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Published in IET Communications
Received on 28th June 2010
Revised on 7th October 2010
doi: 10.1049/iet-com.2010.0530

ISSN 1751-8628

Joint time-frequency-power resource allocation for low-medium-altitude platforms-based WiMAX networks

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Abstract: Low-medium-altitude platforms (LMAPs) are being actively researched and developed as a key solution to improve the performance and services of emergency communications. In order to provide higher capacity, throughput and quality of service guarantee to territorial users in emergency scenarios, a LMAP-based WiMAX system, AirWiMAX, is presented in this paper. Firstly, a hierarchical AirWiMAX topology is presented. Secondly, a joint radio resource allocation is carried out simultaneously at the time, frequency and power domain for the AirWiMAX downlink. This problem is modelled as a cooperative game in which a fairness criterion is enforced. Simulation results show that compared to the other two typical resource allocation algorithms, that is, the max-rate algorithm and the max–min fairness algorithm, the proposed algorithm achieves a good trade-off between the overall system throughput and the fairness.

1 Introduction

There is an increasing interest to the development of airspace platforms in the recent years, for example, balloons, airships or aircrafts carrying equipments for telecommunications, remote sensing or digital broadcasting. Balloons can keep stationary at low-medium altitude of about 2 km, or high altitude of about 20 km for a long period (e.g. 3–5 years) and cover a wide range (e.g. 500 km^2). This makes them very attractive for the future broadband wireless access.

The most important and also the hardest issue for high-altitude stratospheric platforms (HAPs) is the design and implementation of the stratospheric long-endurance airships or aircraft. Placement optimisation of mobile IP home agent entity in HAPs is performed in [1] to significantly reduce network burden. Load balancing mechanisms are well studied in a constellation of HAPs in [2]. Although several big progresses have been achieved so far [3], it will still take at least 5–10 years to make such an HAP system available in real practice.

Captive balloons, which have been widely used in many areas, are a good tool for low-medium-altitude platforms (LMAPs). However, compared with HAPs, it is very difficult for LMAPs to provide globe mobile communications. So LMAPs are considered only as a temporary platform, and there have been only a few studies and testbeds concerning the telecommunication payload systems based on LMAPs [4].

However, when Wenchuan, China was hit by a strong earthquake on 12 May 2008, all the territorial telecommunication systems were damaged, and Wenchuan became an information island. So LMAPs, as emergency communication systems, attract much interest from government, academia and industry.

The telecommunication payload systems on LMAPs can be implemented with various wireless technologies including 3G, LTE, WiMAX, WiFi or combinations of more than one type. As a broadband wireless access system, WiMAX is one of the best candidates capable of delivering real-time voice, video and non-real-time data to static, nomadic or mobile users [5]. Its medium access control (MAC) layer supports a primary point-to-multipoint (PMP) architecture, with an optional mesh topology [6, 7]. However, the current mesh WiMAX in IEEE 802.16x is difficult to be implemented and deployed as it is not compatible with the basic PMP topology [8]. Mobile WiMAX (IEEE 802.16e) uses a variable fast Fourier transform (FFT)-based orthogonal frequency division multiple access (OFDMA) technology [9]. The upcoming relay WiMAX (IEEE 802.16j) aims to deal with challenging radio propagation characteristics and low signal-to-interference and noise ratio (SINR) at the cell edge with the introduction of relay stations [10, 11].

With the rapid development of LMAPs and WiMAX, an aero platform-based WiMAX system, AirWiMAX, is presented in this paper, where mesh routers are placed in captive balloons from about 200 m to 2 km in height.

One of the key technologies in AirWiMAX is radio resource allocation. Efficient resource allocation, which involves bit loading, time-frequency resource assignment and transmission power control, can greatly improve system performance and has attracted much interest. Considering the IEEE 802.16 standard-based wireless mesh network, the authors of [12] propose a joint optimisation method as the sub-optimal solution strategy, in which the power control, scheduling and routing algorithms are designed as integrated mechanisms. As for the wireless mesh networks based on 802.11 protocol [13], capacity is expanded by adding more radios to mesh routers for accessing non-overlapping channels. The issues of channel assignment, resource sharing and bandwidth allocation in WiMAX mesh networks are studied in [14–16].

However, most of the previous resource allocation schemes [17–20], such as water-filling scheme, study how to efficiently maximise the total transmission data rate under power-constrained condition. These schemes can indeed achieve a great efficiency, but the fairness issue has not been taken into consideration. The users with better channel conditions are assigned more resource and have a higher data rate while others suffer from starvation. On the other hand, as for the fairness among users, the max–min criterion has been considered for channel allocation in multi-user orthogonal frequency division multiplex (OFDM) systems [18, 21]. However, there are also some problems. Firstly, this scheme penalises users with better channels and hence reduces the system efficiency seriously. Secondly, it is not easy to guarantee the quality of service (QoS), for example, the minimum rate requirements for different users. In addition, most solutions are too complex for practical implementation. Therefore it is necessary to develop a new approach by considering system efficiency, fairness and complexity altogether.

