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Utility-based resource allocation in orthogonal frequency division multiple access networks

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Abstract: The authors consider network utility maximisation problem in orthogonal frequency division multiple access (OFDMA) networks to study cross-layer, fair and efficient resource allocation. Assuming knowledge of the instantaneous channel gains, this problem is decomposed into rate control and scheduling problems at the transport and medium access control/physical layers, respectively. In contrast to the rate control problem that is solved using subgradient method, the scheduling problem has high computational complexity owing to optimising integer and continuous variables simultaneously. Based on the results from analysing the integer relaxed scheduling problem, computationally efficient adaptive scheduling (CEAS) and opportunistic time division multiple access (Opp-TDMA) scheduling schemes are proposed to joint subcarrier assignment and power allocation. Simulation results demonstrate that aggregate utility achieved in the network with the cooperation between rate control and proposed scheduling schemes outperforms those of previously proposed joint channel-aware and queue-aware scheduling schemes. Also, through comparison with the optimal solution, the authors conclude that CEAS is applicable for OFDMA real-time scheduling due to low computational complexity and high performance.

1 Introduction

The increasing demand for high-bandwidth services in wireless networks increases the importance of resource allocation. Network control mechanisms at different layers should be optimised to fully utilise the capabilities in the network and manage the resource allocation. In wireless networks, there is an inherent coupling between different layers; allocating the resources at the physical layer determines average link rates, which influences link scheduling, routing and flow control in the higher layers. Under such coupling, resource optimisation within layers will not be enough, but a cross-layer approach should be employed to achieve the optimal network performance.

Spectral efficiency and fairness are two key considerations in the resource allocation of wireless networks. Maximising spectral efficiency in terms of aggregate throughput leads to unfair transmission rate for users with poor channel quality. On the other hand, providing absolute fairness in the network decreases efficiency significantly. Therefore an effective trade-off between fairness and efficiency is desired in wireless resource allocation.

Network utility maximisation (NUM) has emerged as an optimisation framework for resource allocation in communication networks [1]. This framework provides a cross-layer design approach and achieves a trade-off between efficiency and fairness by defining utility functions corresponding to network users. In this framework, the degree of utility for each user indicates the level of satisfaction of that user from the received service in the network.

Orthogonal frequency division multiplexing (OFDM) is a widely accepted physical layer technique that divides the entire bandwidth into a set of narrowband subcarriers to encounter fading channel impairments in broadband wireless communication. In an OFDM wireless network, subcarrier channel gains are independent for different users, so a subcarrier in fading for some users may not be in fade for others. Further, different subcarriers can be allocated to different users to provide a flexible orthogonal frequency division multiple access (OFDMA) mechanism. By dynamically assigning subcarriers and allocating the transmission power, network performance can be improved as a result of multiuser diversity [2].

Despite a large body of work done in the utility-based resource allocation in [3–9], no one has considered OFDMA as the transmission technique in MAC/PHY layer. On the other hand, resource allocation schemes proposed for OFDMA in [10–22] have not considered transmission rate optimisation at the transport layer. In other words, flows destined to different users are not controlled as well as isolated from each other, which causes congestion in the network in the case of misbehaving flows.

In this paper, utility-based cross-layer resource allocation framework in OFDMA networks is investigated as shown in Fig. 1. This figure illustrates that resource allocation at MAC/PHY layer affects rate allocation at the transport layer and achieved utility in the NUM problem, accordingly. On the other hand, NUM problem aims at maximising aggregate utility by managing control mechanisms at underlying layers.

