Utility Based Dynamic Subcarrier Allocation for QoS Guarantees in SC-FMDA System

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Abstract. *Two utility based dynamic subcarrier allocation (DSA) algorithms: the max exponential utility (MEU) algorithm and the max weighted exponential utility (MWEU) algorithm are proposed for quality of service (QoS) guarantees in single carrier frequency division multiple access (SC-FDMA) system. With the objective of maximizing the system total utility, the two proposed DSA algorithms are designed based on a cross-layer manner so as to guarantee the diverse QoS requirements of real-time traffic. The proposed MEU algorithm exploits the property of the exponential utility function to provide higher allocation priority for the user in heavy traffic load. Furthermore, the MWEU algorithm is proposed as a kind of priority adjustable DSA scheduling by introducing the grading theory and the weight factor into the utility function. Simulation results indicate that the MEU algorithm is able to achieve outstanding average delay and system rate-sum capacity performance. And the MWEU algorithm can further improve the delay variance and delay violation probability performance by setting appropriate allocation weights. It is also concluded that the adaptive weight factor value of the MWEU algorithm can be derived according to the practical QoS requirements and average packets arrival rate.*

Keywords

Single carrier frequency division multiple access (SC-FDMA), dynamic subcarrier allocation (DSA), quality of service (QoS), utility function; max exponential utility (MEU) algorithm, max weighted exponential utility (MWEU) algorithm.

1. Introduction

In order to overcome the drawback of high peak to average power ratio (PAPR) in orthogonal frequency division multiple access (OFDMA) system, single carrier frequency division multiple access (SC-FDMA) was proposed as an alternative technology for the uplink data transmission with strict transmit power demand. By introducing the discrete Fourier transform (DFT) as the pre-coding prior to OFDMA, SC-FDMA spreads the energy of each data symbol over all the subcarriers, thereby combating deep fades on certain subcarriers and achieving a better frequency diversity and power efficiency [1]. At present, SC-FDMA has been chosen as the access technology for the uplink 3rd generation partnership project long term evolution (3GPP LTE). Since the added DFT pre-coding operation and the inverse discrete Fourier transform (IDFT) in the following OFDMA block can be considered as a pair of inverse operations, SC-FDMA has a virtual single-carrier structure. Whereas it also maintains the properties of the multiple-carrier structure from OFDMA, for example, the high flexibility for dynamic subcarrier allocation (DSA) [2].

DSA is proposed as a kind of channel-aware scheduling with the key idea of dynamically assigning the channel frequency resource according to the channel state information (CSI) in the form of subcarrier. By taking advantages of both the frequency selective nature of the wireless channels and the multiuser diversity of the transmission system, DSA assigns subcarriers to the mobile terminals which experience the favorable transmission response. Based on this concept, the DSA scheduling can effectively improve the system performance by taking efficient use of the radio resource [3], [4]. For wireless networks, there are two classes of transmission applications: non-real-time and real-time traffic. From a whole network architecture point of view, most of the previous studies which focus on the DSA strategies for SC-FDMA system, for instance, the greedy algorithm [5], proportional fair algorithm [6] and the adjustable fairness algorithm [7], only consider the CSI observed in physical layer (PHY-layer). In other words, they all face to the non-real-time applications with no specific quality of service (QoS) requirements. For meeting the QoS performance specifications of the real-time traffic in SC-FDMA system, especially the heavy traffic load application with low latency tolerance, a cross-layer DSA scheduling is introduced from the present OFDM system. By taking an analysis of both the CSI from PHY-layer and the queue state information (QSI) of data link layer, the cross-layer management is able to achieve an attractive tradeoff between spectral efficiency and QoS. On this basis, the utility theory is also introduced to the network pricing system to build a bridge between wireless radio resource and system performance criteria. So as to evaluate the degree to which a dynamic scheduling satisfies the service requirements of user's applications [8]. The utility based joint channel and queue-aware scheduling scheme for OFDMA system has been studied in [9]. However, its average delay performance is poor in high packets arrival rate situation. In [10], a max delay utility (MDU) algorithm is presented for QoS provisioning problem in OFDM, but with a disadvantage of low system capacity.

In this paper, we focus on the QoS guaranteed cross-layer DSA scheduling problem for the uplink SC-FDMA system. Based on the concept of utility theory, two utility based cross-layer DSA algorithms are proposed for the real time applications. Aiming at maximizing the total utility with respect to QoS, the two proposed DSA algorithms exploit both the channel quality and queue state of each user, thereby supporting diverse QoS requirements in wireless networks. The performance of the proposed algorithms is analyzed in terms of four aspects: average delay, delay variance, system rate-sum capacity and delay violation probability.

The rest of the paper is organized as follows. In Section 2, the system model of the uplink DSA for SC-FDMA is described. In Section 3 the two proposed cross-layer DSA algorithms for real-time applications are developed. Then, we present the simulation results in Section 4 and finally, Section 5 draws some conclusions.

