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Subcarrier And Optimal Power Allocation For Cognitive Radio System With Hybird Spectrum Access Mechanism

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ABSTRACT

In this paper investigates the subcarrier and power allocation problem for an OFDMA-based multiuser cognitive radio (CR) system. In particular, for such a CR system, the total transmission rate of CR users is maximized for a given power budget while keeping the interference introduced to the primary-user (PU) receivers' below given thresholds with a certain probability. As the optimal scheme can be highly complex, we also propose a low-complexity suboptimal subcarrier-and-power-allocation scheme. First, a suboptimal subcarrier algorithm is proposed that allocates subcarriers to CR users that not only increase the capacity, but also reduces the interference introduced to the primary user (PU) band. Further, for a given subcarrier allocation an optimal power loading algorithm is proposed that maximizes the capacity of CR users while keeping the interference introduced to the PU band and the total power below a threshold. The selected numerical results show that a significant gain in terms of total achievable transmission rate can be obtained over an USAM or an OSAM**.** The proposed optimal scheme can lead to an unfairness among CR users in sharing the total transmission rate; therefore, we also propose a suboptimal subcarrier-allocation scheme that can guarantee a certain level of fairness among CRusers.

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INTRODUCTION

Radio spectrum is one of the most scarce and valuable resources for wireless communications. Actual field measurements by various groups around the globe e.g., Spectrum- Policy Task Force appointed by the Federal Communications Commission (FCC), have reported that the allocated spectrum is highly underutilized, with utilization ranging from 15 to 85% [1], [2]. Spectrum efficiency can be increased significantly by giving opportunistic access of the frequency bands to a group of cognitive radio (CR) users to whom the band has not been originally allocated. CR is an emerging technology which would allow secondary users (or CR users) to smartly sense and make an efficient use of the available spectrum that has been licensed to primary users (PUs). Due to its flexibility in allocating the spectrum, Orthogonal frequency division multiplexing (OFDM) has been recognized as a modulation technology for CR systems [3]. Since both CR user and primary user (PU) may exist in side-by-side bands yet have different access technologies, mutual interference is the limiting factor for performance of both networks. As there is mutual interference between CR user and PU when they co-exist in side-by-side bands [4], use of the classical loading algorithms e.g., uniform power but variable rate and waterfilling algorithms, for CR system may result in higher mutual interference in the PUs' band. In [5], we proposed power loading algorithms, that maximizes the downlink transmission capacity of the CR user while keeping the interference induced to the PUs below a specified threshold. To exploit unused and underused spectrum bands, two different approaches for a dynamic spectrum access mechanism, namely *the underlay spectrum access mechanism (USAM)* and *the overlay spectrum access mechanism (OSAM)*, have been proposed in the literature [6, Ch. 3]. According to the OSAM, the spectrum utilization can be increased by granting secondary or cognitive users to opportunistically exploit unused frequency bands of primary users (PUs). As such, the secondary users and PUs may coexist in the side-by-side spectral bands [7], [8]. In the OSAM,

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although secondary users and PUs may coexist in the side-by-side bands, there are mutual interferences between the PUs and cognitive users due to the nonorthogonality of the transmitted signals [7]. On the other hand, as per USAM, the PUs and CR users can coexist in the same spectral band (see, e.g., [9]). In other words, the USAM allows simultaneous sharing of underutilized frequency bands by the secondary users along with the PUs. For this scenario, the interference comes mainly due to the coexistence in the same spectral band. The USAM and the OSAM are compared in [10] and [11]. For given interference constraints imposed by the PUs' system, one can conjecture that the CR transmitter may transmit relatively higher transmit power for the OSAM, whereas in the USAM, it may transmit relatively lower power. The contribution of this paper can be summarized as follows.We propose an optimal power-and-subcarrier-allocation scheme for an OFDMA-based CR system with a JOUSAM. As such, for a given power budget, the total transmission rate of the CR users is maximized, whereas the interference introduced to the PUs' receiver is kept below the given limits withcertain probability.1 As the complexity of the optimal powerand-subcarrier-allocation scheme can be high, we propose a low-complexity suboptimal power-allocation scheme. Selected simulation results show that the fairness performance in terms of data rate sharing of the individual CR user for the optimal algorithm can be poor. Therefore, we finally propose a suboptimal subcarrier-allocation algorithm that can improve the fairness performance. Presented numerical results demonstrate that, for given interference constraints, a significant improvement in the transmission rate is achieved by allocating and loading power with the JOUSAM, as compared with either the OSAM or the USAM. These results also show that the suboptimal scheme that has lower complexity than the optimal scheme achieves a higher transmission rate than that of the OSAM or the USAM.