To make a good trade-off between throughput and fairness, many researchers introduced game theory [22, 23] from mathematics and economics into radio resource management, which can maximise the system throughput and, meanwhile, guarantee the fairness [24–29].

In addition, most solutions only consider resource allocation in the frequency domain, but in WiMAX resources can be scheduled in the time, frequency and power domains simultaneously.

In this paper, the simultaneous resource allocation problem in time, frequency and power domains is studied by means of cooperative games. A joint time-frequency-power allocation strategy (JEEP) is proposed to achieve as closely as possible to the Pareto optimal rates under given constraints, that is, the minimum rate of each user and the maximal transmit power of the base station (BS). Ideally, the slot (the minimal time-frequency unit in WiMAX) and power should be allocated jointly to achieve the Nash Bargaining Solution (NBS) of the game. Unfortunately, this ideal approach is too complex to implement. Therefore we separate the time-frequency block and power allocation to reduce the complexity. Furthermore, by using the Lagrange multiplier method, the computation complexity is greatly reduced so that it is suitable for real-time systems.

The rest of this paper is organised as follows. In Section 2, a hierarchical architecture is presented for AirWiMAX, which includes an aerial mesh backbone network and ground PMP access networks. In Section 3, after describing the AirWiMAX downlink model, the features about the cooperative game and NBS are introduced, and the game model of resource allocation for the AirWiMAX downlink is formulated. In Section 4, the JEEP resource allocation algorithm is investigated in detail. Extensive simulations are carried out to evaluate the efficiency and fairness of the proposed JEEP algorithm in Section 5. Conclusions and future researches are drawn in Section 6.

2 Hierarchical architecture for AirWiMAX

2.1 Hierarchical AirWiMAX

The mesh topology was originally used in military applications and is likely to find further application, especially in emergency service operations where planned infrastructure is unavailable. However, current works have concluded that for a mesh WiFi, subscribers cannot self-generate capacity at a rate sufficient to maintain a target level of per-user throughput regardless of network size and population. Thus, this type of mesh topology is unlikely to find widespread commercial applications. Another way that scalability can be achieved is to provide additional capacity in the form of a secondary backbone mesh network, so that a hierarchical architecture is presented for AirWiMAX in this paper, as shown in Fig. 1.

In hierarchical AirWiMAX, the secondary backbone network is composed of aero mesh routers with minimal mobility and high resource (e.g. energy, CPU, memory and size) restriction, and the mesh topology is reserved for the backbone network. The primary access network is composed by ground clients with high mobility, and a PMP topology is reserved for access networks connected to the mesh backbone. Moreover, the mobile clients roam among the routers, and the backbone connects to the core network, for example, internet or the public telephone network, via aero mesh gateways. Hence, an end-to-end connection among the mobile clients and the core network can be easily implemented and deployed in case of emergency. The power consumption of the aero routers and the gateways is an important problem in the aero backbone network. In order to solve this problem, based on the radio-over-fibre technology [30], only the radio remote units are installed at the captive balloons, and all the other parts of the routers and the gateways, for example, the building baseband units, are set on the ground.

This paper therefore focuses on the radio resource allocation for the downlink of ground PMP access networks. Other technical challenges such as backbone connectivity, satellite connectivity or client registration/authorisation will not be discussed.

2.2 Frame structure for ground mobile access networks (IEEE 802.16e)

Currently, the ground mobile access network only supports the PMP topology, and its frame structure follows IEEE

