Adaptive BU Association and Resource Allocation in Integrated PON-WiMAX Networks

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Abstract. This paper addresses the issue of base station user association and resources allocation (BUA-RA) in OFDM-TDMA-based broadband wireless access (BWA) networks under PON-WiMAX integration. With the powerful coordination capability at the optical line terminal (OLT), a key technology of inter-cell collaborative transmission (CT) is incorporated in the integrated network architecture, which is so called cooperative PON-WiMAX network (CPWN). To achieve an efficient integration and inter-cell CT in the CPWNs, BUA-RA is critical to the Quality of Service (QoS) provisioning for each user. In order to minimize the network resource usage, we provide three new BUA-RA schemes, which can be adaptively applied according to the network loads and wireless users' moving speeds. Simulations are conducted to verify the proposed BUA-RA schemes by comparing with those without CT technology and to demonstrate the efficiency of the proposed mathematical formulations and linearization approach.

Keywords: adaptive control, resource assignment, cooperative transmission.

1 Introduction

The next-generation broadband wireless access (NG-BWA) network, such as 3GPP LTE [1], IMT-Advanced [2], or IEEE 802.16m [3], is defined as a high data rate, low delay, and high speed mobility IP based mobile telecommunication system. A novel research paradigm for broadband Fixed/Mobile Convergence (FMC) is initiated by integrating WiMAX and Passive Optical Networks (PONs) at both industry and academia [4] to build such an NG-BWA network. By virtue of the tree topology and point-to-multipoint (P2MP) architecture of the PONs, the deployment and maintenance cost of fibers can be reduced significantly compared with that of traditional point-to-point networks without sacrificing the transmission bandwidth. The cost and performance advantages of a PON make it desirable to serve as the network backhaul

for connecting multiple Optical Network Units (ONUs). The WiMAX is concatenated with the PON by integrating a Base Station (BS) with an ONU such that service coverage extension and superb support of user mobility can be achieved with fast, easy and cost-effective deployment. In the integrated Fiber and Wireless (FiWi) network architecture; we study the issues of BS-user association and resource allocation (BUA-RA) to achieve the following three basic targets of the NG-BWA network: 1) wireless spectrum utilization increase; 2) mobile coverage extension and data rate improvement, especially the users at the edge of a cell; 3) transmission delay decrease.

Orthogonal frequency division multiplexing (OFDM) is a frequency division multiplexing (FDM) scheme utilized as a digital multi-carrier modulation technique. The data is divided into several parallel data streams or channels, one for each sub-carrier. The primary advantages of OFDM are efficient wireless frequency usage, eliminating inter-symbol interference (ISI), low complexity of implement and multiple-input and multiple-output (MIMO)-applicableness. Combining OFDM with time division multiple access (TDMA) or frequency division multiple access (FDMA), two basic multiple access techniques, OFDM-TDMA and OFDMA, are adopted by the IEEE 802.16e standard [5] as two options.

Cooperative transmission (CT) technology is taken as a popular approach for coverage extension and throughput enhancement in wireless networks [6]. The collaboration among distributed BSs is supported by the centralized coordination at the optical line terminal (OLT) by using the space-time coding technique. The integrated PON and WiMAX network that incorporates inter-cell CT technology is called *Cooperative PON-WiMAX network* (*CPWN*) in this paper. With inter-cell CT, the data segments are coded with different space-time codes in the associated BSs. These orthogonal space-time codes are then transmitted to the receiver where the same copy or a portion of the data can be aggregated and jointly decoded. In this way, the end-users' signal to interference plus noise ratio (SINR) can be improved significantly. We aim to exploit the significant performance benefits due to inter-cell CT to achieve the aforementioned targets of the NG-BWA network.

With the powerful computation and control capabilities at the OLT and the high speed optical connection between BSs and OLTs, the whole CPWN network status, such as channel status information (CSI), the bandwidth utilization of each BS, the rate requirement of each end-user, can be updated dynamically. The issues of BUA-RA are critical to the Quality of Service (QoS) provisioning for each user as well as the integrated network performance in terms of capacity. In CPWN, the OLT can execute adaptive resource allocation which also takes into account interference cancellation and optimal connection admission control, etc.

In this research, we propose three new BUA-RA schemes to minimize the network resource usage. These three different BUA-RA schemes are designed for three kinds of users respectively with different moving speed in the CPWN. They are static subscriber (SS), portable subscriber (PS) with walking speed and mobile subscriber (MS) with driving speed. Adaptively choosing one of the three CT BUA-RA schemes based on different moving speeds of users and network loads can achieve a near-optimal BU association and resources allocation solution. We first provide an optimal BUA-RA scheme (CT_LP) with CT technology. In the scheme, a multi-user nonlinear

optimal model is provided with the objective of minimizing time slots usage, and then it is linearized to a linear programming (LP) model which can be solved by LP solver. Then, we introduce two new fast single user BUA-RA schemes, i.e. H_CT_LP and H_CT schemes, which are suitable for real-time operations.