II.System Model:

A.Overall Description:

We assume that, in a given geographical location, a contiguous portion of radio spectrum with total bandwidth W is divided into M bands with respective bandwidth, i.e., W_i (i =1, 2, . . . , M), where

$$\sum_{i=1}^{M} W_i = W$$

These spectrum bands are assigned to different group of PUs, and a particular band may not be used in a given time in a given geographical region. We consider a downlink transmission scenario where a CR transmitter is transmitting information to K CR users using the whole spectrum of bandwidth W dynamically. The CR system uses OFDMA as the multiple-access mechanism, and it divides the whole spectrum into Z subcarriers with spectral distance between two adjacent subcarriers, i.e., $\Delta f = W/Z$. In a given spectrum band, the PUs' system may use any access mechanism that is not known to the CR system. A spectrum sensing mechanism is implemented in the CR system that can identify whether a given subcarrier falls in the bands that are currently occupied by the PUs or not. Without loss of generality, we assume that, in a given time, there are N overlay subcarriers and L underlay subcarriers, where $N + L = Z$. For notational covenience, we denote the underlay subcarriers by set SU and the overlay subcarrier by set SO, where $|SO| = N$, and $|SU| = L$. One possible coexistence scenario of the PUs andCR users in the spectral domain with the JOUSAM is depicted in Fig. 1.

B .Modeling of And Capacity of Interference To Pus Cr Users:

Assuming an ideal Nyquist pulse shaping at the CR transmitter, the power density spectrum of the kth subcarrier can be

$$\varnothing_k(f) = p_k T_S \left({\mathrm{Sin}\pi f T_s}/{\pi f T_s} \right)^2 \tag{1}$$

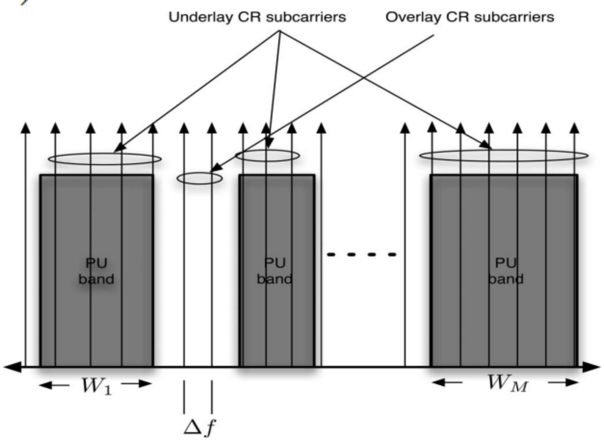

Fig. 1: Example of joint overlay and underlay spectrum access mechanism

Where T_s is the symbol duration, and p_k is the power loaded in the *k* th subcarrier. The total interference introduced to the *l*th Preceiver can be written as [7], [8]

$$i_l^{PU} = |h_l^{SP}|^2 \sum_{u=1}^{K} \sum_{k=1}^{Z} \rho_{u,k}\, P_{u,k}\, T_s\, X \int_{d_{k,l-\frac{\Delta f}{2}}}^{d_{k,l+\frac{\Delta f}{2}}} \left(\mathrm{Sin\pi fT_s} / \mathrm{\pi fT_s} \right)^2 \tag{2}$$

