

Optimal Resource Management with Delay Differentiated Traffic and Proportional Rate Constraint in Heterogeneous Networks

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Abstract—In this paper, we focus on the radio resource management (RRM) in heterogeneous networks with orthogonal frequency division multiple access (OFDMA), and aim to maximize the system sum-rate and meet quality of service (QoS) requirements under the proportional fairness constraint of user rates. The previously proposed resource allocation schemes, which do not differentiate the traffic types or consider the fairness performance, may result in inefficient allocation of radio resources. To tackle this problem, we present an analytical model which takes consideration of two types of the traffic including the Delay-Constraint (DC) traffic and the Best-Effort (BE) traffic, and then formulate the RRM problem as a linear programming (LP) problem. We propose an efficient iterative algorithm to find the optimal solutions by converting this combinatorial problem with exponential complexity into a convex problem or showing that it can be solved in the dual domain. Numerical studies are conducted to evaluate the performance of the proposed algorithm in terms of achievable transmission rate for the DC traffic and fairness for the BE traffic, multiuser diversity, and system throughput.

Index Terms—Heterogeneous networks; optimal resource management; convex optimization; multi-radio access; power control

I. INTRODUCTION

Future broadband wireless networks are expected to support a wide variety of communication services with diverse quality-of-service (QoS) requirements. Applications such as voice transmission and real-time video streaming are very delay-sensitive and need guaranteed throughput, and applications like file transfer are relatively delay tolerant so variable rate transmissions are acceptable [1], [2]. On the other hand, the proportional user-rate constraint is considered as a fairness criterion [3], which balances the tradeoff between the system sum-rate and user fairness. From the physical layer point of view, transmission of best-effort or delay-tolerant traffic can be viewed as an ergodic capacity problem [4], where the goal is to maximize the

long-term average transmission rate. Thus, wireless resources (i.e., radio access technologies (RAT), bandwidth, and power) can be dynamically allocated so as to exploit the time or frequency selectivities of broadband wireless fading channels. Likewise, transmission of delay sensitive traffic can be considered as a delay-limited capacity problem [5] in which a constant transmission rate should be maintained with probability one regardless of channel variations.

Recently, orthogonal frequency division multiple access (OFDMA) has been considered as a promising air interface solution which is widely adopted in the broadband networks, e.g., Worldwide Inter-operability for Microwave Access (WiMAX) and 3GPP-Long Term Evolution (LTE) [6], [7]. The RRM strategies in the OFDMA network have been broadly investigated [8], [9]. Meanwhile, intensive research efforts focused on the RRM strategies in the downlink of OFDMA involved heterogeneous networks [10], [11]. A representative scheme was proposed in [11] which provided universal link layer processing over different RATs for the purpose of multi-radio cooperation and improving connectivity at the radio access level.

As for systems with pure DC traffic, the goal is to minimize the system transmit power while satisfying a basic transmission rate constraint for each user. This is often referred to as margin adaptation [12]. In [13], the authors proposed an iterative algorithm to allocate each user some subcarriers and then determine the power and rate for each user on its allocated subcarriers. In [14], a Joint RRM (JRRM) with bankruptcy-based policies was proposed to take into account the radio resources' diversity, and seek to efficiently distribute radio resources based on the system load and user/service QoS requirements. However, radio resource allocation, such as power and frequency bandwidth, presents a huge challenge for operators in term of exploiting the cooperative diversity and further meeting QoS requirements of diverse service traffic. For systems with pure BE traffic, the problem is often formulated as maximizing the sum-rate of the system subject to a total transmit power constraint [15]. Other formulations for systems with pure BE traffic take user fairness into account. A utility-function based optimization framework, for example, was also discussed in [16] to balance system efficiency and user fairness.

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In this paper, we consider the power and subcarrier allocation problem which aims to maximize the system sum-rate under the proportional user rate constraint in the downlink of OFDMA involved heterogeneous networks, where the DC and BE traffic coexist. Traffics in the system are classified into DC Traffics and BE Traffics based on their traffic delay requirements. In [15], the radio resource is allocated to BE users in the heterogeneous networks framework without service traffic QoS consideration, aiming at the system capacity maximization. The proposed algorithm can completely meet QoS requirement of each DC MMT, in terms of guaranteeing the minimum data rate. The proportional user rate constraint is considered as a fairness criterion, which balances the tradeoff between the system sum-rate and user fairness. A similar problem was studied in [17], but it only discussed the transmit power adaptation based on the assumption of static subcarrier allocation. Instead, our work considers joint power and subcarrier adaptation and is one step forward of the previous work. The analysis shows that this multiuser power and subcarrier allocation problem is a mixed integer programming problem, the complexity of which increases exponentially with the number of subcarriers [18]. To make the problem more tractable, we transform it into a convex programming problem by using time-sharing technique.

