Adaptive Resource Allocation in Multiuser OFDM Systems

Ke Tang(16823384), Fan Wang(11649179)

Abstract
As core technique in 4G wireless system, OFDM is used to efficiently mitigate ISI caused by frequency selective wireless channel and can provide power efficient signaling for a large number of users on the same channel. In multiuser systems, particularly in the downlink section of a cellular system, the users have to share transmit power and subcarriers. In order to improve system performance, these resources should be allocated adaptively to users according to their channel condition. Our project is intended to verify and implement adaptive allocation approaches that maximize system capacity while maintaining proportional fairness and compare their performance. After the implementation of these approaches, we hope to prove that LINEAR method reduces the complexity compared to ROOTFINDING method. In our project, we also propose the equal power method instead of widely used water-filling algorithm to prove that the equal power allocation method can be more efficient while maintaining the total capacity of the system.

I. Introduction

In wireless channels, reflection and refraction usually cause distortion of signals in the receiver, which is known as multipath fading. Inter-symbol interference (ISI) resulting from multipath fading will significantly restricts the data rate and the capacity of wireless systems. As core technology of Fourth Generation (4G) cellular system, OFDM proves to be an efficient technique to mitigate the inter-symbol interference (ISI) and can provide high data rate up to 100Mbps.

OFDM divide data into parallel data streams or channels and distribute these data streams to a large number of orthogonal sub-carriers with equal bandwidth in which data rate is lower and frequency response of the sub-channel on a particular subcarrier is approximately flat. Hence every sub-channel can be treated as flat fading channel without any ISI.

In single user system, OFDM can almost eliminate ISI effectively and the data rate is proved to be maximized when water-filling algorithm is adopted in the frequency domain under the constraint of total transmit power or in the frequency-time domain under the constraint of average transmit power. However, only single user can transmit data on all of the subcarriers and OFDM should be developed to adapt to multiuser systems which is more practical and common in actual wireless systems.

In a multiuser system, OFDM can transmit multiple users' data on different subcarriers, cope with ISI and achieve high data rate, which is well known as Orthogonal Frequency Division Multiple Access (OFDMA). By assigning subsets of subcarriers to individual users, OFDM can allow simultaneous low data rate transmission from different users since the subcarriers are orthogonal. In order to support multiple users, how to allocate available resources such as subcarriers, bit streams and power to different users is very crucial for improving the performance of the system. There are two kinds of resource allocation schemes: fixed resource allocation and adaptive resource allocation. For fixed resource allocation, OFDM can be combined with multiple access using frequency, time or coding separation of the users, which becomes OFDM-TDMA, OFDM-FDMA, and OFDM-CDMA. In these systems, a pre-defined subset of subcarriers, time slots or orthogonal codes are assigned to each user. However, fixed resource allocation is definitely not the optimal solution because of ignoring varying channel conditions. Since different users in different locations may experience different fading conditions of the same wireless channel, adaptive resource allocation scheme can exploit this fact to adaptively distribute available resources based on current channel states. In wireless communication, users in different locations may undergo independent fading so that the probability of all users in deep fading in a particular subcarrier is very low, which means that it can be assured that there is usually some user in good channel condition able to transmit data on that subcarrier yielding multiuser diversity. Consequently, utilizing this nature of wireless channels, adaptive resource allocation scheme can make full use of multiuser diversity and achieve higher data rate and larger capacity.

In order to implement adaptive resource allocation, two categories of optimization techniques are adopted: margin adaptive and rate adaptive. Margin adaptive technique intends to minimize the total transmit power given constraints on the users' data rate or bit error rate, like maintaining fixed data rate for each user. However, rate adaptive technique is to maximize the overall data rate for all users with a total transmit power constraint. The two optimization techniques are always nonlinear and require expensive computations. The complexity of non-linear optimization algorithm can be reduced by converting all variables to integers, but it still increases exponentially with the number of constraints and variables.

