Resource Allocation in User-Centric Wireless Networks

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***Abstract*— This paper presents a behavioral fairness-based resource allocation (RA) algorithm for uplink transmission of a multiuser orthogonal frequency division multiplexing system. The aim of fairness-based RA is to boost users' willingness to start and keep cooperating with each other and behave well to keep their trust and reputation high. An interesting notion of differentiated streams is also included in the proposed RA, which can fine-tune RA result to transfer excess bandwidth and power from real-time streams to non-real-time streams, i.e. increase useful throughput. In order to reduce the complexity of RA, a set of contiguous subchannels are grouped into a chunk to allocate resource chunk by chunk. The effects of users' contribution and the number of subchannels grouped in a chunk on the average throughput is analyzed and shown by numerical simulations.**

***Index Terms*—user-behavior based allocation, fairness based chunk-power-bit allocation, cooperative communications**

I. INTRODUCTION

The fundamental paradigm of User Centric Networks (UCNETs), which aim to share subscribed Internet access and services among users, is started with peer-to-peer (P2P) Internet service model, where users become active service providers instead of being just service consumers. In UCNETs, end-users share their Internet access freely and transparently among themselves in a way that is legally and technically independent from infrastructure and access providers. Currently existing commercial examples of UCNETs are FON, OpenSpark and Whisher [1]. These commercial networks spread by means of the end-user willingness to cooperate and share connectivity.

To provide good and robust connectivity and service in such networking environment, UCNET models should incorporate some essential properties. These properties, as declared in [1] includes: connectivity sharing, cooperation, trust and self-organization. Our main objective in this paper is to motivate users' willingness to "cooperate" with others and keep their trust and reputation at high level through accurate fairness based resource allocation. The term "cooperate" does not only mean relaying others' traffic, but also includes providing other services, such as multimedia content sharing, printer facility sharing, etc. The importance of user cooperation in UCNETs can be easily understood as such a wireless system will be very limited in coverage and not reliable with only few services locally available in case of low or even medium number of users cooperatively sharing their resources.

Besides setting one of the goals to boost user-cooperation and connectivity sharing, the next fundamental issue to consider is to provide high speed transmission over broadband wireless channels to cope with the requirement from the growth of wireless multimedia and data applications. The effect of severe frequency-selective fading in broadband channels is one of the most important obstructions on achieving today's satisfactory transmission rates. Orthogonal frequency division multiplexing (OFDM) is a well technique to eliminate this obstruction by dividing the broadband channel into a number of narrowband subchannels. Accordingly, the channel may be transformed to a frequency non-selective fading channel. This feature makes OFDM-based orthogonal frequency division multiple access (OFDMA) an attractive multiple access technique for high speed wireless communications systems and adopted in UCNETs.

In OFDMA, different subchannels are dynamically allocated to different users with the aim of optimizing a system performance, such as maximizing throughput or minimizing energy, while satisfying system constraints, such as bit-error-rate (BER), data rate or fairness. Multiuser diversity [2] is exploited to improve and achieve optimum possible performance in multiuser wireless systems by properly allocating resources to users depending on instantaneous conditions. It is provided in [3] that by allocating a single subchannel to the user which has the best channel condition, the best performance of the system can be achieved. However, when the number of subcarriers is large, subchannel-based allocation may have large overhead and be very complicated.

To mitigate the complexity and overhead of subchannel-based allocation schemes, the correlation between neighboring subchannels in OFDM systems can be exploited. A simplified RA, chunk-based RA, can be adopted by properly grouping set of adjacent subchannels into a chunk and do relevant RA per chunk [4]. The performance of chunk-based-allocation can approach to the performance of subchannel-based allocation. This is because, in OFDM systems most likely when a subchannel is good (or bad), its adjacent subchannels are also good (or bad) with quite similar channel quality [4].