Traffic flows arrived into user queues are considered non-real time. The elastic nature of this type of traffic allows us to control its rate adaptively according to the amount of allocated resources. Using duality, NUM problem is decomposed into rate control and scheduling problems at the transport layer and MAC/PHY layer, respectively. While the rate control problem is solved using subgradient method, the scheduling problem has high computational complexity due to optimising a non-linear function with both continuous and integer variables. To overcome the difficulty, integer constraints are relaxed and the problem is solved analytically by convex optimisation techniques. Based on the results from this analysis, we propose computationally efficient adaptive scheduling (CEAS) and

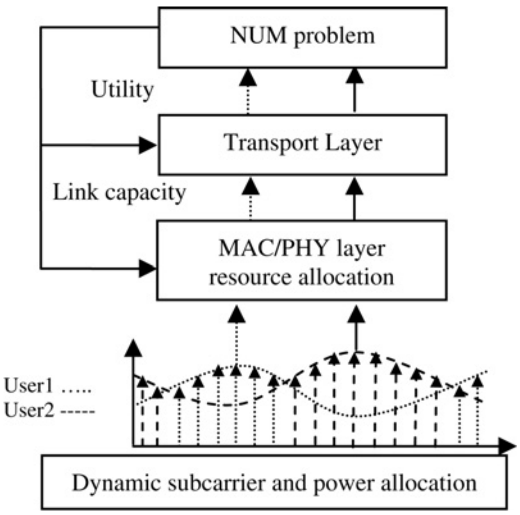

Figure 1 *Cross-layer OFDMA resource allocation*

opportunistic time division multiple access (Opp-TDMA) scheduling schemes. CEAS and Opp-TDMA that are joint channel-aware and queue-aware scheduling schemes are coupled with the rate control mechanism at the transport layer using users' queue-length parameters. The performance of cooperation between the rate control and scheduling mechanisms are evaluated, where CEAS and Opp-TDMA are compared with previously proposed joint channel-aware and queue-aware OFDMA scheduling schemes. Finally, CEAS is compared with the optimal solution of the scheduling problem.

The rest of the paper is organised as follows. Related works are reviewed in Section 2. System model including the network architecture and problem formulation is described in Section 3. The problem is mathematically analysed in Section 4. The proposed scheduling schemes are presented in Section 5 and their performance is evaluated in Section 6. The paper is concluded in Section 7.

2 Related works

The idea of using utility functions in the context of communication networks was first proposed in [1]. NUM framework in wireline networks has been studied in [3, 4]. These studies resulted in several congestion controllers that cause the network to approach the optimum condition asymptotically. The extension of this framework for wireless networks using single transmission channel has been investigated in [5–8]. Here, the difficulty arises as a result of time-varying link capacities and interference among multiple transmissions on adjacent links. As a consequence, a scheduling policy is required to determine the set of simultaneously active links without interference on each other. A utility-based joint power and rate adaptive algorithm is proposed in [9] for wireless *ad hoc* networks. The transmission power and rate of each user will be adjusted to maximise its own net-utility according to the states of channel, which results in a balance between the effective transmission rate and power consumption.

Owing to parallel channels, optimising resource allocation in OFDMA networks is challenging. The literature in this issue is often classified into two categories: (i) maximising aggregate users' throughput subject to a constrained overall power and (ii) minimising the overall power subject to constrained individual users' minimum throughput. Both categories have often formulated the resource allocation as a mixed non-linear integer programming problem.

The first category has been discussed in [10–18]. Resource allocation algorithms have been proposed in [10, 11] to maximise the system throughput while satisfying both real-time and non-real-time quality of service requirements. In [12], ergodic weighted sum rate for an OFDMA system has been maximised subject to total power constraint and imperfect channel-state information (CSI). This paper uses dual optimisation to reduce the complexity of solution. In

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[13], system throughput is maximised for an OFDMA multicast system, where the available radio spectrum is shared among multicast groups by guaranteeing minimum number of subcarriers to be assigned to individual groups.