Where $d_{k,l}$ represents the spectral distance between the *k*th CR subcarrier (i.e., the overlay subcarrier) and the *l*th PU subcarrier (i.e., underlay subcarrier), and variable $\rho_{u,k}$ denotes if the *k*th subcarrier is allocated to the *u*th CR user or not. It takes value 1 if the *k*th subcarrier is allocated to the CR user *u*. Otherwise, it takes value 0. $\rho_{u,k}$ is the transmitted power by the *u*th CR user in the *k* th subcarrier, and h_l^{SP} is the complex fading coefficient between the CR transmitter and the *l*th PU receiver. For convenience, we define a parameter called spectral distance factor 0 ≤ $f(d_{k,l})$ ≤ 1 as follows:

$$f(d_{k,l}) = T_s \int_{d_{k,l-\frac{\Delta f}{2}}}^{d_{k,l+\frac{\Delta f}{2}}} \left(\mathrm{Sin\pi fT_s} / \mathrm{\pi fT_s} \right)^2 \mathrm{df} \tag{3}$$

Using the well-known Shannon capacity formula, the theoretical total transmission rate of all CR users can be written as

$$c = \Delta f \sum_{u=1}^{K} \sum_{k=1}^{Z} \rho_{u,k} \log\left(1 + \frac{|h_{u,k}^{ss}|^2 P_{u,k}}{\sigma^2 + j_{k,u}} \right) \tag{4}$$

where $h_{u,k}^{ss}$ is the complex channel fading coefficient between the CR transmitter and the *u*th CR user in the *k*th subcarrier, σ^2 denotes the additive white Gaussian noise (AWGN) variance, and $j_{k,u}$ denotes the interference introduced to the *k*th subcarrier of the *u*th CR user due to the transmission of all Pus. Interference $j_{k,u}$ is treated as Gaussian in the capacity formula. This assumption is valid when there are large numbers of PU transmitters. It is assumed that the channel amplitude fading gain $|h_{u,k}^{ss}|$ can be estimated at the CR receivers and can be fedback to the CR transmitter perfectly. For a practical reason, it is assumed that the instantaneous channel gains between the CR transmitter and PU receivers are not known at the CR transmitter. However, the statistics of $|h_l^{sp}|$ are known at the CR transmitter. In [9],have argued that, from the pilot signals transmitted by PUs, the mean and the distribution of such fading gains can be estimated. CR receivers can also estimate the interference level $j_{k,u}$ and can feedback to the CR transmitter.

III. Optimal Subcarrier-And-Powerallocation Scheme:

Decouple the joint subcarrier and- power-allocation problem into two separate problems: a subcarrier-allocation problem and a power-allocation problem. First, we propose a subcarrier-allocation scheme and prove that, even after decoupling the joint subcarrier and power allocation, the proposed scheme is optimal.

A. Subcarrier Allocation:

To maximize the total transmission rate, we allocate a particular subcarrier to a CR user that has the highest signal-to-interference-plus-noise ratio for that subcarrier. Thus, $\rho_{u,k} = 1$ for *u* = *u** or 0 if otherwise, where

$$u^* = argmax_u \frac{|h_{u,k}^{ss}|^2}{\sigma^2 + j_{k,u}} \qquad k = 1,2,\ldots z \tag{5}$$

B. Power Allocation:

After performing subcarrier allocation according to (5), the optimization problem can be written a

$$max_{p_{u,k}} \sum_{u=1}^{K} \sum \log_2\left(1 + \frac{|h_{u,k}^{ss}|^2 P_{u,k}}{\sigma^2 + j_{k,u}} \right) \tag{6}$$

$$\sum_{u=1}^{k} \sum_{k \in \Omega_u} \rho_{u,k}\, f(d_{k,l}) \le \frac{I_{th}^{l}}{2\lambda_l^2(-In(1-a))}, l \in s_u \tag{7}$$

$$p_{u,k\geq 0,}\quad for\, u = 1,2,\dots k\ and\ \ k \in \Omega_u \qquad (8)$$

$$\sum_{u=1}^{k}\sum_{k\in\Omega_u} p_{u,k} \leq P_T \qquad (9)$$

IV. Suboptimal Power-Allocation Scheme:

The optimal scheme can be computationally complex. In particular, the complexity of the subcarrier-allocation scheme is $O(KZ)$, whereas the complexity of the power-allocation scheme is exponential in