Many approaches are proposed to accomplish those techniques. Jang and Lee proposed to allocate each subcarrier to the user who has the best channel condition for that particular subcarrier and then distribute power by the water-filling algorithm, which proved to achieve the maximum sum capacity of the system. However, it is not fair that the users who have lower average channel gain will never be assigned any subcarrier while the users having higher average channel gain will take up most of the resources like power and subcarriers for most of the time. Nevertheless, in practical wireless systems, different users usually require different service levels with different data rates. To solve this problem, Shen proposed a method to maximize the system capacity while maintaining predefined proportional data rates to incorporate proportional fairness into the system. But solving non-linear equations involved in this algorithm needs computationally expensive iterations and is not practical in real-time implementation. Eventually, Ian C. Wong further modified this method and reduced the complexity. In this project, we mainly focus on rate adaptive techniques and discuss the last two kinds of optimization methods which can effectively improve the system capacity.

This report is composed of following parts. In section 2, the multiuser OFDM system model is introduced and the optimization objective function is given to solve rate adaptive problem. Section 3 gives the solution to the problem and Section 4 discusses the performance of two proposed approaches in details. Finally, Section 5 shows the implementation and the simulation results and Section 6 gives the conclusion.

II. System Model

We assume that a total of K users share N subcarriers to transmit data given total transmit power P_{total} and total available bandwidth B. Each subcarrier $n(1 \le n \le N)$ of user $k(1 \le k \le K)$ is assigned a power $p_{k,n}$ and subcarriers are assumed not to be shared by different users. It is also assumed that each user experiences independent fading and the channel gain of user k in subcarrier n is $h_{k,n}$ with additive white Gaussian noise (AWGN) $\sigma^2 = N_0 \frac{B}{N}$, where N_0 is the noise power spectral density. So the corresponding signal-to-noise (SNR) in this subcarrier is $H_{k,n} = \frac{h_{k,n}^2}{N_0 \frac{B}{N}}$ and the received SNR for k th user is $p_{k,n} H_{k,n} = p_{k,n} \frac{h_{k,n}^2}{N_0 \frac{B}{N}}$. As our goal is to find an optimal allocation method for subcarrier and power to maximize the sum capacity under total power constraint, we can formulate the optimization problem using equally weighted sum capacity as objective function as

$$\max_{p_{k,n},\rho_{k,n}} \frac{B}{N} \sum_{k=1}^{K} \sum_{n=1}^{N} \rho_{k,n} \log_2 \left(1 + \frac{p_{k,n} h_{k,n}^2}{N_0 \frac{B}{N}} \right) \quad (1)$$

subject to constraints:

$$\rho_{k,n} = \{0,1\} \text{ for all } k,n$$

$$p_{k,n} \ge 0 \text{ for all } k,n$$

$$\sum_{k=1}^{K} \rho_{k,n} = 1 \text{ for all } n$$

$$\sum_{k=1}^{K} \sum_{n=1}^{N} p_{k,n} \le P_{total}$$

where $\rho_{k,n}$ is an indicator to make sure that each subcarrier can only be assigned to one user.

With this model, Jang and Lee proposed a two-step approach to allocate subcarrier and power and then proved that subcarrier should be assigned to only one user who has the best channel gain for that subcarrier. In their approach, the first step is to assign each subcarrier to the user having best channel gain for that subcarrier. After subcarrier assignment, the multiuser OFDM system can be regarded as a single user OFDM virtually and power can be distributed over the subcarriers with the water-filling policy or using their proposed equal power allocation strategy to reduce complexity.

However, in order to have different service levels, fairness with varying priorities should be considered to support proportional different users requiring different data rates. Shen propose a method to control proportional fairness among users. The nonlinear constraints is described as

$$R_1 : R_2 : \ldots : R_K = \gamma_1 : \gamma_2 : \ldots : \gamma_K$$

where $\gamma_k (1 \le k \le K)$ is predetermined data rate ratio according to service level and R_k is the k th user's total data rate defined as

$$R_k = \sum_{n=1}^{N} \frac{\rho_{k,n}}{N} \log_2 \left(1 + \frac{p_{k,n} h_{k,n}^2}{N_0 \frac{B}{N}} \right) \quad (2)$$

With this non-linear constraint, the optimization problem containing both continuous and binary variables becomes very hard to solve. For certain subcarrier allocation, we can find optimal power allocation method to maximize the sum capacity while maintaining proportional fairness. However, the optimization problem described above may have to search in K^N possible subcarrier allocation schemes to get the global maximum sum capacity and the corresponding allocation scheme for subcarriers and power. The computation complexity is extremely expensive so that a suboptimal algorithm is proposed to reduce the complexity burden greatly with little loss of performance. In order to get optimal solution, subcarriers and power should be allocated together. But to reduce the prohibitive complexity, we can allocate subcarriers and power separately to get a suboptimal solution.