The remainder of the paper is organized as follows. Section 2 gives an overview of the related work about fiber-wireless access network and OFDM wireless network management. Section 3 describes the system model of a CPWN. The proposed BUA-RA schemes are provided in section 4. Simulation results and analyses of the BUA-RA schemes are in section 5. Conclusion is given in section 6.

2   Related Works

Research on either optical or broadband wireless access network has been extensively reported in the past. A few research efforts have been reported on the integration of the two networks [4], [7-12]. In [4], the wireless-optical broadband-access network (WOBAN) was described as a promising architecture for next-generation mobile access networks. The authors reviewed some hot optical and wireless access technologies, such as EPON, GPON, Wi-Fi and WiMAX. A novel hybrid WOBAN architecture was presented in their paper; based on it, they compared some BSs placement and routing algorithms. In [7], a framework on integration of EPON and WiMAX for broadband FMC access was proposed, in which the research issues on the MAC layer and integrated control plane were elaborated. An optimal BS placement model in integrated EPON-WiMAX networks was developed in [8], where CT was also incorporated, and bandwidth and power breakdown assignment were jointly considered in the initial long-term network planning and dimensioning phase. In [9], two BU association schemes were put forward for two cases: 1) BS allocates the same time to its users and 2) BS allocates the same throughput to its users. The results showed that the first case was better than the second in terms of fairness and efficiency. In [10], two BS selection algorithms were presented in cooperative cellular network, namely, a genetic-based approach and a sphere decoder inspired approach. Nevertheless, few researches of BU association algorithms have jointly taken resource allocation into account.

In the past ten years, a plethora of resource management schemes have been proposed for various OFDM systems. In [11], an adaptive subcarrier-bit-and-power allocation algorithm was proposed to achieve a dramatic gain in power efficiency. A Lagrangian method of optimization was used to minimize the total transmit power under the constraints of the users' QoS requirements. However, the prohibitively high computational complexity renders it impractical. After that, many other adaptive allocation algorithms with multifarious objectives have been proposed to reduce the complexity of resource allocation algorithm [12-14]. [15] gave an overview of adaptive multi-user resource allocation methodologies. Adaptive modulation, adaptive multiple-access control and adaptive cell selection for SISO- and MIMO- OFDM were introduced. [16] provided two multi-cell resource management strategies for OFDMA-based cellular systems. The authors developed inter-cell interference (ICI), spectral efficiency and the service outage probability models in the research. [17] developed a distributed game theory approach to adaptively allocate the sub-channels,

rates, and power for multi-cell OFDMA networks. To regulate the competition for the resource usage, the authors employed a virtual referee scheme which made their algorithm outperforms the iterative water-filling method in terms of both transmission power consumption and throughput. However, to the best of our survey, few studies have jointly considered BUA-RA scheme in the multi-user multi-cell network scenarios with CT technology. Because of lack of a central controller structure, the researches of cooperative resource allocation schemes mainly focus on using relay nodes or other wireless users to achieve the cooperative communication [18][19]. In our previous research [20] and [21], we provided a serial of BUA-RA schemes for PON+OFDMA and PON+OFDM-TDMA systems respectively. In [20], four LP models were designed to solve four different BUA-RA optimal objectives in the CPWN. [21] provided three BUA-RA schemes to maximize the network throughput.

3   System Model

A general system model for a CPWN is shown in Fig. 1, which is composed of a PON and multiple WiMAX cells as backhaul and front-end wireless access networks, respectively. The major entities in the network model include an OLT, a splitter, a number of fibers and *multiple* ONU-BSs. An OLT functions as a root node in the tree structure. With powerful computing capability and intelligence, the OLT can process the incoming jobs in a parallel fashion. The OLTs can connect to a metropolitan optical network such as a synchronous digital hierarchy (SDH) ring.

To extend from the OLT with fibers, a passive optical splitter fans out to multiple optical fibers connected to a number of ONU-BSs. An ONU-BS is a single device box integrating a PON ONU and a WiMAX BS [7]. In addition to the savings on hardware cost, such integration achieves a flat control plane and seamless integration between the PON and WiMAX, where signaling and control messages can be exchanged directly between the OLT and the end users (fixed or mobile stations). The ONU-BS functions as border devices to interconnect the PON and WiMAX network. The resource management functions are located at the OLT, which can collectively control the BUA-RA of all wireless users within the coverage areas. OFDM-TDMA is used as the multi-access technology by the CPWN.

All network status data, such as time slot usage of each BS, wireless channels status information, data rate requirement of each user, users' moving speed are stored and dynamically updated at OLT. Based on these data, while a new user arrives, OLT can compute the resource and associating BS(s) for the user to satisfy its data rate requirement base on the BUA-RA schemes. According to the moving speed of the user and current network load, OLT can adaptively choose one BUA-RA scheme. In our model, Shannon's channel capacity function is used to estimate the data rate of the user n. The notions are listed in Table 1.

$$R_n = B \times Tp_n \times \log\left(1 + \text{SINR}_n\right) \tag{1}$$

$$\text{SINR}_n = \frac{P_n^R}{N_0 + P_n^I} \tag{2}$$

In the CPWN, one or more BSs can cooperatively transmit to a user with CT, so P^R_n and P^I_n are calculated as follows.

