

# A Dual-Decomposition-Based Resource Allocation for OFDMA Networks With Imperfect CSI

Mohamad Khattar Awad, *Member, IEEE*, Veluppillai Mahinthan, *Member, IEEE*, Mehri Mehrjoo, *Member, IEEE*, Xuemin (Sherman) Shen, *Fellow, IEEE*, and Jon W. Mark, *Life Fellow, IEEE*

**Abstract**—This paper presents a novel scheme for the allocation of subcarriers, rates, and power in orthogonal frequency-division multiple-access (OFDMA) networks. The scheme addresses practical implementation issues of resource allocation in OFDMA networks: the inaccuracy of channel-state information (CSI) available to the resource allocation unit (RAU) and the diversity of subscribers' quality-of-service (QoS) requirements. In addition to embedding the effect of CSI imperfection in the evaluation of the subscribers' expected rate, the resource-allocation problem is posed as a network utility maximization (NUM) one that is solved via decomposing it into a hierarchy of subproblems. These subproblems coordinate their allocations to achieve a final allocation that satisfies aggregate rate constraints imposed by the call-admission control (CAC) unit and OFDMA-related constraints. A complexity analysis shows that the proposed scheme is computationally efficient. In addition, performance evaluation findings support our theoretical claims: A substantial data rate gain can be achieved by considering the CSI imperfection, and multiservice classes can be supported with QoS guarantees.

**Index Terms**—Broadband wireless access networks, call-admission control, dual decomposition, imperfect channel state information, orthogonal frequency-division multiple-access (OFDMA), resource management.

## I. INTRODUCTION

THE INCREASING demand to support multimedia services (e.g., Internet Protocol television, online gaming, and tele-medicine) has led to an increase in transmission bandwidth. As the bandwidth increases, performance degradation is observed due to frequency-selective fading that results in intersymbol interference (ISI) [1], [2]. Orthogonal frequency-division multiple-access (OFDMA) physical (PHY) and medium-access control (MAC) technologies avoid frequency selectivity by transmitting the wideband signal as multiple narrow-band signals over subbands that are supported by subcarriers and with a bandwidth that is less than the channel coherence bandwidth [2], [3]. In addition, OFDMA assigns a subset of the available subcarriers to each subscriber station that is not required to transmit over the full bandwidth; thus,

transmission power can be conserved. Furthermore, as the subcarriers' gains change over time, OFDMA updates its subcarriers' assignment, which results in exploiting multiuser diversity. OFDMA is being considered in current broadband standards because of its indispensable features: exploitation of multiuser diversity, flexibility in resource allocation, conservativity in link budget, and robustness to ISI in frequency-selective fading channels. Examples of networks that adopt OFDMA are the Broadband Wireless Access Networks IEEE 802.16<sup>1</sup> and the Third-Generation Partnership Project Long-Term Evolution (3GPP-LTE) networks [4].

All the aforementioned salient features of OFDMA hinge on the availability of perfect channel state information (CSI) at the resource allocation unit (RAU), which is not the situation in practical networks. Thus, the development of practical resource allocation schemes requires accounting for the inaccuracy of CSI. In addition, the support of multiple services implies diverse throughput requirements in which the call-admission control (CAC) unit becomes important to provide quality-of-service (QoS) guarantees by distributing the network throughput among the supported services. These considerations motivate us to propose a resource allocation scheme for OFDMA networks that allocates subcarriers, power, and rates in conjunction with a CAC unit under the assumption of imperfect CSI.

Although most recent works have posed the resource-allocation problem of OFDMA networks as a network utility maximization (NUM) problem [5]–[9], they depend too heavily on the accuracy of CSI and overlook the availability of the allocated throughput. The works in [6], [8], and [9] have generally focused on maximizing the sum of utilities, without considering the limit imposed by the CAC unit on each service aggregate rate. In other words, the higher the channel gain and the available power, the higher the throughput granted to subscribers. However, in multiservice networks, the aggregate rate allocated to subscribers of each service cannot exceed the prescribed partition of the network throughput, particularly when subscribers have diverse QoS requirements. For example, a particular group of subscribers may be more demanding than the rest of the subscribers, which results in an allocation of the network resources to the former and leaves the latter unsupported. Limiting the aggregate rate that the group of demanding subscribers receives imposes fairness among supported classes and guarantees QoS for each service. Although

Manuscript received May 12, 2009; revised November 6, 2009; accepted January 19, 2010. Date of publication March 4, 2010; date of current version June 16, 2010. The review of this paper was coordinated by Prof. R. Jäntti.

M. K. Awad, X. Shen, and J. W. Mark are with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: mohamad@ieee.org; mveluppi@bbcr.uwaterloo.ca; xshen@bbcr.uwaterloo.ca; jwmark@bbcr.uwaterloo.ca).

V. Mahinthan is with Research In Motion Ltd., Waterloo, ON N2L 3W8, Canada.

M. Mehrjoo is with the Faculty of Electrical and Computer Engineering, University of Sistan and Baluchestan, Zahedan 98155-987, Iran (e-mail: mehrjoo@ece.usb.ac.ir).

Digital Object Identifier 10.1109/TVT.2010.2044820

<sup>1</sup>Worldwide Interoperability for Microwave Access (WiMAX) is a commercialization of IEEE 802.16.

the works in [5], [6], and [10] propose joint resource allocation and CAC schemes that avoid overusing the network throughput by partitioning it over the supported services, the CSI in these schemes is assumed to be perfectly known. However, such perfection is rare, and the performance of multicarrier systems is severely degraded by considering an inaccurate and delayed CSI as perfect and allocating resources based on it [11]–[13].

The main focus of this paper is the resource allocation for OFDMA-based networks with imperfect CSI and multiple classes of services that demand diverse QoS requirements. Allocating resources for OFDMA networks is cross layer in nature; the PHY layer feeds the CSI of all subscribers to the RAU at the MAC layer, which, in turn, allocates resources. The inaccuracy of the reported CSI is modeled as an additive random variable with a known distribution, based on which the expected rate is evaluated. Power allocation is performed by inverting the expected rate function. The OFDMA resource allocation problem is combinatorial in nature with a nonconvex structure; thus, it cannot be solved by convex optimization methods. However, as the number of subcarriers becomes infinitely large, the duality gap tends to zero<sup>2</sup>; hence, the nonconvex problem can be solved in the dual domain [14]. With this dual approach, decomposition methods for NUM [15] can be applied to solve the problem under consideration [8], [25]. Solutions obtained via decomposition have the inherent property of being implementable in both a distributed and a centralized manner; we adopt the centralized implementation and highlight subroutines of the proposed scheme that are distributable. The proposed scheme is presented for OFDMA systems in the downlink mode, and modifications can be incorporated for uplink resource allocation.

The remainder of this paper is organized as follows. Section II introduces the system model of the OFDMA-based point-to-multipoint (PMP) network under consideration. The expected data rate for imperfect CSI is presented in Section III. The mathematical formulation of the resource-allocation problem, along with the proposed scheme, is presented in Section IV. Computational complexity is analyzed in Section V. The performance of the proposed scheme is evaluated in Section VI, followed by conclusions in Section VII.

## II. SYSTEM MODEL

We consider a single-cell scenario of a PMP network. The network consists of one base station (BS) at the center of the cell and multiple subscriber stations. There are  $S$  subscriber stations forming the set  $\mathcal{S} = \{1, \dots, s, \dots, S\}$ . The subscriber stations share a set of  $N_{sc}$  subcarriers available to the cell. In OFDMA networks, a subset  $\mathcal{N}_s^3$  of the network subcarriers is exclusively assigned to one subscriber station. Although, for simplicity, the general presentation focuses on the downlink mode, the proposed resource-allocation scheme is generally applicable to both uplink and downlink modes, as will be shown later.

<sup>2</sup>A zero duality gap implies that both the primal and the dual problems have the same optimal value [14].

<sup>3</sup>The cardinality of the subset  $\mathcal{N}_s$  is denoted by  $N_s$ .

