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Efficient Joint Resource Allocation for OFDM-Based Cooperative Cognitive Radio Networks with Rate-Guarantee

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Abstract

This letter proposes an efficient joint resource allocation scheme for OFDM-based cooperative cognitive radio networks (CRNs) under various practical limitations. Compared with those traditional approaches, which guarantee the transmission rates of cognitive users, the proposed scheme ensures that cognitive users are maintained in proportion to the predefined target rates. Numerical simulation shows that the proposed scheme can achieve a reasonable tradeoff between performance and computational complexity.

Keywords: CRN, OFDM, cooperative communication, resource allocation.

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1. Introduction

Cognitive radio (CR) technology has been proposed to improve the spectrum utilization and provide adaptability for wireless transmission on licensed spectrums [1-3]. The performance of secondary users (SUs) and the spectrum utilization can be further improved by incorporating cooperative communications and orthogonal frequency division multiplexing (OFDM) technology[4-7].

By utilizing the intrinsic flexibility of OFDM in power allocation across subcarriers, a lot of work has already been done on the resource allocation in non-cognitive relay systems [8-10]. However, the resource allocation in OFDM-based cooperative CRNs is more complex than that in a conventional OFDM system because cognitive transmission should protect the communication of primary users (PUs). Its purpose is to optimize the resources so that the CRN's throughput is maximized while the interference induced to the primary system is kept below the pre-specified threshold. Recently, the resource allocation for OFDM-based cooperative CRNs has attracted much attention [11]-[14]. In [11], the resource allocation problem with proportional fairness rate in cognitive OFDM-based wireless network is studied, it achieves a good performance and proportional fairness rate among SUs. In [12], the dual decomposition and subgradient methods are used to find the optimal solution and a genetic algorithm is presented to obtain a suboptimal approach. The work in [13] proposes an improved joint subcarrier and bit allocation scheme for cognitive radio networks. These studies achieve some results, however, they considers limited practical constraints and take only some kinds of resources allocation into consideration. In our early work, an efficient resource allocation algorithm has been proposed in the paper [14], which considers the amplifyand-forward (AF) relaying and adopts a two-step approach to achieve the pairing among subcarriers, optimal relay selection and power allocation. However, the work in [14] is difficult to be directly used in the scene of this letter. By distributing the available total power equally among the subcarriers in both source and destination and assuming that every subcarrier induces the same amount of interference to the PUs, [15] solves the above problems at a sub-optimal performance. Additionally, [15] performes subcarrier pairing and power allocation in a sequential manner for all subcarriers. When a given subcarrier in the source side is paired with another one in the destination side, the latter cannot be used any more for the next steps. Hence, the order of the subcarrier assignment process may slightly degrade the algorithm performance.

The motivation for this letter is two-fold. Firstly, since the allocated subcarriers may not support the required rates for practical applications, it is important to guarantee that the rate of each subcarrier is not below a certain threshold. Secondly, the resource allocation problem is often formulated as a mixed integer programming task and the general algorithms (such as: dual decomposition algorithm) are been used to address the problem. However, these general algorithms almost have high complexity. It will affect the CRN's overall throughput because the communication time of SUs is reduced while the resource allocation time is large. In addition, even if the algorithm complexity is low, the CRN's overall throughput will be affected while the resource allocation algorithm performs poorly. As a consequence, it is valued to propose an efficient resource allocation algorithm that can achieve a good tradeoff between the system performance and the computational complexity. The main contributions of this letter can be summarized as follows: 1) compared to conventional methods, more practical system limitations are considered; 2) enjoying the low and constant computational complexity in given radio scenarios, the proposed algorithm can approximate the performance of the optimal solution and meet the requirement of practical communication systems.

