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Adaptive resources assignment in OFDM-based cognitive radio systems

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ABSTRACT

Spectrum efficiency of orthogonal frequency division multiplexing (OFDM)-based cognitive radio (CR) systems can be improved by adaptive resources allocation. In resources allocation, transmission resources such as modulation level and transmission power are adaptively assigned based on channel variations. The goal of this paper is maximize the total transmission rate of secondary user (SU). Hence, we investigate adaptive power and modulation allocation to achieve this purpose. For power allocation, we investigate optimal and conventional methods and then introduce a novel suboptimal algorithm to calculate the transmission power of each subcarrier. In addition, for adaptive modulation, we consider two kinds of modulations including multi-quadrature amplitude modulation (MQAM) and multi-phase-shift keying (MPSK). Also, simulation results are indicated the performance of our algorithm.

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1. INTRODUCTION

The frequency band is an important resource in wireless communication. Due to increase wireless systems, frequency band has been scare more and more. Therefore, novel methods have been introduced to improve the spectrum performance for overcoming this challenge [1]. Cognitive Radio (CR) is a novel and powerful technique to increase spectrum band performance. In the CR the unlicensed user or the secondary users SU can utilize the frequency spectrum that originally allocated to a licensed user or the primary users (PU). The main challenge for SUs is keep the amount of interference that introduces on the PUs than specified threshold [2]. Several scenarios have introduced by researchers for CR systems. In the one of the most important scenario, that is considered in this research, SUs can use unoccupied parts of spectrum bands between PUs bands. In this scenario, the PUs and SUs are assigned in adjacent bands [3]. Therefore, due to this vicinity, adjacent channel interference (ACI) is produced on both PU receiver (PUR) and SU receiver (SUR) [4].

Hence, it is so important to consider this interference to guarantee the performance of both PU and SU systems. Because of main advantages of OFDM technique, it is used by SUs to utilize the unoccupied portion of spectrum bands [5]. This kind of system is named OFDM-based CR system. As we know, adaptive resources assignment is a technique to increase the performance of the communication systems. Therefore, we consider this technique to improve the performance of the OFDM-based CR system. Therefore, we consider adaptive power allocation that the transmission power of each subcarrier is adaptively assigned based on channel variation [6]. In power allocation, more power is allocated to channels with better channel fading gain and less power allocated to channels with worse channel fading gain [7]. Also, we consider adaptive modulation in this paper. In the adaptive modulation, the modulation level is changed adaptively [8].

The idea behind adaptive modulation is that the transmitter can use the channel in optimum mode regardless channel situations [9]. Due to importance of this research topic, resources allocation in OFDM-based CR systems has investigated in some papers. In the [3] and [4], researchers investigated power allocation in the OFDM-based CR systems and introduced the algorithm for power allocation. Authors in [5], consider effect of the mutual interference on the CR system. In addition, in [10] and [11] authors introduced suboptimal algorithms for power allocation. Although suboptimal algorithms have worse performance than the optimal algorithm but due to their low-complexity procedures, they are the better candidate for practical usages. In [12] authors considered both adaptive modulation and power allocation and introduced a suboptimal power allocation algorithm for OFDM-based CR systems. In the [8] and [12], researchers considered MQAM modulation technique for transmitting data. In the both papers, modulation level is changed adaptively, based on the channel state information. In this research, we first introduce the optimal method for allocating the transmit power and then introduce a novel suboptimal algorithm in the OFDM-based CR systems. In addition, conventional power allocation methods such as water filling and uniform loading algorithms are described in this paper. In the above papers, only MQAM modulation level was investigated while in this paper, we consider two kinds of modulation including MQAM and MPSK. Both modulation schemes are used in modern communication systems, therefore, we compare the performance of them in OFDM-based CR systems. This compression helps to researchers to select the best modulation technique for future researches and applications.

The rest of this paper is organized as follows; in Section 2, we introduce the system model and optimum power allocation. Our suboptimal algorithm is introduced in Section 3. Water filling and uniform loading algorithms are described in Section 4. In Section 5, numerical results are presented.

