Adaptive Subcarrier Allocation for OFDM Relay System

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Abstract—**This paper proposes two scheduling algorithms for subcarrier allocation of OFDM relay system, enhanced two-hop adaptive proportional fairness (E-THAPF) and user-number-dynamic two-hop adaptive proportional fairness (UND-THAPF), aiming to improve the performance of the traditional two-hop proportional fairness (THPF) scheduling algorithm. By modifying the priority of the two hops in THPF in an adaptive fashion, E-THAPF and UND-THAPF can optimize the subcarrier allocation dynamically despite of the subcarriers fluctuation, and thus can keep the system flexible and stable. Moreover, the factor α in the dynamic index of UND-THAPF is made adaptive to the change of the number of users. Simulation results show that the proposed algorithms achieve a better compromise between system fairness and spectral efficiency. In particular, while E-THAPF is designed to be adaptive to different sub-channel conditions, UND-THAPF performs even better for taking number of users into account in the optimization.**

Index Terms—**OFDM, DF relay, E-THAPF, UND-THAPF, spectral efficiency**

I. INTRODUCTION

Cooperative relay is a predominant technology in the next-generation wireless networks, the system capacity must be provided in accordance with the agreed level of quality of service (QoS). For this purpose, to utilize fixed relay station (RS) in cellular network is becoming a wildly accepted approach, in which the air interface is mostly orthogonal frequency division multiplex (OFDM) Resource efficiency is a key issue in this OFDM relay network architecture [1]. According to the different pass-through modes, relay nodes can be divided into two categories: amplify-and-forward (AF) relay and decode-and-forward (DF) relay. DF relay, can dramatically decrease the bit error rate, as the RS processes the received data before transmitting it. In communications dominated by multimedia data services, the system is required to meet the performance requirements of different users [2], [3]. While allocating the wireless resources in the OFDM relay system, the security of users as a key element is required to be taken into consideration [4], [5]. The most challenging work in this area is to design a resource efficient algorithm that can utilize the limited spectrum resource and guarantee the fairness between mobile stations (MS) and RS [6].

Resource allocation in OFDM systems is recognized as an optimization problem [7]. To solve the problem, most current literatures concentrate on adopting dynamic two-hop power allocation methods [8]-[11]. However, if the allocation of subcarriers is out of consideration, there is no way to guarantee both system fairness and throughput. Thus, it is crucial to design suitable resource scheduling algorithms by taking subcarrier allocation issue into account.

So far, there are three major resource scheduling algorithms: max carrier-to-interference ratio (max(C/I)), round-robin (RR) and proportional fairness (PF). Among the three algorithms, max(C/I) can achieve the maximal value of system spectral efficiency, but the fairness can be extremely awful even if the MS or RS with the best channel condition can occupy all resources all the time. On the contrary, round-robin allocates subcarriers by turn, and thus can achieve the maximal value of system fairness. However, it performs too bad to be acceptable in terms of spectral efficiency. Being able to set priority for every user and relay, PF is able to achieve a good trade-off between system spectral efficiency and fairness [12]-[14]. Since a multi-hop system is required to take care of the rate matching however, traditional PF algorithm can't be deployed directly. To cope with this, many recent literatures concentrate more on how to enhance the PF algorithm so that it can be used into two-hop relay system [15]-[19]. In [15] on the basis of PF algorithm, the authors formalize the optimization problem with a number of object functions of fairness and spectral efficiency, and then simplify the functions through multi-hop subcarrier matching method [15]. In [16], THPF is proposed, in which the rate matching factor β is introduced. The priority of being in service of MS keeps changing with the fluctuating factor β. Similarly, the process above can also be to first allocate all MS by PF algorithm, then the BS balance rates of both hops [17]. Upon the proposal of THPF, the problem of how to minimize the system power allocation has been studied [18]-[19] with quite some fresh ideas put forward,

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including to consider the relay system resource allocation problem as a decision model, and to combine the PF algorithm with analytic hierarchy process in order to determine the MS's allocating priority [20]. Lately, some researchers [12], [21]-[23] have studied dynamic strategies by dividing two-hop sub-channels, in which leisure subplot is allocated to MS by BS directly to improve the subplot resource utilization [21].

