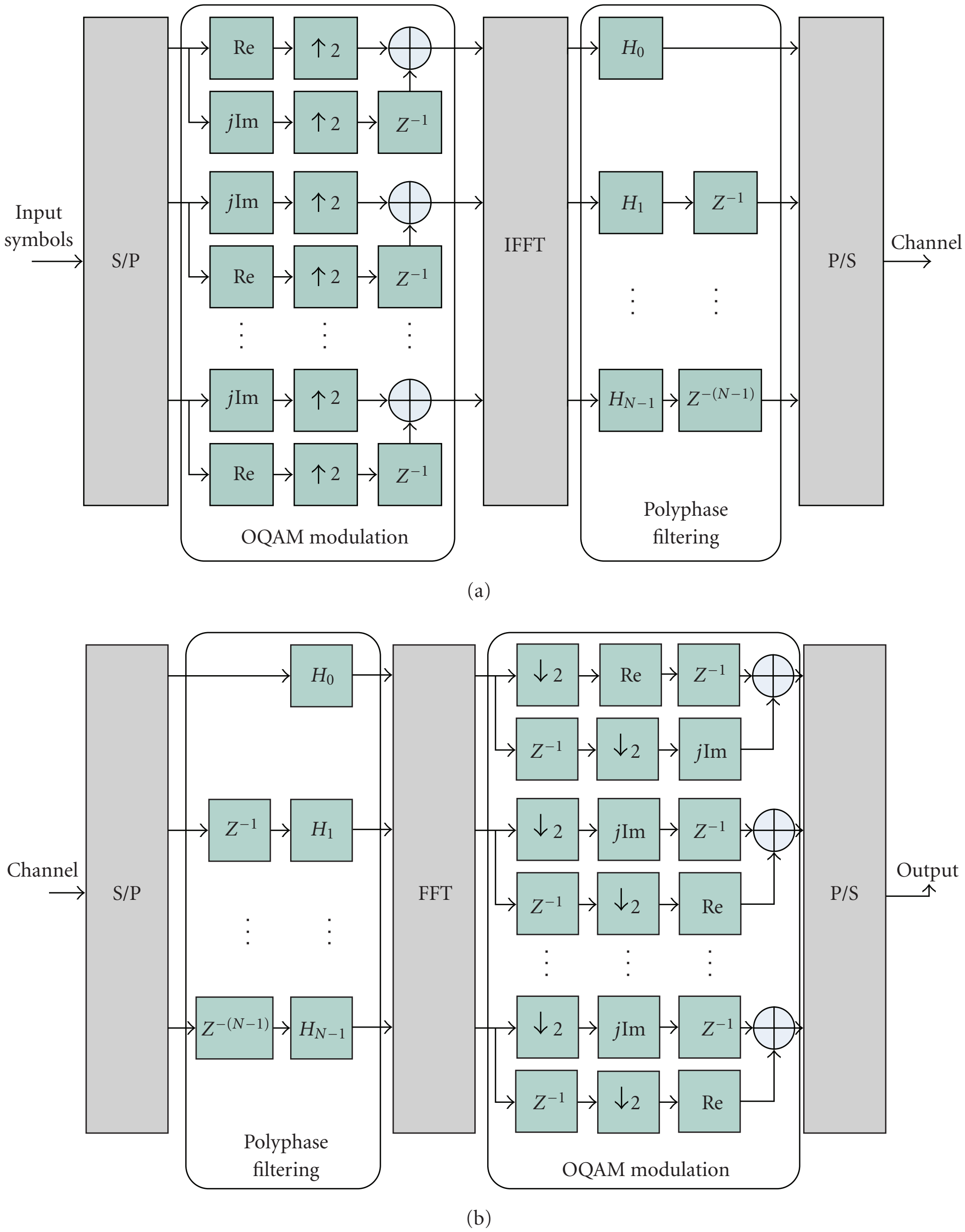


Figure 3: FBMC system's transmitter and receiver.

$\sigma_x^2$. Hence, the FBMC symbols have a zero mean and finite variance $\sigma_r^2 = \sigma_x^2/2$. The PSD of the FBMC can be expressed by [23]

$$\Phi_{\text{FBMC}} = \frac{\sigma_r^2}{\tau_\circ}\sum_k \left| H\left(f - \frac{k}{N}\right)\right|^2, \quad (8)$$

where $H(f)$ is the frequency response of the prototype filter with coefficients $h[n]$ with $n = 0, \ldots, W-1$, where $W = KN$ and $K$ is the length of each polyphase components (overlapping factor) while $N$ is the number of the subcarriers. Assuming that the prototype coefficients have even symmetry around the $(KN/2)^{th}$ coefficient, and the first coefficient is zero [21], we get

$$|H(f)| = h\left[\frac{W}{2}\right] + 2\sum_{r=1}^{W/2-1} h\left[\left(\frac{W}{2}\right) - r\right]\cos(2\pi f r). \quad (9)$$

To make a parallel between OFDM and FBMC, we place ourselves in the situation where both systems transmit the same quantity of information. This is the case if they have the same number of subcarriers $N$ together with duration of $\tau_o$ samples for FBMC real data and $T = 2\tau_o$ for the complex QAM ones [21, 23].

From the relations above we can notice that the PSDs of OFDM and FBMC are the summation of the spectra of

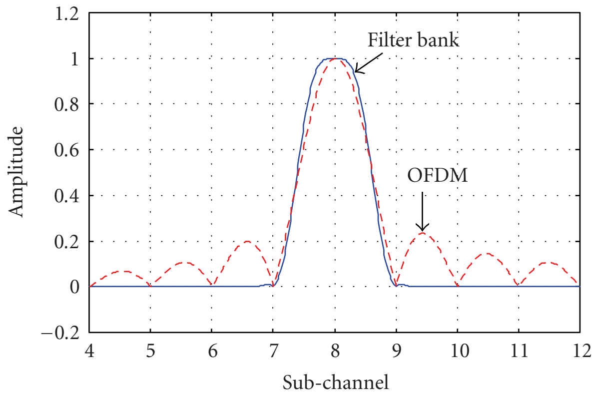


Figure 4: Single subcarrier PSDs of the OFDM and FBMC systems.

the individual subcarriers. Using the PHYDYAS prototype filter [24], Figure 4 plots a single subcarrier power spectral densities of the OFDM and FBMC systems. It can be noted that the FBMC system has very small side lobes in comparison with that of the OFDM system. Note that in order to solve the large sidelobes problem in OFDM system, many methods have already been employed, such as the insertion of guard subcarriers [25] or cancelation subcarriers [26], windowing (in time domain) [27, 28], and filtering before transmitting [29]. It is known that the guard subcarriers decrease the spectral efficiency, while windowing reduces the delay spread tolerance and filtering is more complex and introduces distortion in the desired signals [30].

