# Dynamic Resource Allocation with Finite Buffer Constraint in Broadband OFDMA Networks

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*Abstract*— **This paper presents a dynamic resource allocation scheme for OFDMA-based wireless broadband networks. The problem of maximizing the total packet throughput subject to individual user's outage probability constraint is formulated. The proposed algorithm assumes a finite buffer for the arrival packets and dynamically allocates the radio resource based on users' channel characteristics, traffic patterns and QoS requirements. By performing the radio resource allocation into two steps, namely bandwidth allocation and channel assignment, efficient admission control is realized with low complexity. Specifically, the number of channels to be assigned to each user is first determined based on its traffic requirement and the average SNR. The second stage of the algorithm finds the best channel allocation for the users. Simulations show that the algorithm yields significant lower outage probability and higher throughput than existing multiple access methods.**

## I. INTRODUCTION

Orthogonal frequency division multiplexing(OFDM) has been identified as one of the prime modern schemes for broadband wireless networks, e.g., digital video broadcasting (DVB-T), wireless LAN (802.11a), and fixed broadband access system (802.116a). Its form of modulation that transmits high-speed data via multiple parallel low-rate streams presents excellent platform for fast implementation and excellent preformance over frequency selective channel. Another superior advantage of OFDM is its ability to allocate power and rate optimally among subcarriers, using "water-filling" over the inverse of the channel spectrum, which is capacity achieving from information theory standpoint [1]. One way of applying OFDM to a multi-user scenario is through OFDM-TDMA or OFDM-CDMA [2], where different users are allocated different time slots or different frequency spreading codes. However, each user has to transmit its signal over the entire spectrum. This leads to an averaged-down effect in the presence of deep fading and narrowband interference. Alternatively, one can divide the total bandwidth into traffic channels (one or a cluster of OFDM subcarriers) so that multiple access can be accommodated in an orthogonal frequency division multiple access (OFDMA) fashion. An OFDMA system is defined as one in which each user occupies a subset of subcarriers, and each carrier is assigned exclusively to only one user at any time. One advantage of OFDMA over OFDM-TDMA and OFDM-CDMA is elimination of intra-cell interference, thus avoiding the need of CDMA type of multi-user detection. A more important feature of OFDMA is its capability to exploit network/multiuser diversity by avoiding "null" traffic channels (due to deep fading and narrowband interference). Since different users perceive different channel quality, a null traffic channel for one user may still be favorable to other users. Through judicious subcarrier allocation, the system can potentially outperform interference-averaging techniques by a factor of 2-3 in spectrum efficiency [4].

Clearly, radio resource allocation plays a key roll in optimizing the performance of OFDMA systems. However optimum channel allocation in OFDMA is an NP-hard problem that is fundamentally difficult to tackle. In practice, additional constraints, e.g., individual user's rate requirement, further complicates the problem. Physical layer property based radio resource allocation has been studied in the context of OFDMA systems in recent years. A Lagrangian relaxation algorithm is first introduced in [5] to minimize the total power consumption with constraints on transmission rate for users requiring different classes of services. The approach attempts to iteratively take advantage of the Lagrange method by relaxing an integer subcarrier assignment parameter $\rho_k(n)$ to any value between 0 and 1. Despite of its significant gain over the fixed assignment strategy, the algorithm is computational intensive and is difficult to implement. Linear programming is used in [6] to solve the subcarrier allocation by linearizing the function of rate in term of power. However the linearization can not be generally applied to all types of modulations and it still needs iterations in solving linear programming problem. Non-iterative algorithms are proposed in [3] and [7] to tackle the problem into two steps. Despite of their significance, none of these approaches account for the packet nature of data networks, e.g., buffer overflow is one of the most important causes of the traffic outage. For practical applications, radio resource allocation in wireless networks should be aware of users' traffic characteristics as well as channel profiles.

The objective of this paper is to develop a radio resource allocation strategy which allocates traffic channels according to users' channel conditions as well as traffic patterns. Although many design parameters have been utilized in the literature of network optimization, up till now little attention has been paid on the buffer management in the base station for an OFDMA network. Towards this end, a constrained optimization problem is formulated based on the queueing model built at the base station and is addressed with a two-step algorithm. In the first step, the number of traffic channels for each user is determined based on user's QoS (outage probability) requirement, traffic pattern and the average $SNR$ over the channels. In the second step, the specific set of traffic channels is selected for each user through a Throughput Greedy Maximization (TGM) algorithm developed in this paper to maximize the traffic throughput.

