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Utility-optimization dynamic subcarrier allocation algorithm for SC-FDMA systems①

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Abstract

Two utility-optimization dynamic subcarrier allocation (DSA) algorithms are designed for single carrier frequency division multiple access system (SC-FDMA). The two proposed algorithms aim to support diverse transmission capacity requirements in wireless networks, which consider both the channel state information (CSI) and the capacity requirements of each user by setting appropriate utility functions. Simulation results show that with considerable lower computational complexity, the first utility-optimization algorithm can meet the system capacity requirements of each user effectively. However, the rate-sum capacity performance is poor. Furthermore, the second proposed utility-optimization algorithm can contribute a better trade-off between system rate-sum capacity requirement and the capacity requirements of each user by introducing the signal to noise ratio (SNR) information to the utility function based on the first utility-optimization algorithm, which can improve the user requirements processing capability as well as achieve a better sum-rate capacity.

Key words: single carrier frequency division multiple access (SC-FDMA), dynamic subcarrier allocation (DSA), utility function, transmission capacity requirements, utility-optimization algorithm, greedy algorithm, proportional fair algorithm

0 Introduction

Single carrier frequency division multiple access (SC-FDMA) is proposed as a modified version of orthogonal frequency division multiple access (OFDMA) with similar transmission performance and overall complexity, which brings additional benefit of low peak-to-average power ratio (PAPR) and makes it suitable for uplink transmission by user-terminals. Therefore, SC-FDMA is more applicable for the high speed data services in the uplink with strictly limited transmit power. At present, SC-FDMA has been considered as an alternative multiple access technology to OFDMA in the 3rd generation partnership project long term evolution (3GPP LTE) for uplink data transmission[1,2].

Dynamic subcarrier allocation (DSA) is a kind of channel-aware scheduling, which performs frequency resource allocation based on the channel state information (CSI) observed by the base station. Due to the time-varying and mutually independent feature of wireless multi-path channel, the channel frequency response for different users and different subcarriers are almost uncorrelated. Therefore, a subcarrier for one user is in deep fading, but may be in good channel condition for other users, which can be referred to as the frequency selective nature of wireless channel. The key idea of DSA is to assign subcarriers to mobile terminals with favorable transmission characteristics. DSA scheduling takes the advantage of both the frequency selective nature and the system multiuser diversity to effectively relieve the pressure of scarce wireless resources caused by the increasing access demands of users in wireless networks[3,4]. Furthermore, DSA can also be a kind of service-oriented method to support different quality of service (QoS) by considering practical transmission requirements. For these reasons, DSA has been widely studied and applied in the uplink and downlink LTE systems. Traditional DSA algorithms, for example, the greedy algorithm[5], proportional fair algorithm[6] and max-min algorithm[7] all perform dynamic allocation based on the CSI of the physical layer, and compared with the static subcarrier allocation strategies such as round robin (RR) algorithm it can improve the spectral efficiency thereby enhancing system transmission performance. However,

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they all aim at optimizing the system rate-sum capacity or allocation fairness performance without considering practical transmission requirements in system. Therefore, the channel resource cannot be fully exploited for servicing each access user respectively, that means the allocation utility is low. In Ref. [8], a proportional rate constraint algorithm is proposed, which performs DSA subject to the predetermined allocation constraints. The proportional rate constraint algorithm can be considered as a kind of service-oriented algorithm by setting appropriate allocation constraints according to the transmission requirements of each user. However, the constraint-based allocation only takes effect in the special case when the number of subcarriers is larger than the number of users, therefore, the enhancement of allocation utility is definite and limited.

In order to overcome this drawback and further improve the allocation utility, two utility-optimization algorithms are proposed for meeting the service requirements of each access user in the SC-FDMA system. Both the two proposed utility-optimization algorithms take the advantage of the utility pricing structure to evaluate the CSI and transmission capacity requirements of each user at the same time. Therefore, the channel resource can be fully used for guaranteeing the system rate-sum capacity as well as satisfying the practical capacity demands of each user.