The RA algorithm imposed in this paper constitutes chunk, power and bit allocation approaches. To maximize users' willingness for contributing to the network and behaving well, the achieved data rate proportions among users and resource allocation priorities are related to cooperation, trust and reputation (composite value) of users. Hence, a user that wants to enjoy high speed communications, high quality multimedia stream, non-intermittent connectivity, and so on, should become and stay as a highly cooperative and well behaving user. The RA algorithm also maintains the BER constraint of various applications and users' transmit power threshold.

In the proposed algorithm, non-greedy real-time multimedia streams and greedy non-real-time data streams for a user are considered and differentiated. In order to more precisely and efficiently manage resources for applications of users. In most work on RA, it is usually assumed that there is a single greedy

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application for a user, where there is no upper limit on usable data rate [3][4]. This is not very realistic for real-time streams which has maximum encoding rate. The unlimited data rate assumption for real-time applications can result in providing excess (unusable) resources to applications, which can lead to using resources inefficiently. Because of differentiating streams, an upper bound can be given to the data rate of real-time streams. In this paper, according to this upper bound, resources allocated to users are fine-tuned to reduce waste of resources. Note that when increasing the number of subchannels per chunk in the chunk-based RA, the maximum bits per symbol per chunk increases. When the number of subchannels per chunk is large, its achievable maximum bits per symbol per chunk may be larger than the upper bound data rate of the real-time application. Therefore, an important system design issue, the number of subchannels per chunk, in chunk-based systems can be related to this upper bound as well. The tradeoff here is between the reduction in computational complexity of RA algorithm (as number of subchannels in a chunk increases) and the increase in difference between total achievable data rate per chunk and real-time stream's upper bound, which will be analyzed in this paper.

II. SYSTEM MODEL

The OFDMA system is assumed to have M subcarriers and K active users. Each user is assumed to have two data streams – one real-time multimedia stream and one non-real-time data stream. Accordingly, there are $2K$ data streams in the system. In order to reduce the complexity of RA every M' contiguous subchannels are grouped in a chunk [4]. Hence the system has $N = M / M'$ chunks and each of these chunks is allocated to one stream of a user. RA period is taken to be τ ms.

All subchannels in the system are considered to be Rayleigh fading channels that introduce an additive white Guassian noise (AWGN) with a double-side power spectral density of $N_0/2$. The frequency response, $h_{k,m}$, of user k in channel m is complex Guassian distributed and its magnitude, called fading factor, $\alpha_{k,m}$, is Rayleigh distributed with unitary mean square, $E\{\alpha_{k,m}^2\} = 1$ for all k and m [4]. $h_{k,m}$ is further assumed independent for all users.

For the adaptive modulation scheme, denoting L as the level of modulation, *L-ary* QAM is employed in the system. Accordingly, the set from which L can take values is $\mathbf{L}$ = {0, 2^2, …, 2^b, …, 2^B} = {0, 4, …, L_b, …,L_B}, where b represents the total number of bits per symbol in the QAM and

$$L_b = \begin{cases} 0, & if\ b = 0 \\ 2^b, & if\ b\ is\ even\ and\ 0 < b \le B \end{cases} \quad (1)$$

If mth subchannel is allocated to the kth user and the allocated power is $\varepsilon_{k,m}$, the instantaneous bit-error-rate $\beta_{k,m}$, can be approximated in closed form as [5]

$$\beta_{k,m} \approx 0.2\exp\left(-\frac{1.6 \cdot SNR_{k,m}}{l_{k,m} - 1}\right) = 0.2\exp\left(\frac{c \cdot \varepsilon_{k,m} \cdot \alpha_{k,m}^2}{l_{k,m} - 1}\right) \quad (2)$$

where the received signal to noise ratio, $SNR_{k,m}$, is given by

$$SNR_{k,m} = \frac{\varepsilon_{k,m} \cdot T_s \cdot \alpha_{k,m}^2}{N_0} \quad (3)$$

, and c = -1.6 T_s/N_0 where T_s is the symbol duration.

