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Simulated Annealing Algorithm-based Subcarrier Allocation for Multiuser OFDM Relay Systems

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***Abstract*—Resource allocation for multiuser OFDM relay systems is investigated in this paper. The separate power limits for the base station and the relay station is considered. The resource fairness problems for each user are also presented, including the subcarrier fairness and the proportional end-to-end throughput fairness. This paper introduces a hierarchical scheme to combine the maximum end-to-end throughput and minimum transmit power. The set of the switching levels for the modulation types is applied in this paper. The simulated annealing algorithm is introduced. The methods of the neighborhood search is discussed and compared with two heuristic allocation algorithms. Owing to the characteristic of the relay system, unbalanced throughput among hop links happened. This paper proposed a suitable bit loading approach using water-filling method applied to load bits optimally for each user under the power constraint and the fairness constraints. Each user's hop links are guaranteed to have the balanced throughput. Simulation results show the performances of the effects of the fairness constraints and different subcarrier allocation algorithms.**

***Index Terms*—multihop relay, resource allocation, fairness problem, simulated annealing algorithm**

I. INTRODUCTION

Multihop relay transmission is powerful technique to have the high throughput and the coverage extension. More and more researches are proposed [1-2]. The deployment of relay stations (RS) could not only reduce infrastructure costs and site acquisition, but also increase the mobile battery life. With the aid of relay stations, some problems are supposed to be solved, such as the shadow of buildings, the valley between buildings, and the coverage extension at cell edge or to the isolated area. Recently, the resource allocation for multiuser orthogonal frequency division multiplexing (OFDM) relaying systems have been widely proposed [3-7]. According to the different channel conditions at different locations [5] experienced by users, subcarrier, bit and power allocations are employed in this paper.

This paper investigates the resource allocation of multiuser OFDM relay systems. The system is assumed to decode reliably the source message before forwarding, called decode-and-forward relay scheme [6]. The maximum transmit power for the base station (BS) and the relay station (RS) are considered separately. A user owns the same subcarriers among the multihop links, and a subcarrier is not allowed to share more than one user. A user can communicate with BS in the single-hop link directly, or in the multihop links through RS. The end-to-end throughput for a user is determined by the communication with the maximal throughput.

Two fairness problems among users are considered. The first one is to assign a minimum number of subcarriers for each user. It is an adjustable integer according to systems [7]. The other is to ensure the proportional end-to-end throughput fairness among users [8]. These two fairness constraints could be taken into consideration separately or simultaneously. Meanwhile, this paper introduces a hierarchical scheme to achieve the maximum end-to-end throughput with the minimum transmit power.

Two heuristic subcarrier allocation algorithms [9-10] are well studied in this paper. The concepts are similar with the pure perturbation in [11]. This paper would also combine the heuristic subcarrier allocation algorithms with the simulated annealing (SA) algorithm. The SA algorithm [12-13] can be considered as a generalization of the well known iterative improvement scheme. The set of the switching levels [14] for the modulation types is applied in this paper. Since each subcarrier experiences different channel conditions, the limited transmit power should be allocated to user appropriately. Owing to the characteristic of the relay system and the fairness constraints, unbalanced throughput among hop links happened. This paper proposed a suitable bit loading approach using water-filling method. Each user's hop links are guaranteed to have the balanced throughput.

In simulations, the heuristic subcarrier allocation algorithms and the simulated annealing algorithms are well discussed and compared. Simulation results present the performances for the effects of the fairness constraints. The end-to-end throughput and the required transmit power are compared.

