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# A QoE-based Joint Bandwidth and Power Allocation Method for Multiple RATs in HetNets

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## Abstract

In this letter, we propose an optimal joint bandwidth and power allocation method for heterogeneous wireless networks (HetNets) by maximizing the users' quality of experience (QoE), which is a widely used subjective metric reflecting the users' satisfaction of the multimedia service. By taking two factors into consideration simultaneously: *Rate Factor (RF)* and *Energy Factor (EF)*, we can measure the QoE of end-users effectively. An optimal QoE-driven allocation algorithm is further developed for maximizing the end-users' QoE utility subject to the constraints of transmit bandwidth, power and data rate. The simulation results demonstrate the theoretical analysis.

**Index Terms:** heterogeneous wireless networks, multiple radio access technologies, resource allocation, quality of experience.

## I. Introduction

In recent years, heterogeneous wireless networks (HetNets) are leading the overwhelming evolution trend of wireless net-works. The HetNets with multiple radio access technologies (RATs), where end-users transmit their data over multiple RATs simultaneously, are named as the multi-RAT (MRAT) system, which incorporates RATs such as WLAN and LTE as its sub-systems. With the advances in multi-mode terminals recently, end-user equipments are capable to connect to any available wireless networks in the MRAT system. These multi-mode user equipments (MUEs) are usually equipped with multiple radio interfaces to access any existing wireless access networks simultaneously. Due to the rapid growth of mobile services, the conflict between limited resource and high demand of services in MRAT systems is becoming increasingly significant. Therefore, an effective bandwidth and power allocation method in MRAT systems is becoming a crucial and imperative issue for service providers.

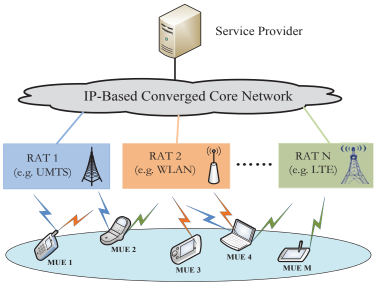

Fig. 1. The MRAT system in HetNets

The bandwidth and power allocation in HetNets has been studied in many works. The authors in [1] and [2] proposed greedy approaches for rate allocation in parallel transmission across HetNets. Joint radio resource allocation was investigated in [3] for maximizing the total capacity of the MRAT system in HetNets frameworks. In [4] and [5], the end-users in the MRAT system were classified into two categories to optimize the MRAT system throughput via optimal resource allocation. The energy efficiency of MRAT systems was discussed in [6] and [7] for allocating radio resource in HetNets. However, aforementioned literatures all neglect the quality of experience (QoE) of end-users for resource allocation in MRAT systems.

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In this letter, we propose a QoE-based joint bandwidth and power allocation method in MRAT systems across HetNets by maximizing the QoE of end-users. Our effective QoE measure-ment is conceived by both data rate and energy consumption. Further, a QoE-driven radio resource allocation algorithm is developed for maximizing the end-users' QoE utility subject to the transmission constraints and service requirements. By the proposed QoE-based allocation method, we can achieve the optimal resource allocation for end-users in MRAT systems.

## II. SYSTEM MODEL

We consider an MRAT associated HetNets consisting of *M* active MUEs and *N* available RATs, as depicted in Fig.1. We assume that both RATs and MUEs are implemented by the reconfigurable software defined radio technology. Hence, each MUE equipped with multiple radio interfaces is capable to access multiple RATs simultaneously. MUEs transmit their data through parallel transmission using different frequency bands across HetNets. In addition, assuming that MRAT systems can operate in orthogonal frequency bands, we disregard the interference among RATs in different frequency bands.