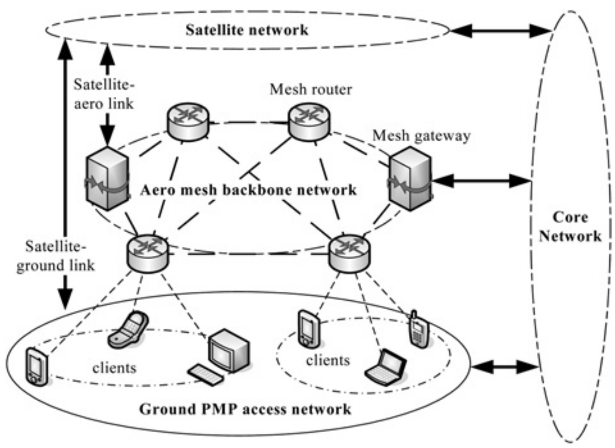

Fig. 1 *Hierarchical architecture for AirWiMAX*

IET Commun., 2011, Vol. 5, Iss. 7, pp. 967–974
doi: 10.1049/iet-com.2010.0530

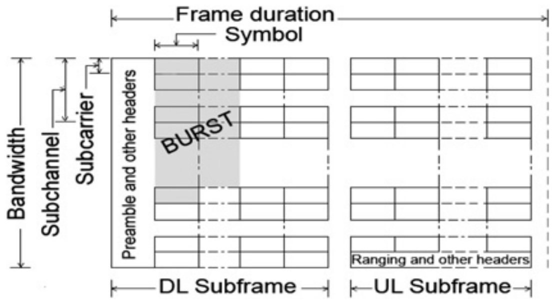

Fig. 2 *OFDMA frame structure for IEEE 802.16e*

802.16e. In 802.16e, the available bandwidth is divided into subchannels, which are the minimum frequency resource unit and are formed by orthogonal subcarriers. Different subchannels are assigned to different users as a multi-access mechanism. On the other hand, the OFDM symbol is the minimum time resource unit. This makes the WiMAX radio resource allocation a matrix-like structure. A slot, which is composed of one subchannel and one, two or three symbols, is the minimum frequency-time resource unit that can be allocated by BSs. The bandwidth should be allocated to the mobile stations (MSs) in the form of continuous groups of slots, called data regions or bursts. The resource allocation depends on demand, channels conditions and QoS requirements. The OFDMA-based frame structure for 802.16e operating in TDD mode can be seen in Fig. 2 [9].

The MAC layer is able to handle different functionalities such as fragmentation, packing, resource allocation, scheduling or retransmission with the appropriate use of uplink-map (UL-MAP), downlink-map (DL-MAP), frame control header and other MAC headings contained in each burst.

3 Preliminary

Radio resource allocation is one of the key technologies in AirWiMAX. For simplicity, in this paper radio resource allocation is considered only in the downlink of ground PMP access networks.

3.1 System model

Consider a typical AirWiMAX downlink scenario, that is, an aero BS and multiple ground MSs. An aero BS can be seen as one router in Fig. 1 that services one ground cell including all the ground mobile clients (i.e. the MSs).

We assume that the available downlink spectrum of one aero BS is divided into N groups of orthogonal subchannels, each of which contains several subcarriers. Different MSs are then allocated with different groups of orthogonal subchannels. Each subchannel has a bandwidth of $\Delta f = B/N$ Hz, where B is the total downlink bandwidth of one aero BS. There are totally K MSs randomly located within the cell. The total transmission power of an aero BS is P^{total}.

It is assumed that each MS can estimate the channel state information (CSI) perfectly and the estimated CSI (e.g. SINR) on each subchannel is made known to the BS via a dedicated feedback channel. So the BS also has the perfect CSI of all the MSs. An available slot allocation is achieved according to CSI, and is made known to all the MSs through DL-MAP and UL-MAP.

Assume that each MS experiences independent fading and additive white Gaussian noise with the variance $\sigma^2 = N_0 B/N$, where N_0 is the noise power spectral density. The channel gain of the kth MS in slot$_{n,t}$ is denoted as $g_{k,n,t}$, where n is the subchannel index and t is the time index. The kth MS's SINR in slot$_{n,t}$ is thus denoted as $\eta_{k,n,t} = p_{k,n,t}\, g_{k,n,t}^2/\sigma^2$, where $p_{k,n,t}$ is the transmit power of the kth MS in slot$_{n,t}$.

The data rate of the kth MS in slot$_{n,t}$ is denoted as $b_{k,n,t} = \log_2(1 + (\eta_{k,n,t}/\Gamma))$ [27], where the constant SINR gap $\Gamma$is set to be $\Gamma = (\ln(5 \times \text{BER}))/-1.6$, and BER is bit error rate.

The slot assignment matrix for the kth MS is denoted as $[\boldsymbol{X}_k]_{N\times T}$, where T is the number of slots on the time dimension in each frame. The element in the 2-dimension matrix $[\boldsymbol{X}_k]_{N\times T}$ is represented by $x_{k,n,t}$ which satisfies

$$x_{k,n,t} = \begin{cases} 1 & b_{k,n,t} > 0 \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

If slot$_{n,t}$ is assigned to the kth MS, we have $x_{k,n,t} = 1$, otherwise, we have $x_{k,n,t} = 0$. Since a slot can be allocated to one MS at most, we have $\sum_{k=1}^{K} x_{k,n,t} = 1, \forall n, t$.

3.2 Cooperative game

In this subsection, some basic concepts and results from the cooperative game and NBS are introduced.

In a bargaining game, there are K MSs competing for the system resource. Let $\boldsymbol{R}$ be a closed and convex subset of $\Re^K$ to represent the set of feasible payoff allocations that the MSs can get if they all work together. Each MS k also demands a minimum payoff $R_{k,\min}$ without any cooperation in order to enter the game. If each MS k involved in the game can achieve its minimal payoff, that is, $R_k \geq R_{k,\min}$, then the pair$(R, R_{\min})$ is called a K-person bargaining game with $R = (R_1, \ldots, R_K)$ and $R_{\min} = (R_{1,\min}, \ldots, R_{K,\min})$

Given the above bargaining game definition, the notion of Pareto optimality is defined as follows.

Definition 1: The point $(R_1, \ldots, R_K)$ is said to be Pareto optimal, if and only if there is no other allocation $R_i^{'}$ such that $R_i^{'} \geq R_i$ holds for any $i \in \{1, 2, \ldots, K\}$, and $R_i^{'} > R_i$ holds for some $i \in \{1, 2, \ldots, K\}$.

