PROPORTIONAL FAIR SCHEDULING OF UPLINK SINGLE-CARRIER FDMA SYSTEMS

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ABSTRACT

We apply novel utility-based scheduling schemes to uplink single carrier frequency division multiple access (SC-FDMA) systems. Two utility functions are used for managing two dimensional resources (time and frequency): user data rate for maximizing system capacity and logarithmic user data rate for proportional fairness. To develop utility-based scheduling algorithms, we revise channel-dependent scheduling (CDS) schemes derived in our previous work [1]. The results show that proportional fair scheduling with logarithmic user data rate can improve the rate-sum capacity up to 100% for localized FDMA and 30% for interleaved FDMA, with the capacity gains equally shared among all users.

I. INTRODUCTION

High-speed wireless data transmission requires adaptive resource allocation to combat radio impairments. Channels with wide bandwidth may experience time and frequency selective fading. When the channel can be estimated, the transmission scheme can be adapted to changing channel characteristics by means of channel-dependent scheduling, adaptive modulation and coding or power control.

In this paper, we investigate utility-based channel-dependent scheduling schemes of uplink single carrier frequency division multiple access (SC-FDMA) systems. SC-FDMA is drawing great attention as an attractive alternative to orthogonal frequency division multiple access (OFDMA) for uplink high speed data services in Long Term Evolution of 3GPP due to the lower peak-to-average-power (PAPR) in the time domain [1],[2],[3]. It can be viewed as DFT-spread OFDMA, where time domain data symbols are transformed to frequency domain by a discrete Fourier transform (DFT) before going through OFDMA modulation. SC-FDMA has two types of sub-carrier mapping: Localized FDMA (L-FDMA) and Interleaved FDMA (I-FDMA). In L-FDMA, the scheduler assigns consecutive sub-carriers to convey information from a particular user. The advantages of frequency selective diversity can be achieved in L-FDMA by assigning consecutive sub-carriers to a user with favorable channel conditions for the assigned sub-carriers. In I-FDMA, users are assigned sub-carriers that are distributed over the entire frequency band in order to avoid allocating adjacent sub-carriers that are simultaneously in a deep fade. By selecting users that have favorable channel conditions over the entire system bandwidth, we obtain multi-user diversity in an I-FDMA system.

A key question we would like to discuss is how we balance time and frequency resources fairly among users while achieving multi-user diversity and frequency selective diversity. To do so, we introduce utility-based scheduling and consider two different utility functions: aggregate user data rate for maximizing system capacity and aggregate logarithmic user data rate for maximizing proportional fairness. In this paper, the channel-dependent scheduling methods proposed in our previous work [1] are revised to provide tractable algorithms for utility-based scheduling.

Utility-based adaptive resource allocation has been studied previously in [4],[5],[6],[7]. Reference [4] defines a model of utility that represents user satisfaction and derives a distributed power control scheme that maximizes the utility of each user. References [5,6] formulate a cross-layer optimization problem in order to maximize a utility function in a downlink OFDMA system. They propose an iterative sorting search algorithm for dynamic sub-carrier allocation and adaptive power allocation. The results show that fairness is achieved by means of the behavior of a marginal utility function. In [7], a simplified scheduling scheme for proportional fairness has been proposed using logarithmic average user data rate. However, the proposed method only allows single user transmission at a time which is not a general case of OFDMA.

Seeking optimal sub-carrier allocation algorithms in uplink SC-FDMA systems by solving a standard form of optimization problem is extremely complex for two reasons: 1) The objective function is formulated as a complex form dependent on chunk allocation and ; 2) There is an additional power constraint for each user. Therefore, finding a tractable solution in resource allocation is a challenging task for uplink data transmission.

This paper is organized as follows: Section II reviews a measure of system capacity when the minimum mean square error (MMSE) frequency domain equalizer (FDE) is employed in the receiver. Section III describes utility-based scheduling schemes for both I-FDMA and L-FDMA. The system analysis including the scheduling schemes and per-

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formance measures is discussed in section IV. Section V presents conclusions.