In order to transmit data in parallel multi-access manner, each MUE should be able to acquire the corresponding transmit bandwidth and power from the available RATs. To reflect the practical data transmission, each MUE is assumed to experience different channel gains and noise. For the link between MUE $i$ $(i = 1, 2, \cdots, M)$ and RAT $j$ $(j = 1, 2, \cdots, N)$, the channel gain and noise power are denoted as $H_{ij}$ and $N_{ij}$, respectively. Further, based on the Shannon theory, the achievable data rate of MUE $i$ $r_i$ can be expressed as

$$r_i = \sum_{j=1}^{N} \beta_j b_{ij} \log_2\left(1+\frac{|H_{ij}|^2 p_{ij}}{N_{ij}\, b_{ij}}\right), \tag{1}$$

where $N$ is the total number of RATs that MUE $i$ can access, $b_{ij}$ is the allocated bandwidth to MUE $i$ from RAT $j$, $p_{ij}$ is the transmit power of MUE $i$ through RAT $j$, and $\beta_j$ $(0 < \beta_j < 1)$ denotes the transmission efficiency which can be guaranteed by RAT $j$ to MUEs. Therefore, the practical transmit rate $r_i$ can be determined by Eq. (1) with the parameter $\beta_j$, which is the fraction of Shannon capacity. For the convenience of analysis later, we define

$$g_{ij} = \frac{|H_{ij}|^2}{N_{ij}}. \tag{2}$$

## III.PROBLEM FORMULATION

The problem of maximizing total end-users' QoE in the MRAT system across HetNets with relevant transmission con-straints and service requirements can be formulated as follows,

$$\max_{\mathrm{b},\mathrm{p}} \quad U(\mathrm{b},\mathrm{p}) = \sum_{i=1}^{M} U_i(\mathrm{b}_i,\mathrm{p}_i) \tag{3}$$

$$\text{s.t.} \quad \sum_{i=1}^{M} b_{ij} \le B_j^{max}, \ \forall j \tag{$c_1$}$$

$$\sum_{j=1}^{N} p_{ij} \le P_i^{\max}, \ \forall i \tag{$c_2$}$$

$$r_i \ge R_i^{\min}, \ \forall i \tag{$c_3$}$$

$$b_{ij} \ge 0, p_{ij} \ge 0, \ \forall i, j \tag{$c_4$}$$

where $U$(x, y) is the QoE utility function of the MRAT system, b is the bandwidth allocation matrix from RATs to MUEs, p is the power allocation matrix from RATs to MUEs, $\mathrm{B}_j^{\max}$ is the total subsystem bandwidth of RAT $j$, $\mathrm{P}_i^{\max}$ is the maximum available power of MUE $i$, $\mathrm{R}_i^{\min}$ is the minimum rate requirements of service for MUE $i$ and $r_i$ is the achievable data rate of MUE $i$ which is given by Eq. (1). Constraint ($c$1) and ($c$2) indicate the transmission constraints of bandwidth and power resulted from the finite resource. And constraint ($c$3) denotes that each MUE needs a constant minimum transmit rate to meet the corresponding service requirements.

In order to quantify the QoE utility reasonably, we use the multiplicative exponent weighting (MEW) method in defining the QoE utility function $U$(x, y) in this letter. Moreover, by weighing factors which are relevant to QoE, such as data rate and energy consumption, we can acquire a practical utility function for assessing the QoE utility of end-users. The QoE utility functional form of MUE $i$ can be further given by [8]

$$U_i(\mathrm{x},\mathrm{y}) = \prod_{k=1}^{n} [u_k(\mathrm{x},\mathrm{y})]^{w_k}, \tag{4}$$

where $n$ denotes the number of considered fnactors, $w_k$ is the weight of the user preference for factor $k$ ($\sum_{k=1}^{n} w_k = 1$) and $u_k$(x, y) is the elementary utility of factor $k$.