II. SYSTEM MODEL

Assume the system has *K* users and *N* subcarriers. A subset of *N* subcarriers is assigned to a user which owns the same subcarriers among the multihop links. The maximum transmit power is P_{BS} and P_{RS} for the base station (BS) and the relay station (RS) respectively. $h_{n,k,l}$ denotes the channel gain that allocated to user *k* at subcarrier *n* at *l*th hop link. The number of bits of the *n*-th subcarrier assigned to user *k* at the *l*th hop link is $r_{n,k,l} \in \{0,1,\ldots,M\}$. The required received power $f_{k,l}$ at a particular data error rate is a function of bits per symbol $r_{n,k,l}$. A subcarrier is not allowed to share more than one user.

$$\rho_{n,k,l} = \begin{cases} 1, & if \ r_{n,k,l} \neq 0 \\ 0, & if \ r_{n,k,l} = 0 \end{cases} \tag{1}$$

Variable $\rho_{n,k,l}$ is either 1 or 0, and the sum of all $\rho_{n,k,l}$ is equal to 1 for any particular *n* at *l*th hop link. The required transmit power at the *l*th hop link can be expressed as

$$P_l = \sum_{n=1}^{N} \sum_{k=1}^{K} \frac{f_{k,l}\left(r_{n,k,l}\right)}{h_{n,k,l}^2} \rho_{n,k,l} \tag{2}$$

The bit error rate must be ensured at a certain level to meet the service quality. A user can communicate with BS in the single-hop link directly, $R'_{k \in D}$, or in the multihop links through RS, $\tilde{R}_k$. The end-to-end available throughput via the multihop links is determined by the link with the minimal throughput.

$$\tilde{R}_k = \min\left\{\sum_{n=1}^{N} r_{n,k,l}\right\}, \quad for \ k = 1,2,\ldots,K \tag{3}$$

$$R_k = \max\left\{R'_{k \in D}, \ \tilde{R}_k\right\} \tag{4}$$

D presents the direct links. The real throughput for a user is determined by the communication with the maximal throughput. The subcarrier, bit and power allocation problem for maximizing the end-to-end throughput is formulated as:

$$\begin{aligned} &\max_{P_{BS}, P_{RS}, \rho_{k,n,l}} \sum_{k=1}^{K} R_k \\ &\text{subject to} \quad P_l \le P_{BS}, \ \text{for } l \in \{1, D\}, P_l \le P_{RS}, \ \text{for } l \notin \{1, D\}, \\ &\sum_{k=1}^{K} \rho_{k,n,l} = 1, \ \text{for } n = 1,2,\ldots,N \\ &\sum_{n=1}^{N} \rho_{k,n,l} \ge \alpha_k, \ \text{for } k = 1,2,\ldots,K \\ &R_1 : R_2 : \ \ldots \ : R_K = \Omega_1 : \Omega_2 : \ \ldots \ : \Omega_K \end{aligned} \tag{5}$$

In this paper, the subcarrier fairness and the proportional end-to-end throughput are both considered. The fourth constraint guarantees a minimum number of subcarriers, α_k, for all users. α_k is an integer between zero and N / K [7]. $\{\Omega_i\}_{i=1}^{K}$ is a set of predetermined values that are used to ensure the proportional end-to-end throughput fairness among users [8]. Owing to the characteristic of the relay systems, the unbalanced channel conditions happened in each hop links. Power would be wasted. This paper also investigates the transmit power based on the achievable maximum end-to-end throughput. The achievable maximum end-to-end throughput in (5) is defined as:

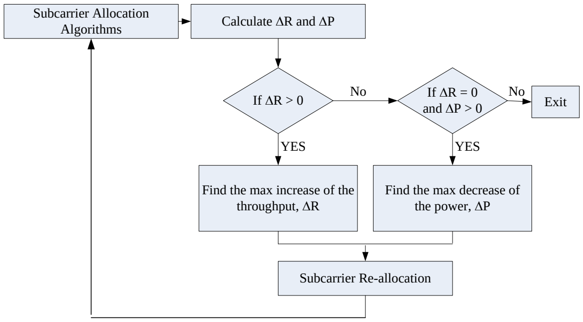

Fig. 1. The subcarrier allocation structure.