The network supports  $L$  QoS classes. Network parameters related to the  $l$ th class are denoted by a superscript  $(l)$ . For example, the set of subscriber stations that subscribe for the  $l$ th class is denoted by  $\mathcal{S}^{(l)}$ . A utility function  $U^s(\bar{r}^s)$  models the  $s$ th subscriber station's satisfaction of the expected data rate  $\bar{r}^s$  assigned to it. The characteristics of utility functions depend on the class of service that each subscriber station opts for. We consider a frequency-selective fading channel between any pair of communicating stations. In OFDMA, the subband bandwidth is smaller than the channel coherence bandwidth; therefore, each subcarrier experiences flat fading. During the  $j$ th slot, the  $s$ th subscriber receives the following OFDM signals:

$$\mathbf{y}^s[j] = \sqrt{\mathbf{P}^s[j]} \mathbf{H}^s[j] \mathbf{x}[j] + \mathbf{z}^s[j] \quad (1)$$

where  $\sqrt{\mathbf{P}^s[j]}$  is a diagonal  $N_s \times N_s$  matrix of  $p_n^s[j] \forall n \in \mathcal{N}_s$ , which is the power allocated by the MAC resource allocation scheme to the  $s$ th subscriber on the  $n$ th subcarrier during the  $j$ th slot.  $\mathbf{H}^s[j]$  is a diagonal matrix of the channel gains, and  $\mathbf{x}[j]$  denotes the data source symbols. The vector  $\mathbf{z}^s$  represents the additive noise, which is modeled as circularly symmetric complex Gaussian random variable  $\mathbf{z}^s \sim \mathcal{CN}(\mathbf{0}, (\sigma_z^s)^2 \mathbf{I})$ .

The CSI is updated every OFDMA frame. At the beginning of the frame, a sequence of OFDM symbols is transmitted by the BS to the subscribers for channel estimation [16]. Each subscriber estimates the channel and forwards its estimate  $\hat{\mathbf{H}}^s$  of the perfect CSI  $\mathbf{H}^s$  to the BS.  $\mathbf{H}^s$  is assumed to be ergodic, and its elements are independent. The slot index  $[j]$  is dropped for notational convenience. Note that the matrix of channel gains is a diagonal of the subcarriers' channel gain vector  $\hat{h}^s$ . Let  $\check{h}^s$  be its estimate available at the RAU; before the next frame estimates arrive, the current frame estimates are treated as deterministic [17], and their delay and estimation error are modeled by  $\check{h}^s$ . Hence, given the channel estimate  $\hat{h}^s$ , the imperfect CSI can be modeled as

$$\check{h}^s = \hat{h}^s + \tilde{h}^s \quad (2)$$

and assumed to be  $\sim \mathcal{CN}(\hat{h}^s, \Sigma_{\tilde{h}^s})$ . The matrix  $\Sigma_{\tilde{h}^s}$  is the error covariance matrix that captures the quality of the channel estimation [18]–[20]. We assume that the estimation errors on different subcarriers are independent; thus,  $\Sigma_{\tilde{h}^s} = (\tilde{\sigma}_\epsilon^s)^2 \mathbf{I}$ , where  $(\tilde{\sigma}_\epsilon^s)^2$  is the estimation error variance. The  $n$ th subcarrier<sup>4</sup> imperfect CSI ( $[\check{h}^s]_n = \check{H}_n^s$ ) is modeled as  $\sim \mathcal{CN}(\hat{H}_n^s, (\tilde{\sigma}_\epsilon^s)^2)$ . Therefore, its square follows a noncentral chi-square probability density function (pdf) given by [21]

$$f_X(x) = \frac{1}{(\tilde{\sigma}_\epsilon^s)^2} e^{-\frac{(|\hat{H}_n^s|^2 + x)}{(\tilde{\sigma}_\epsilon^s)^2}} \mathfrak{I}_0 \left( 2 \sqrt{\frac{|\hat{H}_n^s|^2 x}{(\tilde{\sigma}_\epsilon^s)^4}} \right) \quad (3)$$

where  $\mathfrak{I}_0(\cdot)$  is the zeroth-order modified Bessel function of the first kind. The random variable  $|\check{H}_n^s|^2$  is denoted by  $X$  for notational convenience. Fig. 1 shows the aforementioned modeling parameters on an illustrative PMP network.

<sup>4</sup> $[\mathbf{x}]_n$  denotes the  $n$ th element of vector  $\mathbf{x}$ .

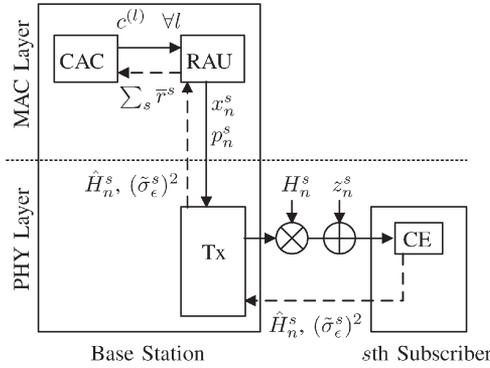


Fig. 1. Illustrative PMP network of one subscriber station and a BS showing various components involved in resource allocation. Tx and CE, respectively, stand for transmitter and channel estimator.

### III. EXPECTED RATE WITH IMPERFECT CHANNEL-STATE INFORMATION

The BS receives a deterministic channel gain estimate of each subcarrier  $\hat{H}_n^s$  and the estimation error statistical information for each subscriber. Based on the model in (2), the achievable rate  $r_n^s$  is a function of the imperfect CSI random variable  $X$  (i.e.,  $|\hat{H}_n^s|^2$ ), which can be written as

$$r_n^s = \log_e \left( 1 + \frac{p_n^s X}{\Delta (\sigma_z^s)^2} \right). \quad (4)$$

Because Shannon's capacity is an upper bound and cannot be achieved in practice,  $\Delta$  is added to model the gap between the expected rate achieved by a specific modulation scheme and the upper bound [3]. The pdf of the random variable  $Q = p_n^s X / \Delta (\sigma_z^s)^2$  is given by

$$f_Q(q) = \frac{1}{\Omega_Q^2} e^{-\frac{\theta_Q^2 + q}{\Omega_Q^2}} \mathcal{J}_0 \left( 2 \sqrt{\frac{\theta_Q^2 q}{\Omega_Q^4}} \right) \quad (5)$$

where  $1/\Omega_Q^2 = \Delta (\sigma_z^s)^2 / 2 p_n^s (\tilde{\sigma}_\epsilon^s)^2$ , and  $\theta_Q^2 = p_n^s |\hat{H}_n^s|^2 / \Delta (\sigma_z^s)^2$ . By substituting the series representation of  $\mathcal{J}_0(\cdot)$  [22, eq. 8.447(1)] in (5), we obtain

$$f_Q(q) = \frac{1}{\Omega_Q^2} e^{-\frac{\theta_Q^2 + q}{\Omega_Q^2}} \sum_{t=0}^{\infty} \frac{\theta_Q^{2t} q^t}{\Omega_Q^{4t} (t!)^2}. \quad (6)$$

Given the pdf  $f_Q(q)$ , the expected achievable rate can be written as

$$E[r_n^s] = E[\log_e(1 + Q)] \quad (7)$$

$$= \int_0^{\infty} \log_e(1 + q) f_Q(q) dq \quad (8)$$

$$= \frac{e^{-\frac{\theta_Q^2}{\Omega_Q^2}}}{2\Omega_Q^2} \sum_{t=0}^{\infty} \frac{\theta_Q^{2t}}{\Omega_Q^{4t} (t!)^2} \int_0^{\infty} \log_e(1 + q) e^{-\frac{q}{\Omega_Q^2}} q^t dq. \quad (9)$$

By [22, eq. 4.222(8)], we obtain

$$E[r_n^s] = \frac{e^{-\frac{\theta_Q^2}{\Omega_Q^2}}}{2\Omega_Q^2} \sum_{t=0}^{\infty} \frac{\theta_Q^{2t} \Omega_Q^{2(t+1)}}{\Omega_Q^{4t} (t!)^2} \sum_{m=0}^t \frac{t!}{(t-m)!} \times \left[ \frac{(-1)^{t-m-1}}{\Omega_Q^{2(t-m)}} e^{\frac{1}{\Omega_Q^2}} Ei \left( \frac{-1}{\Omega_Q^2} \right) + \sum_{j=1}^{t-m} \frac{(j-1)!}{-\Omega_Q^{2(t-m-j)}} \right] \quad (10)$$

where  $Ei(\cdot) = -\int_{-\infty}^{\infty} (e^t/t) dt$  is the exponential integral function.