The interpretation of Pareto optimum is that it is impossible to find another point which leads to strictly superior payoff for all the MSs simultaneously. There might be an infinite number of Pareto optimal points. One way to obtain suitable Pareto optimal operating points is by introducing fairness criteria. In the paper, we use the criterion of fairness NBS. The idea is that after the minimal requirements are satisfied for all MSs, the rest of the resources are allocated proportionally to MSs according to their channel conditions. Therefore NBS can provide a unique and fair Pareto optimal operating point, the concept of which is given in [29] as follows.

Definition 2: Given $R = (R_1, \ldots, R_K)$ and $R_{\min} = (R_{1,\min}, \ldots, R_{K,\min})$, define $R^* = (R_1^*, \ldots, R_K^*) = \Pi(R, R_{\min})$ R^* in $\boldsymbol{R}$ is an NBS, if the following axioms are satisfied: minimum required payoff, Pareto optimality, irrelevant alternatives axiom, linearity axiom and symmetry axiom.

Owing to the characterisation of the NBS, the set of the bargaining solutions is determined as follows.

Theorem 1: Let $\boldsymbol{K} = \{1, 2, \ldots, K\}$ be the set of indices of MSs who are able to achieve performance strictly superior to their minimal payoff. Then there exists a unique NBS that satisfies all axioms in Definition 2. This solution is the unique solution of the maximisation problem

$$\max \prod_{k\in\mathcal{K}} (R_k - R_{k,\min}) \quad (2)$$

The maximisation problem results in the unique NBS, the proof has been made in [28].

It has been shown in [24] that (2) is equivalent to

$$\max \sum_{k\in\mathcal{K}} \ln(R_k - R_{k,\min}) \quad (3)$$

From Theorem 1, the NBS of the OFDMA game is the solution of the following global optimisation problem

$$\text{NBS: } \max_{\text{X,P}} \sum_{k\in\mathcal{K}} U_k(R_k) = \max_{\text{X,P}} \sum_{k=1}^{K} \ln(R_k - R_{k,\min}) \quad (4.1)$$

$$\text{subject to: } p_{k,n,t} \geq 0, \quad \forall k, n, t \quad (4.2)$$

$$x_{k,n,t} = \{0, 1\}, \quad \forall k, n, t \quad (4.3)$$

$$\sum_{k=1}^{K} x_{k,n,t} = 1, \quad \forall n, t \quad (4.4)$$

$$\sum_{k=1}^{K}\sum_{n=1}^{N} p_{k,n,t} = P^{\text{total}} \text{ for each time slot} \quad (4.5)$$

where $U_{\mathrm{k}}(R_{\mathrm{k}}) = \ln(R_k - R_{k,\min})$ is the utility of the kth MS, and $\boldsymbol{X}$ and $\boldsymbol{P}$ denote the subchannel allocation matrix and the power allocation matrix, respectively. For comparison, the objective functions of the max-rate optimisation [17, 18] and max–min optimisation [21] can be, respectively, defined as

$$\text{max-rate: } \max_{\boldsymbol{X},\boldsymbol{P}} \sum_{k\in\mathcal{K}} R_k \quad (5)$$

$$\text{max-min fairness: } \max_{\boldsymbol{X},\boldsymbol{P}} \min_{k\in\mathcal{K}} \{R_k\} \quad (6)$$

The optimisation problem in (4) is an NP-hard combinatorial problem, it is necessary to decompose it into several sub-problems of lower complexity in order to derive a sub-optimal solution. For implementation purpose, we separate the optimisation problem into two sub-problems, that is, slot allocation and power allocation.

4 Time-frequency-power resource allocation

In order to reduce the complexity, the JEEP resource allocation, is divided into the following three steps.

4.1 Time-frequency resource allocation

In this algorithm, to simplify the problem, the transmission power is equally distributed among the subchannels as follows

$$p_{k,n,t} = \begin{cases} P^{\text{Total}}/N, & x_{k,n,t} = 1 \\ 0, & x_{k,n,t} = 0 \end{cases} \quad (7)$$

To further simplify the problem, the slot assignment indicators $x_{k,n,t}$ are relaxed to be a real number in [0, 1]. Therefore under the condition of fixed power allocation, which means the power allocation matrix $\boldsymbol{P}$ is known, the optimisation problem (4) can be mathematically simplified as follows

$$\text{NBS: } \max_{x_{k,n,t}} \sum_{k=1}^{K} U_k(r_k) \quad (8)$$

$$\text{subject to } \begin{cases} \sum_{k=1}^{K} x_{k,n,t} = 1, & \forall n, t \\ x_{k,n,t} \geq 0, & \forall k, n, t \\ r_k \geq r_{k,\min} & \forall k \end{cases} \quad (9)$$

where r_k is the average bit rate of the kth MS in a frame. We have $r_k = \sum_{S_k} x_{k,n,t}\, b_{k,n,t}$, and S_k is the set of slots assigned to the kth MS.

