Joint Uplink Resource Allocation Algorithm with Proportional-Fair in Heterogeneous Wireless Networks

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Abstract—In this paper, we exploit the uplink radio resource allocation considering proportional fairness among users in heterogeneous wireless networks. Meanwhile, multi-mode user terminals are assumed to have the capability of using multiple radio access technologies simultaneously. To this end, a joint optimization problem is formulated for power and bandwidth allocation for uplink transmission. Since the formulated primal problem is difficult to solve directly, we make continuous relaxation and obtain a near-optimal solution using Karush-Kuhn-Tucker conditions, and then propose a joint resource allocation algorithm. Simulation results show the proposed algorithm work, and the algorithm provides superior system throughput and much better fairness among users comparing to a heuristic algorithm.

Index Terms—Heterogeneous Wireless Networks (HWNs), Proportional Fairness (PF), Radio Resource Management (RRM), Optimization

I. INTRODUCTION

With the rapid development of wireless communications, various radio access technologies (RATs), such as 2G/3G cellular, satellite, Bluetooth, LTE, LTE-Advanced, IEEE 802.11, IEEE 802.16, IEEE 802.20, are widespread deployed. These RATs have different capabilities in terms of bandwidth, latency, coverage area, load or cost. Each individual RAT cannot meet all the needs of the users. Therefore, the future of wireless communications must be the integration of such RATs, which is defined as heterogeneous wireless networks (HWNs) [1]. As the concept of HWNs has been proposed, multi-mode user equipments (UEs), which have the capability of accessing multiple access networks, appear on the market. For such cases, HWNs can help to support user roaming and lead to better service quality to mobile users.

In literature, various works have studied the related problem in heterogeneous wireless networks. Literature [1] summarized different research aspects of heterogeneous networks, such as network selection, handoff, multimedia applications [2] and radio resource management. Then, Wang concluded useful mathematical models for research of HWNs [3], including utility function method [4], game theory [5, 6], machine learning method [7] and optimization method [8-17]. Each of these models has its own difficulties. For instance, it is hard to design a reasonable utility function, or to use game theory appropriately.

Radio resource management mechanism is a very important component of the integrated HWNs. Therefore, it is meaningful to design a proper radio resource allocation scheme in order to achieve enhanced performance for the networks.

The problem of radio resource allocation in a heterogeneous wireless access medium is widely addressed. Two types of radio resource management mechanisms can be distinguished in such a heterogeneous environment [12]. This classification is based on whether a single radio interface or multiple radio interfaces of an UE are used simultaneously for the same application. The first type, which is referred to as single-network resource allocation, includes the solutions that utilize a single radio interface of each UE. In other words, each UE obtains its required data rate from a single access network at any time instant. The second type, which is referred to as multi-accessing resource allocation, includes the solutions where multiple radio interfaces of each UE are used simultaneously to satisfy the user’s data rate requirement. In other words, the UE obtains its required data rate from all wireless access networks available at its location.

For the second type, UEs implementing cognitive radio (CR) over software defined radio (SDR) [18] is considered. It is assumed that a multi-mode, multi-band UE implemented by the reconfigurable SDR technology has ability to access multi-RAT through a single or simultaneous transmissions, where spectrum bands of multi-RAT are not highly distributed. Furthermore, multi-mode, multi-band UE are considered as a CR terminal on SDR, which are capable of accessing different RATs and operating bandwidth. Meantime, it is regarded that each multi-mode, multi-band UE does not require multiple RF chains to take advantage of all these different RATs simultaneously, although each RAT occupies different
bandwidth. With the help of CR and SDR, the second mechanism is essential in order to satisfy the required data rate by UEs via different available RATs and to make efficient utilization of the available resources from these networks.

As we mentioned before, optimization method has taken lots of attention recently on the research in HWNs. Furthermore, there exist various works that study the problem of resource allocation by using optimization method, which can be further classified in two categories by transmission direction: downlink [8-11] and uplink [12-16]. In this paper, we focus on power and bandwidth allocation in uplink transmission. The existing literature [12] proposed a joint bandwidth and power resource allocation algorithm aiming at the system capacity maximization but the bandwidth is continuous. Furthermore, literatures [13-16] investigated this subject considering more constraints. In [13], the author improved the Newton iteration method for solving the optimization problem, and literature [14] considers maximum transmission power constraint. Literature [15, 16] further exploited the uplink radio resource allocation to provide an optimal solution with QoS support of different classes of service traffic, but the purpose of optimization problem is the system capacity as well, and the bandwidth allocated is continuous, which is not reasonable in practical environment.