From (2), the achievable bits/symbol, $r_{k,m}$, of the kth user on the mth subchannel can be derived as

$$r_{k,m} = b_{k,m} = \log_2 l_{k,m} = \log_2\left(1 + \frac{c \cdot \varepsilon_{k,m} \cdot \alpha_{k,m}^2}{\ln(5\beta_{k,m})}\right). \quad (4)$$

It can be seen that the modulation level, $l_{k,m}$, and the achievable bits/symbol, $r_{k,m}$, are proportional to fading factor (channel quality).

In the case of chunk-based resource allocation, where a number of contiguous subchannels are grouped into a chunk, the modulation level and transmit power per subchannel is the same for all subchannels within a chunk. By defining $\tilde{l}_{k,n}$ and $\tilde{\varepsilon}_{k,n}$ as the modulation level and the assigned power per subchannel in the nth chunk for the kth user, we can obtain $l_{k,m} = \tilde{l}_{k,n}$ and $\varepsilon_{k,m} = \tilde{\varepsilon}_{k,n}$, where $m = nM, \ldots, (n+1)M' - 1$.

Therefore, the average BER, $\beta_{k,n}$, of the kth user on nth chunk can be given as

$$\beta_{k,n} = \frac{1}{M'}\sum_{m=nM'}^{(n+1)M'-1}\beta_{k,m} = \frac{1}{M'}\sum_{m-nM'}^{(n+1)M'-1} 0.2\exp\left(\frac{c \cdot \varepsilon_{k,m} \cdot \alpha_{k,m}^2}{l_{k,m} - 1}\right). \quad (5)$$

According to [4] $\beta_{k,n}$ can be approximated as

$$\beta_{k,n} \approx 0.2\exp\left(\frac{c \cdot \tilde{\varepsilon}_{k,n} \cdot \tilde{\alpha}_{k,n}^2}{\tilde{l}_{k,n} - 1}\right) \quad (6)$$

where

$$\tilde{\alpha}_{k,n}^2 = \frac{1}{M'}\sum_{m=nM'}^{(n+1)M'-1}\alpha_{k,m}^2 . \quad (7)$$

Furthermore considering the achievable bits/symbol, $r_{k,m}$; since modulation levels of all subchannels within a chunk are the same, $r_{k,m}$ on all subchannels will also be the same. Hence, the achieved bits/symbol/subchannel on the nth chunk for the kth user can be given as

$$\tilde{r}_{k,n} = \tilde{b}_{k,n} = \log_2 \tilde{l}_{k,n} = r_{k,nM'} \quad (8)$$

where $r_{k,nM'}$ is given by (4). And the total bits/symbol/chunk, rate achieved by a chunk, $r_{total}(k,n)$, is calculated by $M'\tilde{r}_{k,n}$.

III. CHUNK, POWER AND BIT ALLOCATION

In the UCNET, enjoying high-speed data and high-quality multimedia services rather than slow data and low-quality multimedia services, in a fair way depending on users' composite value, is an adequate incentive for network users to share their resources and provide cooperation. Therefore, in order to boost users' willingness of sharing resources and cooperation, a dynamic fairness-based resource allocation scheme is proposed in this section to provide better service to better behaving users, by adopting a composite value c_k to represent the *k*th user's cooperation, trust and reputation in the network. That is, more cooperative, trustful and reputed users will get more resources than average and/or bad behaving users. To achieve the target of the proposed RA, the aim of the dynamic resource allocation approach is to maximize the uplink throughput meanwhile to balance the tradeoff between capacity and fairness.

An objective function is set up to maximize the uplink throughput under relevant constraints, one of which is to ensure proportional fairness with respect to users' composite value. Also the BER constraint of applications and the transmit power constraint of users are taken into account.