2. System Model

The block diagram of uplink SC-FDMA system with DSA scheduling is illustrated in Fig.1. As shown in the figure, the dynamic assignment is performed by the resource scheduler in the base station (BS). After learning the channel condition, queue states and QoS requirements of all the users, the scheduler decides appropriate allocation strategy based on the obtained information. And then sends it to the mobile terminals via downlink control signals [11]. In practical SC-FDMA system, subcarriers are

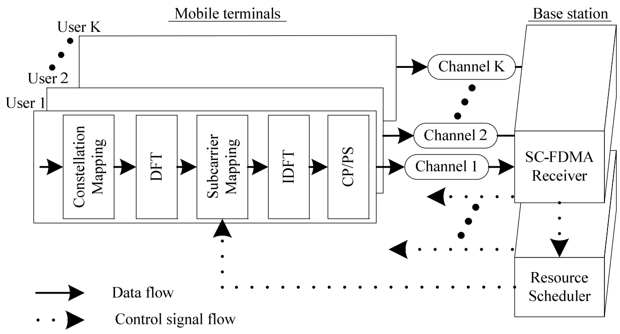

Fig. 1. SC-FDMA system dynamic subcarrier allocation block diagram.

assigned in the form of "chunk" rather than individually for the purpose of reducing the computational complexity. Where each chunk consists of a subset of subcarriers and the number of subcarriers in each chunk is regarded as the minimum unit for once allocation. LTE specifies that the transmissions are organized into radio frames with each including 10 subframes. And for the subframe which consists of 2 slots is referred to as the transmission time interval (TTI). In SC-FDMA system, the DSA is performed once every TTI for all the chunks, where the length of each TTI is T [12].

2.1 QoS Metrics

For real-time applications, the system rate-sum capacity, delay violation probability, average delay and delay variance are four QoS performance metrics for wireless networks. In this paper, we consider the DSA scheduling applied for SC-FDMA system with K terminals, L subcarriers and N chunks. Thus, each chunk consists of $M=L/N$ subcarriers. Let $\mathrm{K}=\{1,2,\ldots K\}$ denote the user index set; and $\mathrm{N}=\{1,2,\ldots N\}$ denote the set of chunks. The equal bit equal power (EBEP) allocation scheme is adopted for each chunk. 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 system to combat ISI. Based on this architecture, the signal to noise ratio (SNR) of symbol delivered for user k at TTI t with MMSE equalization can be given by [13]

$$\gamma_{k,I_{ch,k}}(t)=\left(\frac{1}{\frac{1}{\left|I_{sub,k}^{(t)}\right|}\sum_{l\in I_{sub,k}^{(t)}}\frac{\gamma_{k,l}(t)}{\gamma_{k,l}(t)+1}}-1\right)^{-1} \tag{1}$$

where $\gamma_{k,l}(t)$ is the SNR of subcarrier l for user k at TTI t; $\left|I_{sub,k}^{(t)}\right|$ is the number of subcarriers assigned to user k at TTI t, and $I_{ck,k}^{(t)}$ denotes the set of chunks allocated to user k at TTI t.

According to Shannon's formula, the capacity of user k with chunks $I_{ch,k}$ at TTI t can be expressed as

$$C_{k,I_{ch,k}}(t)=\frac{B\left|I_{ck,k}^{(t)}\right|}{N}\log_2\left[1+\gamma_{k,I_{ch,k}}(t)\right]. \tag{2}$$

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

$$C_{sum}(t)=\sum_{k=1}^{K}C_{k,I_{ch,k}}(t). \tag{3}$$

During dynamic allocation, we consider the constrains that each chunk cannot be shared among users during one TTI, which is mathematically expressed as

$$\begin{aligned}&\bigcup_{k_i\in\mathrm{K}} I_{ck,k_i}^{(t)}\subseteq\mathrm{N}\\&I_{ck,k_i}^{(t)}\cap I_{ck,k_j}^{(t)}=\varnothing,\ k_i\neq k_j,\ \forall k_i,k_j\in\mathrm{K}\end{aligned} \tag{4}$$

For the delay violation probability which is defined as

$$\Pr\left\{T_k>T_{th,k}\right\}\le\delta_k \tag{5}$$

where T_k is the packet delay for user k, $T_{th,k}$ and δ_k are the delay threshold and the maximum allowable probability for user k respectively.

It is assumed that the queue size for each user is infinite, and during each TTI, the amount of bit in the queue of user k is $Q_k(t)$. With the amount of arrival bits of $a_k(t)$, the evolution equation of queue length can be obtained as [14]

$$Q_k(t+1) = Q_k(t) - \min\left(Q_k(t), C_{k,I_{ch,k}}(t)T\right) + a_k(t). \quad (6)$$

Furthermore, to analyze the QoS performance with respect to the average waiting time, the average delay for user k at TTI t is defined as

$$W_k(t) = \frac{\bar{Q}_k(t)}{\lambda_k} \quad (7)$$

where λ_k is the average arrival bit rate for user k, and $\bar{Q}_k(t)$ is the average queue length for user k at TTI t, which can be observed by taking use of an exponentially weighted low-pass window as

$$\bar{Q}_k(t) = (1-\rho_w)\bar{Q}_k(t-1) + \rho_w \bar{Q}_k(t) \quad (8)$$

where $\rho_w = T/T_w$, and T_w is the window size.