Fairness, as well as efficiency, needs to be considered when designing radio resource allocation schemes for heterogeneous environment. Proportional fairness, which is widely adopted to maintain the transmission rate fairness among users in cellular networks [19, 20] and relay-aided networks [21], can achieve better balance between system capacity and fairness. However, considering proportional fairness, existing related research, especially about uplink radio resource management in HWNs, is very rare. Literature [9] considered max-min fairness in downlink IEEE 802.11/IEEE 802.16 integration HWNs, but the algorithm is not scalable for any HWNs.

In this paper, the multi-access resource allocation problem in heterogeneous wireless access networks is investigated. Based on the proportional-fair of UEs under the constraint of resource, we study joint bandwidth allocation and power allocation problem in uplink HWNs, and formulate the problem as a joint optimization problem. Since the problem is hard to solve directly, we make continuous relaxation and use Lagrangian dual decomposition method to solve it. Through solving the problem, the near optimal solution of primal problem is obtained.

The innovation of this paper can be summarized as the following two points: first of all, our proposed algorithm is with the purpose of maximize proportional fairness of UEs, which fills the research gap in uplink multi-accessing HWNs. Secondly, the bandwidth which is allocated to UEs from RATs must be times of resource unit (RU) bandwidth of that RAT, which is very essential for the algorithm to be implemented in the practical environment.

The rest of this paper is organized as follows. Section II describes the system model of HWNs and formulates the optimization problem. Section III analyzes the optimization resource allocation problem, then obtains near optimal solution, and presents the algorithm for this problem. Section IV presents numerical simulation results and discussions. Finally, conclusions are drawn in Section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

A geographical region covered by wireless access networks with N RATs is considered. Any of the base stations/ access points (BSs/APs) belongs to one RAT. There are M UEs randomly distributed in the region. Furthermore, it is assumed that UEs are able to support all kinds of RATs. Different networks have overlapped coverage in some areas. An exemplary scenario with three RATs is depicted in Fig. 1.

As shown in Fig. 1, UE 1 could access RAT 1, RAT 2 and RAT 3, UE 2 could access both RAT 1 and RAT 2, whereas UE 3 could only access RAT 1 for data transmission.

It is assumed that channel condition is flat during each transmission time interval. In order to transmit data, each UE should obtain bandwidth from multiple RATs, then through power allocation, $UE_m$ can get total data rate as follow.

$$R_m = \sum_{n=1}^{K} r_{mn}$$

where $r_{mn}$ is the data rate. $UE_m$ obtains from $RAT_n$, $\eta_m$ ($0 \leq \eta_m \leq 1$) [15] denotes average bit error rate from $UE_m$ to $RAT_n$, $\beta_n$ ($0 \leq \beta_n \leq 1$) [11] represents the system efficiency which can be guaranteed by $RAT_n$ to all UEs. From equation (1), $\beta_n$ defines the validity of each RAT throughput because it can express the offered system efficiency. Hence, $RAT_n$ which has a better coder and decoder scheme, can have a higher $\beta_n$ value. For instance, $\beta_n$ could be 0.6 and 0.29 for LTE (1x2) and WiMAX Wave 1, respectively [11]. $\Delta_n$ is resource unit
(RU) bandwidth of RAT\textsubscript{n}, \( K \) is the number of RUs that RAT\textsubscript{n} allocate to UE\textsubscript{m}, \( p_{mn}^\delta \) denotes the transmission powers from UE\textsubscript{m} to RAT\textsubscript{n} spent on subcarrier \( k \). And \( g_{mn}^k \) represents the normalized channel gain between UE\textsubscript{m} and RAT\textsubscript{n} over subcarrier \( k \), which can be calculated as

\[
g_{mn}^k = \frac{l_{mn}^{\delta} |h_{mn}^k|^2}{N_r_{mn}},
\]

where \( h_{mn}^k \) represents the small-scale fading coefficient between UE\textsubscript{m} and RAT\textsubscript{n} on subcarrier \( k \). The path loss from UE\textsubscript{m} to RAT\textsubscript{n} is \( l_{mn} \). \( N_r_{mn} \) denotes noise power spectral density.