$$P^R_n = \sum_{m=1}^{M} A_{mn} P^r_{mn} \tag{3}$$

$$P^I_n = \sum_{m=1}^{M} \left(1 - A_{mn}\right) P^r_{mn} \tag{4}$$

where

$$A_{mn} = \begin{cases} 1 & \text{BS } m \text{ associates user } n \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

For simplicity, we use the path loss model [22] to estimate the signal power of user n from BS m. In the real network, the receive power can be obtained by the user, and then feedback to the OLT.

$$P^r_{mn} = P^t_m \times \left(\frac{d_0}{d_{mn}}\right)^{\alpha} \tag{6}$$

4   BUA-RA Schemes

In this section, we will introduce three BUA-RA schemes in the CPWN. The BU association concerns which BS(s) should be associated with a specific user; and resource allocation is to determine how many time slots should be allocated to a specific user from the associated BS(s) within a CPWN.

The subscribers are classified into three categories in the CPWN, i.e., 1) static subscriber (SS), 2) portable subscriber (PS), and 3) mobile subscriber (MS).

1) As the SS is fixed in the network, the CSI of the SS is relatively stable; and after the network initialization, the SSs' resource allocation rarely refresh. So, the SSs can tolerant a time consuming resource allocation method to obtain an optimal solution. In this paper, we formulate the BUA-RA as an LP, in which all SSs' requirements are considered at the same time (so-called multi-user LP scheme).

For the mobile subscriber, i.e. PS and MS, the BUA-RA should be more efficient than the SS, since their CSI changes more frequently. The RA should be refreshed after user's CSI changed.

2) The PS moves slowly, typically a subscriber using a notebook, a netbook, or a cell phone with a walking speed. The CSI of the PS changes slowly, so we don't need a very fast BUA-RA scheme. If normally a solution can be obtained in 1.5 second, the scheme is acceptable. The second scheme allocates resource to each PS one by one by an LP model (so-called single-user LP scheme).

3) The MS moves fast in the network, such as a computer in the vehicle. The CSI of the MS changes continually, so RA should be refreshed very fast. We provide a fast heuristic RA scheme (so-called single-user heuristic scheme) for the MS, which can obtain the solution in 10ms.
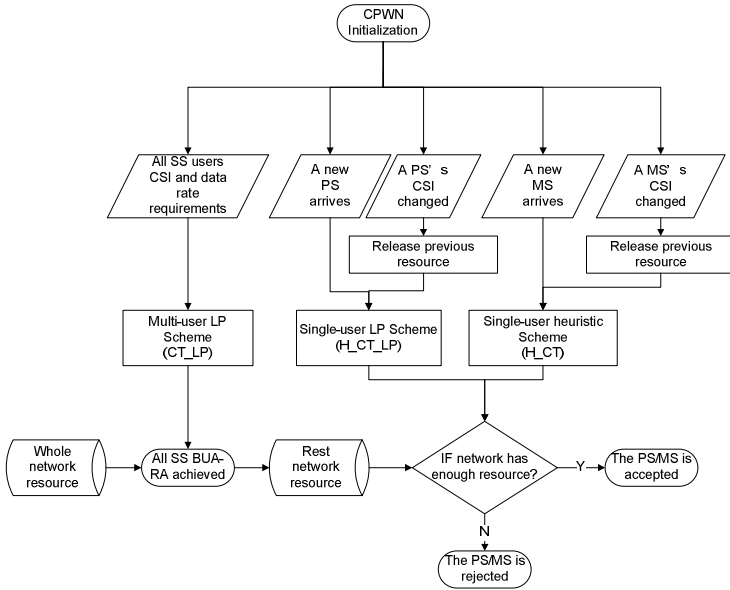

Fig. 2 Flowchart of BUA-RA

The BUA-RA procedure in the CPWN is shown in Fig. 2. When a network initiated, the first optimal scheme is solved by using some LP tools to assign BSs and allocate resources for all the SSs. Then for the PSs and MSs, the second BUA-RA scheme or the third one can be chosen based on their moving speeds. If there is no enough resource remaining in the network, the user will be blocked. If a user moves out of the CPWN, the original allocated resource will be released and re-allocated. For the sake of fair resource allocation, we assume all the users have the same priority to be admitted.

The notations adopted in the problem formulation are introduced as follows. The decision variable Tp_{mn} denotes the time slots allocated to user n from BS m. Tp_{mn} is normalized to percentage of the total time slots of a BS. If Tp_{mn} is larger than 0, it means that BS m is associated with user n; otherwise it does not associate with the user. Table 1 lists all the notations.