According to the analysis above, the previous efforts in the two-hop relay system mostly concentrate on balancing the rate of both of the two hops. To the best of our knowledge, there is no proposal that can solve the existing problem in PF algorithm where, when the channels' condition varies relatively large, there is no guarantee on an acceptable and stable system fairness [24]. Also, no existing research modifies the priority of both hops, and thus fails to make the scheduling strategy more real-time or to improve the spectral efficiency notably. Furthermore, very little work attempts to design a scheduling algorithm in an adaptive way by dynamically modifying the priority of the two hops. This paper proposes two novel algorithms based on THPF for the two-hop relay cooperative system. Both algorithms modify the priority formulas of the two hops. The first algorithm, E-THAPF can set the priorities of two hops dynamically according to the channel conditions of MS, and so it can change the scheduling strategy easily according to the communication conditions of different users. This makes the system highly real-time and flexible, and thus improves the spectral efficiency dramatically. The second algorithm, UND-THAPF provides the user-number-dynamic mechanism through which the system is able to optimize the scheduling strategy along with the changing number of users. This is extraordinary helpful to meet the demands of realistic scenario.

The rest of this paper is organized as follows. The system model is presented in Section 2. In Section 3, we describe two enhanced two-hop proportional relay cooperative scheduling algorithms. The simulation results are presented and analyzed in Section 4. Finally, the conclusions are given in Section 5.

II. System Model

This paper adopts a three-node relay model, in which BS node locates in the cell center, M RS uniformly distributed at two-thirds of the cell radius [12], K MS randomly distributed in the cell and N subcarriers can be allocated.

In this paper, we assume that BS are able to detect overall channel conditions, the system uses the two-hop half-duplex DF relay and is able to obtain subcarriers by scheduling automatically. Moreover, RS nodes work on half-duplex model transmitting and receiving data on different timeslots [1]. A MS within the two-thirds radius of a BS will be served directly by BS, and the MS user is called direct user or 1st hop user. Similarly, MSs out of the two-thirds radius of the BS are served by RS, and the MS users are called the relay link users or 2nd hop users. In each transmit time interval (TTI), one timeslot is separated into the 1st timeslot and the 2nd timeslot, correspondingly, one relay link is divided into the 1st hop link and the 2nd hop link [16]. The system model is illustrated as the Fig. 1.

In the 1st timeslot, BS transmits data to MS or RS (the solid line in Fig. 1), and in the 2nd timeslot, RS transmits data to MS while BS is silent (the broken line in Fig. 1).

The bandwidth of the system is B (Hz), and the power is evenly distributed at every subcarrier. We use $SNR_{k,n}$ to represent the signal-to-noise ratio (SNR) on the sub-channel n from direct users MS_k to BS, $SNR_{m,n}$ for the SNR on sub-channel n from RS to BS, and $SNR_{k,m,n}$ as the SNR on sub-channel n from relay link user $MS_{k,m}$ to RS.

The set of direct users is U_D. U_R represents the set of RS, and U_{Rm} is the set of relay link users served by RS. U_N is the set of all subcarriers, and k_m denotes user k is served by RS m. What's more, $a_{k,n}$ represents whether sub-channel n is allocated to user k; $a_{k,n}$=1 indicates that it is allocated, otherwise that it is not allocated. $C_{k,n}$ is the Shannon theoretical capacity of user k on the sub-channel n. In the same way, we define $a_{m,n}$ and $C_{m,n}$ to represent the allocation condition and Shannon theoretical capacity of RS m. As for relay link user k, $a_{k,m,n}$ denotes whether sub-channel n is allocated to user k via relay m, and the Shannon theoretical capacity is $C_{k,m,n}$.