2.2 Utility Functions

In cross-layer resource management architecture, utility function offers a tangible metric for pricing the benefit of taking use of certain radio resource to grantee the practical transmission services. Specifically, for the real-time applications with diverse QoS requirements, the main idea of utility pricing system is to map the channel frequency resource and QoS requirements into the corresponding evaluation values, and then solve the established utility-based optimization problem by taking appropriate DSA scheduling [15]. On this basis, the utility function for the cross-layer DSA scheduling can be formulated as $U_k(W_k(t))$, which is relative to the average waiting time of each user. Obviously, the degree of benefit, i.e. utility, decreases with the increase of delay. Therefore, the utility function for QoS provisioning is assumed to be a decreasing function with respect to average delay. As given in [10], the objective function for the utility based cross-layer optimization which subjects to allocation constrains in (4) can be formulated as

$$\max \sum_{k \in K} \frac{\left|U_k'(W_k(t))\right|}{\hat{\lambda}_k} \min\left(C_{k,I_{ch,k}}(t); \frac{Q_k(t)}{T}\right) \quad (9)$$

where $\hat{\lambda}_k$ is the estimated arrival bit rate of user k. and U_k' is the marginal utility function defined as

$$U_k'(W_k(t)) = \left.\frac{\partial U_k(W_k)}{\partial W_k}\right|_{W_k = W_k(t)}. \quad (10)$$

In practice, it is difficult to accurately predict the arrival bit rate at the BS. Thus, we set $\hat{\lambda}_k = \bar{C}_k$, where $\bar{C}_k$ is the long-term average rate-sum capacity (i.e. service rate) of user k.

3. Utility Based Cross-layer DSA Algorithm for SC-FDMA

In this section, we present two utility based DSA schemes for QoS guarantees in SC-FDMA system: the max exponential utility (MEU) algorithm and the max weighted exponential utility (MWEU) algorithm. Both of the two proposed DSA algorithms are designed on a cross-layer manner by taking both the current CSI from the PHY-layer as well as the QSI from data link layer into consideration.

3.1 The Max Exponential Utility Algorithm

As mentioned in section 2.2, the utility pricing system can be exploited in DSA scheduling for the purpose of supporting diverse QoS requirements by establishing appropriate mapping between channel resource and QoS performance. Therefore, how to effectively formulate the utility function is a core problem of DSA scheduling, especially for real-time traffic with heavy traffic load. To solve this problem and emphasize on the user with long waiting time in queue, the proposed MEU algorithm adopts the exponential function with respect to average delay as the utility function. Moreover, the allocation utility quantifying the scheduling benefit should be inversely proportional to the average delay. Thus, the utility function of the MEU algorithm can be expressed as

$$U_k(W_k) = -\exp(W_k). \quad (11)$$

According to the results derived in [10], the marginal utility function of MEU algorithm is given by

$$\left|U_k'(W_k)\right| = \exp(W_k). \quad (12)$$

Due to the exponential function property, the MEU scheduling can provide higher priority for the user suffering from long waiting time in queue so as to ensure its allocation superiority over other users. In other words, for improving the QoS provision capability, some admission opportunities are switched from the low average delay users to some users with high average delay during allocation. On this basis, by maximizing the total exponential utility functions with respect to average delay, the established utility pricing system can be optimized for QoS guarantees. Therefore, the objective function of MEU algorithm can be formulated as

$$\max \sum_{k \in K} \frac{\exp(W_k(t))}{\bar{C}_k} \min\left(C_{k,I_{ch,k}}(t); \frac{Q_k(t)}{T}\right). \quad (13)$$

For simplifying the expression, we let

$$E_k(t) = \frac{\exp(W_k(t))}{\bar{C}_k} \min\left(C_{k,I_{ch,k}}(t); \frac{Q_k(t)}{T}\right). \quad (14)$$

Thus, the optimal allocation is derived as

$$\left(k,n,t\right)=\arg\max_{k\in\mathrm{K}}\left\{E_k\left(t\right)\right\} \tag{15}$$

where (k, n, t) represents that chunk n is assigned to user k at TTI t.

The allocation procedure can be formulated as follows:

Algorithm 1 The MEU algorithm

Initialization:

Let $I_{user}^{(t)} \leftarrow \mathrm{K}=\{1,2,\mathrm{K}\ K\}$; $I_{chunk}^{(t)} \leftarrow \mathrm{N}=\{1,2,\mathrm{K}\ N\}$;

Let $I_{ck,k}^{(t)} \leftarrow \varnothing$ for all $k\in I_{user}^{(t)}$;

while $I_{chunk}^{(t)} \neq \varnothing$:

  if $\sum_{k\in\mathrm{K}} Q_k\left(t\right)\neq 0$ (not all user queues are empty)

   while $I_{chunk}^{(t)} \neq \varnothing$:

    Calculate $E_k\left(t\right)$ for $k\in I_{user}^{(t)}$ according to (14);

    Find the user k^* in $I_{user}^{(t)}$ and chunk n^* in $I_{chunk}^{(t)}$ that $\left(k^*,n^*,t\right)=\arg\max_{k\in\mathrm{K}}\left\{E_k\left(t\right)\right\}$;

    $I_{ck,k^*}^{(t)} \leftarrow I_{ck,k^*}^{(t)} \cup\left\{n^*\right\}$;

    $I_{chunk}^{(t)} \leftarrow I_{chunk}^{(t)} -\left\{n^*\right\}$;

    Update $Q_{k^*}\left(t\right)$ that

$$Q_{k^*}\left(t\right)\leftarrow Q_{k^*}\left(t\right)-\min\left(C_{k^*}(t)T;Q_{k^*}(t)\right);$$

   end while

 else if $\sum_{k\in\mathrm{K}} Q_k\left(t\right)=0$ (all user queues are empty)