Assuming that only path loss is considered, and the RUs that RAT\textsubscript{n} allocate to UE\textsubscript{m} are adjacent. Let \( g_{mn} = g_{mn}^k \), therefore, the data rate of UE\textsubscript{m} can be rewritten as

\[
R_m = \sum_{n=1}^{N} R_{mn} = \sum_{n=1}^{N} \left( 1 - \eta_{mn} \right) \beta_{x_m} \log_2 \left( 1 + g_{mn} p_{mn} x_m \right),
\]

where \( x_m \) is allocated bandwidth to UE\textsubscript{m} from RAT\textsubscript{n}, and \( p_{mn} \) is transmission power of UE\textsubscript{m} to RAT\textsubscript{n}.

B. Problem Formulation

Having the system model introduced, we now present the formal problem formulation. In addition, proportional fairness problem can be formulated as maximizing the sum of logarithmic user data rate [16], so that the optimization problem that we focus on can be formulated as Problem (P1).

\[
\text{(P1):} \quad \max \sum_{m=1}^{M} \ln R_m = \max \sum_{m=1}^{M} \ln \left( \sum_{n=1}^{N} R_{mn} \right)
\]

\[
= \max \sum_{m=1}^{M} \ln \left( \sum_{n=1}^{N} \left( 1 - \eta_{mn} \right) \beta_{x_m} \log_2 \left( 1 + g_{mn} p_{mn} x_m \right) \right),
\]

s.t. \( a) \sum_{m=1}^{M} x_m \leq X, \forall n \)

\( b) \sum_{n=1}^{N} p_{mn} \leq P, \forall m \)

\( c) x_m, p_{mn} \geq 0, \forall m, n \)

\( d) x_m = t \Delta, t \in \left\{ 0, 1, \ldots, \left\lfloor \frac{X}{\Delta} \right\rfloor \right\}, \forall m, n \)

where \( X \) and \( P \) stand for the total system bandwidth of RAT\textsubscript{n}, and maximum transmission power of UE\textsubscript{m}, respectively. Constraint d) guarantees that bandwidth that allocated to UE\textsubscript{m} from RAT\textsubscript{n} has to be times of RU bandwidth of RAT\textsubscript{n}. The inequality a) and b) denote that there is a total system bandwidth of each RAT and transmission power constraint of each UE due to resource finiteness.

However, Problem (P1) is a mixed integer programming problem, which is nondeterministic polynomial time complete. An exhaustive search of the problem space is needed to find the optimal solution, but it is infeasible in practice. To make Problem (P1) tractable, we relax \( x_m \) to be a real number without constraint d). Therefore, we can obtain problem as Problem (P2).

Problem (P2) is convex, consequently, a variety of ready-to-use algorithms exists to solve it [22], and local optimal solution is the global optimal solution. Then, we further could solve Problem (P1). The details are in next section.

\[
\text{(P2):} \quad \max \sum_{m=1}^{M} \ln R_m = \max \sum_{m=1}^{M} \ln \left( \sum_{n=1}^{N} R_{mn} \right)
\]

\[
= \max \sum_{m=1}^{M} \ln \left( \sum_{n=1}^{N} \left( 1 - \eta_{mn} \right) \beta_{x_m} \log_2 \left( 1 + g_{mn} p_{mn} x_m \right) \right),
\]

s.t. \( a) \sum_{m=1}^{M} x_m \leq X, \forall n \)

\( b) \sum_{n=1}^{N} p_{mn} \leq P, \forall m \)

\( c) x_m, p_{mn} \geq 0, \forall m, n \)