2. SYSTEM MODEL

The model of the system is shown in Figure 1, where a SU is located between *L* PUS. As discussed is the previous section, the SU uses OFDM to use frequency holes. Therefore, the secondary user divides frequency holes into *N* flat subcarriers with a bandwidth Δf. Spectrum allocation is behind of this paper scope, hence, we assume spectrum allocation has done and the values of Δf and *N* are known. SU transmitter (SUT) utilizes ideal Nyquist pulse. Each spectrum band of PU is equal to B. the maximum value of interference that SU can introduce on each PUR is equal to i-th. Figure 2, indicates system model in a spatial domain. h^{i}_{ss} is the channel fading gain of SUT- SUR channel over i-th subcarrier. h^{ℓ}_{sp} is the channel fading gain of SUT - ℓ-th PUR channel.

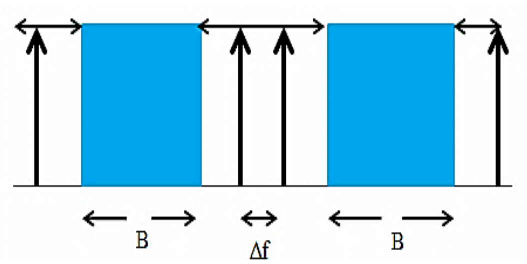

Figure 1. System model in frequency domain

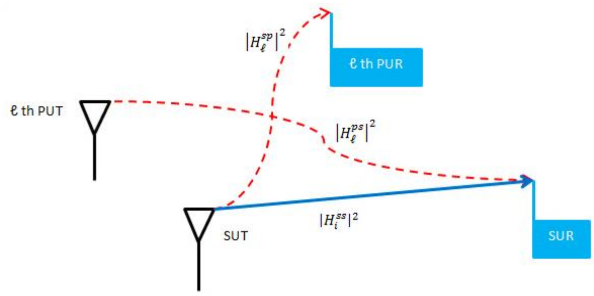

Figure 2. System model in spatial domain

We consider two kinds of modulation. It is worth to note that the SU can use only one kind of these modulation schemes at the same time; i.e. the SU can use MQAM or MPSK, but it cannot use both of them simultaneously. On the other word, the designer of the CR system should select MPSK or MQAM modulation based on the results of this paper. As mentioned before, in adaptive modulation, only modulation level is determined adaptively. For MQAM modulation scheme the bit error rate (BER) can be approximately written as follows [13]:

$$BER_i = 0.2\exp\left(\frac{-1.5P_i\left|h_i^{ss}\right|^2}{(M_i-1)\left(\sigma^2+\sum_{\ell=1}^{L}J_i^{\ell}\right)}\right) \tag{1}$$

where P_i indicates transmission power of SU on i-th subcarriers. The variance of the additive white Gaussian noise (AWGN) and the interference produces by the ℓ-th PU on SUR are equal to σ^2 and J_i^ℓ, respectively. By supposing BER_0 as BER target, we are able to calculate modulation level at each subcarrier by Equation (1):

$$M_i = 1 + \frac{-1.5}{\ln(5BER_0)} \frac{P_i \left|h_i^{ss}\right|^2}{\sigma^2 + \sum_{\ell=1}^{L} J_i^\ell} \tag{2}$$

The number of bits per symbol can be calculated by Equation (3) as follows:

$$b_i = \log_2(M_i) = \log_2\left(1 + \frac{-1.5}{\ln(5BER_0)} \frac{P_i \left|h_i^{ss}\right|^2}{\sigma^2 + \sum_{\ell=1}^{L} J_i^\ell}\right) \tag{3}$$

The transmission rate of SU in bits/sec can be calculated as follows:

$$C_i = b_i \times \frac{1}{T_s} \tag{4}$$

where T_s is the symbol duration. For MPSK modulation, the BER can be written as follows [13]:

$$BER_{MPSK} = 0.05 \exp\left(\frac{-6}{2^{1.9b} - 1} \frac{P_i \left|h_i^{ss}\right|^2}{\sigma^2 + \sum_{\ell=1}^{L} J_i^\ell}\right) \tag{5}$$

Similar to MQAM modulation, after some mathematical manipulation, the transmission rate for SU when it uses MPSK modulation can be obtained by following equation:

$$C_i = \frac{1}{1.9T_s} \log_2\left(1 + \frac{-6}{\ln(20BER_0)} \frac{P_i \left|h_i^{ss}\right|^2}{\sigma^2 + \sum_{\ell=1}^{L} J_i^\ell}\right) \tag{6}$$