  Calculate $C_{k,n}\left(t\right)$ for $k\in I_{user}^{(t)}$ according to (2);

  Find the user k' in $I_{user}^{(t)}$ and chunk n' in $I_{chunk}^{(t)}$ that $\left(k',n',t\right)=\arg\max_{k\in\mathrm{K}}\left\{C_{k,n}\left(t\right)\right\}$;

  $I_{ck,k'}^{(t)} \leftarrow I_{ck,k'}^{(t)} \cup\left\{n'\right\}$;

  $I_{chunk}^{(t)} \leftarrow I_{chunk}^{(t)} -\left\{n'\right\}$;

 end if

end while

In initialization, we group all the users and all the chunks waiting to be scheduled in the system into $I^{(t)}{}_{user}$ and $I^{(t)}{}_{chunk}$ respectively. It should be noticed that, two kinds of real-time user queue states are considered during allocation procedure. And the allocation criterion which is adopted for each state in MEU algorithm depends on the corres-ponding queue status. More specifically, in the situation that not all the real-time user queues are empty, the MEU algorithm performs utility based optimal assignment for QoS guarantees. While in the scenario when all the real-time user queues are empty, the greedy based allocation is performed according to [5], thereby further improving the spectral efficiency.

3.2 The Max Weighted Exponential Utility Algorithm

The MEU algorithm proposed in section 3.1 is able to handle the real-time QoS guarantees by giving high priority to the user with long average delay. However, the provided allocation priority is fixed, which is insufficient to handle the heavy traffic load with both fierce resource competition and strict delay constraint. Thus, it is an urgent need for DSA scheduling to achieve a more rational and flexible allocation priority distribution among users. Based on this concept, the MWEU algorithm is proposed for further enhancing the high-speed bursty data service with heavy traffic load and outburst arrival data. By introducing scheduling weights to the utility function of the MEU algorithm, the proposed MWEU algorithm can provide adjustable allocation priorities for the users according to the QoS requirements and queue congested states, thereby achieving a high degree of flexibility for QoS provisioning in real-time applications. Under this consideration, the weighted utility function and its marginal function for the MWEU algorithm can be defined as

$$U_k\left(W_k\right)=-\frac{\exp\left(\gamma_k W_k\right)}{\gamma_k}, \tag{16}$$

$$\left|U_k'\left(W_k\right)\right|=\exp\left(\gamma_k W_k\right) \tag{17}$$

where γ_k is the adjustable weight factor with the lower bound of 1. When γ_k equals to 1, it means that all the users have the same allocation priorities. While for the larger values of γ_k, the scheduler will provide higher priority for the corresponding user. The upper bound of γ_k depends on the practical QoS requirements and the level of network congestion, which will be discussed in the following part.

During allocation procedure, we also introduce the concept of grading theory, and set the threshold for the high priority allocation as W_k^{th} . Specifically, if the average waiting time $W_k(t)$ is longer than W_k^{th} , we set $\gamma_k>1$; otherwise, $\gamma_k=1$. Therefore, the objective function of the MWEU algorithm can be formulated as

$$\max\sum_{k\in\mathrm{K}}E_k\left(t\right)$$
$$E_k\left(t\right)=\frac{\exp\left(\gamma_k W_k\right)}{\bar{C}_k}\min\left(C_{k,I_{ch,k}}(t);\frac{Q_k(t)}{T}\right) \tag{18}$$

where $\begin{cases}\gamma_k=1 & \text{for } W_k\left(t\right)\leq W_k^{th}\\ \gamma_k>1 & \text{for } W_k\left(t\right)>W_k^{th}\end{cases}$.

Obviously, when γ_k=1, the MWEU algorithm is equivalent to the MEU algorithm.

The allocation procedure can be formulated as follows:

Algorithm 2 The MWEU algorithm

```
Initialization: (The same with Algorithm 1);
while I_chunk^(t) ≠ ∅ :
  if Σ_{k∈K} Q_k(t) ≠ 0 (not all user queues are empty)
    for k ∈ I_user^(t) :
      Calculate W_k(t) according to (7);
      if W_k(t) ≤ W_k^th
        Calculate E_k(t) according to (14);
      else if W_k(t) > W_k^th
        Calculate E_k(t) according to (18);
      end if
    end for
    Find the user k* in I_user^(t) and chunk n* in I_chunk^(t) that
    (k*, n*, t) = arg max_{k∈K} {E_k(t)};
    I_{ck,k*}^(t) ← I_{ck,k*}^(t) ∪ {n*};
    I_chunk^(t) ← I_chunk^(t) − {n*};
    Update Q_{k*}(t) that
    Q_{k*}(t) ← Q_{k*}(t) − min(C_{k*}(t)T; Q_{k*}(t));
  else if Σ_{k∈K} Q_k(t) = 0 (all user queues are empty)
    The same with the else if part in Algorithm 1;
  end if
end while
```

Similar to the MEU algorithm in section 3.1, the MWEU algorithm considers two real-time user queue states during allocation process as well. In the scenario that not all the real-time user queues are empty, the MWEU algorithm first checks the average delay state of each user. If it exceeds the predetermined delay threshold W_k^{th}, the scheduler will assign the corresponding weight enhanced priority to that user so as to fully guarantee its allocation superiority. This means that the user suffering from comparatively higher average delay which above the delay threshold will take the absolute advantage over other users during allocation. Furthermore, the weighted enhanced allocation priority in MWEU algorithm is flexible, which can be adjusted according to the practical QoS requirements and traffic density. Consequently, the MWEU algorithm can effectively handle the high-speed bursty data service by taking rational allocation priority distribution among users. While in the scenario when all the user queues are empty, the MWEU algorithm will perform greedy based allocation for fully utilizing the wireless spectral resource.