Without loss of generality, we simply take two factors into consideration simultaneously when measuring the QoE: *Rate Factor (RF)* and *Energy Factor (EF)*. Further, based on the functional form given in Eq. (4), the $U$(b, p) in Eq. (3) can be expressed specifically as

$$\begin{aligned} &\mathrm{U}(\mathrm{b},\mathrm{p}) \\ &=\sum_{i=1}^{M}\{[RF_i(\mathrm{b}_\mathrm{i},\mathrm{p}_\mathrm{i})]^{w_1}\cdot[EF_i(\mathrm{p}_\mathrm{i})]^{w_2}\} \\ &=\sum_{i=1}^{M}\left\{\left[\frac{r_i}{l_i}\right]^{w_1}\left[1-\frac{\sum_{j=1}^{N}p_{ij}}{P_i^{max}}\right]^{w_2}\right\} \\ &=\sum_{i=1}^{M}\left\{\left[\frac{1}{l_i}\sum_{j=1}^{N}\beta_j\,b_{ij}\log_2\left(1+\frac{g_{ij}\,p_{ij}}{b_{ij}}\right)\right]^{w_1}\left[1-\frac{\sum_{j=1}^{N}p_{ij}}{P_i^{max}}\right]^{w_2}\right\}, \quad (5)\end{aligned}$$

where $l_i$ is the upper bound of the transmit rate for MUE $i$ which can be calculated as $l_i=\log_2 e\cdot P_i^{\max}\sum_{j=1}^{N}g_{ij}$. In terms of the QoE measurement in the objective function given in Eq.(5), $w_1$ and $w_2$ are the weight parameters of two considered factors with $w_1+w_2=1$ based on their emphasis on $RF$ and $EF$. The value of $w_1$ is increasing with the emphasis on transmit rate. On the other hand, the value of $w_2$ denotes the significance of energy consumption with a positive correlation.

Before proceeding further, we can prove that the objective function in Eq. (5) is concave with respect to {b, p}. In the meantime, the constraints of $(c_1)\sim(c_3)$ are concave or linear with respect to b or p. This signifies that an optimal solution can be found by the relevant convex optimization method, where a local maxima is also the global maxima [9].

## IV. QOE-DRIVEN RADIO RESOURCE ALLOCATION

### A. Optimal Resource Allocation

According to our discussion, the QoE utility maximization problem can be solved by a proper convex optimization method due to its concavity. The Lagrangian function of the optimiza-tion model given by Eq. (3) with constraints $(c_1)\sim(c_4)$ can be further obtained by

$$\begin{aligned} &L(b_{ij},p_{ij};\lambda_j,\mu_i,\omega_i) \\ &=\sum_{i=1}^{M}\left\{\left[\frac{1}{l_i}\sum_{j=1}^{N}\beta_j\,b_{ij}\log_2\left(1+\frac{g_{ij}\,p_{ij}}{b_{ij}}\right)\right]^{w_1}\left[1-\frac{\sum_{j=1}^{N}p_{ij}}{P_i^{max}}\right]^{w_2}\right\} \\ &\quad+\sum_{j=1}^{N}\lambda_j\left(\mathrm{B}_j^{max}-\sum_{i=1}^{M}b_{ij}\right)+\sum_{i=1}^{M}\mu_i\left(P_i^{max}-\sum_{j=1}^{N}p_{ij}\right) \\ &\quad+\sum_{i=1}^{M}\omega_i\left[\sum_{j=1}^{N}\beta_j\,b_{ij}\log_2\left(1+\frac{g_{ij}\,p_{ij}}{b_{ij}}\right)-R_i^{min}\right]. \quad (6)\end{aligned}$$

In the Lagrangian function given in Eq. (6), the shadow prices $\lambda_j$, $\mu_i$ and $\omega_i$ are nonnegative Lagrange multipliers for constraints $(c_1)\sim(c_3)$. To solve the problem, we need take derivatives with respect to $b_{ij}$ and $p_{ij}$ respectively at the specific value of $i$ and $j$ in Eq. (6).