Z and is $O(Z3)$. Therefore, here, we propose a low-complexity suboptimal power-allocation scheme. According to the proposed suboptimal scheme, the subcarrier allocation remains the same, as mentioned in (3.5). However, we propose a suboptimal power-allocation scheme whose complexity is lower. Based on the heuristic that the underlay subcarriers may introduce higher interference to the PU receivers compared with the overlay subcarriers, we propose to allocate less power to the underlay subcarriers compared with the overlay subcarriers. In what follows, we describe our proposed suboptimal power-allocation scheme. In the following description, for clarity, we remove index *u* as the power allocation in a given subcarrier is done once it has been assigned to a particular user.According to the suboptimal scheme, we propose to allocate equal amount of power in each underlay subcarrier. However, the overlay subcarriers are allocated power according to a ladder profile, as described in [8]. This ladder profile is based on the heuristic that the subcarriers, which are closer to a PU band, introduce more interference to the PU band, and they should be allocated with relatively less amount of power. The power profile for underlay subcarriers, which are allocated with equal amount of power, can be expressed as

$$p_l^{subopt,un} = P^{un},\quad l \in s_u \qquad (10)$$

The overlay subcarriers are allocated power in a ladder fashion, where step size of the ladder is constant. Basically, we propose to allocate P^{ov} power to the overlay subcarrier that is closest to a PU band. Then, we propose to allocate $2P^{ov}$ power to the next closest overlay subcarrier. Mathematically, the power profile for overlay subcarriers can be expressed as

$$p_l^{subopt,ov} = P^{ov} X\, i_n,\qquad n \in s_o \qquad (11)$$

where $i_n = \left[\frac{\Delta_n}{\Delta f}\right]$ and Δ_n is the spectral distance between the *n*th overlay subcarrier and the closest PU band. Now, we introduce design factor *x* by which the power in an underlay subcarrier is less than the power in the overlay subcarrier that is closest to a PU band, and mathematically, we can write

$$P^{OV} = x\, X\, P^{un} \qquad (12)$$

The best value of factor *x* is determined by simulations. Now, the power profile can be determined if the value of *P*un is known. The value of *P*un is determined such that both power budget constraint in (17) and *L* interference constraints in (15) are satisfied. Basically, for each of the (*L* + 1) constraints (the total power constraint and *L* interference constraints), a corresponding value of *P*un is determined. Among these (*L* + 1) power values, the minimum value is chosen as it will satisfy all the (*L* + 1) constraints. For notational convenience, let us define the power value corresponding to the *l*th (*l* = 1, 2, . . . , *L* + 1) constraint in an underlay subcarrier that is closest to a PU by *P*un(*l*). The power values in the CR subcarriers that satisfy the total power constraint can be written as

$$\sum_{l=1}^{L} p_l^{subopt,un} + \sum_{n=1}^{N} p_n^{subopt,ov} = P_T \qquad (13)$$

V. Comparison With The Overlay Spectrum Access Mechanism And The Underlay Spectrum Access Mechanism:

The subcarrier-and-power-allocation problem for CR systems has already been studied in the literature, and usually, either the OSAM or the USAM is considered. Therefore, here, to compare our proposed optimal and suboptimal power-and-subcarrier-allocation algorithms for the JOUSAM with the existing spectrum access mechanisms, i.e., the OSAM and the USAM, we describe a subcarrier and power algorithm for the OSAM and the USAM.

