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Utility-based bandwidth allocation algorithm for heterogeneous wireless networks

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Abstract In next generation wireless network (NGWN), mobile users are capable of connecting to the core network through various heterogeneous wireless access networks, such as cellular network, wireless metropolitan area network (WMAN), wireless local area network (WLAN), and ad hoc network. NGWN is expected to provide high-bandwidth connectivity with guaranteed quality-of-service to mobile users in a seamless manner; however, this desired function demands seamless coordination of the heterogeneous radio access network (RAN) technologies. In recent years, some researches have been conducted to design radio resource management (RRM) architectures and algorithms for NGWN; however, few studies stress the problem of joint network performance optimization, which is an essential goal for a cooperative service providing scenario. Furthermore, while some authors consider the competition among the service providers, the QoS requirements of users and the resource competition within access networks are not fully considered. In this paper, we present an interworking integrated network architecture, which is responsible for monitoring the status information of different radio access technologies (RATs) and executing the resource allocation algorithm. Within this architecture, the problem of joint bandwidth allocation for heterogeneous integrated networks is formulated based on utility function theory and bankruptcy game theory. The proposed bandwidth allocation scheme comprises two successive stages, i.e., service bandwidth allocation and user bandwidth allocation. At the service bandwidth allocation stage, the optimal amount of bandwidth for different types of services in each network is allocated based on the criterion of joint utility maximization. At the user bandwidth allocation stage, the service bandwidth in each network is optimally allocated among users in the network according to bankruptcy game theory. Numerical results demonstrate the efficiency of the proposed algorithm.

Keywords heterogeneous wireless network, bandwidth allocation, utility function, bankruptcy game theory

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1 Introduction

Next generation wireless network (NGWN) is expected to integrate different radio access technologies (RATs) and to support user services with different quality-of-service (QoS) requirements. These access technologies may exhibit heterogeneous characteristics in terms of coverage area, the techniques of network

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management, the capability of service providing, service cost, etc. In the integrated scenario of RATs, mobile terminals (MTs) are allowed to seamlessly switch among various access networks and to be served at lower cost and with better QoS. However, this desired function demands seamless coordination of the heterogeneous radio access network (RAN) technologies. Although individual radio resource management (RRM) schemes may work optimally within their respective RANs, they may not perform efficiently in NGWN if different RRM schemes are not properly managed. Hence, a major issue is how to jointly utilize the resources of the different RANs in an efficient manner while achieving the desired QoS.

In recent years, some researches have been conducted to design novel RRM architectures [1,2] and algorithms for integrated RATs. The proposed RRM architectures can be categorized as network-centric, user-centric and hybrid architectures. In order to guarantee user seamless roaming and service continuity, a novel architecture called integrated inter-system architecture (IISA) is proposed in [3], which enables the integration and interworking of current wireless systems and supports user mobility management while roaming among access networks. Ref. [4] presents a cooperative framework based on distributed joint radio resource management (JRRM) where the concept of producer-consumer interaction in a market place is emphasized so that the requirements of both operators and users can be satisfied. A new JRRM architecture is proposed in [5] to provide efficient management for resources of heterogeneous access networks. By jointly managing system resources, resource managers of all networks are capable of achieving optimum resource allocation, in both centralized and distributed manner. Nevertheless, no specific user requirements are stressed in the proposed scheme.

Some researches focus on RRM algorithm design for wireless networks. As both resource utilization efficiency and the impacts of RRM on system performance are complicated systematic quantities characterized by multiple associated factors, exact mathematical descriptions are prohibited. Utility function [6], originating in economics theory, has been applied for solving resource management issues. Ref. [7] proposes an analytical solution for performance evaluation of dynamic policies for routing real-time jobs among parallel single-processor queues and presents a utility-aware dynamic routing policy to improve the expected accrued utility of the parallel system. A new framework called dynamic QoS-based bandwidth allocation (DQBA) is proposed in [8] to support heterogeneous traffic with different QoS requirements in Worldwide Interoperability for Microwave Access (WiMAX) networks. The allocated bandwidth is dynamically adjusted for ongoing and new arrival connections based on traffic characteristics and service demand in order to maximize the system capacity. In [9], the user spectrum allocation problem under multiple service providers (SPs) is modeled as a user welfare maximization problem and the optimal allocation policy is designed as a function of link gains and network efficiency. Ref. [10] proposes a new utility based cooperation scheme that allows cognitive radio (CR) users to relay the signals of primary users in exchanging for spectrum, and the power optimization of both the primary users and the CR users are defined as the utility function.