Meanwhile, based on the Lagrangian function of the primal problem expressed by Eq. (6), we can obtain its dual problem as follows[9]:

$$D(\lambda_j,\mu_i,\omega_i)=\sup_{b_{ij}\geq 0,\,p_{ij}\geq 0} L(b_{ij},p_{ij};\lambda_j,\mu_i,\omega_\mathrm{i}). \quad (7)$$

According to the convex optimization analysis, strong duality holds between the primal problem and its dual problem due to the concavity of the primal problem, where the optimal duality gap is zero. This means that the best bound which can be obtained from the Lagrange dual function is tight. Thus the optimal solution can always be acquired by solving its dual problem given in Eq. (7) without any performance loss. Therefore, in the following proposed algorithm, we can use the gradient-based method to approach to the optimal solution, which is proved to be feasible if the iterative step size is appropriately set. In this letter, we apply the gradient projection method to obtain the optimal values of bandwidth and power, because it converges faster towards a local maxima compared with other non-gradient methods. To be specific, the update expressions for bandwidth and power can be obtained respectively by

$$b_{ij}^{k+1}=\left[b_{ij}^{k}+\delta\frac{\partial L}{\partial b_{ij}}\right]^{+},\ \forall i,j, \quad (8)$$

$$p_{ij}^{k+1}=\left[p_{ij}^{k}+\varepsilon\frac{\partial L}{\partial p_{ij}}\right]^{+},\ \forall i,j, \quad (9)$$

where $[x]+=\max\{x,0\}$ and $\delta$, $\varepsilon$ are the step sizes for primal variable $b_{ij}$, $p_{ij}$ respectively. As long as the step sizes $\delta$, $\varepsilon$ are properly chosen, the update expressions given in Eq. (8) and Eq. (9) can always converge to the optimal values of $b_{ij}$ and $p_{ij}$. To update the Lagrange multiplier values for the optimal solution, we pay attention to the continuously differentiable dual function. Likewise, by utilizing the gradient projection method, the updated nonnegative multiplier value for bandwidth and power allocation can be obtained by

$$\lambda_j^{k+1}=\left[\lambda_j^{k}+\gamma_1\frac{\partial D}{\partial\lambda_j^{k}}\right]^{+}=\left[\lambda_j^{k}+\gamma_1\left(\sum_{i=1}^{M}b_{ij}^{k}-B_j^{max}\right)\right]^{+}, \quad (10)$$

$$\mu_i^{k+1}=\left[\mu_i^{k}+\gamma_2\frac{\partial D}{\partial\mu_i^{k}}\right]^{+}=\left[\mu_i^{k}+\gamma_2\left(\sum_{j=1}^{N}p_{ij}^{k}-P_i^{max}\right)\right]^{+} \quad (11)$$

$$\begin{aligned}\omega_i^{k+1}&=\left[\omega_i^{k}+\gamma_3\frac{\partial D}{\partial\omega_i^{k}}\right]^{+} \\ &=\left[\omega_i^{k}+\gamma_3\left(\sum_{j=1}^{N}\beta_j\,b_{ij}^{k}\log_2\left(1+\frac{g_{ij}\,p_{ij}^{k}}{b_{ij}^{k}}\right)-R_i^{min}\right)\right]^{+}, \quad (12)\end{aligned}$$

where $\gamma = \{\gamma_1, \gamma_2, \gamma_3\}$ is a step size vector. By taking iterations, we can finally solve the optimization problem of the MRAT system in HetNets, which achieves our goal of maximizing total end-users' QoE utility.

### B. Proposed QoE-Driven Algorithm

The outline of our proposed QoE-driven radio resource allocation algorithm for MRAT systems in HetNets is illustrated in **Algorithm 1**. In our proposed algorithm, the gradient projection method is applied as a basic approach for solving the optimization problem. Through appropriate iterations, the proposed algorithm can achieve the dynamic radio resource allocation for MUEs which need to meet the corresponding service requirements and transmission constraints.