A. Power and Subcarrier Allocation in OSAM:

Here, we describe the subcarrier-and-power-allocation algorithm for the OSAM where the power is allocated to *N* overlay subcarriers, and the *L* underlay subcarriers are nulled. The power profile for the OSAM, i.e., *pov,∗u, k* , is obtained by solving the following optimization problem:

$$max_{ov} c^{ov} = \sum_{u=1}^{k} \sum_{k\in\Omega_u^{ov}} \rho_{u,k} log_2\left(1+\frac{\left|h_{u,k}^{ss}\right|^2 P_{u,k}}{\sigma^2 + j_{k,u}}\right) \tag{14}$$

$$\sum_{u=1}^{k} \sum_{k\in\Omega_u^{ov}} P_{u,k}^{ov} f(d_{k,l}) \le \frac{I_{th}^{l}}{2\lambda_l^2(-In(1-a))}, l \in s_u \tag{15}$$

$$P_{u,k}^{ov} \ge 0, for\ u = 1,2,\dots k\ and\ k \in \Omega_u^{ov} \tag{16}$$

$$\sum_{u=1}^{k} \sum_{k\in\Omega_u^{ov}} P_{u,k}^{ov} \le P_T \tag{17}$$

where Ω_u^{ov} is the set of subcarriers assigned to user *u* in the OSAM by performing subcarrier allocation according to (3.5). Using the similar procedure in Appendix A, the optimization problem in (3.14) subject to the constraints in (3.15)–(3.17) can be solved, and the power for each subcarrier for underlay spectrum access can be written as

$$p_{u,k}^{ov,*} = \left[\frac{1}{\alpha_l f(d_{k,l}) + \gamma} - \frac{\sigma^2 + j_{k,u}}{\left|h_{u,k}^{ss}\right|^2}\right], \quad for\ k \in \Omega_u^{ov} \tag{18}$$