The rest of this paper is organized as follows. In Section 2, we introduce the system model of heterogeneous networks and RRM assumptions. In Section 3 we formulate the resource allocation problem as a convex optimization problem by introducing time-sharing variables and present analytical frameworks of the optimal solution. In Section 4, the problem is solved by using dual method and a low-complexity suboptimal algorithm is proposed. Numerical simulation results and analysis are illustrated in Section 5. Finally, Section 6 concludes the full paper.

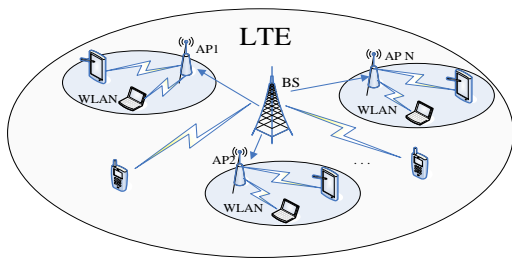


Fig. 1 Heterogeneous networks with 3GPP LTE network and WLANs.

II. SYSTEM MODEL AND RRM ASSUMPTIONS

We consider a heterogeneous network, which consists of one LTE network ($j=0$) and L WLANs ($j \geq 1$). As shown in Fig. 1, the access points (APs) of WLANs and base station (BS) of LTE are properly located with overlapped coverage. We assume that the coverage of all WLANs is within the coverage of LTE. There is no inter-network interference because WLANs and LTE operate on individual frequency bands. In addition, there is no interference between WLANs, which can be

achieved by assigning non-overlapping channels for them. The total i Multi-Mode Terminals (MMTs) can connect both or either of LTE and WLANs.

In the LTE network, the total bandwidth is divided into F subcarriers and one RRM time consists of M OFDM symbol intervals. Hence, there are total $N = FM$ resource elements during one time frame basis, each frame corresponds to one subcarrier during one OFDM symbol interval. The achievable data rate of user i at resource element n is denoted by r_{0in} , where $n = (a-1)F + b$ corresponds to the resource element index of the b -th subcarrier in the a -th OFDM symbol ($1 \leq a \leq M$, $1 \leq b \leq F$, $1 \leq n \leq N$).

The fading coefficients of all users are assumed to remain unchanged within each transmission frame but can vary from one frame to another. It assumed that all channel information is perfectly known at the central controller, which can be embedded with the base station. Typically, the channel information can be collected by estimating it at each MMT and sending it to the base station via a feedback channel, or through channel estimation of the uplink in a time-division duplex system. Through the power/bit and subcarrier allocation algorithm, the central controller allocates different subcarriers to different users and determines the amount of power/bits to be transmitted on each subcarrier based on the instantaneous channel inputs.

The broadband wireless channel is assumed to be frequency-selective Rayleigh fading between the base station and each user terminal. However, the channel in each subcarrier is narrow enough to experience flat fading. Let r_{in} denote the transmission rate of user i on subcarrier n in bits per OFDM symbol. It depends on the channel gain h_{in} and the allocated power P_{in} of user i on subcarrier n . In general, r_{in} can be expressed as

$$r_{in} = \beta_0 B_0 \log_2(1 + P_{in} |h_{in}|^2 / (\Gamma N_0 B_0)) \quad (1)$$

where N_0 is the power spectral density of AWGN and Γ is a constant, usually called the signal to noise ratio (SNR) gap [12].

In WLAN, we consider an enhanced version of distributed coordination function (DCF) with a reservation-based medium access control (MAC) protocol [19]. The users can completely avoid collisions by incorporating the backoff information in the MAC header. Thus, for the sake of simplicity, the users access WLAN in a TDMA manner. Each user can occupy the whole bandwidth in its allocated time fraction. Full power transmission is assumed and the achievable data rate of user i in the j -th WLAN is denoted by r_{ij} . Similar to (1), r_{ij} can be expressed as

$$r_{ij} = \beta_j B_j \log_2(1 + \frac{P_{ij} |h_{ij}|^2}{\Gamma N_0 B_j}) \quad (2)$$

In (1) and (2), β gives us the validity of each subsystem because it can express the offered system spectral efficiency. Hence, a RAT j , which has deployed a

better turbo decoder with more iterations or better interleaver, can have a higher β value than other RATs with a conventional Viterbi decoder, for the same encoder. For instance, β could be 0.6 and 0.29 for LTE (1x2) and WiMAX Wave 1 [20] respectively.

III. PROBLEM FORMULATION AND OPTIMAL RESOURCE ELEMENT ALLOCATION

A. Problem Formulation

In this work, we consider a heterogeneous wireless network environment consisting of M active MMTs which are requesting diverse services and L available RATs as depicted in Fig. 1. Assuming that M MMTs are classified by heterogeneous service traffic delay requirements: the first class users who have DC service traffic rate r_i ($i = 1, 2, \dots, K$) which requires a minimum constant transmission rate, known as DC MMTs [21]. And the remaining $(M - K)$ MMTs transmit BE service traffic, known as BE MMTs. In order to transmit service data by multi-access manner, each MMT should obtain the radio resource from the available RATs. The traffic for the remaining $(M - K)$ BE MMTs has no delay constraint and can be delivered in the best-effort manner. However, the traffic for BE MMTs needs to be guaranteed proportional fairness [22].