In this paper, our goal is to obtain transmission power of subcarriers to maximize overall transmission rate of SU. It is worth to notice, once the transmission power is obtained, we can calculate modulation level. As mentioned in the introduction section, SUT must attend to interference power threshold (*I-th*) that introduces on PUs bands to guarantee the quality of service (QoS) of PUs. Hence, the total interference (*I*) that introduces by SU on PUs should be less than the specific threshold value. In addition, because of practical restriction, SUT can transmit only finite values of power. Therefore, the overall transmission power of SU must less than maximum power budget (P_{max}). The value of ACI introduces by the i-th OFDM-subcarrier of SU on the PUR spectrum band is related to SU's transmission power, symbol duration, and the spectral distance between i-th subcarrier and PU band [14]. Therefore, the ACI can be calculated as follows:

$$I_i^\ell = P_i K_i^\ell \tag{7}$$

where

$$K_i^\ell = \left|h_\ell^{sp}\right|^2 T_s \int_{d_{i\ell} - B_\ell/2}^{d_{i\ell} + B_\ell/2} \left(\frac{\sin(\pi f T_s)}{\pi f T_s}\right)^2 df \tag{8}$$

where d_i^{ℓ} is the spectral distance between ℓ^{th} bands of PU and ith subcarrier of SU. By considering these issues, an optimization problem for maximizing total transmits power of SU can be written mathematically as follows:

$$C = \max_{P_i} \sum_{i=1}^{N} C_i \tag{9}$$

Subject to:

$$\sum_{i=1}^{N} P_i \le P_{\max} \tag{10}$$

$$\sum_{i=1}^{N} I_i^{\ell} \le I_{th} \quad ; \quad \forall \ell \tag{11}$$

$$P_i \ge 0 \;\; ; \;\; \forall i \tag{12}$$

This problem is convex optimization; therefore, we apply KKT conditions to obtain optimal power at each subcarrier. The optimal transmission power at each subcarrier when the SU utilize MQAM modulation is calculated by the following equation:

$$P_i^{*} = \max\left\{0, \frac{1}{\beta + \sum_{\ell=1}^{L} \gamma_{\ell} K_i^{\ell}} - \frac{\sigma^2 + \sum_{\ell=1}^{L} J_i^{\ell}}{\frac{-1.5}{\ln\left(5BER_0\right)} \left|h_i^{ss}\right|^2}\right\} \tag{13}$$

It is worth to note that, for MPSK modulation, optimal power can be calculated by the same strategy. Therefore, for simplicity, we only describe an optimal solution for MQAM modulation.

Proof- by using convex optimization and applying Karush-Kuhn-Tucker (KKT) conditions, the optimal solution can be calculated as follows:

$$L = -\sum_{i=1}^{N} \log_2\left(1 + \frac{-1.5}{\ln\left(5BER_0\right)} \frac{P_i \left|h_i^{ss}\right|^2}{\sigma^2 + \sum_{\ell=1}^{L} J_i^{\ell}}\right) - \alpha_i P_i + \beta\left(\sum_{i=1}^{N} P_i - P_{\max}\right) + \sum_{\ell=1}^{L}\sum_{i=1}^{N} \gamma_{\ell}\left(I_i - I_{th}\right) \tag{14}$$

$$\frac{\partial L}{\partial P_i} = 0 \;\; \Rightarrow \;\; \frac{1}{P_i + \frac{\sigma^2 + \sum_{\ell=1}^{L} J_i^{\ell}}{\frac{-1.5}{\ln\left(5BER_0\right)} \left|h_i^{ss}\right|^2}} + \alpha_i - \beta - \sum_{\ell=1}^{L} \gamma_{\ell} K_i^{\ell} = 0 \tag{15}$$

$$\beta \ge 0 \tag{16}$$

$$\gamma_{\ell} \ge 0 \;\; ; \;\; \forall \ell \tag{17}$$

$$\alpha_i \ge 0 \;\; ; \;\; \forall N \tag{18}$$

$$\beta\left(\sum_{i=1}^{N} P_i - P_{budget}\right) = 0 \tag{19}$$

$$\gamma_\ell \left(\sum_{i=1}^{N} I_i - I_{th} \right) = 0 \quad ; \quad \forall \ell \tag{20}$$

$$\alpha_i P_i = 0 \tag{21}$$

where *α, β* and *γ* are Lagrange parameters. By removing α_i from Equation (15) and then:

$$\frac{1}{P_i + \dfrac{\sigma^2 + \sum_{\ell=1}^{L} J_i^\ell}{\dfrac{-1.5}{\ln(5BER_0)} \left| h_i^{ss} \right|^2}} \le \beta + \sum_{\ell=1}^{L} \gamma_\ell K_i^\ell \tag{22}$$

$$\frac{P_i}{P_i + \dfrac{\sigma^2 + \sum_{\ell=1}^{L} J_i^\ell}{\dfrac{-1.5}{\ln(5BER_0)} \left| h_i^{ss} \right|^2}} - P_i \beta - P_i \sum_{\ell=1}^{L} \gamma_\ell K_i^\ell = 0 \tag{23}$$