II. SC-FDMA SYSTEMS

We consider time synchronized uplink SC-FDMA transmission with system bandwidth B Hz. The time axis is divided into transmit time intervals (TTIs) as a basic unit of time scheduling (e.g. 0.5msec). The total bandwidth is partitioned into L sub-carriers. A set of sub-carriers comprises a chunk, and one or multiple chunks can be allocated to each user in each TTI. The number of sub-carriers per chunk is $M= L/N$, where N denotes the number of chunks. Thus, the number of sub-carriers in a chunk is regarded as a minimum resource unit for sub-carrier allocation in the frequency domain. There are two types of sub-carrier mapping: L-FDMA and I-FDMA. A chunk in an L-FDMA system consists of M consecutive sub-carriers. Sub-carriers in a chunk of I-FDMA are distributed over the entire bandwidth with equi-distance frequency spacing. Fig. 1 shows an example of chunk structures for I-FDMA and L-FDMA, where there are 16 sub-carriers and 4 chunks.

We assume that the base station has perfect knowledge of the channel gains of all users in the time and frequency domains. The data constellations of the allocated users are also determined in the base station, and transmitted to the terminals via downlink control signals. In general, different transmit powers or different bit constellations can be allocated to the different chunks when a user occupies multiple chunks. Similar to OFDMA, chunk-based greedy power and bit loading can be employed with SC-FDMA. However, the improvement in throughput may not be significant enough to justify the added complexity. As a realistic solution, we consider equal-bit-equal-power (EBEP) allocation for each chunk. Thus, we assume that the power assigned to each sub-carrier is determined as $P_k^{(sub)}=P_k/|I_{sub,k}|$, where P_k is the total transmit power of user k, $I_{sub,k}$ is the sub-carrier index set assigned to user k, and $|I_{sub,k}|$ is the number of sub-carriers assigned to user k. $I_{ch,k}$ is the assigned chunk set of user k and $I_{sub}^{(n)}$ denotes the set of sub-carriers in chunk n.

$$I_{sub,k} = \bigcup_{n\in I_{ch,k}} I_{sub}^{(n)} \tag{1}$$

Then, the SNR for the data delivered by chunks in $I_{ch,k}$ can be derived as (2) when minimum mean square error frequency domain equalization is implemented in the receiver to mitigate inter-symbol interference [1].

$$\gamma\left(P_k, I_{ch,k}\right) = \left(\frac{1}{\frac{1}{\left|I_{sub,k}\right|}\sum_{i\in I_{sub,k}} \frac{\gamma_{i,k}}{\gamma_{i,k}+1}} - 1 \right)^{-1}, \gamma_{i,k} = \frac{P_k^{(sub)} H_{i,k}}{\sigma_i^2} \tag{2,3}$$

where σ_i^2 is the noise power of sub-carrier i, and $H_{i,k}$ is the channel gain of sub-carrier i for user k. $\gamma_{i,k}$ is the SNR of sub-carrier i for user k. Using Shannon's formula, the achievable data rate of user k with chunks $I_{ch,k}$, has upper bound

$$C_k\left(P_k, I_{ch,k}\right) = \frac{B\left|I_{ch,k}\right|}{N}\cdot \log_2\left[1+\gamma\left(P_k, I_{ch,k}\right)\right] \text{ (bps).} \tag{4}$$

III. UTILITY-BASED SCHEDULING: CHUNK ALLOCATION

Utility is an economic concept representing level of satisfaction, and it is used for balancing the efficiency and fairness among users [4]. Since user data rate is a key parameter to determine user satisfaction in wireless communications, utility can be defined as a monotonically increasing function of user data rate. Our objective is to find utility-based EBEP chunk allocation. Thus, a general optimization problem is formulated as (5), where the goal is to find an optimum index set of the assigned chunks $I_{ch,k}$, for all users in order to maximize the sum of user utility at T-th TTI. A superscript T is added in the equations to denote time index.