Thus, we have

$$r_i \geq R_i^{\min}, i = 1, 2, \dots, K, \quad (3)$$

$$r_{K+1} : r_{K+2} : \dots : r_M = \gamma_{K+1} : \gamma_{K+2} : \dots : \gamma_M \quad (4)$$

where R_i^{\min} ($i = 1, 2, \dots, K$) is the minimum rate constraint for DC MMTs and γ_i ($i = K+1, K+2, \dots, M$) is the proportional fairness parameter for BE MMTs.

In the LTE-WLAN heterogeneous networks, we formulate the sum-rate maximization problem with diverse proportional user rate constraint as

$$\max \sum_{i=1}^M R_i \quad (5a)$$

$$\text{subject to } \sum_{j=0}^L \chi_{ij} \leq 1, \forall i, \quad \chi_{ij} \in \{0, 1\}, \forall i, j \quad (5b)$$

$$\sum_{i=1}^M f_{in} \leq 1, \forall n, \quad f_{in} \in \{0, 1\}, \forall i, n \quad (5c)$$

$$\sum_{i=1}^M t_{ij} \leq 1, \forall j, \quad 0 \leq t_{ij} \leq 1, \forall j, i \quad (5d)$$

$$R_i \geq R_i^{\min}, \forall i = 1, 2, \dots, K, \quad (5f)$$

$$\frac{R_i}{\gamma_i} = \frac{R_{k+1}}{\gamma_{k+1}}, \forall i \in k+1, k+2, \dots, M \quad (5g)$$

where j denotes the index of network, i.e., network $j=0$ is the 3GPP LTE network and $j(1 \leq j \leq L)$ is the j -th WLAN. χ_{ij} denotes the network selection parameter of user i at network j . f_{ij} is the resource allocation parameter of user i in the resource element n of LTE, and t_{ij} is the time fraction allocation parameter of user i in the j -th WLAN. The constraint (5b) guarantees that each user can

only access a single network within each RRM time scale, and (5c) guarantees that each resource element in LTE is exclusively occupied by a single user. R_i is the data rate of user i , and (5g) is the proportional user rate constraint, in which $\{\gamma_{k+1}, \gamma_{k+2}, \dots, \gamma_M\}$ is the set of predetermined values that are used to ensure fairness among the users [9], [23].

To tackle the problem, we use the constraint relaxation method to deal with the integer constraints (5b) and (5c) [24]. First, the networks where a user equipment can access multiple networks RATs simultaneously are named multi-radio access (MRA) system, which accommodates RATs such as LTE, and WLAN. So we relax the single network selection constraint, i.e., set $\alpha_{ij} = 1$ for all i and j , so that each user is allowed to transmit its data over multiple RATs simultaneously. Second, we allow one resource element can be shared to multiple users in LTE, e.g., in an FDMA manner instead of exclusively allocating one resource element to a single user. By this means, the data rate of user i can be expressed as $R_i = \sum_{n=1}^N f_{in} r_{0in} + \sum_{j=1}^L t_{ij} r_{ij}$, in which $0 \leq f_{ij} \leq 1$ represents the portion of resource element n allocated to user i . Finally, the problem (5) can be reformulated as

$$\max \sum_{i=1}^M R_i \quad (6a)$$

$$\text{subject to } \sum_{i=1}^M f_{in} \leq 1, \forall n, \quad 0 \leq f_{in} \leq 1, \forall i, n \quad (6b)$$

$$\sum_{i=1}^M t_{ij} \leq 1, \forall j, \quad 0 \leq t_{ij} \leq 1, \forall i, j \quad (6c)$$

$$R_i = \sum_{n=1}^N f_{in} r_{0in} + \sum_{j=1}^L t_{ij} r_{ij} \quad (6d)$$

$$R_i \geq R_i^{\min}, \forall i = 1, 2, \dots, K, \quad (6e)$$

$$\frac{R_i}{\gamma_i} = \frac{R_{k+1}}{\gamma_{k+1}}, \forall i \in k+1, k+2, \dots, M \quad (6f)$$

which becomes an LP problem. It is obvious that the problem is feasible and bounded and therefore a unique optimal solution exists [25]. Since multi-access and resource element sharing are allowed, the optimal solution provides an upper-bound of the user rate.

B. Time-Sharing based Optimal Resource Element Allocation

By the means of time sharing, the resource element allocations in LTE are approximated as time fraction allocation in a TDMA manner, i.e., OFDM-TDMA. This time-sharing technique has been frequently used in the context of subcarrier assignment in multiuser OFDM systems to convert a mixed integer programming problem into a convex optimization problem [26,27]. We define ρ_{ij} as the time fraction allocation parameter for user i , respectively in LTE ($1 \leq j \leq N$) and WLANs ($N+1 \leq j \leq N+L$) [23].