Given the expected data rate to be supported, the power allocation phase of the proposed scheme requires solving (10) for  $p_n^s$ , which is computationally extensive. Alternatively, after evaluating (10) offline, the expected achievable rate can be represented by a simpler function that can efficiently be inverted for power. Note that  $E[\log_e(1 + x)] \approx E[\log_e(x)] + \vartheta(x)$ , where  $\vartheta(x)$  is an approximation error correction term that approaches zero for large values of  $x$ . Similarly, (7) can be written as

$$E[r_n^s] = E[\log_e(1 + Q)] \quad (11)$$

$$\simeq E[\log_e(Q)] + \vartheta(p_n^s) \quad (12)$$

$$\simeq \log_e \left( \frac{|\hat{H}_n^s|^2}{(\tilde{\sigma}_\epsilon^s)^2} \right) - Ei \left( \frac{-|\hat{H}_n^s|^2}{(\tilde{\sigma}_\epsilon^s)^2} \right) + \log_e \left( \frac{(\tilde{\sigma}_\epsilon^s)^2}{\Delta (\sigma_z^s)^2} \right) + \log_e(p_n^s) + \vartheta(p_n^s) \quad (13)$$

where  $E[\log_e(Q)]$  is given in [23], and  $\vartheta(p_n^s) = \alpha(\hat{H}_n^s, (\tilde{\sigma}_\epsilon^s)^2) \times (p_n^s)^{-\beta(\hat{H}_n^s, (\tilde{\sigma}_\epsilon^s)^2)} + \gamma(\hat{H}_n^s, (\tilde{\sigma}_\epsilon^s)^2)$  is an approximation error-correction term. The parameters  $\alpha$ ,  $\beta$ , and  $\gamma$  are found by curve fitting the difference  $E[r_n^s] - E[\log_e(Q)]$  to a power decaying function;  $E[r_n^s]$  is evaluated by (10). These parameters are stored in lookup tables for a range of practical values of  $|\hat{H}_n^s|^2$  and  $(\tilde{\sigma}_\epsilon^s)^2$ . Rearranging (13) results in the following:

$$\log_e(p_n^s) + \vartheta(p_n^s) \simeq -\log_e \left( \frac{|\hat{H}_n^s|^2}{(\tilde{\sigma}_\epsilon^s)^2} \right) + Ei \left( \frac{-|\hat{H}_n^s|^2}{(\tilde{\sigma}_\epsilon^s)^2} \right) - \log_e \left( \frac{(\tilde{\sigma}_\epsilon^s)^2}{\Delta (\sigma_z^s)^2} \right) + E[r_n^s]. \quad (14)$$

Note that the right-hand side of (14) is a function of  $|\hat{H}_n^s|^2$  and  $(\tilde{\sigma}_\epsilon^s)^2$ , which are known deterministic values to the RAU. For notational convenience, we denote the constant term  $-\log_e(|\hat{H}_n^s|^2/(\tilde{\sigma}_\epsilon^s)^2) + Ei(-|\hat{H}_n^s|^2/(\tilde{\sigma}_\epsilon^s)^2) - \log_e((\tilde{\sigma}_\epsilon^s)^2/\Delta(\sigma_z^s)^2)$  by  $\Psi$ . The required power to support the

expected rate  $E[r_n^s]$  for given  $|\hat{H}_n^s|^2$  and  $(\tilde{\sigma}_\epsilon^s)^2$  is found by Maple<sup>5</sup> to be

$$p_n^s = \exp \left\{ \frac{W_0(-\beta\alpha e^{\beta(E[r_n^s]-\gamma-\Psi)}) + \beta(E[r_n^s]-\gamma-\Psi)}{\beta} \right\} \quad (15)$$

where  $W_0(\cdot)$  is the Lambert's  $W$  function given by  $W_0(\cdot) = \sum_{i=1}^{\infty} ((-i)^{i-1}/i!)(\cdot)^i$ .

#### IV. PROBLEM FORMULATION AND PROPOSED SOLUTION

We formulate the resource allocation problem as a constrained NUM problem, where the objective function is a maximization of the sum of the subscribers' utility functions. The constraints are related to the specifications of the network under consideration, namely, the per-service allocated aggregate rate limit, power limitation, and exclusive subcarrier assignment. Let  $x_n^s \in \{0, 1\}$ , where  $x_n^s = 1$  means that the  $n$ th subcarrier is allocated to the  $s$ th subscriber, and  $x_n^s = 0$  otherwise. Furthermore, let  $\bar{r}^s$  be the expected rate allocated to the  $s$ th subscriber of the subcarriers assigned to it (i.e.,  $\mathcal{N}_s$ ); mathematically,  $\bar{r}^s = \sum_{n \in \mathcal{N}_s} E[r_n^s]$ . The CAC unit receives the allocation results from the RAU and updates the RAU with the throughput partitioning results  $c^{(l)} \forall l$  (see Fig. 1). The CAC schemes available in the literature (e.g., [5], [7], [10], and [24]) can be applied here. In the downlink mode, the power available to the network is limited by the BS power, which is denoted by  $P_{BS}$ . Mathematically, the optimization problem is

$$\max_{x_n^s, p_n^s} \sum_s U^s(\bar{r}^s) \quad (16)$$

$$\text{s.t.} \quad \sum_{s \in \mathcal{S}^{(l)}} \bar{r}^s \leq c^{(l)}, \quad \forall l \quad (17)$$

$$\sum_s x_n^s \leq 1, \quad \forall n \quad (18)$$

$$\sum_s \sum_{n=1}^{N_{sc}} p_n^s \leq P_{BS} \quad (19)$$

$$x_n^s \in \{0, 1\}. \quad (20)$$

The set of constraints in (17) limits the  $l$ th-class subscribers' allocated aggregate expected rate to  $c^{(l)}$ . Constraints in (18) satisfy the exclusive subcarrier allocation of OFDMA [3]. Constraint (19) limits the total power allocated to  $P_{BS}$ .

The resource allocation problem is combinatorial in nature due to the subcarrier exclusive assignment constraint, which results in a nonconvex feasible space. Generally, solving nonconvex problems in the dual domain provides only an upper bound that is at a distance from the optimum known as the "duality gap." However, resource allocation for multicarrier transmissions is a special case in which the duality gap becomes zero as the number of subcarriers approaches infinity [14]. In networks with a number of subcarriers as small as 64, a duality gap of less than  $10^{-5}$  can be achieved, which is acceptable in practice [25].

These results suggest solving the problem in the dual domain. One of the effective methods for solving NUM problems is dual decomposition, where the dual problem is decomposed into multiple subproblems that are easier to solve than the primal. The master dual problem sets the prices for resources and reports them to the decomposed subproblems, which, in turn, decide the amount of resources to be consumed [15].

A Lagrangian is formed by relaxing the constraints in (17) as follows:

$$D(\bar{r}^s, \boldsymbol{\lambda}) = \sum_l \left[ \sum_{s \in \mathcal{S}^{(l)}} [U^s(\bar{r}^s) - \lambda^{(l)} \bar{r}^s] + \lambda^{(l)} c^{(l)} \right] \quad (21)$$

where  $\lambda^{(l)} \geq 0 \forall l$  are the classes' set of Lagrange multipliers (i.e., prices). If the  $l$ th-class throughput is overutilized,  $\lambda^{(l)}$  increases, and the converse is true. The problem can be solved by solving its dual as follows:

$$\begin{aligned} \min_{\boldsymbol{\lambda}} \quad & d(\boldsymbol{\lambda}) \\ \text{s.t.} \quad & \boldsymbol{\lambda} \geq \mathbf{0} \end{aligned} \quad (22)$$

where  $d(\boldsymbol{\lambda}) = \min_{\bar{r}^s} D(\bar{r}^s, \boldsymbol{\lambda})$ , and  $\boldsymbol{\lambda}$  is a vector of  $\lambda^{(l)} \forall l$ . The Lagrange multipliers are updated with the following subgradient method for each multiplier [14], [15], [26]:

$$\lambda^{(l)}(t+1) = \left[ \lambda^{(l)}(t) - \kappa \left( c^{(l)} - \sum_{s \in \mathcal{S}^{(l)}} \bar{r}^{s*}(\lambda^{(l)}(t)) \right) \right]^+ \quad (23)$$

where  $\kappa = 0.1/\sqrt{t}$  is a diminishing step size,  $[\cdot]^+$  denotes  $\max(\cdot, 0)$ , and  $t$  is the iteration index. Here,  $\bar{r}^{s*}(\lambda^{(l)}(t))$  is the optimum value obtained by solving the following problem for a given  $\lambda^{(l)} \forall l$ :

$$\max_{x_n^s, p_n^s} \sum_l \sum_{s \in \mathcal{S}^{(l)}} [U^s(\bar{r}^s) - \lambda^{(l)} \bar{r}^s] \quad (24)$$

$$\text{s.t.} \quad \sum_s x_n^s \leq 1, \quad \forall n \quad (25)$$

$$\sum_s \sum_{n=1}^{N_{sc}} p_n^s \leq P_{BS} \quad (26)$$

$$x_n^s \in \{0, 1\}. \quad (27)$$

The problem in (24) can be rewritten by introducing the set of auxiliary variables  $b^s \forall s$  as follows:

$$\max_{x_n^s, p_n^s} \sum_l \sum_{s \in \mathcal{S}^{(l)}} [U^s(b^s) - \lambda^{(l)} b^s] \quad (28)$$

$$\text{s.t.} \quad \sum_s x_n^s \leq 1, \quad \forall n \quad (29)$$

$$\sum_s \sum_{n=1}^{N_{sc}} p_n^s \leq P_{BS} \quad (30)$$

$$x_n^s \in \{0, 1\} \quad (31)$$

$$\bar{r}^s \geq b^s, \quad \forall s. \quad (32)$$

<sup>5</sup>Maplesoft, version 11.02.