If $\beta + \sum_{\ell=1}^{L} \gamma_\ell K_i^\ell \le \dfrac{\dfrac{-1.5}{\ln(5BER_0)} \left| h_i^{ss} \right|^2}{\sigma^2 + \sum_{\ell=1}^{L} J_i^\ell}$, then Equation (22) can only hold if $P_i^* \ge 0$ and by solving Equation (23), we have;

$$P_i^* = \frac{1}{\beta + \sum_{\ell=1}^{L} \gamma_\ell K_i^\ell} - \frac{\sigma^2 + \sum_{\ell=1}^{L} J_i^\ell}{\dfrac{-1.5}{\ln(5BER_0)} \left| h_i^{ss} \right|^2} \tag{24}$$

Therefore, the optimal transmit power on the i^{th} subcarrier can be written as Equation (13).

3. PROPOSED ALGORITHM

Due to the complexity of optimal method, suboptimal methods have introduced in several papers. The optimal solution is too complex because in this method all constraints are considered simultaneously. The idea behind suboptimal methods is they try to consider constraints separately. Hence, in this section, we first consider constraints due to a restriction of ACI on PUs bands and then consider constraints due to maximum power budget. We assume the transmission power allocated to each subcarrier is obtained by the following equation:

$$p_i = X \frac{\left| h_i \right|^2}{k_i^\ell} \tag{25}$$

where *X* is a constant parameter. For calculating *X*, we substitute Equation (25) into Equation (10). Therefore, *X* can be calculated. Therefore, the transmission power of i^{th} subcarrier of OFDM-based CR system due to ℓ^{th} PU activity is obtained as:

$$p_i = \frac{I_{th}\left|h_i\right|^2}{k_i^{\ell}\sum_{i=1}^{N}\left|h_i\right|^2} \tag{26}$$

For calculating transmission power due to maximum power budget, we use a standard water-filling algorithm. If the SU uses MQAM modulation scheme, transmission power due to this constraint can be obtained from Equation (27) and if the SU uses MPSK modulation, the transmission power is calculated from Equation (28):

$$P_i^{\max} = \max\left\{0, \frac{1}{\mu} - \frac{\sigma^2 + \sum_{\ell=1}^{L} J_i^{\ell}}{\frac{-1.5}{\ln\left(5BER_0\right)}\left|h_i^{ss}\right|^2}\right\} \tag{27}$$

$$P_i^{\max} = \max\left\{0, \frac{1}{\mu} - \frac{\sigma^2 + \sum_{\ell=1}^{L} J_i^{\ell}}{\frac{-6}{\ln\left(20BER_0\right)}\left|h_i^{ss}\right|^2}\right\} \tag{28}$$

where μ is a Lagrange parameter by substituting these Equations. Into Equation (11), Lagrange parameter is obtained. Therefore, the final allocated power to ith subcarrier is a value that satisfies all constraints in Equation (10) and Equation (11), i.e.:

$$P_i = \min\left\{P_i^1, P_i^2, \ldots, P_i^L, P_i^{\max}\right\} \tag{29}$$

4. CONVENTIONAL ALGORITHMS

Several algorithms have used for conventional OFDM systems. Two common algorithms are uniform loading and water filling algorithms. Water filling algorithm is an optimal algorithm for power allocation in OFDM systems. In this algorithm, power is allocated to subcarriers such that power budget constraint is satisfied is all situations. In uniform loading algorithm, equal power allocated to all subcarriers. However, these algorithms need some adjustments to use in CR systems, because in these systems, extra constraints should be considered. These constraints cause from PU activity. In [12] authors indicated that if the SU uses uniform loading algorithm the transmission power can be calculated from:

$$P = \min\left\{\frac{I_{th}}{\sum_{i=1}^{N} K_i^1}, \frac{I_{th}}{\sum_{i=1}^{N} K_i^2}, \ldots, \frac{I_{th}}{\sum_{i=1}^{N} K_i^L}, \frac{P_{\max}}{N}\right\} \tag{30}$$