III. PROPORTIONAL-FAIR JOINT RESOURCE ALLOCATION ALGORITHM

A. Solution of Problem (P2)

The lagrangian function of Problem (P2) is first given by:

\[
L(x, p; \lambda, \mu) = \sum_{m=1}^{M} \ln \left( \sum_{n=1}^{N} \left( 1 - \eta_{mn} \right) \beta_{x_m} \log_2 \left( 1 + g_{mn} p_{mn} x_m \right) \right) + \sum_{n=1}^{N} \lambda_n \left( X - \sum_{m=1}^{M} x_m \right) + \sum_{n=1}^{N} \mu_n \left( P - \sum_{m=1}^{N} p_{mn} \right) - \sum_{n=1}^{N} \lambda_n x_m - \mu_n \left( \sum_{m=1}^{M} p_{mn} - \mu_n P_m \right) + \sum_{n=1}^{M} \lambda_n X_n
\]

where \( \lambda = [\lambda_1, \lambda_2, \ldots, \lambda_N] \) and \( \mu = [\mu_1, \mu_2, \ldots, \mu_N] \) are nonnegative Lagrange multipliers for the constraints a) and b), respectively.

By using Karush-Kuhn-Tucker (KKT) conditions [22], we can obtain

\[
\frac{\partial L}{\partial x_m} = \frac{1}{R_m} (1 - \eta_{mn}) \beta_{x_m} \log_2 \left( 1 + g_{mn} p_{mn} x_m \right) - \frac{g_{mn} p_{mn}}{x_m + g_{mn} p_{mn}} \lambda_n \leq 0,
\]

\[
\frac{\partial L}{\partial \lambda_n} = X - \frac{1}{R_m} \sum_{m=1}^{M} \left( 1 - \eta_{mn} \right) \beta_{x_m} \log_2 \left( 1 + g_{mn} p_{mn} x_m \right) - \mu_n P_m \mu_n \leq 0,
\]

\[
\frac{\partial L}{\partial \mu_n} = P - \sum_{m=1}^{N} p_{mn} \mu_n \mu_n \leq 0.
\]
\[
\frac{\partial L}{\partial p_m} = \frac{1}{R_m} (1 - \eta_m) \beta_n \left( \frac{g_m p_m}{x_m + g_m p_m} \right) \ln 2 - \mu_m \leq 0
\]

\[
x_m = \frac{1}{R_m} \frac{(1 - \eta_m) \beta_n \left( 1 + \frac{g_m p_m}{x_m + g_m p_m} \right) \ln 2} - \lambda_n = 0, \quad \text{(9)}
\]

\[
p_m = \frac{\partial L}{\partial p_m} = p_m \left( \frac{1}{R_m} (1 - \eta_m) \beta_n \left( \frac{g_m p_m}{x_m + g_m p_m} \right) \ln 2 - \mu_m \right) = 0
\]

\[
\lambda_n \left( X_n - \sum_{m=1}^{M} x_m \right) = 0, \quad \text{(11)}
\]

\[
\mu_m \left( P_m - \sum_{n=1}^{N} p_m \right) = 0. \quad \text{(12)}
\]

Then, using equations (8) and (10), the relation between bandwidth allocation \(x_m\) and power allocation \(p_m\) can be obtained as:

\[
p_m = x_m^* \left[ \frac{(1-\eta_m) \beta_n}{\ln 2 \cdot R_m \mu_m} \frac{1}{g_m} \right]^+, \quad \text{(13)}
\]

where \([\cdot]^+ = \max\{z, 0\}\).

From equation (13), in order to get the optimal \(x_m, \forall m, n\) and \(p_m, \forall m, n\) solution, we need to have one to them at least. Therefore, we utilize the gradient method [22] to update the bandwidth allocation \(x_m, \forall m, n\) as follows:

\[
x_m^{\theta+1} = x_m^\theta - \alpha \left( \frac{\partial L}{\partial x_m} \right), \quad \forall m, n \quad \text{(14)}
\]

where \(\theta\) is the iteration index, and \(\alpha\) is the step size, which is converge to optimal value as long as it is appropriately chosen [22]. After \(x_m, \forall m, n\) is obtained, \(p_m, \forall m, n\) then can be determined by using expression (13).