A two-step approach to maximise the overall data rate while maintaining the proportional fairness among users has been proposed in [14]. First, based on user's average channel gain, the number of subcarriers to be assigned to each user is increased gradually until the user minimum rate is satisfied. Secondly, non-linear equations are solved for power allocation. In [15], assuming a fixed modulation level for all subcarriers assigned to each user, the problem has been formulated as an integer programming problem. Then, this problem has been solved suboptimally using linear programming. A novel cross-layer adaptive resource allocation strategy with hybrid adaptive array and switched-beam smart antennas suitable for OFDM networks has been proposed in [17]. In [16], a utility-based theoretical framework for OFDMA resource allocation has been proposed subject to concave utility functions and infinite number of subcarriers. In [18], a channel-aware and queue-aware joint subcarrier and power allocation (CAQA + JSPA) OFDMA scheduling scheme has been proposed. This scheme that requires optimising power allocation, after each subcarrier is assigned, has high computational complexity. It has been shown that this scheme outperforms channel-aware only, fixed power allocation and modified largest weighted delay first (MLWDF) [23] schemes.

The second category of OFDMA resource allocation has been discussed in [19–22]. In [19], minimising the transmission power subject to users' minimum rate requirement has been formulated as a convex problem by relaxing integer constraints. In [20], based on user's average channel gain, first the number of subcarriers assigned to each user is determined. Secondly, subcarrier assignment as a combinatorial set partitioning problem is performed to minimise the transmission power. Power minimisation has been formulated as a linear programming problem in [21] and several heuristic schemes have been proposed. Minimising the average transmit power under individual average rate and error probability constraints has been investigated in [24] subject to limited channel-state feedback.

3 System model and problem formulation

The network architecture and radio transmission model are described in Section 3.1, then the NUM problem is formulated in Section 3.2.

3.1 Network architecture and radio transmission model

We consider downlink transmission in an OFDMA network with point to multipoint infrastructure and a set $\Phi = \{s{:}s = 1, 2, \ldots, S\}$ of users in Fig. 2. Data traffic of user s is admitted to the network with rate r_s and buffered in a separate queue in the base station (BS).

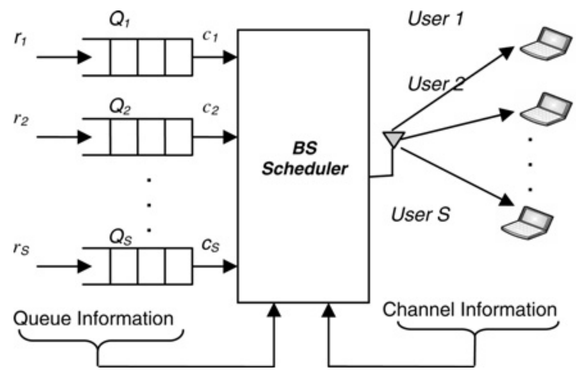

Figure 2 *Network architecture*

The scheduler located in BS assigns a set $\Omega = \{k{:}k = 1, 2, \ldots, K\}$ of OFDM subcarriers to users and allocates a portion of BS power, $P_{\rm BS}$, to each subcarrier, through which each link capacity c_s corresponding to user s is determined. The scheduling decision is made periodically at the beginning of a number of OFDM symbols, noted as time slot. Both CSI and queue-state information that will be used in the scheduling policy are assumed to be available at the scheduler and remain unchanged during each scheduling interval.

Signal-to-noise ratio of subcarrier k on link s during each time slot is defined as $h_{sk}\,p_k$, where p_k is the allocated power to this subcarrier. Moreover, $h_{sk} = |H_{sk}|^2/N$, where N represents noise power density and H_{sk} is the channel gain depending on path loss, shadowing and fading. Accordingly, the number of transmitted bits of user s on subcarrier k is defined as

$$c_{sk} = \log_2 (1 + h_{sk}p_k)\ \text{bps/Hz} \tag{1}$$

3.2 Problem formulation

Let $R = \{r_s \geq 0{:}s \in \Phi\}$ be the set of user arrival rates and $\Psi = \{\boldsymbol{C}{:}\boldsymbol{C} = [c_1, c_2, \ldots, c_S]\}$ denotes the set of all feasible link capacity vectors. Also, assume that each user s is associated with a utility function U_s that is continuously differentiable, non-decreasing and strictly concave for elastic traffic. NUM problem that is aimed at maximising the sum of utilities subject to constraints posed by the network can be formulated in P1 as in the following

$$\text{P1:} \max_{R,C} \sum_s U_s(r_s) \tag{2}$$

subject to

$$0 \leq r_s \leq c_s,\quad \text{for all } s \tag{3}$$

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

Constraint (3) states that arrival rate into a queue should not

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exceed the corresponding link capacity. Also, link capacity vector should lie within the feasible region according to (4).

