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Greedy Algorithm: Exploring Potential of Link Adaptation Technique in Wideband Wireless Communication Systems

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1. Introduction

As the development of multimedia communication and instantaneous high data rate communication, great challenge appears for reliable and effective transmission, especially in wireless communication systems. Due to the fact that the frequency resources are decreasing, frequency efficiency obtains the most attention in the area, which motivates the research on link adaptation technique. Link adaptation can adjusts the transmission parameters according to the changing environments [1-2]. The adjustable link parameters includes the transmit power, the modulation style, etc. All these parameters are adjusted to achieve:

1. Satisfactory Quality of Service (QoS). This helps guarantee the reliable transmission. It requires that the bit error rate (BER) should be lower than a target.
2. Extra high frequency efficiency. This brings high data rate. It can be described with throughput (in bit/s/Hz).

In conventional systems with link adaptation, water-filling algorithm is adopted to obtain the average optimization for both QoS and frequency efficiency [3]. But the transmit power may vary a lot on different time, which brings high requirement for the implementation and causes such algorithm not applicable in practical systems.

Recently, wideband transmission with orthogonal frequency division multiplexing (OFDM) technique is being widely accepted, which divides the frequency band into small sub-carriers [4]. Hence, link adaptation for such system relates to adaptation in both time and frequency domain. The optimization problem becomes how to adjust the transmit power and modulation style for all sub-carriers, so as to achieve the maximum throughput, subject to the constraint of instantaneous transmit power and BER requirement. The transmit power and modulation style on every sub-carrier may impact the overall performance, which brings much complexity for the problem [5].

In order to provide a good solution, we resort to Greedy algorithm [6]. The main idea for the algorithm is to achieve global optimization with local optimization. It consists of many allocation courses (adjusting modulation style equals to bit allocation). In each course, the algorithm reasonably allocates the least power to support reliable transmission for one additional bit. Such allocation course is terminated when transmit power is allocated. After allocation, the power on each sub-carrier can match the modulation style to provide reliable

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transmission, the total transmit power is not higher than the constraint, and the throughput can be maximized with reasonable allocation.

We investigate the performance of Greedy algorithm with aid of Matlab. With the simulation result, we can observe that:

1. The transmit power is constraint as required with the algorithm;
2. The algorithm can satisfy the BER requirement;
3. It brings great improvement for the throughput.

Hence we conclude that Greedy Algorithm can bring satisfactory QoS and high frequency efficiency. In order to interpret it in great detail, we will gradually exhibit the potential of Greedy algorithm for link adaptation. The chapter will conclude the following sections:

Section 1: As an introduction, this section describes the problem of link adaptation in wireless communication systems, especially in OFDM systems.

Section 2: As the basis of the following sections, Section 2 gives out the great detail for the theory of link adaptation technique, and presents the problem of the technique in OFDM systems.

Section 3: Greedy Algorithm is employed to solve the problem of Section 2 for normal OFDM systems. And the theory of Greedy Algorithm is provided in the section. We provide comprehensive simulation results in the section to prove the algorithm can well solve the problem.

Section 4: Greedy Algorithm is further applied in a multi-user OFDM system, so as to bring additional great fairness among the transmissions for all users. Simulation results are provided for analysis.

Section 5: OFDM relaying system is considered. And we adopt Greedy Algorithm to bring the optimal allocation for transmit power and bits in all nodes in the system, so as to solve the more complex problem for the multi-hop transmission. We also present the simulation result for the section.

Section 6: As a conclusion, we summarize the benefit from Greedy Algorithm to link adaptation in wireless communication systems. Significant research topics and future work are presented.

2. Link Adaptation (LA) in OFDM systems

In OFDM systems, system bandwidth is divided into many fractions, named sub-carriers. Information is transmitted simultaneously from all these sub-carriers, and because different sub-carriers occupy different frequency, the information can be recovered in the receiver. The block diagram for such systems is shown in Fig. 1.

As far as multiple streams on all these sub-carriers are concerned, the problem came out about how to allocate the transmit power and bits on all the sub-carriers, so as to bring highest throughput with constraint of QoS, or BER requirement. Due to the fact that there exists channel fading and that the impact with different sub-carrier varies because of the multi-path fading, the allocation should be different for different sub-carriers. The system can be described with the following equation.

$$R_n = H_n \sqrt{P_n} S_n + N_n \tag{1}$$

where S_n denotes the modulated signal on the n-th sub-carrier, which carries b_n bits with normalized power; P_n denotes the transmit power for the sub-carrier; H_n denotes the channel fading for the sub-carrier; N_n denotes the additive white Gaussian noise (AWGN) with variance of σ^2; and R_n denotes the received signal on the sub-carrier.

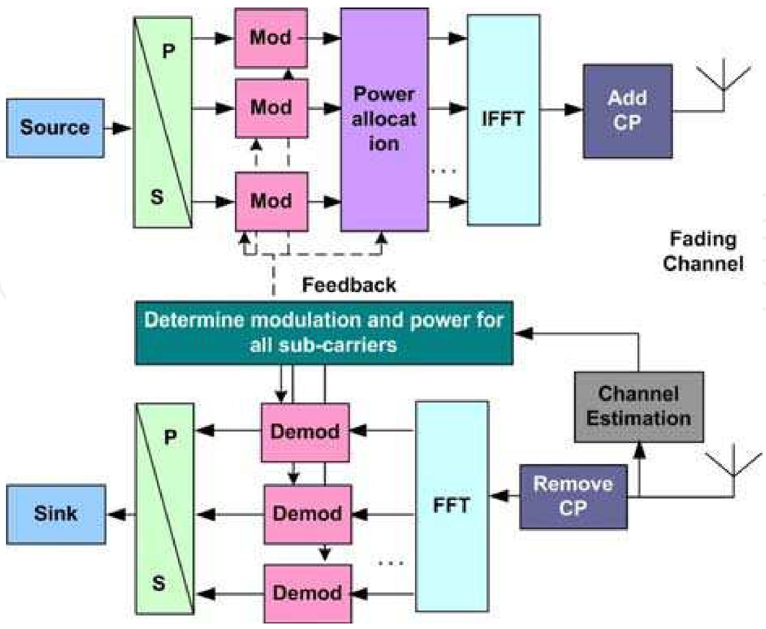

Fig. 1. Block diagram for OFDM with link adaptation

In that case, the received signal-to-noise ratio (SNR) can be calculated as

$$SNR_n = |H_n|^2 P_n / \sigma^2 \tag{2}$$

In order to satisfy the requirement of BER, the received signal should satisfy that SNR_n is larger than a certain threshold, or T_v for the v-th modulation. In the chapter, we assume that the target BER is 10^{-3}. Hence, the constraint of BER can be described as

$$SNR_n > T_v \tag{3}$$

As for the transmit power, it is required that the total transmit power should be constraint to a certain value P. That is to say

$$\frac{1}{N}\sum_{n=1}^{N} P_n \le P \tag{4}$$

As a conclusion, the optimization problem is how to determine b_n and P_n to maximize throughput, i.e.

$$\arg\max_{b_n, P_n} \sum_{n=1}^{N} b_n \tag{5}$$

subject to equations (3) and (4).

3. Application of greedy algorithm in OFDM systems

The Greedy algorithm can be applied in solving the problem of (5). For the research in the section, we assume the parameters for the candidate modulation as shown in Table 1, where the thresholds are obtained through simulation.

In order to obtain the maximum throughput across all these N sub-carriers, Greedy algorithm can be taken advantage of. The problem can be seen as a problem with global optimization, and Greedy algorithm can help achieve the global optimization with a lot of local optimization. The theory of Greedy algorithm can be understood from an example shown in Fig. 2.

v	Modulation	Number of bits $b(v)$	$T(v)$
0	No transmission	0	0
1	QPSK	2	9.78dB
2	16QAM	4	16.52dB
3	64QAM	6	22.52dB

Table 1. Candidate modulation and parameters

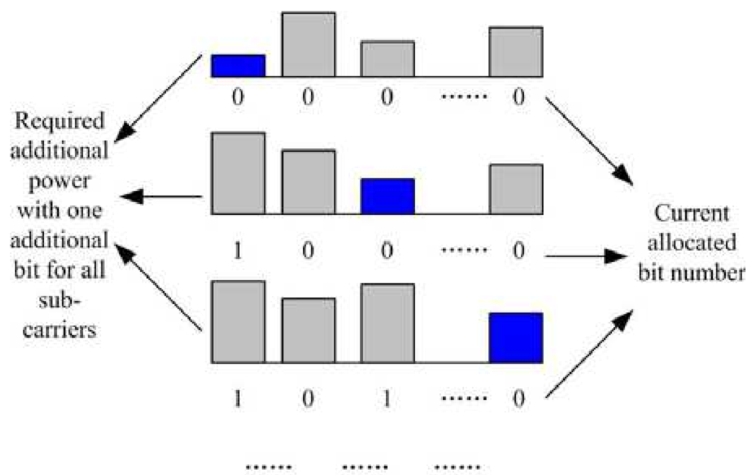

Fig. 2. Theory of the application of Greedy algorithm in OFDM systems

In the initialization step, all the sub-carrier is allocated with 0 bit. And the required additional power with one additional bit for all sub-carriers can be calculated. The local optimization is to allocate one bit to the sub-carrier with the least required power. Hence, as shown in Fig. 2, the 1st sub-carrier is allocated with 1 bit. And the required additional power with one additional bit for it is updated. In the second allocation, the 3rd sub-carrier obtains the least required additional power. Hence it is allocated with 1 bit. The processes continue until all sub-carriers are allocated with the maximum bits or the power is not enough to support one further bit. When the processes end, the global optimization is achieved and the current allocation is the optimal allocation with the maximum throughput. Due to the candidate modulations in Table 1, the incremental bit number is 2 in the research.