1 System model

Fig. 1 illustrates the DSA procedure of an uplink SC-FDMA system. Before allocation, the base station acquires CSI and transmission requirements of each user, and then decides appropriate allocation strategies according to the acquired information. Finally, the corresponding DSA schemes are transmitted to the mobile terminals via downlink control signals. In a practical SC-FDMA system, subcarriers have to be assigned in the form of "chunk" rather than individually, where each chunk consists of a subset of subcarriers and the number of subcarriers in each chunk is regarded as the

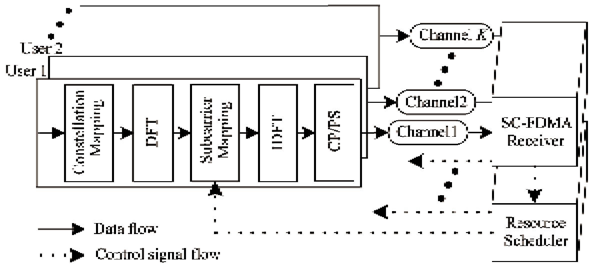

Fig. 1 SC-FDMA system DSA block diagram

minimum unit for each allocation. In this paper, the DSA algorithm applied in localized-FDMA (L-FDMA) system is considered with the allocation constrains that each user can get one or more than one chunks, while each chunk can be only assigned to one user during one transmission time interval (TTI)[9].

In this paper, a SC-FDMA system with K terminals, L subcarriers and N chunks is considered, so each chunk consists of $M = L/N$ subcarriers. The system adopts equal bit equal power (EBEP) allocation for each chunk[10]. Since SC-FDMA is a type of single carrier modulation technology which may suffer from the inter-symbol interference (ISI), the minimum mean square error (MMSE) frequency domain equalization is implemented in order to combat ISI[11]. Let $I_{ch,k}$ denote the set of chunks allocated to user k, and $|I_{sub,k}|$ represents the number of subcarriers assigned to user k, the signal to noise ratio (SNR) value of each user with MMSE equalization can be given by

$$\gamma_k(P_k, I_{ch,k}) = \left(\frac{1}{\dfrac{1}{|I_{sub,k}|} \times \sum\limits_{l \in I_{sub,k}} \dfrac{\gamma_{k,l}}{\gamma_{k,l}+1}} - 1 \right)^{-1} \quad (1)$$

where $\gamma_{k,l} = P_k^{(sub)} \times H_{k,l}/\sigma_l^2$ is the SNR of subcarrier l for user k, σ_l^2 is the noise power of subcarrier l, $H_{k,l}$ is the channel gain of subcarrier l for user k, P_k and $P_k^{(sub)}$ are the total power and the transmit power assigned to each subcarrier of user k, respectively.

Using Shannon's formula, the capacity of user k is

$$C_k(P_k, I_{ch,k}) = \frac{B \times |I_{ch,k}|}{N} \times \log_2[1 + \gamma_k(P_k, I_{ch,k})] \quad (2)$$

Hence, the rate-sum capacity of the SC-FDMA system can be computed as

$$C_{sum} = \sum_{k=1}^{K} C_k(P_k, I_{ch,k}) \quad (3)$$

2 Utility-optimization algorithm

Communication networks introduce the utility theory to evaluate the capability that system satisfies the transmission requirements of access users. Furthermore, the benefit of using certain system resources for practical transmission services can be measured by taking the advantage of utility function[12,13]. The basic idea of utility-optimization-based DSA scheduling is to map transmission requirements into the corresponding utility. Based on this structure, the system can handle multiple types of traffic in wireless networks by maximizing the aggregate utility with respect to the service requirements of each access user[14]. In this paper, four kinds of best effort traffics with different capacity requirements in Rayleigh channel environment are considered. During the allocation procedure, the scheduler evaluates both CSI and transmission requirements of each user by setting appropriate utility function. Thus, the channel resource can be fully exploited for guaranteeing diverse capacity demands. The objective function of the utility-optimization algorithm is

$$\max \sum_{k=1}^{K} U_k(C_k^{req}, C_k) \quad (4)$$

where U_k is the utility function of user k, C_k^{req} is the transmission capacity demand of user k.