Therefore, we use the gradient method to update the Lagrange multipliers \(\lambda = [\lambda_1, \lambda_2, ..., \lambda_n]\) and \(\mu = [\mu_1, \mu_2, ..., \mu_n]\) for the optimal solution as equations (15) and (16).

\[
\lambda_n^{\theta+1} = \lambda_n^\theta - \alpha \left( X_n - \sum_{m=1}^{M} x_m \right)^+, \quad \forall n
\]

\[
\mu_m^{\theta+1} = \mu_m^\theta - \alpha \left( P_m - \sum_{n=1}^{N} p_m \right)^+, \quad \forall m
\]

where \(\theta\) is the iteration index, the same as expression (14), \(\alpha_\lambda\) and \(\alpha_\mu\) the step sizes for \(\lambda = [\lambda_1, \lambda_2, ..., \lambda_n]\) and \(\mu = [\mu_1, \mu_2, ..., \mu_n]\), respectively. Convergence to the optimal solution is guaranteed by choosing appropriate step sizes [22].

B. Solution of Problem (P1)

In order to obtain solution of prime Problem (P1), the bandwidth allocation \(x_m, \forall m, n\), calculated by last subsection, need to be adjusted to satisfy the constraint condition d) in expression (4). The bandwidth adjustment process (BAP) we proposed can be described as the following four steps:

Step 1: Based on III.A, \(x_m, \forall m, n\) and \(p_m, \forall m, n\) are obtained;

Step 2: Adjust \(x_m, \forall m, n\) due to constraint d) by:

\[
x_m = \frac{x_m}{\Delta_n} \cdot \Delta_n, \forall m, n
\]

Step 3: Calculate available system bandwidth of \(RAT_n, \forall n\) by

\[
X_n = X_n - \sum_{m=1}^{M} x_m, \forall n
\]

Step 4: \(RAT_n, \forall n\) should assign RU to \(UE_n\), which could have most increment of \(\ln R_n\) until available system bandwidth \(X_n\) less than one RU, which is in accord with proportional fairness:

For \(RAT = 1: N\) When \((X_n \geq \Delta_n)\)

Choose \(UE_n\) which satisfies:

\[
m^* = \arg \max_{n=1, ..., M} \left( \ln R_n \left( p_m + \Delta_n \right) - \ln R_n \left( p_m + x_m \right) \right)
\]

Allocate one RU to \(UE_n\), and update the bandwidth allocation and available system bandwidth as:

\[
x_m = x_m \Delta_n, \quad X_n = X_n - \Delta_n
\]

C. The Proposed Joint Bandwidth and Power Allocation Algorithm

In the solution described in III.A, we can see from equations (7), (13) and (14), that for \(UE_n\), both the bandwidth allocation result \(x_m\) and power allocation result \(p_m\) are related to \(R_n\), while \(R_n\) is also the function with respect to \(x_m\) and \(p_m\). Therefore, \(x_m\) and \(p_m\) should be obtained by an iterative method. In this paper,
the method of updating $R_m$ iteratively as expression (21) is adopted.

$$ R_{m}^{l+1} = R_{m}^{l} - \xi \left( R_{m}^{l} - \sum_{n=1}^{N} (1 - \eta_{mn}) \beta_{mn} \log \left( 1 + \frac{g_{mn}P_{mn}}{x_{mn}} \right) \right), \quad (21) $$

where $l$ is the rate iteration index, and $\xi \in (0, 1)$ are sequences of step sizes of $\{R_{m}^{l}\}$. Convergence is guaranteed when the sequences of step sizes are chosen properly [22].

According to the analysis described before, our proposed joint bandwidth and power allocation algorithm can be summarized in Table 1. Note that only updating Lagrange multipliers $\lambda = [\lambda_1, \lambda_2, ..., \lambda_N]$ should be in RATs, but other calculations in our proposed algorithm are all in UEs.