$$\max \sum_{k=1}^{K} U\left(R_k^{(T)} \middle| P_k, I_{ch,k}^{(T)}\right) \tag{5}$$

To calculate data rate for a given SNR, we use the upper bound of achievable data rate in (4). Therefore, the instantaneous data rate of user k at t-th TTI is represented as $C_k^{(t)}(P_k, I_{ch,k}^{(t)})$. Then, the average data rate of user k over T TTIs is calculated as (6).

$$\left[R_k^{(T)} \middle| P_k, I_{ch,k}^{(T)}\right] = \frac{1}{T}\sum_{t=1}^{T} C_k^{(t)}\left(P_k, I_{ch,k}^{(t)}\right) \text{ (bps)} \tag{6}$$

The orthogonality of the users stems from the fact that each user occupies different sub-carriers:

$$\text{If } n\in I_{ch,j}\text{, then } n\notin I_{ch,k} \text{ for } j,k\in\{1,2,\cdots,K\}, j\neq k \tag{7}$$

For EBEP allocation, the transmit power of each sub-carrier $P_k^{(sub)}$ is determined by (8).

$$P_k = P_{\max} \rightarrow P_k^{(sub)} = \frac{P_{\max}}{\left|I_{sub,k}\right|} \tag{8}$$

If the user data rate is regarded as a utility function, the resource allocation with the objective function in (5) with constraints in (7) and (8) maximizes rate-sum capacity ignoring fairness among users. Therefore, only some users near the base station may occupy most of the resources. On the other hand, logarithmic user data rate as a utility function provides proportional fairness as shown in [7]. The optimum solution entails combinatorial comparisons with high complexity since the optimization problem has a nonlinear objective function with nonlinear and discrete constraints. Instead of solving the optimization problem, we provide a chunk allocation scheme improving the marginal utility using the following procedures.

A. Localized FDMA

We define the marginal utility as the difference between the utility obtained when chunk n is allocated to user k and the utility of user k in the absence of a chunk allocation at the current TTI. In order to shorten the description, we omit the superscript of time index hereafter.

$$\Lambda_{n,k} = U\left(R_k \middle| I_{ch,k} = \{n\}\right) - U\left(R_k \middle| I_{ch,k} = \{\phi\}\right) \tag{9}$$

Using (9), a necessary rule for optimality is derived as follows.

Property 1. If A^* is a set of users with chunk allocations that maximize the sum in (5), the selected user for each chunk lies in the set of N-th best users with respect to the marginal utility derived in (9) with the chunk.

$$A^* = [a_1, a_2, \cdots, a_N] \rightarrow a_n \in S_{ch,n} = [b_{n,1}, b_{n,2}, \cdots, b_{n,N}] \text{ for } \forall n \quad (10)$$

$$b_{n,i} = \arg \max_{k \in [1,2,\cdots,K]}^{(i)} \Lambda_{n,k} \quad (11)$$

In (10) and (11), a_n is the user allocated chunk n. $S_{ch,n}$ is a set of best users (N users) where each element $b_{n,i}$, denotes the i-th highest user with respect to the marginal utility with chunk n. This property can be proven by contradiction of the converse.

- Greedy chunk allocation based on marginal utility

From property 1, we pick N best users per chunk with respect to the marginal utility in (9), and add them into the set of available users.