2.1 The first utility-optimization algorithm

The first utility-optimization algorithm aims at satisfying the transmission requirements of each user in the system, which provides higher allocation priority for the access user with higher transmission capacity demand while in poor channel quality condition. According to the utility theory, the allocation priority in DSA scheduling depends on its corresponding utility function. Specifically, high utility implies high priority; otherwise the priority is low. It is assumed that the utility function U_k of the first utility-optimization algorithm for each user is proportional to its capacity demand while inversely proportional to its average channel capacity:

$$U_k = \frac{C_k^{req}}{C_k^{aver}} \quad (5)$$

where C_k^{aver} is the average capacity of user k, I_{chunk} is the set of all the chunks in the system.

$$C_k^{aver} = \frac{1}{|I_{chunk}|} \times C_k(P_k, I_{chunk}), \ k \in I_{user} \quad (6)$$

As shown in Eq.(2), the channel capacity of each user increases with its SNR. For simplifying the allocation procedure, the average capacity of user k is measured by its average SNR as shown in Eq.(7).

$$\gamma_k^{aver} = \frac{1}{|I_{chunk}|} \times \gamma_k(P_k, I_{chunk}), \ k \in I_{user} \quad (7)$$

Hence, the utility function of the first utility-optimization algorithm can be simplified as

$$U_k = \frac{C_k^{req}}{\gamma_k^{aver}} \quad (8)$$

The allocation procedure of the first utility-optimization algorithm is formulated in Fig.2, where $I_{user}^{all} = \{1,2,\cdots,K\}$ and $I_{user}^{unsat} = \{1,2,\cdots,K\}$ are the set of all users and the set of users with unsatisfied capacity requirements, respectively, $I_{chunk} = \{1,2,\cdots,N\}$ consists of all the available chunks.

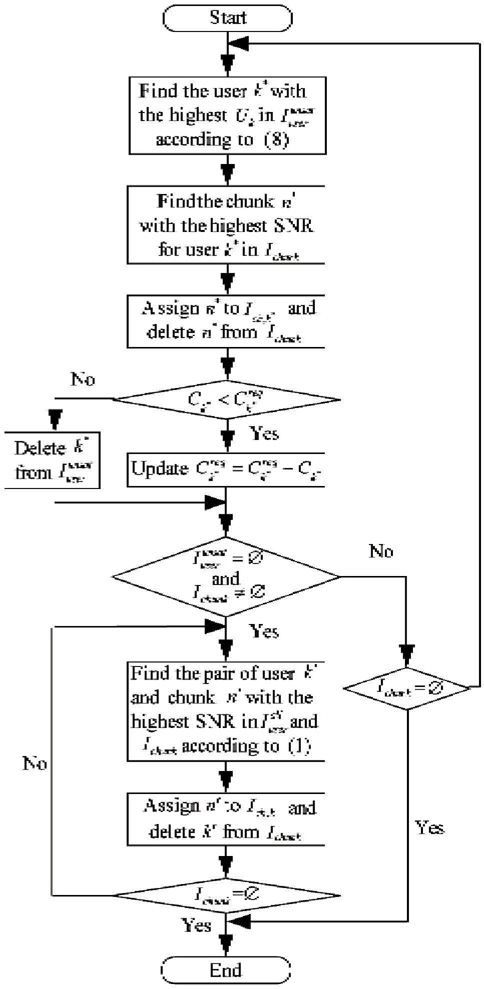

Fig. 2 Flow chart of the first utility-optimization algorithm

In order to achieve the objective of maximizing the total utility, the scheduler finds the user with the maximum utility during iterations, and then allocates the chunk which is in the best channel condition to that user. Thus, the channel resource can be fully exploited for supporting diverse capacity requirements.