Fig. 3 shows the BER performance with Greedy algorithm, and the performance with fixed modulation of QPSK, 16QAM and 64QAM is shown for comparison, where *SNR* in the x-axis denotes the average SNR in the link. From the figure, the fixed modulation schemes have bad performance. Only when *SNR* is as high as 30dB can the BER achieve 10^{-3}. When Greedy algorithm is adopted, the BER performance can achieve the target BER with all *SNR* cases. Hence, it can be concluded that Greedy algorithm can satisfy the requirement of BER very well. Fig. 4 gives out the throughput performance with Greedy algorithm. As *SNR* rises larger, the throughput can achieve higher, with the maximum of 6 bits/symbol which denotes that all sub-carriers adopt 64QAM in this case. According to Greedy algorithm, the throughput is maximized.

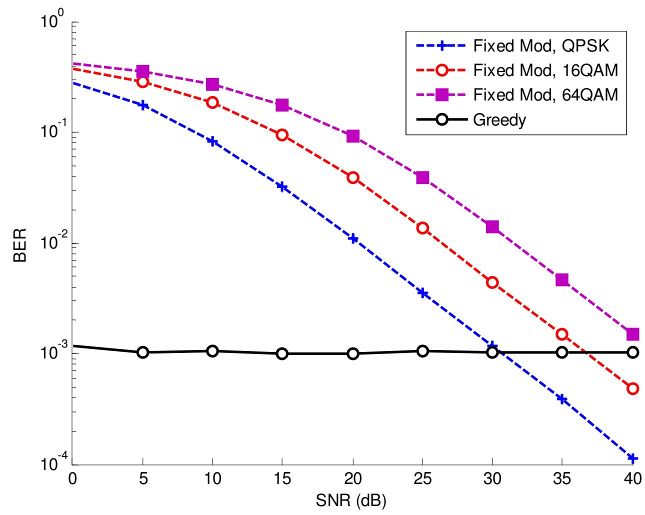

Fig. 3. BER performance with fixed modulation and Greedy algorithm

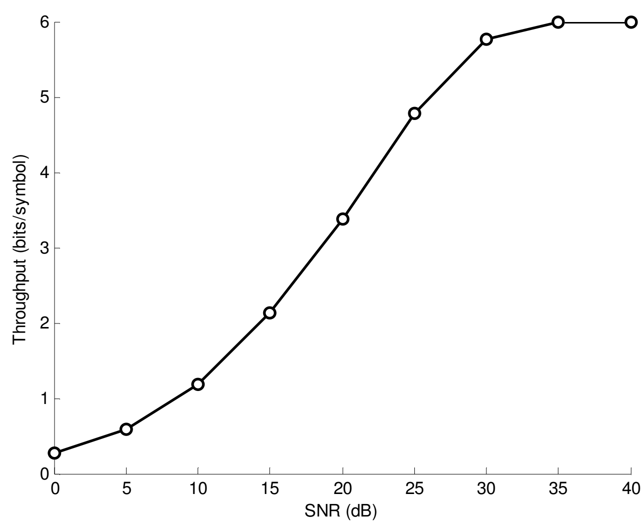

Fig. 4. Throughput performance with Greedy algorithm

4. Application of greedy algorithm in multi-user OFDM systems

When multiple users are concerned, the problem becomes more complex. The block diagram for a typical multi-user adaptive OFDM system is shown in Fig. 5. Downlink transmission is taken for research in the section. It is assumed that channel state information (CSI) regarding to all users is available for the base station (BS). In the transmitter on BS, resource allocation is carried out according to CSIs regarding to all the users, so as to determine the allocated sub-carriers for each user, as well as the transmit power for sub-carriers and loaded bits on them. Different loaded bits correspond to different modulation. All users' bits are modulated accordingly, after which inverse discrete Fourier transform (IDFT) is carried out and cyclic prefix (CP) is added to form OFDM symbols to transmit. In the receiver on each mobile terminal (MT), symbols in frequency domain are obtained after removing CP and DFT. Relevant demodulation is carried out for all sub-carriers, and source bits for each user are recovered finally after demodulation.

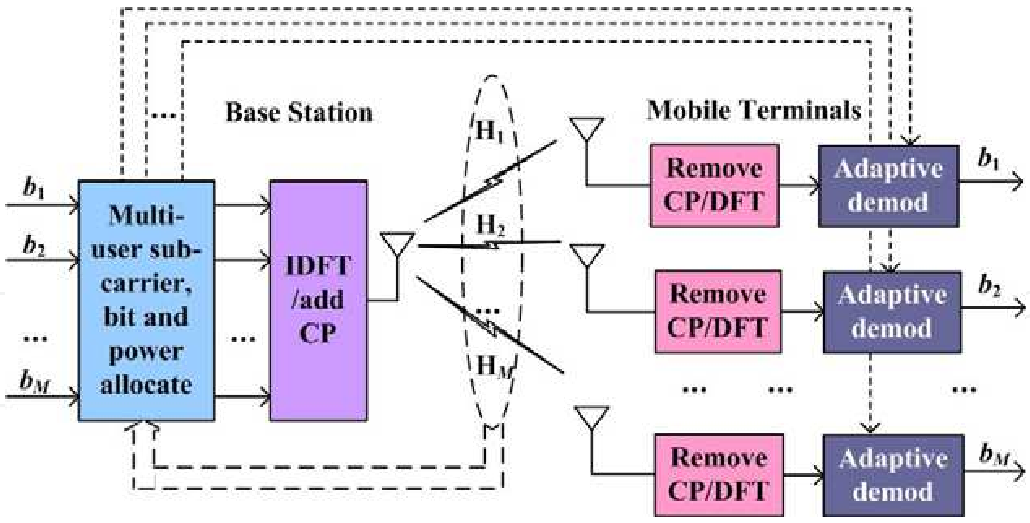

Fig. 5. A typical multi-user adaptive OFDM downlink

Considering a multi-user adaptive OFDM system with M users and N sub-carriers, the multi-user adaptive system model can be described as:

$$R_{m,n} = H_{m,n}\sqrt{P_{m,n}}S_{m,n} + N_{m,n} \tag{6}$$

where $S_{m,n}$ denotes power-normalized modulated symbol on the n-th sub-carrier for the m-th user; it contains $b_{m,n}$ source bits. In order to eliminate interference among the users, each sub-carrier can be allocated to only one user in the system, i.e. $if\ b_{m,n} > 0,\ then\ b_{m',n} = 0(\forall m' \neq m)$. $P_{m,n}$ denotes allocated power for $S_{m,n}$. $H_{m,n}$ denotes channel transfer function for $S_{m,n}$. $P_{m,n}$ and $b_{m,n}$ is determined according to $H_{m,n}$ by the "multi-user sub-carrier, bit and power allocation" block as shown in Fig. 5. $N_{m,n}$ denotes the additive white Gaussian noise (AWGN) with variance σ^2. $R_{m,n}$ is the received symbol in the receiver on the m-th MT.

4.1 Multi-user resource allocation problem

From (6), the received SNR can be calculated as

$$\gamma_{m,n} = |H_{m,n}|^2 P_{m,n} / \sigma^2 \tag{7}$$

As for conventional multi-user OFDM systems, each user is allocated with N/M sub-carriers with constant power fixedly. The throughput is very low since it is very likely that many users are allocated with sub-carriers with poor CSI. And the fairness performance is also poor. Adaptive resource allocation can take advantage of CSIs for all users to improve system performance through reasonable allocation of sub-carriers, bits and power. The multi-user adaptive problem for an OFDM system can be described as maximizing overall throughput while satisfying requirement of fairness, subject to power restriction and QoS requirement. Consequently, the problem can be described in the following way.

$$\max \sum_{n=1}^{N}\sum_{m=1}^{M} b(v_{m,n}) \tag{8}$$

subject to

$$\max_{m \neq m'} \left| \sum_{n=1}^{N} [b(v_{m,n}) - b(v_{m',n})] \right| \leq b_0 \qquad \text{(a)}$$
$$P_{m,n} \geq T(v_{m,n})\sigma^2 / |H_{m,n}|^2 \qquad \text{(b)} \qquad (9)$$
$$\sum_{m=1}^{M}\sum_{n=1}^{N} P_{m,n} \leq P_T \qquad \text{(c)}$$

where $v_{m,n}$ denotes the index of a candidate modulation ($v_{m,n}$ =1, 2, …, V); P_T denotes the total transmit power; $T(v_{m,n})$ indicates the least required SNR when adopting $v_{m,n}$-th modulation (one modulated symbol containing $b(v_{m,n})$ bits) to ensure QoS guaranteeing (BER lower than a certain value), i.e. Pm,n is determined to satisfy $\gamma_{m,n} \geq T(v_{m,n})$, so as to transmit $b(v_{m,n})$ bits with the target BER requirement; b_0 is the upper limit for maximum difference of allocated bits numbers among all users. Accordingly, (9a) is set to guarantee fairness requirement among all users, (9b) is used to satisfy requirement of QoS, and (9c) is to ensure the transmit power restriction.
In this section, 4 candidate modulations in Table 1 are considered. b_0 is set to be 0. And V is 4. BER performance versus SNR of received symbol can be calculated through

$$\varepsilon^b(\gamma) = 2\left(1 - 1/\sqrt{2^b}\right) Q\left(\sqrt{3/(2^b - 1)\gamma}\right) \qquad (10)$$

where $Q(x) = 1/\sqrt{2\pi}\int_x^{\infty} e^{-u^2/2}du$, and b=2, 4, 6 correspond to QPSK, 16QAM and 64QAM, respectively. Parameters for the candidate modulations and least required SNR for BER lower than 10^{-3} are summarized in Table 1.