If the SU uses MQAM modulation and uses water filling algorithm, the transmission power is corresponding to minimum values of Equation (31) and Equation (32) [12]:

$$\sum_{i=1}^{N} \max\left\{0, \frac{1}{\mu} - \frac{\sigma^2 + \sum_{\ell=1}^{L} J_i^{\ell}}{\frac{-1.5}{\ln\left(5BER_0\right)}\left|h_i^{ss}\right|^2}\right\} = P_{\max}^{u\ell} \tag{31}$$

$$\sum_{i=1}^{N} \max\left\{0, \frac{1}{\mu} - \frac{\sigma^2 + \sum_{\ell=1}^{L} J_i^{\ell}}{\frac{-1.5}{\ln(5BER_0)}\left|h_i^{ss}\right|^2}\right\} = P_{\max} \tag{32}$$

In Equation (31) and Equation (32), maximum power is obtained from the following equation:

$$P_{\max}^{u\ell} = N \times P_U^{\ell} \tag{33}$$

If the SU uses MPSK modulation, similar to above equations, transmission power can be calculated.

5. SIMULATION RESULTS

In this section, we explain our algorithm by numerical results. We assume the number of primary users is equal to two (*L*=2) and the bandwidth of PU (*B*) is equal to 2MHz. Also, the SU uses OFDM technique for using unused sections of spectrum bands. The number of subcarriers is 6 (*N*=6) and the bandwidth (*Δf*) is equal to 0.3125MHz. Symbol duration for SU (T_s) is 4µs. Channels have Rayleigh distribution. Average power gain for $|h_i^{ss}|^2$, $|h_1^{sp}|^2$ and $|h_2^{sp}|^2$ are -5, -10 and -7 dB, respectively. The value of AWGN variance is 10^{-8} watt. The values of Jiℓ are random value with an average 10^{-6} watt. The amount of BER target is assumed to be 10^{-3}. The average transmission rates for whole algorithms are obtained from 100,000 independent simulation runs. Figure 3, indicates channel capacity and transmission rate at each subcarrier. Transmission rate is calculated for both MQAM and MPSK modulation level, separately. It is observed, in some subcarriers, MPSK has better performance than MQAM and in other subcarriers, MQAM has better performance. In addition, we observed transmission rate and channel capacity for subcarriers is different to each other. It is obvious because channels have different fading gains. Due to this difference, adaptive resources allocation is an appropriate technique in wireless communication systems.

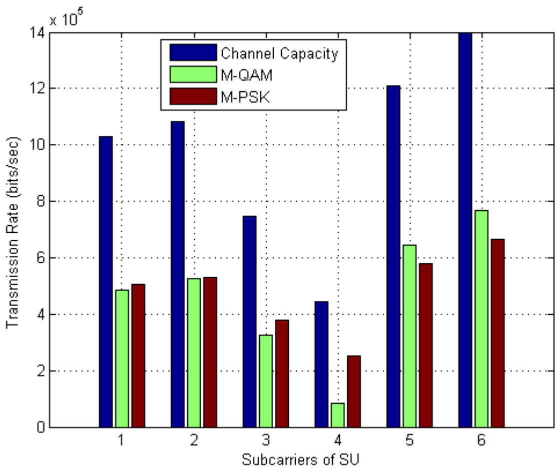

Figure 3. Transmission rate for different subcarriers

Figure 4 indicates channel capacity and transmission rate for MPSK and MQAM modulation vs. interference threshold. We observe both modulation schemes have approximately same results. Based on this figure we can conclude although both MPSK and MQAM are proper modulation scheme, but for high value of the threshold power, the performance of the MPSK modulation technique is better than MQAM modulation technique. Figure 5 indicates the performance of different power allocation algorithms vs. interference threshold. We observe capacity is increased by increasing the value of the threshold. It is obvious by increasing threshold, SUT can allocate more power. In addition, we observe, the optimal algorithm has the best performance. The suboptimal algorithm has the better performance than a conventional algorithm and the uniform loading algorithm has the worst performance.