First we assume equal power distribution over all subcarriers and determine the subcarriers allocation on all users. The subcarrier allocation algorithm is

Step 1: Initialization

Set $R_k = 0, \Omega_k = \emptyset$ for $k = 1, 2, \ldots, K$ and $A = \{1, 2, \ldots, N\}$

Step 2: For $k = 1$ to K

(a) Find n satisfying $\left|H_{k,n}\right| \geq \left|H_{k,j}\right|$ for all $j \in A$

(b) Let $\Omega_k = \Omega_k \bigcup \{n\}$, $A = A - \{n\}$ and update R_k according to (2)

Step 3: While $A \neq \emptyset$

(a) Find k satisfying $R_k / \gamma_k \leq R_i / \gamma_i$ for all $i, 1 \leq i \leq K$

(b) For the found k, find n satisfying $\left|H_{k,n}\right| \geq \left|H_{k,j}\right|$ for all $j \in A$

(c) For the found k and n, let $\Omega_k = \Omega_k \bigcup \{n\}$, $A = A - \{n\}$ and update R_k according to (2)

In this kind of subcarrier allocation scheme, each user can use as many subcarriers with good condition as possible. In each iteration, the user with lowest proportional data rate can choose the subcarrier with the highest channel-to-noise ratio so that rough proportional fairness can be achieved.

After subcarrier allocation, the optimization problem is turned into

$$\max_{p_{k,n}} \frac{B}{N} \sum_{k=1}^{K} \sum_{n \in \Omega_k} \log_2 \left(1 + \frac{p_{k,n} h_{k,n}^2}{N_0 \frac{B}{N}} \right) \tag{3}$$

subject to constraints:

$$p_{k,n} \geq 0 \text{ for all } k, n$$

$$\sum_{k=1}^{K} \sum_{n \in \Omega_k} p_{k,n} \leq P_{total}$$

$$R_1 : R_2 : \ldots : R_K = \gamma_1 : \gamma_2 : \ldots : \gamma_K$$

where Ω_k is the set of subcarriers assigned to user k. Using Lagrangian multiplier, the optimal power allocation for certain user k is derived as

$$p_{k,n} = p_{k,1} + \frac{H_{k,n} - H_{k,1}}{H_{k,n} H_{k,1}} \tag{4}$$

$$p_{k,1} = \frac{P_k - V_k}{N_k} \tag{5}$$

which is well known as water-filling algorithm indicating that subcarriers with good condition can get more power. So the total power allocated to user k is

$$P_k = \sum_{n=1}^{N_k} p_{k,n} = N_k p_{k,1} + \sum_{n=2}^{N_k} \frac{H_{k,n} - H_{k,1}}{H_{k,n} H_{k,1}} \tag{6}$$

and the proportional data rates can be written as

$$\frac{1}{\gamma_1} \cdot \frac{N_1}{N} \left(\log_2 \left(1 + H_{1,1} \frac{P_{1,tot} - V_1}{N_1} \right) + \log_2 W_1 \right)$$

$$= \frac{1}{\gamma_k} \cdot \frac{N_k}{N} \left(\log_2 \left(1 + H_{k,1} \frac{P_{k,tot} - V_k}{N_k} \right) + \log_2 W_k \right) \tag{7}$$

for $k = 1, 2, \ldots, K$, where

$$V_k = \sum_{n=2}^{N_k} \frac{H_{k,n} - H_{k,1}}{H_{k,n} H_{k,1}} \tag{8}$$

$$W_k = \left(\prod_{n=2}^{N_k} \frac{H_{k,n}}{H_{k,1}} \right)^{\frac{1}{N_k}} \tag{9}$$

and N_k is the number of subcarriers allocated to user k.

Given the total power constraint

$$P_{total} = \sum_{k=1}^{K} P_k = \text{constant} \tag{10}$$

we now have K non-linear equations with variables $P_k (1 \leq k \leq K)$. Numerical iterative method like Newton-Raphson can be used to solve these equations but this is so computationally expensive for real systems. In two special cases, these equations can be simplified and solved in efficient manner.