4.2 Multi-user adaptive resource allocation methods

The optimal joint problem of sub-carrier, bit and power allocation is a NP-hard combinatorial problem. It is quite difficult to determine how many and which sub-carriers should be assigned to every user subject to many restrictions as shown in (9). Some existing typical methods are introduced in [7-11]. They perform well in some aspects, but for services with tight fairness requirement, these solutions cannot provide nice performance.

A. Existing methods

According to [7-11], there have been many methods to allocate resources including sub-carriers, bits and power to multiple users. The fixed sub-carrier allocation method allocates the same number of sub-carriers to each user fixedly, and then adopts the optimal Greedy algorithm [6] to carry out bit-loading and power allocation on all sub-carriers [9]. This merit of the method is quite simple, and fairness can be guaranteed in a certain degree since each user is allocated with the same number of sub-carriers. But since it is very likely that many users are allocated with sub-carriers with poor CSI, the throughput is low; and because CSIs of different users vary much, fairness performance is also poor.
Typically, [11] provides another solution. In each allocation, a user is assigned with one sub-carrier with the best CSI from the remaining un-allocated sub-carriers. For allocations with odd indices, the order to allocate sub-carriers is from the 1st user to the M-th user. For

allocations with even indices, the order is from the M-th user to the 1st user. Allocation continues until all sub-carriers are assigned. The optimal Greedy algorithm is then adopted to accomplish bit-loading and power allocation. The ordered allocation method avoids that some user's sub-carriers have much better CSI than other users, and fairness can be improved much over the fixed method.

The fixed allocation method and ordered allocation method both allocate resources in two steps, and fairness is fine in some degree by allocation equal number of sub-carriers to each user. But because CSI of different users may vary greatly, allocating the same number of sub-carriers to all users may not provide enough fairness for some services with tight fairness requirement. Therefore, a multi-user sub-carrier, bit and power allocation method is introduced in the following, which can bring to much better fairness than the existing methods, while achieving high throughput and satisfying QoS requirement.

B. Proposed method

In the proposed method, sub-carriers are allocated equally to all users firstly as initialization. This step realizes coarse sub-carrier allocation. Second, bits and power are loaded on the sub-carriers following the optimal Greedy algorithm for all users. Coarse resource allocation is fulfilled in the two steps, and they can benefit much for the overall throughput. In order to improve fairness as required, the next step is added. In the 3rd step, sub-carriers, bits and power are adjusted among all users. This step can be seen as fine adjustment for the resources. The three steps can be described as follows.

1. Coarse sub-carrier allocation

This step is to allocate sub-carriers to all users with high throughput and coarse fairness among all users. The numbers of allocated sub-carriers are the same for all users. In every allocation, if the CSI relating the m-th user and the n-th sub-carrier is the best, the n-th sub-carrier will be allocated to the m-th user. The allocation for one user will be terminated when the user has been allocated with N/M sub-carriers. We make the assumptions: $\Theta=\Theta\backslash\{n\}$ denotes removing the n-th sub-carrier from the set Θ, and ϕ denotes the null set; $c(n)$ denotes the index of user who is allocated with the n-th sub-carrier; N_m denotes the number of allocated sub-carriers for the m-th user. The processes for this step are as follows.

$$\Theta = \{1,2,\ldots,N\}; \Psi = \{1,2,\ldots,M\}$$

$$c(n) = 0, \forall n \in \Theta; N_m = 0, \forall m \in \Psi$$

while $\Psi \neq \phi$

$\{ \quad [m,n] = \arg\max_{m\in\Psi, n\in\Theta} |H_{m,n}|$

$\quad c(n) = m$

$\quad \Theta = \Theta \backslash \{n\}$

$\quad N_m = N_m + 1$

$\quad$ **if** $N_m = N/M$, **then** $\Psi = \Psi \backslash \{m\}$

$\}$

2. Coarse bit loading and power allocation

The optimal Greedy algorithm is adopted in this step to realize bit loading and power allocation on all the sub-carriers. We assume that: v_n denotes the index of the modulation adopted on the n-th sub-carrier; P_0 denotes the remaining power; P_n indicates power allocated on the n-th sub-carrier, and W_n denotes the required additional power in order to adopt a next higher order modulation. Then the step can be described as follows.

$$\Theta = \{1, 2, ..., N\}; \Psi = \{1, 2, ..., M\}$$
$$\underline{H}_n = H_{c(n),n}, \forall n \in \Theta$$
$$v_m = 0, \forall m \in \Psi; P_n = 0, \forall n \in \Theta$$
$$P_0 = P_T$$
$$W_n = T(1)\sigma^2 / |\underline{H}_n|^2$$
$$\textbf{while } P_0 \geq \min_{n\in\Theta} W_n$$
$$\{ \quad n = \arg\min_{n\in\Theta} W_n$$
$$P_0 = P_0 - W_n$$
$$P_n = P_n + W_n$$
$$v_n = v_n + 1$$
$$\textbf{if } v_n = V, \textbf{then } W_n = \infty$$
$$\textbf{else } W_n = [T(v_n + 1) - T(v_n)]\sigma^2 / |\underline{H}_n|^2$$
$$\}$$

3. Fine sub-carriers, bits and power allocation

After Step 2, the numbers of allocated sub-carriers for all users are the same, and the most bits are loaded to the sub-carriers through Greedy algorithm. However, due to the fact that CSI for all users varies much, the numbers of loaded bits may vary much for all users. This causes big difference in allocated bits for all users. Hence, Step 3 is used to make modification to the allocated sub-carriers and bits: reallocate sub-carriers of the user with the most number of loaded bits to the user with the least number of loaded bits. In each iteration, we assume the U^{max}-th and the U^{min}-th user obtain the most and the least number of loaded bits for current allocation scheme, respectively. This step reallocates one sub-carrier of the U^{max} -th user to the U^{min} -th user to balance the allocated bits among the users, so as to guarantee the fairness; and in order not to bring down the throughput greatly, the sub-carrier with the worst CSI for the U^{max} -th user is reallocated to the U^{min} -th user. After the re-allocation of sub-carriers, Greedy algorithm is adopted again for bit-loading on the new sub-carrier allocation scheme. The iterations continue until the difference among the loaded bits of all users is low enough. Since this step reallocates the sub-carriers for balance among the loaded bits for all users, the overall throughput may be reduced, but fairness can be guaranteed better. We assume that β_m denotes the loaded bits for the m-th user; S^{max} and S^{min} denotes sub-carriers set which contains sub-carriers allocated to the U^{max} -th user and U^{min} -th user, respectively; S0 denotes the sub-carrier with worst CSI for the U^{max} -th user. Step 3 can be realized as follows.

$$\beta_m = \sum_{\hat{n}\in\{n \mid c(n)=m\}} b(v_{\hat{n}});$$

$$U^{\max} = \arg\max_m(\beta_m); U^{\min} = \arg\min_m(\beta_m)$$

while $\beta_{U^{\max}} - \beta_{U^{\min}} > b_0$

$\{ \quad S^{\max} = \{n \mid c(n) = U^{\max}\}, S^{\min} = \{n \mid c(n) = U^{\min}\}$

$\quad S_0 = \arg\min_{n\in S^{\max}}\{\mid H_{U^{\max},n} \mid\}$

$\quad c(S_0) = U^{\min}$

$\quad \underline{\Theta} = S_0 \bigcup S^{\min}$

$\quad P_0 = P_0 + \sum_{n'\in\underline{\Theta}} P_{n'};\ P_{n'} = 0$

$\quad \underline{H}_{n'} = H_{U^{\min},n'};\ W_{n'} = T(1)\sigma^2 / \mid \underline{H}_{n'} \mid^2, v_{n'} = 0, \quad \forall n' \in \underline{\Theta}$

$\quad$ **while** $P_0 \geq \min_{n'\in\underline{\Theta}} W_{n'}$

$\quad \{ \quad n' = \arg\min_{n'\in\underline{\Theta}} W_{n'}$

$\quad\quad P_0 = P_0 - W_{n'}$

$\quad\quad P_{n'} = P_{n'} + W_{n'}$

$\quad\quad v_{n'} = v_{n'} + 1$

$\quad\quad$ **if** $v_{n'} = V$, **then** $W_{n'} = \infty$

$\quad\quad$ **else** $W_{n'} = [T(v_{n'}+1) - T(v_{n'})]\sigma^2 / \mid \underline{H}_{n'} \mid^2 \}$

$\quad \beta_m = \sum_{\hat{n}\in\{n \mid c(n)=m\}} b(v_{\hat{n}});$

$\quad U^{\max} = \arg\max_m(\beta_m); U^{\min} = \arg\min_m(\beta_m)$

$\}$

4.3 Simulation results

In order to give comprehensive evaluation to the proposed method, simulation is carried out and analyzed in the section. The adopted channel model is a typical urban (TU) multi-path channel composed of 6 taps with the maximum time delay of 5μs [12] and the maximum moving velocity is 5kmph. The carrier frequency is 2.5GHz. The system bandwidth is 10MHz, and 840 sub-carriers are available, i.e. N=840. Sub-carrier spacing is 11.16 kHz, and CP is set to be 5.6μs to eliminate inter-symbol interference. Candidate modulation schemes in Table 1 are employed for adaptive modulation (bit loading). The proposed method is compared with the fixed allocation method from [9] and ordered allocation method from [11]. And performance for BER, throughput and fairness is provided.