4 Mathematical analysis

Under assumption of convex sets R and $\boldsymbol{C}$, we define the Lagrangian function corresponding to P1 as

$$L_1(R, \mathbf{C}, \boldsymbol{\Lambda}) = \sum_s U_s(r_s) - \sum_s \lambda_s(r_s - c_s) \quad (5)$$

and corresponding dual function as

$$\begin{aligned} D_1(\boldsymbol{\Lambda}) &= \sup\{(L(R, \mathbf{C}, \boldsymbol{\Lambda}) : R \geq 0, \mathbf{C} \in \Psi)\} \\ &= \sup_{R\geq 0}\left\{\sum_s (U_s(r_s) - \lambda_s r_s)\right\} + \sup_{C\in\Psi}\left\{\sum_s \lambda_s c_s\right\} \end{aligned} \quad (6)$$

where $\boldsymbol{\Lambda} = \{\lambda_s \geq 0 : s \in \Phi\}$ is the vector of Lagrange multipliers. With convexity of P1, we solve it in the dual domain [25] as

$$\text{P2: } \min_{\Lambda\geq 0} D_1(\boldsymbol{\Lambda}) \quad (7)$$

As seen from (6), evaluating the dual function for a given $\boldsymbol{\Lambda}$ is decomposed into the following problems as

$$\text{P3: } \max_{R\geq 0} \sum_s (U_s(r_s) - \lambda_s r_s) \quad (8)$$

and

$$\text{P4: } \max_{\boldsymbol{C}\in\Psi} \sum_s \lambda_s c_s \quad (9)$$

Objective functions in P3 and P4 are, respectively, functions of arrival rates into queues and link capacities, that is, departure rates from queues. Accordingly, they are denoted as the rate control problem and the scheduling problem, respectively. We discuss the solution of dual problem P2 in the following and leave the solution of P3 and P4 to Sections 4.1 and 4.2, respectively.

To solve P2, we employ iterative subgradient method. Starting with an initial $\lambda_s(0)$ for all s, at each time slot t with a given $\lambda_s(t)$, the optimal value of arrival rates $r_s(t)$ and link capacities $c_s(t)$ are obtained from P3 and P4, respectively. Then Lagrange multipliers are updated at time slot $t+1$ using

$$\lambda_s(t+1) = [\lambda_s(t) + \kappa(r_s(t) - c_s(t))]^+, \quad \forall s \quad (10)$$

where $-(r_s(t) - c_s(t))$ is the subgradient of dual function with respect to λ_s in (6). Moreover, step size $\kappa > 0$ is chosen small enough to ensure the convergence [26]. Inspecting (10), we can say that it is equivalent to user s queue length variation along time, $Q_s(t)$, and write $\lambda_s(t) = \kappa Q_s(t)$. Since both P3 and P4 include Lagrange multipliers, we conclude that rate control and scheduling mechanisms are coupled via users' queue length parameters.

4.1 Rate control problem solution

Obtaining $\lambda_s(t)$ at time slot t in (10), the rate control problem P3 in (8) is decomposable into S subproblems and each one can be solved independently. By taking differentiation with respect to r_s in subproblem corresponding to user s, and using the subgradient method, the optimal arrival rate is obtained as

$$r_s(t+1) = r_s(t) + \kappa(VU_s'(r_s(t)) - \lambda_s(t)), \quad \forall s \quad (11)$$

where $(U_s'(r_s(t)) - \lambda_s(t))$ is the subgradient of P3 objective function with respect to $r_s(t)$, and $\kappa > 0$ is step size. Moreover, V is a desired constant that determines how aggressively controller (11) reacts to the same queue length levels, that is, generates more or less data.