Initialization: Add all chunks to the set of available chunks I_{avail_chunk} and N best users per each chunk are regarded as the candidates to assign the chunk.

$$I_{avail\_chunk} = \{1, 2, \cdots, N\}, S_{ch,n} = [b_{n,1}, b_{n,2}, \cdots, b_{n,N}], \forall n \quad (12)$$

Step 1 (Chunk selection): Find a chunk which has the highest marginal utility defined in (9) among all available chunks and users. For each available user j and chunk n, find the pair, where

$$[n^*, j^*] = \arg \max_{n \in I_{avail\_chunk}, j \in S_{ch,n}} \Lambda_{n,j} \quad (13)$$

Step 2 (Chunk allocation): Find a user (k) who can maximize the marginal utility when chunk n* is additionally allocated to a user and the utility without chunk n*. Then, allocate chunk n* to user k* as follows.*

$$\tilde{I}_{ch,k} = I_{ch,k} \cup \{n^*\} \text{ for } \forall k \in S_{ch,n^*} \quad (14)$$

$$k^* = \arg \max_{k \in I_{avail\_user}} \left[U\left(R_k \middle| P_{\max}, \tilde{I}_{ch,k}\right) - U\left(R_k \middle| P_{\max}, I_{ch,k}\right) \right] \quad (15)$$

$$I_{ch,k^*} = I_{ch,k^*} \cup \{n^*\} \quad (16)$$

Step 3: Delete the chunk from the set of available chunks i.e. I_{avail_chunk}=I_{avail_chunk}-{n^*}. Repeat steps 1, 2 and 3, until all chunks are allocated.

The steps above assign each chunk to the user obtaining highest marginal utility for a given chunk. However, it is neither necessary nor sufficient for optimality.

B. Interleaved FDMA

Since each chunk in I-FDMA consists of distributed sub-carriers, the channel quality is similar for all chunks. Therefore, chunk allocations similar to the approach taken with L-FDMA do not provide significant improvements. Instead, the scheduling for I-FDMA aims to allocate a chunk to the user that can obtain highest marginal utility. At first, we define a representative channel gain to noise ratio for user k over the entire set of sub-carriers:

$$\Omega_k \equiv \frac{1}{L} \sum_{l=1}^{L} \frac{H_{l,k}}{\sigma_l^2} \quad (17)$$

Then, we estimate SNR of the data delivered with $N_{ch,k}$ chunks as

$$\tilde{\gamma}(P_k, N_{ch,k}) = \frac{P_k}{MN_{ch,k}} \Omega_k, \quad (18)$$

which is derived from (2) by replacing each $H_{l,k}/\sigma_l^2$ with Ω_k. Using (18), the instantaneous data rate of user k is estimated as (19) and the estimate of average data rate of user k at T-th TTI is updated as (20). Superscript (t) is added into the equations to represent the time index.

$$\tilde{C}_k^{(t)}\left(P_k, N_{ch,k}^{(t)}\right) = \frac{BN_{ch,k}^{(t)}}{N} \log_2\left[1 + \tilde{\gamma}\left(P_k, N_{ch,k}^{(t)}\right)\right] \text{ (bps)} \quad (19)$$

$$\left[\tilde{R}_k^{(T)} \middle| P_k, N_{ch,k}^{(T)}\right] = \frac{1}{T}\left[\sum_{t=1}^{T-1}\left\{C_k^{(t)}\right\} + \tilde{C}_k^{(T)}\left(P_k, N_{ch,k}^{(T)}\right)\right] \text{ (bps)} \quad (20)$$

$C_k^{(t)}$ is the actual and instantaneous data rate transmitted over t-th TTI. We omit the superscript of time index hereafter. Similar to the case of L-FDMA, we define an estimate of marginal utility as

$$\tilde{\Lambda}_k = U\left(\tilde{R}_k \middle| P_k, N_{ch,k} = 1\right) - U\left(\tilde{R}_k \middle| P_k, N_{ch,k} = 0\right) \quad (21)$$

Using (21), we identify the N best users as the candidates for chunk allocation.

$$I_{best} = \{a_1, a_2, \cdots, a_N\}, \; a_i = \arg \max_k^{(i)} \tilde{\Lambda}_k \quad (22)$$

where a_i is the user index of i-th best user with respect to $\tilde{\Lambda}_k$. Next, the objective is to find the number of assigned chunks for each user in set I_{best} and Fig. 3 shows the procedures of chunk assignment using greedy allocations. In Fig. 3, we have two operations: Greedy allocation and flooring.