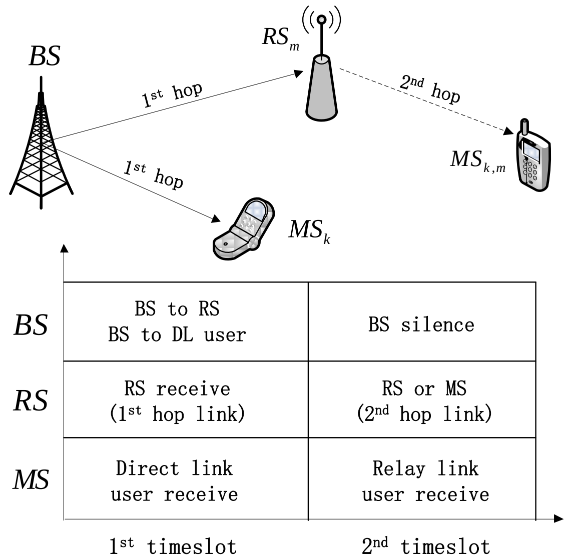

Fig. 1. System model

As we assume an even distribution of power allocation on sub-channels, according to Shannon formula, the theoretical maximal rate of direct user MS_k is [16], [18]

$$C_{k,n}=B_n\log_2(1+SNR_{k,n}) \quad (1)$$

In the 1st hop, the theoretical maximal rate of relay R_m is

$$C_{m,n}=B_n\log_2(1+SNR_{m,n}) \quad (2)$$

In the 2nd hop, the theoretical maximal rate of relay link user $MS_{k,m}$ on the sub-channel n is

$$C_{k,m,n}=B_n\log_2(1+SNR_{k,m,n}) \quad (3)$$

B_n denotes the bandwidth of every sub-channel.

$$SNR_{k,n}=P_n g_{k,n}/\Gamma\sigma^2 \tag{4}$$

P_n represents the transmit power of BS on every sub-channel, $g_{k,n}$ expresses the sub-channel gain between BS and direct user k on sub-channel n.

$$SNR_{m,n}=P_n g_{m,n}/\Gamma\sigma^2 \tag{5}$$

$g_{m,n}$ is the gain between BS and RS R_m on sub-channel n.

$$SNR_{k,m,n}=P_m g_{k,m,n}/\Gamma\sigma^2 \tag{6}$$

in which P_m is transmitting power on sub-channel n.

$$\sigma^2=N_0 B_n \tag{7}$$

is the power of White Gaussian noise.

$$\Gamma=-\ln(5\times BER)/1.5 \tag{8}$$

is a factor affected by bit error rate [20].

As for direct user MS_k the achieved transmitting rate in the 1st timeslot is [16, 18]

$$r_k=\sum_{n=1}^{N} a_{k,n} C_{k,n},\ k\in U_D \tag{9}$$

The achieved data rate of the relay link user $MS_{k,m}$ in the 2nd hop is

$$r_{k,m,n}^{(2)}=\sum_{n=1}^{N} a_{k,m,n} C_{k,m,n},\ k\in U_{Rm} \tag{10}$$

The achieved data rate of RS m in 1st hop can be expressed as

$$r_m=\sum_{n=1}^{N} a_{m,n} C_{m,n},\ m\in U_R \tag{11}$$

The total data rate of RS n in the first timeslot is acquired by all relay link users served by it, thus the achieved data rate of the relay link user k can be expressed as

$$r_{k,m,n}{}^{(1)}=r_m{}^{(1)}\frac{r_{k,m,n}{}^{(2)}}{\sum_{k\in U_{R_m}} r_{k,m,n}{}^{(2)}} \tag{12}$$

The transmitting rate of relay link user k is determined by the minimal rate of two hops [2, 16, 18, 20], therefore

$$r_{k,m,n}=\min\{r_{k,m,n}{}^{(1)}, r_{k,m,n}{}^{(2)}\},\ k\in U_{Rm} \tag{13}$$