The first special case is high channel-to-noise ratio case, when the channel-to-noise ratio is high in the subcarriers and the power provided is very high, V_k is relatively small compared to P_k so that we assumed that $V_k = 0$ and $H_{k,1} P_k / N_k >> 1$. With these assumptions, the proportional data rates can be simplified as

$$\left(\frac{H_{1,1} W_1}{N_1} \right)^{\frac{N_1}{\gamma_1}} \left(P_1 \right)^{\frac{N_1}{\gamma_1}} = \left(\frac{H_{k,1} W_k}{N_k} \right)^{\frac{N_k}{\gamma_k}} \left(P_k \right)^{\frac{N_k}{\gamma_k}} \tag{11}$$

and the total power constraint can be expressed in simpler way as

$$\sum_{k=1}^{K} c_k \left(P_k \right)^{d_k} - P_{total} = 0 \tag{12}$$

where

$$c_k = \begin{cases} 1 & \text{if } k=1 \\ \dfrac{\left(\dfrac{H_{1,1}W_1}{N_1}\right)^{\frac{N_1\gamma_k}{N_k\gamma_1}}}{\dfrac{H_{k,1}W_k}{N_k}} & \text{if } k=2,3,\ldots,K \end{cases} \tag{13}$$

and

$$d_k = \begin{cases} 1 & \text{if } k=1 \\ \dfrac{N_1\gamma_k}{N_k\gamma_1} & \text{if } k=2,3,\ldots,K \end{cases} \tag{14}$$

so that numerical algorithm can be applied to solve this problem and as iterative method for root finding are needed, this kind of method is called ROOTFINDING.

The other special case is linear case, when linear condition is satisfied as

$$N_1 : N_2 : \cdots : N_K = \gamma_1 : \gamma_2 : \cdots : \gamma_K \tag{15}$$

so that the non-linear constraint can be transformed into linear equations as

$$\begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & a_{2,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 0 & \cdots & a_{K,K} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_K \end{bmatrix} = \begin{bmatrix} P_{total} \\ b_2 \\ \vdots \\ b_K \end{bmatrix} \tag{16}$$

where

$$a_{k,k} = -\frac{N_1}{N_k}\frac{H_{k,1}W_k}{H_{1,1}W_1} \tag{17}$$

$$b_k = \frac{N_1}{H_{1,1}}\left(W_k - W_1 + \frac{H_{1,1}V_1W_1}{N_1} - \frac{H_{k,1}V_kW_k}{N_k}\right) \tag{18}$$

for $k = 2,3,\ldots,K$. This set of simultaneous linear equations can be easily solved because of its well ordered symmetric and sparse structure and the complexity is significantly reduced.

In practical system, rough proportionality is acceptable since proportionality corresponds to different service levels which often have soft differentiation rather than a strict one. Hence, Wong etc. proposed a method to utilize this nature to reduce the complexity of the non-linear optimization problem while maintaining performance. The algorithm is:

Step 1: Determine the number of subcarriers N_k to be initially assigned to each user.

Step 2: Assign the subcarriers to each user while ensuring rough proportionality.

Step 3: Assign the total power P_k for user k to maximize the capacity while enforcing the proportionality.

Step 4: Assign the power $p_{k,n}$ for each user's subcarriers subject to its corresponding total power constraint P_k

In first step, we give the reasonable assumption that the proportion of subcarriers for each user is approximately the same as their data rate proportion after power allocation which roughly satisfies the proportionality

$$N_1 : N_2 : \cdots : N_K = \gamma_1 : \gamma_2 : \cdots : \gamma_K$$

The number of subcarriers assigned to user k is determined by

$$N_K = \lfloor \gamma_k N \rfloor \tag{19}$$

Then in second step, we should assign N_K number of subcarriers to user k and allocate the remaining $N^* = N - \sum_{k=1}^{K} N_k$ subcarriers to maximize the total capacity of the system while keeping rough proportionality.