## 3. Problem Formulation

The transmission rate of the $i^{th}$ subcarrier, $R_i$, with the transmit power $P_i$ can be evaluated using the Shannon capacity formula and is given by

$$R_i(P_i, h_i) = \Delta f \log_2\left(1 + \frac{P_i|h_i|^2}{\sigma_i^2}\right), \tag{10}$$

where $h_i$ is the subcarrier fading gain from the CBS to the user. $\sigma_i^2 = \sigma_{\text{AWGN}}^2 + \sum_{l=1}^{L} J_i^l$ where $\sigma_{\text{AWGN}}^2$ is the mean variance of the additive white Gaussian noise (AWGN) and $J_i^l$ is the interference introduced by the $l^{th}$ PUs band into the $i^{th}$ subcarrier. The interference from PUs to the $i^{th}$ subcarrier is assumed to be the superposition of large number of independent components, that is, $\sum_{l=1}^{L} J_i^l$. Hence, we can model the interference as AWGN. This assumption may not be valid for low number of PU bands but can be considered as a good approximation for large number of PU bands. The same model can be found in [6, 15, 17]. Remark that the nature of the PUs interference on SUs band is the same on both OFDM and FBMC systems. The difference is only in the SUs interference to the PU bands, which is in that case FBMC has significantly lower interference, because of its significantly smaller sidelobes as compared to those of OFDM.

Assuming that each subcarrier band is narrow, subcarriers can be approximated as channel with flat fading gains [31, 32]. It will be assumed that the channel changes slowly so that the channel gains will be constant during transmission. The total achievable rate for OFDM and FBMC systems is evaluated by summing the transmission rate across the different subcarriers [7, 33]. All the instantaneous fading gains are assumed perfectly known at the CR system and there is no intercarrier interference (ICI). Let $v_{i,m}$ to be a subcarrier allocation indicator, that is, $v_{i,m} = 1$ if and only if the subcarrier is allocated to the $m^{th}$ user. It is assumed that each subcarrier can be used for transmission to at most one user at any given time. Our objective is to maximize the total capacity of the CR system subject to the instantaneous interference introduced to the PUs and total transmit power constraints. Therefore, the optimization problem can be formulated as follows:

$$P1 : \max_{P_{i,m}} \sum_{m=1}^{M} \sum_{i=1}^{N} v_{i,m} R_{i,m}(P_{i,m}, h_{i,m}) \tag{11}$$

subject to

$$v_{i,m} \in \{0, 1\}, \quad \forall i, m, \tag{12}$$

$$\sum_{m=1}^{M} v_{i,m} \leq 1, \quad \forall i, \tag{13}$$

$$\sum_{m=1}^{M} \sum_{i=1}^{N} v_{i,m} P_{i,m} \leq P_T, \tag{14}$$

$$P_{i,m} \geq 0, \quad \forall i \in \{1, 2, \ldots, N\}, \tag{15}$$

$$\sum_{m=1}^{M} \sum_{i=1}^{N} v_{i,m} P_{i,m} \Omega_i^l \leq I_{th}^l, \quad \forall l \in \{1, 2, \ldots, L\}, \tag{16}$$

where $N$ denotes the total number of subcarriers, $M$ is the number of users, $I_{th}^l$ denotes the interference threshold prescribed by the $l^{th}$ PU, and $P_T$ is the total SUs power budget. $L$ is the number of the active PU bands. Inequality (13) ensures that any given subcarrier can be allocated to at most one user.

The optimization problem $P1$ is a combinatorial optimization problem and its complexity grows exponentially with the input size. In order to reduce the computational complexity, the problem is solved in two steps by many of the suboptimal algorithms [9–12]. In the first step, the subcarriers are assigned to the users and then the power is allocated for these subcarriers in the second step. Once the subcarriers are allocated to the users, the multiuser system can be viewed virtually as a single user multicarrier system. As proved in [9], the maximum data rate in downlink can be obtained if the subcarriers are assigned to the user who has the best channel gain for that subcarrier as described in Algorithm 1.

By applying Algorithm 1, the values of the channel indicators $v_{i,m}$ are determined and hence for notation simplicity, single user notation can be used. The different channel gains can be determined from the subcarrier allocation step as follows:

$$h_i = \sum_{m=1}^{M} v_{i,m} h_{i,m}. \tag{17}$$

Therefore, problem $P1$ in (11) can be reformulated as follows:

$$P2: \max_{P_i} \sum_{i=1}^{N} \log_2\left(1 + \frac{P_i |h_i|^2}{\sigma_i^2}\right) \tag{18}$$

subject to

$$\sum_{i=1}^{N} P_i \Omega_i^l \le I_{th}^l \quad \forall l \in \{1, 2, \ldots, L\}, \tag{19}$$

$$\sum_{i=1}^{N} P_i \le P_T, \tag{20}$$

$$P_i \ge 0 \quad \forall i \in \{1, 2, \ldots, N\}. \tag{21}$$

The problem $P2$ is a convex optimization problem. The Lagrangian can be written as [17]

$$G = -\sum_{i=1}^{N} \log_2\left(1 + \frac{P_i^* |h_i|^2}{\sigma_i^2}\right) + \sum_{l=1}^{L} \alpha_l \left(\sum_{i=1}^{N} P_i^* \Omega_i^l - I_{th}^l\right) + \beta\left(\sum_{i=1}^{N} P_i^* - P_T\right) - \sum_{i=1}^{N} P_i^* \mu_i, \tag{22}$$

where $\alpha_l, l \in \{1, 2, \ldots, L\}$, $\mu_i, i \in \{1, 2, \ldots, N\}$, and $\beta$ are the Lagrange multipliers. The Karush-Kuhn-Tucker (KKT) conditions can be written as follows:

$$\begin{gathered} P_i^* \ge 0, \quad \forall i \in \{1, 2, \ldots, N\}, \\ \alpha_l \ge 0, \quad \forall l \in \{1, 2, \ldots, L\}, \\ \beta \ge 0, \\ \mu_i \ge 0, \quad \forall i \in \{1, 2, \ldots, N\}, \\ \alpha_l \left(\sum_{i=1}^{N} P_i^* \Omega_i^l - I_{th}^l\right) = 0, \quad \forall l \in \{1, 2, \ldots, L\}, \\ \beta\left(\sum_{i=1}^{N} P_i^* - P_T\right) = 0, \\ \mu_i P_i^* = 0, \quad \forall i \in \{1, 2, \ldots, N\}, \\ \frac{\partial G}{\partial P_i^*} = \frac{-1}{\sigma_i^2/|h_i|^2 + P_i^*} + \sum_{l=1}^{L} \alpha_l \Omega_i^l + \beta - \mu_i = 0, \end{gathered} \tag{23}$$

and also the solution should satisfy the total power and interference constraints given by (20) and (19). Rearranging the last condition in (23) we get

$$P_i^* = \frac{1}{\sum_{l=1}^{L} \alpha_l \Omega_i^l + \beta - \mu_i} - \frac{\sigma_i^2}{|h_i|^2}. \tag{24}$$

**Initialization:**
Set $v_{i,m} = 0 \quad \forall i, m$
**Subcarrier Allocation:**
  **for** $i = 1$ to $N$ **do**
    $m^* = \underset{m}{\operatorname{argmax}}\{h_{i,m}\}$; $v_{i,m^*} = 1$
**end for**

Algorithm 1: Subcarriers to user allocation.