The remainder of the presentation is organized as follows. In Section 2, the system model is described and the constrained optimization problem is formulated. Section III derives the two-step algorithm. In Section IV, performance of the system is analyzed by establishing throughput upper bound and outage probability lower bound. Simulation results are studied in Section IV and the paper is then concluded in Section V.

## II. SYSTEM MODEL AND PROBLEM FORMULATION

### A. System Model and Assumptions

The following assumptions are invoked for the ensuing analysis:

- Perfect knowledge of users' channels and centralized traffic channel allocation at the base station.
- Presence of a multiple access protocol which notifies users of the resource allocation decision made by the base station.
- Adaptive modulation on each traffic channel .

The system under consideration assumes perfect users' channel state informations at the base station (BS). Channel allocation algorithm is implemented at the base station and users are notified of the channel assignment through a multiple access protocol. Users then employ adaptive modulation [8] on each traffic channel assigned to them according to the channel characteristics (e.g., the $SNR$).

Consider an OFDMA system with $M$ users and a total of $N$ traffic channels. Packets coming into user $m$'s buffer is modeled as a Poisson process with independent rate $\lambda_m$. For all practical purposes, a finite buffer of size $d_m$ packets is allocated to user $m$. The channel conditions associated with users are characterized by an $SNR$ matrix $\mathbf{V}_{\mathrm{M}\times\mathrm{N}}$ with entries $\nu_{mn}$ denoting the $SNR$ level seen by the $m^{th}$ user on channel $n$. Using adaptive modulation, the maximum number of bits (denote as $u$) the channel can transmit per unit time is expressed by certain function $u = f(v)$ [9] [3] [8]. As a result, the channel profile matrix $\mathbf{V}$ is fully characterized by a rate matrix $\mathbf{U} = f(\mathbf{V})$. There are various approximations on $f(\cdot)$. For example, in [3] $u = \left(\frac{v}{0.6}\right)^{1/3}$ at a certain bit error rate $P_e = 10^{-6}$ and $u = 0.31\,(10\log v - 0.67)$ at $P_e = 10^{-5}$ in [8]. All of them are all bounded by capacity expression [9]:

$$u = Blog_2(1+\nu) \tag{1}$$

Let $\mathbf{X}_{\mathrm{M}\times\mathrm{N}}$ be a channel assignment index matrix with entries $x_{mn},\ x_{mn} \in \{0,1\}$, in which $x_{mn} = 1$ indicates that the $n^{th}$ channel been assigned to the $m^{th}$ user and $x_{mn} = 0$ otherwise. As explicated early, no OFDMA traffic channel can be shared by more than one users at the same time. Therefore, one of the constraints that must be satisfied is:

$$\sum_{m=1}^{M} x_{mn} = 1 \ \forall n = 1,2,...,N.$$

### B. Problem Formulation

Although many design parameters has been used in network optimization, given that traffic outage (defined as packet blocking probability) and throughput receive most attentions in the buffer management at the base station, and have great impact on the system design, we seek to develop a radio resource allocation strategy which maximizes the traffic throughput at the base station subject to individual user's QoS (packet outage probability) requirement. The constrained optimization problem is thus formulated as follows:

$$\begin{aligned} &\underset{X}{Max}\ \eta_{total} = \sum_{m=1}^{M} \eta_m \\ &subject\ to\ 1)\ P_m < O_m\ \forall m = 1,2,...,M; \\ &\qquad\qquad\quad 2) \sum_{m=1}^{M} x_{mn} = 1\ \forall n = 1,2,...,N. \end{aligned} \tag{2}$$

where $\eta_m$, $P_m$ and $O_m$ denote user $m$'s traffic throughput, outage probability and the pre-determined outage probability requirement.

### C. Problem Re-formulation and Simplification

The problem formulation above does not explicitly relates the throughput with the channel condition and other traffic/network parameters. In order to make the optimization problem more tractable, we need to form a simple expression between the outage probability $P_m$, the throughput $\eta_m$, the packet arrival rate $\lambda_m$, buffer size $d_m$ and the processing rate $u_m$. The following preposition establishes the relation between these parameters.