- Greedy alloc.[N, I_{avail_user}, $\mathbf{N}_{ch}$] allocates N additional chunks to I_{avail_user} when a number of chunks are already allocated to each user. $\mathbf{N}_{ch}$ is a set of number of chunks allocated to each user in the set of I_{avail_user}. We repeat the following procedures until all N chunks are newly allocated.

$$k^* = \arg \max_{k \in I_{avail\_user}} \left[U\left(\tilde{R}_k \middle| P_k, N_{ch,k} + 1\right) - U\left(\tilde{R}_k \middle| P_k, N_{ch,k}\right) \right] \quad (23)$$

$$N_{ch,k^*} = N_{ch,k^*} + 1 \quad (24)$$

- Flooring: There is a restriction to chunk allocation where the number of sub-carriers assigned to each user should be a power of 2 in order to maintain equidistant sub-carrier mapping and lower PAPR. It follows that the number of assigned chunks per user is also a power of 2 if the number of sub-carriers per chunk is a power of 2. Thus, the number of assigned chunks derived in greedy allocation has to be floored to the nearest integer 2^x, $x \in \{1,2,\ldots,\log_2 N\}$ but the integer should be less than the number of assigned chunks required to be floored as (25).

$$N_{ch,k}^{F} = \lfloor N_{ch,k} \rfloor_{2^x},\ 2^x \le N_{ch,k},\ x \in \{1,2,\ldots,\log_2 N\} \quad (25)$$

To maintain equidistant sub-carrier mapping, chunks in I-FDMA have a tree structure as illustrated in Fig. 2. As shown in Fig 2, we can group the chunks so that the sub-carriers in the group are placed with equidistance as in Fig. 1 (b). If one set in a level is allocated to a user, the "descendent" sets can't be assigned to other users. Then, the following procedures referred from [8] are used for equidistant chunk/sub-carrier mapping.

- Chunk/Equidistant sub-carrier mapping

1) Find tree obeying the equidistance rule

2) Choose a user with the highest number of assigned chunks and select a set of chunks in the level which equals the number of assigned chunks. Eliminate all "descendent" sets in the tree.

3) Choose an available set for the user with the second highest number of assigned chunks and eliminate all "descendent" sets in the tree.

4) Repeat for all assigned users

Once the index of chunks assigned to each user is determined from the procedures above, we use (2), (3), and (4) to calculate the instantaneous data rate transmitted at the TTI. Thus, user data rate is updated as (6) with the instantaneous data rate.

IV. Performance Evaluations

We have simulated the utility-based scheduling schemes derived in the previous section. We compare them with the performance of a round-robin scheduling scheme. We have simulated frequency selective fading of K users at each TTI using (26) and (27), and collected the sum of average user data rate after a "system time (200 TTIs)", where the time duration of 1 TTI is 0.5 msec. The simulation is repeated over many times to obtain a statistical average. Path-loss and shadowing are generated randomly but they are assumed to be constant during the system time. Thus, each user is assumed to be stationary or slowly moving. We also assume that the multi-path fading component is time invariant over a TTI but changes independently at each TTI. Path-loss is modeled by (26) where the distance d (km) between user and the base station is randomly generated with the density function $f_d(d)=2d/D^2$. D denotes the cell radius which is set to 1 km.

$$L_{loss,k,dB} = 128.1 + 37.6\log_{10} d_k + \xi_k \quad (26)$$

where ξ_k is a shadowing parameter modeled by a normally distributed random variable with standard deviation 8 dB. We consider the multi-path fading channel in which a discrete time channel impulse response model is used as (27) where $T_s(=1/B)$ denotes the sampling time of multi-path components. Zeros are padded into the time domain so that the total length of $v(n)$ = L(total number of sub-carriers).

$$v(n) = \begin{cases} A \cdot \sqrt{P_{rel}(\tau_l)} \cdot w(\tau_l), & \text{if } nT_s = \tau_l \\ 0, & \text{Otherwise} \end{cases} \quad (27)$$

where w(τ_l) is a zero mean complex Gaussian noise process and τ_l is the propagation delay of path l. A is a normalized parameter such that the average power $E[\sum|v(n)|^2]$ =1 watt. $P_{rel}(\tau_l)$ is a relative power of path l. We consider a typical urban area propagation model with 6 tap setting specified in [13], as listed in table 1.