Since $P_i^* \ge 0$, we get

$$\frac{\sigma_i^2}{|h_i|^2} \le \frac{1}{\sum_{l=1}^{L} \alpha_l \Omega_i^l + \beta - \mu_i}. \tag{25}$$

If $\sigma_i^2/|h_i|^2 < 1/(\sum_{l=1}^{L} \alpha_l \Omega_i + \beta)$, then $\mu_i = 0$ and hence

$$P_i^* = \frac{1}{\sum_{l=1}^{L} \alpha_l \Omega_i^l + \beta} - \frac{\sigma_i^2}{|h_i|^2}. \tag{26}$$

Moreover, if $\sigma_i^2/|h_i|^2 > 1/(\sum_{l=1}^{L} \alpha_l \Omega_i^l + \beta)$, from (24) we get

$$\frac{1}{\sum_{l=1}^{L} \alpha_l \Omega_i^l + \beta - \mu_i} \ge \frac{\sigma_i^2}{|h_i|^2} \ge \frac{1}{\sum_{l=1}^{L} \alpha_l \Omega_i^l + \beta}, \tag{27}$$

and since $\mu_i P_i^* = 0$ and $\mu_i \ge 0$, we get that $P_i^* = 0$.

Therefore, the optimal solution can be written as follows:

$$P_i^* = \begin{cases} \dfrac{1}{\sum_{l=1}^{L} \alpha_l \Omega_i^l + \beta} - \dfrac{\sigma_i^2}{|h_i|^2} & \text{if } \dfrac{\sigma_i^2}{|h_i|^2} < \dfrac{1}{\sum_{l=1}^{L} \alpha_l \Omega_i^l + \beta}, \\ 0 & \text{if } \dfrac{\sigma_i^2}{|h_i|^2} \ge \dfrac{1}{\sum_{l=1}^{L} \alpha_l \Omega_i^l + \beta}, \end{cases} \tag{28}$$

or more simply, (28) can be written as the follows:

$$P_i^* = \left[\frac{1}{\sum_{l=1}^{L} \alpha_l \Omega_i^l + \beta} - \frac{\sigma_i^2}{|h_i|^2}\right]^+, \tag{29}$$

where $[x]^+ = \max(0, x)$. Solving for $L + 1$ Lagrangian multipliers is computational complex. These multipliers can be found numerically using ellipsoid or interior point method with a complexity $\mathcal{O}(N^3)$ [17, 34]. In what follows we will propose a low complexity algorithm that achieves near optimal performance.

## 4. Proposed Algorithm

The optimal solution for the optimization problem has a high computational complexity which makes it unsuitable for the practical applications. A low complexity algorithm is proposed in [17]. The subcarriers nulling and deactivating throughout this algorithm degrade the system capacity and causing the algorithm to have a limited performance in low interference constraints. To overcome the drawbacks of this algorithm, a low complexity power allocation algorithm will be presented.

As described in [5, 17], most of the interference introduced to the PU bands is induced by the cognitive transmission in the subcarriers where the PU is active as well as the subcarriers that are directly adjacent to the PU bands. Considering this fact, it can be assumed that each subcarrier is belonging to the closest PU band and only introducing interference to it, then the optimization problem $P2$ can be reformulated as follows:

$$P3: \max_{P_i'} \sum_{i=1}^{N} \log_2\left(1 + \frac{P_i' |h_i|^2}{\sigma_i^2}\right) \tag{30}$$

subject to

$$\begin{gathered} \sum_{i \in N_l} P_i' \Omega_i^l \leq I_{th}^l \quad \forall l \in \{1, 2, \ldots, L\}, \\ \sum_{i=1}^{N} P_i' \leq P_T, \\ P_i' \geq 0 \quad \forall i \in \{1, 2, \ldots, N\}, \end{gathered} \tag{31}$$

where $N_l$ denotes the set of the subcarriers belong to the $l^{th}$ PU band. Using the same derivation leading to (29), we get

$$P_i' = \left[\frac{1}{\alpha_l' \Omega_i^l + \beta'} - \frac{\sigma_i^2}{|h_i|^2}\right]^+, \tag{32}$$

where $\alpha_l'$ and $\beta'$ are the non-negative dual variables corresponding to the interference and power constraints respectively. The solution of the problem still has high computational complexity which encourages us to find a faster and efficient power allocation algorithm.

If the interference constraints are ignored in $P3$, the solution of the problem will follow the well-known waterfilling interpretation [35]

$$P_i^{'(P_T)} = \left[\lambda - \frac{\sigma_i^2}{|h_i|^2}\right]^+, \tag{33}$$

where $\lambda$ is the waterfilling level. On the other side, if the total power constraint is ignored, the Lagrangian of the problem can be written as [15]

$$\begin{aligned} G^{(\text{Int})} = &-\sum_{i \in N_l} \log_2\left(1 + \frac{P_i^{'(\text{Int})} |h_i|^2}{\sigma_i^2}\right) \\ &+ \alpha_l^{'(\text{Int})} \left(\sum_{i \in N_l} P_i^{'(\text{Int})} \Omega_i^l - I_{th}^l\right), \end{aligned} \tag{34}$$

where $\alpha_l'$ is the Lagrange multiplier. Equating $\partial G^{(\text{Int})} / \partial P_i^{'(\text{Int})}$ to zero, we get

$$P_i^{'(\text{Int})} = \left[\frac{1}{\alpha_l^{'(\text{Int})} \Omega_i^l} - \frac{\sigma_i^2}{|h_i|^2}\right]^+, \tag{35}$$

where the value of $\alpha_l'$ can be calculated by substituting (35) into $\sum_{i \in N_l} P_i^{'(\text{Int})} \Omega_i = I_{th}^l$ to get

$$\alpha_l^{'(\text{Int})} = \frac{|N_l|}{I_{th}^l + \sum_{i \in N_l} \left(\Omega_i^l \sigma_i^2 / |h_i|^2\right)}. \tag{36}$$

It is obvious that if the summation of the allocated power under only the interference constraints is lower than or equal the available total power budget, that is, $\sum_{i=1}^{N} P_i^{'(\text{Int})} \leq P_T$, for all $i \in \{1, 2, \ldots, N\}$, then (35)-(36) will be the optimal solution for the optimization problem $P3$. In most of the cases, the total power budget is quite lower than this summation, and hence the Power Interference (PI) constrained algorithm, referred to as *PI-Algorithm*, is proposed to allocate the power under both total power and interference constraints.

In order to solve the optimization problem $P3$, we can start by assuming that the maximum power that can be allocated for a given subcarrier $P_i^{\text{Max}}$ is determined according to the interference constraints only by using (35)-(36) for every set of subcarriers $N_l$, for all $l \in \{1, 2, \ldots, L\}$. By such an assumption, we can guarantee that the interference introduced to PU bands will be under the prespecified thresholds. Once the maximum power $P_i^{\text{Max}}$ is determined, the total power constraint is tested. If the total power constraint is satisfied, then the solution has been found and is equal to the maximum power that can be allocated to each subcarrier, that is, $P_i' = P_i^{\text{Max}}$. Otherwise, the available power budget should be distributed among the subcarriers giving that the power allocated to each subcarrier is lower than or equal to the maximum power that can be allocated to each subcarrier $P_i^{\text{Max}}$, and hence the following problem should be solved:

$$P4: \max_{P_i^{W.F}} \sum_{i=1}^{N} \log_2\left(1 + \frac{P_i^{W.F} |h_i|^2}{\sigma_i^2}\right) \tag{37}$$

subject to

$$\begin{gathered} \sum_{i=1}^{N} P_i^{W.F} \leq P_T, \\ 0 \leq P_i^{W.F} \leq P_i^{\text{Max}}. \end{gathered} \tag{38}$$

The problem $P4$ is called *"cap-limited"* waterfilling [36]. The problem can be solved efficiently using the concept of the conventional waterfilling. Given the initial waterfilling solution, the channels that violate the maximum power $P_i^{\text{Max}}$ are determined and upper bounded with $P_i^{\text{Max}}$. The total power budget is reduced by subtracting the power assigned so far. At the next step, the algorithm proceeds to successive waterfilling over the subcarriers that did not violate the maximum power $P_i^{\text{Max}}$ in the last step. This procedure is repeated until the allocated power $P_i^{W.F}$ does not violate the maximum power $P_i^{\text{Max}}$ in any of the subcarriers in the new iteration. The *"cap-limited"* waterfilling algorithm implementation is described in Algorithm 2.