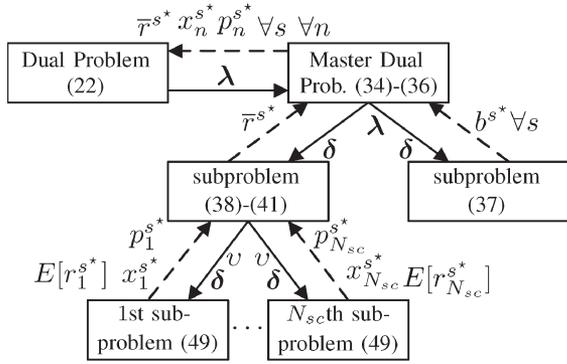


Fig. 2. Hierarchy of the decomposed dual problem.

Constraint (32) is relaxed by forming the Lagrangian

$$W(b^s, \lambda^{(l)}, \delta^s) = \sum_l \sum_{s \in \mathcal{S}^{(l)}} [U^s(b^s) - \lambda^{(l)} b^s + \delta^s (\bar{r}^s - b^s)] \quad (33)$$

where  $\delta^s$  is the Lagrange multiplier associated with the  $s$ th subscriber.  $\delta^s$  demands a rate allocation for the  $s$ th subscriber. The dual problem<sup>6</sup> is given by

$$\min_{\lambda, \delta} w(\lambda, \delta) \quad (34)$$

$$\text{s.t. constraints (29)–(31)}$$

$$\lambda \geq \mathbf{0} \quad (35)$$

$$\delta \geq \mathbf{0} \quad (36)$$

where  $w(\lambda, \delta) = \max_{b^s} W(b^s, \lambda^{(l)}, \delta^s)$ . The dual problem can be separated into two problems [8]. The first is a utility maximization problem, i.e.,

$$w'(\lambda, \delta) = \max_{b^s} \sum_l \sum_{s \in \mathcal{S}^{(l)}} [U^s(b^s) - \lambda^{(l)} b^s - \delta^s b^s] \quad (37)$$

and the second is a subcarrier, rate, and power allocation problem, i.e.,

$$w''(\delta) = \max_{p_n^s, x_n^s} \sum_l \sum_{s \in \mathcal{S}^{(l)}} \delta^s \bar{r}^s \quad (38)$$

$$\text{s.t. } \sum_s x_n^s \leq 1, \quad \forall n \quad (39)$$

$$\sum_s \sum_{n=1}^{N_{sc}} p_n^s \leq P_{BS} \quad (40)$$

$$x_n^s \in \{0, 1\}. \quad (41)$$

Note that each of the dual problems (37) and (38) can individually be solved to obtain their optimums (i.e.,  $b^{s*}$  and  $\bar{r}^{s*}$ ) while being coordinated by the master dual problem (34) (see Fig. 2). Multipliers  $\delta^s \forall s$  are iteratively updated at each iteration  $t$  by the subgradient method, i.e.,

$$\delta^s(t+1) = [\delta^s(t) + \kappa (b^{s*}(\delta^s(t)) - \bar{r}^{s*}(\delta^s(t)))]^+ \quad (42)$$

<sup>6</sup> $\delta$  denotes a vector of  $\delta^s \forall s$ .

where  $\kappa$  is a diminishing step size. At each iteration,  $b^{s*}(\delta^s(t))$  is obtained for each subscriber by maximizing (37) for  $b^s$ , where the utility functions are assumed to be concave. The coupling constraints (39) and (40) pose complication in solving (38). However, relaxing constraint (40) decouples the problem into multiple per-subcarrier subproblems, which also satisfies (39). Therefore, a Lagrangian can be formed, i.e.,

$$Z(\bar{r}^s, p_n^s, \delta, v) = \sum_l \sum_{s \in \mathcal{S}^{(l)}} \delta^s \sum_n E[r_n^s] + v \left( P_{BS} - \sum_s \sum_{n=1}^{N_{sc}} p_n^s \right). \quad (43)$$

The Lagrange multiplier  $v$  is interpreted as the price of using  $P_{BS}$ . Let  $\min_{\delta, v} z(\delta, v) = \max_{p_n^s, x_n^s} Z(\bar{r}^s, p_n^s, \delta, v)$ . Because the duality gap is zero, the dual problem

$$\min_{\delta, v} z(\delta, v) \quad (44)$$

$$\text{s.t. } \sum_s x_n^s \leq 1, \quad \forall n \quad (45)$$

$$x_n^s \in \{0, 1\} \quad (46)$$

$$\lambda \geq \mathbf{0} \quad (47)$$

$$v \geq 0 \quad (48)$$

is now decoupled into  $N_{sc}$  maximization subproblems, i.e.,

$$\arg \max_s \delta^s E[r_n^s] - v p_n^s, \quad \forall n. \quad (49)$$

For each expected rate  $E[r_n^s]$  to be supported, the required power  $p_n^s$  is obtained by (15). These maximization subproblems are solved per subcarrier. In other words, the subcarrier is exclusively assigned to the  $s$ th subscriber that maximizes (49) on that particular subcarrier; thus, constraint (39) is also satisfied.  $\delta$  is passed down from (34), and  $v$  is updated by the following subgradient method:

$$v(\ddot{t}+1) = \left[ v(\ddot{t}) - \ddot{\kappa} \left( P_{BS} - \sum_s \sum_n p_n^{s*}(v(\ddot{t})) \right) \right]^+ \quad (50)$$

where  $\ddot{\kappa}$  is the step size, and  $\ddot{t}$  is the iteration index.  $p_n^{s*}(v(\ddot{t}))$  is obtained by solving the per-subcarrier problems (49) for a specific  $v(\ddot{t})$ . Fig. 2 shows the decomposition of the master dual problem into a hierarchy of subproblems and the interaction among them.

**Algorithm 1** Pseudocode of the proposed scheme

- 1: *Pre-optimization phase*
- 2: **for**  $s = 1$  to  $S$  **do**
- 3:     **for**  $n = 1$  to  $N_{sc}$  **do**
- 4:         Search lookup tables for  $\alpha, \beta$  and  $\gamma$
- 5:         **for**  $k = 1$  to  $K$  **do**
- 6:             Solve (15) for  $p_n^s$
- 7:         **end for**
- 8:     **end for**

9: **end for**  
10: *Optimization phase*  
11: Initialize  $\lambda^l \forall l$   
12: Initialize  $\delta^s \forall s$   
13: **for**  $s = 1$  to  $S$  **do**  
14:     Solve the derivative of (37) for  $b^{s*}$   
15:      $b^{s*} \leftarrow b^s$   
16: **end for**  
17: Initialize  $v$   
18: **for**  $n = 1$  to  $N_{sc}$  **do**  
19:      $\arg \max_s \delta^s E[r_n^s] - v p_n^s$   
20:      $s^* \leftarrow s$   
   Allocate  $n$ th subcarrier  
21:      $\mathcal{N}_{s^*} \leftarrow \mathcal{N}_{s^*} \cup \{n\}$   
   Allocate power  
22:      $p_n^{s^*} \leftarrow p_n^s$   
23: **end for**  
24:     update  $v(\dot{t} + 1) = [v(\dot{t}) - \ddot{\kappa}(P_{BS} - \sum_s \sum_n^{N_{sc}} p_n^{s*}(v(\dot{t})))^+]^+$   
25: Repeat lines 17 to 23 until convergence  
26:  $\bar{r}^{s*} \leftarrow \sum_n^{N_s} E[r_n^s] \forall s$   
27:     update  $\delta^s(\dot{t} + 1) = [\delta^s(\dot{t}) + \dot{\kappa}(b^{s*}(\delta^s(\dot{t})) - \bar{r}^{s*}(\delta^s(\dot{t})))^+]^+$   
28: Repeat lines 12 to 26 until convergence  
29:     update  $\lambda^l(t + 1) = [\lambda^l(t) - \kappa(c^l - \sum_{s \in \mathcal{S}^{(l)}} \bar{r}^{s*}(\lambda^l(t)))^+]^+$   
30: Repeat lines 11 to 28 until convergence

Based on the mathematical formulations and derivations presented earlier, the pseudocode of the proposed scheme is outlined in Algorithm 1. The scheme is divided into two phases: a preoptimization phase and an optimization phase. The preoptimization phase prepares the possible expected rate levels  $K$  and their corresponding power allocations, which are given by (15), based on the received imperfect CSI (lines 2 to 9). This phase can be implemented in both a centralized manner, as in lines 2 to 9 at the BS, and a distributed manner, by which each subscriber searches the lookup tables for  $\alpha$ ,  $\beta$ , and  $\gamma$ , evaluates the required power allocations, and reports them to the BS. Either of the implementations provides the same result, but questions arise about how much computation the subscriber station can perform and how much reporting overhead the feedback channel can support. Hence, it is a tradeoff between the computational complexity at the BS and the feedback reporting overhead.