2.2 The second utility-optimization algorithm

In some cases, the first utility-optimization algorithm has to allocate chunks to the users in poor channel condition in order to satisfy capacity demands of each user. That means the enhancement of user requirements processing capability is at the expense of the system capacity, therefore, it is not applicable for the transmission system with strict capacity requirements. For further improving allocation performance, the second utility-optimization algorithm is proposed by introducing SNR information based on the utility function of the first utility-optimization algorithm. The modified utility function can effectively enhance the user requirements processing capability by taking fully use of CSI during allocation, and at the same time provide higher allocation priority for the users in better channel condition, thereby achieving a better trade-off between system rate-sum capacity requirement and capacity demands of each user. The utility function of the second utility-optimization algorithm is given by

$$U_{k,n} = \gamma_{k,n} \times \frac{C_k^{req}}{\gamma_k^{aver}} \tag{9}$$

where $U_{k,n}$ is the utility function of user k for chunk n.

The allocation blow chart of the second utility-optimization algorithm is shown in Fig. 3. As shown in the figure, the scheduler of the second utility-optimization algorithm finds the pair of user and chunk with the maximum utility instead of only considering the user utility during allocation iterations.

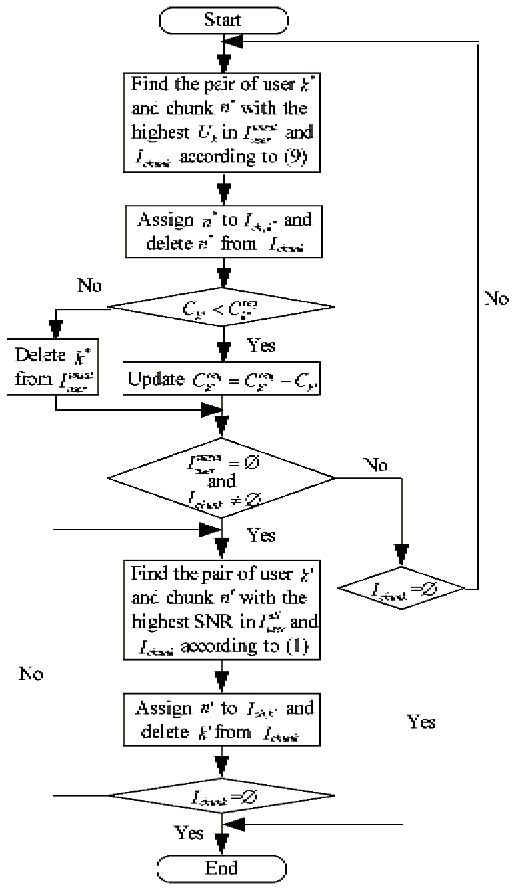

Fig. 3 Flow chart of the second utility-optimization algorithm

3 Computational complexity analysis

In this section, the computational complexity of all the considered DSA algorithms is analyzed.

3.1 Theoretical complexity analysis

Firstly, the theoretical complexity of the proposed algorithms in terms of the number of calculations is measured. For the SC-FDMA system with K users and N chunks, it is assumed that in each iteration the number of available chunks in I_{chunk} is n, and the number of users in I_{user}^{unsat} is k. When $K < N$, the first utility-optimization algorithm calculates the utility of each user and finds the user with the highest utility by taking $k + k - 1$ operations. Then the available chunk with the highest SNR is assigned to that user, which needs $n - 1$ comparisons. After that, the scheduler detects whether the capacity requirement of that user is satisfied and updates the C_k^{req} and I_{user}^{unsat} according to the comparison results. Since the following allocation process depends on the state of I_{chunk} and I_{user}^{unsat} which is unpredictable. The theoretical complexity of the proposed algorithms is measured by the maximum number of computational operations. On this condition, a special case is considered that the capacity requirements of users are always unsatisfied, and all the users need to participate in the next round of allocation. That means the number of users in I_{user}^{unsat} is unchanged as K. Furthermore, as the allocation constraints demand that each chunk can only be assigned to one user during each TTI, the number of available chunks in I_{chunk} keep on decreasing as the allocation goes on. In consequence, the theoretical complexity of the first utility-optimization algorithm is given by $\sum_{n=1}^{N}[K + (K-1) + (n-1) + 4] = 2NK + \frac{1}{2}(N^2 + 5N)$. When $K \geqslant N$, the system chunks are inadequate for servicing all the users and I_{user}^{unsat} will not be empty. Thus, the theoretical complexity of the first utility-optimization algorithm is given by $\sum_{n=1}^{N}[K + (K-1) + (n-1) - 2] = 2NK + \frac{1}{2}(N^2 + N)$.

