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Utility maximisation in channel-aware and queue-aware orthogonal frequency division multiple access scheduling based on arrival rate control

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Abstract: A channel-aware and queue-aware (CAQA) scheduling scheme is proposed for the downlink of orthogonal frequency division multiple access (OFDMA) networks. The scheduling scheme cooperates with a rate control policy, which controls arrival rates to the base station queues. The network resource allocation is formulated as a utility maximisation problem, which is decomposed into a CAQA OFDMA scheduling problem and a rate control problem. The authors decompose the scheduling problem into subproblems of rate allocation to subcarriers and propose a joint subcarrier assignment and rate allocation (JSARA) solution for the problem. Simulation is conducted to evaluate the performance of JSARA in terms of throughput, queue length and dropping probability. In addition, JSARA performance gain in allocating users' arrival rates and achieved aggregate utility, in cooperation with a rate control policy, is investigated.

1 Introduction

Multicarrier transmission in the form of orthogonal frequency division multiplexing (OFDM) is a promising technique to provide spectral efficiency in broadband wireless networks. OFDM divides a broadband channel into a set of non-interfering narrowband subcarriers. In a multiuser OFDM network, orthogonal frequency division multiple access (OFDMA) is deployed in which different subcarriers are allocated to different users. As the channel gains of subcarriers are independent for different users, multiuser diversity [1] can be used, for example, based on instantaneous channel state information (CSI), opportunistic scheduling assigns subcarriers and allocates power adaptively to enhance the network performance. Despite aggregate throughput maximisation, opportunistic scheduling, however, prevents users with poor channel qualities to access the channel most of the time. This issue causes unexpected growth of queue lengths which results in either congestion and large delays or data loss when buffer sizes are limited.

To mitigate the drawback of opportunistic scheduling, channel-aware and queue-aware (CAQA) scheduling has been proposed in [2–7]. CAQA scheduling improves buffer management and avoids instability by allocating network resources based on both simultaneous channel state and queue state information (QSI). Modified largest weighted delay first (M-LWDF) schemes for single carrier and multicarrier CAQA scheduling are proposed in [2] and [3, 4], respectively. The M-LWDF objective is to maximise a weighted sum rate function, where the weights are correspondent to packet delays and queue lengths of real-time and non-real-time traffics, respectively. The packets delay, that is, the packets waiting time in the queues, are measured based on the carried time stamps of real-time traffic. To ease the computation process of OFDMA scheduling, the average waiting time is estimated based on the average queue lengths in [5]. Then a combination of dynamic subcarrier assignment (DSA) and adaptive power allocation (APA) schemes [8] is used to optimise packets waiting time. Assuming uniform power allocation, first subcarriers are assigned dynamically, and then a greedy power allocation algorithm is used for bit loading. As a measure of queue states, we have defined a queue stability criterion to be deployed in CAQA subcarrier assignment in [6]. In [3–6], subcarriers are assigned based on uniform power allocation assumption, but a joint subcarrier and power allocation (JSPA) algorithm is proposed for CAQA OFDMA scheduling in [7]. In JSPA, a user power allocation is optimised whenever a new subcarrier is allocated to that user.

Although the performance of CAQA scheduling is affected by the queue lengths and accordingly arrival rates, none of the aforementioned papers considers controlling arrival rates. In fact, they presume a static set of arrival rates to the base station (BS) queues. Furthermore, these works evaluate the queuing performance from the multiple access control/physical (MAC/PHY) layer point of view, which does not represent the network utility and users' service satisfaction at upper layers. To clarify, consider a network where the channel qualities of the users are different. To compensate for the queue length growth of the users with low channel gains, CAQA scheduling mostly allocates resources to the users with low channel gains, which degrades the network resource utilisation. Finally, despite the better performance of joint subcarrier assignment and power allocation in [7] compared with the subcarrier assignment with uniform power allocation, computational complexity is high due to the large number of power allocation optimisation.