TABLE I
RELATIVE POWERS OF DELAY PROFILE [13]

Delay (μsec)	0.0	0.2	0.6	1.6	2.4	5.0
Rel.Pwr.(dB)	-3.0	0.0	-2.0	-6.0	-8.0	-10.0

The channel gain of sub-carrier i for user k can be expressed as (28) where $L_{loss,k}$ denotes a linear scale of path-loss and shadowing of user k assumed to be constant over all sub-carriers and the system time.

$$H_{i,k} = \frac{|V_k(i)|^2}{L_{loss,k}},\ V_k(i) = \sum_{l=1}^{L} v_k(l)\exp\left[-\frac{2\pi i l}{T_s}\right] \quad (28,29)$$

The simulation results in Figures 4-8 use the following abbreviations:

- R-L-FDMA: L-FDMA with N users selected by round-robin.
- S-L-FDMA: The proposed CDS method of L-FDMA.
- R-I-FDMA: I-FDMA with N users selected by round-robin.
- S-I-FDMA: The proposed CDS method of I-FDMA.

Fig. 4 and 5 show the rate-sum capacity where the sum of user data rates (Fig. 4) and the sum of the logarithmic user data rates (Fig. 5) are the utility functions. Fig. 6 and 7 show the average user data rate as a function of user distance from the base station. In Fig. 4 we see that the scheduling gain of the case of rate utility increases with increasing number of users. This is because the scheduler selects the closer users which can transmit with higher data rate in addition to the gain of selecting users in excellent channel condition. If there are more users, the possibility of locating some users at closer distance to the base station increases. As a result of this, the scheduled transmissions achieve significant improvements for both I-FDMA and L-FDMA. For the case of logarithmic rate utility in Fig. 5, the scheduling gain stops increasing beyond approximately 32 users. With 32 users, maximizing logarithmic rate utility can increase system capacity by a factor of 1.8 for L-FDMA and 1.26 for I-FDMA.

Comparing Fig. 6 and 7, we see that the scheduling scheme based on the logarithmic user data rate provides proportional fairness whose gains are shared among all users, while the gains of CDS are concentrated to the users near the base station when the user data rate is considered as the utility function. Fig. 8 shows the outage probability which is defined as P_r(user data rate<minimum required

data rate). Considering user capacity at 1% outage probability and minimum required rate of 144 Kbps, we can say that round-robin scheduling supports less than 20 users but our proposed schemes can support 24 users for I-FDMA and 48 users for L-FDMA. Table II compares round-robin scheduling and utility-based scheduling with logarithmic user data rate, with respect to system capacity, and fairness.

TABLE II
COMPARISONS OF UTLITY-BASED SCHEDULING AND ROUND-ROBIN SCHEDULING (LOGARITHMIC RATE UTILIITY)

Type	S-L-FDMA	R-L-FDMA	S-I-FDMA	R-I-FDMA
Rate-sum capacity (32 users)	18 Mbps	10 Mbps	12 Mbps	9.55 Mbps
Fairness (32 users)	0.417	0.334	0.352	0.334
User capacity	48 users	Less than 20	24 users	Less than 20

* Fairness = average user data rate of users at the cell boundary (900m-1km) / average user data rate.
* User capacity: Number of users allowed 1% outage probability when the minimum rate equals to 144 Kbps

V. CONCLUSIONS

In this paper, we developed utility-based channel dependent scheduling (CDS) schemes and showed that the proposed methods with logarithmic user data rate as a utility function provided proportional fairness with the gains of CDS shared among all users. L-FDMA with CDS is more desirable than I-FDMA because L-FDMA exploits frequency selective scheduling. Our schemes can be utilized to design efficient radio access networks for uplink SC-FDMA systems. A similar method can be applied to chunk-based uplink OFDMA systems as well.