2. System Model and Problem Formulation

2.1 System Model

Consider an OFDM-based cooperative CRN as shown in **Fig. 1**, where SUs coexist with the primary system in a same geographical region. Due to the existence of obstacles or long distances, the source and the destination lack direct communication link. Therefore, M relays are deployed to assist the cognitive communications. The frequency band B of CRN is divided into N subcarriers, and the bandwidth of each subcarrier is Δf . Meanwhile, the CRN can utilize primary bandwidths under the condition that its interference to PU is lower than the interference threshold I_{th} . Each relay m, $m \in [1,...,M]$, operates in a half-duplex mode decode-and-forward (DF) manner over a subcarrier pair (j,k), i.e., the subcarrier j of the source SU and the subcarrier k of the destination SU.

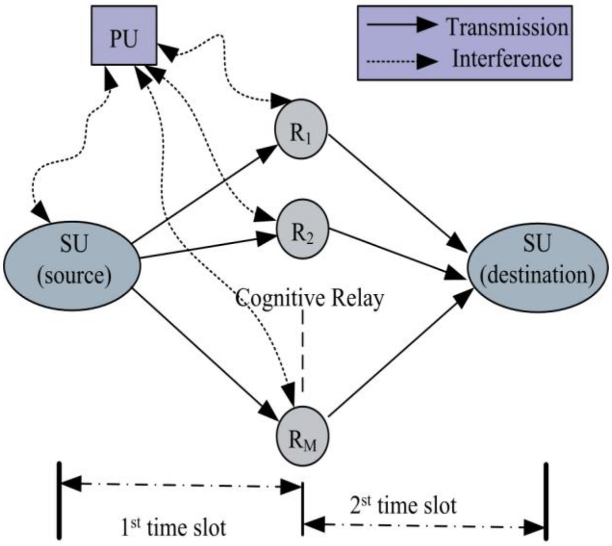

Fig. 1. System model of OFDM-based cooperative cognitive radio network

In an OFDM-based CRN, the interference from the i^{th} subcarrier of SU to the PU can be formulated as [16]:

$$I_i = \int_{d_i - B/2}^{d_i + B/2} G_i P_i T_s \left(\frac{\sin \pi f T_s}{\pi f T_s}\right)^2 df \quad = P_i \rho_i \tag{1}$$

where d_i represents the spectral distance between the i^{th} subcarrier and the PU band, G_i denotes the square of the channel gain between the i^{th} subcarrier and the PU band. P_i is the transmission power emitted by the i^{th} subcarrier, T_s is the symbol duration, and ρ_i denotes the interference factor of the i^{th} subcarrier to the PU band. Meanwhile, as shown in (2), the interference power induced by a PU signal with power spectrum density $\vartheta(e^{jw})$ into the i^{th} subcarrier can be formulated as an additive white Gaussian noise (AWGN) by applying the law of large number or by assuming independent and random Gaussian codewords by PU and SU [17-18]

$$J_i = \int_{d_i-\Delta f/2}^{d_i+\Delta f/2} G_i \vartheta(e^{jw})dw \tag{2}$$

For the channel between the source SU and the m^{th} relay (resp. the m^{th} relay to the destination SU), denote the square of the channel coefficient over the $j^{th}(resp.k^{th})$ subcarrier as $H_{j,m}(resp.H_{m,k})$, the transmission power over this subcarrier as $P_{j,m}(resp.P_{m,k})$, and AWGN~*CN* (0, $\sigma^2_{AWGN_{j,m(m,k)}}$). The achivable communication rate over the subcarrier pair (j,m,k) can be evaluated by

$$R(j,m,k) = \frac{1}{2}\min\begin{cases} R_{j,m} = \log_2(1+\dfrac{P_{j,m}H_{j,m}}{\sigma^2_{j,m}}) \\ R_{m,k} = \log_2(1+\dfrac{P_{m,k}H_{m,k}}{\sigma^2_{k,m}}) \end{cases} \tag{3}$$

where $\sigma^2_{j,m(m,k)} = \sigma^2_{AWGN_{j,m(m,k)}} + J_{j(k)} \cdot \sigma^2_{AWGN_{j,m(m,k)}}$ is the variance of the AWGN on the source to the m^{th} relay (m^{th} relay to destination) link and $J_{j(k)}$ is the interference introduced by the PU signal into the j^{th} (k^{th}) subcarrier.