The solution $P_i^{W.F}$ of the problem $P4$ is satisfying the total power constraint of the problem $P3$ with equality which is not the case for the different interference constraints $I_{th}^l$. Since it is assumed that $P_i^{W.F} \leq P_i^{\text{Max}}$, some of the powers allocated to subcarriers will not reach the maximum allowable values. This will make the interference introduced to the PU bands below the thresholds $I_{th}^l$. In order to take advantage of all the allowable interference, the values of the

(1) **Initialize** $\mathcal{F} = \mathcal{M} = \mathcal{N} = \{1, 2, \ldots, N\}$, $\overline{P_i} = P_i^{\text{Max}}$, and $S = P_T$.
(2) Sort $\left\{ T_i = \dfrac{\sigma_i^2}{|h_i|^2}, i \in \mathcal{N} \right\}$ in decreasing order with $J$ being the sorted index. Find the waterfilling $\lambda$ as follows:
  (a) $T_{\text{sum}} = \sum_{i \in \mathcal{N}} T_i$, $\lambda = (T_{\text{sum}} + S)/|\mathcal{N}|$, $n = 1$.
  (b) **While** $T_{J(n)} > \lambda$ **do**
    $T_{\text{sum}} = T_{\text{sum}} - T_{J(n)}$, $\mathcal{N} = \mathcal{N} \setminus \{J(n)\}$, $\lambda = (T_{\text{sum}} + S)/|\mathcal{N}|$, $n = n + 1$
   **end while**
  (c) Set $P_i^{W.F} = [\lambda - T_i]^+, \forall i \in \mathcal{F}$
(3) **repeat**
  **if** $P_i^{W.F} \geq \overline{P_i}$
  Let $P_i^{W.F} = \overline{P_i}$, $S = S - P_i^{W.F}$, $\mathcal{M} = \mathcal{M} \setminus \{i\}$, $\mathcal{N} = \mathcal{M}$, and go to step 2;
  **end if**
 **until** $P_i^{W.F} \leq \overline{P_i}, \forall i \in \mathcal{F}$

Algorithm 2: Cap-limited waterfilling.

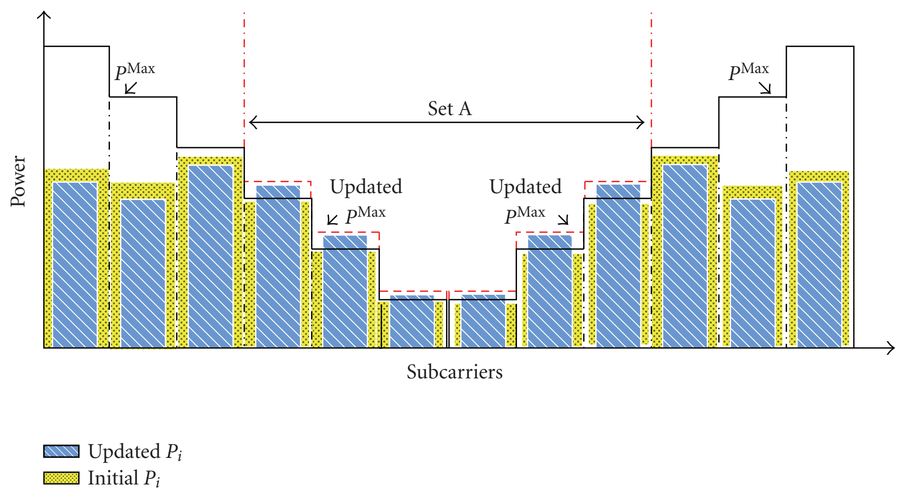


Figure 5: An Example of the SUs allocated power using PI-Algorithm.

maximum power that can be allocated to each subcarrier $P_i^{\text{Max}}$ should be updated depending on the left interference. The left interference can be determined as follows:

$$I_{\text{Left}}^l = I_{th}^l - \sum_{i \in N_l} P_i^{W.F} \Omega_i^l. \tag{39}$$

Assuming that $A_l \subset N_l$ is the set of the subcarriers that reach its maximum, that is, $P_i^{W.F} = P_i^{\text{Max}}$, for all $i \in A_l$, then, $P_i^{\text{Max}}$, for all $i \in A_l$ can be updated by applying (35)-(36) on the subcarriers in the set $A_l$ with the following interference constraints:

$$I_{th}^{\prime l} = I_{\text{Left}}^l + \sum_{i \in A_l} P_i^{W.F} \Omega_i^l. \tag{40}$$

After determining the updated values of $P_i^{\text{Max}}$, the *"cap-limited"* waterfilling is performed again to find the final solution $P_i' = P_i^{W.F}$. Now, the solution $P_i'$ is satisfying approximately the interference constraints with equality as well as guaranteing that the total power used is equal to $P_T$. A graphical description of the *PI-Algorithm* is given in Figure 5 while the implementation procedures are described in Algorithm 3.

The computational complexity of Step 2 in the proposed PI-Algorithm (Algorithm 3) is $\sum_{l=1}^{L} \mathcal{O}(|N_l| \log |N_l|) \leq \mathcal{O}(N \log N)$. Steps 4 and 6 of the algorithm execute the *"cap-limited"* waterfilling which has a complexity of $\mathcal{O}(N \log N + \eta N)$, where $\eta \leq N$ is the number of the iterations. Step 5 has a complexity of $\sum_{l=1}^{L} \mathcal{O}(|A_l| \log |A_l|) + \mathcal{O}(L) \leq \mathcal{O}(N \log N) + \mathcal{O}(L)$. Therefore, The overall complexity of the algorithm is lower than $\mathcal{O}(N \log N + \eta N) + \mathcal{O}(L)$. The value of $\eta$ is estimated via simulation to be lower than five, that is, $\eta \in [0, 5]$. Comparing to the computational complexity of the optimal solution, $\mathcal{O}(N^3)$, the proposed algorithm has much lower computational complexity specially when the number of the subcarriers $N$ increased.

## 5. Simulation Results

The simulations are performed under the scenario given in Figure 1. A multicarrier system of $M = 3$ cognitive users and $N = 32$ subcarriers is assumed. The values

(1) **Initialize** $\mathcal{N} = \{1, 2, \cdots, N\}$, $\mathcal{N}_l = N_l$, $I^l_{\text{Left}} = 0$, $S = P_T$ and $\mathcal{A}_l = \emptyset$.