In addition, we introduce a variable s_{ij} and define it as $s_{ij} = \rho_{ij} P_{ij}$ for all i and j . Clearly, s_{ij} becomes the actual amount of power allocated to user i on subcarrier j in LTE ($1 \leq j \leq N$) and on j -th WLAN ($N+1 \leq j \leq N+L$), whereas P_{ij} is the power as if subcarrier or WLAN AP is occupied by user i only. If $\rho_{ij} = 0$, we always have $s_{ij} = 0$ but P_{ij} is not necessarily equal to zero. For notation brevity, we let $\alpha_{ij} = |h_{ij}|^2 / \Gamma_k N_0 B_j$ for all i and j and call it the effective channel-to-noise ratio (CNR) of user i on subcarrier j . Here, for the purpose of generality, the subindex i is added to the SNR gap Γ to include the case when each user has different BER requirements if adaptive modulation and coding is used. The total transmit power from the base station and WLAN AP is fixed and given by P_T . So, R_i can be expressed as:

$$R_i = \sum_{j=1}^{N+L} \beta_j B_j \rho_{ij} \log_2(1 + s_{ij} \alpha_{ij} / \rho_{ij}) \quad (7)$$

With the aid of time-sharing factors ρ_{ij} , we now readily transform the problem (6) into:

$$\max \sum_{i=1}^M R_i \quad (8a)$$

$$\text{subject to } R_i \geq R_i^{\min}, \quad \forall i = 1, 2, \dots, K, \quad (8b)$$

$$\frac{R_i}{\gamma_i} = \frac{R_{K+1}}{\gamma_{K+1}}, \quad \forall i \in K+1, K+2, \dots, M \quad (8c)$$

$$\sum_{i=1}^M \sum_{j=1}^{N+L} s_{ji} = P_T \quad (8d)$$

$$\sum_{i=1}^M \rho_{ij} = 1, \quad \forall j \quad (8e)$$

$$s_{ij} \geq 0, 0 \leq \rho_{ij} \leq 1, \quad \forall i, j \quad (8f)$$

where P_T is the total transmit power from the LTE base station and WLAN APs. The objective function (8a) is a sum of functions of the form $f(\rho_{ij}, s_{ij}) = \beta_j B_j \rho_{ij} \log_2(1 + s_{ij} C / \rho_{ij})$, where C is the positive constant. By evaluating the Hessian matrix of $f(\rho_{ij}, s_{ij})$ at ρ_{ij} and s_{ij} , we can prove that $f(\rho_{ij}, s_{ij})$ is concave [28]. Thus, the objective function, which is positive linear combination of concave functions, is concave. Moreover, since the inequality constraint functions in (8b) are convex and the constraints in (8c)-(8f) are all affine, the feasible set of this optimization problem is convex. Therefore, the convex optimization problem (8) has a unique optimal solution, which can be obtained in polynomial time.

IV. OPTIMAL RADIO RESOURCE ALLOCATION ALGORITHM FOR MULTI-ACCESS

A. Optimal Radio Resource Allocation Analysis

For the optimal solution of capacity maximum problem, the Lagrangian is given,

$$\begin{aligned} L(s_{ij}, \rho_{ij}, \lambda_j, \mu, v_i, \omega_i) = & \sum_{i=1}^M \sum_{j=1}^{N+L} \beta_j B_j \rho_{ij} \log_2(1 + \frac{s_{ij} \alpha_{ij}}{\rho_{ij}}) \\ & + \sum_{j=1}^{N+L} \lambda_j (1 - \sum_{i=1}^M \rho_{ij}) + \mu (P_T - \sum_{i=1}^M \sum_{j=1}^{N+L} s_{ji}) \\ & + \sum_{i=1}^K v_i (\sum_{j=1}^{N+L} \beta_j B_j \rho_{ij} \log_2(1 + \frac{s_{ij} \alpha_{ij}}{\rho_{ij}}) - R_i^{\min}) \\ & + \sum_{i=K+1}^M \omega_i (\sum_{j=1}^{N+L} \beta_j B_j \rho_{(K+1)j} \log_2(1 + \frac{s_{(K+1)j} \alpha_{(K+1)j}}{\rho_{(K+1)j}}) \\ & - \frac{\gamma_{K+1}}{\gamma_i} \sum_{j=1}^{N+L} \beta_j B_j \rho_{ij} \log_2(1 + \frac{s_{ij} \alpha_{ij}}{\rho_{ij}})) \end{aligned} \quad (9)$$

where shadow prices λ_j, μ, v_i and ω_i are nonnegative Lagrange multipliers for the constraints. By taking derivatives with respect to λ_j, μ, v_i and ω_i respectively, we can get a general differentiation of (9) for both types of service traffic by Karush-Kuhn-Tucker (KKT) conditions [28]:

$$\frac{dL}{d\rho_{ij}} = \tilde{\beta}_j B_j \log_2(1 + \frac{s_{ij} \alpha_{ij}}{\rho_{ij}}) - \frac{\tilde{\beta}_j B_j \alpha_{ij} s_{ij}}{(\rho_{ij} + \alpha_{ij} s_{ij}) \ln 2} - \lambda_j \leq 0 \quad (10)$$

$$\frac{dL}{ds_{ij}} = \frac{\tilde{\beta}_j \alpha_{ij} \rho_{ij}}{(\rho_{ij} + \alpha_{ij} s_{ij}) \ln 2} - \mu \leq 0 \quad (11)$$

The inequation (10) and (11) are necessary and sufficient conditions for ρ_{ij} and s_{ij} .