Similarly, the theoretical complexity of the second utility-optimization algorithm can also be obtained. Moreover, the theoretical complexity of the proportional rate constraint algorithm and the greedy algorithm is summarized in Ref. [15]. Table 1 presents the theoretical complexity of all the considered DSA algorithms in this paper. Apparently, for the practical SC-FDMA

Table 1 Theoretical complexity for DSA algorithms

Algorithm	Computational complexity
The first utility-optimization algorithm	$K < N: 2NK + (N^2 + 5N)/2$ $K \geqslant N: 2NK + (N^2 + N)/2$
The second utility-optimization algorithm	$K < N: (N^2 + 2N)K + 3N$ $K \geqslant N: (N^2 + 2N)K + N$
Greedy algorithm	$(N^2 + 11N)K/2 - 2N$
Proportional rate constraint algorithm	$K < N: (K^3 + K)/2 + (N^3 - 3N)/2$ $K \geqslant N: (N^2 + N)K/2 - N$

system, when the number of chunks N is constant, all the DSA algorithms in Table 1 have linear complexity which increases with the number of user K, except the proportional rate constraint algorithm when $K < N$.

3.2 Actual computation time analysis

The actual computation time of all the considered algorithms is derived by simulation in order to further demonstrate the former theoretical analysis. As mentioned above, the theoretical complexity of the proposed two utility-optimization algorithms are measured by the maximum number of computation operations. In practice, the number of users in I_{user}^{all} will decrease during the iteration process, therefore, the actual computation time is much lower than the theoretical results. As shown in Fig. 4, with the increasing number of users, all the considered DSA algorithms have linear complexity except the proportional rate constraint algorithm in the scenario when $K < N$. Furthermore, the first utility-optimization algorithm has the lowest computational complexity, and the complexity of the second utility-optimization algorithm is higher than the first one but significantly lower than the greedy algorithm. That is because the second algorithm introduces the SNR information of each chunk to the utility function. During allocation, the modified utility function needs to be calculated for not only all the users, but also for all the pairs of users and chunks. In addition, the search space for allocation is also extended.

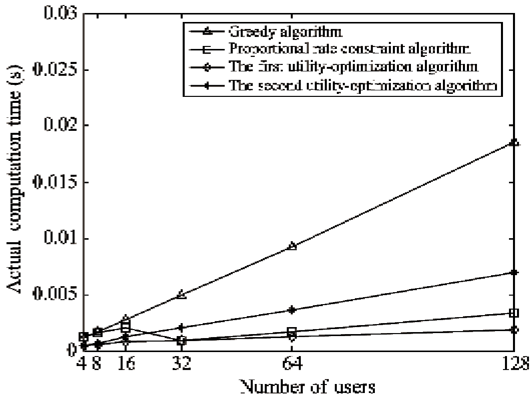

Fig. 4 Actual computation time

4 Simulation results and analysis

In this section, the performance of the two proposed utility-optimization algorithms is compared with the greedy algorithm, the proportional rate constraint algorithm and the RR algorithm in terms of three aspects: user requirements processing capability, rate-sum capacity and system average bit error rate (BER).

Four kinds of best effort applications with different capacity requirements are considered. The parameters of the considered traffic are shown in Table 2. The wireless channel is modeled as the ITU-R vehicular channel model A with 6 paths described in Table 3[16]. As a kind of typical multipath channel model, the vehicular channel has long multipath delay, which will cause severe frequency selectivity in the frequency domain; while on the other hand, provide high flexible for the DSA scheduling based on the frequency selectivity nature of wireless channel. It is assumed that the base station has perfectly acquired the CSI of all the terminals in each TTI, and the channel state estimation as well as the allocation scheme transmission is instantaneous without considering the DSA feedback delay. The system parameters assumed in our analysis are shown in Table 4.