In the optimization phase, the power, rate, and subcarrier allocations are optimized while satisfying the network constraints. In the following, the network constraints along with their related subroutines in Algorithm 1 are discussed.

- 1) *A subcarrier is exclusively allocated to one subscriber.*  
In lines 18 to 23, each subcarrier is allocated to the subscriber that maximizes the term  $\delta^s E[r_n^s] - v p_n^s$  by searching over a matrix of supported expected rate levels for all subscribers. The required power to support the granted rate is allocated to the subscriber on the  $n$ th subcarrier (line 22). Note that the cardinality of the set

$\mathcal{N}_s$  is denoted by  $N_s$ , which is the number of subcarriers allocated to the  $s$ th subscriber.

- 2) *The aggregate rate allocated to the  $l$ th service is limited to a partition of the throughput  $c^{(l)}$ .* The Lagrange multiplier  $\lambda^{(l)}$  represents the price of utilizing  $c^{(l)}$ . As the scheme evolves, overutilizing  $c^{(l)}$  increases  $\lambda^{(l)}$ , and the converse is true (line 29). The unavailability of throughput for a specific class of service  $l$  is signaled via  $\lambda^{(l)}$  to line 14, where the minimum rate (i.e., auxiliary variable  $b^s$ ) to be allocated to the subscribers is obtained. For example, let the utility function be the concave function  $U^s(b^s) = \varsigma \log(b^s)$ ; therefore, solving the derivative of (37) for each term of the summation gives  $b^s = \varsigma / \lambda^{(l)} + \delta^s$ . Hence, an increase in  $\lambda^{(l)}$  decreases  $b^s$ , and the scheme tends to allocate a lower rate to subscribers of the  $l$ th class of service by reducing the demand variable (i.e., Lagrange multiplier  $\delta^s$ ) (line 27).
- 3) *The total allocated power is limited to the BS power  $P_{BS}$  in the downlink mode, and the power allocated to each subscriber is limited to its specific power constraint  $P_s$  in the uplink mode.* The power supply is controlled by the Lagrange multiplier  $v$  (line 24). If the BS power is overutilized, the price  $v$  increases, resulting in a decrease in the term  $\arg \max_s \delta^s E[r_n^s] - v p_n^s$ . Thus, the scheme tends to allocate a lower rate, which requires less power. In the uplink mode, the allocated power to each subscriber is constrained by its maximum available power (i.e., device battery power), which is denoted by  $P_s$ . Therefore, the constraint in (19) is replaced with  $\sum_{n \in \mathcal{N}_s} p_n^s \leq P_s$ , and the subgradient algorithm in line 24 is replaced with

$$v^s(\dot{t} + 1) = \left[ v^s(\dot{t}) - \ddot{\kappa} \left( P_s - \sum_{n \in \mathcal{N}_s} p_n^{s*}(v^s(\dot{t})) \right) \right]^+ \quad \forall s. \quad (51)$$

Thus, each subscriber has a specific multiplier  $v^s$  that prices the supply of its power.

## V. COMPLEXITY ANALYSIS

Computational complexity is a major factor in implementing resource allocation schemes for OFDMA networks. However, the resource allocation problem for OFDMA networks is known to be NP-hard, and obtaining an exhaustive search allocation is computationally very expensive. The exclusive subcarrier assignment constraint makes the problem a complex combinatorial one that becomes harder when the power and per-service aggregate rate constraints are considered. The proposed scheme is low in computational complexity due to the adopted decomposition approach. The following complexity analysis estimates the execution time of the proposed scheme in relation to the input size.

Let  $T_{24}$ ,  $T_{27}$ , and  $T_{29}$  be, respectively, the number of iterations required for each of the subgradient methods in lines 24, 27, and 29 of the Algorithm 1 to converge. Furthermore, let  $J$  be the length of the lookup table (line 4). It can be seen that the preoptimization phase is  $\mathcal{O}(SN_{sc}(J + K))$ . Starting with the most inner loop (lines 18 to 23), each

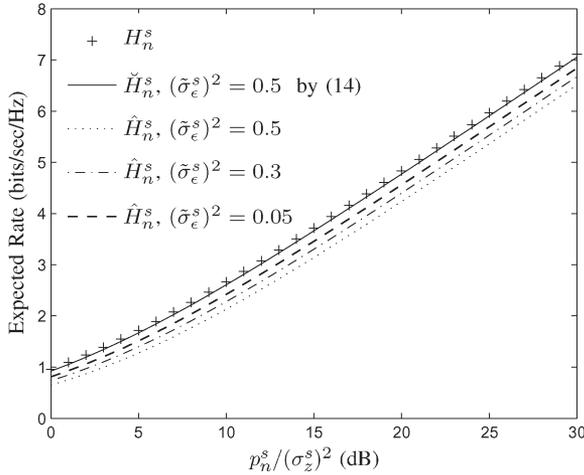


Fig. 3. Expected rate achieved given perfect CSI  $H_n^s$  (first scenario), estimated CSI with error ignored  $\hat{H}_n^s$  (second scenario), and estimated CSI with error considered  $\check{H}_n^s$  (third scenario—proposed).

cycle of the  $N_{sc}$  cycles requires  $KS$  comparisons, and it takes  $T_{24}$  for convergence, resulting in  $\mathcal{O}(T_{24}N_{sc}KS)$ . The loop in lines 13 to 16 is  $\mathcal{O}(S)$  because it cycles  $S$  times. Thus, the optimization phase is  $\mathcal{O}(T_{27}T_{29}(S + T_{24}N_{sc}KS))$ . Therefore, the overall resource allocation scheme complexity is  $\mathcal{O}(SN_{sc}(J + K)) + \mathcal{O}(T_{27}T_{29}(S + T_{24}N_{sc}KS))$ . Whereas an exhaustive search for allocating subcarriers and rates only is exponential (i.e.,  $\mathcal{O}((KS)^{N_{sc}})$ ), the proposed scheme is linear (i.e.,  $\mathcal{O}(T_{24}KS N_{sc})$ ) in terms of the number of subcarriers<sup>7</sup> available to the cell, which implies a major reduction in the computational complexity.

## VI. PERFORMANCE EVALUATIONS

Simulations are presented in this section to evaluate the proposed scheme's performance in terms of the expected rate gain achieved by considering the CSI imperfection at the MAC layer, the performance in limiting the allocated classes' expected rate to a partition of throughput specified by the CAC scheme, and the satisfaction of OFDMA constraints.

A frequency-selective fading and Rayleigh distributed channel is simulated based on a six-tap time-varying model. A 512 discrete Fourier transform of the delay tap gains generates 512-subcarrier CSI. The subscribers' channels experience distance-dependent fading that follows the power inverse law [27]. In our simulation, the path loss exponent is set to 2. In the network under consideration, the RAU knows the estimated CSI of each subcarrier  $\hat{H}_n^s$  for each particular subscriber  $s$  in addition to the estimation error variance  $(\sigma_\epsilon^s)^2$ . Various network parameters' distributions and assumptions are stated in the system model (see Section II).

Fig. 3 shows the expected rate achieved by one subscriber station over 500 samples of the channel for a range of power-

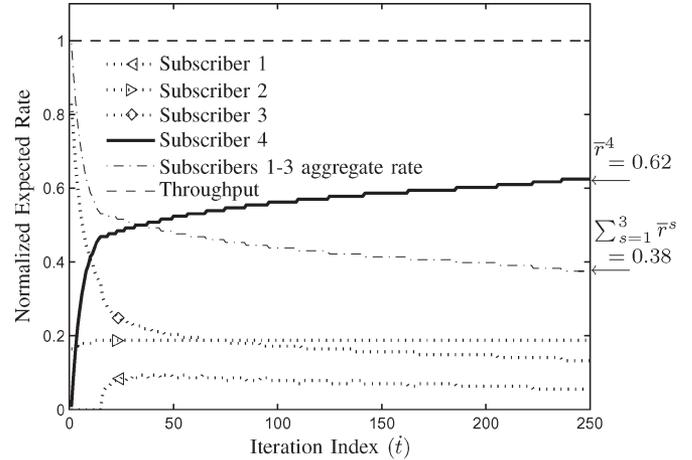


Fig. 4. Expected rate allocated as the scheme evolves *without* the classes' aggregate rate limit constraints.

to-noise ratios  $p_n^s / (\sigma_z^s)^2$ . To show the gain achieved by considering the channel estimation error, three scenarios are studied.