For $1 \leq i \leq K$, we have

$$\tilde{\beta}_j = (1 + v_i) \beta_j, i = 1, 2, \dots, K \quad (12)$$

For $K+1 \leq i \leq M$, we have two cases

$$\tilde{\beta}_j = (1 + \sum_{k=K+2}^M \omega_k) \beta_j, i = K+1 \quad (13)$$

$$\tilde{\beta}_j = (1 - \omega_i \frac{\gamma_{K+1}}{\gamma_K}) \beta_j, i = K+2, \dots, M \quad (14)$$

With inequation (10) and (11), we have

$$\rho_{ij} \cdot \frac{dL}{d\rho_{ij}} = 0, \quad (15)$$

$$s_{ij} \cdot \frac{dL}{ds_{ij}} = 0. \quad (16)$$

Let $\{\rho_{ij}\}$ be any given subcarrier assignment scheme. Differentiating the Lagrangian in (9) with respect to s_{ij} and substituting the result into the KKT condition (11), we obtain:

$$P_{ij} = \frac{s_{ij}}{\rho_{ij}} = [\frac{v_i}{\mu \ln 2} - \frac{1}{\alpha_{ij}}]^+ \quad (17)$$

for $i = 1, 2, \dots, K, K+1, \dots, M$. and $j = 1, 2, \dots, L+N$. Here, $[z]^+ = \max\{z, 0\}$. In equation (17), the optimal power allocation follows the standard water-filling approach, except that the allocated power is only on for the time fraction ρ_{ij} . The water level of each channel per MMT may differ from one another. And in order to obtain the optimal ρ_{ij} and s_{ij} solution, we must have one of them. Based on problem (9), the dual problem can be expressed as follows:

$$D(\lambda_j, \mu, v_i, \omega_i) = \max L(s_{ij}, \rho_{ij}, \lambda_j, \mu, v_i, \omega_i) \quad (18)$$

According to the convex analysis [29], strong duality (zero dual gap) holds between the optimum of primal problem (9) and its dual problem (18). Thus the optimal solution for primal problem can always be found by solving (18) without any performance loss. Hence, in the following proposed algorithm, we use the gradient projection method [28] to approach to the optimal solution, which is proved to be feasible if the iterative step sizes are properly chosen. So, we utilize the best-response method to update the bandwidth as follows:

$$\rho_{ij}^{k+1} = [\rho_{ij}^k + \delta \frac{dL}{d\rho_{ij}}]^+, \quad \forall i, j, \quad (19)$$

$$\rho_{ij}^{k+1} = \begin{cases} \rho_{ij}^k + \delta[(1+v_i)\beta_j B_j \log_2(1 + \frac{s_{ij}\alpha_{ij}}{\rho_{ij}}) - \lambda_j]^+, & \text{if } i = 1, 2, \dots, K \\ \rho_{ij}^k + \delta[(1 + \sum_{k=K+2}^M \omega_k)\beta_j B_j \log_2(1 + \frac{s_{ij}\alpha_{ij}}{\rho_{ij}}) - \lambda_j]^+, & \text{if } i = K+1 \\ \rho_{ij}^k + \delta[(1 - \omega_i \frac{\gamma_{K+1}}{\gamma_K})\beta_j B_j \log_2(1 + \frac{s_{ij}\alpha_{ij}}{\rho_{ij}}) - \lambda_j]^+, & \text{if } i = K+2, K+3, \dots, M \end{cases} \quad (20)$$

where δ is the constant step size for primal variable ρ_{ij} . It can converge to optimal value as long as the step size δ is appropriately chosen. After ρ_{ij} is solved, s_{ij} can be determined by using (17). To update the Lagrange multiplier values for the optimal solution, we consider the continuously differentiable dual function. Using the gradient projection approach, the updated nonnegative multiplier value for power allocation is given by

$$\lambda_j^{k+1} = [\lambda_j^k + \varepsilon_1 \frac{dD}{d\lambda_j}]^+ = [\lambda_j^k + \varepsilon_1 (\sum_{i=1}^M \rho_{ij} - 1)]^+, \quad (21)$$

$$\mu^{k+1} = [\mu^k + \varepsilon_2 \frac{dD}{d\mu}]^+ = [\mu^k + \varepsilon_2 (\sum_{i=1}^M \sum_{j=1}^{N+L} s_{ji} - P_T)]^+, \quad (22)$$