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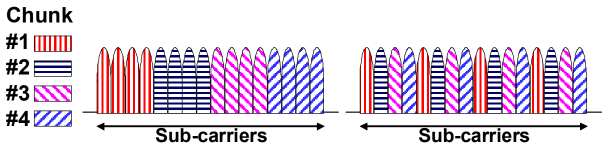

Fig. 1 An example of chunk structures (L:16,M:4) (a) L-FDMA (b) I-FDMA

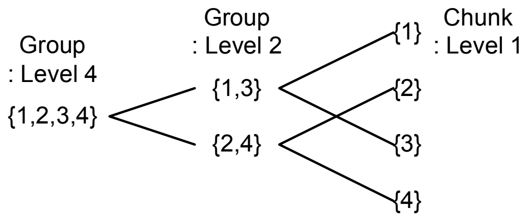

Fig. 2 An example of chunk tree structure (16 sub-carriers, 4 chunks)

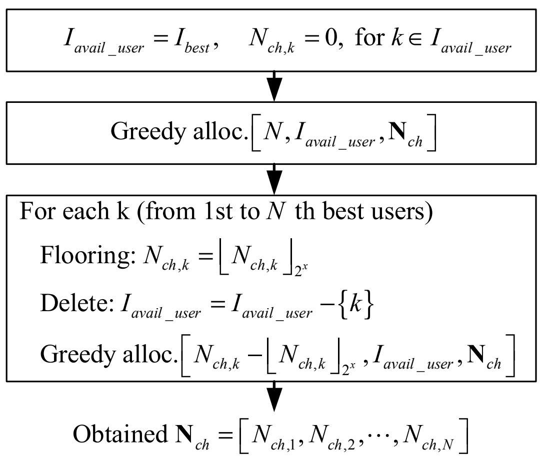

Fig. 3 Assignment of number of chunk for I-FDMA

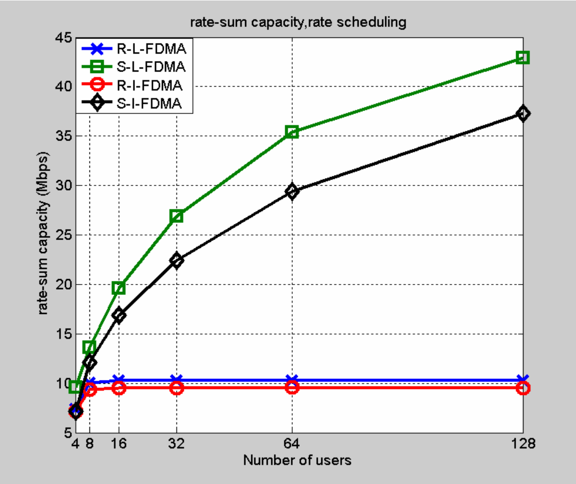

Fig. 4 Rate-sum capacity of shared users (utility: user data rate, L=256, N=8, B=5MHz, Noise power per Hz=-160dBm)

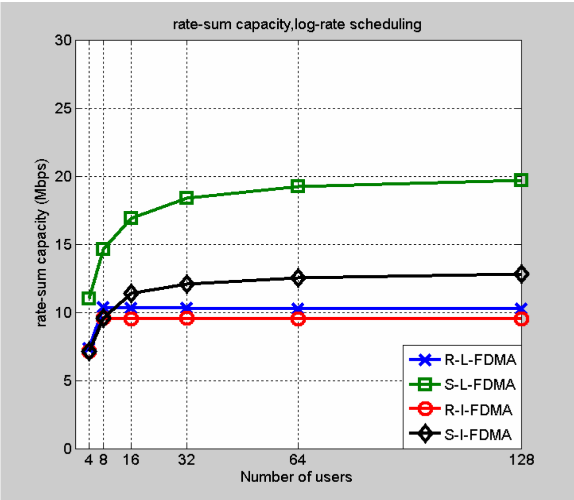

Fig. 5 Rate-sum capacity of shared users (utility: logarithmic user data rate, L=256, N=8, B=5MHz, Noise power per Hz=-160dBm)