4.1   Multi-user LP Scheme (CT_LP)

In the optimal scheme, the BUA-RA problem is formulated as a multi-user optimization model to minimize the total time slots consumption of the BSs in a CPWN, where the CT technology is employed. The objective is to:

Table 1. Notations

Symbol	Notation
R_n	The data rate of user n
α	The path-loss exponent
d_0	The reference distance to BS antenna
N_0	The noise power
d_{mn}	The distance between user n and BS m
P^R_n	The signal power received by user n
P^I_n	The interference signal power received by user n
P^r_{mn}	The transmission power received by user n from BS m
P^t_m	The transmission power of BS m
N	The number of total users
M	The number of total BSs
B	The total wireless bandwidth
R^{Req}_n	The data rate required by user n
A_{mn}	The associating indicator of user n and BS m
Tp_{mn}	The normalized time slots allocated to user n from BS m
x_{jn}	The associating indicator of user n and AM j
Tp_{jn}	The normalized time slots allocated to user n by AM j
Tp_n	The normalized time slots allocated to user n

AM: associating mode

$$\text{minimize} \sum_{m=1}^{M} \sum_{n=1}^{N} Tp_{mn} A_{mn} \tag{7}$$

which is subject to the following constraints:

1) Total time slot constraint

$$\sum_{n=1}^{N} Tp_{mn} A_{mn} \leq 1, \forall m = 1...M \tag{8}$$

2) Data rate requirement of each user

$$R_n = B \times Tp_{mn} \times \log\left(1 + \frac{\sum_{m=1}^{M} A_{mn} P^r_{mn}}{N_0 + \sum_{m=1}^{M}\left(1 - A_{mn}\right) P^r_{mn}}\right) \geq R^{\text{Req}}_n, \ \forall n = 1...N \tag{9}$$

Because constraints (8) and (9) are non-linear, we apply the following approach to linearize them. Because of using CT technology, a user can be associated with one or more BSs. The number of associating BS(s) of a user can be from 1 to M. So, we define $J (= 2^M - 1)$ as associating mode which indicates the number of BSs to be potentially chosen to associate a user in the CPWN. Describing the jth association mode with binary number, we will have following table:

Table 2. Bit (b_{jm}) Map of association mode

j	b_{jM}	...	b_{jm}	...	b_{j2}	b_{j1}
1	0	...	0	...	0	1
2	0	...	0	...	1	0
:	:	:	:	:	:	:
J	1	1	1	1	1	1

The mth bit (b_{jm}) of the integer number j indicates whether BS m associates a user or not, in the jth association mode.

$$b_{jm} = \begin{cases} 1 & \text{BS } m \text{ associates a user in } j\text{th association mode} \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

Then we have:

$$LOG\_SINR_{jn} = \log\left(1 + \frac{\sum_{m=1}^{M} b_{jm} P_{mn}^r}{N_0 + \sum_{m=1}^{M}\left(1 - b_{jm}\right) P_{mn}^r}\right) \tag{11}$$

The LP model of this BUA-RA scheme (CT_LP) can be expressed as follows:
Objective:

$$\text{minimize} \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{j=1}^{J} \left(b_{jm} \times Tp_{jn}\right) \tag{12}$$

Constraints:
1) Total time slots constraint of each BS

$$\sum_{n=1}^{N} \sum_{j=1}^{J} \left(b_{jm} \times Tp_{jn}\right) \leq 1, \forall m = 1...M \tag{13}$$

2) Data rate requirement of each user

$$R_n = \sum_{j=1}^{J} \left(Tp_{jn} \times (B \times LOG\_SINR_{jn})\right) \geq R_n^{\text{Req}}$$
$$\forall n = 1...N \tag{14}$$

3) A user can only use one associating mode

$$\sum_{j=1}^{J} x_{jn} = 1 \tag{15}$$

$$x_{jn} - Tp_{jn} \geq 0, \forall j = 1...J, \forall n = 1...N \tag{16}$$

4) Variables

$$Tp_{jn} \in [0, 1] \tag{17}$$

$$x_{jn} \in \{0, 1\} \tag{18}$$

$$x_{jn} = \begin{cases} 1 & j\text{th association mode is used to associate user } n \\ 0 & \text{otherwise} \end{cases}$$

Constraint (13) ensures that the total allocated time slots to each user are no more than the total time slots of one BS. Constraint (14) makes sure that the data rate requirement of each user must be satisfied. Constraints (15) and (16) stipulate that one user can only use one associating mode. Equations (17) and (18) state the boundaries of the decision variables.

In practice, the SSs mainly refer to as the residential and business users which have certain unchanged rate requirements when being subscribed. And the optimal BUA-RA for each SS can be obtained *off-line* by solving the above LP model. However, the BUA-RA for mobile users are required to be *on-line,* namely, quick response to the instantaneous connection requests of mobile users requires fast BUA-RA schemes.

In the following two sections, we present two schemes for PS and MS, respectively. Heuristic BUA-RA schemes are used for these mobile users, which assign BS and allocates resource to each new user one by one, based on user's requirement and current network status. Let TS_m (=1) to be the normalized total time slots of BS m, F_m to be the free time slots of BS m, W_m is the total reserved working time slots of BS m ($TS_m = W_m + F_m$).