*Proposition 1:* The traffic throughput and the outage probability of the m$th$ user can be expressed as follows:

$$\eta_m = \eta(\lambda_m, \mu_m, d_m) = \lambda_m(1 - P_m) \tag{3}$$

where

$$P_m = P(\lambda_m, \mu_m, d_m) = \frac{\lambda_m(\mu_m - \lambda_m)e^{-2\frac{(\mu_m-\lambda_m)(d_m-1)}{\lambda_m}}}{\mu_m^2 - \lambda_m^2 e^{-2\frac{(\mu_m-\lambda_m)(d_m-1)}{\lambda_m}}}. \tag{4}$$

*Proof:* Given the index matrix $\mathbf{X}$ and the transmission rate matrix $\mathbf{U}$, the ability of clearing out queued packets from user $m$'s buffer is determined by its maximum transmission rate:

$$\mu_m = \sum_{n=1}^{N} u_{mn}x_{mn} = \sum_{n\in\Phi_m} u_{mn} \tag{5}$$

where $\Phi_m = \{n : x_{mn} = 1, 1 \le n \le N\}$ denotes the traffic channel set assigned to user $m$ with a total of $N_m$ traffic channels in it.

For an OFDM system, the transmission interval between any two consecutive symbols is a predetermined constant (defined as time slot). Thus for user m, the packet arrival and the packet transmission process can be modeled as an $M/D/1/d_m$ queue, a special case of $M/G/1/d_m$ queue, with arrival rate $\lambda_m$, processing rate $\mu_m$ and buffer size

$d_m$. An accurate analysis of $M/G/1/d_m$ buffer occupancy and the blocking probability can be found in [10]. However the calculation involves recurrent solving of the mean busy period in an $M/G/1/d_m$ queue, and cannot be expressed in closed-form. According to [11], among the five approximation formulas for $M/G/1/d_m$ systems, Gelenbe's formula is the most accurate and robust one:

$$P_m = P(\lambda_m, \mu_m, d_m) = \frac{\lambda_m(\mu_m - \lambda_m)e^{-2\frac{(\mu_m-\lambda_m)(d_m-1)}{\lambda_m a^2+\mu_m s^2}}}{\mu_m^2 - \lambda_m^2 e^{-2\frac{(\mu_m-\lambda_m)(d_m-1)}{\lambda_m a^2+\mu_m s^2}}} \tag{6}$$

where $a^2$ and $s^2$ are the squared coefficients of variations of the arrival and service processes, respectively. In case of the $M/D/1/d_m$ system, $a^2 = 1$ and $s^2 = 0$, which gives us the result in (4). With the outage probability, the throughput of user $m$, i.e., actual load that join the queue, can be expressed as (3). ■

In the following analysis, we shall use these closed-form approximation expressions for outage probability and throughput calculation. Notice that the processing rate $\mu_m$ is decided by radio resource allocation.

## III. RADIO RESOURCE ALLOCATION STRATEGY

If the only design criteria is to maximize the total throughput, the simplest and most intuitive way would be to assign each channel to the user who has the maximum transmission rate (the highest $SNR$). The approach is proposed (termed adaptive-OFDMA) in [8] and [1]. Assuming that users always have data for transmission, adaptive-OFDMA yields excellent performance with respect to system capacity. However when used in a packet date network with various traffic patterns, it introduces the following problem: the outage probability is almost one for users without enough channels and zero for users who get more than enough channels. Without incorporating traffic characteristics, adaptive-OFDMA cannot respond to various traffic patterns among users, leading to resource wastes in practical applications. Clearly, the first requirement for a radio resource allocation strategy is to account for users' traffic characteristics as well as channel information.

From the view point of a particular user, there are essentially two types of decisions to be made: how many and which channels are assigned to it. The number of channels a user needs is mostly related to the bandwidth requirement for meeting its QoS (in our case, the outage probability). On the other hand, which specific set of traffic channels assigned to the user has more impacts on the total network throughput. Usually, bandwidth allocation is difficult to be separated from channel assignment since the two have a joint impact on system performance. With better channels assigned to it, the user would have higher packet processing ability (transmission rate) and correspondingly, a decease in bandwidth demand. On the other hand, failing to get the best several channels, the user would have an increase in bandwidth demand.

We propose a radio resource allocation algorithm that is divided into two steps: bandwidth allocation (BA) and channel assignment (CA). The first step is used to decide bandwidth requirement of each user in order to satisfy its outage requirement. In the second step, the total throughput is maximized by selecting the "right" channel set for each user. The two steps address different aspects of the optimization problem as we stated in (2). Based on this algorithm, an admission control mechanism becomes readily available.