4. Simulation Results and Analysis

In this section, the performance of the two proposed utility based cross-layer DSA algorithms is analyzed in terms of four aspects: average delay, delay variance, system rate-sum capacity and delay violation probability.

4.1 Simulation Configuration

The simulation parameters for the SC-FDMA system assumed in our analysis are presented in Tab. 1. It is assumed that the BS has perfectly acquired the CSI of all the terminals during each TTI. And the channel state estimation as well as the allocation scheme transmission is performed instantaneously without considering the DSA feedback delay. The wireless channel is modeled as an ITU-R vehicular channel model A, with 6 paths [16], [17]. All simulations were run for 10000 TTIs, and the results were averaged. Furthermore we consider a single-cell localized SC-FDMA cellular system with the radius of 1 km. Each terminal is assumed to be uniformly and independently distributed with stationary or slowly moving, thus the path loss is modeled by

$$PL(d) = 128.1 + 37.6\log_{10} d_k + \xi_k \quad (dB) \tag{19}$$

where d_k (km) is the distance between the terminal k and BS; ξ_k is the log-normal shadowing.

System parameters	Values
Total available bandwidth	5 MHz
Radio frequency carrier	2 GHz
System sampling rate	200 ns
Cyclic prefix length	4 µs
Transmission time interval (*T*)	1 ms
Total transmit power of each user	1 W
Number of subcarriers	256
Number of chunks	32
Number of users	16
AWGN power spectral density	-192 dB/Hz
Slow shadowing standard deviation	8 dB
Bit and power allocation method	EBEP
Modulation method	QPSK
Equalization scheme	MMSE

Tab. 1. Simulation parameters for SC-FDMA system.

Since this paper focuses on handling the real-time traffic with both heavy traffic load and strict delay constraint, we consider the video traffic as the application scenario, which is generated on a two-state ON-OFF basis. In the ON state, the coming packet has a variable arrival rate; whereas in the OFF state no packet is generated [18]. With reference to [10] and [19], the corresponding parameters of the video traffic are shown in Tab. 2.

In this paper, the allocation threshold for the MWEU algorithm is set as the average waiting time of all the users during each TTI.

$$W_k^{th}(t) = \frac{1}{K}\sum_{k \in \mathrm{K}} W_k(t). \quad (20)$$

Traffic parameters	Values
Mean ON period	1.47s
Mean OFF period	1.92 s
Packet length	32 bits/packet
Delay bound	400 ms
Packet arrival model	Poisson process
Delay violation probability	5 %
Average packets arrival rate	4-10 packets /timeslot/user

Tab. 2. Simulation parameters for video traffic.

4.2 Simulation Results

Based on the above simulation model, the performance of the proposed MEU algorithm and MWEU algorithm is compared with the traditional PF and MDU algorithm in this part. Furthermore, the upper bound of the weight factor in MWEU algorithm is also derived by taking an analysis of average delay and system rate-sum capacity performance with respect to different weight factor values.

In Fig. 2, the average delay performance of all the considered algorithms is evaluated versus different packets arrival rate. It is apparent that the average delay increases with the average arrival rate, especially in high traffic load scenario. That is because with limited wireless spectral resource, the high traffic density results in severe congestion in networks, which will cost long time for packets waiting to be transmitted in the queue buffers. Specifically, as a kind of fairness-oriented scheduling, the PF algorithm focuses on providing maximum capacity fairness for non-real-time users without considering QoS requirements. Therefore, the PF algorithm suffers from long waiting time in real-time applications, while the average delay of all the cross-layer DSA algorithms in Fig. 2 is short. On the other hand, considering the cross-layer algorithms based on both CSI and QSI, the average delay performance of the proposed MEU algorithm is superior to the MDU algorithm, especially in the case of high packets arrival rate. That is due to the property of the exponential utility function,

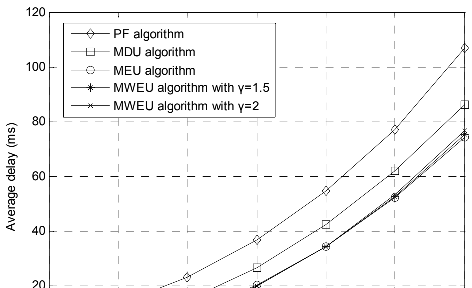

Fig. 2. Average delay versus average arrival rate.

which can provide higher priority for the user suffering from long waiting time to avoid network congestion. Furthermore, it can be observed that with allocation weight γ increase, the average delay of the MWEU algorithm increases slightly. However, even in the high arrival rate scenario, the MWEU algorithm (with $\gamma = 1.5$ and 2) still has the similar average delay performance with the MEU algorithm, and substantially outperforms the MDU algorithm. For example, when the average arrival rate is 9 packets/timeslot/user, the average delay of the MEU and MWEU algorithm is only 84.0% and 67.8% of the MDU and PF algorithm respectively.