A. BER performance

BER performance reflects the ability to satisfy QoS requirement. As mentioned above, target BER of 10^{-3} is investigated in the section. So it is required that the resource allocation methods should bring BER lower than 10^{-3}. BER performance with different methods is shown in Fig. 6. Cases for different user number (M= 2, 8, 20) are exhibited. It can be observed that BER is just lower than 10^{-3} for systems with all the resource allocation methods and for different M. Hence, all the methods, including the proposed method, can guarantee QoS requirement for such kind of service.

A. Overall throughput

In order to show the transmission ability of these methods, overall throughput is investigated as shown in Fig. 7. Here the overall throughput is defined as the total transmittable bits per symbol for the system, and can be calculated through

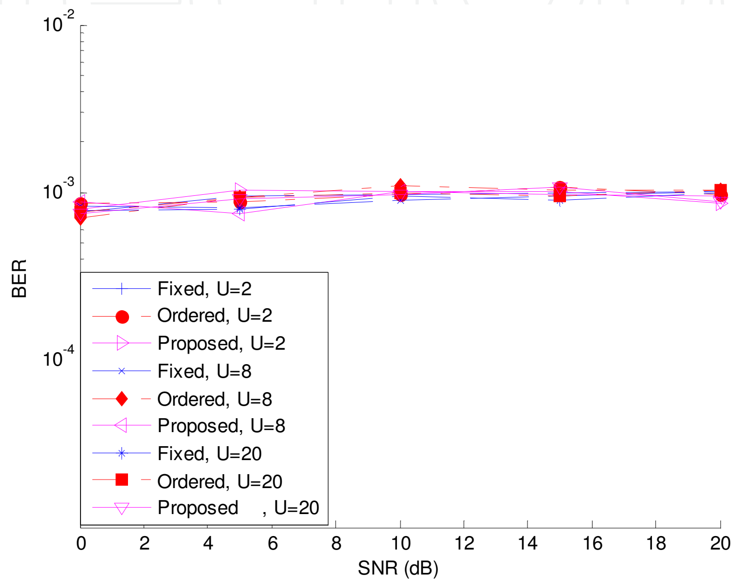

Fig. 6. BER v. s. *SNR* for systems with different methods

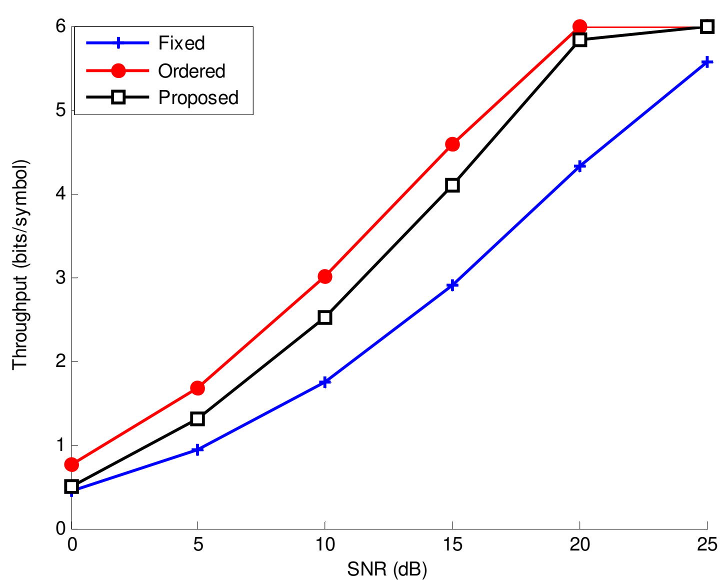

Fig. 7. Overall throughput v. s. *SNR* for *M*=8

$$\beta = 1/N \sum_{n=1}^{N} b(v_n)(1-\varepsilon) \tag{11}$$

where ε denotes BER. Performance with fixed method, ordered method and the proposed method when M=8 in the section is given out. As can be seen from Fig. 7, performances for the ordered method can obtain the highest overall throughput among all the methods, and throughput for the fixed sub-carrier allocation method is the worst. When SNR is low, the proposed method obtains lower throughput than that with the ordered method, but larger than the fixed method. When SNR=10dB, it obtains 0.8bits/symbol gain over the fixed method, about 46% improvement. When SNR is high enough, the proposed method can obtain the same overall throughput as the ordered method. When SNR=20dB, it obtains 1.3bits/symbol gain over the fixed method, and only 0.15bits/symbol lower than the ordered method. The throughput is lower as the cost for excellent fairness, as will be introduced below.

B. Fairness

Though there is little difference in the overall throughput for the proposed method compared with the ordered method, the fairness can be guaranteed very well.

Firstly, we investigate the allocated bit for all users. Fig. 8 shows an example to the allocated bits of all users for different methods when M=8 and SNR=25dB. It can be seen that, when the fixed method is adopted, allocated bits number varies much for all the 8 users, the difference between the bits number of the users with most allocated bits and the least allocated bits is as high as 34bits; when the ordered method is adopted, fairness is improved much, and the maximum difference among the allocated bits of all the users is 3 bits. When the proposed method is adopted, all users are allocated with the same number of bits; what's more, the number of bits allocated to the users are almost the same as the maximal value with the ordered method, and much larger than that with the fixed method.

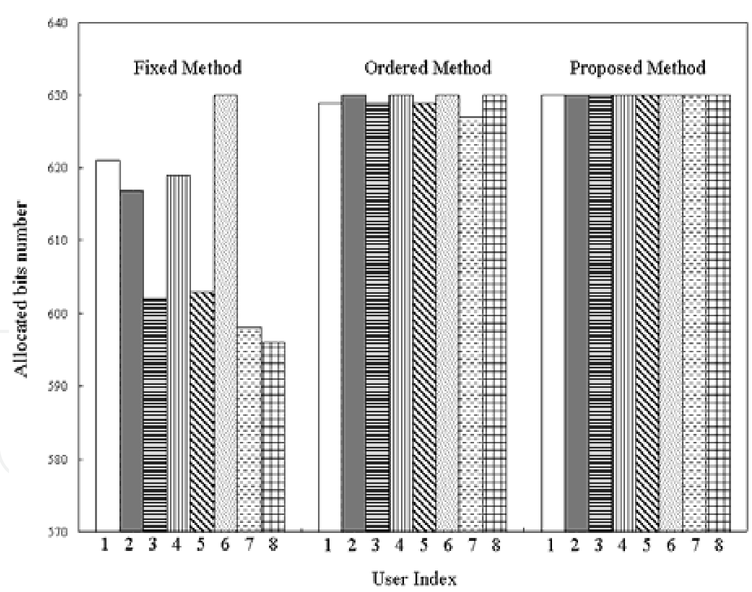

Fig. 8. Allocated bits number for all users with difference methods when M=8 and SNR=25dB

Since Fig. 8 is only an example, further work was carried out to prove the advantage of the proposed method. Since there exist channel fading and AWGN for all links, the rightly demodulated bits (or transmittable bits) should be concerned most to evaluate the fairness performance. Therefore, we take the transmittable bits variance (TBV) among all users to evaluate fairness performance of all the methods. TBV can be calculated through

$$TBV = E[|\beta_m \varepsilon_m - E(\beta_m \varepsilon_m)|^2] \tag{12}$$

where $E[\cdot]$ denotes expectation operation; and ε_m denotes BER for the m-th user. Hence, if TBV is large, the transmittable bits numbers for all the users vary much, and such method cannot bring good fairness to the system. Low TBV denotes that the numbers for transmittable bits for all the users are quite near, which means that such method is a fair resource allocation solution.

Transmittable bits variances for the 3 methods versus user number for *SNR*=15dB are shown in Fig. 9. As the number of users increases, the average allocated bits number decreases, so TBV is reduced. For the fixed method, the transmittable bit variance is quite high, which can be explained by the fact that channel fading for different users varies greatly. As for the ordered method, since fairness is guaranteed through allocating the same number of sub-carriers according to CSI of all users, TBV is lower than the fixed method. But the variance is still high, when there are 4 users in the system, TBV can reach more than 10000. The proposed method can perform excellent in fairness. Fig. 9 indicates that it obtains much lower TBV than the fixed method and the ordered method. When the number of users is 4, TBV can be further reduced by about 80% compared to the ordered method.