$$v_i^{k+1} = [v_i^k + \varepsilon_3 \frac{dD}{dv_i}]^+ = [v_i^k + \varepsilon_3 (\sum_{j=1}^{N+L} r_{ij} - R_i^{\min})]^+, \quad (23)$$

$$\omega_i^{k+1} = [\omega_i^k + \varepsilon_4 \frac{dD}{d\omega_i}]^+ = [\omega_i^k + \varepsilon_4 (\sum_{j=1}^{N+L} r_{(K+1)j} - \frac{\gamma_{K+1}}{\gamma_i} \sum_{j=1}^{N+L} r_{ij})]^+ \quad (24)$$

where $\vec{\varepsilon} = \{\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4\}$ is a constant step size vector. From iterations, we can solve the optimal problem of the multiaccess in heterogeneous networks with traffic differentiation which maximizes system total capacity under the proportional user rate constraint.

B. The Proposed Optimal Resource Allocation Algorithm

Algorithm 1 at MMT i

Step 1) Initialization step. Select initial values for

$\delta, \vec{\varepsilon}, \rho_{ij}^0, s_{ij}^0, \mu^0, v_i^0, \omega_i^0$, and λ_j^0 .

Set iteration count $k=0$.

Step 2) Calculate ρ_{ij}^{k+1} using gradient projection method.

$$\rho_{ij}^{k+1} = [\rho_{ij}^k + \delta \frac{dL}{d\rho_{ij}}]^+, \quad \forall i, j,$$

Step 3) Determine $\frac{s_{ij}}{\rho_{ij}} = [\frac{1}{\mu \ln 2} - \frac{1}{\alpha_{ij}}]^+ \quad \forall i, j,$

Step 4) if Iteration reaches the convergence precision (condition) of ρ_{ij} and s_{ij} or the maximum iteration number

then

Transmit data packet to the RAT(s) using

ρ_{ij}^{k+1} and s_{ij}^{k+1}

else

Update μ^{k+1}, v_i^{k+1} and ω_i^{k+1} using $\rho_{ij}^{k+1}, s_{ij}^{k+1}$

information.

$k \leftarrow k+1$, goto step 2)

end if

Algorithm 2 at access point of RAT j

Step 1) Compute λ_j^{k+1} using ρ_{ij}^{k+1} information.

Step 2) Update the new λ_j^{k+1} value to all MMTs.

Step 3) $k \leftarrow k+1$, goto step 1)

Based on the optimality conditions for multi-access with service traffic differentiation, the proposed algorithm uses the Projected Gradient method as a basis for the optimization solution as shown in Algorithms 1 and 2. Since the dual function $D(\lambda_j, \mu, v_i, \omega_i)$ is convex, a gradient-type algorithm can minimize $D(\lambda_j, \mu, v_i, \omega_i)$ by updating $D(\lambda_j, \mu, v_i, \omega_i)$ simultaneously along some appropriate search directions, which is guaranteed to converge to the optimal solution. In general, $D(\lambda_j, \mu, v_i, \omega_i)$ is not differentiable, and thus its gradient does not exist.

Then, this algorithm gives a distributed decision making manner for the multi-access radio resource allocation problem with the intention of total system capacity maximization. And the proposed algorithm complexity is a step size and initial value related function [29]. Although (7) could be solved via centralized optimization techniques where convergence is guaranteed without signaling overhead, it is preferred to use a distributed optimization approach to make a decision at each MMT under perfect synchronized updates[15], [30].

V. PERFORMANCE EVALUATION

A. Simulation Assumptions

As shown in Fig. 2, we consider the LTE-WLAN networks with a two-dimension distribution model.

The cell radius of WLAN is 200m. The BS of the LTE network is located at coordinate (0, 0), with a cell radius of 500m and a three-sector antenna pattern. One LTE sector is partially overlapped with the coverage of two WLANs, in which two APs are respectively located at

coordinates (300m, -200m) and (300m, 200m). We consider the RRM strategy for the users that are randomly distributed in that LTE sector. For LTE, an urban environment, indoor terminals, 2 GHz frequency band, and 10 MHz bandwidth are assumed. We consider shadowing and path loss as a channel propagation model. The channels for different users are assumed to be independent. We also assume that the path losses from the base station to all user terminals are the same. The average channel gain on each subcarrier is normalized. In practice, when uncoded QAM constellation is used the SNR gap of 8.2 dB corresponds to a BER requirement of 10^{-5} . The detailed parameters of LTE network are listed in Table. I [31]. For WLAN, the transmit power of AP is 23dBm, the pathloss model is $38.2 + 30\log(d)$ and the AWGN power at the user is -90dBm. As illustrated in [32], the achievable transmission data rates of users are determined by the link adaptation scheme, i.e., based on the link level simulation results for SNR versus rate.