In Fig. 3, the allocation fairness performance indicated by the variance of average delay is evaluated versus different packets arrival rate for all the considered algorithms. As can be seen, with the increase of packets arrival rate, the delay variance performance of all the considered algorithms degenerates significantly. This can be explained by the fact that with the packets arrival rate increases, the frequency resource competition among users becomes increasingly fierce, which will result more fluctuations in average delay of each user, i.e., delay variance. Furthermore, the MDU algorithm has a good delay variance performance, which is better than the proposed MEU algorithm. That is because with emphasis on the user suffering from long average delay, the improvement of MEU algorithm in QoS provisioning is achieved with slightly performance deterioration of light traffic load user. Thus, the delay variance of the MEU algorithm is higher. However, by introducing the grading concept and weight factor to the utility based allocation procedure, the MWEU algorithm can further provide a rational allocation priority distribution among users in heavy traffic load. Therefore, the MWEU algorithm is able to achieve a better balance of average delay among system users, thereby effectively improving the allocation fairness performance. It is apparent that the delay variance performance of the MWEU algorithm achieves steadily improvement as the weight factor γ increases, which gets close to that of the MUD al-

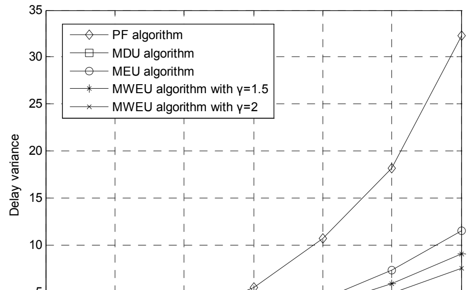

Fig. 3. Delay variance versus average arrival rate.

gorithm. For example, when the average arrival rate is 9 packets/timeslot/user, the MWEU algorithm with $\gamma = 2$ shows 17.7% and 34.1% lower delay variance than the MWEU algorithm with $\gamma = 1.5$ and the MEU algorithm respectively. But its delay variance performance improvement is achieved at the expense of slightly average delay performance decrease as illustrated in Fig. 2.

The system rate-sum capacity performance of all the considered algorithms versus different packets arrival rate is shown in Fig. 4. Unlike the cross-layer algorithms taking QSI into account during allocation, the PF algorithm is performed independent with the queue state. Thus, the increase of packets arrival rate has no significant effect on the capacity performance of the PF algorithm. For clear demonstration, we only evaluate the rate-sum capacity performance of all the cross-layer algorithms considered in this paper. As shown in Fig. 4, the system capacity decreases as the average arrival rate increases. This can be explained by the fact that in delay sensitive application with heavy traffic load, the cross-layer algorithm has to emphasize the real-time performance for QoS guarantees, which will result in degradation in system capacity performance. In other words, there is a tradeoff between spectral efficiency and QoS performance for DSA scheduling. As can be seen, when the average arrival rate is 9 packets/timeslot/user, the rate-sum capacity of the proposed MEU algorithm is 4.7% better than the MDU algorithm. Moreover, a further improvement can also be achieved by the MWEU algorithm as the weight factor γ increase. With $\gamma = 2$, the MWEU algorithm shows 3.0% and 7.8% higher rate-sum capacity than the MEU algorithm and the MDU algorithm respectively. That means the MWEU algorithm is able to contribute an effective tradeoff between spectral efficiency and QoS performance by providing appropriate allocation priorities among users.

In Fig. 5, the performance of delay violation probability for all the considered algorithms is measured versus different packets arrival rate. We define the delay violation probability as the occurrence probability of delay violations for each user over all the timeslots in this paper. As can be seen that the delay violation probability of all the considered algorithms significantly increase with the packets arrival rate. Because with heavier traffic load, the limited frequency resource becomes increasing insufficient for quantifying the QoS requirements of all the users. It can be observed that the proposed MEU and MWEU algorithms both substantially outperform the PF algorithm particularly when the traffic density is high. Furthermore, a better delay violation probability performance can be achieved by the MWEU algorithm. And with the weight factor γ increase, the delay violation probability of the MWEU algorithm decreases apparently, which is closed to that of the MDU algorithm. This result confirms our analysis that the MWEU algorithm can effectively guarantee the QoS provisioning by distributing a rational priorities among users. It should be noticed that the delay violation probability of the proposed MEU and MWEU algorithm is higher than the MDU algorithm, but still definitely meet the maximum delay violation probability requirement for video traffic application as shown in Tab. 2. This means that the two proposed algorithm can significantly improve the average delay performance with tolerable degradation in delay violation probability. The full comparison of all the considered DSA algorithms is shown in Tab. 3 under the condition that the average arrival rate of the video traffic is 9 packets/timeslot/user.

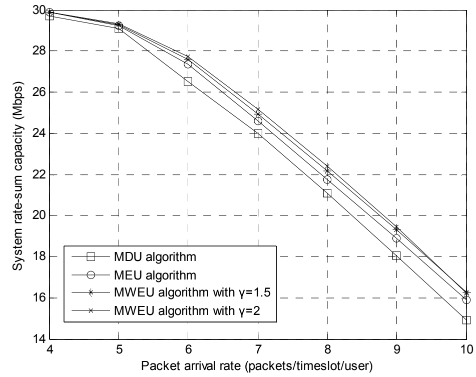

Fig. 4. System rate-sum capacity versus average arrival rate.