2.2 Problem Formulation

Our objective is to maximize the CRN's throughput by optimizing the subcarrier pairing, relays assignment, and the distribution of the available power among the assigned subcarrier pairs, while satisfying multiple practical constraints. Therefore, the optimization problem can be formulated as follows

$$\begin{aligned}
&\max_{\varphi_{(j,m)},\phi_{(m,k)}} \sum_{m=1}^{M}\sum_{j=1}^{N}\sum_{k=1}^{N} \varphi_{(j,m)}\phi_{(m,k)}R(j,m,k) \\
&\text{s.t.} \\
&C1: \sum_{m=1}^{M}\sum_{j=1}^{N} P_{j,m} \le P_S && \text{(source power constraint)} \\
&C2: \sum_{k=1}^{N} P_{m,k} \le P_m, \forall m && \text{(relays individual power constraints)} \\
&C3: \sum_{m=1}^{M}\sum_{j=1}^{N} P_{j,m}\rho_j \le I_{th} && \text{(Interference at the first time slot)} \\
&C4: \sum_{m=1}^{M}\sum_{k=1}^{N} P_{m,k}\rho_{m,k} \le I_{th} && \text{(Interference at the second time slot)} \\
&C5: R(j,m,k) \ge R_{th}, \forall j,m,k && \text{(rate – guarantee constraint)} \\
&C6: \sum_{j=1}^{N} \varphi_{(j,m)} \le 1, \forall m, \sum_{k=1}^{N} \phi_{(m,k)} \le 1, \forall m && \text{(link pairing constraint)} \\
&C7: \varphi_{(j,m)} \in \{0,1\}, \phi_{(m,k)} \in \{0,1\} && \text{(link pairing constraint)}
\end{aligned} \tag{4}$$

where P_S and P_m are the available power of the source SU and the m^{th} relay respectively.

I_{th} denotes the interference threshold prescribed by PU while R_{th} is the rate-guarantee threshold. ρ_j and $\rho_{m,k}$ are the j^{th} (k^{th}) subcarrier interference factors to the PU band from the source SU and the m^{th} relay respectively. The interference factor in the first time slot depends only on the source SU subcarrier index and the interference factor in the second time slot depends on the destination SU subcarrier index as well as the assigned relay. In addition, $\varphi_{(j,m)}=1$ if the j^{th} subcarrier from the source is paired with the m^{th} relay and $\varphi_{(j,m)}=0$ otherwise, while $\phi_{(m,k)}=1$ if the m^{th} relay receives the signal on the j^{th} subcarrier of the source SU and retransmits it on the k^{th} subcarrier of the destination SU, and $\phi_{(m,k)}=0$ otherwise. In practice, the channel gains between the SUs can be obtained by classical channel estimation techniques, while the channel gains between the SUs and PU can be obtained by estimating the received primary signal power based on the prior knowledge of primary transmit power levels and channel reciprocity [19]-[22].

As a mixed binary integer programming problem, the duality gap of (4) is asymptotically zero for sufficiently large N [23], and we can solve the dual problem of (4) to obtain the asymptotically optimal solution for (4). However, this solution incurs a high computational complexity for the resource allocation algorithm. To remedy this, the next section will propose an efficient joint resource allocation algorithm.

3. Proposed Resource Allocation Algorithm

In order to decrease the computational complexity without sacrificing system performance, we propose a novel heuristic algorithm, which jointly considers subcarrier pairing, relay assignment and power allocation. For the simplicity of further description, define the sets $\boldsymbol{L_1}=\{(j,m)\,|\,\varphi_{(j,m)}=1\}$, $\boldsymbol{L_2}=\{(j,m)\,|\,\varphi_{(j,m)}=0\}$ and $\boldsymbol{L_3}=\{(m,k)\,|\,\phi_{(m,k)}=1\}$. Without loss of generality, assume the noise variance to be constant for all subcarriers and users, i.e. $\sigma^2_{j,m}=\sigma^2_{m,k}=\sigma^2$.