Table 2 Transmission capacity requirements

Type	Capacity demands (Mbps)	Ratio (%)
1	0.25	20
2	0.5	40
3	1.0	30
4	1.5	10

Table 3 ITU-R Vehicular channel model A, with 6 paths

Tap	Relative delay (ns)	Average Power (dB)	Doppler Spectrum
1	0	0.0	Classic
2	310	−1.0	Classic
3	710	−9.0	Classic
4	1090	−10.0	Classic
5	1730	−15.0	Classic
6	2510	−20.0	Classic

Table 4 Simulation parameters for SC-FDMA system

System parameters	Values
Total available bandwidth (MHz)	5
System sampling rate (ns)	200
Number of subcarriers (L)	512
Number of chunks (N)	32
Cyclic prefix length (μs)	4
Total transmit power (W)	1
Radio frequency carrier (GHz)	2
System rate-sum capacity (Mbps)	20
Modulation method	QPSK
Equalization scheme	MMSE
Average SNR (dB)	14
Maximum SNR (dB)	28
AWGN power spectral density (dB · W/Hz)	−80

In Fig. 5, the performance of user requirements processing capability for all the considered algorithms is evaluated in terms of the number of users meeting their corresponding capacity demands in the system. The total number of users in the system ranges from 4 to 128. As shown in the figure, the greedy algorithm and the RR algorithm perform allocation without considering the practical transmission requirements. Therefore, with the increasing number of users, the capacity demands of most users cannot be satisfied. On the other hand, the proportional rate constraint algorithm can perform service-oriented allocation by setting appropriate allocation constraints according to the user capacity demands. However, the constraint-based allocation takes effect only after allocating one chunk to each user in system based on the concept of greedy algorithm. That means the available channel resource for the service-oriented allocation is limited, therefore the enhancement of allocation utility is limited. The two proposed utility-optimization algorithms consider both the CSI and transmission capacity requirements of each user at the same time. It can be observed that the user requirements processing capability of the first utility-optimization algorithm is significantly better than the greedy algorithm, the proportional rate constraint algorithm and the RR algorithm, especially when the number of users in system exceeds the number of chunks. That is because the utility function of the first utility-optimization algorithm takes user capacity requirements into account. And during the allocation procedures, the scheduler keeps on detecting whether the capacity requirements of each user are satisfied. If not, the unsatisfied user will participate in the next allocation iteration until being satisfied, or there is no available chunk in I_{chunk}. Moreover, the second utility-optimization algorithm shows better user requirements processing capability than the first algorithm by introducing SNR information to the utility function. During the allocation, the scheduler assigns appropriate allocation priorities to each user by evaluating the utilities based on both the SNR information and user requirements. Therefore, CSI and channel resource can be fully exploited for serving the user capacity requirements, so as to achieve a further improvement of the user requirements processing capability.

Fig. 6 illustrates the rate-sum capacity performance of all the considered algorithms with the total number of users in the system ranging from 4 to 128. As shown in the figure, the greedy algorithm aims to maximize the system capacity, which searches for the user with the best CSI during allocation procedure. Therefore, a better rate-sum capacity performance can be achieved by the greedy algorithm, whereas the user requirements processing capability is poor. During the allocation, the first utility-optimization algorithm provides higher allocation priorities for the access users with higher transmission capacity demands. However, the utility function of the first utility-optimization algorithm does not consider the current SNR of each chunk; thus, the channel resource will be allocated to the users in poor channel quality condition. As shown in Figs 5 and 6, the first utility-optimization algorithm has better user requirements processing capability compared to the greedy algorithm, but its rate-sum capacity is low. Therefore, the enhancement of user requirements processing capability in the first utility-optimization algorithm is achieved at the expense of the system capacity performance. Furthermore, the second utility-optimization algorithm calculates allocation utilities based on the capacity requirements as well as the current SNR, thereby providing higher priorities for the