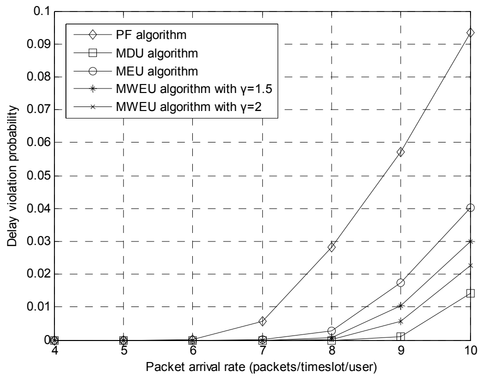

Fig. 5. Delay violation probability versus delay threshold.

Performance	PF	MDU	MEU	MWEU γ=1.5	MWEU γ=2.0
Average delay (ms)	76.90	62.09	52.17	52.50	53.26
Delay variance	18.14	2.34	7.36	5.89	4.85
System rate- sum capacity (Mbps)	8.24	18.04	18.88	19.31	19.44
Delay violation probability (%)	5.71	0.11	1.73	1.03	0.57

Tab. 3. Numerical results of simulation.

Next, we emphasize the feature of weight factor γ in MWEU algorithm to further analyze its impact on average delay and rate-sum capacity performance, so as to get appropriate weighted value for QoS provisioning. In Fig. 6 and Fig. 7, the performance of the proposed MWEU algorithm with respect to different γ value is compared with the MDU algorithm in the scenario when the average packets arrival rate is 9 packets/timeslot/user. As mentioned above, the weight factor γ is related to the allocation priority for which the possibility of a user can get the corresponding frequency resource. Thus, combined with the grading theory, the scheduler of the MWEU algorithm can assign higher priority for the user in heavy traffic load by setting larger γ. In other words, with appropriate γ, the proposed MWEU algorithm can effectively balance the individual delay performance among users. However, the improvement of individual delay performance in MWEU algorithm is at the cost of system overall delay performance. As shown in Fig. 6, the average delay of the MWEU algorithm increases with the weight factor γ. It should be noticed that when $\gamma > 8.5$, the average delay of MWEU algorithm exceeds the MDU algorithm. Thus, for provisioning the real-time applications with strict average delay constraint, the upper bound of γ should not lower than 8.5 on this arrival rate scenario.

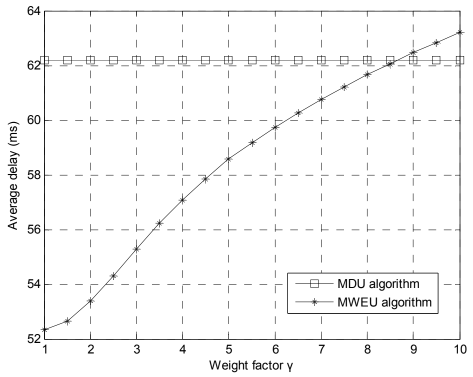

Fig. 6. Average delay versus weight factor.

Similarly, as illustrated in Fig. 7, the MWEU algorithm achieves its maximum system rate-sum capacity when $\gamma = 2$. And with a further increase of γ, the system capacity of the MWEU algorithm decreases apparently. This is due to the tradeoff between spectral efficiency and QoS performance of DSA scheduling in the preceding analysis. Notice that with $\gamma > 7.5$, the MWEU algorithm loses its advantage in system rate-sum capacity over the MDU algorithm. Consequently, for the purpose of achieving excellent QoS performance (i.e. system rate-sum capacity, average delay and delay variance) in a cross-layer scheduling manner, the MWEU algorithm should set appropriate weight factor γ which depends on the practical QoS requirements and average arrival rate of real-time applications.

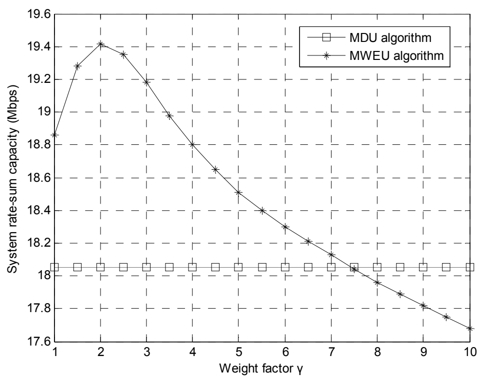

Fig. 7. System rate-sum capacity versus weight factor.

5. Conclusions

In this paper, two utility based cross-layer DSA algorithms: the MEU algorithm and the MWEU algorithm were designed for SC-FDMA system. Aiming at supporting diverse QoS requirements of real-time applications in wireless networks, the two proposed algorithms measure the CSI observed in PHY-layer as well as the QSI obtained at data link layer at the same time by setting appropriate utility functions. Simulation results indicate that by exploiting the exponential utility function, the MEU algorithm can achieve a good average delay and system rate-sum capacity performance; but with a tolerable deterioration in delay variance and delay violation probability performance for video traffic application. Therefore, the MEU algorithm is applicable for the real-time applications with both strict average delay and system capacity performance requirements. For further improving the service performance in real-time applications with low delay variance and delay violation probability requirements, the MWEU algorithm is proposed by introducing the grading concept and weight factor during the allocation procedure. The main idea of the MWEU algorithm is to offer adjustable priorities among access users thereby achieving an effective tradeoff between spectral efficiency and QoS. Furthermore, based on the analysis of the MWEU algorithm performance, the upper and lower bounds of the weight factor can be obtained according to the practical QoS requirements and average packets arrival rate. As shown in the simulation results, by setting appropriate weight factors, the MWEU algorithm can achieve a low delay variance as well as improvement of the system capacity performance.