(2) $\forall l \in \{1, 2, \cdots, L\}$, sort $\left\{ H_i = \dfrac{\sigma_i^2}{|h_i|^2}\Omega_i^l, i \in \mathcal{N}_l \right\}$ in decreasing order with $k$ being the sorted index.

Find the $P_i^{\text{Max}}$ as follows:

(a) $H_{\text{sum}} = \sum_{i\in\mathcal{N}_l} H_i$, $\alpha_l^{'(\text{Int})} = |\mathcal{N}_l|/(I^l_{th} + H_{\text{sum}})$, $n = 1$.

(b) **while** $\alpha_l^{'(\text{Int})} > H^{-1}_{k(n)}$ **do**

$H_{\text{sum}} = H_{\text{sum}} - H_{k(n)}$, $\mathcal{N}_l = \mathcal{N}_l \setminus \{k(n)\}$, $\alpha_l^{'(\text{Int})} = |\mathcal{N}_l|/(I^l_{th} + H_{\text{sum}})$, $n = n + 1$

**end while**

(c) Set $P_i^{\text{Max}} = \left[ \dfrac{1}{\alpha_l^{'(\text{Int})}\Omega_i^l} - \dfrac{\sigma_i^2}{|h_i|^2} \right]^+$

(3) **if** $\sum_{i\in\mathcal{N}} P_i^{\text{Max}} \le P_T$

Let $P'_i = P_i^{\text{Max}}$ and stop the algorithm.

**end if**

(4) Execute the "*cap-limited*" waterfilling (Algorithm 2) and find the set $\mathcal{A}_l \subset N_l$ where $P_i^{W.F} = P_i^{\text{Max}}$.

(5) Evaluate $I^l_{\text{Left}} = I^l_{th} - \sum_{i\in N_l} P_i^{W.F}\Omega_i^l$ and set $\mathcal{N}_l = \mathcal{A}_l$, $I^l_{th} = I^l_{\text{Left}} + \sum_{i\in\mathcal{A}_l} P_i^{W.F}\Omega_i^l$ and apply again only step 2 to update $P_i^{\text{Max}}$.

(6) Execute the "*cap-limited*" waterfilling (Algorithm 2) and set $P'_i = P_i^{W.F}$.

Algorithm 3: PI-Algorithm.

of $\Delta f$ and $P_T$ are assumed to be 0.3125 MHz and 1 watt, respectively. AWGN of variance $10^{-6}$ is assumed. Without loss of generality, the interference induced by PUs to the SUs band is assumed to be negligible. The channel gains $h$ and $g$ are outcomes of independent, identically distributed (i.i.d) Rayleigh distributed random variables (rv's) with mean equal to "1" and assumed to be perfectly known at the (CBS). OFDM and FBMC-based cognitive radio systems are evaluated. The OFDM system is assumed to have a 6.67% of its symbol time as cyclic prefix (CP). For FBMC system, the prototype coefficients are assumed to be equal to PHYDYAS coefficients with overlapping factor $K = 4$ and are defined by [24, 37]

$$h[n] = 1 - 1.94392\cos\left(\frac{2\pi n}{128}\right) + \sqrt{2}\cos\left(\frac{4\pi n}{128}\right) - 0.470294\cos\left(\frac{6\pi n}{128}\right), \quad 0 \le n \le 127, \tag{41}$$

The optimal solution is implemented using the interior point method. We refer to the method proposed in [17] by Zhang algorithm. All the results have been averaged over 1000 iterations.

Two interference constraints belonging to two active PU bands, that is, $L = 2$, is assumed as given in Figure 6. Each active PU band is assumed to have six subcarriers where $|N_1| = |N_2| = 16$. The achieved capacity using optimal, PI and Zhang algorithms for different interference constraints where $I^1_{th} = I^2_{th}$ is plotted in Figure 7. It can be noted that the proposed PI-algorithm approaches the optimal solution and outperforms Zhang algorithm. The effect of assuming that every subcarrier is belonging to the closest PU band and introducing interference to it only on the net interference introduced to the active PU bands is studied in Figures 8 and 9 for $PU_1$ and $PU_2$, respectively. It can be observed that the net interference induced using the PI-algorithm is approximately satisfying the prespecified interference constraints which makes the assumption reasonable. Unlike the OFDM-based CR system, the interference induced by the FBMC-based system does not reach the pre-specified thresholds. This is because the FBMC-based CR system reaches to the maximum interference that can be introduced to the PU using the given power budget. Moreover, the interference induced by the proposed algorithm is less than that using Zhang algorithm. Returning to Figure 7, one can notice that the interference constraints after $I^l_{th} = 10m$ Watt start to have no effect on the achieved capacity of the FBMC system. This indicates also that the FBMC system reaches the maximum interference for the given power budget. The small difference between the net interference values after $I^l_{th} = 10m$ Watt is due to averaging over different channel realizations. The achieved capacity of the different algorithms is plotted in Figure 10 with lower values of the interference constraints. It can be noticed that Zhang algorithm has a limited performance with low interference constraints because the algorithm turns off the subcarriers that have a noise level more than the initial waterfilling level and never uses these subcarriers again even if the new waterfilling level exceeds its noise level. Moreover, the algorithm deactivates some subcarriers, that is, transmit zero power, in order to ensure that the interference introduced to PU bands is below the prespecified thresholds. The lower the interference constraints, the more the deactivated subcarriers which justifies the limited performance of this algorithm in low interference constraints.

To show the efficiency of transmitting over the active PU bands as well as the nonactive bands, Figures 11 and 12 plot the achieved capacity using the PI algorithm with and without allowing the SUs to transmit over the PU active bands. The capacity of the CR system transmitting on both the active and nonactive bands is more than that one transmitting only on the nonactive band. Since the cognitive transmission in the active PU band introduces

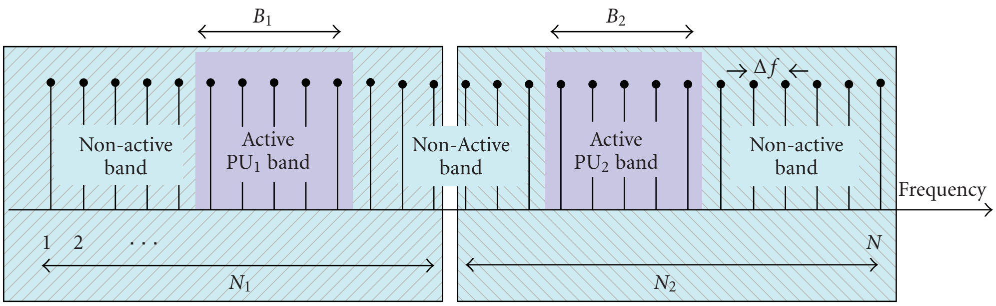


Figure 6: Frequency distribution with two active PU bands.