As mentioned in Section I, to be able to differentiate between streams of a user, an additional parameter q is introduced in the formulation to represent the index of streams (q = 0 for non-real-time, q = 1 for real-time). Hence, for the fairness-based RA, the optimization problem is formulated as

$$R_{total} = \max_{\tilde{b}_{k,n,q},\rho_{k,n,q}} \sum_{k=0}^{K-1}\sum_{n=0}^{N-1}\sum_{q=0}^{1}\rho_{k,n,q}M'\tilde{b}_{k,n,q} \tag{9}$$

subject to

$$\rho_{k,n,q} = \{0,1\} \; and \; \sum_{k=0}^{K-1}\sum_{q=0}^{1}\rho_{k,n,q} \le 1 \; for\ all\ n, \tag{9a}$$

$$\sum_{n=0}^{N-1}\sum_{q=0}^{1}\rho_{k,n,q}M'\tilde{\varepsilon}_{k,n,q} \le \varepsilon_0 \; for\ all\ k, \tag{9b}$$

$$\sum_{n=0}^{N-1}\rho_{k,n,1}M'\tilde{b}_{k,n,1} \le \overline{R}_{\max,\mathrm{Realtime}} \; for\ all\ k, \tag{9c}$$

$$\begin{aligned} &R_{0,0} : R_{0,1} : \ldots : R_{K-1,q=0} : R_{K-1,q=1} \\ &= \gamma_{0,0} : \gamma_{0,1} : \ldots : \gamma_{K-1,q=0} : \gamma_{K-q,q=1} \end{aligned} \tag{9d}$$

where $\rho_{k,n,q}$ indicates whether *n*th chunk is allocated to the *q*th stream of *k*th user (i.e $\rho_{k,n,q} = 1$) or not (i.e $\rho_{k,n,q} = 0$). Constraint (9a) ensures that a chunk can be allocated only to one data-stream of a user. Constraint (9b) makes sure that the total aggregated transmit power of a user does not exceed the preset transmit power threshold ε_0. The maximum achievable encoded data rate limit for real-time streams is provided by constraint (9c). $\overline{R}_{\max,\mathrm{Realtime}}$ is the threshold for maximum data rate that real-time streams can be enabled. This upper limit is useful to prevent waste of allocating excess data rate (and transmit power) since real-time applications cannot benefit from greater data rate than what they actually need. The last constraint, (9d), is used to ensure reception of proportional capacity between users based on their composite value. $\{R_{k,q}\}_{k=0,q=0}^{K-1,1}$ is the total data rate reached by the *q*th application of *k*th user and it is defined as

$$R_{k,q} = M'\sum_{\Omega_{k,q}}\log_2\left(1+\frac{c\cdot\tilde{\varepsilon}_{k,n,q}\cdot\tilde{\alpha}^2{}_{k,n}}{\ln(5\overline{\beta})}\right) for\ all\ k\ and\ q, \tag{10}$$

where $\Omega_{k,q}$ is the set of chunks allocated for *q*th application of *k*th user. $\{\gamma_{k,q}\}_{k=0,q=0}^{K-1,1}$ in (9d) is the proportion value of the *q*th application of the *k*th user to ensure proportional fairness based on users' composite value, and it is defined as

$$\gamma_{k,0} = \gamma_{k,1} = (c_k)/c_0 + c_1 + \cdots + c_{K-1}, \; for\ all\ k. \tag{11}$$

Optimization problem in (9) is difficult to solve as it contains both continuous variables, such as $\tilde{\varepsilon}_{k,n,q}$, and binary variables, such as $\rho_{k,n,q}$. Further the nonlinear constraints of the problem increase the difficulty in finding the optimum solution. Therefore, a suboptimal approach dividing the resource allocation process into two steps is proposed in this section to simplify the RA problem. The first step is chunk allocation that is based on users' proportional fairness requirements and their channel quality. The second step is the joint power and bit allocation, which is based on the users' total transmit power and applications BER constraint.

A. Chunk Allocation

The basic idea is to allocate chunks with bests channel quality to users as much as possible. At each chunk allocation iteration if *q*th stream of the *k*th user has lowest proportional capacity $R_{k,q}/\gamma_{k,q}$, for this user, the chunk with best channel quality is detected among set of available chunks A. Initially, A includes all the chunks. Once the chunk is allocated to the *q*th stream, this chunk is removed from A and the stream's value of achieved proportional capacity is updated.