To improve CAQA scheduling performance in OFDMA networks and make it system-wide efficient, we use a utility maximisation framework and a rate controller that cooperates with the CAQA scheme. In single carrier networks, queue-aware scheduling cooperating with a rate controller achieves fair resource allocation and stability [9, 10]. We extend this cooperation to the downlink of multicarrier OFDMA networks and formulate CAQA scheduling with arrival rate control as a utility maximisation problem. The problem is decomposed into a rate control problem and a CAQA scheduling problem. The rate control problem formulates a rate control policy that adjusts arrival rates to the BS queues. We use subgradient method to solve this problem. In contrast, the scheduling problem formulates subcarrier assignment with adaptive and discrete modulation rates as an integer programming problem. We additionally decompose this problem into subproblems of rate allocation to subcarriers, and propose a low-complexity joint subcarrier assignment and rate allocation scheme (JSARA). The proposed scheme coordinates with the rate controller through queue parameters to determine link rates, that is, departure rates from the BS queues. Finally, the JSARA performance in terms of the queue length, dropping probability and throughput is compared with the ones of DSA + APA and JSPA.

The rest of the paper is organised as follows. Network model and problem formulation are described in Section 2. Decomposing the problem into rate control and scheduling problems are presented in Section 3. In Section 4, we present the OFDMA scheduling problem formulation, solution and complexity analysis. Simulation results are given in Section 5, and the paper is concluded in Section 6.

2 Network model and problem formulation

We describe the network architecture and radio transmission model in Section 2.1, and formulate the resource allocation problem in Section 2.2.

2.1 Network architecture and radio transmission model

We consider downlink transmission in an OFDMA network with point to multipoint infrastructure and a set $\Phi = \{s | s = 1, 2, \dots, S\}$ of users in Fig. 1. The arrival rates from the backbone network to the BS queues, r_s's, are controlled by a rate controller.

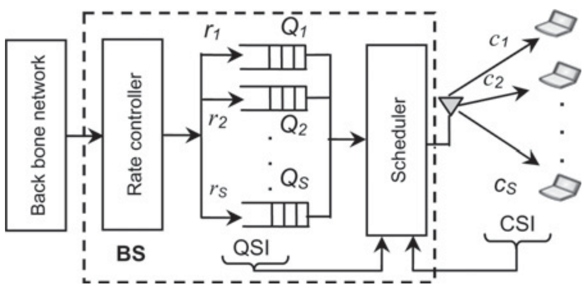

Fig. 1 *Network architecture*

The BS scheduler assigns a set $\Omega = \{k | k = 1, 2, \dots, K\}$ of OFDM subcarriers to links and allocates a portion of the BS power, P_{BS}, to each subcarrier to determine link rates c_s's. CSI is fed back to the scheduler through error-free channels. The rate control and scheduling decisions are made periodically at the beginning of each downlink frame containing a number of OFDM symbols denoted as time slot. CSI remains unchanged within a time slot but may change randomly and independently across time slots.

Signal-to-noise ratio of subcarrier k on link s during a time slot is given as $h_{sk} p_k$, where p_k is the allocated power to this subcarrier. Moreover $h_{sk} = |H_{sk}|^2/N$, where N denotes the noise power density, and H_{sk} depends on the path loss, shadowing and fading. We consider a discrete rate allocation to subcarriers with a finite set of modulation rates $D = \{0, 1, \dots, M\}$, where M is the highest modulation rate. Accordingly, the number of transmitted bits on subcarrier k, when it is assigned to user s, is

$$c_{sk} = \min\{\lfloor \log_2(1 + h_{sk} p_k) \rfloor, M\} \text{ bps/Hz} \tag{1}$$

2.2 Problem formulation

Let $\psi = \{C | C = [c_1, \dots, c_s]\}$ be the set of all feasible link rate vectors and $R = [r_1, \dots, r_s]$ denotes the set of long-term average arrival rates. Each user s is associated with a utility function U_s, which is continuously differentiable, non-decreasing and strictly concave for elastic traffic. The utility values indicate the level of users' satisfaction of received service in the network. We formulate the resource allocation as a network utility maximisation problem

$$P1: \max_{R,C} \sum_{s \in \Phi} U_s(r_s) \tag{2}$$

$$\text{Subject to} \quad 0 \le r_s \le c_s \quad \text{for all } s \in \Phi \tag{3}$$

$$C \in \Psi \tag{4}$$

Constraint (3) indicates that the long-term average arrival rate of queue s should not exceed the link rate c_s, that is, queue s departure rate. In addition, the link rate vectors should be in the feasible region according to (4).