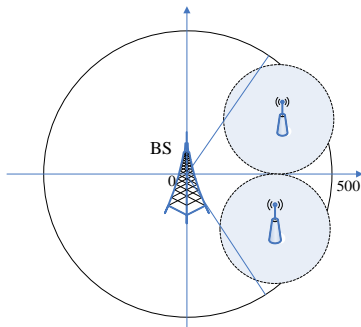


Fig. 2. System model of LTE-WLAN networks

TABLE I. SIMULATION PARAMETERS IN THE LTE NETWORK

Parameter	Value
Number of Subcarriers	1024
Bandwidth	10MHz
BS TX Power	43dBm
Noise Power Density	-174dBm/Hz
Noise Figure	9dB
SNR Gap	$-\log(5\text{BER target})/1.5$
Target BER	$\text{BER}_{\text{target}} = 10$
Shadowing	Log-normal, 8dB standard deviation
Multipath Fading	3GPP typical urban

B. Simulation Results

In the simulation of the convergent data rate solution, it is assumed that there are 3 MMTs, which are randomly distributed in region. 1 DC ($R_i^{\min} = 12\text{Mbps}$) MMT and 2 BE ($\gamma_2:\gamma_3=1:1$) ones transmit their data over multiple RATs, simultaneously. An example for how to find the optimal radio resource allocation scheme is provided in Fig. 3. The proposed algorithm provide transmission data rate convergence to the optimal solution of MMTs transmission data rate, which are jointly determined by the actual amount of transmit power allocated to user and time-sharing factor optimal values. According to the optimal allocation strategies, it is observed that both BE users obtain the same amount of transmission rate under the proportional fairness resource allocation principle. As a result, optimal resource allocation algorithm with QoS

support is feasible an efficiently iterate to the global optimal solution.

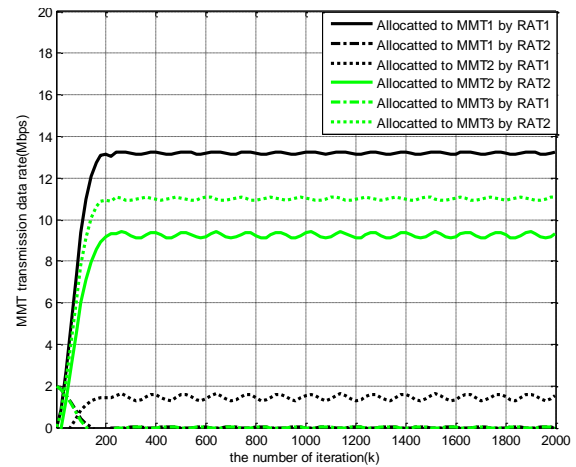


Fig. 3. The convergent data rate solution of the proposed optimal resource management

To evaluate the effectiveness of the proposed optimal resource allocation algorithms, we also present the results for existing algorithm [15] in comparison, which most closely related to the work in this paper. In [15], the optimal resource allocation is investigate to support parallel MRA scheme for much higher system capacity from a viewpoint of a scheduler, but without service traffic QoS consideration. In Fig. 4, we simulate all MMTs composed of only DC MMTs ($K=6$) and compare the QoS guarantee performance for DC traffic with minimum rate constraints. The reference minimum rate denotes the minimum rate requirements for DC MMTs. It is obvious that there are data rate gaps for some DC users (MMT 2, 3, 6), because the existing algorithm in [15] can't differentiate QoS requirement. However, the proposed algorithm can completely meet QoS requirement of each DC MMT, in terms of guaranteeing the minimum data rate.

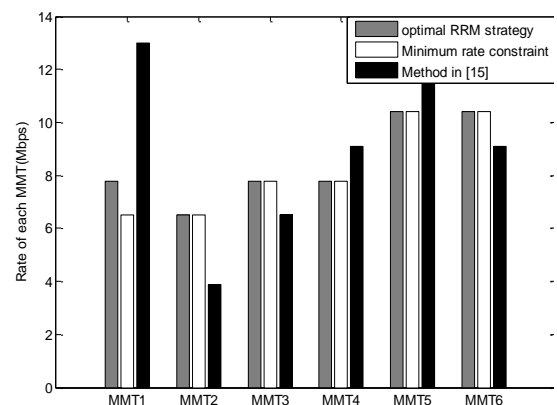


Fig. 4. An illustration of DC MMTs resource allocation of proposed algorithm and the method in [15].

Then, the RRM strategies are compared in terms of Fairness Index (FI) and Additional Datarate Ratio (ADR) [33]. With the given proportional rate ratios, the optimal fairness index is 0.9. We set 10 DC MMTs and 10~50 BE MMTs with equal fairness in the simulation and vary the SNR for MMTs. The fair index is defined as

$$FI(R_i) = (\sum_{i=K+1}^M R_i)^2 / ((M-K) * \sum_{i=K+1}^M R_i^2) \quad (25)$$

where r_i is the transmission data rate of MMT i . And to weight the degree of satisfaction, we define additional data rate ratio for DC MMTs as follows:

$$ADR(R_i, R_i^{\min}) = \sum_{i=1}^K (R_i - R_i^{\min}) / R_i^{\min} \quad (26)$$