At chunk allocation, equal power allocation is assumed across all chunks. This results in a suboptimal allocation but it should be done to avoid prohibitive computational burden, in case of joint allocation of chunks and power. The algorithm for suboptimal chunk allocation is described as follows

1) *Initialization*

a) Set $R_{k,q} = 0$, $\Omega_{k,q} = \varnothing$ for all k and q and A = {0, 1, …, N-1} where $\varnothing$ stands for empty set.

2) *Chunk Allocation*

a) Find k and q satisfying

$$\frac{R_{k,q}}{\gamma_{k,q}} \le \frac{R_{i,q}}{\gamma_{i,q}} \; among\ all\ i = \{0,1,\ldots,K-1\}\ and\ q = \{0,1\}$$

b) Find n satisfying $\tilde{\alpha}_{k,n}^2 \ge \tilde{\alpha}_{k,j}^2$ for all $j \in A$

c) Let $\Omega_{k,q} = \Omega_{k,q} \cup \{n\}$, $A = A - \{n\}$ and update $R_{k,q}$ according to (10)

After chunk allocation, the set of chunks allocated to the *q*th stream of the *k*th user is, $\Omega_{k,q}$, known for all users and streams and $\Omega_{k,q}$ are disjoint for all k and q and

$\Omega_{0,0} \cup \Omega_{0,1} \cup \ldots \cup \Omega_{K-1,q=0} \cup \Omega_{K-1,q=1} \in \{0,1,\ldots,N-1\}$. Now our goal of maximizing sum capacity, while satisfying constraints and maintaining proportional fairness, becomes a computationally feasible problem.

B. *Power and Bit Allocation*

For a certain determined chunk allocation, the optimization problem can be formulated as

$$R_{total} = \max_{\widetilde{b}_{k,n,q}} \sum_{k=0}^{K-1} \sum_{q=0}^{1} \sum_{n \in \Omega_{k,q}} M' \widetilde{b}_{k,n,q} \tag{12}$$

subject to

$$\sum_{q=0}^{1} \sum_{n \in \Omega_{k,q}} M' \widetilde{\varepsilon}_{k,n,q} \le \varepsilon_0 \ \textit{for all } k \tag{12a}$$

$$R_{k,1} = \sum_{n \in \Omega_{k,1}} M' \widetilde{b}_{k,n,1} \le \overline{R}_{\max,\mathrm{Re}altime} \ \textit{for all } k \tag{12b}$$

$$\begin{aligned} &R_{0,0} : R_{0,1} : \ldots : R_{K-1,q=0} : R_{K-1,q=1} \\ &= \gamma_{0,0} : \gamma_{0,1} : \ldots : \gamma_{K-1,q=0} : \gamma_{K-1,q=1} \ \textit{for all } k \textit{ and } q. \end{aligned} \tag{12c}$$

The optimization problem in (12) can be solved by using Lagrangian method, as shown in [6]. The solution of problem is equivalent to finding the maximum of following function

$$\begin{aligned} L = {} & M' \sum_{k=0}^{K-1} \sum_{q=0}^{1} \sum_{n \in \Omega_{k,q}} \widetilde{b}_{k,n,q} + \sum_{k=0}^{K-1} \lambda_k \left(\sum_{q=0}^{1} \sum_{n \in \Omega_{k,q}} M' \widetilde{\varepsilon}_{k,n,q} - \varepsilon_0 \right) \\ & + \sum_{k=0}^{K-1} \mu_k \left(\sum_{n \in \Omega_{k,1}} M' \widetilde{b}_{k,n,q} - \overline{R}_{\max,\mathrm{Re}altime} \right) \\ & + \sum_{k=1}^{K-1} \sum_{q=0}^{1} \eta_{k,q} \left(R_{0,0} - \frac{\gamma_{0,0}}{\gamma_{k,q}} R_{k,q} \right) + \eta_{0,1} (R_{0,0} - R_{0,1}) \end{aligned} \tag{13}$$

where λ_k, μ_k and $\eta_{k,q}$ are Lagrangian parameters.