In the proposed resource allocation algorithm, the total power and interference constraints of source SU and each relay are divided into T portions i.e. $\Delta P=P_S/T$, $\overline{\Delta P}=P_m/T$, $\Delta I=I_{th}/T$. For every power portion, we search over all the subcarriers and relays to find out the best subcarrier pair (j^*,m^*,k^*).

Table 1 summarizes the details of the proposed algorithm. Step 1 initializes all the variables and step 2 accomplishes the joint power allocation, relay assignment and subcarrier pairing. For a given power portion $(\min(\Delta p,\Delta I/\rho_j))$ of the source SU, step 2(a) achieves the pairing among the subcarriers and all relays and gets the best link (j^*,m^*). According to the chosen best relay m^*, step 2(b) assigns the best subcarrier in destination SU to get the ultimate best communication link (j^*,m^*,k^*) for the given power portion $(\min(\overline{\Delta P},\Delta I/\rho_{m^*,k},P^{\max}_{m^*,k}))$ in the best relay m^*, where $P^{\max}_{m^*,k}$ is the power threshold obtained by letting the rate achieved in the link between the best relay m^* and the destination SU equal to that in the link between j^* to m^*. Finally, step 3 guarantees the transmission rate for satisfying the QoS requirement of cognitive communication.

Table 1. Joint resource allocation algorithm

Algorithm 1

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1) Initialization:

a) Allocated source-relay pair: $\boldsymbol{L_1}=\varnothing$,

b) Available source-relay pair: $\boldsymbol{L_2}=\{(j,m)|j=1,...,N,\ m=1,...,M\}$

c) Allocated relay-destination par: $\boldsymbol{L_3}=\varnothing$

d) Available subcarriers in destination: $\boldsymbol{D}=\{k|k=1,2,...,N\}$

e) Power portion: $\Delta P = P_S / T$, $\overline{\Delta P} = P_m / T$, $1 \le m \le M$

f) Interference portion: $\Delta I = I_{th} / T$

g) Initial power allocation: $P_{j,m}^0 = P_{m,k}^0 = 0$, $1 \le j,k \le N$, $1 \le m \le M$.

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2) for $t = 1$ **to** T

a) Allocate a power portion to the source-relay pair to achieve the maximum rate gain.

For every $(j,m) \in \boldsymbol{L_1}$ and $(j,m) \in \boldsymbol{L}_2$, Let $P_{j,m}^t = P_{j,m}^{t-1} + \min(\Delta p, \Delta I / \rho_j)$, $\Delta R_t = R_{j,m}^t - R_{j,m}^{t-1}$, find (j^*, m^*) satisfying $(j^*, m^*) = \arg\max_{(j,m)} \Delta R_t$. The power allocation of the source is shown as:

$$\begin{cases} P_{j^*,m^*}^t = P_{j^*,m^*}^{t-1} + \min(\Delta p, \Delta I / \rho_{j^*}) & (j^*, m^*) \\ P_{j,m}^t = P_{j,m}^{t-1} & (j,m) \ne (j^*, m^*) \end{cases} \tag{5}$$

The pairing between the subcarriers of the source and all the relays keep to the following rules:

Case 1: If $(j^*, m^*) \in \boldsymbol{L_1}$, set $\boldsymbol{L_1}=\boldsymbol{L_1}$ and $\boldsymbol{L}_2=\boldsymbol{L}_2$.

Case2: If $(j^*, m^*) \in \boldsymbol{L}_2$, remove the source-relay pair (j^*, m^*) from $\boldsymbol{L}_2$, and set $\boldsymbol{L_1} = \boldsymbol{L_1} + (j^*, m^*)$.

b) Allocate a power portion to the relay-destination pair to achieve the maximum rate gain.

For the chosen relay m^*, there are two situations for subcarrier paring.