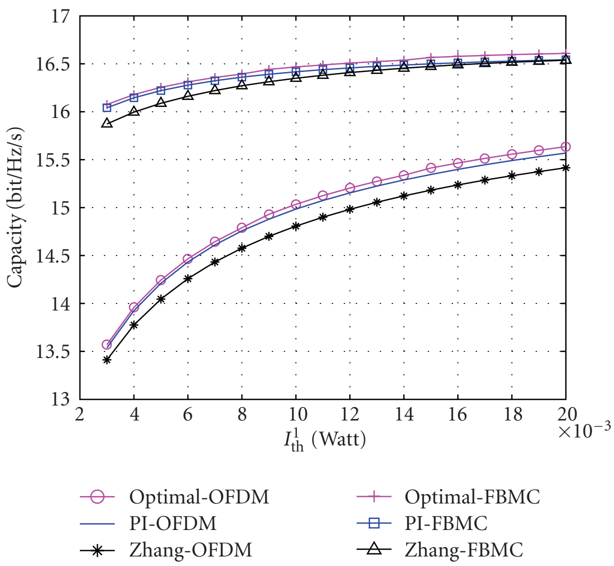


Figure 7: Achieved capacity versus allowed interference threshold for OFDM- and FBMC-based CR systems—two active PU bands.

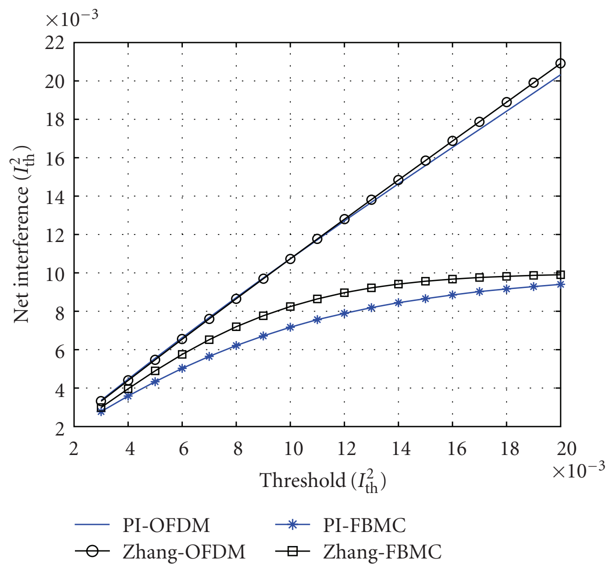


Figure 9: Total interference introduced to the $PU_2$ versus interference threshold.

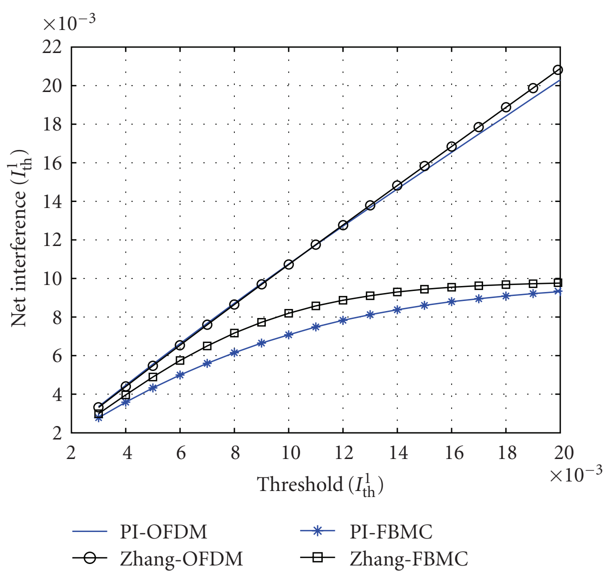


Figure 8: Total interference introduced to the $PU_1$ versus interference threshold.

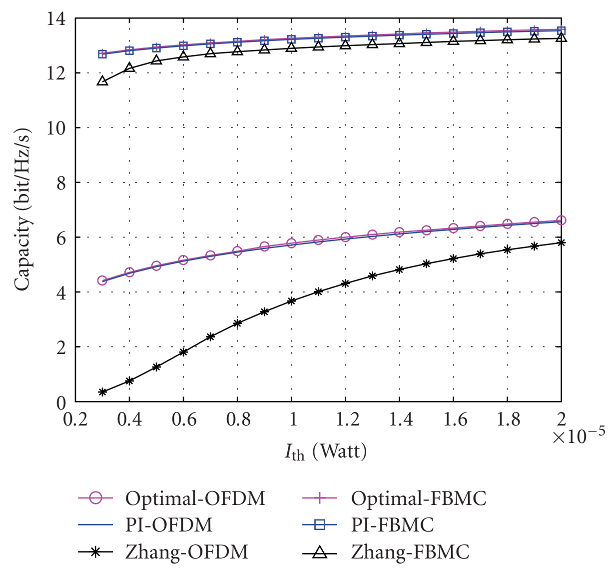


Figure 10: Achieved CR versus allowed interference threshold (low) for OFDM- and FBMC-based CR systems—two active bands.

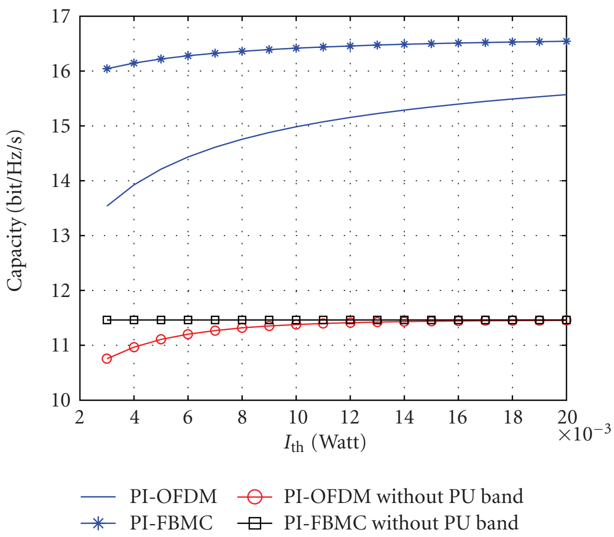


Figure 11: Achieved capacity versus allowed interference threshold with and without transmitting over active bands—two active PU bands.

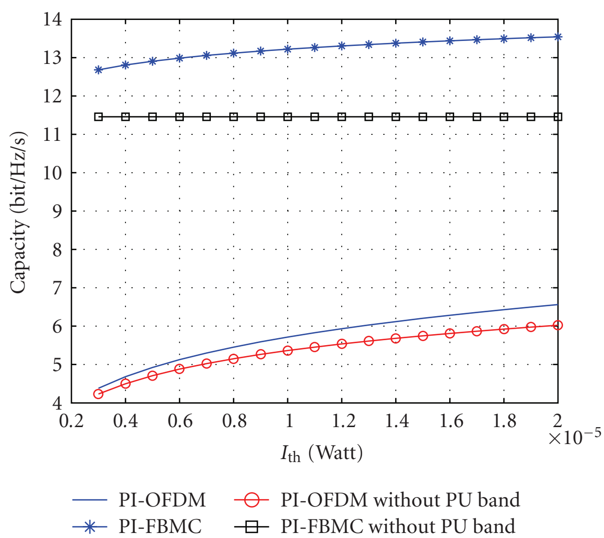


Figure 12: Achieved capacity versus allowed interference threshold (low) with and without transmitting over active bands—two active PU bands.

more interference to the PUs than the other subcarriers, low power levels can be used in these bands with low interferences constraints. This justifies why the difference between the two systems decreases when the interference constraints decrease.