The subcarrier allocation algorithm is very similar to Shen etc.'s subcarrier allocation method with a few modifications, which is described as following:

Step 1: Initialization

$$c_{k,n} = 0 \text{ for } k = 1,2,\ldots,K; \quad n = 1,2,...,N$$

$$R_k = 0 \text{ for } k = 1,2,\ldots,K$$

$$p = P_{tot} / N^2$$

$$A = \{1,2,\ldots,N\}$$

Step 2: for $k = 1$ to K

Sort $R_k = 0$ in ascending order

$$n = \arg\max_{n\in A} \left|H_{k,n}\right|$$

$$c_{k,n} = 1$$

$$N_k = N_k - 1$$

$$A = A - \{n\}$$

$$R_k = R_k + \frac{B}{N}\log_2(1 + pH_{k,n})$$

Step 3: While $\|A\| > N^*$

$$\kappa = \{1,2,...,K\}$$

$$k = \arg\min_{k\in\kappa} R_k / \gamma_k$$

$$n = \arg\max_{n\in A} \left|H_{k,n}\right|$$

if $N_k > 0$

$$c_{k,n} = 1$$

$$N_k = N_k - 1$$

$$A = A - \{n\}$$

$$R_k = R_k + \frac{B}{N}\log_2(1 + pH_{k,n})$$

else

$$\kappa = \kappa - \{k\}$$

Step 4: $\kappa = \{1,2,...,K\}$

for $n = 1 : N^*$

$$k = \arg\max_{k \in \kappa} \left| H_{k,n} \right|$$

$$c_{k,n} = 1$$

$$R_k = R_k + \frac{B}{N} \log_2 (1 + pH_{k,n})$$

$$\kappa = \kappa - \{k\}$$

First all the variables are initialized and equal power distribution is assumed. Secondly, each user is assigned the best channel for them and the data rate R_k for each user is updated. Then the remaining subcarriers are assigned to users using the greedy policy that in each iteration, the user who has the lowest proportional data rate can choose the best channel. When user k has got N_k number of subcarriers, he can't get any more subcarriers. Finally, for the rest N^* subcarriers, each user can get at most one best channel in order to avoid the user having good channel condition to get all the remaining subcarriers. By this algorithm, rough proportionality

$$N_1 : N_2 : \cdots : N_K \approx \gamma_1 : \gamma_2 : \cdots : \gamma_K \tag{20}$$

can be implemented. When $N \to \infty$ and $N >> k$, the proportionality can be achieved more perfectly. After finishing subcarrier assignment, due to linear case, we can just solve the linear equation to get optimal power allocation. By reordering, LU factorization and forwards-backwards substitution, we can get the total power needed to be assigned to each user as

$$P_1 = \left(P_{total} - \sum_{k=2}^{K} \frac{b_k}{a_{kk}} \right) \Bigg/ \left(1 - \sum_{k=2}^{K} \frac{1}{a_{kk}} \right) \tag{21}$$

and

$$P_k = (b_k - P_1) / a_{kk} \text{, for } k = 2, \ldots, K \tag{22}$$

As the total power for each user is determined, the power allocation for each subcarrier in one user can be implemented by water-filling algorithm, which is described before. This 4-step approach is called LINEAR.

III. Performance comparison:

First of all, we consider the complexity of the two rate adaptive methods given the total number of users K and the total number of subcarriers N. In subcarrier allocation step, both ROOTFINDING and LINEAR methods require approximately $O(KN \log_2 N)$ operations to sort and allocate the subcarriers to users. In power allocation step, LINEAR method only requires 1 division, $2(K-1)$ multiplications and $3(K-1)$ subtractions so that the complexity is $O(K)$. In practice, the complexity is approximately $O(nK)$, where n is the number of function evaluations and is typically around 10. As function evaluation usually involves non-integer powers of real numbers, ROOTFINDING method is obviously more complex than simple linear case in LINEAR method. The complexity of the two methods is compared in Table 1:

Table 1

	ROOTFINDING	LINEAR
Subcarrier allocation step	$O(KN \log_2 N)$	$O(KN \log_2 N)$
Power allocation step	$O(nK)$	$O(K)$

During implementation of LINEAR method, we develop a new method to distribute power. After allocating subcarriers and obtaining the total power for each user, we try to distribute equal power to each subcarrier of certain user instead of using widely used water-filling algorithm. Obviously, equal power allocation is simpler than iterative water-filling algorithm and can save more time for operation, which is very important in real-time wireless system. When there is little difference between the total capacities of the two methods, water-filling algorithm can be replaced by equal power allocation method since efficiency can be improved without significant loss of performance.