In the following, we analyse the simplified problem in (8) and (9) using the Lagrange multiplier method, and the Lagrange penalty function is defined as

$$L(x, \lambda, \gamma, \mu) = \sum_{k=1}^{K} U_k(r_k) - \sum_{n=1}^{N}\sum_{t=1}^{T} \lambda_{n,t}\left(\sum_{k=1}^{K} x_{k,n,t} - 1\right) + \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{t=1}^{T} \gamma_{k,n,t}x_{k,n,t} - \sum_{k=1}^{K} \mu_k(r_{k,\min} - r_k)$$

where $\lambda_{n,t}$, $\gamma_{k,n,t}$ and μ_k are non-negative Lagrange multipliers. Then take the derivatives with respect to $x_{k,n,t}$, and the Karush–Kuhn–Tucker condition [31] is given as follows

$$[U_k'(r_k) + \mu_k] \times b_{k,n,t} - \lambda_{n,t} + \gamma_{k,n,t} = 0 \quad (10)$$

and

$$\gamma_{k,n,t} \times x_{k,n,t} = 0, \quad \forall k, n, t \quad (11)$$

$$\mu_k(r_{k,\min} - r_k) = 0, \quad \forall k \quad (12)$$

Under the assumption of $\sum_{k=1}^{K} R_{k,\min} \leq B$, the constraints $r_k > r_{k,\min}$ are non-native and hence $\mu_k = 0$ for all $k = 1, 2, \ldots, K$.

Thus, if the nth subchannel is allocated only to the kth MS, from (10)–(12), we have $x_{k,n,t} > 0$, $\gamma_{k,n,t} = 0$ and

$$U_k'(r_k) \times b_{k,n,t} = \lambda_{n,t} \quad (13)$$

If the nth subcarrier is not allocated to the kth MS, from (10)–(12), we have $x_{k,n,t} = 0$, $\gamma_{k,n,t} \geq 0$ and

$$U_k'(r_k) \times b_{k,n,t} \leq \lambda_{n,t} \quad (14)$$

Considering that $\lambda_{n,t}$ is a constant value for all MSs in a slot, from (13) and (14), we can conclude that if $\text{slot}_{n,t}$ is allocated to the kth MS, then $U_k'(r_k) \times b_{k,n,t}$ gets the maximum value. So we have the following closed form of the slot assignment

$$k^* = \arg\max_k [U_k'(r_k) \times b_{k,n,t}] \quad (15)$$

where k^* represents that $\text{slot}_{n,t}$ should be assigned to the k^*th MS. Its computational complexity is only $O(\text{KNT})$, which is suitable for real-time systems compared to the combinatorial optimisation problem of which the computational complexity is K^{NT}.

IET Commun., 2011, Vol. 5, Iss. 7, pp. 967–974
doi: 10.1049/iet-com.2010.0530

4.2 Power resource allocation

So far we have studied the slot allocation problem under the assumption that the same power is assigned among subchannels; therefore based on the achieved slot allocation, the power optimisation problem in (4) can be formulated as

$$\text{NBS: } \max_{p_n} \sum_{k=1}^{K} \text{In}(r_k - r_{k,\min})$$
$$= \max_{p_n} \sum_{k=1}^{K} \text{In}\left\{ \sum_{n=1}^{N} x_{k,n,t} \Delta f \log_2\left(1 + \frac{p_n h_{k,n,t}}{\Gamma}\right) - r_{k,\min} \right\} \quad (16)$$

$$\text{subject to: } \begin{cases} p_n \geq 0 \\ \sum_{n=1}^{N} p_n \leq P^{\text{Total}} \text{ for each time slot} \end{cases} \quad (17)$$

where $h_{k,n,t} = g^2_{k,n,t}/\sigma^2$ [27], p_n is the transmit power on the nth subchannel, and $x_{k,n,t}$ is the determined results after performing the slot allocation. Thus, we just need to allocate transmit power among subchannels. Again using Lagrange multiplier methods we can obtain the Lagrange function as follows

$$L(\boldsymbol{p}, \lambda) = \sum_{k=1}^{K} U_k(r_k(\boldsymbol{p})) - \lambda\left(\sum_{n=1}^{N} p_n - P^{\text{Total}}\right) \quad (18)$$

Note that

$$\frac{\partial L}{\partial p_n} = \frac{\partial U_\mu}{\partial r_\mu}\frac{\partial r_\mu}{\partial p_n} - \lambda \quad (19)$$

where the μth MS is allocated with the nth subchannel.

From (17), we can have

$$\frac{\partial r_\mu}{\partial p_n} = \frac{h_{\mu,n,t}\Delta f}{\Gamma + p_n h_{\mu,n,t}} \quad (20)$$

Substituting (20) into (19) and setting it to be 0, we have

$$\frac{\partial L}{\partial p_n} = U'(r_\mu)\frac{h_{\mu,n,t}\Delta f}{\Gamma + p_n h_{\mu,n,t}} - \lambda = 0 \quad (21)$$

Thus, we obtain

$$p_n = \frac{U'(r_\mu)\Delta f}{\lambda} - \frac{\Gamma}{h_{\mu,n,t}} \quad (22)$$