- 1) In the first scenario, the RAU has perfect knowledge of the CSI (i.e.,  $H_n^s$ ), which is shown to achieve the highest expected rate but is not possible in practice.
- 2) In the second scenario, the RAU assumes the estimate  $\hat{H}_n^s$  to be perfect and ignores the estimation and delay error. The expected rate decreases as the estimation error variance increases as shown by lines labeled as  $\hat{H}_n^s, (\sigma_\epsilon^s)^2 = 0.05, 0.0, \text{ and } 0.5$  in Fig. 3. Note that the plots are in bits per second per hertz; thus, the difference between the expected rate for the aforementioned two scenarios is scaled by the transmission bandwidth. Therefore, as the transmission bandwidth increases, the loss in expected rate increases in the second scenario.
- 3) The third scenario represents our proposed model where the RAU has knowledge of the estimate  $\check{H}_n^s$  and the estimation error statistics  $(\sigma_\epsilon^s)^2 = 0.5$ .

Based on this knowledge and (15), the expected rate (solid line in Fig. 3) is close to the one achieved when the RAU has perfect knowledge of the CSI, as in the first scenario (line marked with +).

Whereas the aforementioned simulation shows how a substantial rate gain can be achieved by considering the CSI imperfection, in the following, we show how the proposed resource allocation scheme maintains the aggregate rate limit for each service class in a multiservice network. In addition to the aforementioned PHY-layer simulation setup, consider a cell with four subscribers that are randomly distributed in the cell. The BS offers two classes of service; three of the subscribers subscribe to the first class  $\{s \in \mathcal{S}^{(1)} : s = 1, 2, 3\}$ , and the fourth subscriber subscribes to the second class  $\{s \in \mathcal{S}^{(2)} : s = 4\}$ . The first-class subscribers are considered to be less demanding for rate than the second-class subscribers. Thus, the first-class and second-class subscribers are considered, respectively, to have the following utility functions  $U^s(\bar{r}^s) = \log(\bar{r}^s)$  for  $s = 1, 2, \text{ and } 3$  and  $U^4(\bar{r}^4) = 15 \log(\bar{r}^4)$ . Intuitively, a large amount of resources is expected to be allocated to the fourth subscriber station if constraints are not imposed on

<sup>7</sup>In OFDMA networks, the number of subcarriers can be as large as 2048.

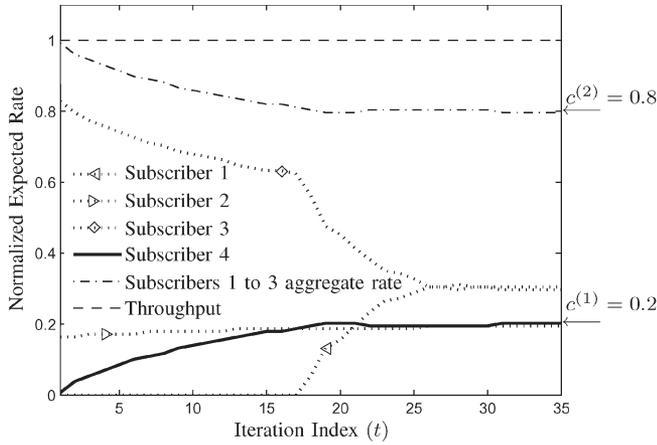


Fig. 5. Expected rate allocated as the scheme evolves with the classes' aggregate rate limit constraints (proposed scheme).

each class aggregate rate. This scenario is simulated by setting the Lagrange multipliers of problem (34) to zero, i.e.,  $\lambda = \mathbf{0}$ . Fig. 4 shows the expected rates allocated to subscribers. Subscribers 1–3 subscribe to class 1, while subscriber 4 subscribes to class 2. The rates are normalized to the network throughput over this allocation instance. It is clearly observed that the scheme allocates 62% of the network throughput to the demanding subscriber (i.e., second-class subscriber), while it allocates only 38% to the three subscribers of the first class, as shown by their aggregate rate  $\sum_{s \in \mathcal{S}^{(1)}} \bar{r}^s = 0.38$ , when the scheme converges. In this scenario, the scheme allocates an even higher rate if the demanding subscribers have a better channel condition than the rest, which may result in not supporting the less demanding subscribers. The difference among the rates allocated to the first-class subscribers is due to the difference in their subcarriers gains. Our proposed scheme constrains the aggregate rate allocated to each class subscriber to its limit reported by the CAC scheme while satisfying the power and subcarriers exclusive allocation constraints.

Consider that the CAC scheme limits the first-class aggregate rate to 80% and the second class to 20% (i.e.,  $c^{(1)} = 0.8$  and  $c^{(2)} = 0.2$ ). We rerun the simulation with the same network parameters (i.e., utility functions, channels, and subscribers), while  $\lambda$  is evaluated by (34). Fig. 5 shows the expected rates allocated to subscribers when limits are imposed on the classes' aggregate rates. Subscribers 1–3 subscribe to class 1, while subscriber 4 subscribes to class 2. We observe that, at convergence, the rate allocated to the demanding subscriber is reduced from 62% to 20%. The 42% that became available is now shared among the first-class subscribers; thus, their aggregate rate increases from 38% to 80%. Both classes' allocated rates are limited to their capacities specified by the CAC scheme that satisfies the QoS requirements of each class of service. In both scenarios, the proposed scheme exclusively allocates each subcarrier to one subscriber and maintains a limit of  $P_{BS}$  on the power allocated to all subscribers.

Next, we demonstrate the performance of the proposed scheme on the uplink mode. We consider a single cell with six subscriber stations. The first three subscribers are more demanding than the last three; thus, their utility functions are

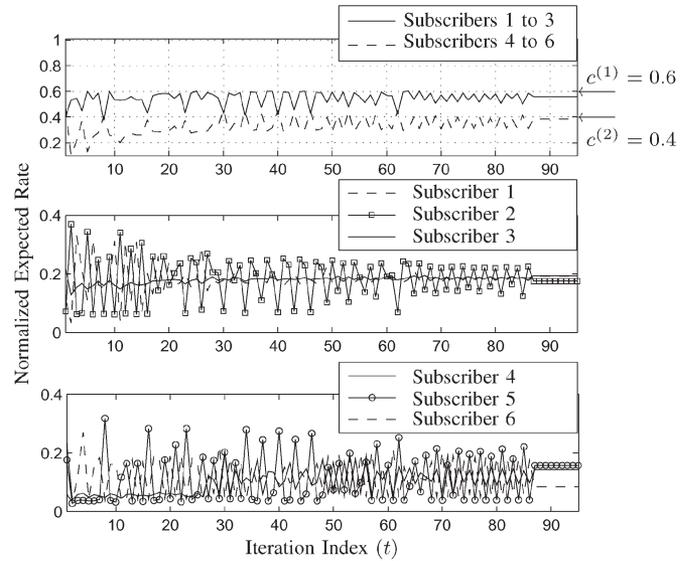


Fig. 6. Normalized expected rate allocated as the scheme evolves to (top) each class, (middle) subscribers of class 1, and (bottom) subscribers of class 2.