RC algorithm can be used if there is only one active PU band, that is, $L = 1$. The RC algorithm allocates the subcarriers and bits considering the relative importance between the power needed to transmit and the interference induced to the PU band. In order to compare the proposed PI-algorithm with RC algorithm, One active PU band with "12" subcarriers will be assumed as given in Figure 13. For

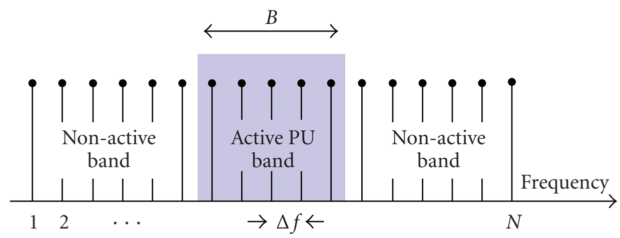


Figure 13: Frequency distribution with one active PU band.

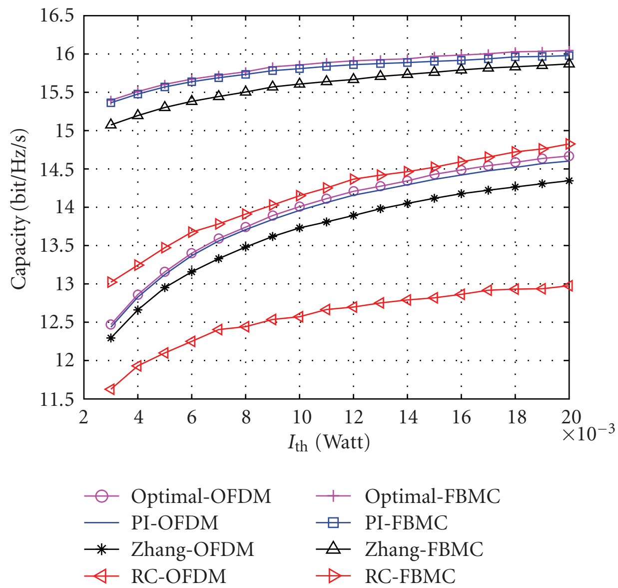


Figure 14: Achieved capacity versus allowed interference threshold for OFDM- and FBMC-based CR systems—one active PU band.

fair comparison, the same bit mapping used in [16] is considered as follows:

$$b_i = \left\lfloor \log_2\left(1 + \frac{P_i' |h_i|^2}{\sigma_i^2}\right)\right\rfloor, \tag{42}$$

where $b_i$ denotes the maximum number of bits in the symbol transmitted in the $i^{th}$ subcarrier and $\lfloor \cdot \rfloor$ denotes the floor function. Figures 14 and 15 show that the proposed algorithm performs better than the RC and Zhang algorithms. In low interference constraints, RC algorithm performs better than Zhang algorithm because of the limited performance of Zhang algorithm with low interference constraints.

For all the so far presented results, the capacity of FBMC-based CR system is higher than that of OFDM-based one because the sidelobes in FBMC's PSD is smaller than that in OFDM which introduces less interference to the PUs. Moreover, the inserted CP in OFDM-based CR systems reduces the total capacity of the system. It can be noticed also that the interference condition introduces a small restriction on the capacity of FBMC-based CR systems which is not the case in OFDM-based CR systems. The significant increase in the capacity of FBMC-based CR systems over the OFDM-based ones recommends the FBMC as a candidate for the CR network applications.

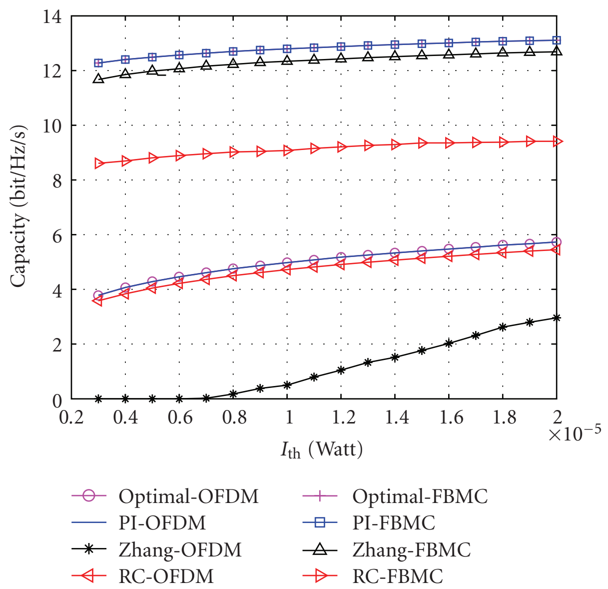


FIGURE 15: Achieved capacity versus allowed interference threshold (low) for OFDM- and FBMC-based CR systems—one active PU band.

## 6. Conclusion

In this paper, a low complexity suboptimal resource allocation algorithm for multicarrier-based CR networks is presented. Our objective was to maximize the total downlink capacity of the CR network while respecting the available power budget and guaranteeing that no excessive interference is caused to the PUs. With a significant reduction in the computational complexity from $\mathcal{O}(N^3)$ to $\mathcal{O}(N \log N + \eta N) + \mathcal{O}(L), \eta \in [0, 5]$, It is shown that the proposed PI-algorithm achieves a near optimal performance and outperforms the suboptimal algorithms proposed so far. It is found that the net total interference introduced to the PUs band is relatively not affected by assuming that each subcarrier is belonging to the closest PU band and only introducing interference to it. Its demonstrated also that capacity of the CR system uses the nonactive as well as the active bands is more than that only uses the nonactive bands. Simulation results prove that the FBMC-based CR systems have more capacity than OFDM-based ones. FBMC offers more spectral efficiency and introduces small interference to the PUs. The obtained results contribute in recommending the use of FBMC physical layer in the future cognitive radio systems. Developing a resource allocation algorithm that considers the fairness among different users as well as their quality of service (QoS) will be the guideline of our future research work towards better radio resource management.

## Acknowledgment

This work was partially supported by the European ICT-2008-211887 project PHYDYAS.

## References

[1] Federal Communication Commission, "Spectrum Policy Task Force," Report of ET Docket 02-135, November 2002.

[2] J. Mitola III, "Cognitive radio for flexible mobile multimedia communications," in *Proceedings of IEEE International Workshop on Mobile Multimedia Communications (MoMuC '99)*, pp. 3–10, San Diego, Calif, USA, November 1999.

[3] T. A. Weiss and F. K. Jondral, "Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency," *IEEE Communications Magazine*, vol. 42, no. 3, pp. S8–S14, 2004.

[4] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, 2005.

[5] T. Weiss, J. Hillenbrand, A. Krohn, and F. K. Jondral, "Mutual interference in OFDM-based spectrum pooling systems," in *Proceedings of the 59th IEEE Vehicular Technology Conference (VTC '04)*, vol. 59, Milan, Italy, May 2004.

[6] B. Farhang-Boroujeny and R. Kempter, "Multicarrier communication techniques for spectrum sensing and communication in cognitive radios," *IEEE Communications Magazine*, vol. 46, no. 4, pp. 80–85, 2008.