IV. Simulation results

In order to simulate the real wireless communication environment, we use frequency selective multipath channel containing six independent Rayleigh multipaths with an exponentially decaying profile. 10 different channel realizations with 100 sample time samples for each realization are used and proportional ratios are assigned to each user at each channel realization. Other parameters are set as follows:

Table 2: Simulation Parameters

Total Power	Total Bandwidth	Total Subcarriers	Number of Users	Average SNR	BER	SNR Gap
1W	1MHz	64	4-16	38dB	10^{-3}	3.3

According to these parameters, we have implemented the three kinds of rate adaptive methods mentioned before. In the simulations, LINEAR method using water-filling algorithm is denoted as LINEAR-WF and the one using equal power allocation is mentioned as LINEAR-EQ.

First, we compare the overall capacities of the three methods and the results are shown in Fig 1. As expected, LINEAR-WF and LINEAR-EQ can achieve greater capacity than ROOTFINDING. Moreover, the capacities of LINEAR-WF and LINEAR-EQ are almost the same proving that LINEAR-EQ can reduce complexity while maintaining the performance.

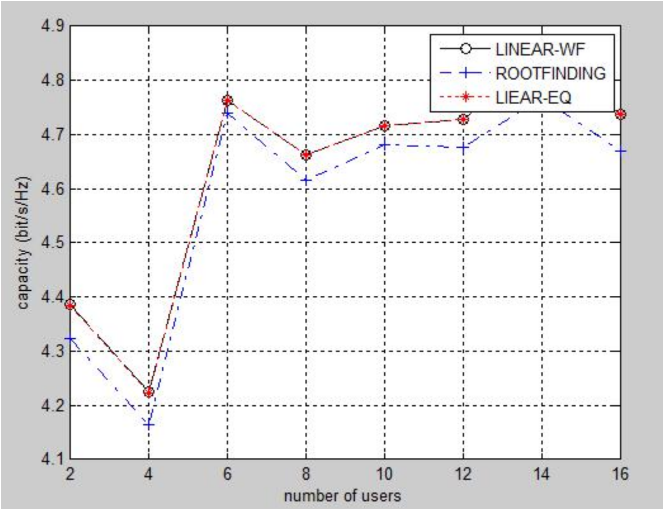

FIGURE I

Overall capacity comparison

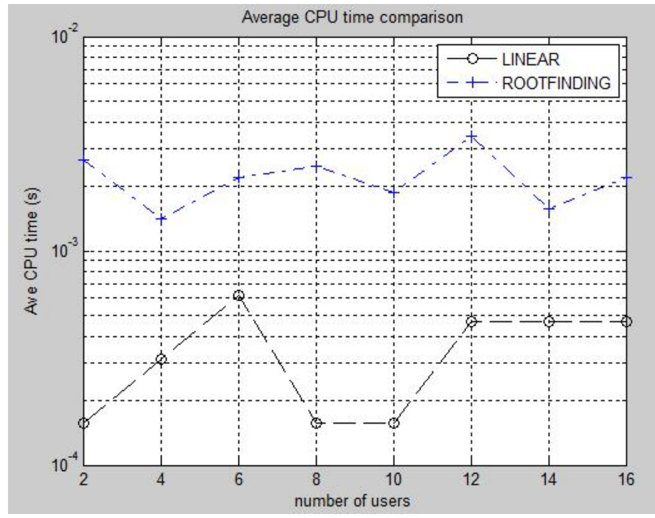

FIGURE III

Complexity comparison between LINEAR and ROOTFINDING

Secondly, we investigate the proportionality of the three methods and compare the normalized proportional data rates for each user to the predetermined proportions, which is shown in Fig 2. From the results, we can see clearly that the approximate proportionality is maintained by all three methods. We can see again that there is very little difference in capacities of LINEAR-WF and LINEAR-EQ.