### *A. Bandwidth Allocation (BA)*

Based on the constraint in (2), the outage probability for $mth$ user's packets should satisfy the following inequality:

$$P_m = \frac{\lambda_m(\mu_m - \lambda_m)e^{-2\frac{(\mu_m-\lambda_m)(d_m-1)}{\lambda_m}}}{\mu_m^2 - \lambda_m^2 e^{-2\frac{(\mu_m-\lambda_m)(d_m-1)}{\lambda_m}}} < O_m.$$

Assume $\theta_m$ is the root of the equation:

$$\frac{\lambda_m(\theta_m - \lambda_m)e^{-2\frac{(\theta_m-\lambda_m)(d_m-1)}{\lambda_m a^2+\theta_m s^2}}}{\theta_m^2 - \lambda_m^2 e^{-2\frac{(\theta_m-\lambda_m)(d_m-1)}{\lambda_m a^2+\theta_m s^2}}} = O_m$$

or

$$\theta_m = P^{-1}(\lambda_m, O_m, d_m).$$

It is easy to prove that $\frac{\partial P_m}{\partial \mu_m} < 0$, therefore, $P_m < O_m$ for $\forall \mu_m > \theta_m$. As a result, the first constraint in (2) can be simplified as:

$$\mu_m > \theta_m. \tag{8}$$

It is difficult to give a closed-form expression of $\theta_m$ in terms of $\lambda_m, O_m$ and $d_m$. However, in practice a numerical solution can be easily obtained.

The following proposition establishes a direct relationship between the number of traffic channels needed for the $m^{th}$ user (in order to satisfy its outage probability requirement) and its traffic and channel conditions.

*Proposition 2:* Let $N_m = \lceil \theta_m / \overline{\mu_m} \rceil$, where $\overline{\mu_m}$ denotes the geometric mean of user $m$'s transmission rate over all the channels. By allocating no less than $N_m$ traffic channels to user m, its outage probability requirement can be satisfied almost surely.

*Proof:* Since the arithmetic mean is larger than or equal to the geometric mean,

$$\mu_m = \sum_{n=1}^{N} u_{mn} x_{mn} \geq N_m \left( \Pi_{n=1}^{N} \left(u_{mn}\right)^{x_{mn}} \right)^{1/N_m} = N_m \overline{\mu_{m1}} \tag{9}$$

where $\overline{\mu_{m1}}$ denotes the geometric mean of user m's transmission rate over the channel set assigned to it. If the right side of (9) is larger than or equal to $\theta_m$, then (8) can be satisfied and so does the first constraint in (2). However at this stage, we are yet to decide on the exact channel set for each user. We can replace $\overline{\mu_{m1}}$ with $\overline{\mu_m}$ in view that the channel assignment (CA) procedure will likely yield a subset of channels for user m no worse than its average condition. As a result,

$$\mu_m \geq N_m \overline{\mu_{m1}} \geq N_m \overline{\mu_m} \geq \theta_m. \tag{10}$$

■

To summarize, BA procedure is described as follows:

```
For $m = 1 : M$ do
1) $\overline{\mu_m} \leftarrow \left(\Pi_{n=1}^{N}(\mu_{mn})\right)^{1/N}$;
2) $\theta_m \leftarrow P^{-1}(\lambda_m, O_m, d_m)$;
3) $N_m = \lceil \theta_m / \overline{\mu_m} \rceil$.
end for
```

After BA, the first constraint in (2) now becomes a restriction on the number of traffic channels assigned to users:

$$\sum_{n=1}^{N} x_{mn} \geq N_m \ \forall m. \tag{11}$$

### B. Channel Assignment (CA)

After we obtain the number of traffic channels assigned to each user, the remaining problem is to determine the exact set of traffic channels for them so that the traffic throughput at the base station is maximized. Combining (2) and (11), the optimization problem is restated as follows:

$$\begin{aligned} & \underset{X}{Max} \sum_{m=1}^{M} \eta_m \\ subject\ to \quad & 1) \sum_{n=1}^{N} x_{mn} \geq N_m \ \forall m; \\ & 2) \sum_{m=1}^{M} x_{mn} = 1 \ \forall n. \end{aligned} \tag{12}$$