3 Problem decomposition

Owing to discrete link rate vectors of ψ, $P1$ is not convex and hence solving it in the dual domain results in non-zero duality gap [11]. According to the seminal conclusion on multicarrier systems in [12], as the number of carriers increases, duality gap decreases. As the number of subcarriers in practical OFDMA networks is sufficiently large, we use dual decomposition to solve $P1$. Relaxing constraint (3), we write the Lagrangian function as

$$L_1(R, C, \Lambda) = \sum_{s \in \Phi} U_s(r_s) - \sum_{s \in \Phi} \lambda_s (r_s - c_s) \tag{5}$$

where $\Lambda = \{\lambda_s \ge 0\}$ is the vector of Lagrange multipliers.

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Accordingly, the dual function is given by

$$D_1(\Lambda) = \sup\{(L_1(R, C, \Lambda): R \geq 0, C \in \Psi)\}$$
$$= \sup_{R\geq 0}\left\{\sum_{s\in\Phi}(U_s(r_s) - \lambda_s r_s)\right\} + \sup_{C\in\Psi}\left\{\sum_{s\in\Phi}\lambda_s c_s\right\} \quad (6)$$

and the corresponding dual problem is

$$P2\colon \min_{\Lambda\geq 0} D_1(\Lambda) \quad (7)$$

Using (6) to evaluate $D_1(\Lambda)$ for a given Λ, we obtain the following optimisation problems

$$P3\colon \max_{R\geq 0}\sum_{s\in\Phi}(U_s(r_s) - \lambda_s r_s) \quad (8)$$

and

$$P4\colon \max_{C\in\Psi}\sum_{s\in\Phi}\lambda_s c_s \quad (9)$$

Problem $P3$ determines the arrival rates to the BS queues, and problem $P4$ optimises the link rates. Therefore they are called rate control problem and scheduling problem, respectively.

Given the solutions of $P3$ and $P4$, we use subgradient method to solve the dual problem $P2$. Starting with an initial $\lambda_s^0 \geq 0$ for all s, at each time slot t with a given λ_s^t, the optimal value of arrival rate, r_s^t, and link rate, c_s^t, are obtained from $P3$ and $P4$, respectively. Then, Lagrange multipliers are updated by

$$\lambda_s^{t+1} = [\lambda_s^t - \kappa(c_s^t - r_s^t)]^+ \quad \text{for all } s \quad (10)$$

where $(c_s^t - r_s^t)$ is the subgradient of the dual function with respect to λ_s. Moreover, the step size $\kappa > 0$ is chosen small enough to ensure the convergence [13]. It can be deduced from (10) that λ_s is a multiplication of the queue length Q_s of user s, that is, $\lambda_s = \kappa Q_s$. This derivation implies that each queue length is obtained from a stochastic subgradient method, which is shown to converge statistically to within a neighbourhood of the optimal value [14]. Using this derivative, we rewrite the scheduling problem $P4$ as

$$\max_{C\in\Psi}\sum_{s\in\Phi} Q_s c_s \quad (11)$$

As c_s's depend on the channel status and Q_s's represent the queue lengths, the objective function (11) can be interpreted as a CAQA scheduling scheme. Moreover, the queue lengths can be considered as coordinating parameters between the rate control and the scheduling problems.

In Fig. 2, the above decomposition approach is presented.

Given the dual solution of (10), we solve $P3$ and $P4$. According to (8), problem $P3$ can be decomposed into users' rate control subproblems, which are solved using subgradient method. The arrival rate s is updated by

$$r_s^{t+1} = [r_s^t + \kappa(VU_s'(r_s^t) - \lambda_s^t)]^+ \quad (12)$$

where $(U_s'(r_s^t) - \lambda_s^t)$ is the subgradient of the objective function in $P3$ with respect to r_s, and $\kappa > 0$ is the step size. The constant value V determines how aggressively the controller reacts to the same queue length levels [9]. We discuss the solution of $P4$ in Section 4.

Algorithm 1

```
Input: CSI over time.
Output: r_s and c_s for all s over time.
begin
    Set t=0, initialise λ_s for all s.
    while (1) do
        for all s
            Given λ_s^t, obtain r_s^t and c_s^t from P3 and P4, respectively.
            Using (10), update λ_s^{t+1} for the next time slot.
        end for
        return r_s^t and c_s^t for all s.
        t = t+1.
    end while
end
```

Fig. 2 *Decomposition algorithm*

4 Scheduling problem: formulation and solution

We reformulate the scheduling problem by specifying OFDMA resource constraints in Section 4.1. The solution of the scheduling problem is presented in Section 4.2, and the complexity analysis is brought in Section 4.3.