4.2   Single-User LP Scheme (H_CT_LP)

In the second BUA-RA scheme, we use the similar LP model and the same notations as above optimal scheme to minimize the time slot usage to satisfy the data rate requirement of a new user. The single user LP model is expressed as follows:

Objective:

$$\text{minimize} \sum_{m=1}^{M} \sum_{j=1}^{J} \left(b_{jm} \times Tp_{jn} \right) \tag{19}$$

Constraints:
1) All the associating BS(s) should have enough free time slot

$$\sum_{j=1}^{J} \left(b_{jm} \times Tp_{jn} \right) \leq F_m \tag{20}$$

2) Data rate requirement of the new user

$$R_n = \sum_{j=1}^{J} \left(Tp_{j_n} \times (B \times LOG\_SINR_{j_n}) \right) \geq R_n^{\text{Req}} \tag{21}$$

3) The new user can only use one association mode

$$\sum_{j=1}^{J} x_{j_n} = 1 \tag{22}$$

$$x_{j_n} - Tp_{j_n} \geq 0 \tag{23}$$

4) Variables

$$Tp_{j_n} \in [0,\ 1] \tag{24}$$

$$x_{j_n} \in \{0,\ 1\} \tag{25}$$

If the LP has no solution, the user's requirement will be rejected.

4.3   Single-User Heuristic Scheme (H_CT)

This fast heuristic scheme (H_CT) is designed for the MS. This scheme tries to associate a new user via following five steps:

Step 1:   Find the closest BS m to the new user n, denote the minimum distance as $d_{min} = d_m$, BS m will associate the user.

Step 2:   Find the next closest BS l which has distance d_l to the user n.

Step 3:   If $d_l - d_{min} < \Delta d\_ct$, then the user l will also associate the user n, go back *Step 2*; otherwise go to Step 4.

Step 4:   Calculate the amount of time slots (Tp_n) to be allocated to the user by following formulas

$$Tp_n = R_n / \left(B \times SINR\_CT_n \right) \tag{26}$$

$$SINR\_CT_n = \log \left(1 + \frac{\sum_{m=1}^{M} A_{mn} P_{mn}^r}{N_0 + \sum_{m=1}^{M} (1 - A_{mn}) P_{mn}^r} \right) \tag{27}$$

Step 5:   Check if all the associating BS(s) have enough time slots. If YES, then the user will be associated by the BS(s), update time slots usage info of all association BS(s) at OLT by (28) and (29); if NO, the user will be rejected.

$$TS_m = W_m + Tp_n \tag{28}$$
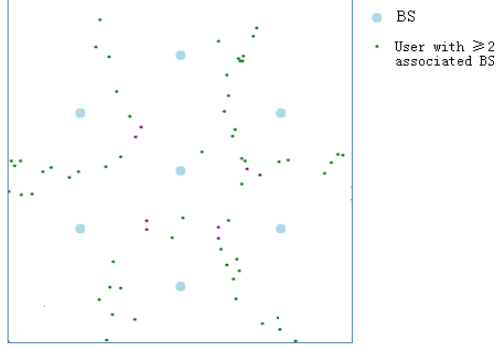
Fig. 3. Users with two or more associating BSs

$$F_m = F_m - Tp_n \tag{29}$$

d_m is the distance from the BS m to the new user n. Δd_ct is the maximum acceptable difference between the distance of the cooperative BSs to the user and the d_{min}. If distance difference is greater than Δd_ct, the BS will not be selected as a cooperative associating BS. The small points in Fig. 3 show the positions of the users who have two or more associating BSs (shown as big light-blue points). This figure is obtained by the simulation of the CT_LP scheme. From this figure, we can find that the users with CT are always distributed in the middle area of two or three BSs. So, we can conclude that a user is suitable to use CT when it is at the edge area of the cells. We use Δd_ct to control the scope of this area. By observing the CT_LP scheme simulation results such as Fig. 3, we can estimate the suitable value of the Δd_ct.

5   Simulation Results

In this section, the performances of the proposed BUA-RA schemes are evaluated; and we also compare against the conventional resource allocation schemes without using CT technology; more specifically, three non-CT BUA-RA schemes (NCT_LP, H_NCT_LP, and H_NCT) corresponded to the proposed schemes are used as the benchmarks. The simulation program is coded by C#, and the LP models are solved by the CPLEX version 11.0 [23]. All the simulations are conducted on a computer with Intel Pentium D-805 CPU and 1G memory. We are interested in testing the time slots usage performance, the network capacity (the total data rate of associated users in the network), and the computation complexity of these schemes.

Fig. 4 illustrates the simulated network which is similar to conventional cellular networks in. In the simulated network, seven BSs, represented as the big point in Fig. 4, are located in a $1500 \times 1500 m^2$ area. The setting of simulation parameters is shown in Table 3. We examine 63 scenarios, where a different numbers of mobile
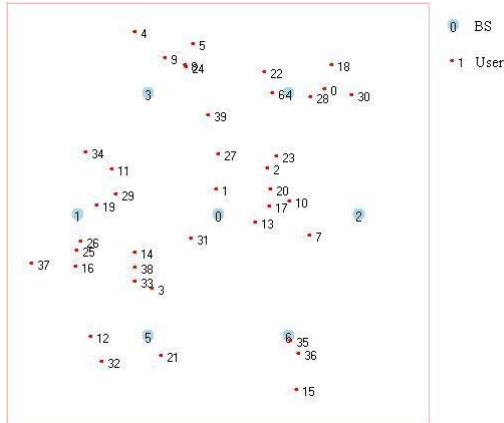
Fig. 4. A snapshot on the mobile user distribution in the AOI. The 7 BSs are fixed.

users are launched and randomly moving in the area of interest (AOI). Table 4 shows the data rates of a user for all 63 scenarios. After running a BUA-RA scheme in each scenario, the expected output is the total time slots usage in percentage, total unassociated users in percentage, and the computation time for each user.