Following the Lagrangian method to find the optimum power allocation for user *k*, we differentiate (13) with respect to $\widetilde{\varepsilon}_{k,n,q}$ and set each derivative to 0 to obtain

$$\left. \frac{\partial L}{\partial \widetilde{\varepsilon}_{k,n,q}} \right|_{k \ge 1} = M' \frac{\partial \widetilde{b}_{k,n,q}}{\partial \widetilde{\varepsilon}_{k,n,q}} + \lambda_k M' + \mu_k M' \frac{\partial \widetilde{b}_{k,n,1}}{\partial \widetilde{\varepsilon}_{k,n,1}} + \eta_{k,q} \left(-\frac{\gamma_{0,0}}{\gamma_{k,q}} \frac{\partial R_{k,q}}{\partial \widetilde{\varepsilon}_{k,n,q}} \right) \tag{14}$$

$$\left. \frac{\partial L}{\partial \widetilde{\varepsilon}_{0,n,0}} \right|_{\substack{k=0 \\ q=0}} = M' \frac{\partial \widetilde{b}_{0,n,0}}{\partial \widetilde{\varepsilon}_{0,n,0}} + \lambda_0 M' + \sum_{k=1}^{K-1} \sum_{q=0}^{1} \eta_{k,q} \left(\frac{\partial R_{0,0}}{\partial \widetilde{\varepsilon}_{0,n,0}} \right) \tag{15}$$

$$\left. \frac{\partial L}{\partial \widetilde{\varepsilon}_{k,n,1}} \right|_{\substack{k=0 \\ q=1}} = M' \frac{\partial \widetilde{b}_{0,n,1}}{\partial \widetilde{\varepsilon}_{0,n,1}} + \lambda_0 M' + \mu_0 M' \frac{\partial \widetilde{b}_{0,n,1}}{\partial \widetilde{\varepsilon}_{0,n,1}} + \eta_{0,1} \left(\frac{\partial R_{0,1}}{\partial \widetilde{\varepsilon}_{0,n,1}} \right). \tag{16}$$

By assuming that chunks *n* and *m* are allocated to *q*th application of *k*th user: i.e. *m* and $n \in \Omega_{k,q}$, optimal power distribution between chunks can be derived from (14) to (16) as follows. From (14), one obtains

$$\frac{\partial \widetilde{b}_{k,n,q}}{\partial \widetilde{\varepsilon}_{k,n,q}} = \frac{\partial \widetilde{b}_{k,m,q}}{\partial \widetilde{\varepsilon}_{k,m,q}} \tag{17}$$

Since $\widetilde{b}_{k,n,q}$ is given by (8),

$$\frac{\partial \widetilde{b}_{k,n,q}}{\partial \widetilde{\varepsilon}_{k,n,q}} = \frac{c \cdot \widetilde{\alpha}_{k,n}^2}{\ln(5\overline{\beta}) + c \cdot \widetilde{\alpha}_{k,n}^2 \cdot \widetilde{\varepsilon}_{k,n,q}} \cdot \frac{1}{\ln 2} \tag{18}$$

Replacing derivatives in (17) by (18) and letting $H_{k,n} = (c \cdot \widetilde{\alpha}_{k,n}^2) / \ln(5\overline{\beta})$, one obtains

$$\frac{H_{k,n}}{1 + \widetilde{\varepsilon}_{k,n,q} H_{k,n}} = \frac{H_{k,m}}{1 + \widetilde{\varepsilon}_{k,m,q} H_{k,m}}. \tag{19}$$