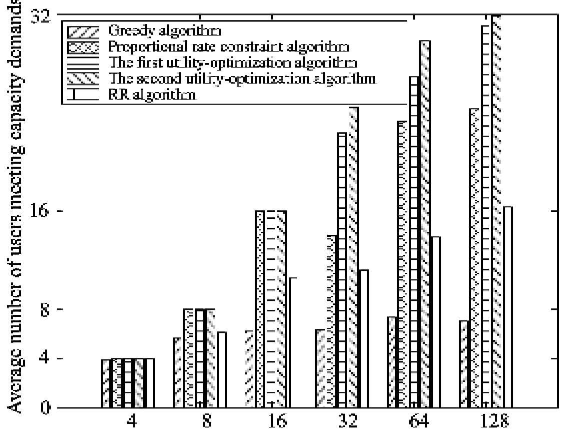

Fig. 5 User requirements processing capability

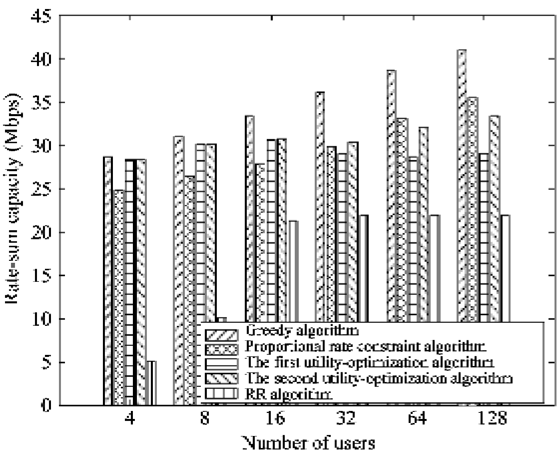

Fig. 6 System rate-sum capacity

users in good channel condition. Thus, appropriate allocation priorities can be derived for system users. Based on this concept, the second utility-optimization algorithm can achieve higher frequency efficiency by avoiding allocating chunks to the user in poor channel condition. As shown in Figs 5 and 6, the second utility-optimization algorithm achieves significantly improvement in the system capacity compared to the first utility-optimization algorithm, and maintains excellent user requirements processing capability at the same time.

The transmission reliability performance of all the considered algorithms is shown in Fig. 7 in terms of the average BER with $K = 16$. As shown in the figure, BER of the two proposed utility-optimization algorithms is higher than that of the greedy algorithm. That is because unlike the greedy algorithm taking full use of the channel resource to guarantee the transmission reliability, the two proposed utility-optimization algorithms enhance the user requirements processing capability by sacrificing the frequency efficiency. Furthermore, due to the outstanding requirements processing capability, the reliability performance of the two proposed algorithms is significantly superior to the proportional rate constraint algorithm and the RR algorithm.

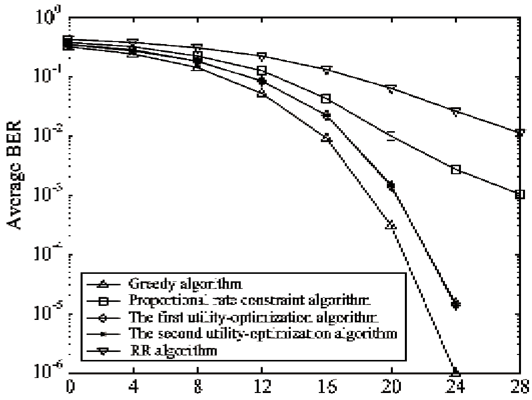

Fig. 7 System average BER

5 Conclusions

In this paper, two service-oriented DSA algorithms: the first utility-optimization algorithm and the second utility-optimization algorithm are proposed for the uplink SC-FDMA system based on the utility theory. With the objective of satisfying the transmission requirements of each user in the system, the two proposed algorithms measure both CSI and transmission capacity requirements of each user at the same time by setting appropriate utility functions. Simulation results indicate that the first utility-optimization algorithm can achieve a good user requirements processing capability with fairly low computational complexity. Thus, it is applicable for the service-oriented applications with low complexity demand. However, the system capacity of the first algorithm is low. For further improving the allocation performance, the second utility-optimization algorithm is proposed by introducing SNR information to the utility function. It is shown that with the slightly increasing computational complexity, the second utility-optimization algorithm can achieve a better trade-off between system capacity requirements and capacity demands of each user by taking fully use of CSI and channel resource. Therefore, the second utility-optimization algorithm can effectively improve the user requirements processing capability as well as achieve a better sum-rate capacity.

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