$$\sum_{k=1}^{K} R_k = R_k^{\max} \tag{6}$$

The subcarrier, bit and power allocation problem for minimizing the transmit power based on the achievable maximum end-to-end throughput is formulated as

$$\begin{aligned} &\min_{r_{n,k,l}, \rho_{n,k,l}} \sum_{l=1}^{L} P_l = \sum_{n=1}^{N} \sum_{k=1}^{K} \sum_{l=1}^{L} \frac{f_{k,l}\left(r_{n,k,l}\right)}{h_{n,k,l}^2} \rho_{n,k,l} \\ &\text{subject to} \quad \sum_{n=1}^{N} r_{n,k} = R_k^{\max}, \ \text{for } k = 1,2,\ldots,K \end{aligned} \tag{7}$$

This paper will investigate a solution that is the achievable maximum end-to-end throughput with the minimum transmit power requirement.

III. MAXIMUM THROUGHPUT AND MINIMUM POWER

This paper introduces a hierarchical scheme that the achievable maximum end-to-end throughput with the minimum transmit power is guaranteed. The minimum transmit power is supposed to be obtained after the system achieves the maximum end-to-end throughput. The structure of the hierarchical scheme is shown in Fig. 1. After some allocation algorithms, the increase of the throughput, Δ*R*, and the decrease of the power, Δ*P*, would be both calculated. If the increase of the throughput exists, the subcarriers are re-allocated. If not, the decrease of the power is considered. The system will terminate when there are no increase of the throughput and the decrease of the power. The hierarchical scheme would seek for the solution which has the maximum end-to-end throughput with the least transmit power requirement at all hop links.

IV. PROPOSED ALLOCATION ALGORITHM WITH SIMULATED ANNEALING ALGORITHM

Two existent heuristic subcarrier allocation algorithms are well studied in this paper. The first one is Wong's subcarrier allocation algorithm [9]. Constructive Initial Assignment (CIA) is introduced. After the CIA operation, it swaps the subcarriers between users iteratively to improve the performance. The numbers of subcarriers assigned to each user is predetermined and fixed throughout the process. Owing to this drawback, the enhanced subcarrier allocation algorithm [10] performs either the swapping or the reallocation operation. The number of subcarriers for each user would change adaptively and iteratively. These subcarrier assignment

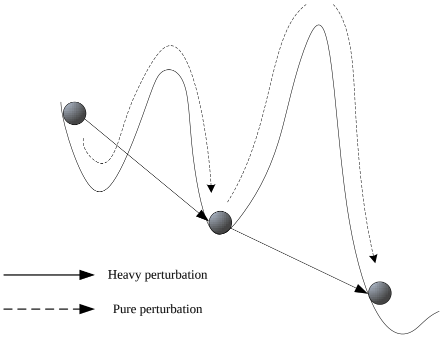

Fig. 2. The cost of the transitions between solutions.

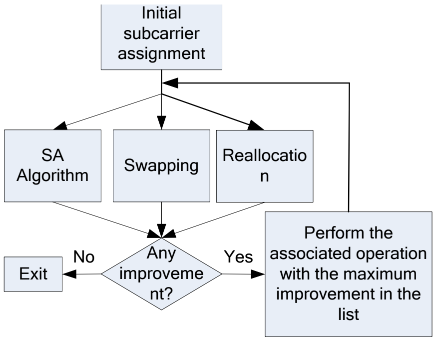

Fig. 3. Block diagram of the proposed allocation algorithms.

procedures could be same as the methods of the neighborhood search in the simulated annealing (SA) algorithm.

The simulated annealing (SA) algorithm is an algorithm that is effective for optimization problems. The algorithm can be considered as a generalization of well known iterative improvement scheme. The initial value would be replaced by the neighborhood value with the better fitness. SA occasionally allows "uphill moves" to solutions of higher cost according to the Metropolis algorithm [15]. The important parameters in SA are the neighborhood and the temperature. When the neighborhood range is too small, it tends to fall into a local minimum. As for the temperature, it is used as a control parameter. The temperature parameter is gradually decreased throughout the iterations. At the initial stage of the SA algorithm, the higher temperature is appropriate to increase the probability of accepting a worse next stage to prevent from falling into suboptimal solutions. Main components of the simulated annealing algorithm are as

A. *Solution presentation*

The solution presentation with *N* elements means a subcarrier assignment solution associated with the optimization problem. Its value is coded as an integer at the range of 1 to *K* that stands for an index of a user. Only one single solution is evaluated, which is a $S_{1\times N}$ vector.