III. Enhanced Two-Hop Proportional Algorithm & User-Number-Adaptive Two-Hop Proportional Algorithm

Traditional PF algorithm provides a good tradeoff between system spectral efficiency and fairness in conventional non-relay OFDM wireless system. For two-hop relay system, THPF [16] is proposed to provide a guarantee of fairness of both hops. Some other studies based on THPF aim to make some improvements [2], [18]. Nevertheless, the spectral efficiency of THPF and its improved versions are still unacceptable in real-life scenarios. Meanwhile, it's been proven that even PF algorithm can't guarantee a good and stable system fairness in case when the channel condition of certain users fluctuate too large [24]. Moreover, very little study concentration on changing the algorithms into an adaptive fashion by modifying the priority of two hops dynamically, which can make the system more flexible and intellective. This paper aims to notably improve the spectral efficiency of THPF algorithm, and make the two-hop cooperative relay system more intellectual and flexible.

In particular for the 2nd hop, THPF algorithm simply adopts the original PF algorithm to allocate wireless resource, in which users with bad channel conditions may occupy resources improperly. This declines spectral efficiency drastically. Our idea is to additively combine PF with max(C/I) algorithm on the prerequisite of ensuring acceptable system fairness. This can improve the spectral efficiency. The modified the priority formula is expressed as

$$PRI_{k,m,n}=\frac{C_{k,m,n}}{\bar{r}_{k,m,n}}+\beta\frac{C_{k,m,n}}{\bar{r}_{k,m}} \tag{14}$$

where $\bar{r}_{k,m,n}$ is the average rate of user k in the T time window, T is the time window of the exponential weighed average data rate function.

$$\bar{r}_{k,m}=\frac{1}{\|U_{R_m}\|}\sum_{k\in U_{R_m}} C_{k,m,n} \tag{15}$$

Equation (15) demonstrates that the average rate of all users in the service range of relay m, $\beta C_{k,m,n}/\bar{r}_{k,m}$ is largely determined by the channel conditions. The factor β is a constant the value of which will be analyzed in the following section. Obviously, the better the channel condition, the bigger the value of $C_{k,m,n}$ as well as the higher the priority of the users.

As for the 1st hop, a dynamic index factor $\alpha+C_{m,n}/\bar{r}_m$ is added to ensure system fairness in case when the channel condition fluctuates drastically. When the factor becomes greater than 1, BS is more likely to allocate sub-channels to users who have better link states. Considering the balance of fairness and throughput, we modify the priority formula into

$$PRI_{m,n}=\frac{C_{m,n}^{\left(\alpha+\frac{C_{m,n}}{\bar{r}_m}\right)}}{\bar{r}_{m,n}} \tag{16}$$

where $\bar{r}_{m,n}$ denotes the average rate of relay m in the time window T. The average rate of relay is determined by the 2nd hop [16]

$$\bar{r}_{m,n} = \frac{1}{\| U_{R_m} \|} \sum_{m \in U_{R_m}} \bar{r}_{k,m,n} \tag{17}$$

$$\bar{r}_m = \frac{1}{M} \sum_{m=1}^{M} C_{m,n} \tag{18}$$

Equation (18) represents the average theoretical maximal rate on sub-channel, and α is a constant.

Similarly, the priority of the direct user k is expressed as

$$PRI_{k,n} = \frac{C_{k,n}^{\left(\alpha + \frac{C_{k,n}}{\bar{r}_k}\right)}}{\bar{r}_{k,n}} \tag{19}$$

where $\bar{r}_{k,n}$ is the average rate of the direct user k in the time window T. The average rate of all direct users on sub-channel n can be represented by

$$\bar{r}_k = \frac{1}{\| U_D \|} \sum_{k \in U_D} C_{k,n} \tag{20}$$

Then the average data rate of $\bar{r}_{k,n}$ and $\bar{r}_{k,m,n}$ is [19]

$$\bar{r}(t) = (1 - 1/T) \cdot \bar{r}(t-1) + r(t)/T \tag{21}$$

where $\bar{r}(t-1)$ represents the average rate in the last schedule cycle time window, $r(t)$ is the instantaneous rate after this schedule. If one MS or RS is being allocated for a long time, the value of $\bar{r}(t)$ will increase, then its value of priority would be limited.