4.1 Scheduling problem formulation

We consider adaptive modulation rates on each subcarrier. The link rate c_s is the sum of modulation rates of those subcarriers assigned to that link, that is, $c_s = \sum_{k\in\Omega}\sum_{m\in D} m\rho_{skm}$, where $m \in D$. We define ρ_{skm} as a binary variable which is equal to 1 if subcarrier k is assigned exclusively to link s with modulation rate m and 0 otherwise. To avoid inter-link interference, each subcarrier is assigned only to one link, that is, $\sum_{s\in\Phi}\sum_{m\in D}\rho_{skm} = 1$ for all k. In addition, the total allocated power to the subcarriers should not exceed the BS power P_{BS}, that is, $\sum_{s\in\Phi}\sum_{k\in\Omega}\sum_{m\in D} p_k\rho_{skm} \leq P_{BS}$. Let subcarrier k be assigned to link s with modulation rate m. From (1), we have $m \leq \log_2(1 + h_{sk}p_k)$ that implies $(2^m - 1)/h_{sk} \leq p_k$. Therefore the power constraint can be stated as

$$\sum_{s\in\Phi}\sum_{k\in\Omega}\sum_{m\in D}\left(\frac{2^m - 1}{h_{sk}}\right)\rho_{skm} \leq P_{BS} \quad (13)$$

Accordingly, discrete rate CAQA OFDMA scheduling problem is presented by

$$P5\colon \max_{\{\rho_{skm}\}} \sum_s Q_s \sum_k \sum_m m\rho_{skm} \quad (14)$$

$$\text{Subject to} \quad \sum_s \sum_m \rho_{skm} = 1 \quad \text{for all } k \quad (15)$$

$$\sum_s \sum_k \sum_m \left(\frac{2^m - 1}{h_{sk}}\right)\rho_{skm} \leq P_{BS} \quad (16)$$

$$\rho_{skm} \in \{0, 1\} \quad \text{for all } s,\ k \ \text{and} \ m \quad (17)$$

Problem $P5$ is an integer programming problem, where the optimal solution is obtained by exhaustive search with high complexity [15]. The complexity grows exponentially with the number of users, subcarriers and modulation rates. This difficulty motivated us to propose a suboptimal solution, explained in Section 4.2.

4.2 Scheduling problem solution

We investigate a JSARA solution by decomposing $P5$ into subproblems of rate allocation to subcarriers. We relax the power constraint in (16) and form the partial Lagrangian function as

$$L_2(\rho, \mu) = \sum_s \sum_k \sum_m Q_s m \rho_{skm} - \mu \left(\sum_s \sum_k \sum_m \left(\frac{2^m - 1}{h_{sk}} \right) \rho_{skm} - P_{\rm BS} \right) \quad (18)$$

where μ is the Lagrange multiplier. Using (18), the corresponding dual function is written

$$D_2(\mu) = \sup_\rho \{ L_2(\rho, \mu) : \text{constraint (15) and (17)} \}$$
$$= \sup_\rho \left\{ \sum_k \sum_s \sum_m \left(Q_s m - \mu \frac{2^m - 1}{h_{sk}} \right) \rho_{skm} : \text{constraint (15) and (17)} \right\} + \mu P_{\rm BS} \quad (19)$$

We evaluate this function, for a given μ, by decomposing it into k subproblems corresponding to subcarriers

$$P6: \max_{\{\rho_{skm}\}} \sum_s \sum_m \left(Q_s m - \mu \frac{2^m - 1}{h_{sk}} \right) \rho_{skm} \quad (20)$$

$$\text{Subject to} \quad \sum_s \sum_m \rho_{skm} = 1 \quad (21)$$

$$\rho_{skm} \in \{0, 1\} \quad \text{for all } s \quad \text{and} \quad m \quad (22)$$

Considering (21) and (22), each subcarrier can be assigned to only one link with one modulation rate. Consequently, the optimal solution is achieved when subcarrier k is assigned to link s_k with modulation rate m_k as

$$(s_k, m_k) = \arg\max_{(s,m)} \left(Q_s m - \mu \frac{2^m - 1}{h_{sk}} \right) \quad (23)$$