B. *Transition mechanisms between solutions*

It is also named as the neighborhood search. The neighborhood search is to select one or more elements randomly and change values under a specific temperature. The concept of a flip-flop [11] is to replace with each other, and it is similar with [9], which is iteratively swapping the subcarrier between users. In [10], the enhanced subcarrier allocation algorithm is proposed by performing reallocation operation. It is also similar with the neighborhood search which is to select only one element and change it [11]. [9-10] search for solutions exhaustively while the mechanism is processed randomly in the simulated annealing algorithm. We calculate the variance average (*VA*) [18] of the $S_{1\times N}$ vector.

$$VA = \sum_{i=1}^{N} \left(S_i - \bar{S} \right)^2 \Big/ N \tag{8}$$

where "-" denotes an averaged value. If the current *VA* is smaller than the previous *VA*, the number of elements to change should increase and vise versa. The *VA* value is held in the integer range from 1 to 3. The neighborhood search scheme is allowed to occasionally propose heavy perturbations. This scheme aims to jump out a local minimum. Fig. 2 shows the cost of the transitions between solutions.

C. *Cooling procedure*

At the initial stage of the SA algorithm, the higher temperature is appropriate. The temperature is gradually decreased throughout the iterations. According to [15], the cost function is the throughput and the power in this paper. If the increase of the throughput ΔR or the decrease of the power ΔP exists, the new solution is accepted and displaced. If not, the new solution would be accepted when the accepted probability is larger than a random number. ΔE is $|\Delta R|$ or $|\Delta P|$. The accepted probability is:

$$\Pr(\Delta E) = \exp^{\left(-\Delta E / K_B T_t\right)} \quad \text{and} \quad T_t = \lambda T_{t-1} \tag{9}$$

where K_B is the Boltzmann's constant and T is the temperature. λ is a less-than-one constant. In this paper, the system energy ΔE must be non-positive and the accepted probability must be larger than a random number. The simulated annealing procedure keeps going until the terminal criterion is met.

D. *Simulated annealing algorithm terminal criterions*

The simulated annealing algorithm terminal criterions are the final temperature and the maximum number of iterations.

The new proposed subcarrier allocation executes the swap [9], the reallocation [10], or the simulated annealing algorithm shown in Fig. 3.

V. BIT LOADING APPROACHES

Because of the unbalanced channel conditions, unbalanced throughput among hop links happened. The end-to-end throughput could not be guaranteed and limited to the minimum throughput at a specific hop link. Water-filling method to load bits is employed in the view of users in this paper. Each user's hop links would have the balanced throughput. The end-to-end throughput can be also determined and guaranteed by the constraints of the subcarrier fairness and the throughput fairness separately or simultaneously. Water-filling method for bit loading with multiuser OFDM is described below:

$$\Delta P_L = \Delta \sum_{l=1}^{L} P_l\left(r_{n,k,l}\right) = \sum_{l=1}^{L} {f_{k,l}\left(r_{n,k,l}+1\right) - f_{k,l}\left(r_{n,k,l}\right)} \Big/ {h_{n,k,l}^{2}} \text{, for } n \in S_k \qquad (10)$$

where S_k is the set of the index of subcarriers assigned to the *k*th user. Water-filling method would load a bit at a time to the subcarrier which requires the least additional power under the limited power to obtain the maximal end-to-end throughput. The concept of this greedy approach is obtained when the end-to-end throughput fairness is considered in this paper. Replace $\left(r_{n,k,l}+1\right)$ by $\left(r_{n,k,l}+\left\{\Omega_i^*\right\}_{i=1}^{K}\right)$ in (10). One or more bits, $\left\{\Omega_i^*\right\}_{i=1}^{K}$, according to the proportional end-to-end throughput fairness among users, are loaded to all users at the same time in each bit loading process.