Here we derive a Throughput Greedy Maximization (TGM) algorithm for channel assignment. The key strategy is to find a user for each channel so that its impact on the total throughput increase is maximized. The TGM algorithm is based on greedy sensing, and is carried out without iterations. It is optimal for the specific channel that is being assigned. Specifically, the channel is assigned to the user that can increase the throughput to the maximum amount. We should keep in mind that each user can not ask for more than $N_m$ channels. This constraint is used to guarantee that all the users get enough bandwidth they need to meet the outage probability requirement. The TGM algorithm is described as follows:

```
For each traffic channel $n = 1 : N$ do
$G_m \leftarrow \eta(\lambda_m, \mu_m + u_{mn}, d_m) - \eta(\lambda_m, \mu_m, d_m) \ \forall m$
$m^* \leftarrow \arg\max_m G_m$;
    while( $sizeof\ (\Phi_{m^*}) \geq N_{m^*}$ & $n \leq N_r$)
        $G_{m^*} = -\infty$;
        $m^* \leftarrow \arg\max_m G_m$;
    end while
$x_{m^*n} \leftarrow 1$;
$\mu_{m^*} \leftarrow \mu_{m^*} + u_{m^*n}$;
$\Phi_{m^*} \leftarrow \Phi_{m^*} \cup \{n\}$.
end for.
```

### C. Admission Control

With the knowledge of bandwidth (number of traffic channels) required for each user after BA step, admission control can then be easily implemented. Let $N_r = \sum_{m=1}^{M} N_m$, the number of channels required from all the accessing users. Without loss of generality, let us assume $N_1 \leq N_2 \leq ... \leq N_M$. If $N_r < N$, i.e., there is not enough traffic channels for the assignment, one simple approach is to drop user $M$ which requires the most bandwidth and recalculate $N_r$ until the bandwidth requirement for each user can be satisfied. Such admission control uses informations of the traffic patterns, channel characteristics and the QoS requirements of users.

## IV. THROUGHPUT UPPER BOUND

A loose upper bound of the throughput can be obtained by calculating the system's maximum packet processing ability (summation of the maximum entry in each column of $\mathbf{U}$):

$$\Psi = \sum_{n=1}^{N} \max_{m}(u_{mn}). \tag{13}$$

This upper bound is reached when the following two conditions are satisfied: 1) Adaptive-OFDMA is used for channel allocation. Users' packet processing abilities are then computed as $\mu_m = \sum_{n=1}^{N} u_{mn} x_{mn} \ \forall m$; 2) For each OFDM symbol transmission, user $m$ always has at least $\mu_m$ number of packets waiting in its buffer for transmission. However, the second condition is not reasonable for practical application, especially when the system is lightly loaded.

Deriving an explicit expression of the upper bound through (2) is difficult. However maximizing the packets transmitted for each OFDM symbol transmission leads to an upper bound in the throughput. Denote $Q_m(i)$ as the queue length of user $m$ (number of packets left in user $m$th buffer) and $u_{mn}(i)$ as the transmission ability of user $m$ on channel $n$ at the start of $i^{th}$ time slot. We seek to find an allocation index $\mathbf{X}(i)$ so that the total number of packets transmitted is maximized for slot $i$. Since for each channel $n$, if assigned to user $m$, the maximum number of packets that can be transmitted is $\min(Q_m(i), u_{mn}(i))$. This can be explained by the fact that channel $n$ can only transmits $u_{mn}(i)$ packets in one transmission if $u_{mn}(i) < Q_m(i)$, or transmits $Q_m(i)$ (all the packets in user $m$'s buffer) if $u_{mn}(i) > Q_m(i)$. Based on current buffer occupancy $Q_m(i)\ \forall m$ and channel condition, a channel allocation index can be found throughput current slot throughput maximization (CSTM) algorithm. The resulting packets transmitted is maximized for slot $i$ based on CSTM. The key strategy of it is to assign a user to each channel, and the user that results in the maximized transmission packets is selected for it. CSTM is summarized as follows:

```
At the start of slot i:
For $n = 1 : N$
$m^* \leftarrow \underset{m}{argmax}\ \min(Q_m(i), u_{mn}(i))$
$x_{m^*n(i)} = 1$;
$Q_m(i) = Q_m(i) - u_{m^*n}(i)$
End For
```

Since the algorithm above yields an upper bound for current slot $i$, using it for each slot would result in an upper bound of throughput for the whole system. The algorithm does not utilize statistic information of the traffic. Instead it relies on the instantaneous information of the current buffer occupancy. Despite its impracticality (in obtaining the upper bound by updating resource allocation for each slot), the scheme does provide us the insight to evaluate the performance of any algorithm.