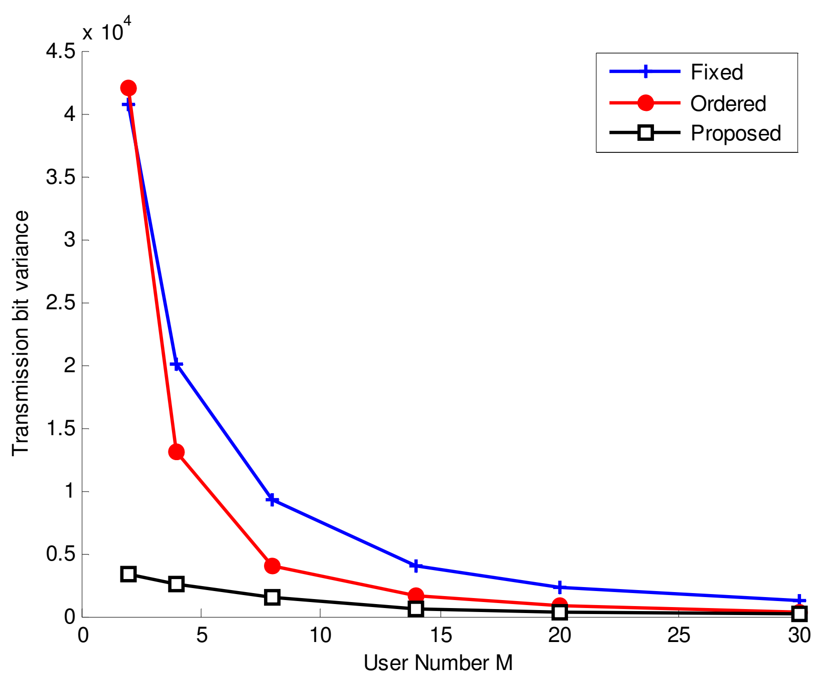

Fig. 9. Transmitted bits variance among users v. s. *M* for *SNR*=15dB

From the simulation results and analysis we can see that, the proposed method takes advantage of Greedy algorithm for many times, and can obtain nice BER performance, so it can provide required QoS guaranteeing. It can bring much larger throughput (more than 40%) than the fixed method. It performs a little worse than the ordered method, but when fairness is concerned, the cost is worthy. The proposed method with application of Greedy algorithm for many times can bring excellent fairness performance over the other methods. It is recommended to be adopted for services with tight fairness requirement among all users.

5. Application of greedy algorithm in OFDM relaying systems

The Greedy algorithm can be also adopted in OFDM relaying systems. In this section, we carry out research into the adaptive bit and power allocation technique in relaying system. Since there are several modes for relaying system, we take amplify-and-forward (AF) mode for example.

5.1 AF-OFDM relaying system model

AF-OFDM relaying system model is shown in Fig. 10, where a two-hop system is considered for its implementation advantages. In the first hop, source bits are modulated, and are allocated with a certain power at source station (SS). Then the modulated signals construct OFDM symbols, which are transmitted to relay station (RS). At RS, power amplification is carried out after signals on all sub-carriers are obtained. In the second hop, these signals are transmitted to the destination station (DS). After demodulation to the received signals on all the sub-carriers, source bits are recovered finally. During both hops, signals experience channel fading and AWGN. Channel transfer functions for the two hops are independent with each other since the two hops happen between different transmitters and receivers on different time slots.

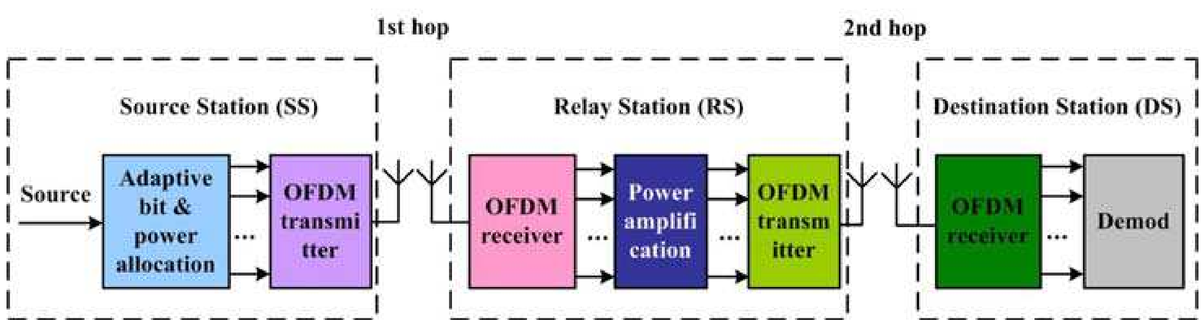

Fig. 10. AF-OFDM relaying system model

We first introduce the basic model. Assume there are K sub-carriers in the OFDM system, and the channel transfer function of the k-th sub-carrier in the i-th hop is $H_{i,k}$. Then the first hop can be expressed as:

$$R_k = H_{1,k}\sqrt{P_{1,k}}S_k + n_{1,k} \tag{13}$$

where S_k and $P_{1,k}$ denote the modulated signal and allocated power on the k-th sub-carrier, respectively; $E[|S_k|^2]=1$; $n_{1,k}$ denotes AWGN with variance of σ_1^2; R_k denotes the received signal at RS.

Amplification is carried out at RS. Assume the amplification factor is ρ_k. Therefore, the average transmit power of the k-th sub-carrier at RS on the second hop is $P_{2,k} = |\rho_k R_k|^2$. Hence, ρ_k can be calculated as

$$\rho_k = \sqrt{P_{2,k}/|R_k|^2} = \sqrt{P_{2,k}/[|H_{1,k}|^2 P_{1,k} + \sigma_1^2]} \tag{14}$$

The second hop can be expressed as:

$$D_k = H_{2,k}\rho_k R_k + n_{2,k} = H_{1,k}H_{2,k}\rho_k\sqrt{P_{1,k}}S_k + H_{2,k}\rho_k n_{1,k} + n_{2,k} \tag{15}$$

where D_k denotes the received signal on the k-th sub-carrier at DS, and $n_{2,k}$ denotes AWGN with variance of σ_2^2. In the section, we consider $\sigma_1^2=\sigma_2^2=\sigma^2$. From (15) we can obtain the SNR of D_k as follows:

$$\gamma_k = [|H_{1,k}H_{2,k}|^2 \rho_k{}^2 P_{1,k}]/[|H_{2,k}|^2 \rho_k{}^2 \sigma_1^2 + \sigma_2^2] \tag{16}$$

We take adaptive bit allocation into account, i.e. modulation on all sub-carriers can be adjusted according to the channel condition. We assume that L candidate modulations can be selected, and every signal with the l-th (l=1, 2, …, L) modulation is loaded with $b(l)$ bits. The candidate modulations in the research and their throughputs are shown in Table 2. We assume that the k-th sub-carrier adopts the l_k-th modulation. Hence, the adaptive bit and power allocation (ABPA) problem in a two-hop AF-OFDM relaying system is described as how to allocate bits and power in the transmission (i.e. l_k, $P_{1,k}$ and $P_{2,k}$), so as to maximize system throughput subject to BER requirement and power constraint. In the section, we assume the target BER (BER_{tgt}) to be 10^{-3}. Hence γ_k should be higher than a certain threshold so as to achieve BER_{tgt}. We assume the threshold for the l_k -th modulation is $T(l_k)$, which is also provided in Table I for BER_{tgt} =10^{-3}.

v	Modulation	Number of bits $b(v)$	$T(v)$ (dB)
0	No transmission	0	0
1	QPSK	2	9.78dB
2	16QAM	4	16.52dB
3	64QAM	6	22.52dB
4	256QAM	8	28.4
5	1024QAM	10	35.0

Table 2. Candidate modulation and parameters

Since power constraint may be different for different application scenarios, we research into IPC problem and APC problem in the section, respectively.

5.2 ABPA problem and solutions with IPC

From the analysis above, the ABPA problem with IPC can be described as

$$\underset{l_k, P_{1,k}, P_{2,k}}{\arg\max} \sum_{k=1}^{K} b(l_k) \tag{17}$$

subject to

$$\begin{aligned} 1/K\sum_{k=1}^{K}(P_{1,k}+P_{2,k}) \le P \qquad & \text{(a)} \\ BER_k = BER_{tgt} \qquad & \text{(b)} \end{aligned} \tag{18}$$

Equation (18a) denotes the IPC requirement, i.e. the instantaneous total power cannot be larger than P. And (18b) illustrates BER requirement. From (16) and Table 2, (18b) can be replaced by (19).

$$|H_{1,k}H_{2,k}|^2\ \rho_k{}^2 P_{1,k}/[|H_{2,k}|^2\ \rho_k{}^2\sigma_1^2+\sigma_2^2]=T(l_k) \tag{19}$$

Assume that $G_{i,k}=|H_{i,k}|/\sigma_i^2$, ($i$=1,2). According to (14), we can further rewrite (19) as

$$G_{1,k}G_{2,k}P_{1,k}P_{2,k}/[G_{1,k}P_{1,k}+G_{2,k}P_{2,k}+1]=T(l_k) \tag{20}$$

Usually, such problem can be solved with Greedy algorithm [13], whose main concept is to achieve the global optimal allocation with many local optimal allocations. During every local optimal allocation, the least additional bits are allocated to the sub-carrier which requires the least additional power to satisfy BER requirement. Such allocations continue until the remaining power is not enough to support more bits. According to Table 2, the least additional bit number for every allocation is 2 in the section.

Since the allocation of power relates to $P_{1,k}$ and $P_{2,k}$, we discuss the problem for different cases: 1) Adaptive PA at SS or RS; 2) Adaptive PA at SS and RS.