In other words, $\rho_{skm} = 1$ if $(s, m) = (s_k, m_k)$, otherwise $\rho_{skm} = 0$. The dual variable μ is obtained from the dual problem

$$P7: \min_{\mu \geq 0} D_2(\mu) \quad (24)$$

Starting with an initial value μ^1, at iteration n with dual variable μ^n, the pair (s_k, m_k) for each subcarrier k is obtained from (23). Then, μ is updated by

$$\mu^{n+1} = \left[\mu^n - \sigma \left(P_{\rm BS} - \sum_k \frac{2^{m_k} - 1}{h_{s_k k}} \right) \right]^+ \quad (25)$$

where $(P_{\rm BS} - \sum_k (2^{m_k} - 1)/h_{s_k k})$ is the subgradient of $D_2(\mu)$ with respect to μ, and σ is the step size. Owing to discrete modulation rates, (25) does not converge precisely. Therefore the duality gap DG, which is the difference between the primal and the dual objective functions in (14) and (24), is not exactly 0 [11]. We use the condition $|DG| < \varepsilon$ to terminate the iterations and obtain a suboptimal solution, where ε is a small enough value.

In summary, the solution of JSARA scheduling scheme is presented in Fig. 3.

4.3 Complexity analysis

We compare the complexity of JSARA with the ones of DSA + APA and JSPA. At each iteration of JSARA, each subcarrier is allocated to a user by finding the maximum value of queue-length × rate in a vector with $S \times M$ entries. Therefore JSARA complexity is $O(N_\mu \times K \times S \times M)$, where N_μ is the number of iterations required for the convergence of (25) in Fig. 3. In DSA + APA, first every subcarrier is assigned to a user and then the power of all subcarriers is optimised by a greedy bit loading algorithm. At each iteration of this algorithm, the subcarrier with the minimum additional required power is selected for bit loading. Therefore the complexity is $O(K(S + N_{G_1}))$, where N_{G_1} is the number of required iterations for the convergence of the corresponding bit loading algorithm. Unlike DSA + APA, JSPA optimises power allocation whenever a new subcarrier is assigned to a user. Therefore JSPA complexity is $O(K(S + N_{G_2}K))$, where N_{G_2} is the number of iterations required for the convergence of the bit loading algorithm in JSPA. With $K = 512$, $S = 16$, $M = 6$ and 2000 realisations of a frequency selective fading channel, the average value of N_μ, N_{G_1} and N_{G_2} in the simulation is 12, 1180 and 164, respectively.

In summary, the complexity order of JSPA is quadratic with respect to the number of subcarriers. This complexity is high compared with those of JSARA and DSA + APA, where the complexity order is linear with respect to the number of subcarriers.

Algorithm 2

```
00: Input: Q = {Q_s}, H = {h_sk}.
01: Output: ρ = {ρ_skm}.
02: begin
03:     Set n=1 and initialise μ^1.
04:     while (1) do
05:         for all k
06:             Given μ^n, obtain the pair (s_k, m_k) from (23).
07:         end for
08:         Compute the duality gap DG.
09:         if (|DG| > ε)
10:             Update μ^{n+1} by equation (25).
11:             n=n+1.
12:             Go to step 05.
13:         else
14:             break.
15:         end if
16:     end while
17:     for all k
18:         if (s, m) = (s_k, m_k)
19:             ρ_skm = 1.
20:         else
21:             ρ_skm = 0.
22:         end if
23:     end for
24:     return ρ = {ρ_skm}.
25: end
```

Fig. 3 *JSARA scheduling scheme*

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5 Performance evaluation

We consider downlink transmission in an OFDMA network with a point to multipoint infrastructure. There are 512 subcarriers occupying a 5 MHz frequency band. Simulations are performed over 1200 realisations of a frequency selective fading channel, which is assumed to be 6-tap Rayleigh fading with 0.9 μs RMS delay spread. The exponential power delay profile is $g_s e^{-(l-1)}$, where g_s is the first path's average power gain, and l is the path index. We consider 32 users with different channel gains $g_s = 16$ dB, 15.5 dB, … , 0.5 dB, for $s = 1, 2, \ldots, 32$, respectively. Single-sided power spectral density of noise, N_0, is unity, and the total transmission power is 15 W. We evaluate JSARA performance in Section 5.1, and investigate the cooperation performance of the rate controller and CAQA scheduling in Section 5.2. In both subsections, we compare the performance of JSARA with JSPA [7] and DSA + APA [8].