VI. SIMULATIONS

A resource allocation approach is presented for the two-hop relaying system in this paper. The frequency selective wireless channel model used in [16] is adopted. Perfect channel estimation is assumed to be known. The channel power of the received signal for each user is varied because of the various path losses at the different locations. A single cell with one RS is considered. A BS is located at the cell center. The cell radius is 1km. The RS sets in 600m far from BS. Users are uniformly distributed from the RS to the edge of the cell radius. The propagation model [17] is used. The BS-RS link and the RS-user link are supposed to be in line-of-sight while the BS-user link is in non-line-of-sight.

In the initial population, subcarriers are equally distributed to all users by the CIA operation according to the first hop link's channel condition. The set of the switching levels for the modulation types is employed in [14] for QPSK, 16QAM, and 64QAM. The effects of the subcarrier fairness and the proportional end-to-end throughput fairness are well considered in the simulations. Two cases are experimented. *Case1*: The subcarrier fairness is considered. α is set as 1. *Case2*: The subcarrier and the proportional end-to-end throughput fairness are both considered. We set $\alpha = N/2K$ and $\left\{\Omega_i\right\}_{i=1}^{K} = 1$. Simulations are shown from Figs. 4 to Fig. 7 respectively. Simulation results show for 4, 6, and 8 users. The number of subcarriers is 48. Other simulation parameters are as follows. The mobile speed is 4km/h. The central frequency is 5GHz. The frame duration is 10ms. The channel bandwidth is 1.25MHz. The noise density is 174dBm/Hz. Two existing subcarrier allocation algorithms are compared. *HSA1*: [9]. *HSA2*: [10].

In the simulation, Fig. 4 shows the end-to-end throughput performances for two cases. The BS power sets to 6W, and the RS transmit power sets to 1W. When the number of users increases, the end-to-end throughput falls. *Case 1* would achieve higher the end-to-end throughput because *Case 2* has more constraints than *Case 1*. Fig. 4 also shows that better subcarrier allocation algorithms would obtain higher the end-to-end throughput performances

In *Case 1*, we only set the subcarrier constraint. Our goal is to maximize the end-to-end throughput before minimizing the total transmit power. All algorithms introduced and proposed in this paper would do their best-effort to maximize the end-to-end throughput under the power constrains. Obviously, subcarriers would tend to allocate to the user with the best channel conditions. All algorithms except CIA achieve almost the same end-to-end throughput in Fig. 4. That is because the distance of the BS-RS link is further than the RS-user link. Path loss is much serious in the BS-RS link. The end-to-end throughput would be limited by the BS-RS link. The required transmit power is shown in Fig. 5. The comparison of the relative power points out those different algorithms could require different transmit power. HSA1 is limited by the fixed number of subcarriers for users. Therefore, HSA1 is not able to reduce the transmit power as much as HSA2 and the proposed algorithm. Owing to the loose subcarrier constraint and limit of the BS-RS link, the power reduction is not obviously different among HSA2, and the proposed algorithm shown in Fig. 5.

In *Case 2*, Constraints of the subcarrier and the proportional end-to-end throughput fairness are both considered. The relative power among users for different subcarrier allocation algorithms is compared in Fig. 6. The proposed algorithms would have better performances both in higher spectral efficiencies in Fig. 4 and lower transmit power in Fig. 6. We also compare the convergence rates for HSA1, HSA2, and the proposed algorithm with 4 users in Fig. 7. The proposed algorithm has the higher power reduction in iteration, and achieves a better performance.