Table 3. Simulation parameters setting

Parameters	$B(MHz)$	$P_m(w)$	$N_0{}^*(w)$	$d_0(m)$	α	Δd_ct
Value	20	20	1×10^{-6}	1	2.5	100

* The thermal noise power (N_0) is assumed equivalent at any point in the network.

Table 4. Data rate of a user in each scenario (*Mbps*)

Number of Users	Total Data Rate Requirement (Mbps)								
	20	40	80	120	160	200	250	320	400
20	1	2	4	6	8	10	12.5	16	20
40	0.5	1	2	3	4	5	6.25	8	10
80	0.25	0.5	1	1.5	2	2.5	3.125	4	5
100	0.2	0.4	0.8	1.2	1.6	2	2.5	3.2	4
160	0.125	0.25	0.5	0.75	1	1.25	1.5625	2	2.5
250	0.08	0.16	0.32	0.48	0.64	0.8	1	1.28	1.6
400	0.05	0.1	0.2	0.3	0.4	0.5	0.625	0.8	1

To generalize the randomness due to the user mobility, each data in the simulation is the average result by run a BUA-RA scheme on 50 different user distributions in each scenario. We show the criteria in two dimensions, 1) under same number of

users, the results are shown as a function of the total data rate requirements; 2) under same total data rate requirement, the results are shown as a function of the number of users. Before showing the three performance results, we will introduce a criterion for the multi-user LP scheme in following sub-section.

5.1   How Many Times the LP Models Cannot Be Solved

The multi-user LP schemes try to accept all the SSs in the network and satisfy their data rate requirements. If the LP model cannot be solved, it means that some users' requirements cannot to be satisfied and these users cannot be accepted in the network. Obviously, if the total data rate requirement is higher than the capacity of the network, the LP model will fail to find a solution.

A. Under same number of users and different total data rates
Fig. 5 shows that there are more no solution times of the NCT_LP scheme than the CT_LP scheme, when the total data rate requirement reaches 80 Mbps or higher. Because of CT_LP using CT technology, we know that the network capacity is increased by using CT. All the results show the same situation; we only choose some figures of them to show in Fig. 5.
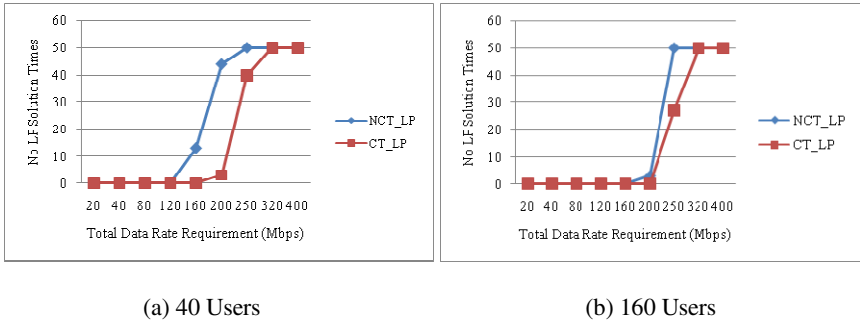

(a) 40 Users   (b) 160 Users

Fig. 5. No LP Solutions Times

B. Under same total data rates and different number of users
Fig. 6 shows: when the total data rate requirements are the same, the more users in the network, the less no LP solution times will happen. In other words, when the number of user in the network increases, the resource of the network can be used more efficient and the capacity of the network will increase. Moreover, it is observed that the CT_LP scheme outperforms NCT_LP in terms of network capacity.

5.2   Total Time Slots Usage

We take the summation of time slots (normalized to percentage) allocated to each user as measure on how much system resource is spent on satisfying the given traffic load
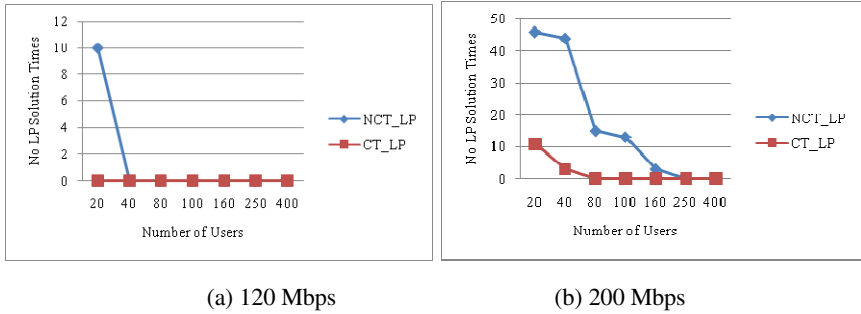
(a) 120 Mbps   (b) 200 Mbps

Fig. 6. No LP Solutions Times

demand. Obviously, a specific BUA-RA scheme achieves better performance if less total time slot is consumed in a wireless network to satisfy a given pattern of traffic load demand.