(i) $m^* \in \{m | L_3\}$. For every subcarrier in the destination $k \in \boldsymbol{D}$ and $k \in \{k | (m^*, k)\}$, compute the required power to achieve a rate in the link (m^*, k) equal to that in the link (j^*, m^*). We can get a power threshold $P_{m^*,k}^{\max}$ by setting $R_{j^*,m^*}^t = R_{m^*,k}^t$. Set $P_{m^*,k}^t = P_{m^*,k}^{t-1} + \min(\overline{\Delta P}, \Delta I / \rho_{m^*,k}, P_{m^*,k}^{\max})$, $\overline{\Delta R_t} = R_{m^*,k}^t - R_{m^*,k}^{t-1}$, find k^* satisfying $k^* = \arg\max_k \overline{\Delta R_t}$. If $k^* \in \{k | (m^*, k)\}$, set $\boldsymbol{D} = \boldsymbol{D}$ and $\boldsymbol{L_3} = \boldsymbol{L_3}$. If $k^* \in \boldsymbol{D}$, remove the subcarrier k^* from $\boldsymbol{D}$, and set $\boldsymbol{L_3} = \boldsymbol{L_3} + (m^*, k^*)$.

(ii) $m^* \notin \{m | \boldsymbol{L_3}\}$. For every subcarrier in the destination $k \in \boldsymbol{D}$, compute the power threshold $P_{m^*,k}^{\max}$ by setting $R_{j^*,m^*}^t = R_{m^*,k}^t$. Set $P_{m^*,k}^t = P_{m^*,k}^{t-1} + \min(\overline{\Delta P}, \Delta I / \rho_{m^*,k}, P_{m^*,k}^{\max})$, and find k^* satisfying $k^* = \arg\max_k R_{m^*,k}^t$.

Remove the subcarrier k^* from $\boldsymbol{D}$, and set $\boldsymbol{L_3} = \boldsymbol{L_3} + (m^*, k^*)$.

From the situations (**i**) and (**ii**), we can get the best subcarrier pair (j^*, m^*, k^*). Set $\phi(m^*, k^*) = 1$, the power allocation in the best relay is shown as:

$$\begin{cases} P^t_{m^*,k^*} = P^{t-1}_{m^*,k^*} + \min(\overline{\Delta P}, \Delta I / \rho_{m^*,k}, P^{\max}_{m^*,k}) & k^* \\ P^t_{m^*,k} = P^{t-1}_{m^*,k} & k \neq k^* \end{cases} \tag{6}$$

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3) Rate-guarantee

a) Remove relay-destination pairs that do not satisfy the rate threshold.

Let $R(j^*, m^*, k^*) = R^T_{m^*,k}$. If $R(j^*, m^*, k^*) \le R_{th}$, remove the subcarrier pair (m^*, k^*) from $\boldsymbol{L_3}$, i.e. $\boldsymbol{L_3} = \{(m^*, k^*) \mid R(j^*, m^*, k^*) \ge R_{th}\}$. The overall throughput of the CRN is described as $R_{Total} = \sum_{\boldsymbol{L_3}} R(j^*, m^*, k^*)$.

For the proposed efficient algorithm, every iteration requires no more than MN^2 function evaluations.Therfore, the complexity of the proposed algorithm is $O(TMN^2)$ where T is always not big. For the optimal solution that obtaines by using dual decomposition technique and sub-gradient methods, MN^2 function evaluations are performed to find the power allocation in every iteration. Afterwards, M function evaluations are performed for every possible subcarrier pair where there are N^2 different subcarrier pairs. By including the computational complexity of the Hungarian method, the optimal algorithm has a complexity of $O(S(MN^2) + N^3)$ where S is the number of iterations required to converge and is usually large value. We can find the complexity of [15] is $O(MN^2)$ in the reference.

4. Simulation results

In this section, we demonstrate the performance of the proposed resource allocation algorithm using Monte Carlo simulation over 1000 realizations. We compare the proposed algorithm with the other two schemes: the optimal solution and the scheme in [15], where the optimal solution is obtained by using the dual decomposition technique and sub-gradient methods. In all simulations, the channel gains are obtained from independent Rayleigh distributed random variables with mean equal to 1. Ts, B, M, N and σ^2 are assumed to be 5μs, 20MHz, 5, 64 and 0.0001 respectively. The parameters in the simulations are described in **Table 2**.