4.2 OFDMA scheduling problem solution

In this subsection, we focus on constraint $\boldsymbol{C} \in \Psi$ in P4 and derive resource allocation constraints in a single-hop OFDMA network. Considering (1), we express the capacity of link s corresponding to user s as $c_s = \sum_{k\in\Omega} \rho_{sk} \log_2(1 + h_{sk} p_k)$, where ρ_{sk} is a binary-valued index that is 1 if subcarrier k is assigned to user s, otherwise 0. Link capacity vector $\boldsymbol{C}$ in this network not only depends on the CSI, but also is limited with some resource constraints. First, to avoid intra-cell interference, each subcarrier is restricted to be assigned to one user exclusively, that is, $\sum_{s\in\Phi} \rho_{sk} = 1$ for all k. Secondly, as BS power is limited, the overall allocated power to all subcarriers should not exceed P_{BS}, that is, $\sum_{k\in\Omega} p_k \leq P_{\text{BS}}$. Considering these constraints along with $\lambda_s = \kappa Q_s$, we reformulate P4 as the joint channel-aware and queue-aware OFDMA scheduling problem P5 at each time slot as

$$\text{P5: } \max_{\rho, P} \sum_s Q_s \sum_k \rho_{sk} \log_2(1 + h_{sk} p_k) \quad (12)$$

subject to

$$\sum_s \rho_{sk} = 1, \quad \text{for all } k \quad (13)$$

$$\rho_{sk} \in \{0, 1\}, \quad \text{for all } k, s \quad (14)$$

$$\sum_k p_k \leq P_{\text{BS}} \quad (15)$$

According to P5, each user is allowed to be allocated a number of subcarriers at each time slot. Therefore time slot allocation in the context of OFDMA is inherently incorporated into this formulation. Owing to both integer and continuous variable sets, $\rho = \{\rho_{sk}\}$ and $P = \{p_k\}$, finding the optimal solution to P5 burdens so high computational complexity that arises the requirement of

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suboptimal solution for real-time scheduling. To achieve this goal, we relax integer constraint on the set ρ temporarily to investigate suboptimal solutions, that is, it is assumed that this set can involve any value in the range [0, 1]. Hereby, ρ_{sk} can be interpreted as the time-sharing factor of subcarrier k for user s. In that case, the problem will become convex and the Lagrangian function is defined as

$$L_2(\rho, P, \Gamma, \mu) = \sum_s Q_s \sum_k \rho_{sk} \log_2(1 + h_{sk} p_k) - \sum_k \gamma_k \left(\sum_s \rho_{sk} - 1 \right) - \mu \left(\sum_k p_k - P_{\rm BS} \right) \tag{16}$$

where $\Gamma = \{\gamma_k\}$ and $\mu \geq 0$ are Lagrange multipliers associated with constraint (13) and (15), respectively. With the convexity of the integer relaxed problem, the necessary conditions for the optimal solution (ρ^*, P^*) become [26]

$$\frac{\partial L_2}{\partial \rho_{sk}}|_{(\rho,P)=(\rho^*,P^*)} = Q_s \log_2(1 + h_{sk} p_k^*) - \gamma_k \begin{cases} > 0, & \text{if } \rho_{sk}^* = 1 \\ = 0, & \text{if } 0 < \rho_{sk}^* < 1 \\ < 0, & \text{if } \rho_{sk}^* = 0 \end{cases} \quad \text{for all } k, s \tag{17}$$

and

$$\frac{\partial L_2}{\partial p_k}|_{(\rho,P)=(\rho^*,P^*)} = \sum_s \frac{Q_s \rho_{sk}^* h_{sk}}{\ln 2(1 + h_{sk} p_k^*)} - \mu \begin{cases} = 0, & \text{if } p_k^* > 0 \\ < 0, & \text{if } p_k^* = 0 \end{cases}, \quad \text{for all } k \tag{18}$$