VII. CONCLUSION

This paper presents a hierarchical scheme to combine the maximum end-to-end throughput and the minimum transmit power for the resource allocation of multiuser OFDM relay systems. Due to the characteristic properties of wireless channels, the resource fairness problems for all users are considered. The subcarrier fairness and the end-to-end throughput fairness are both studied in this paper. Two existent heuristic subcarrier allocation algorithms are introduced and discussed. These subcarrier assignment procedures could be viewed as the methods of the neighborhood search in the simulated annealing algorithm. The simulated annealing algorithm is clearly introduced, and the methods of the neighborhood search are well discussed. Because of the unbalanced channel conditions, a suitable bit loading approach using water-filling method is employed in the view of users in this paper in order to satisfy the balanced throughput among hop links and the fairness constraints. Simulation results show the performances of the effects of the fairness constraints and different subcarrier allocation algorithms.

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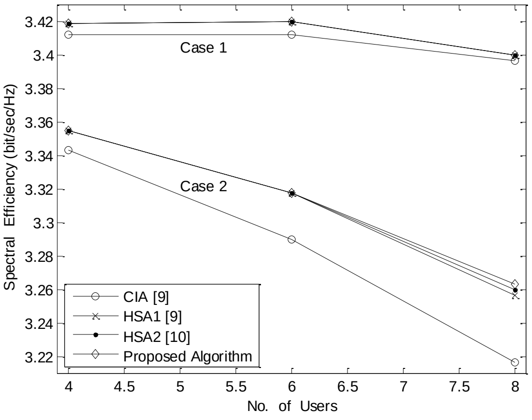

Fig. 4. Simulations for *Case 1* and *Case 2* with different subcarrier and fairness constraints. The required BER is 10^{-2}.

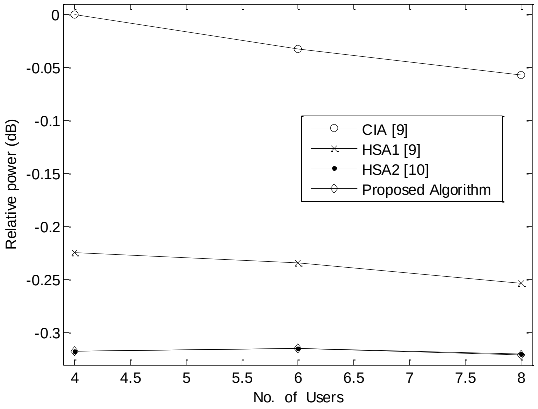

Fig. 5. Simulations for *Case 1* among different numbers of users.

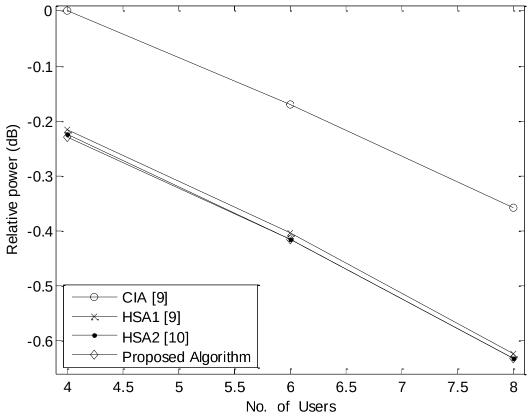

Fig. 6. Simulations for *Case 2* among different numbers of users.

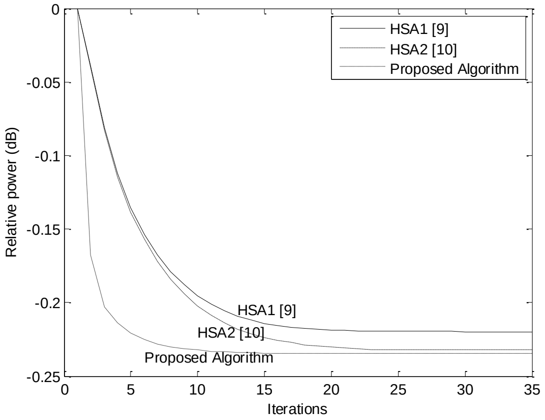

Fig. 7. Simulations for *Case 2* with 4 users. Convergences of three subcarrier allocation algorithms varying with iterations are compared.