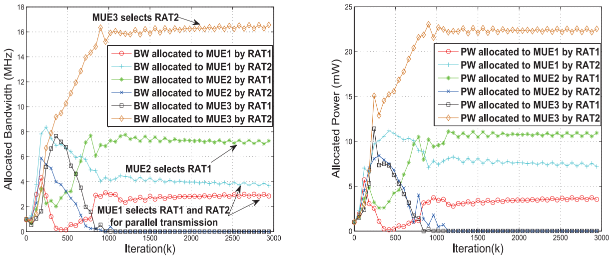
**Algorithm 1:** QoE-Driven Resource Allocation Algorithm

```
Input:
    $\delta, \varepsilon$ (constant step size for primal variable);
    $\gamma = \{\gamma_1, \gamma_2, \gamma_3\}$ (constant step size for dual variable);
    $b_{ij}^0, p_{ij}^0, \lambda_j^0, \mu_i^0, \omega_i^0$ (initial value for iteration);
    $\epsilon_1, \epsilon_2$ (convergence precision);
    $K$ (maximum iteration number).
Output:
    $b_{ij}^{k+1}, p_{ij}^{k+1}$ (the optimal value for transmission).
Initialize $\delta, \varepsilon, \gamma = \{\gamma_1, \gamma_2, \gamma_3\}$.
for ($k = 0, k \leq K$) do
    if $k = 0$ then
        Initialize $b_{ij}^0, p_{ij}^0, \lambda_j^0, \mu_i^0, \omega_i^0$;
    else
        Compute $b_{ij}^{k+1}, p_{ij}^{k+1}$ by gradient projection;
        $b_{ij}^{k+1} = \left[b_{ij}^k + \delta \frac{\partial L}{\partial b_{ij}}\right]^+, \forall i, j$
        $p_{ij}^{k+1} = \left[p_{ij}^k + \varepsilon \frac{\partial L}{\partial p_{ij}}\right]^+, \forall i, j$
        if $(|b_{ij}^{k+1} - b_{ij}^k| \leq \epsilon_1, |p_{ij}^{k+1} - p_{ij}^k| \leq \epsilon_2) \| (k = \mathrm{K})$ then
            Transmit data with RAT(s) using $b_{ij}^{k+1}, p_{ij}^{k+1}$;
            Loop end;
        else
            Update $\lambda_j^{k+1}, \mu_i^{k+1}, \omega_i^{k+1}$ using $b_{ij}^{k+1}, p_{ij}^{k+1}$;
            $\lambda_j^{k+1} = [\lambda_j^k + \gamma_1(\sum_{i=1}^{M} b_{ij}^{k+1} - B_j^{max})]^+$
            $\mu_i^{k+1} = [\mu_i^k + \gamma_2(\sum_{j=1}^{N} p_{ij}^{k+1} - P_i^{max})]^+$
            $\omega_i^{k+1} = [\omega_i^k + \gamma_3(\sum_{j=1}^{N} \beta_j b_{ij}^{k+1} \log_2(1 + \frac{g_{ij} p_{ij}^{k+1}}{b_{ij}^{k+1}}) - R_i^{min})]^+$
            $k \leftarrow k + 1$
return $b_{ij}^{k+1}, p_{ij}^{k+1}$.
```

Moreover, our optimization problem is solved in a distributed manner by the proposed algorithm, where the optimal allocation value of $b_{ij}$ and $p_{ij}$ is determined by each MUE instead of RAT subsystem. Therefore, this algorithm also manifests the pos-sibility and reasonability of a distributed optimization method for MRAT system, while guaranteeing the global QoE utility maximization. In addition, the complexity of the proposed algorithm is relevant to the number of MUEs and RATs, and its performance is affected by the initial value for iteration as well as the step size.