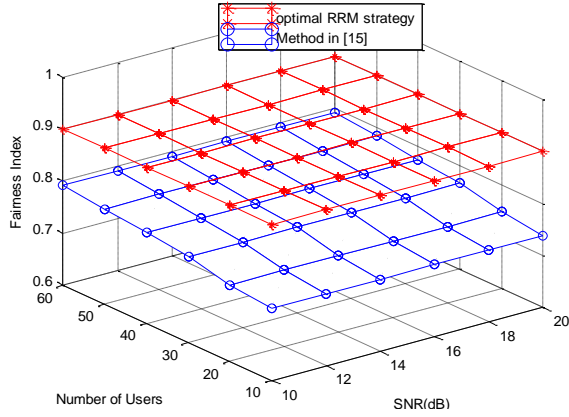


Fig. 5. Performance comparison in terms of fairness index

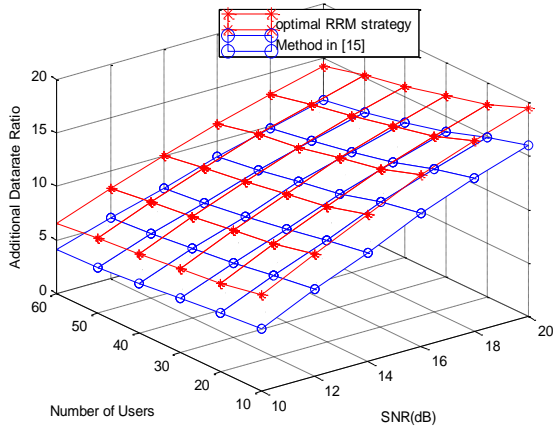


Fig. 6. Performance comparison in terms of additional datarate ratio

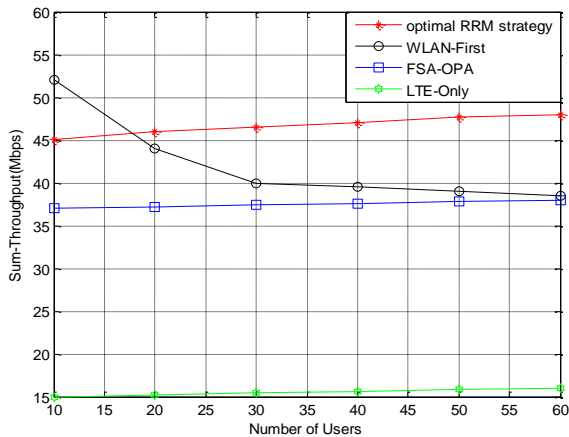


Fig. 7. Performance comparison in terms of sum-rate

In Fig. 5 and Fig. 6, both FI for BE MMTs and ADR for DC MMTs are presented to compare the degree of satisfaction which the resource allocation algorithms affects. We can see that the FI and ADR of the optimal resource allocation algorithms are improved more 12%

and 3% than those of the existing algorithm [15] on average respectively. The simulation result shows that the proposed algorithm outperforms than the existing algorithm [15] in QoS guaranteeing, since the proposed algorithm does not only tend to allocate resource to guarantee DC traffic QoS requirements, but fairness is also considered among BE MMTs. Fig. 7 compares the RRM strategies in terms of system sum-rate. To evaluate the advantage of proposed optimal algorithm, we consider three conventional RRM strategies for performance comparison, i.e., the LTE-only, the WLAN-first and Fixed Subcarrier Assignment with Optimal Power Allocation (FSA-OPA) [24]. In the last scheme, all the M users are treated equally and each is assigned the same number of subcarriers in LTE and time slots in WLAN. Except for the WLAN-first strategy, a stable sum-rate is observed in all the other RRM strategies, i.e., the sum-rate does not change much as the number of users increases. The optimal RRM case has the highest sum-rate, while LTE-only has the lowest one. For the FSA-OPA strategy, it has 17% lower sum-rate than the optimal RRM case. The WLAN-first case achieves higher sum-rate when the number of users is small. However, as the number of users increases, the sum-rate gradually decreases, since the overload situation may happen.

VI. CONCLUSION AND FUTURE WORK

An optimal resource allocation algorithm for multi-access in heterogeneous networks is proposed in this paper. We investigated this problem from the physical layer perspective and aimed to maximize the sum-rate of BE traffic, while maintaining individual basic rates of DC traffic for each channel realization and guaranteeing proportional fairness for the remaining BE MMTs under a total power constraint. By using the time-sharing technique, we converted this combinatorial problem with exponential complexity into a convex problem, and developed an efficient iterative algorithm with polynomial complexity. The optimal solution for original problem can always be found by solving its dual problem without any performance loss. Significant improvement is observed on the MMTs' transmission rate and fairness performance compared with other conventional RRM schemes. Furthermore, we can achieve stable system sum-rate, which is higher than that of most previous strategies.

For future work, it would be interesting to further study algorithms with faster convergence speed and reduced complexity.

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