The formula [19] (22) is used to calculate the system fairness, in which R_k is the average rate of the k users of the entire system. The greater value of F_R, the better the system fairness is.

$$F_R = \left(\sum_{k=1}^{K} R_k \right) \Big/ \left(K \sum_{k=1}^{K} R^2{}_k \right) \tag{22}$$

A. E-THAPF ALGORITH

There are two major parts of E-THAPF for the two hops. In the first part sub-carriers are allocated to the user of the highest priority through RS. In the second part, BS allocates subcarriers to the direct user or RS of the highest priority.

Part one (2nd hop):

Step 1. Initialize parameters of relay link users: Search the user k in the User sets, which makes the values of $C_{k,m,n}$ and $r_{k,m,n}$ be zero.

Step 2. Find out the best sub-channel of every user through formula (23):

$$n_k = \arg\max_k (C_{k,m,n}) \tag{23}$$

Step 3. Calculate the priorities of every user on every channel according to formula (14). Find out the user k^* with the greatest priority as the schedule principle:

$$k^* = \arg\max_k \left(\frac{C_{k,m,n}}{\bar{r}_{k,m,n}} + \beta \frac{C_{k,m,n}}{\bar{r}_{k,m}} \right) \tag{24}$$

Further, allocate sub-channel n^* to user k^* followed by refreshing the set of subcarriers:

$$U_n = U_n - n^* \tag{25}$$

Step 4. Repeat Step 2 and Step 3 until all the sub-channels have been allocated.

Part two (1st hop):

Step 1. Find out the best sub-channel attaching direct users or relays by formula (26):

$$n^{*\prime} = \arg\max_k (C_{m,n}, C_{k,n}) \tag{26}$$

Step 2. Calculate priorities of direct users and relays on every sub-channels according to the formula (19) and (16). Based on the rule of scheduling:

$$k^{*\prime} = \arg\max_k \left\{ PRI_{m,n}, PRI_{k,n} \right\} \tag{27}$$

in which $k^{*\prime} \in U_R \cap U_D$, to obtain the relay m^* or direct user k^* who have the greatest priority, and allocate sub-channel $n^{*\prime}$ to it. Then, refresh the set of sub-carriers through formula (28):

$$U_{N\,s} = U_N - n^{*\prime} \tag{28}$$

Step 3. Repeat Step 1 and Step 2 until all the sub-carriers have been allocated.

Step 4. Balance the rates of two-hops.

In the algorithm E-THAPF, the α in the index factor of the 1st hop is constant which leads to drastic decreasing of fairness with the increasing of the number of users, however, the users number can't be constant in the real-life scenario. To match the need of realistic scenario, we propose the UND-THAPF algorithm, in which the value of α is determined by the number of users.

B. UND-THAPF ALGORITHM

The process of the 2nd hop is the same as that of E-THAPF. Thus, we just discuss the 1st hop here. The process is as follows.

Step 1. Find out the best sub-channel attaching direct users or relays by formula (29)

$$n^{*\prime} = \arg\max_k (C_{m,n}, C_{k,n}) \tag{29}$$

Step 2. Obtain the value α according to the number of users c:

$$\alpha = i - j\frac{C}{N} \quad (30)$$

i and j are 3 and 2.4 (the best value in simulating), N is the total number of sub-carriers.