Table 2. Simulation parameters

Name	$P_S = P_m$ （dBm）	I_{th} （dBm）	R_{th} (Bit/Hz/Sec)	T
Fig.2	-20—5	0	0	200
Fig.3	0	-20—20	0	200
Fig.4	-3	0	0—0.1	200
Fig.5	0	0	0	0-200
Fig.6	-20—6	-20-6	0	200

Fig. 2 shows the achieved overall throughput of the different algorithms vs. the available power budgets. One can notes that the overall throughput grows with the increase of power budgets as the CRN become able to use more power on the different subcarriers. It is worth noticing that our proposed algorithm performs much better than the scheme in [15] and the gap between the proposed algorithm and the optimal solution is very small, suggesting that the proposed scheme provides a good approximation to the optimal. Additionally, the gaps among the proposed algorithm and the other two schemes are very close in the high power budgets region. This is because that the interference induced to the primary system should be kept below the pre-specified threshold to ensure the QoS of PUs.

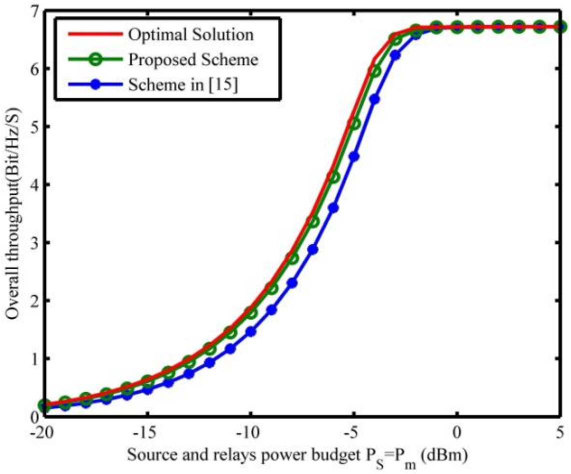

Fig. 2. Overall throughput vs. available power budgets with $P_S = P_m$.

Fig. 3 depicts the achieved overall throughput of the different algorithms vs. the interference constraint. It can be found that our proposed algorithm outperforms the scheme in [15] and achieves a near optimal performance with much less computational complexity. Additionally, we can observe that the overall throughput grows with the increase of interference threshold, and all the algorithms have a near performance in the low interference threshold region. Furthermore, the gaps among the proposed algorithm with the other two schemes are increased with the interference threshold increased.

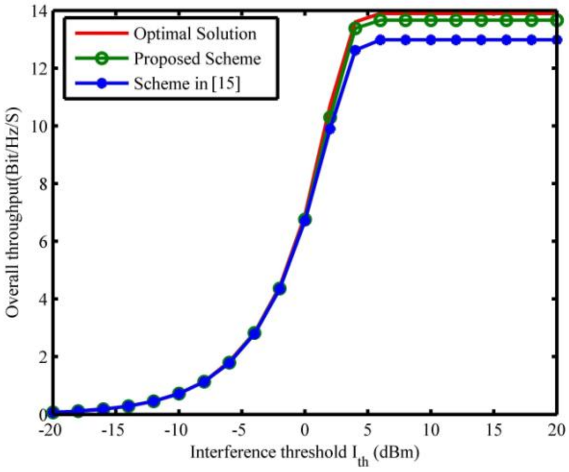

Fig. 3. Overall throughput vs. allowed interference threshold.

From **Fig. 4**, we can see that the overall throughput decreases as rate-guarantee threshold grows for all the algorithms. This is because that the rate provided by some allocated subcarriers may be too low for practical usage. In order to ensure communication requirement, these poor quality links are discarded. In addition, we can observe that our proposed algorithm performs much better than the scheme in [15] and the gap between the proposed algorithm and the optimal solution is very small, suggesting that the proposed scheme provides a good approximation to the optimal.