### Table 1. The Proposed Joint Resource Allocation Algorithm

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>Initialize iterations index $\theta = 0$, step size $\alpha_1, \alpha_2$ and $\alpha_3$ with nonnegative values, and $p_{mn}, \forall m, n$ with nonnegative values; Update the channel condition parameters $g_{mn}, \forall m, n$ and estimate system average bit error rate parameters $\eta_{mn}, \forall m, n$;</td>
</tr>
<tr>
<td>Step 2</td>
<td>Initialize rate iteration index $l = 0$, and $R_{m}^{l}, \forall m$ with nonnegative values;</td>
</tr>
</tbody>
</table>
| Step 3 | For UE $m = 1:M$ 
For RAT $n = 1:N$ 
Update $s_{mn}, \forall m, n$ via equation (14); 
Calculate $p_{mn}, \forall m, n$ based on equation (13); 
End For 
End For 
For UE $m = 1:M$ 
Update $R_{m}, \forall m$ according to equation (21); 
End For |
| Step 4 | Update rate iteration index $l = l + 1$, repeat Step 3 until $R_{m}, \forall m$ converge; |
| Step 5 | Update $\lambda_1$ and $\mu_{mn}$ based on equation (15) and (16), respectively; |
| Step 6 | Let iterations index $\theta = \theta + 1$, go back to step 2 until $s_{mn}, \forall m, n$ converge; |
| Step 7 | Apply Bandwidth Adjustment Process (BAP), described in III.B, then UEs could transmit data to the RATs using $s_{mn}, p_{mn}, \forall m, n$. |

IV. PERFORMANCE EVALUATION

A. Simulation Parameters

In simulation, the geographical region with $N=3$, which is entirely covered by RATs = 3G IEEE 802.16, RATs = LTE, and RATs = IEEE 802.11b is considered. Assume that all the RATs have same efficiency. The M UEs are randomly distributed in this region. A mobility model with UEs moving according to a random walk model inside the coverage area is adopted with a randomly assigned UE mobility rate [0, 3 km/h] and a randomly chosen direction. Channel fading is randomly chosen. The remaining simulation parameters are listed in Table 2. Numerical performance evaluation results are averaged over 1000 times repeated simulations. Every time, all UEs are relocated.

### Table 2. Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$RAT_1$</td>
<td>total system bandwidth $X_1$</td>
<td>10</td>
</tr>
<tr>
<td>$RAT_2$</td>
<td>total system bandwidth $X_2$</td>
<td>10</td>
</tr>
<tr>
<td>$RAT_3$</td>
<td>total system bandwidth $X_3$</td>
<td>16.6</td>
</tr>
<tr>
<td>$RAT_{31}$</td>
<td>RU bandwidth $\Delta_1$</td>
<td>525.12</td>
</tr>
<tr>
<td>$RAT_{32}$</td>
<td>RU bandwidth $\Delta_2$</td>
<td>575</td>
</tr>
<tr>
<td>$RAT_{33}$</td>
<td>RU bandwidth $\Delta_3$</td>
<td>312.5</td>
</tr>
<tr>
<td>$RAT_{1}$</td>
<td>system efficiency $\beta_1$</td>
<td>1</td>
</tr>
<tr>
<td>$RAT_{2}$</td>
<td>system efficiency $\beta_2$</td>
<td>1</td>
</tr>
<tr>
<td>$RAT_{3}$</td>
<td>system efficiency $\beta_3$</td>
<td>1</td>
</tr>
<tr>
<td>$U_{max}$</td>
<td>maximum TX power $P_{max, \forall m}$</td>
<td>20</td>
</tr>
<tr>
<td>Noise power spectral density $N_{0, \forall m}$</td>
<td>$-174$ dBm/Hz</td>
<td></td>
</tr>
<tr>
<td>Average bit error rate $\eta_{mn}, \forall m, n$</td>
<td>$(10^{-1}, 1)$</td>
<td></td>
</tr>
<tr>
<td>Number of UEs</td>
<td>$M$</td>
<td>14/2:24</td>
</tr>
</tbody>
</table>

B. Results and Analysis

An example for our proposed solution without bandwidth adjustment process.

Illustrations of corresponding Lagrange multipliers $\lambda = [\lambda_1, \lambda_2, ..., \lambda_N]$ and $\mu = [\mu_1, \mu_2, ..., \mu_N]$, when the proposed algorithm without bandwidth adjustment process is applied, are in Fig. 2 and Fig. 3, respectively. Particularly, HWNs with $M=30$. It can be seen that $\lambda$ of 3G, LTE and WLAN, $\mu$ of UEs (e.g. UE 1, UE 12, UE 23 for example) can converge to the optimal solutions, which guaranteed by choosing appropriate step sizes. As a result, our proposed algorithm without bandwidth adjustment process is feasible and can efficiently converge to the global optimal solution.