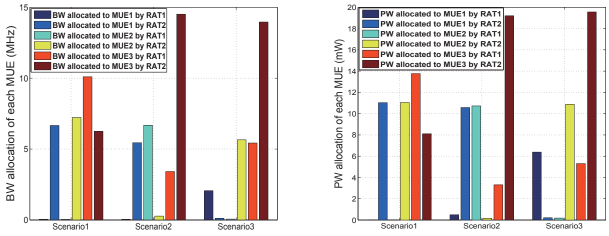
## V. SIMULATION RESULTS

We simulate an MRAT system consisting of two RAT subsystems. We assume that there is a cellular base station and a wireless access point deployed in our MRAT system, where the coverage area is partially overlapping. Meanwhile, the total subsystem bandwidth (i.e. $B_j^{max}$, $j = 1, 2$) for cellular base station and wireless access point are set to be 10MHz and 20MHz, respectively, with a reasonable spectral efficiency (i.e. $\beta_j$ , $j = 1, 2$ : $\beta_1 = 0.4$, $\beta_2 = 0.6$). In terms of different kinds of MUEs, the constraints of the maximum transmit power (i.e. $P_i^{max}$) are ranged from 10mW to 25mW and the minimum data rate requirements (i.e. $R_i^{min}$) of their services vary from 0.1Mbps to 1Mbps, which is based on the practical communication scenario [3]-[5].



(a) bandwidth allocation (b) power allocation

**Fig.2.** The convergent solution of the proposed algorithm



(a) bandwidth allocation (b) power allocation

**Fig.3.** The optimal allocation under different scenarios

In Fig.2(a), there are 3 MUEs with maximum power constraints of 12mW, 12mW, 24mW, respectively, and the *RF* is equally treated with the *EF* when measuring QoE (i.e. $w_1 = w_2 = 0.5$). The proposed algorithm can converge to the optimal solution of MUEs transmit bandwidth with sufficient iterations under this simplified scenario. From Fig.2(b), we observe that our QoE-driven algorithm can also acquire optimal MUEs transmit power by iterating to its stable solution. As a result, our QoE-driven allocation algorithm can efficiently allocate the bandwidth and power in an optimal manner.

The transmit bandwidth allocation in different scenarios is presented in Fig.3(a). And the allocation result of transmit power is illustrated by Fig.3(b). We consider three scenarios as shown in TABLE I. According to the distribution of factor weight in TABLE I, it is noted that the *EF* has been paid more attention in Scenario 1, while the *RF* has been attached much more emphasis in Scenario 3. In Scenario 2, we strike a balance between *RF* and *EF* when measuring the QoE of end-users.

TABLE I
TYPICAL SCENARIOS FOR MRAT SYSTEM

| **Scenario** | $w_1$ (***RF*** **weight**) | $w_2$ (***EF*** **weight**) |
|---|---|---|
| Scenario 1 (*EF* preferred) | 0.2 | 0.8 |
| Scenario 2 (balanced) | 0.5 | 0.5 |
| Scenario 3 (*RF* preferred) | 0.8 | 0.2 |

In Fig.4, we observe that our proposed QoE-driven radio resource allocation algorithm outperforms the other three semi-dynamic or static algorithms. The proposed dynamic algorithm can always achieve higher QoE utility compared with other algorithms under these typical scenarios shown in TABLE 1.

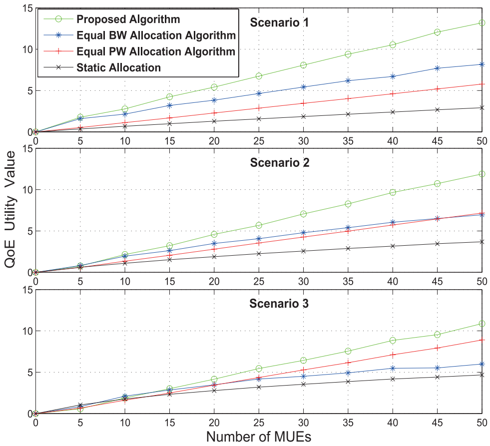


**Fig.4.** The performance comparison among different algorithms

## VI.CONCLUSIONS

In this letter, we have proposed a QoE-based joint bandwidth and power allocation method for MRAT associated HetNets. Through our effective QoE measurement, the optimal radio re-source allocation in MRAT systems has been obtained with con-sideration of both data rate and energy consumption. A QoE-driven radio resource allocation algorithm is further developed for maximizing the total QoE utility ofend-users in MRAT systems subject to the corresponding service requirements and transmission constraints. The optimal joint bandwidth and power allocation can be achieved by our proposed method so as to optimize the end-users' experience.

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