Without loss of generality, it can be assume that $H_{k,0} \le H_{k,1} \le \ldots \le H_{k,N_{k,q}-1}$ for all *k* and define $N_{k,q}$ as the number of chunks in $\Omega_{k,q}$, n_i^q as the *i*th chunk in the ascending list of chunks allocated to *q*th stream, where *i* = {0, 1, …, $N_{k,q}$ - 1}. Then, (19) can be rewritten as

$$\widetilde{\varepsilon}_{k,n_i^q,q} = \widetilde{\varepsilon}_{k,n_0^q,q} + \frac{H_{k,n_i^q} - H_{k,n_0^q}}{H_{k,n_i^q} H_{k,n_0^q}} \tag{20}$$

for *i* = 0, 1, …, $N_{k,q} - 1$, *k* = 0, 1, …, *K*-1 and *q* = {0, 1}. Equation (20) shows the power distribution on chunk *i* for the *q*th application of user *k*. It is shown that more power will be put on the chunks with higher channel quality. This matches the water-filling concept in resource allocation [7].

Defining $\varepsilon_{k,total}$ as the total power allocated for user *k* and using (20), $\varepsilon_{k,total}$ can be expressed as

$$\begin{aligned} \varepsilon_{k,total} = {} & \sum_{q=0}^{1} \sum_{i=0}^{N_{k,q}-1} \widetilde{\varepsilon}_{k,n_i^q,q} = N_{k,q=0} \widetilde{\varepsilon}_{k,n_0^{q=0},q=0} + N_{k,q=1} \widetilde{\varepsilon}_{k,n_0^{q=1},q=1} \\ & + \sum_{q=0}^{1} \sum_{i=1}^{N_{k,q}-1} \frac{H_{k,n_i^q} - H_{k,n_0^q}}{H_{k,n_i^q} H_{k,n_0^q}} = \varepsilon_0 \end{aligned} \tag{21}$$

for *k* = 0, 1, …, *K*-1, *i* = 0, 1, …, $N_{k,q} - 1$ and *q* = {0, 1}.

Further considering $\gamma_{k,0} = \gamma_{k,1}$ from (11) we can argue that the data rate achieved by both applications should be the same

$$\begin{aligned} & \sum_{i=0}^{N_{k,q=0}} \log_2 \frac{\left(\ln(5\overline{\beta}) + \left[\widetilde{\varepsilon}_{k,n_0^{q=0},q=0} + \frac{H_{k,n_i^{q=0}} - H_{k,n_0^{q=0}}}{H_{k,n_i^{q=0}} H_{k,n_0^{q=0}}} \right] \cdot H_{k,n_i^{q=0}} \right)}{\ln(5\overline{\beta})} = \\ & \sum_{i=0}^{N_{k,q=1}} \log_2 \frac{\left(\ln(5\overline{\beta}) + \left[\widetilde{\varepsilon}_{k,n_0^{q=1},q=1} + \frac{H_{k,n_i^{q=1}} - H_{k,n_0^{q=1}}}{H_{k,n_i^{q=1}} H_{k,n_0^{q=1}}} \right] \cdot H_{k,n_i^{q=1}} \right)}{\ln(5\overline{\beta})} \end{aligned} \tag{22}$$

The optimal power allocation $\widetilde{\varepsilon}_{k,n_i^q,q}$ for all *k*, *q* and *i* can be determined by applying numerical algorithms, such as Newton's root-finding method [6], to find the zero of (21) and (22). Then, achievable bits/symbol $\widetilde{b}_{k,n,q}$ is obtained from (4).

Now as fine-tuning step, excess bandwidth and energy from real-time stream of a user is transferred (recycled) to its non-real-time stream depending on the real-time stream's upper bound, b_{th}, and achieved rate.

IV. NUMERICAL RESULTS

In this section users' average throughput as a function of composite value c_k and the average system throughput with respect to the number of subchannels in a chunk (chunk size) is analyzed. Analysis is done to show the effectiveness of composite values in RA and differentiated streams on system design. Unless noted otherwise, the system parameters are assumed as follows: Number of subchannels M = 48 and chunk size M' = 2. The number of active users in the system K = 8 and the set of user composite values c_k = {1, 2, 3, 4}. Further, the BER of streams $\overline{\beta} = 10^{-3}$. The average signal to the noise ratio on each subchannel is 20dB.