## SIMULATION RESULTS

The considered OFDMA system consists of one base station with $N = 128$ OFDMA traffic channels and $M = 64$ users. The traffic intensity (packet arrival rate) distribution among users are randomly generated. Then a Poisson distribution is used to generate the number of arrival packets for each time slot. The simulation parameters used are:

| | |
|---|---|
| Bandwidth of the system | $1M$ |
| Number of users M | 64 |
| Number of channels N | 128 |
| Buffer size | 20 packets/user |
| Average $SNR$ level for each user | $3dB$ |
| Traffic intensity distribution | Random |
| Channel delay spread | $25\mu s$ |
| Multi-path intensity profile | Exponential profile |

Table. 1 Simulation parameters

Performances of the algorithm are studied using the following performance measurements: 1) the throughput, the average number of packets transmitted per slot; 2) performance balances among users, the variances of outage probabilities among users; and 3) the average packet processing ability for each user, the average transmission rate used for each user.

Four algorithms are simulated: 1) Bandwidth allocation-Channel assignment(BCOFDMA), which is proposed in section III; 2) Adaptive-OFDMA (AOFDMA) [8] which allocates each channel to the user who has the maximum entry in matrix $\mathbf{U}$; 3) Improved Adaptive-OFDMA (IAOFDMA), which is the same with Adaptive-OFDMA except that each user can not have more than certain number of channels, and the number of channels decided for each user is proportional to their packet arrival rates; and 4) ROFDMA, which assigns the channel randomly but with the same number of channel constraints for users as IAOFDMA.

### *A. Throughput Versus Traffic Intensity*

Fig. 1 give the throughput comparisons of the upper bound and the four algorithms described above. It is seen that BCOFDMA yields the highest throughput while AOFDMA is the worst among the four. The worst performance of adaptive OFDMA can be explained by its channel assignment criteria that assigns the channel to the user with the highest $SNR$ level: the outage probability is almost 1 for those users who are far from the base station and almost 0 for those users who are near the base station, resulting in unbalanced queue lengths and outage probabilities among users. The situation is even worse with unbalanced traffics. On the contrary, BCOFDMA utilizes the traffic information as well as channel condition to distribute radio resources intelligently, therefore gives the best performance over the other three algorithms. For the same reason, IAOFDMA outperforms ROFDMA which assigns channel randomly. Notice that throughputs of all the algorithms (including the upper bound) can not exceed $\Psi$. In simulations $\Psi$ is obtained as 240 packets/slot based on (13).

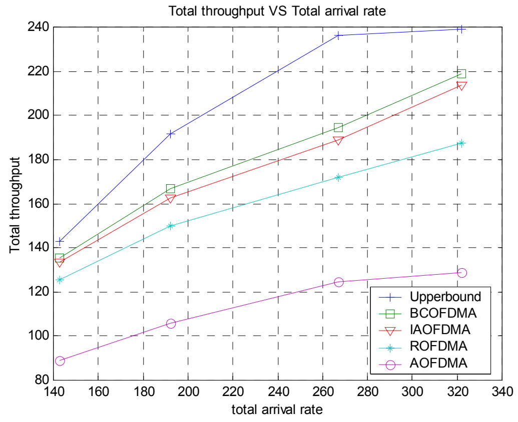

Fig. 1. Throughput VS Traffic intensity

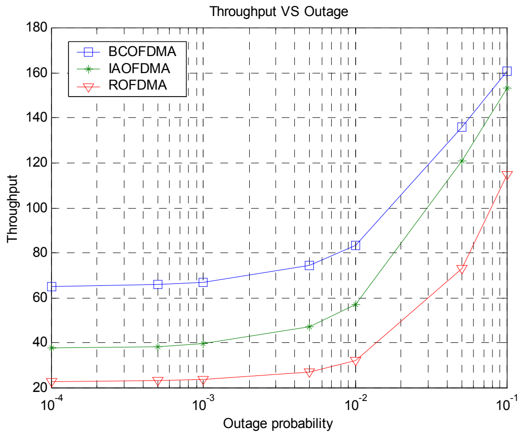

Fig. 2. Throughput VS Outage probability .