Noticing the fact that $\sum_{n=1}^{N} p_n = P^{\text{Total}}$ in the actual condition, then we have

$$\frac{1}{\lambda}\sum_{n=1}^{N} U'(r_\mu)\Delta f - \sum_{n=1}^{N}\frac{\Gamma}{h_{\mu,n,t}} = P^{\text{Total}} \quad (23)$$

Solving for λ and substituting the result back into (22), we obtain

$$p_n = \frac{U'(r_\mu)}{\sum_{n=1}^{N} U'(r_\mu)}\left(P^{\text{Total}} + \sum_{n=1}^{N}\frac{\Gamma}{h_{\mu,n,t}}\right) - \frac{\Gamma}{h_{\mu,n,t}} \quad (24)$$

If the maximum value of utility is normalised to 1, then we have

$$\frac{U'(r_\mu)}{\sum_{n=1}^{N} U'(r_\mu)} = \frac{1}{N}$$

and

$$p_n = \frac{1}{N}\left(P^{\text{Total}} + \sum_{n=1}^{N}\frac{\Gamma}{h_{\mu,n,t}}\right) - \frac{\Gamma}{h_{\mu,n,t}} \quad (25)$$

So the optimal power is

$$p_n^* = \begin{cases} \frac{1}{N}\left(P^{\text{Total}} + \sum_{n=1}^{N}\frac{\Gamma}{h_{\mu,n,t}}\right) - \frac{\Gamma}{h_{\mu,n,t}}, & \text{if } x_{k,n,t} = 1 \\ 0, & \text{otherwise} \end{cases} \quad (26)$$

4.3 Time-frequency-power resource allocation

To summarise, in the above two steps, firstly, assume that the transmission power is equally distributed among all the subchannels. Therefore the slot assignment can be obtained according to (15). Secondly, based on the achieved slot allocation results, the power optimisation problem in each slot can thus be solved according to (26). However, this is not the Pareto optimum, that is, not the JEEP resource allocation.

So in the third step, we substitute the power allocation results achieved in the second step into the first step and calculate the slot assignment again, as shown in Fig. 3. This

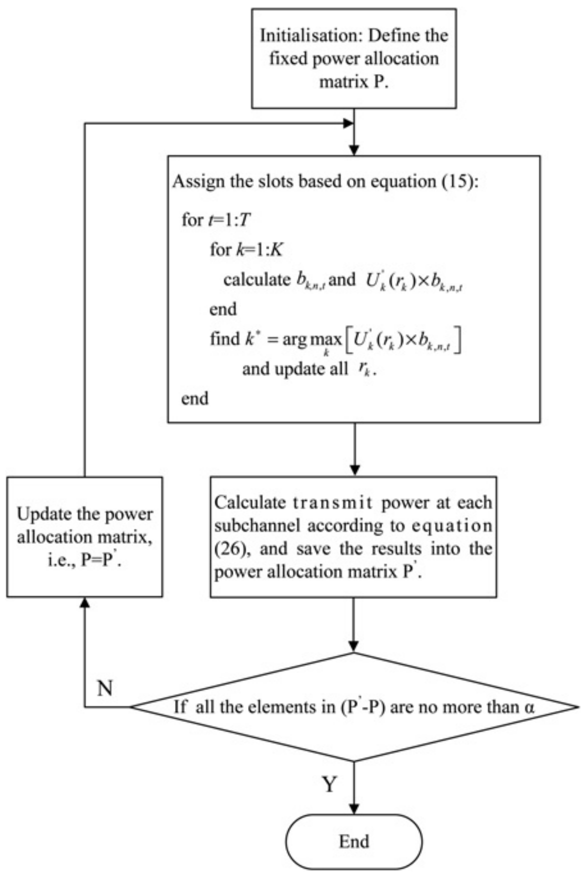

Fig. 3 *JEEP resource allocation*

iteration will be run repeatedly until the results get convergence, and α is the result error that determines the termination of the whole algorithm.

5 Performance evaluation

We perform the following simulations to evaluate the proposed JEEP resource allocation algorithm in AirWiMAX.

5.1 Simulation scenario

We set a hierarchical AirWiMAX topology with seven aero routers installed at captive balloons of 2 km in height, each of which services one cell on the ground. We consider a rectangular area of 180×180 km on the ground where clients are randomly distributed in this area. Besides, the inter-cell interference is considered. Obviously, the coverage area of AirWiMAX is much larger than that of WiMAX. Normally, it is supposed to set thousands of ground BSs to cover such an area.

The values of the parameters used for simulations are specified in IEEE 802.16e standard [9]. Owing to the better air-ground radio environment, the transmit power of routers is decreased to 30 dBm and their antenna gain is 16 dBi, which are less than those defined in 802.16e. Hence, it would be much easy to implement the aero routers at captive balloons. Some of the main parameters are given in Table 1.

For general bandwidth configurations, the occupations of resources in a frame are 50% for DL, and 50% for UL. Four different types of service requirements are considered, which are VoIP, web-browsing, video and file-download with data rate of 64, 128, 384 and 1024 kbps, respectively.