Step 3. Calculate priorities of direct users and relays according to formula (19) and (16). Acquire the direct user k^* or relay m^* who have the greatest value of priority on basis of schedule rule:

$$k^{*\prime} = \arg\max_{k} \left\{ PR\mathrm{I}_{m,n}, PRI_{k,n} \right\} \quad (31)$$

in which $k^{*\prime} \in U_R \cup U_D$, then allocate sub-carrier $n^{*\prime}$ to it. Refresh the set of sub-carriers (28).

Step 4. Repeat Step 1 and Step 2 until all the sub-carries have been allocated.

Step 5. Balance the rates of two hops.

IV. Simulation Results

There are three major types of signal attenuation in two-hop cooperative relay system: Large scale fading, Shadow fading and Multipath fading. In this paper, the transmission between BS and RS is defined as line-of-sight transmission, and that between RS and MS is Non-line-of-sight transmission.

WINNER B5a is used as the line-of-sight model:

$$PL=36.5+23.5\log_{10}(d)+20\log_{10}(f/2.5)+X_\sigma \quad (32)$$
$$30\text{m}<d<8\text{km}$$

WINNER C2 is used as the none-line-of-sight model:

$$PL=38.4+35.0\log_{10}(d)+20\log_{10}(f/5)+X_\sigma \quad (33)$$
$$50\text{m}<d<5\text{km}$$

d is the distance between transmitting node and receiving node with unit m. f denotes the frequency of carrier with unit GHz. X_σ is logarithmic normally distributing in both line-of-sight and non-line-of-sight models, in which the variance range from 3.4 dB to 8 dB. Detailed simulation parameters and their values are presented in Table I.

TABLE I. Simulation Parameters for System Model

PARAMETER	VALUE
Number of users	10-80
Multipath taps	6
Center frequency	5 GHz
Cell radius	600 m
Sub-carrier capacity	128
Sub-carrier frequency	120 kHz
Noise PSD	–174 dBm
Maximum Doppler shift	20 Hz
Transmit power of BS	46 dBm
Transmit power of RS	38 dBm
Time window length	100
TTI	5 ms

Fig. 2 shows the comparison of spectral efficiency between the proposed algorithms (E-THAPF & UND-THAPF) and original THPF algorithm, in which the E-THAPF is divided into three kinds of sub-algorithms for the three values of α in formula [9]. It can be found out that the spectral efficiency of all three kinds of algorithms increase as a gradually gentle rate as the linear increase of number of users. As for algorithm E-THAPF, the modification combining max(C/I) with THPF contributes greatly to the improvement of spectral efficiency. Meanwhile, the modified priority formula, in which the value of α can be any number (here are 1, 2, 3), endows the system with the ability to change the throughput flexibly and intellectually.

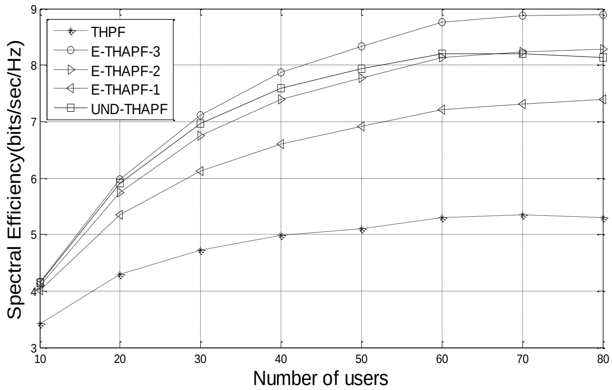

Fig. 2.System spectral efficiency vs. Number of users of two novel algorithms and original THPF algorithm

Fig. 3 illustrates that the greater value of α the lower of the system fairness. The simulation results validate that modifying α into adaptive changing its value depends on fluctuations of number of users contributes a lot to the stability of system fairness.

To demonstrate the predominance of the two proposed algorithms more intuitively, the comparison of spectral efficiency and fairness between E-THAPF, UND-THAPF and THPF as well as max(C/I) are shown in the Fig. 4 and Fig. 5. In E-THAPF algorithm, we adopt $\alpha=1$ which is able to achieve a better compromise between fairness and throughput.