5.1 Scheduling scheme performance

The performance of the proposed scheduling scheme without considering the rate controller is investigated. We assume the arrival rate to each user queue follows a Poisson distribution with 0.7 Mbps mean.

The average throughput and the average queue length of each user over the simulation time are shown in Figs. 4*a* and *b*, respectively. As shown, the higher is the channel gain, the more is the throughput and the smaller is the queue length. Furthermore, the difference between successive queue lengths increases as the channel gain decreases.

To clarify the difference among the scheduling schemes in Fig. 4, we illustrate the average number of assigned subcarriers to users and the average allocated power per subcarrier in Figs. 5*a* and *b*, respectively. Comparing with JSARA, JSPA and DSA + APA assign subcarriers based on the uniform power assumption. Therefore according to the objective function (11), queue-length × rate, the subcarrier assignment of JSPA and DSA + APA depends on users queue lengths significantly, and a high number of subcarriers are allocated to the users with large queue lengths, as shown in Fig. 5*a*. The power allocation in Fig. 5*b* shows that DSA + APA allocates more power to the users with higher channel gains to maximise the spectral efficiency. Moreover, as JSPA optimises power allocation of each user separately, more power than that of DSA + APA is allocated to low gain subcarriers. Therefore users with lower channel gains achieve higher throughput using JSPA rather than DSA + APA scheduling.

Unlike JSPA and DSA + APA, JSARA mitigates the effect of large queue lengths by considering the effect of large queue lengths in both subcarrier assignment and power allocation. This approach results in assigning large number of subcarriers to high channel gain users and remarkably

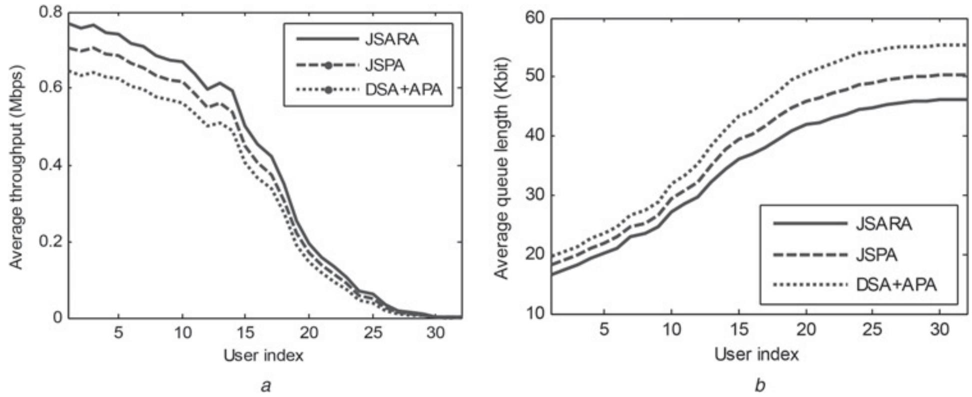


Fig. 4 *Average throughput and the average queue length of each user over the simulation time*

a Average throughput
b Average queue length of users

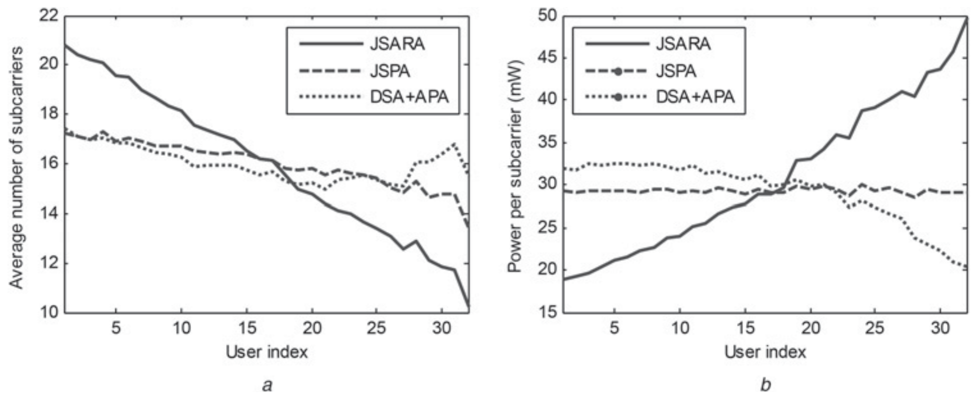


Fig. 5 *Average number of assigned subcarriers to users and the average allocated power per subcarrier*

a Average number of assigned subcarriers to users
b Average allocated power per subcarrier

high power allocation to users with low channel gains. In other words, JSARA compensates the small number of subcarriers assignment with high power allocation to low channel gain users. This joint optimisation in JSARA results in improved performance in terms of throughput and queue length, as shown in Fig. 4.