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References

[1] VARAHRAM, P., ALI, B. M. A low complexity partial transmit sequence for peak to average power ratio reduction in OFDM systems. *Radioengineering*, 2011, vol. 20, no. 3, p. 677 - 682.

[2] MYUNG, H. G., GOODMAN, D. J. *Single Carrier FDMA a New Air Interface for Long Term Evolution*. United Kingdom: John Wiley & Sons, 2008.

[3] ZUKANG, S., ANDREWS, J. G., EVANS, B. L. Adaptive resource allocation in multiuser OFDM systems with proportional rate constraint. *IEEE Transactions on Wireless Communications*, 2005, vol. 4, no. 6, p. 2726 - 2737.

[4] SADR, S., ANPALAGAN, A., RAAHEMIFAR, K. Radio resource allocation algorithms for the downlink of multiuser OFDM communication systems. *IEEE Communications Surveys and Tutorials*, 2009, vol. 11, no. 3, p. 92 - 106.

[5] JUNSUNG, L., MYUNG, H. G., KYUNGJIN, O., GOODMAN, D. J. Channel-dependent scheduling of uplink single carrier

FDMA systems. In *Proceedings of the 64th Vehicular Technology Conference*. Canada (Montreal), 2006, p. 1 - 5.

[6] HOON, K., YOUNGNAM, H. A proportional fair scheduling for multicarrier transmission systems. *IEEE Communications Letters*, 2005, vol. 9, no. 3, p. 210 - 212.

[7] LI, Y. B., ZHANG, X., YE, F., GAO, Z. G. Adjustable fairness dynamic subcarrier allocation algorithm for SC-FMDA systems. *Systems Engineering and Electronics*, 2011, vol. 33, no. 6, p. 1377 to 1382.

[8] ANDREWS, M., KUMARAN, K., RAMANAN, K., STOLYAR, A., WHITING, P., VIJAYAKUMAR, R. Providing quality of service over a shared wireless link. *IEEE Communications Magazine*, 2001, vol. 39, no. 2, p. 150 - 154.

[9] KATOOZIAN, M., NAVAIE, K., YANIKOMEROGLU, H. Utility-based adaptive radio resource allocation in OFDM wireless networks with traffic prioritization. *IEEE Transactions on Wireless Communications*, 2009, vol. 8, no. 1, p. 66 - 71.

[10] SONG, G. C. *Cross-Layer Resource Allocation and Scheduling in Wireless Multicarrier Networks*. Ph.D.dissertation, Georgia Tech, 2005.

[11] LI, Y. B., HUANG, H., YE, F. An improved cooperative spectrum sensing in cognitive radio. *Journal of Computational Information Systems*, 2012, vol. 8, no. 4, p. 1399 - 1406.

[12] MYUNG, H. G., KYUNGJIN, O., JUNSUNG, L., GOODMAN, D.J. Channel-dependent scheduling of an uplink SC-FDMA system with imperfect channel information. In *Proceedings of the Wireless Communications and Networking Conference*. Las Vegas (United States), 2008, p. 1860 - 1864.

[13] LI, Y. B., ZHANG, X., YE, F. A stepwise subcarrier allocation algorithm for SC-FDMA systems. *Journal of Digital Content Technology and its Applications*, 2011, vol. 5, no. 9, p. 272 - 280.

[14] SONG, G. C., LI, Y., CIMINI, L. J. JR., ZHENG, H. Joint channel-aware and queue-aware data scheduling in multiple shared wireless channels. In *Proceedings of Wireless Communications and Networking Conference*, Atlanta (United States), 2004, p. 1939 – 1944.

[15] SONG, G. C., LI, Y. Utility-based resource allocation and scheduling in OFDM-based wireless broadband networks. *IEEE Communications Magazine*, 2005, vol. 43, no. 12, p. 127 - 134.

[16] BIAGIONI, A., FANTACCI, R., MARABISSI, D., TARCHI, D. Adaptive subcarrier allocation schemes for wireless OFDMA systems in WiMAX networks. *Selected Areas in Communication*, 2009, vol. 27, no. 2, p. 217 - 225.

[17] HARADA, H., PRASAD, R. *Simulation and Software Radio for Mobile Communications*. Artech House, 2002.

[18] KONG, Z., KWOK, Y. K., WANG, J. Z. A low-complexity QoS-aware proportional fair multicarrier scheduling algorithm for OFDM systems. *IEEE Transactions on Vehicular Technology*, 2009, vol. 58, no. 5, p. 2225 - 2235.

[19] CHENG, H. T., ZHUANG, W. H. Joint power-frequency-time resource allocation in clustered wireless mesh networks. *IEEE Network*, 2008, vol. 22, no.1, p. 45 - 51.

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