According to these conditions, the derivatives evaluated at the optimum point must be zero if the maximum occurs within the feasible region. On the other hand, the derivatives must be positive along all directions pointing towards the interior of the feasible region, if the maximum occurs at a boundary point. From (17), we conclude that

$$\rho_{sk}^* = \begin{cases} 1, & \text{if } \gamma_k < Q_s \log_2(1 + h_{sk} p_k^*) \\ 0, & \text{if } \gamma_k > Q_s \log_2(1 + h_{sk} p_k^*) \end{cases} \tag{19}$$

Since each subcarrier can be assigned only to one user, it is inferred from (19) that subcarrier k is to be assigned to user s^* according to

$$s^* = \arg\max_s (Q_s \log_2(1 + h_{sk} p_k)) \tag{20}$$

That is, ρ_{sk} is set to 1 for each k, if $s = s^*$, otherwise 0. As a result, for a given vector of power allocation P, subcarriers can be assigned using (20). On the other hand, assuming a given set of subcarrier assignment $\rho = \rho_{sk}$, the optimal power allocation is achieved through a weighted water-filling approach as in the following

$$p_k = [Q_{s^*} \mu^* - 1/h_{s^* k}]^+, \quad \text{for all } k \tag{21}$$

where $\mu^* = (1/\mu)\ln 2$ is obtained using a binary search algorithm such that $\sum_k p_k = P_{\rm BS}$.

5 Proposed OFDMA scheduling schemes

Since communication networks require real-time scheduling, proposing algorithms that speed up the scheduling while obtaining near optimal performance is of high importance. Based on the mathematical analysis in Section 4, we propose two low complex but suboptimal OFDMA scheduling schemes in this section: CEAS and Opp-TDMA.

CEAS scheme employs an iterative approach based on the separate optimisation of subcarrier assignment and power allocation. The total power is equally distributed among subcarriers initially. For a given power allocation at each iteration, subcarriers are assigned using (20), and then power is allocated to subcarriers according to (21). This scheme is shown in Algorithm 1, in which obj(n) is the value of P5 objective function at iteration n and ε is a desirable small enough constant.

Algorithm 1: CEAS scheme	
Step 1: Initialise $n = 0$, $p_k(n) = P_{BS}/K$ for all k.	
Step 2: do {	
Step 3:	$n = n + 1$.
Step 4:	assign subcarriers according to (20).
Step 5:	allocate power according to (21).
Step 6:	} while($\lvert obj(n) - obj(n-1) \rvert > \varepsilon$).

Inspiring from TDMA systems where the whole frequency band is assigned only to one user at a time slot, here we propose adaptive Opp-TDMA scheduling scheme in Algorithm 2. Our motivation to propose this scheduling is to compare it with CEAS in which different subcarriers can be allocated to different users at a time. At each time slot of Opp-TDMA, channel gain $\bar{h}_s$ for each user s is obtained by averaging over all corresponding subcarrier channel gains. Based on this gain, all of subcarriers are assigned to the user who maximises P5 objective function under assumption of uniform power allocation to subcarriers. Then, power allocation is optimised using (21).

Algorithm 2: Opp-TDMA scheme
Step 1: Obtain $\bar{h}_s = E\{h_{sk}\}$ for all s.
Step 2: Choose user s^* to be assigned all subcarriers according to: $s^* = \arg\max_s (Q_s \sum_{k \in \Omega} \log_2(1 + \bar{h}_s P_{BS}/K))$.
Step 3: Optimise power allocation to subcarriers according to (21).

6 Performance evaluation

In this section, performance evaluation of the cooperation between rate control and proposed scheduling schemes will be provided. We consider OFDMA downlink transmission in a network consisting of 128 subcarriers over a 1 MHz frequency band along with a total transmission power equal to 10 W. The channel is assumed to be six-tap Rayleigh fading with 0.9 μs root mean square delay spread and an exponential power delay profile $g_s e^{-(l-1)}$, where g_s is the first path's average power gain and l is the index of path l. We consider 16 users with different subcarrier channel gains $g_s = 0, -0.3, -0.6, \ldots, -4.5$ dB for $s = 1, 2, 3, \ldots, 16$, respectively. Also, single-sided power spectral density of noise, N_0, is assumed to be unity.