A. Adaptive PA at SS or RS

When $P_{2,k}$ is fixed and $P_{1,k}$ can be adjusted according to channel condition, we assume

$$P_{2,k}=P^{RS},\frac{1}{K}\sum_{k=1}^{K}P_{1,k}=P^{SS}=P-P^{RS} \tag{21}$$

From (20), when the k-th sub-carrier adopts the l_k-th modulation, we can get the required power as follows.

$$P_{1,k}^{SS}(l_k)=T(l_k)[G_{2,k}P^{RS}+1]/G_{1,k}[G_{2,k}P^{RS}-T(l_k)] \tag{22}$$

Hence, in order to further load additional 2 bits on the k-th sub-carrier, the required additional power is

$$\Delta P_k^{SS}=P_{1,k}^{SS}(l_k+1)-P_{1,k}^{SS}(l_k) \tag{23}$$

According to Greedy algorithm, the sub-carrier with the minimum ΔP_k^{SS} will be allocated with 2 bits during every allocation. Such allocations will be terminated when the remaining power is not enough to support more bits.

When $P_{1,k}$ is fixed and $P_{2,k}$ can be adjusted, we assume

$$P_{1,k}=P^{SS},1/K\sum_{k=1}^{K}P_{2,k}=P^{RS}=P-P^{SS} \tag{24}$$

We take the similar measures to the scheme with adaptive PA at SS. In this case, when the k-th sub-carrier adopts the l_k-th modulation, the required power for the sub-carrier is as follows.

$$P_{2,k}^{RS}(l_k)=T(l_k)[G_{1,k}P^{SS}+1]/G_{2,k}[G_{1,k}P^{SS}-T(l_k)] \tag{25}$$

And the least additional power to further load additional 2 bits on the k-th sub-carrier is

$$\Delta P_k^{RS}=P_{2,k}^{RS}(l_k+1)-P_{2,k}^{RS}(l_k) \tag{26}$$

The sub-carrier with minimum ΔP_k^{SS} is allocated with additional 2 bits in every allocation. The courses continue until the remaining power is not enough to support more bits.

B. Adaptive PA at SS and RS

When $P_{1,k}$ and $P_{2,k}$ can both be adjusted, we assume $P_k = P_{1,k} + P_{2,k}$. According to [14], the optimal power allocation strategy to achieve the highest capacity is described as follows.

$$P_{1,k} = P_k / \{1 + \sqrt{[G_{1,k} P_k + 1]/[G_{2,k} P_k + 1]}\}, P_{2,k} = P_k / \{1 + \sqrt{[G_{2,k} P_k + 1]/[G_{1,k} P_k + 1]}\} \quad (27)$$

We combine (27) with (20), and get the following equation.

$$G_{1,k} G_{2,k} P_k^2 / [\sqrt{G_{1,k} P_k + 1} + \sqrt{G_{2,k} P_k + 1}]^2 = T(l_k) \quad (28)$$

According to Greedy algorithm, once we obtain the required power P_k on the k-th sub-carrier with the l_k-th modulation for k=1, 2, …, K, we can determine the sub-carrier which requires the least additional power to support additional 2 bits for every local optimal allocation. From (28), we obtain a quadratic equation regarding P_k as follows.

$$\alpha_2 P_k^2 + \alpha_1 P_k + \alpha_0 = 0 \quad (29)$$

where

$$\begin{aligned} \alpha_2 &= G_{1,k}^2 G_{2,k}^2 \\ \alpha_1 &= -2G_{1,k} G_{2,k} T(l_k)(G_{1,k} + G_{2,k}) \\ \alpha_0 &= -4G_{1,k} G_{2,k} T(l_k) + T(l_k)^2 (G_{1,k} - G_{2,k})^2 \end{aligned}.$$

Consequently, when the k-th sub-carrier adopts the l_k-th modulation, the least required power is

$$P_k^{SS,RS}(l_k) = \begin{cases} (-\alpha_1 - \sqrt{\alpha_1^2 - 4\alpha_0\alpha_2})/2\alpha_2, if \ -\alpha_1 \ge \sqrt{\alpha_1^2 - 4\alpha_0\alpha_2} \\ (-\alpha_1 + \sqrt{\alpha_1^2 - 4\alpha_0\alpha_2})/2\alpha_2, if -\alpha_1 < \sqrt{\alpha_1^2 - 4\alpha_0\alpha_2} \end{cases} \quad (30)$$

5.3 ABPA Problem and solutions with APC

Unlike the ABPA problem with IPC, the problem with APC requires the average total power to be limited to P. So the problem can be described as

$$\arg\max_{l_k, P_{1,k}, P_{2,k}} \sum_{k=1}^{K} \iint_{(G_{1,k}, G_{2,k})} b(l_k) p(G_{1,k}, G_{2,k}) dG_{1,k} dG_{2,k} \quad (31)$$

subject to

$$\begin{aligned} &1/K \sum_{k=1}^{K} \iint_{(G_{1,k}, G_{2,k})} (P_{1,k} + P_{2,k}) p(G_{1,k}, G_{2,k}) dG_{1,k} dG_{2,k} = P \quad \text{(a)} \\ &G_{1,k} G_{2,k} P_{1,k} P_{2,k} / [G_{1,k} P_{1,k} + G_{2,k} P_{2,k} + 1] = T(l_k) \quad \text{(b)} \end{aligned} \quad (32)$$

where $p(G_{1,k}, G_{2,k})$ denotes the probability of $(G_{1,k}, G_{2,k})$; (32a) and (32b) illustrates APC and BER requirement, respectively.

According to [15], distributions of channel transfer functions for all sub-carriers are the same in an OFDM system. So we omit the subscript k in the following description. Note that the following operation is carried out for all sub-carriers. We assume that Φ_l denotes (G_1, G_2) set whose elements support the l-th modulation. Hence we rewrite the problem as follows.

$$\arg\max_{l,P_1,P_2} \sum_{l=1}^{L} \iint_{(G_1,G_2)\in\Phi_l} b(l)\, p(G_1,G_2)\, dG_1 dG_2 \tag{33}$$

subject to

$$\begin{aligned} &\iint_{(G_1,G_2)} (P_1+P_2)\, p(G_1,G_2)\, dG_1 dG_2 = P && \text{(a)} \\ &G_1G_2P_1P_2/[G_1P_1+G_2P_2+1] = T(l) && (b) \end{aligned} \tag{34}$$

Similar to the problem with IPC, we discuss the problem for different cases: 1) Adaptive PA at SS or RS; 2) Adaptive PA at SS and RS.

A. Adaptive PA at SS or RS

Assume that P_2 is fixed, and P_1 can be adjusted according to channel condition, we assume that

$$P_2 = P^{RS},\ \iint_{(G_1,G_2)} P_1\, p(G_1,G_2)\, dG_1 dG_2 = P^{SS} = P - P^{RS} \tag{35}$$

Similar to (25), when the l-th modulation is adopted, the required power is

$$P_1^{SS}(l) = T(l)[G_2P^{RS}+1]/G_1[G_2P^{RS}-T(l)] \tag{36}$$

Then (35) and (36) can be combined to be

$$\sum_{l=1}^{L} \iint_{(G_1,G_2)\in\Phi_l} \frac{T(l)[G_2P^{RS}+1]}{G_1[G_2P^{RS}-T(l)]}\, p(G_1,G_2)\, dG_1 dG_2 = P^{SS} \tag{37}$$

Hence, the problem of (34) becomes to be which (G_1, G_2) elements belong to Φ_l (l=1, 2, …, L), i.e. which (G_1, G_2) area belongs to Φ_l, so as to maximize average throughput under the constraint of BER and transmit power. Usually, such kind of problem may be solved with aid of Lagrange method. We assume that

$$\begin{aligned} J = &\sum_{l=1}^{L} \iint_{(G_1,G_2)\in\Phi_l} b(l)\, p(G_1,G_2)\, dG_1 dG_2 \\ &+\lambda\left[P^{SS} - \sum_{l=1}^{L} \iint_{(G_1,G_2)\in\Phi_l} \frac{T(l)[G_2P^{RS}+1]}{G_1[G_2P^{RS}-T(l)]}\, p(G_1,G_2)\, dG_1 dG_2\right] \end{aligned} \tag{38}$$

However, from (38) we can notice that double integrals referring to G_1 and G_2 are involved, and it is impossible to transfer (38) into another problem with single integral. Hence the $(G_1,$

G_2) area for Φ_l cannot be determined with Lagrange method. In order to solve the problem, we utilize the definition of integral to consider another problem as follows.

$$\sum_{l=1}^{L} \sum_{\substack{i,j\in(1,2,\ldots,N)\\(i\Delta G,\, j\Delta G)\in\Phi_l}} b(l)\,p(i\Delta G, j\Delta G)\Delta G^2 \tag{39}$$

subject to

$$\sum_{l=1}^{L} \sum_{\substack{i,j\in(1,2,\ldots,N)\\(i\Delta G,\, j\Delta G)\in\Phi_l}} \frac{T(l)[\,j\Delta G P^{RS}+1]}{i\Delta G[\,j\Delta G P^{RS}-T(l)]}\,p(i\Delta G, j\Delta G)\Delta G^2 = P^{SS} \tag{40}$$

where ΔG is a small real number. Consequently, when N approaches infinity and ΔG approaches infinitesimal, the problem of (39) is just the same as the problem of (33).
We observe the problem of (39), and can find that it can be described as how to allocate bits and power for N^2 different (G_1, G_2) elements, so as to maximize the system throughput. Such problem is similar to the problem in Section 5.2, and can also be solved with Greedy algorithm. With aid of computer simulation, we can obtain the (G_1, G_2) area to adopt the l-th modulation, i.e. Φ_l for all l. The areas of Φ_l when P/σ^2=30dB for Rayleigh fading channel are depicted in Fig. 11, where different colour denotes (G_1, G_2) areas for different modulations.