[7] H. Zhang, D. L. Ruyet, and M. Terre, "On spectral efficiency analysis between OFDM/OQAM and OFDM based CR networks," in *Proceedings of the IEEE Vehicular Technology Conference (VTC '09)*, Barcelona, Spain, 2009.

[8] B. Farhang-Boroujeny, "Filter bank spectrum sensing for cognitive radios," *IEEE Transactions on Signal Processing*, vol. 56, no. 5, pp. 1801–1811, 2008.

[9] J. Jang and K. B. Lee, "Transmit power adaptation for multiuser OFDM systems," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 2, pp. 171–178, 2003.

[10] D. Kivanc, G. Li, and H. Liu, "Computationally efficient bandwidth allocation and power control for OFDMA," *IEEE Transactions on Wireless Communications*, vol. 2, no. 6, pp. 1150–1158, 2003.

[11] Z. Shen, J. G. Andrews, and B. L. Evans, "Optimal power allocation in multiuser OFDM systems," in *Proceedings of IEEE Global Telecommunications Conference (GLOBECOM '03)*, vol. 1, pp. 337–341, San Francisco, Calif, USA, December 2003.

[12] C. Y. Wong, R. S. Cheng, K. B. Letaief, and R. D. Murch, "Multiuser OFDM with adaptive subcarrier, bit, and power allocation," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 10, pp. 1747–1758, 1999.

[13] P. Wang, M. Zhao, L. Xiao, S. Zhou, and J. Wang, "Power allocation in OFDM-Based cognitive radio systems," in *Proceedings of IEEE Global Telecommunications Conference (GLOBECOM '07)*, pp. 4061–4065, 2007.

[14] G. Bansal, M. J. Hossain, and V. K. Bhargava, "Adaptive power loading for OFDM-based cognitive radio systems," in *Proceedings of IEEE International Conference on Communications (ICC '07)*, pp. 5137–5142, Glasgow, UK, 2007.

[15] G. Bansal, M. J. Hossain, and V. K. Bhargava, "Optimal and suboptimal power allocation schemes for OFDM-based cognitive radio systems," *IEEE Transactions on Wireless Communications*, vol. 7, no. 11, pp. 4710–4718, 2008.

[16] T. Qin and C. Leung, "Fair adaptive resource allocation for multiuser OFDM cognitive radio systems," in *Proceedings of the 2nd International Conference on Communications and Networking in China (ChinaCom '07)*, August 2007.

[17] Y. Zhang, *Resource allocation for OFDM-based cognitive radio systems*, Ph.D. dissertation, University of British Columbia, Vancouver, Canada, December 2008.

[18] G. Stuber, S. Almalfouh, and D. Sale, "Interference analysis of TV-band whitespace," *Proceedings of the IEEE*, vol. 97, no. 4, pp. 741–754, 2009.

[19] M. Shaat and F. Bader, "Power allocation with interference constraint in multicarrier based cognitive radio systems," in *Proceedings of the 7th International Workshop on Multi-Carrier Systems and Solutions (MCSS '09)*, Herrsching, Germany, May 2009.

[20] J. G. Proakis and M. Salehi, *Communication Systems Engineering*, Prentice-Hall, Upper Saddle River, NJ, USA, 2nd edition, 2002.

[21] L. G. Baltar, D. S. Waldhauser, and J. Nossek, "Out-of-band radiation in multicarrier systems: a comparison," in *Proceedings of the International Workshop on Multi-Carrier Systems & Solutions (MC-SS '07)*, pp. 107–116, Springer, May 2007.

[22] B. Hirosaki, "An orthogonally multiplexed QAM system using the discrete fourier transform," *IEEE Transactions on Communications Technology*, vol. 29, no. 7, pp. 982–989, 1981.

[23] A. Skrzypczak, P. Siohan, and J.-P. Javaudin, "Power spectral density and cubic metric for the OFDM/OQAM modulation," in *Proceedings of the 6th IEEE International Symposium on Signal Processing and Information Technology (ISSPIT '06)*, Vancouver, Canada, August 2006.

[24] "PHYDYAS-Physical layer for dynamic spectrum access and cognitive radio," http://www.ict-phydyas.org/.

[25] A. Jayalath and C. Tellambura, "Reducing the out-of-band radiation of OFDM using an extended guard interval," in *Proceedings of the 53rd Vehicular Technology Conference (VTC '01)*, vol. 2, pp. 829–833, Rhodes, Greece, May 2001.

[26] S. Brandes, I. Cosovic, and M. Schnell, "Reduction of out-of-band radiation in OFDM systems by insertion of cancellation carriers," *IEEE Communications Letters*, vol. 10, no. 6, pp. 420–422, 2006.

[27] Y.-P. Lin and S.-M. Phoong, "Window designs for DFT-based multicarrier systems," *IEEE Transactions on Signal Processing*, vol. 53, no. 3, pp. 1015–1024, 2005.

[28] H. A. Mahmoud and H. Arslan, "Sidelobe suppression in OFDM-based spectrum sharing systems using adaptive symbol transition," *IEEE Communications Letters*, vol. 12, no. 2, pp. 133–134, 2008.

[29] A. Vahlin and N. Holte, "Optimal finite duration pulses for OFDM," *IEEE Transactions on Communications*, vol. 44, no. 1, pp. 10–14, 1996.

[30] R. Xu and M. Chen, "Spectral leakage suppression of DFT-based OFDM via adjacent subcarriers correlative coding," in *Proccedings of IEEE Global Telecommunications Conference (GLOBECOM '08)*, pp. 3029–3033, December 2008.

[31] A. Amini, R. Kempter, L. Lin, and B. Farhang-Boroujeny, "Filter bank multitone: a candidate for physical layer of cognitive radio," in *Proceedings of the Software Defined Radio Technical Conference and Product Exhibition (SDR '05)*, Orange County, Calif, USA, November 2005.

[32] A. Amini, R. Kempter, and B. Farhang-Boroujeny, "A comparison of alternative filterbank multicarrier methods in cognitive radios," in *Proceedings of the Software Defined Radio Technical Conference and Product Exhibition (SDR '06)*, Orlando, Fla, USA, November 2006.

[33] H. Zhang, D. Le Ruyet, and M. Terre, "Spectral efficiency comparison between OFDM/OQAM- and OFDM-based CR networks," *Wireless Communications and Mobile Computing*, vol. 9, no. 11, pp. 1487–1501, 2009.

[34] S. Boyd and L. Vandenberghe, *Convex Optimization*, Cambridge University Press, Cambridge, UK, 2004.

[35] A. Leke and J. Cioffi, "A maximum rate loading algorithm for discrete multitone modulation systems," in *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM '97)*, vol. 3, pp. 1514–1518, 1997.

[36] N. Papandreou and T. Antonakopoulos, "Bit and power allocation in constrained multicarrier systems: the single-user case," *EURASIP Journal on Advances in Signal Processing*, vol. 2008, Article ID 643081, 14 pages, 2008.

[37] M. Bellanger, "Filter banks and OFDM-OQAM for high throughput wireless LAN," in *Proceedings of the 3rd International Symposium on Communications, Control, and Signal Processing (ISCCSP '08)*, pp. 758–761, St Julians, Malta, March 2008.