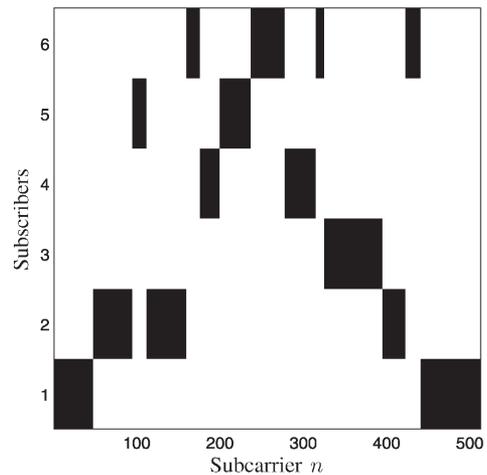


Fig. 7. Subcarrier allocation to each subscriber at convergence.

considered to be, respectively,  $U^s(\bar{r}^s) = 5 \log(\bar{r}^s)$  for  $s = 1, 2$ , and 3, and  $U^s(\bar{r}^s) = \log(\bar{r}^s)$  for  $s = 4, 5$ , and 6. In addition, they subscribe to two different classes, i.e.,  $\{s \in \mathcal{S}^{(1)} : s = 1, 2, 3\}$  and  $\{s \in \mathcal{S}^{(2)} : s = 4, 5, 6\}$ . In the uplink mode, each subscriber has a power constraint that corresponds to its available battery power (i.e.,  $P_s$ ); thus, the power allocated to each subscriber has to be limited to  $P_s$ . Subscribers are simulated to have equal power constraints for simplicity. The first and second classes of service aggregate rates, which are determined by the CAC scheme, are assumed to be  $c^{(1)} = 60\%$  and  $c^{(1)} = 40\%$ , respectively. Fig. 6 shows the evolutions of expected rate allocation for each subscriber and the aggregate rate for each class. Similar to the downlink mode, the presented scheme limits the aggregate rate of each class to the partition of the throughput allocated to it. It is observed that the convergence speed for uplink is slower than that for downlink, as shown in Fig. 5. This decrease in convergence speed is due to the increase in the number of power constraints in uplink compared to that in downlink. To investigate the exclusive subcarrier assignment, the checkerboard plot in Fig. 7 shows that each subcarrier of

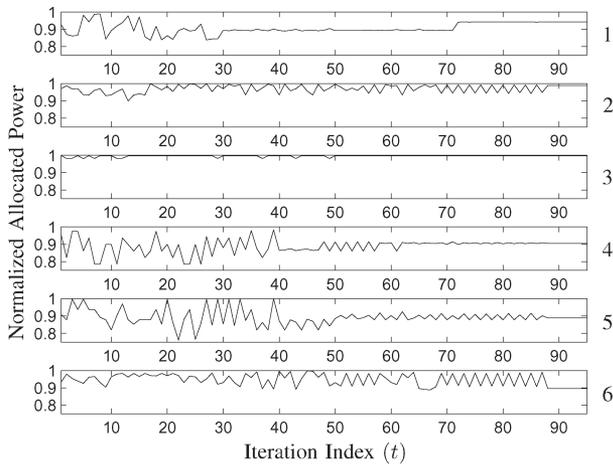


Fig. 8. Normalized allocated power to each subscriber station in the uplink mode (i.e.,  $\sum_{n \in \mathcal{N}_s} p_n^s / P_s$ , for  $s = 1, \dots, 6$ ) as the scheme evolves. Numbers on the right indicate the subscriber index.

the 512 subcarriers is allocated to a subscriber station; black areas indicate the range of subcarriers allocated to a subscriber station. Similar performance in allocating subcarriers has also been observed for the downlink mode. In addition, the normalized power allocated to each subscriber (i.e.,  $\sum_{n \in \mathcal{N}_s} p_n^s / P_s$ , for  $s = 1, \dots, 6$ ) is shown in Fig. 8. It can be seen that the power allocated to each subscriber never exceeds its power limit  $P_s$ , for  $s = 1, \dots, 6$ . The power allocated to some subscribers is more than the power allocated to the rest because of their low channel gain on their allocated subcarriers.

## VII. CONCLUSION

A novel resource-allocation scheme for OFDMA-based PMP networks has been proposed. The proposed scheme solves the resource allocation problem in the dual domain by decomposing it into several subproblems at the MAC layer while considering channel estimation and delay errors at the PHY layer. Simulation results show that the proposed scheme satisfies OFDMA network constraints (i.e., exclusive subcarrier and maximum power allocations) in addition to maintaining the classes' aggregate expected rate limits, which are imposed by a CAC unit to satisfy the QoS requirements of each class. The results support our theoretical claim that the proposed scheme achieves an expected rate close to the one achieved when the RAU has perfect knowledge of the channel. These results demonstrate that a significant gain can be achieved by taking the CSI imperfection into consideration. Our future research work will focus on the development of a queuing model to analyze the performance of the proposed scheme in terms of the blocking probability and the average number of supported connections.

## REFERENCES

- [1] M. K. Awad, K. T. Wong, and Z. Li, "An integrated overview of the open literature's empirical data on the indoor radiowave channel's delay properties," *IEEE Trans. Antennas Propag.*, vol. 56, no. 5, pp. 1451–1468, May 2008.
- [2] J. Cai, X. Shen, and J. Mark, "Downlink resource management for packet transmission in OFDM wireless communication systems," *IEEE Trans. Wireless Commun.*, vol. 4, no. 4, pp. 1688–1703, Jul. 2005.
- [3] M. Mehrjoo, M. K. Awad, and X. Shen, "Resource allocation in OFDM-based WiMAX," in *WiMAX Network Planning and Optimization*. Boca Raton, FL: CRC, 2009, ser. Wireless Networks and Mobile Communications Series, pp. 113–131.
- [4] *3rd Generation Partnership Project (3GPP) Specifications Home Page*, 2008. [Online]. Available: <http://www.3gpp.org/specs/specs.htm>
- [5] D. Niyato and E. Hossain, "A queuing-theoretic and optimization-based model for radio resource management in IEEE 802.16 broadband wireless networks," *IEEE Trans. Comput.*, vol. 55, no. 11, pp. 1473–1488, Nov. 2006.
- [6] G. Song, Y. Li, and M. Inc, "Utility-based resource allocation and scheduling in OFDM-based wireless broadband networks," *IEEE Commun. Mag.*, vol. 43, no. 12, pp. 127–134, Dec. 2005.
- [7] B. Rong, Y. Qian, and K. Lu, "Integrated downlink resource management for multiservice WiMAX networks," *IEEE Trans. Mobile Comput.*, vol. 6, no. 6, pp. 621–632, Jun. 2007.
- [8] T. Ng and W. Yu, "Joint optimization of relay strategies and resource allocations in cooperative cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 328–339, Feb. 2007.
- [9] C. Y. Ng and C. W. Sung, "Low complexity subcarrier and power allocation for utility maximization in uplink OFDMA systems," *IEEE Trans. Wireless Commun.*, vol. 7, pt. 1, no. 5, pp. 1667–1675, May 2008.
- [10] Y. Xiao, C. Chen, and Y. Wang, "Fair bandwidth allocation for multi-class of adaptive multimedia services in wireless/mobile networks," in *Proc. IEEE VTC*, Rhodes, Greece, May 2001, pp. 2081–2085.
- [11] A. Leke and J. Cioffi, "Impact of imperfect channel knowledge on the performance of multicarrier systems," in *Proc. IEEE GLOBECOM*, Sydney, Australia, Aug. 1998, pp. 951–955.
- [12] H. Lichte, S. Valentin, F. Eitzinger, M. Stege, C. Unger, and H. Karl, "Integrating multiuser dynamic OFDMA into IEEE 802.11a and prototyping it on a real-time software-defined radio testbed," in *Proc. Int. Conf. TRIDENTCOM*, Orlando, FL, May 2007, pp. 1–9.
- [13] J. Gross, H. Karl, and A. Wolisz, "On the effect of inband signaling and realistic channel knowledge on dynamic OFDM-FDMA systems," in *Proc. Eur. Wireless*, Barcelona, Spain, Feb. 2004.
- [14] W. Yu and R. Lui, "Dual methods for nonconvex spectrum optimization of multicarrier systems," *IEEE Trans. Commun.*, vol. 54, no. 7, pp. 1310–1322, Jul. 2006.
- [15] D. Palomar and M. Chiang, "A tutorial on decomposition methods for network utility maximization," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 8, pp. 1439–1451, Aug. 2006.
- [16] J. Cai, X. Shen, and J. Mark, "Robust channel estimation for OFDM wireless communication systems—An  $H_\infty$  approach," *IEEE Trans. Wireless Commun.*, vol. 3, no. 6, pp. 2060–2071, Nov. 2004.
- [17] S. Zhou and G. Giannakis, "Optimal transmitter Eigen-beamforming and space-time block coding based on channel mean feedback," *IEEE Trans. Signal Process.*, vol. 50, no. 10, pp. 2599–2613, Oct. 2002.
- [18] Y. Yao and G. Giannakis, "Rate-maximizing power allocation in OFDM based on partial channel knowledge," *IEEE Trans. Wireless Commun.*, vol. 4, no. 3, pp. 1073–1083, May 2005.
- [19] Z. Zhou and B. Vucetic, "Design of adaptive modulation using imperfect CSI in MIMO systems," *Electron. Lett.*, vol. 40, no. 17, pp. 1073–1075, Aug. 2004.
- [20] T. Yoo and A. Goldsmith, "Capacity and power allocation for fading MIMO channels with channel estimation error," *IEEE Trans. Inf. Theory*, vol. 52, no. 5, pp. 2203–2214, May 2006.
- [21] J. Proakis, *Digital Communication*. New York: McGraw-Hill, 2001.
- [22] I. Gradshteyn, I. Ryzhik, D. Zwillinger, and A. Jeffrey, *Table of Integrals, Series, and Products*. New York: Academic, 2007.
- [23] A. Lapidoth and S. Moser, "Capacity bounds via duality with applications to multiple-antenna systems on flat-fading channels," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2426–2467, Oct. 2003.
- [24] K. Suresh, I. S. Misra, and K. Saha, "Bandwidth and delay guaranteed call admission control scheme for QoS provisioning in IEEE 802.16e mobile WiMAX," in *Proc. IEEE GLOBECOM*, 2008, pp. 1–6.
- [25] I. C. Wong and B. L. Evans, "OFDMA downlink resource allocation for ergodic capacity maximization with imperfect channel knowledge," in *Proc. IEEE GLOBECOM*, Washington, DC, Nov. 2007, pp. 3729–3733.
- [26] N. Z. Shor, *Minimization Methods for Non-Differentiable Functions*. New York: Springer-Verlag, 1985.
- [27] J. W. Mark and W. Zhuang, *Wireless Communications and Networking*. Englewood Cliffs, NJ: Prentice-Hall, 2003.