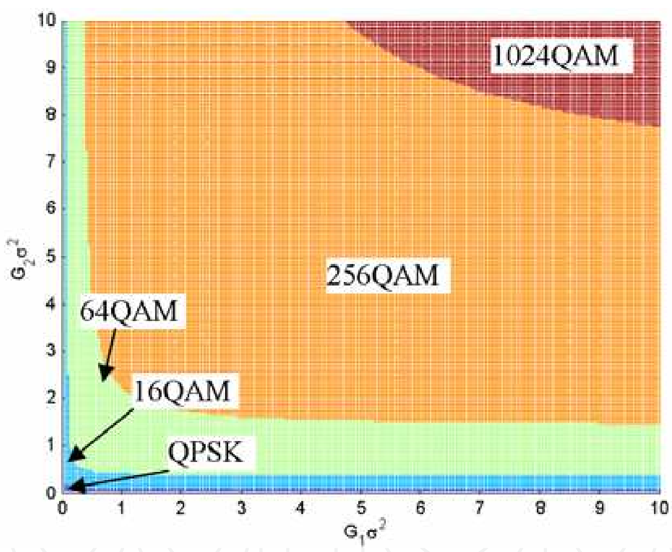

Fig. 11. Area of Φ_l for scheme with adaptive PA at SS

When P_1 is fixed and P_2 can be adjusted according to channel condition, we assume that

$$P_1 = P^{SS},\quad \iint_{(G_1,G_2)} P_2\, p(G_1,G_2)dG_1 dG_2 = P^{RS} = P - P^{SS} \tag{41}$$

With the same method, we can obtain the (G_1, G_2) area to adopt the l-th modulation, i.e. Φ_l for all l. The areas of Φ_l when P/σ^2=30dB for Rayleigh fading channel are depicted in Fig. 12.

B. Adaptive PA at SS and RS

When P_1 and P_2 can both be adjusted, we have to determine l, P_1, and P_2 jointly. We assume $P_A = P_1 + P_2$, and follow the similar allocation to (27) to allocate power at SS and RS. In order

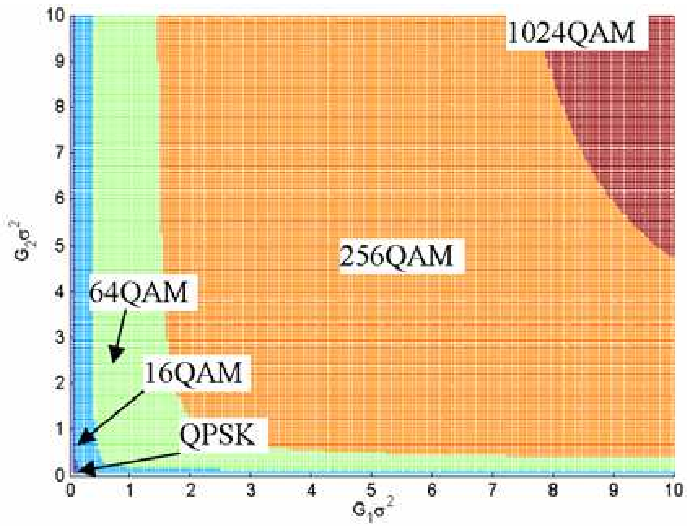

Fig. 12. Area of Φ_l for scheme with adaptive PA at RS

to determine the (G_1, G_2) area for the l-th modulation, we consider another problem as follows.

$$\sum_{l=1}^{L} \sum_{\substack{i,j\in(1,2,\ldots,N)\\(i\Delta G,\, j\Delta G)\in\Phi_l}} b(l)\, p(i\Delta G, j\Delta G)\Delta G^2 \tag{42}$$

subject to

$$\sum_{l=1}^{L} \sum_{\substack{i,j\in(1,2,\ldots,N)\\(i\Delta G,\, j\Delta G)\in\Phi_l}} b(l)\, p(i\Delta G, j\Delta G)\Delta G^2 \tag{38a}$$

With the same method above, we can obtain Φ_l for all l in the case. The areas of Φ_l when P/σ^2=30dB for Rayleigh fading channel are depicted in Fig. 13.

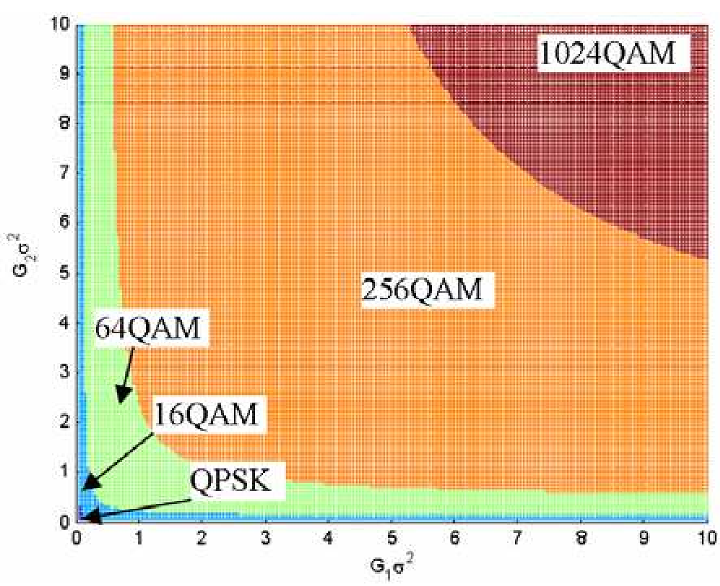

Fig. 13. Area of Φ_l for scheme with adaptive PA at SS and RS

From Fig. 11 to Fig. 13, we can see that the boundaries between the areas of Φ_l are like hyperbolas. The areas of Φ_l for the scheme with adaptive PA at SS and the scheme with adaptive PA at RS are reverse. As for the scheme with adaptive PA at SS and RS, the areas to adopt higher order modulation (e.g. 1024QAM) are wider than the other two schemes. That is to say, this scheme is more likely to adopt higher order modulation (allocated with more bits), because both P_1 and P_2 can be adjusted and more adaptation can be obtained.

5.4 Simulation and analysis

In order to evaluate the performance of the proposed solutions in the section, numerical simulation is carried out, in which both large-scale fading and small-scale fading are both taken into consideration. The number of sub-carriers is 32. We assume $H_{1,k} = h_{1,k}\sqrt{D_{SR}^{-\eta}}$, and $H_{2,k} = h_{2,k}\sqrt{D_{RD}^{-\eta}}$, where $h_{1,k}$ and $h_{2,k}$ denote the small-scale fading, and they follow Rayleigh distribution; D_{SR} and D_{RD} denote the distance between SS and RS, and distance between RS and DS, respectively; D_{SR} + D_{RD} =1. η denotes path loss exponent for large-scale fading, which is 4 in the simulation; $H_{1,k}$ and $H_{2,k}$ are assumed to be available for SS and RS. For reason of fairness, we assume P_{SS} = P_{RS} = $P/2$. For the following description, we define SNR=P/σ^2. The text in the legend is made short, e.g. "adaptive SS" is short for "adaptive PA at SS".

1) BER performance: First, we investigate BER performance of the proposed schemes in the section. Fig. 14 gives out their BER performance vs. SNR for the schemes. When SNR is low, low order modulation (e.g. QPSK) may be adopted frequently; when SNR is high, higher order modulation (e.g. 256QAM) may be adopted, so BER remains almost the same as that when SNR is low. It can be seen that all solutions can bring to BER performance close to the target BER 10^{-3}. This is because the power allocation at SS and RS can make the SNR of received signals to be the threshold to satisfy $BER_{tgt.}$ Hence, the proposed schemes can perform well in BER performance.

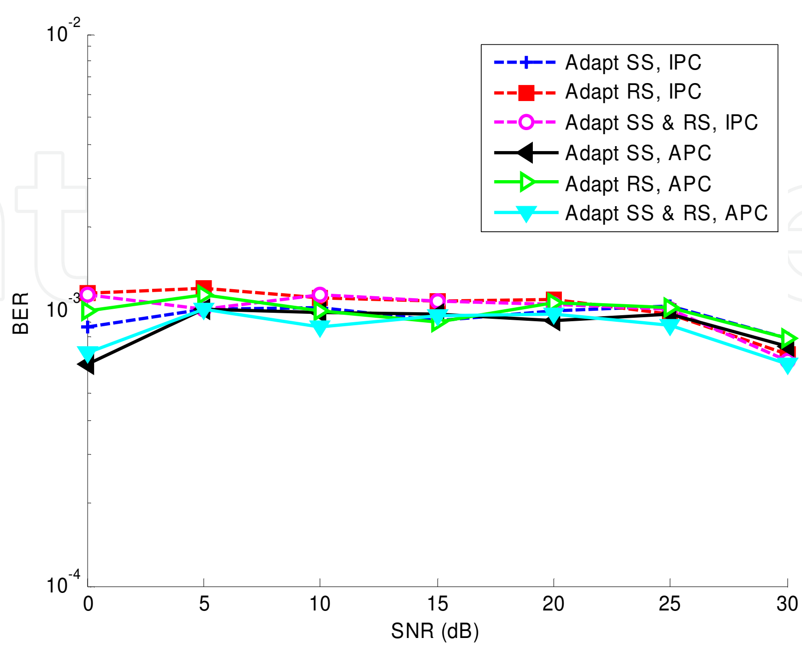

Fig. 14. BER vs. SNR for the solutions when D_{SR}=0.5

2) Transmit power constraint: Fig. 15 shows the cumulative distribution function (CDF) of the normalized total power P_A/P, where $P_A = 1/K\sum_{k=1}^{K}(P_{1,k}+P_{2,k})$. As for the three schemes with IPC, the distributions of P_A are almost the same. The value of P_A/P ranges from 0.92 to 1, which means that the instantaneous total power P_A is always lower than P, which is the requirement of IPC. As for the three schemes with APC, the distributions of P_A are almost the same, too. Hence, for the scheme of adaptive PA at SS and RS, though the transmit power can both be adjusted at SS and RS, the range for the total power is not improved, i.e. more adaptation on power doesn't cause the total power to vary more. From the figure, P_A of the schemes with APC can range more widely than that with IPC, from 0.75 to 1.25 approximately, but its mean value is restricted to be P. Compared with the scheme with IPC, the scheme with APC can take use of more power in average.