Fig. 1 shows the users' average throughput as a function of composite value c_k (comp. val.). The results are presented as *bars* in the figure, where *bar*(*k,q*) represents $E(\widetilde{b}_{k,n,q})$, the average bits/symbol of *k*th user's *q*th stream, i.e. *bar*(*2,0*) represents average bits/symbol achieved by second user's real-time stream. With increased composite value, the rising trend of achieved bits/symbol for both streams can be clearly seen from figure. This boosts cooperation incentives of users to aim for higher composite value. Further, for greedy non-real time streams there is no limit for increase in $E(\widetilde{b}_{k,n,q})$, see *bar*(*k, 1*) at Fig. 1. However, due to upper limit (i.e. 12 bits/symbol in our experiments) the growth in $E(\widetilde{b}_{k,n,q})$ is limited for real-time streams, *bar(k, 0)*. The effect of upper limit is obvious in Fig. 1 when composite value c_k = 4. In RA fine-tuning, excess resources are recycled to non-real time streams to achieve higher useful throughput (see *bar*(*7,1*) and *bar*(*8,1*) at Fig. 1).

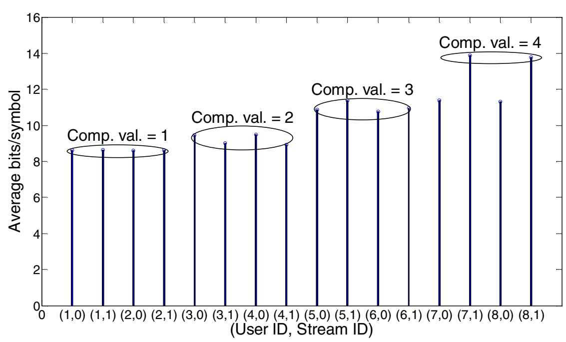

Fig. 1. Average bits/symbol versus (User ID, Stream ID) as function of composite value (comp. val.)

Average system throughput as a function of SNR for various chunk sizes M' is shown in Fig. 2. Significant increase in average system throughput with respect to increasing SNR shows the benefit of adaptive modulation. More important aspect at Fig. 2 is the system performance regarding chunk sizes M'. It can be seen that the performance is similar when M' = 1 and 2, one can achieve similar performance with subchannel-based RA while reducing complexity. However, when M' = 4 there is a significant degradation in system throughput. This is because, with more subchannels in a chunk, the achieved bits/symbol per chunk will be high and b_{th} will be violated frequently. Hence more recycling (re-allocation) of bandwidth and energy will cause larger deviation from the optimal chunk and power allocation. As result user's average throughput and system's throughput will reduce.

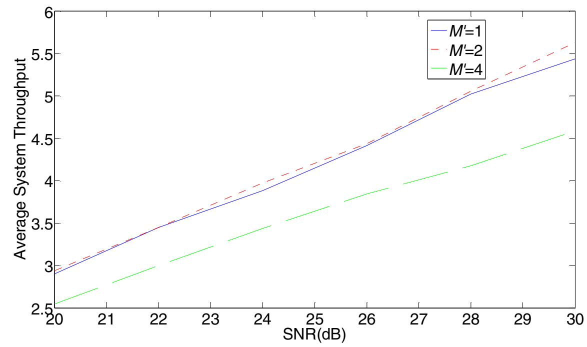

Fig. 2. Average system throughput versus SNR

V. CONCLUSION

A behavioral fairness-based chunk, power and bit allocation algorithm is presented. At the proposal, achievable rate proportions and RA priorities are related to composite value of users to maximize user willingness to contribute and behave well. The notion of differentiated streams in RA is another important aspect considered by the paper, as it enables resource recycling to achieve higher useful throughput / reduce waste of resources.

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