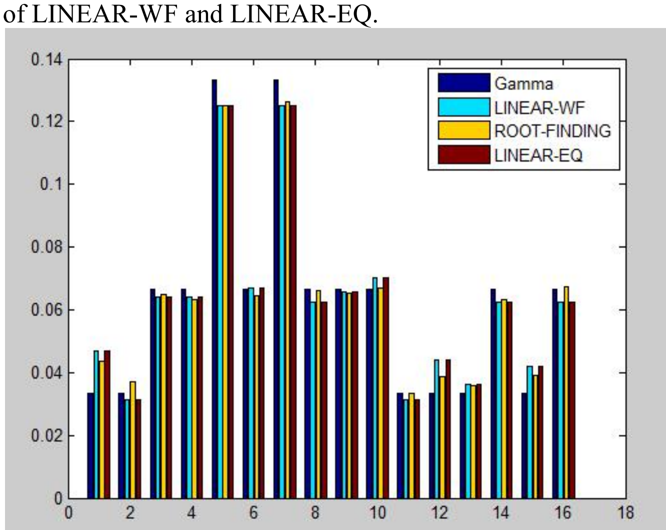

FIGURE II

Proportionality comparison

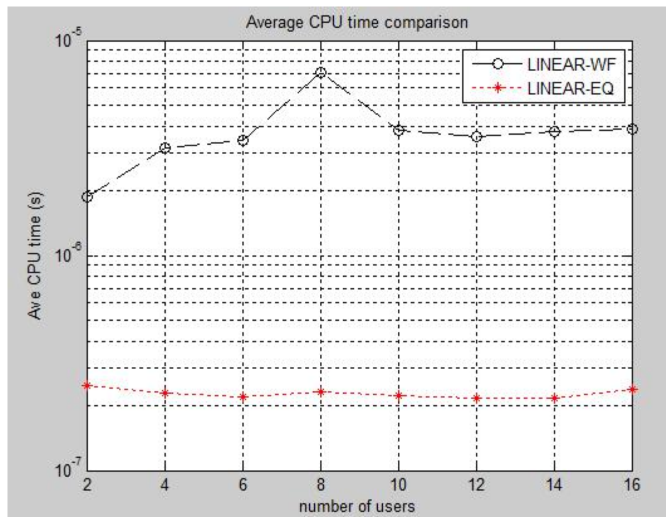

FIGURE IV

Complexity comparison between LINEAR-WF and LINEAR-EQ

Finally, we compare the complexity of LINEAR and ROOTFINDING and the complexity of LINEAR-WF and LINEAR-EQ respectively. As shown in Fig 3 and Fig 4, average CPU time for LINEAR is significantly less than that for ROOTFINDING and average CPU time for LINEAR-EQ is obviously less than that for LINEAR-WF, which verifies the analysis before. Hence, it is proved that LINEAR with equal power allocation can be more efficient than LINEAR with water-filling algorithm without negligible loss of performance.

V. Conclusion and Future Outlook

OFDM is very effective tool to mitigate ISI and improve the total capacity in 4G cellular system. In downlink of multiuser system, adaptive resource allocation scheme is needed to make full use of multiuser diversity. Two kinds of adaptive allocation methods, rate adaptive and margin adaptive methods are introduced to increase the system performance. In this project, we mainly focus on rate adaptive methods which maximize the total data rate under the total power constraint. Jang and Lee's method proves to maximize the system capacity but it doesn't consider the proportional fairness, which is very important for implementation of different service levels. Shen introduces a method to include proportional fairness and maximize the total data rate under the assumption of high channel-to-noise ratio, denoted as ROOTFINDING method. Wong further reduces the complexity of the method by turning the nonlinear constraint into linear equations, represented as LINEAR method. In our project, we also propose to allocation equal power to each subcarrier after subcarrier allocation instead of widely used water-filling algorithm to reduce the complexity and save the operation time. It is proved that the equal power allocation method can be more efficient while maintaining the total capacity of the system.

VI. REFERENCES

[1] *J. Jang and K. B. Lee, "Transmit Power Adaptation for Multiuser OFDM Systems", IEEE Journal on Selected Areas in Communications, vol. 21, no. 2, pp. 171-178, Feb. 2003.*

[2] *Z. Shen, J. G. Andrews, and B. L. Evans, "Adaptive Resource Allocation in Multiuser OFDM Systems with Proportional Fairness", IEEE Transactions on Wireless Communications, accepted for publication.*

[3] *I. C. Wong, Z. Shen, B. L. Evans, J. G. Andrews, "A Low Complexity Algorithm for Proportional Resource Allocation in OFDMA*

[4] *H. Rohling and R. Grunheid, "Performance comparison of different multiple access schemes for the downlink of an OFDM communication system," in Proc. IEEE Vehicular Technology Conf., Phoenix, AZ, pp. 1365–1369, 1997.*