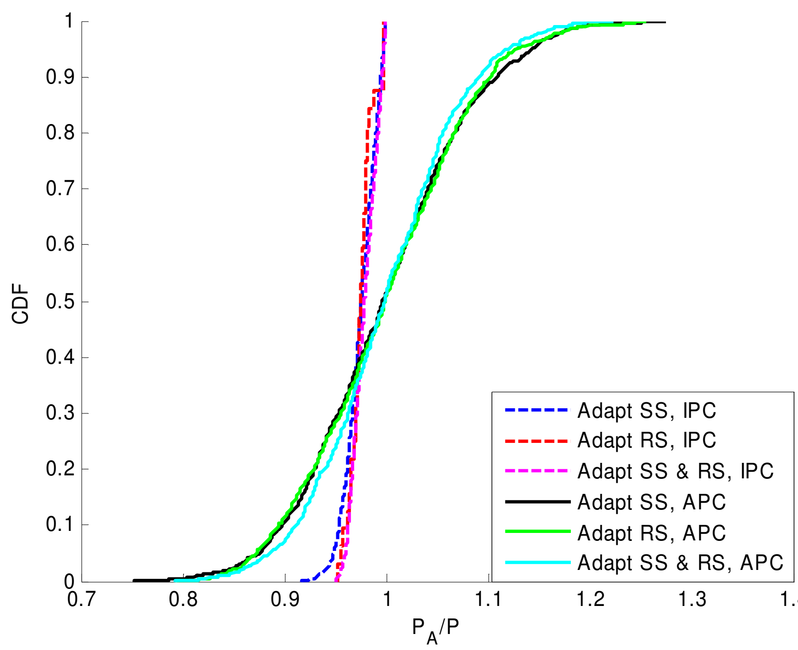

Fig. 15. CDF of total power for the solutions when D_{SR}=0.5 and SNR=20dB

3) System throughput: Fig. 16 and Fig. 17 gives out the system throughput vs. DSR when *SNR* equals to 0dB and 20dB, respectively. The throughput is calculated as the average correctly transmitted bit number per OFDM symbol divided by the number of sub-carriers. Throughput may be 0 because the channel condition is terrible and "no transmission" is adopted. The schemes with IPC has lower throughput than that with APC, due to the fact that they obtains different constraint for total transmit power. When *SNR* equals to 0dB, the difference can achieve 10% (0.04bits/symbol). When *SNR* is higher, throughputs for IPC and APC solutions are quite close, because the impact of transmit power constraint is not dominant for throughput when *SNR* is high.

As a conclusion, the Greedy algorithm can be applied into OFDM relaying system to achieve the maximum throughput subject to the BER and transmit power constraint.

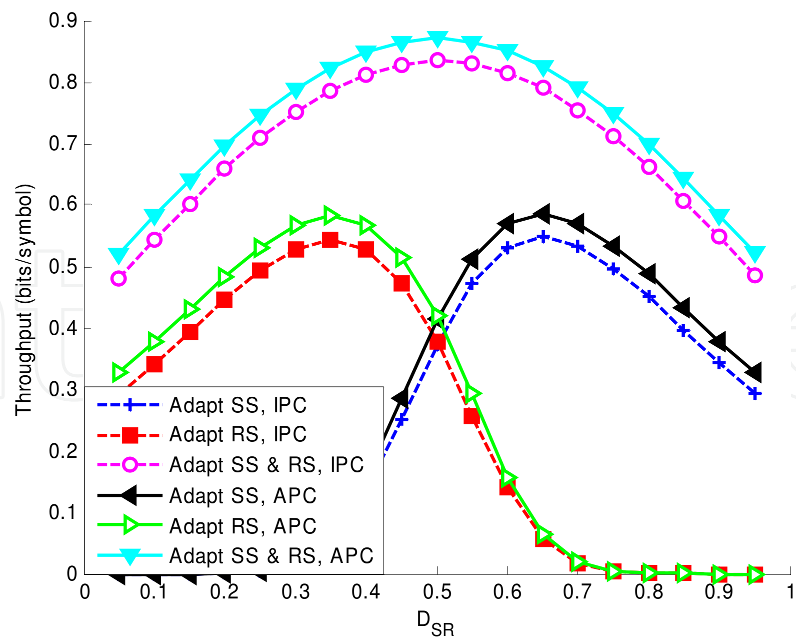

Fig. 16. System throughput vs. D_{SR} for the solutions when SNR=0dB

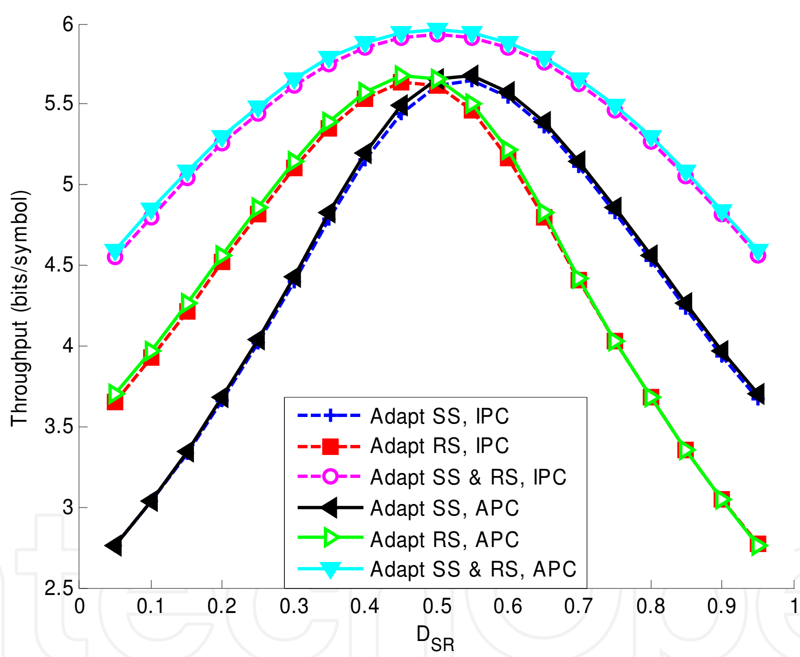

Fig. 17. System throughput vs. D_{SR} for the solutions when SNR=20dB

6. Conclusion

In this chapter we have presented the potential of link adaptation technique in wideband wireless communication systems with aid of Greedy algorithm. Link adaptation in OFDM systems is introduced firstly in section 2, i.e. how to allocation bits and power in all sub-carriers to maximize the throughput. The optimal solution can be obtained with Greedy algorithm. The detail description is given out in section 3. Simulation results are shown, which indicate that the throughput is maximized with guaranteed BER performance. When multiple user case is concerned, the problem gets more complex. The section 4 provides a novel solution, which takes use of Greedy algorithm for several times to obtain better fairness than the existing schemes. Simulation is also carried out to show the performance. Furthermore, due to the fact that relaying technique is an important component for future systems, the link adaptation in relaying systems is researched in section 5. AF-OFDM systems are investigated. The problem can be described as how to allocate bits and power in SS and RS to obtain the highest throughput subject to BER and transmit power constraint. Greedy algorithm helps to achieve the optimal result. Numeral simulation results indicate the proposed scheme perform well with satisfied BER and transmit power constraint. Further conclusions are obtained through the research. As a conclusion, with aid of Greedy algorithm, the potential of link adaptation technique is explored greatly.

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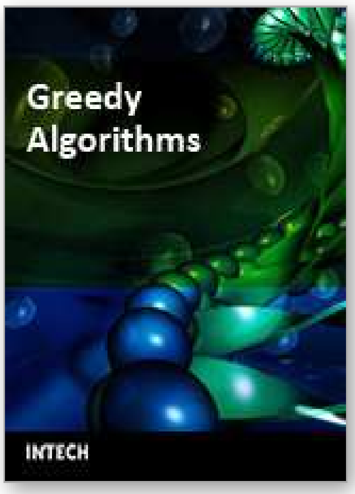

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Each chapter comprises a separate study on some optimization problem giving both an introductory look into the theory the problem comes from and some new developments invented by author(s). Usually some elementary knowledge is assumed, yet all the required facts are quoted mostly in examples, remarks or theorems.