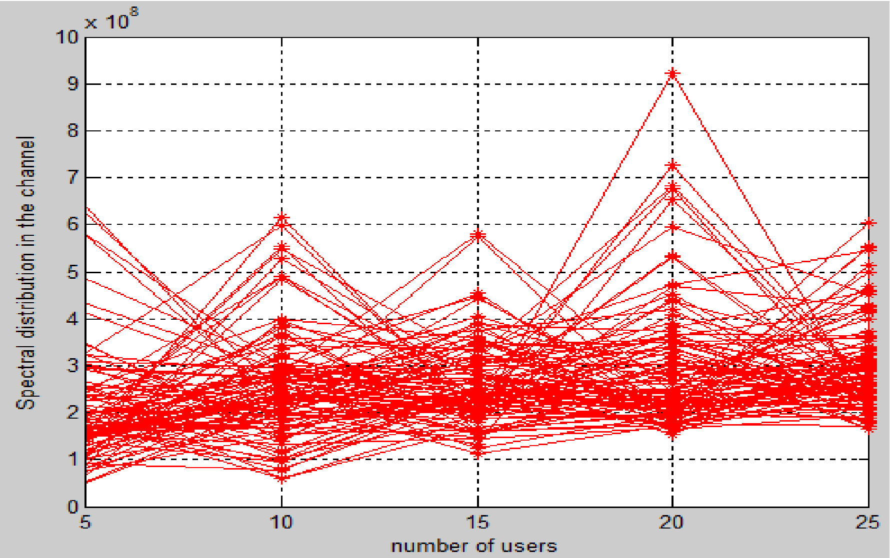

Fig. 2: spectral distribution versus number of user for various scheme

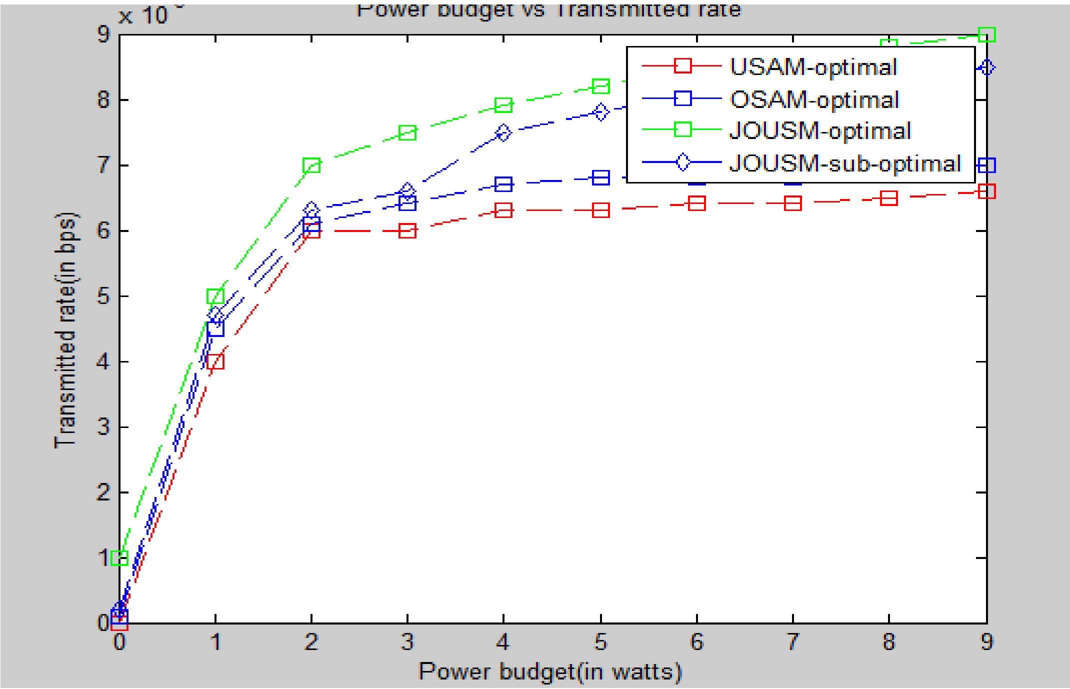

Fig. 3: Total achievable transmission rate versus total power budget

B. Power and Subcarrier Allocation in USAM:

It is obvious that the USAM is an inefficent method as it will have inferior performance. However, for the completeness of this paper, here, we describe the subcarrier and power allocation for USAM. With the USAM, only the underlay subcarriers, i.e., the subcarriers in set *Su*, are used for CR transmission. In particular, the *L* underlay subcarriers are allocated among *K* CR users, whereas all the overlay subcarriers in *So* are nulled (i.e., assigned with zero power). To achieve the best performance for the CR system with the USAM, the power is allocated in underlay subcarriers such that the total transmission rate with overlay subcarriers *C*un is maximized while maintaining the total power budget constraint and keeping the total interference introduced to the PU receivers below the specified thresholds. Specifically, the power for the *k*th subcarrier with underlay spectrum access *p*un, *k* is obtained by solving the followinoptimization problem:

$$max_{un} c^{un} = \sum_{u=1}^{k} \sum_{k\in\Omega_u^{un}} \rho_{u,k}\, log_2\left(1+\frac{\left|h_{u,k}^{ss}\right|^2 P_{u,k}}{\sigma^2 + j_{k,u}}\right) \tag{19}$$

Subject to

$$\sum_{u=1}^{k} \sum_{k\in\Omega_u^{un}} P_{u,k}^{un}\, f(d_{k,l}) \le \frac{I_{th}^{l}}{2\lambda_l^2(-In(1-a))}, l \in s_u \tag{20}$$

$$P_{u,k}^{un} \ge 0, for\ u = 1,2,\dots k\ and\ k \in \Omega_u^{un} \tag{21}$$

$$\sum_{u=1}^{k} \sum_{k\in\Omega_u^{un}} P_{u,k}^{un} \le P_T \tag{22}$$

where Ω_u^{un} is the set of subcarriers assigned to user *u* in underlay spectrum access by performing subcarrier allocation according to (5). The optimization problem in (3.19) subject to the constraints in (3.20)–(3.22) can be solved, and the power for each subcarrier for underlay spectrum access can be written as

$$p_{u,k}^{un,*} = \left[\frac{1}{\alpha_l f(d_{k,l}) + \gamma} - \frac{\sigma^2 + j_{k,u}}{\left|h_{u,k}^{ss}\right|^2} \right], \qquad for\ k \in \Omega_u^{un} \tag{23}$$