Assume that CSI of each MS is also perfectly known at its BS. The empirical channel model is an ITU channel model for vehicular systems [32]. The path loss is modelled by

$$\mathrm{PL} = 20\log_{10}(4\pi d_0/l) + 10\sigma\log_{10}(d/d_0) \tag{27}$$

where $d_0 = 100$ m, l is the wavelength in metres, and σ is the path-loss exponent.

5.2 Performance of the proposed JEEP resource allocation algorithm in the AirWiMAX downlink

In order to evaluate the performance of the proposed JEEP resource allocation algorithm, the well-known max-rate and max–min algorithms are also performed for the AirWiMAX downlink in the same scenarios. In the max-rate algorithm, in order to achieve the maximum data rate, more subchannels are allocated to the MSs with better channel conditions, as discussed in (5). However, the max–min algorithm aims to have all the MSs achieve the same data rate; so more subchannels are allocated to the MSs with worse channel conditions, as discussed in (6).

Table 1 Simulation parameters

carrier frequency	3.5 G
frame length	8 ms
number of subchannels	8
number of timeslots in a frame	20
FFT size	2048
modulation mode	BPSK

Fig. 4 shows the average system throughput per cell, and each MS randomly chooses one of the four types of service. Fig. 5 shows the fairness of each MS, and the 1024 kbps traffic is used. The downlink bandwidth is set to be 10 MHz for both cases and all the MSs are randomly distributed in the seven cells.

Fairness is evaluated in terms of the fairness index β [21], which is defined as

$$\beta = \frac{\left(\sum_{i=1}^{K} B_i\right)^2}{K\sum_{i=1}^{K} B_i^2} \tag{28}$$

where K is the number of the MSs currently in the system, B_i is the bandwidth that assigned to the ith MS, $1 \le i \le K$.

The max-rate algorithm makes full use of MSs with better channel conditions (i.e. they are allocated with more subchannels), so obviously its system throughput is the maximum among the three algorithms, as shown in Fig. 4. However, it faces the fairness problem, as shown in Fig. 5. In order to serve the MSs with the worst channel conditions, the max–min algorithm always allocates more subchannels to those MSs with worse channel conditions. Thus, this algorithm can achieve a good fairness among all the MSs. However, it decreases the achievable throughput of MSs with good channel conditions. So its system throughput is the lowest among the three algorithms. As for our proposed JEEP algorithm, after satisfying the QoS demands ($R_{\min}$), the resources are proportionally allocated according to each MS's channel conditions. Thus, the proposed JEEP algorithm achieves a good trade-off between the other two algorithms in terms of the system throughput and fairness property.

Fig. 6 shows the average system throughput under different size of downlink bandwidth. In this scenario, 700 MSs are