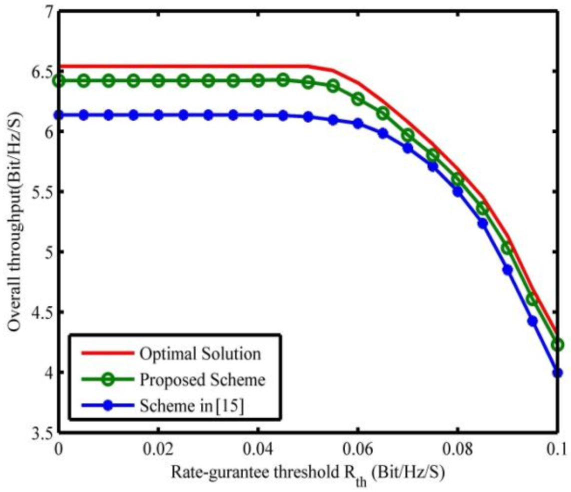

Fig. 4. Overall throughput vs. rate-guarantee threshold.

Fig. 5 illustrates the overall throughput of the proposed scheme vs. the values of “T”. It can be found the overall throughput increases with the values of “T”. However, with the increase of “T”, the system performance improvement amount will gradually decrease when “T” increases to a certain extent.

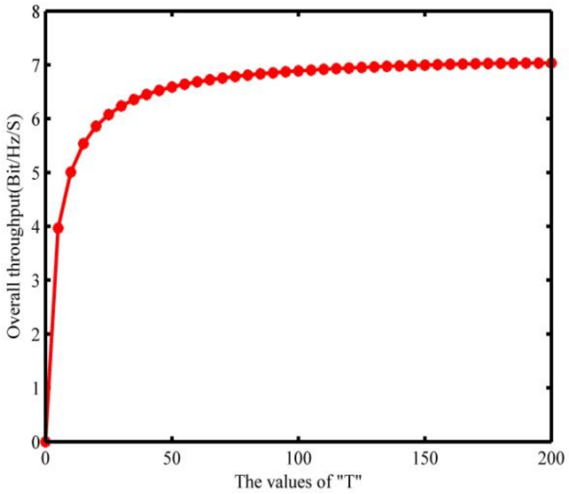

Fig. 5. Overall throughput vs. the values of “T”.

Fig. 6 plots the overall throughput of the proposed schemes vs. different interference threshold and power constraint to clarify the different regions. By fixing one of the constraints, it can be found that the overall throughput increases with the other up to a certain point, and the change of the constraint value does not affect the overall throughput when the value exceed the certain point.

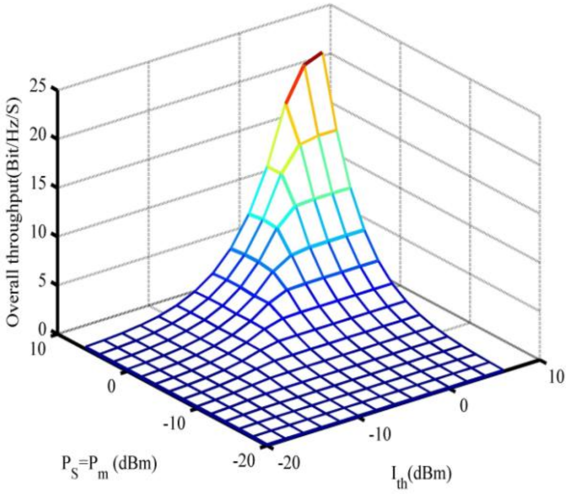

Fig. 6. Overall throughput vs. different interference threshold and power constraint.

Compare to general algorithms (such as: dual decomposition algorithm, genetic algorithm), the proposed algorithm has a much smaller complexity while performs excellently that makes it scalable. In addition, the simulation results show that multiple simulations have similar optimal solution. It suggests that the proposed algorithm has a good stability.

5. Conclusion

In this paper, a Low-Complexity high performance resource allocation algorithm is investigated that jointly considers subcarrier pairing, best relay selection and power allocation scheme. The proposed algorithm shows to perform closely to the optimal solution with much less complexity, Moreover, the proposed algorithm outperforms the scheme in [15] and has a good scalability and stability.

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