In applications with uncontrolled arrival rates (e.g. user datagram protocol (UDP)), buffer overflows cause the arrival traffic to be dropped. Further comparison of the schemes in terms of the bit-blocking probability is shown in Fig. 6, where a limited buffer size of 60 kbits per user is considered. High channel gain users experience remarkably low bit dropping because of the short queue lengths, whereas dropping probability of low channel gain users increases as the channel gains decrease. JSARA demonstrates the least bit dropping probability among the other schemes by keeping the queue lengths short.

5.2 Rate control and scheduling cooperation performance

We evaluate the proposed scheduling performance when the users' arrival rates are controlled by (12). Proportional fairness [16] is maintained among arrival rates by maximising their aggregate logarithmic utility functions in *P*1.

The average throughputs and queue lengths are shown in Figs. 7*a* and *b*, respectively. Although achieved curves show similar trends to the ones in Fig. 4, the overall performance is improved, that is, throughput increases and queue length decreases. This difference is due to the controlled arrival rates in this subsection, which avoids queue lengths from unexpected growth and therefore results in an efficient resource allocation in all schemes. No bit dropping is observed, because all queue lengths are small enough compared with the buffer sizes. Moreover, average packet waiting time in queues as another performance metric is shown in Fig. 8, which is in accordance with the aforementioned results in Fig. 7.

Finally, the average allocated arrival rates to the users and the network aggregate utility over the simulation time are given in Figs. 9*a* and *b*, respectively. Owing to the existence of the rate controller with logarithmic utility functions in (12), small queue lengths result in high arrival rates, as shown in Fig. 9*a*. Contrary to the results obtained for equally arrival rates in Section 5.1, the allocated arrival rates in Fig. 9*a* conforms to the achieved throughputs shown in Fig. 7*a*. In other words, network queues remain stable using the rate controller. Moreover in accordance with arrival rates to queues in Fig. 9*a*, the aggregate utility of JSARA outperforms the ones of JSPA and DSA + APA as shown in Fig. 9*b*.

As a complementary of the complexity analysis, the average running time of the scheduling schemes algorithms are shown in Table 1. The results confirm the analysis in