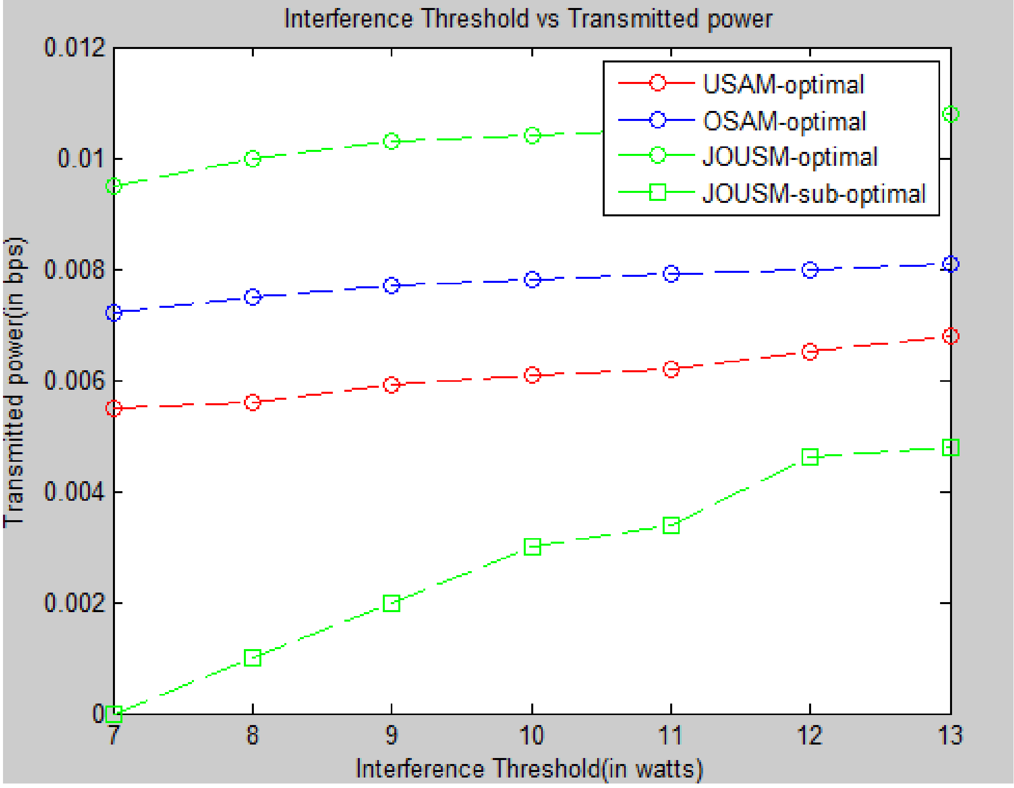

Fig. 4: Total Achievable transmission rate versus interference threshold for various scheme

Conclusion:

In this paper, we have studied a subcarrier-and-power allocation problem for an OFDMA-based CR system that uses a JOUSAM. In particular, for such a CR system, we developed an optimal subcarrier-and-power-allocation algorithm. As the optimal scheme is highly complex, we also proposed a low-complexity suboptimal scheme whose operation is faster than the optimal scheme. The proposed algorithm maximizes the capacity of CR users while simultaneously maintaining the interference and power constraints. These results also showed that the proposed suboptimal scheme, which has relatively lower operational complexity, provides significant improvements in performance.

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