### *B. Throughput Versus Outage Probability*

Fig. 2 compares BCOFDMA, IAOFDMA and ROFDMA on their throughputs in term of outage probability. At a outage probability of $10^{-3}$, there is a near $50\%$ throughput gap between BCOFDMA and IAOFDMA, and about $200\%$ throughput gap between BCOFDMA and ROFDMA. When the outage probability is $10^{-2}$, BCOFDMA has a near $100\%$ throughput improvement over IAOFDMA and about $300\%$ throughput improvement over ROFDMA.

### *C. Balances Among User*

We have pointed out that unbalanced queue lengths among users account for the worst performance of AOFDMA. In fact, the performance on the throughput and outage probability can be reflected as the balances among users. Fig. 3 studies

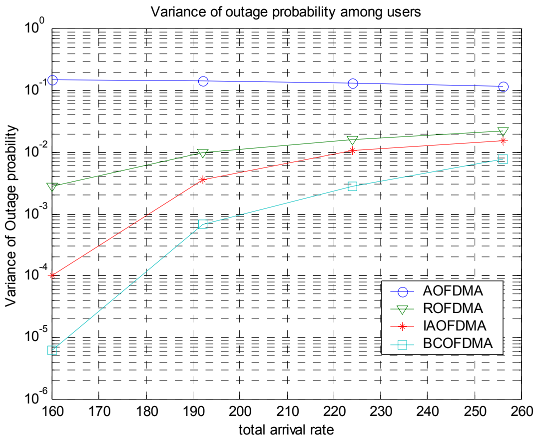

Fig. 3. Variance of outage probability VS Traffic intensity

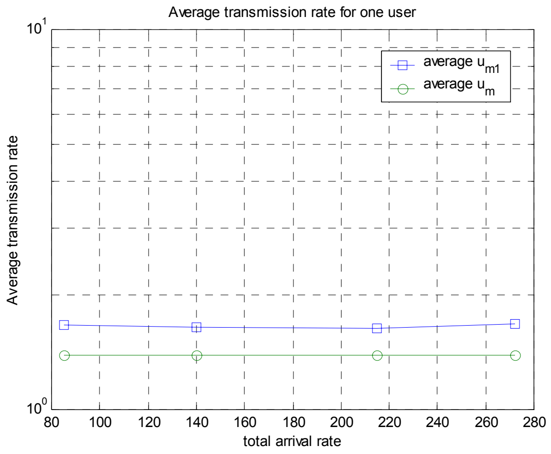

Fig. 4. Average transmision rate VS traffic intensity.

the variances of outage probabilities among users. For all the simulated traffic intensities, BCOFDMA remains the one which has the lowest variance, indicating more balanced performance among users than the other three. IAOFDMA has lower variance than ROFDM and AOFDMA being the worst one. The comparisons on variances of outage provide insights on how the algorithm manage the channel assignment criteria. It turns out that BCOFDMA optimizes the performance by trying to balance queue lengths and outage probability among users during radio resource management, and more balanced queue lengths lead to improved system capacity.

### *D. Packet Processing Ability*

In the bandwidth allocation step, BCOFDMA algorithm uses the geometric mean $\overline{\mu_m}$ over all the channels to approximate the geometric mean $\overline{\mu_{m1}}$ of the actual channel set assigned to user $m$. The reason that we can make such an approximation is that by distributing resource intelligently, $\overline{\mu_{m1}} \geq \overline{\mu_m}$ is almost guaranteed. Fig. 4 shows a comparison of $\overline{\mu_{m1}}$ and $\overline{\mu_m}$. Since $\overline{\mu_{m1}} \geq \overline{\mu_m}$ holds for all the simulated traffic rates, it provides a proof of the inequality (10), and the fact that $\overline{\mu_{m1}}$ is close to $\overline{\mu_m}$ also indicates the effectiveness of the two-step algorithm.

## V. CONCLUSION

In this paper, a dynamic radio resource allocation algorithm for OFDMA system has been derived based on users' traffic and channel statistic information. The main idea of the scheme is to first estimate the bandwidth allocation to satisfy the outage requirement from each user, and then the traffic throughput is maximized through a TGM algorithm developed in this paper. By dividing the radio resource allocation into two steps, admission control can be easily realized without iteration. Simulations show that the algorithm yields near-optimal throughput and significant lower outage probabilities at the base station compared to existing access methods.

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