A. Under same number of users and different total data rates
From Fig. 7, we can only conclude that when the total data rate requirement increases, the time slots usage also increases. However, it is difficult to figure out which method of the six has the best time slots usage performance. We will find out the result in next sub-section.
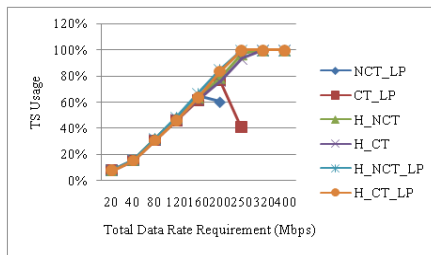

Fig. 7. Total Time Slot Usage (100 Users)

B. Under same total data rates and different number of users
Fig. 8 shows that at low and mid network load (total data rate requirement < 160Mbps), the CT_LP and H_CT_LP schemes outperform H_CT in terms of time slot usage performance. H_CT costs a little more time slots than these two schemes; however it can save more resource (about 2%) than the other three NCT schemes.

Fig. 9 shows that when the network load becomes high (total data rate requirement ≥ 200 Mbps), the performance of H_CT_LP becomes worse. This is because when a new user arrives, the H_CT_LP scheme always tries to accept its requirement sometime the channel status of the new user is very poor, it will cost too many
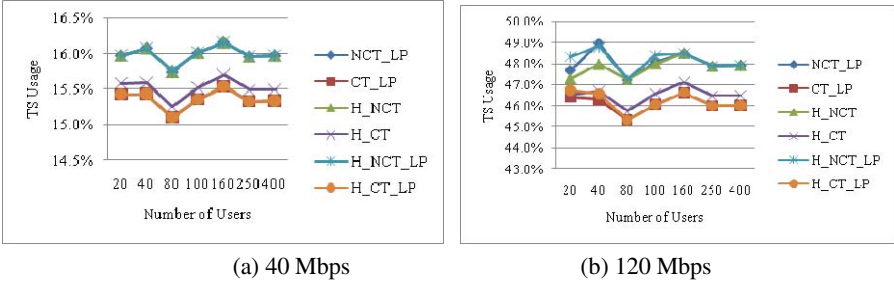
(a) 40 Mbps   (b) 120 Mbps

Fig. 8. Total Time Slot Usage

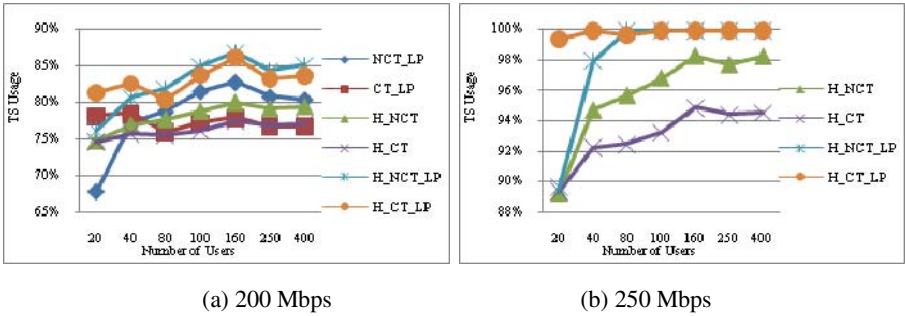(a) 200 Mbps   (b) 250 Mbps

Fig. 9. Total Time Slot Usage

resources (time slots) to satisfy the user's data rate; then, the resource will be exhausted fast. However, under this situation the H_CT scheme will reject the new user whose channel status is not good, because it will cost too many resources to accept such a user; and then it can save some resource to accept more future users with good channel condition. At high network load, the H_CT scheme can save 5-10% time slots than the other schemes.

When the total data requirement is higher than 300Mbps, the network is overload, and then the time slot usage reaches 100%.

5.3   Percentage of Unassociated Users

A network capacity efficient BUA-RA scheme should be able to accept as more users as possible; in the other words, the network capacity, i.e. total accepted data rate, is higher. We use the total number of unassociated users (normalized to percentage) as the criterion of the network capacity efficiency.

A. Under same number of users and different total data rates
For the multi-user LP scheme, when some user is unacceptable by the network, the LP problem will not be solved, which is shown in the first sub-section (5.1). However, for the heuristic scheme, when a new arrival user's requirement cannot be