**Mohamad Khattar Awad** (S'02–M'09) received the B.A.Sc. degree in electrical and computer engineering (communications option) from the University of Windsor, Windsor, ON, Canada, in 2004 and the M.A.Sc. and Ph.D. degree in electrical and computer engineering from the University of Waterloo, Waterloo, ON, Canada, in 2006 and 2009, respectively.

He is currently a Research Assistant with the Broadband Communications Research Group, Department of Electrical and Computer Engineering, University of Waterloo. His research interests include wireless communications, wireless network resource allocation, and acoustic vector-sensor signal processing.

Dr. Awad received the Ontario Research & Development Challenge Fund Bell Scholarship in 2008 and 2009 and the University of Waterloo Graduate Scholarship in 2009.



**Veluppillai Mahinthan** (S'02–M'08) received the B.Sc.Eng. degree in electrical and electronic engineering from the University of Peradeniya, Peradeniya, Sri Lanka, in 2000, the M.Eng. degree from National University of Singapore, Singapore, in 2003, and the Ph.D. degree in electrical and computer engineering from the University of Waterloo, Waterloo, ON, Canada, in 2007, respectively.

From 2000 to June 2001, he was an Instructor with the Department of Electrical and Electronic Engineering, University of Peradeniya. From July 2001 to August 2003, he was a Research Scholar with the Institute for Infocom Research (*I<sup>2</sup>R*), Singapore. From September 2003 to September 2007, he was a Research Assistant with the Centre for Wireless Communication, University of Waterloo. From October 2007 to September 2008, he was a Postdoctoral Fellow and Adjunct Lecturer with the Department of Electrical and Computer Engineering, University of Waterloo. From October 2008 to January 2008, he was a Postdoctoral Fellow with the Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON. He is currently with Research In Motion Ltd., Waterloo. His current research interests are in wireless communications, including cooperative diversity, performance analysis of cross-layer communications, channel and mobile speed estimation, radio-frequency firmware design and implementation, and signal processing for communications.



**Mehri Mehrjoo** (M'06) received the B.A.Sc. and the M.A.Sc. degrees from Ferdowsi University, Mashad, Iran, in 1993 and 1996, respectively, and the Ph.D. degree from the University of Waterloo, Waterloo, ON, Canada, in 2008.

From 2008 to 2009, she was a Postdoctoral Fellow with the University of Waterloo. She is currently with the Faculty of Electrical and Computer Engineering, University of Sistan and Baluchestan, Zahedan, Iran. Her research interests are in the areas of resource allocation, performance analysis of wireless protocols, and vehicular communication.



**Xuemin (Sherman) Shen** (M'97–SM'02–F'09) received the B.Sc. degree in electrical engineering from Dalian Maritime University, Dalian, China, in 1982 and the M.Sc. and Ph.D. degrees in electrical engineering from Rutgers University, New Brunswick, NJ, in 1987 and 1990, respectively.

He is currently a Professor and the University Research Chair with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. He is a coauthor of three books and has published more than 400 papers and book chapters on wireless communications and networks, control, and filtering. His research focuses on resource management in interconnected wireless/wired networks, ultra-wideband wireless communications networks, wireless network security, wireless body area networks, and vehicular ad hoc and sensor networks.

Dr. Shen is a registered Professional Engineer of Ontario, and a Distinguished Lecturer of the IEEE Communications Society. He received the Excellent Graduate Supervision Award in 2006 and the Outstanding Performance Award in 2004 and 2008 from the University of Waterloo, the Premier's Research Excellence Award in 2003 from the Province of Ontario, and the Distinguished Performance Award in 2002 and 2007 from the Faculty of Engineering, University of Waterloo. He is serving as the Technical Program Committee Chair for the 2010 IEEE Vehicular Technology Conference, the Tutorial Chair for the IEEE International Conference on Communications, the Technical Program Committee Chair for the IEEE Global Telecommunications Conference, a General Cochair for the International Conference on Communications and Networking in China and the International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks, and the Founding Chair for IEEE Communications Society Technical Committee on Peer-to-Peer Communications and Networking. He also has served/serves as a Founding Area Editor for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, the Editor-in-Chief for *Peer-to-Peer Networking and Application*, and an Associate Editor for the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, *Computer Networks*, *ACM/Wireless Networks*, etc. He has also served as a Guest Editor for the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, *IEEE Wireless Communications*, *IEEE Communications Magazine*, *ACM Mobile Networks and Applications*, etc.



**Jon W. Mark** (M'62–SM'80–F'88–LF'03) received the B.A.Sc. degree in electrical engineering from the University of Toronto, Toronto, ON, Canada, in 1962 and the M.Eng. and Ph.D. degrees in electrical engineering from McMaster University, Hamilton, ON, in 1968 and 1970, respectively.

From 1962 to 1970, he was an Engineer and then a Senior Engineer with Westinghouse Canada Ltd., where he conducted research on advanced sonar signal processing. From 1968 to 1970, he was on leave from Westinghouse Canada Ltd. to pursue

Ph.D. studies at McMaster University under the auspices of an NRC PIER Fellowship. He joined the Department of Electrical Engineering (now known as the Department of Electrical and Computer Engineering), University of Waterloo, Waterloo, ON, in September 1970 and was promoted to the rank of Full Professor in July 1978. He served as the Department Chairman from July 1984 to June 1990. During this period, the department introduced the computer engineering degree program and changed its name to the Department of Electrical and Computer Engineering. He was on sabbatical leaves with the IBM Thomas J. Watson Research Center, Yorktown Heights, NY, as a Visiting Research Scientist from 1976 to 1977, with Bell Labs, Murray Hill, NJ, as a Resident Consultant from 1983 to 1984, with the Université Pierre et Marie Curie, Paris, France, as an Invited Professor from 1990 to 1991, and with the National University of Singapore, Singapore, as a Visiting Professor from 1994 to 1995. He established the Center for Wireless Communications (CWC) at the University of Waterloo in 1996 with a \$1 million from Ericsson Canada as seed money. He is currently a Distinguished Professor Emeritus and the founding Director of the CWC with the University of Waterloo. He is a coauthor of recent books entitled *Wireless Communications and Networking* (Prentice-Hall, 2003), *Multimedia Services in Wireless Internet* (Wiley, 2009), and *Wireless Broadband Networks* (Wiley, 2009). His current research interests are in wireless communications and wireless/wireline interworking in general and cooperative communications, cognitive radio, cross-layer design, etc., in particular.

Dr. Mark is a Fellow of the Canadian Academy of Engineering. He is the recipient of the 2000 Canadian Award in Telecommunications Research for significant research contributions, scholarship, and leadership in the fields of computer communication networks and wireless communications and the 2000 Award of Merit by the Educational Foundation of the Association of Chinese Canadian Professionals for significant contributions in telecommunications research. He has served as a member of a number of editorial boards, including editorships with the IEEE TRANSACTIONS ON COMMUNICATIONS, WIRELESS NETWORKS, AND TELECOMMUNICATION SYSTEMS. He has served as a member of the Inter-Society Steering Committee of the IEEE/ACM TRANSACTIONS ON NETWORKING during the period 1992–2003 (as the Steering Committee Chair during 1999–2000) and a member of the IEEE Communications Society Awards Committee during 1995–1998.