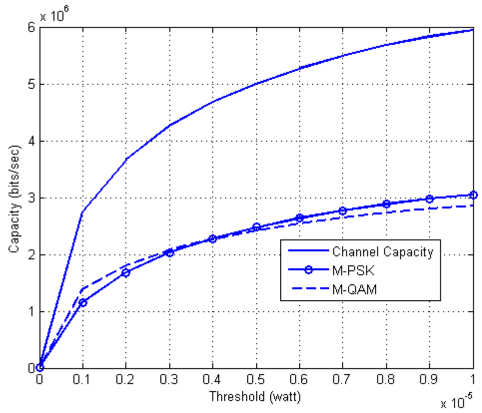

Figure 4. Transmission rate vs. interference threshold for different modulation

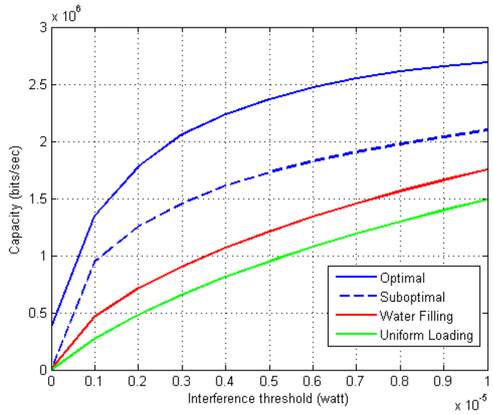

Figure 5. Capacity vs. Interference threshold for different algorithms

Figure 6 shows the capacity vs. power budget for different modulation schemes. Capacity and transmission rates are increased by increasing the value of power budget. In addition, it is observed, for low value of the power budget, M-PSK modulation technique has the better performance than MQAM modulation while for high power budget value, MQAM modulation has the better performance. Figure 7 shows the performance of different algorithms vs. power budget. We observed suboptimal algorithm has worse performance than the optimal algorithm while its performance is the better than water-filling and uniform loading algorithms.

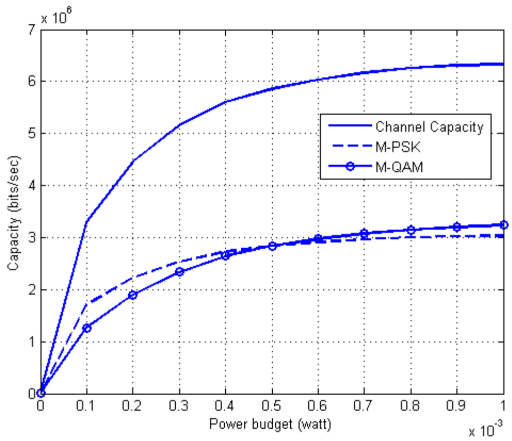

Figure 6. Transmission rate vs. power budget for different modulation

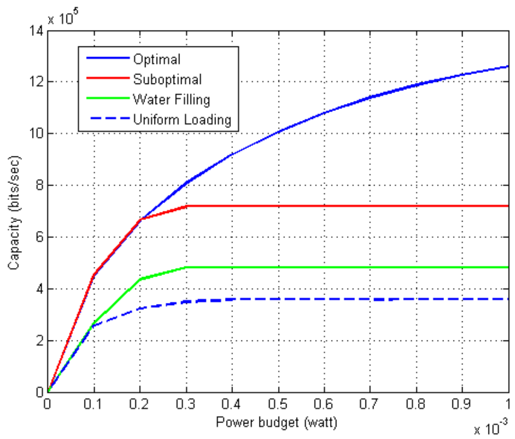

Figure 7. Transmission rate vs. power budget for different algorithms

Although the complexity of our algorithm is equal to the water-filling algorithm and equal to O(LN)+O(N log(N)), our suboptimal algorithm has the better performance than the water-filling algorithm. In addition, the complexity of the uniform loading algorithm is O(LN). Though an optimal algorithm has the best performance, it has high complexity. Its complexity is equal to O(N3).

6. CONCLUSION

A low-complexity suboptimal power allocation algorithm is proposed in this research in OFDM-based CR systems. This suboptimal algorithm is based on interference power threshold that introduces by SUT on PURs and channel power gain between SUT-SUR. The performance of this suboptimal algorithm is better than water filling and uniform loading algorithms. Though the performance of this algorithm is worse than the optimal algorithm, the complexity of it is less than an optimal algorithm. Problem is formulated such that we can calculate of modulation level of subcarriers based on allocated power. Indeed, in this method, modulation level and transmission power are calculated simultaneously. In this paper, we consider two kinds of modulation schemes, separately, including MQAM and MPSK. Simulation results indicate both modulation strategies have approximately same results.

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