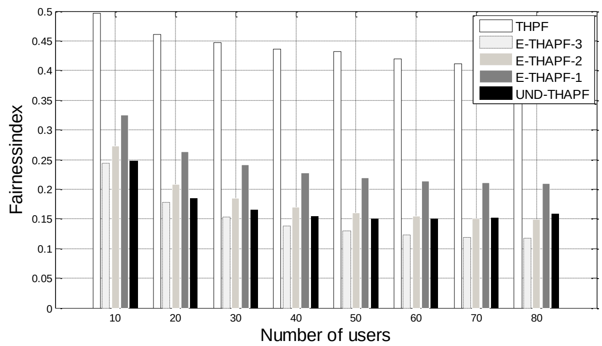

Fig. 3. System fairness vs. Number of users of two novel algorithms and original THPF algorithm

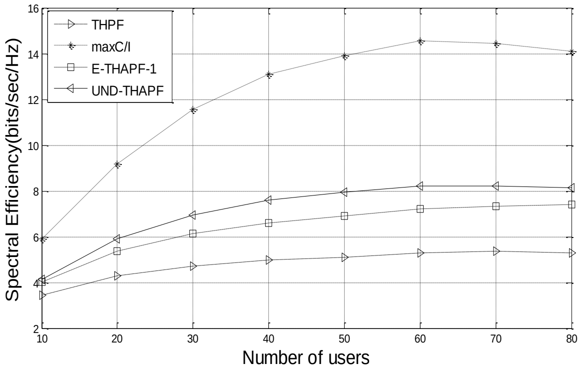

Fig. 4. System spectral efficiency vs. Number of users of two novel algorithms, THPF and max(C/I) algorithm

Fig. 3 and Fig. 4 show us that the system spectral efficiencies of two proposed algorithms are notably greater than original THPF. Obviously, as for spectral efficiency, max(C/I) has the greatest value, notwithstanding, its system fairness is absolutely unacceptable according to Fig. 5. Speaking of the two novel algorithms, E-THAPF has a higher value of fairness than that of UND-THAPF, but UND-THAPF can achieve a much greater value of spectral efficiency and endow the system more intellect and plasticity making it be able to meet the demands of realistic scenarios.

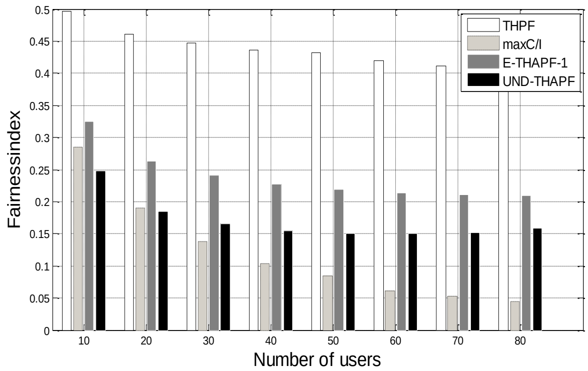

Fig. 5. System fairness vs. Number of users of two novel algorithms and original THPF algorithm

V. Conclusions

The major object of this paper is to notably improve the spectral efficiency of THPF algorithm, and modify the priority formula to endow the two-hop relay system with adaptability, as well as, make it more intellectual and plastic. In the 2nd hop, E-THAPF and UND-THAPF both combine PF algorithm with max(C/I) algorithm to improve the spectral efficiency dramatically. In the 1st hop, we introduce a dynamic factor to the priority formula giving a higher priority to users and relays who occupying better quality of data link. Simulation results show that the spectral efficiency of both two proposed algorithms is much greater than that of THPF. Being able to optimize the scheduling strategy with the change of the number of users, UND-THAPF is even better to meet the demands of realistic scenarios. Both E-THAPF and UND-THAPF can achieve perfect tradeoffs between system throughput and fairness.

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