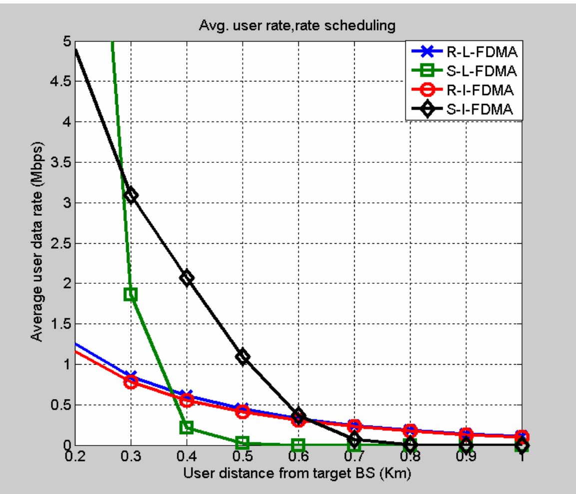

Fig. 6 Average user data rate between user distances (utility: user data rate, L=256, N=8, B=5MHz, Noise power per Hz=-160dBm)

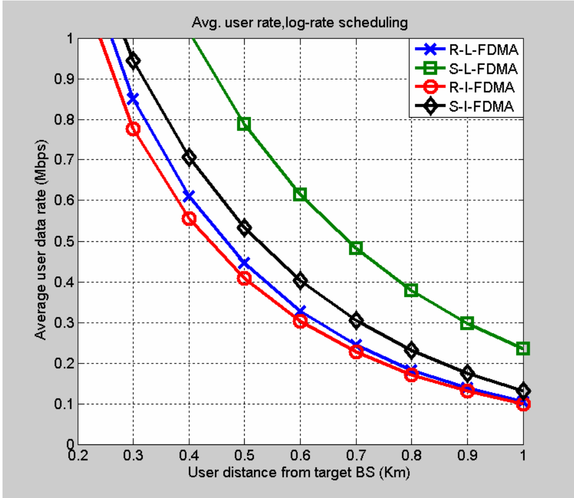

Fig. 7 Average user data rate between user distances (utility: logarithmic user data rate, L=256, N=8, B=5MHz, Noise power per Hz=-160dBm)

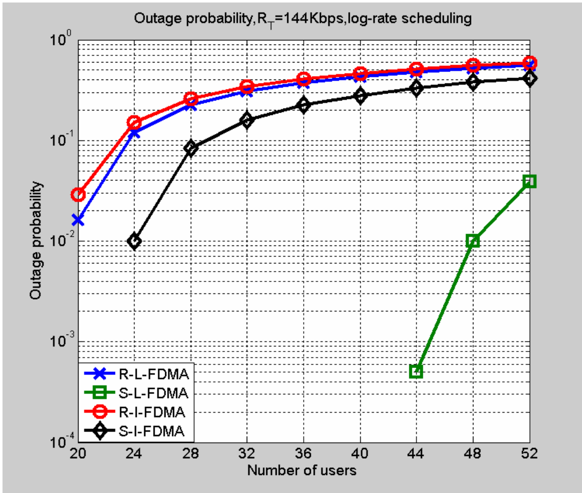

Fig. 8 Outage probability (utility: logarithmic user data rate, minimum required data rate=144Kbps, L=256, N=8, B=5MHz, Noise power per Hz=-160dBm)