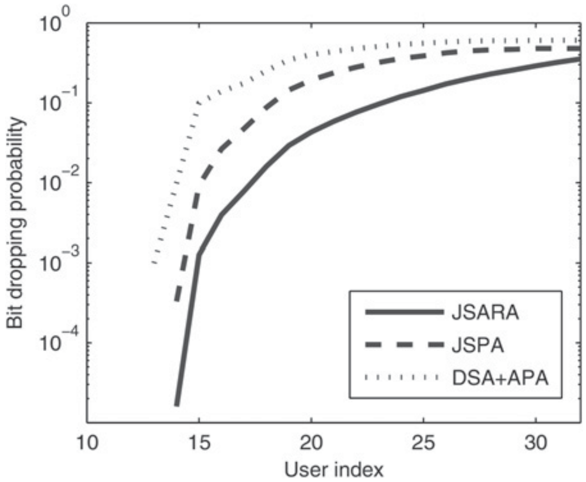


Fig. 6 *Bit dropping probability of users*

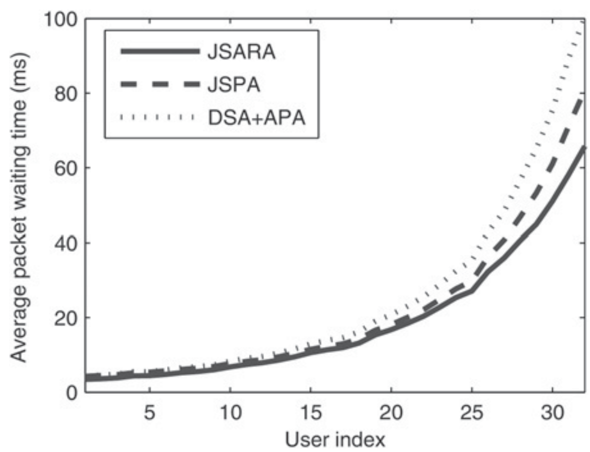
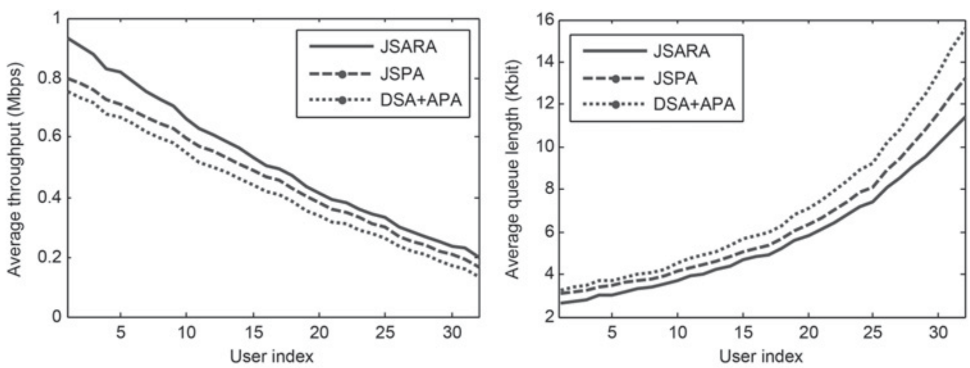


Fig. 8 *Average packet waiting time (ms)*



a *b*

Fig. 7 *Average throughputs and queue lengths*

a Average throughput
b Average queue length of users

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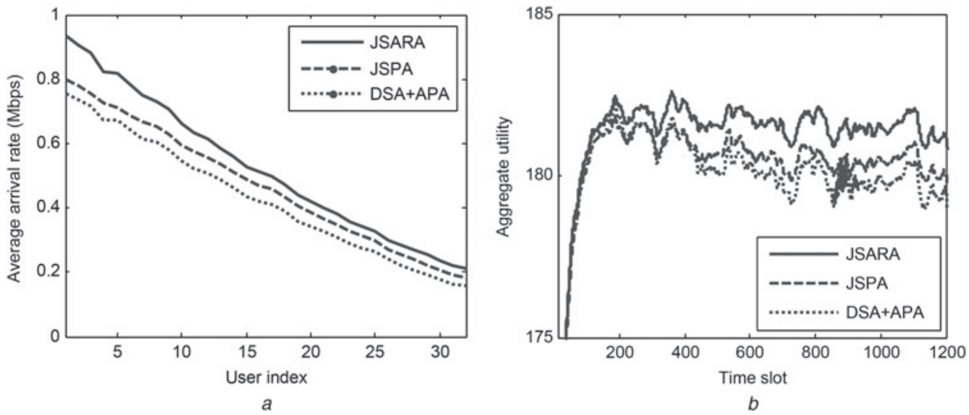

Fig. 9 Average allocated arrival rates to the users and the network aggregate utility over time

a Average arrival rates of users
b Network aggregate utility over time

Table 1 Average running time of the scheduling schemes algorithms (ms)

Scheme	JSARA	JSPA	DSA + APA
Time, ms	74	3118	1177

Section 4.3, where JSARA outperforms the two other schemes. JSPA has the highest running time as it optimises the power allocation on assigning each subcarrier. Furthermore, the iterative bit-loading algorithm in DSA + APA makes it computationally complex than JSARA.

In summary, CAQA scheduling results in efficient resource allocation when it cooperates with a rate controller.

6 Conclusion

We have proposed a JSARA CAQA OFDMA scheduling scheme, in cooperation with a rate controller. The performance of the proposed scheme with and without cooperation with the rate controller has been evaluated. We have observed that CAQA scheduling performance is highly affected by the traffic arrival rates to the queues. Uncontrolled arrival rates result in large queue lengths, which degrade the CAQA scheduling performance. Simulation results demonstrate that first JSARA outperforms OFDMA scheduling schemes with disjoint subcarrier assignment and power allocation in terms of the network aggregate utility. Second, lower queue lengths with no dropping probability and higher throughputs are achieved by the cooperation between the rate controller and the CAQA scheduling.

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