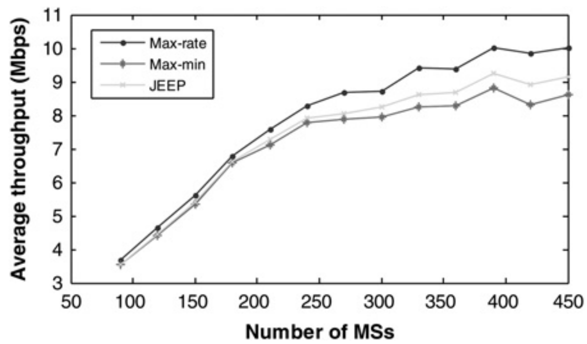

Fig. 4 *Network throughput against number of MSs*

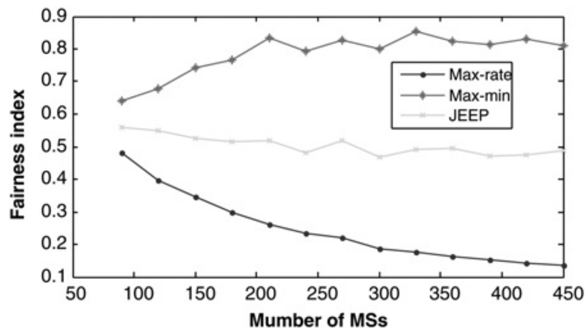

Fig. 5 *Fairness against number of MSs*

IET Commun., 2011, Vol. 5, Iss. 7, pp. 967–974
doi: 10.1049/iet-com.2010.0530

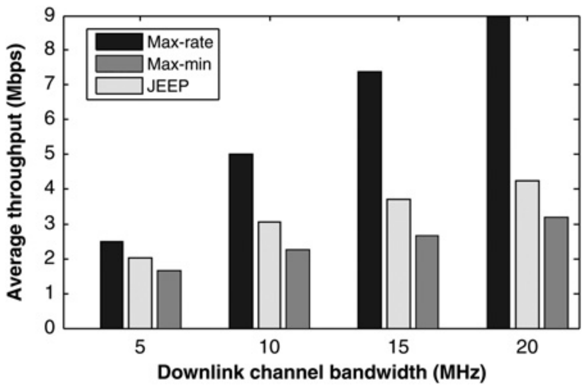

Fig. 6 *Network throughput against channel bandwidth*

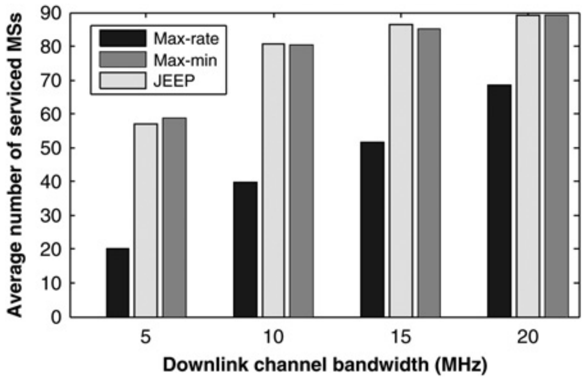

Fig. 7 *Number of serviced MSs against channel bandwidth*

randomly distributed in the seven cells. Fig. 7 shows the number of MSs that the network can serve. The 64 kbps VoIP traffic is considered for both cases.

As shown in Fig. 6, the max-rate algorithm achieves the maximum throughput, and the max–min algorithm obtains the minimum throughput, while the JEEP algorithm is a trade-off of the other two. However, the average number of serviced MSs in the max–min and JEEP algorithm is higher than that in the max-rate algorithm.

Fig. 8 shows the average system throughput per cell under different types of services, and 300 MSs are distributed randomly in the seven cells. Fig. 9 shows the number of MSs that the network can serve. In both cases, the downlink bandwidth is set to be 10 MHz.

For the light traffic requirement, that is, 64 and 128 kbps, system throughput and the number of serviced MSs in the three algorithms is almost the same as the system is not saturated. Thus, each allocation algorithm can handle the network traffic efficiently. However, when the required service rate increases, the system resource cannot support all the requirements. The three resource allocation algorithms show different performance. For example, the system throughput of the max-rate algorithm increases sharply, but the number of serviced MSs decreases sharply too. The JEEP algorithm shows a good trade-off property compared with the other two algorithms.

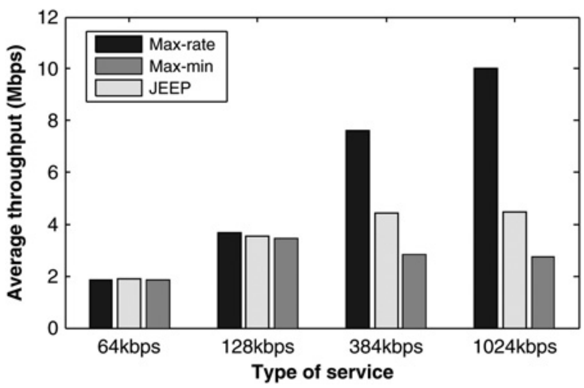

Fig. 8 *Network throughput against service requirements*

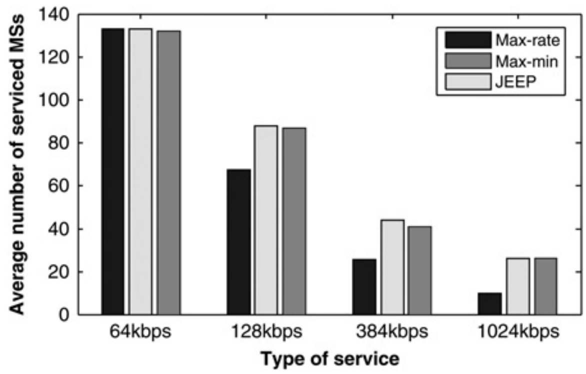

Fig. 9 *Number of serviced MSs against service requirements*

6 Conclusions

In this paper, firstly, in order to take full advantage of LMPS and WiMAX, a hierarchical mesh topology is presented for AirWiMAX in emergency scenarios, which includes an aero mesh backbone network and ground PMP access networks. The main advantage of AirWiMAX is that it is easy and fast to deploy, which is the key issue on emergency services. Secondly, a cooperative game theory is introduced to develop a fair algorithm for adaptive resource allocation in the downlink of ground access networks. To reduce the computation complexity, the proposed JEEP algorithm divided the JEEP resource allocation into three steps, a slot allocation, a power allocation and iteration. By using the Lagrange multiplier method, the JEEP algorithm reduces complexity further. Simulation results show that the JEEP algorithm provides much better performance than that of the max–min scheme in terms of system throughput and better performance than that of the max-rate in terms of fairness. That is to say, the JEEP algorithm finds a good trade-off between system throughput and fairness.

We are carrying out researches in the following two topics. Firstly, we introduce the mesh topology into the ground PMP access networks, and are researching JEEP resource algorithms for the PMP/Mesh hybrid access networks in both downlink and uplink. Secondly, we are researching joint time-frequency-code-power resource algorithms for AirWiMAX.

7 Acknowledgments

This work is supported by the 111 Project (B08038), State Key Laboratory of Integrated Services Networks (ISN090105), Program for New Century Excellent Talents in University (NCET-08-0810), National Natural Science Foundation of China (No. 60772137) and UK-China Science Bridges: R&D on (B)4 G Wireless Mobile Communications.

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