accepted, the user will be rejected by the network, and then the user will be recorded as an unassociated user by our simulation program. Fig. 10 shows that when the total data rate requirement increases, the percentage of unassociated users increase too. By comparing the performances of the six schemes, we can find that at low network load (total data requirement ≤ 80 Mbps), there is no unassociated user by using any scheme; at mid load (120-160 Mbps), CT_LP can accept all users, when other schemes begin to reject some users; at high load (total data rate requirement 200-250 Mbps) the CT_LP scheme cannot get solution, at this time H_CT_LP plays the best, and H_CT is a little worse, but better than the NCT schemes; when the network is overload (total data rate requirement > 250 Mbps), H_CT outperforms of all the other schemes in the terms of unassociated users performance, however H_CT_LP plays worse, this result well matches what is observed in the previous sub-section (5.2-B). Over all, the CT schemes perform better than the NCT ones.
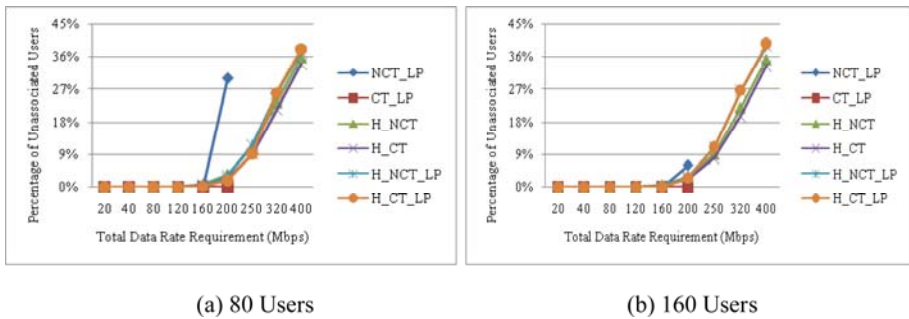

(a) 80 Users   (b) 160 Users

Fig. 10. Percentage of Unassociated Users

B. Under same total data rates and different number of users

When the network load is low (total data rate requirement ≤ 80 Mbps), the number of unassociated user is zero, so we don't show the figures here. By observing Fig. 11, we can easily obtain same conclusions as previous sub-section (5.3-A). On the other hand, the similar character as the sub-section (5.1-B) can also be found here; that is when the number of users increases, the percentage of unassociated users decreases.

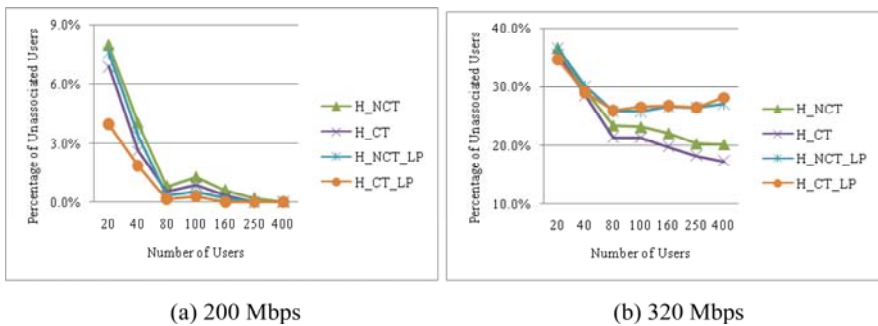(a) 200 Mbps   (b) 320 Mbps

Fig. 11. Percentage of Unassociated Users

5.4   Computation Time

All results of the different number of users and different total data rate requirements show the similar situation, thus we only choose 100 users and 160 Mbps results to show in Table 5 and Table 6.

By observing the result tables, we know that the CT_LP scheme takes the longest time to obtain a solution, especially when the network is close to the full load. The single-user LP scheme costs much less time than the optimal one; however for the H_CT_LP scheme, the 1.33 second computation time is good enough for the low speed PSs. Just as well, H_CT works so efficient that it only costs around 10 msec to calculate the association BS and the time slot for a high speed MS user.

Table 5. Computation Time (sec) (100 Users)

BUA-RA schemes	Total Data Rate Requirement (Mbps)					
	20	**80**	**160**	**200**	**250**	**320**
CT_LP	9.90	10.10	49.18	120.53	1595.78	10.05
H_CT_LP	1.33	1.33	1.33	1.34	1.35	1.31
H_CT	0.0090	0.0089	0.0092	0.0091	0.0090	0.0090

Table 6. Computation Time (sec) (160 Mbps)

BUA-RA schemes	Number of Users in the Network					
	20	**40**	**80**	**100**	**160**	**250**
CT_LP	23.54	25.23	60.63	49.18	30.55	61.84
H_CT_LP	1.31	1.33	1.34	1.33	1.33	1.33
H_CT	0.0091	0.0089	0.0095	0.0092	0.0102	0.0118

6   Conclusion

This paper has proposed three BU association and resource allocation (BUA-RA) schemes for the integrated PON-WiMAX networks where OFDM-TDMA and inter-cell CT technology are employed, we have integrated evaluated these three schemes and further compared against the conventional BUA-RA schemes which do not have the CT technology. The simulation results show the network capacity and resource usage efficiency can be increased by using the CT technology.

The multi-user LP scheme, CT_LP, can obtain the optimal BUA-RA for the SSs. For the PSs, when the network load is not high, the H_CT_LP scheme is suitable, since it can obtain a better solution than the H_CT scheme in a relative short time (less than 1.5 second); however, when the network load become high, the H_CT scheme should be used. For the high speed MSs whose wireless channel statuses are changed fast, the H_CT scheme is a good choice, since it can calculate the BUA-RA result within 10ms.

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