We provide an event-driven simulation platform in MATLAB consisting of rate control, scheduling and channel modules. The rate control module provides the scheduling one with queue length parameters and obtains link capacities from it. The channel module generates a Rayleigh frequency-selective fading channel in the time domain and acquires its K-point fast Fourier transform to obtain individual subcarrier channel gains. Achieved gains are fed into the scheduling module to obtain link capacities. We perform simulation over 3000 realisation of frequency-selective fading channels with logarithmic utility function for all users.

We compare our proposed algorithms, CEAS and Opp-TDMA, with joint channel-aware and queue-aware scheduling schemes, CAQA + JSPA in [18], and MLWDF in [23] extended for OFDMA networks. CAQA + JSPA similar to CEAS allows each user to be allocated a number of subcarriers at each time slot, but MLWDF assigned all subcarriers to only one user at each time slot. In the following, the performance of cooperation between rate control and scheduling mechanisms are presented.

The average arrival rates into queues and their corresponding queue lengths in the simulation are shown in Figs. 3*a* and *b*, respectively. As shown, higher channel gains result in higher performance in all schemes, that is, higher arrival rates and smaller queue lengths. This behaviour is in accordance to the rate controller in (11), where higher queue length decreases arrival rate and vice versa. While difference between the performances of users with different channel gains is quietly observed in our proposed schemes, CAQA + JSPA and MLWDF provide all the users with approximately the same performance. This is due to the fact that in these schemes, allocated link capacity for a user at a time slot is reversely proportional to the achieved average link capacity of that user so far. Therefore users tend to receive less variables rates as well as queue lengths.

Aggregate utilities achieved in the network against time are shown in Fig. 4*a* that converge approximately after 1000 time slots. As seen, CEAS and CAQA + JSPA, in which different subcarriers can be allocated to different users at a time, outperform the schemes Opp-TDMA and MLWDF, in which all subcarriers are allocated to only one user at a time. We can state this improvement as a result of multiuser diversity in OFDMA. In addition, while Opp-TDMA and MLWDF have approximately the same performance, CEAS achieves higher utility than CAQA + JSPA. This is due to the analytical subcarrier assignment based on (21) in CEAS in contrast to heuristic subcarrier assignment in CAQA + JSPA.

Moreover, in terms of computational complexity, CAQA + JSPA optimises power allocation after each subcarrier is assigned, whereas CEAS optimises power allocation after assigning all subcarriers. Accordingly, the computational complexity of CEAS is approximately K times less than that of CAQA + JSPA.

Multiuser diversity in OFDMA networks is also investigated. According to this diversity, as the number of users increases, a given subcarrier will most likely be assigned to the user with higher channel gain, which improves the performance accordingly. We show average aggregate utility achieved in network against the number of

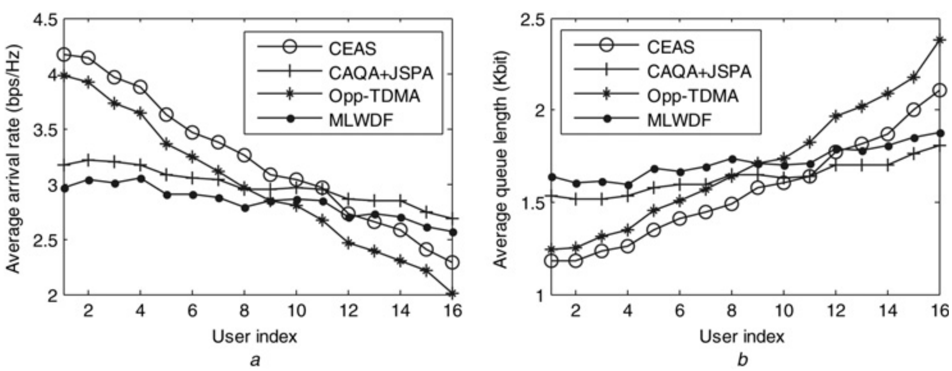

Figure 3 *Average arrival rate of users and corresponding queue length*

a Average arrival rate (bps/Hz)
b Average queue length (Kbit)