![Figure 2](image-url)
UE. From the results, it can be seen that UE 2 uses all of three RATs for data transmission. The data rates converge to a unique solution, which are jointly determined by bandwidth and power convergent values.

Even though our proposed Algorithm without Step 7 might be rather complex and costly to implement, it could be utilized as an upper bound reference on the achievable gains in HWNs.

In simulation, we will show the performance of the algorithms from two aspects: system capacity and UEs fairness.

Here, system capacity is defined as the sum data rate of all the UEs. Proportional fairness between UEs is validated by Fairness Index (FI) function [23], which is defined as:

$$FI = \frac{\left(\sum_{n=1}^{M} R_{n}\right)^{2}}{M \sum_{n=1}^{M} R_{n}^{2}}$$

(22)

Performance comparison of different algorithms

For comparison, we evaluate the performance of multi-RAT HWNs using different algorithms besides our proposed algorithm.

The comparing algorithms are given below:

Scheme 1: Our proposed algorithm without bandwidth adjustment process.

Scheme 2: Algorithm in literature [12]: It provides the optimal solution with aiming at maximizing system capacity, but bandwidth allocation is continuous value.

Scheme 3: Based on Scheme 2, and add bandwidth adjust process.

Scheme 4: A heuristic algorithm: power allocation applies water-filling, while RATs allocate bandwidth to UEs equally.

Scheme 5: Based on Scheme 4, and add bandwidth adjust process.

The system capacity versus the number of UEs is illustrated in Fig. 5. Since more UEs lead to larger multiuser diversity gain, it can be observed that with the increase of the UE numbers, the system capacity increases in all the six schemes. We can also observe that Scheme 2 can always obtain the best system capacity because it obtains the optimal solution for maximum capacity. Meanwhile, Scheme 1, which is our proposed algorithm without bandwidth adjustment process, provides the second best capacity, which gives the upper bound performance for proportional-fair problems. Our proposed algorithm outperforms Scheme 5 because it considers jointly resource allocation. From another side, we can see that all the schemes with bandwidth adjust process suffer system capacity loss, the reason it that bandwidth is times of RU.
With regard to fairness, from Fig. 6, we can observe that Scheme 1, which is our proposed algorithm without bandwidth adjustment process, achieves the highest FI versus the number of UEs. Our proposed algorithm achieves the lower FI and system capacity than Scheme 1, but much better FI than the others algorithms. As shown in Fig. 6, the FI of our proposed algorithm is stable regardless of the number of UEs. From another side, we can see that all the schemes with bandwidth adjust process obtain better the FI between UEs. The reason is that the bandwidth adjustment process we proposed considers proportional fairness. The simulation results demonstrate the validity of bandwidth adjust process.

To sum up, even though our proposed algorithm might be rather complex, and costly to implement, it could be utilized as an upper reference on the achievable gains before bandwidth adjust process. When regarding to BAP, utilized as an upper reference on the achievable gains could be rather complex, and costly to implement, it could be considering FI.

V. CONCLUSIONS

The joint resource allocation algorithm for multi-access in uplink heterogeneous wireless networks is proposed in this paper, which fills the gap exploiting the uplink radio resource management considering proportional fairness in HWNs. We investigated the problem of maximizing the proportional-fair of UEs, while subjecting to resource constraints. Compared to existing related research, the research in this paper has the following features. Firstly, it considers proportional fairness, and joint resource allocation problem in the condition that UEs can obtain the data rate from all the available networks simultaneously. Secondly, the bandwidth which is allocated to UEs from RATs must be times of resource unit bandwidth of that RAT, which is very essential for the algorithm to be implemented in a practical environment. The performed simulations confirm that, our proposed solution before bandwidth adjust process could be utilized as upper bound reference, and compared to the existing other algorithms, the proposed algorithm could achieve higher proportional fairness between UEs, and obtain a better balance between system capacity and fairness as well.

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REFERENCES


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