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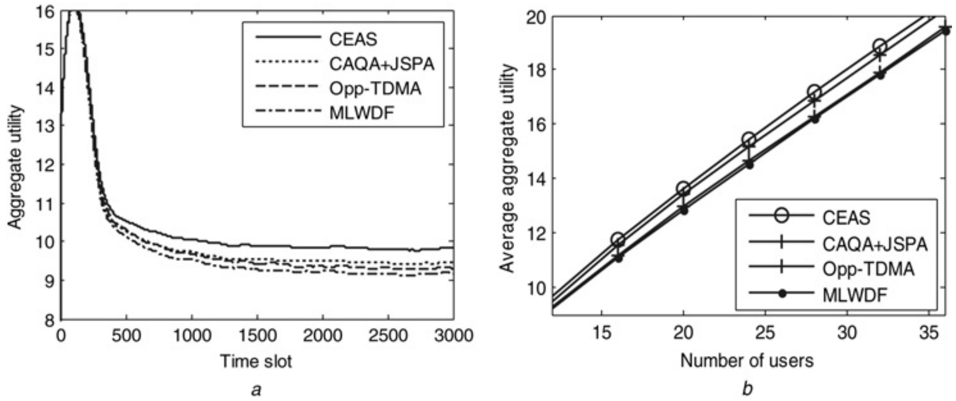

Figure 4 *Aggregate utilities against time and the number of users*

a Aggregate utility against time
b Average aggregate utility against the number of users

Table 1 CEAS against optimal solution

Arrival rate, bps/Hz	CEAS	Optimal
r_1	7.56	7.57
r_2	7.51	7.53
r_3	7.19	7.2
r_4	6.8	6.8
utility	11.43	11.45

users in Fig. 4*b*, when all users have the same channel gain. As seen, CEAS has the best performance and also utility value increases as the number of users increases due to the multiuser diversity gain.

Finally, in order to evaluate the suboptimal performance of CEAS compared to an optimal solution, the scheduling problem P5 is solved using MATLAB optimisation toolbox. Owing to long running time required by the optimal solution, we consider a small-scale scenario consisting of 64 subcarriers and four users for 1000 realisation of frequency-selective fading channels. Running time of the optimal solution (4.1 h) is approximately 6000 times that of CEAS (2.5 s). Users' average arrival rates and aggregate utility are shown in Table 1.

As shown, the performance of CEAS is approximately the same as optimal solution with substantially lower running time. Therefore CEAS can be considered to be implemented in real-time scheduling because of high performance and low complexity.

7 Conclusion

Maximising aggregate utility in OFDMA networks has been decomposed into cooperating and controlling mechanisms at different layers, rate control and scheduling mechanisms in this paper. The rate control problem at the transport layer adjusts arrival rates into queues by a subgradient method that causes the network to approach the optimal condition asymptotically. On the other hand, the scheduling problem at MAC/PHY layer that determines queues' departure rates has high complexity due to optimising both integer and continuous variables. To solve the channel-aware and queue-aware scheduling problem, we relaxed integer constraints temporarily and solve it using convex programming. Based on the results from this solution, we proposed CEAS and Opp-TDMA schemes. Simulating the cooperation between rate controls and scheduling mechanisms has been performed with frequency-selective fading channels. Achieved results demonstrate that proposed scheduling schemes demonstrate higher performance compared to their counterpart joint channel-aware and queue-aware scheduling schemes. In addition, low complexity and high performance of CEAS make it applicable for OFDMA real-time scheduling.

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