Applying utility function in heterogeneous integrated networks is considered in the literature. Ref. [11] proposes a utility based access selection algorithm with the target of achieving load balancing between the universal mobile telecommunication system (UMTS) and wireless local area network (WLAN). In [12], a distributed multi-service resource allocation algorithm for constant bit rate (CBR) and variable bit rate (VBR) services in a heterogeneous wireless access environment is presented. The utility function of each individual access system is defined and the utility maximization problem is optimally solved for resource allocation in a distributed manner. Ref. [13] proposes a novel economic model for radio resource allocation for both code-division multiple-access (CDMA) network and WLAN. The problem of radio resource allocation for both networks is formulated as the network welfare maximization issue, and a joint access control strategy is designed for achieving efficient resource sharing and load balancing. A utility-based bandwidth allocation algorithm is proposed in [14], and the utility fairness within the wireless access networks and among different access networks is considered.

Previous studies mainly focus on the utility optimization of individual access networks, and few of them stress the problem of joint network performance optimization, which is the essential goal for a cooperative service providing scenario. Furthermore, while some authors consider the competition among the SPs, the QoS requirements of users and the competition of users within access networks, which can be formulated as a game model, are not fully considered. Game theory has been applied in modeling resource management issues in a competitive scenario. A game theoretical model is proposed in [15] to characterize the decentralized interactions among heterogeneous sensors and the utility function is modeled and optimized to achieve the desired frame success rate of the sensor nodes. In [16], a non-cooperative game-theoretical framework for bandwidth allocation and admission control in heterogeneous wireless systems is formulated. Through modeling the non-cooperative relations between networks and users, the bandwidth amount allocated for each access network in a given area is optimally designed, and the bandwidth allocation scheme for a connection in each access network is proposed based on the maximization of the connection utility. Considering the dynamic competition among service providers and among users, the authors of [17] develop a two-level game framework. The underlying dynamic service selection is modeled as an evolutionary game based on replicator dynamics and an upper bandwidth allocation differential game is formulated to model the competition among different service providers. In [18], the bandwidth allocation problem in a heterogeneous wireless access network is modeled as two-level game model, and both users selecting networks and network allocating bandwidth are considered. However, only the performance of individual networks is considered, the joint system performance is neglected. Moreover, it is assumed that the same amount of bandwidth is allocated to the users of the same type of services, which is relatively impractical.

In this paper, we extend the problem of bandwidth allocation for heterogeneous wireless access networks discussed in [18] to a more complicated yet practical, application scenario. More specifically, we focus on the problem of bandwidth allocation among multiple users with various types of services. Instead of considering the profit maximum of individual access networks, the joint performance of multiple access networks is stressed, based on which an optimal bandwidth allocation scheme is proposed. Furthermore, in designing the bandwidth allocation scheme, multiple factors, including joint network performance, load balancing among access networks, and user QoS requirements, etc. are taken into account.

A new JRRM architecture is presented in this paper, which supports information monitoring and bandwidth allocation of the integrated networks, and then an optimal bandwidth allocation scheme for heterogeneous integrated networks is proposed. The new scheme comprises two successive stages, service bandwidth allocation and user bandwidth allocation. At the service bandwidth allocation stage, the optimal amount of bandwidth for different types of services in each network is allocated based on the criterion of joint network utility maximization. Then, at the user bandwidth allocation stage, the service bandwidth allocated for each network is optimally allocated among users in the network according to bankruptcy game theory.

The rest of this paper is organized as follows. The proposed JRRM architecture is described in Section 2. The utility function based optimization for service bandwidth allocation in heterogeneous wireless access networks is described in Section 3. In Section 4, the bankruptcy game model for user bandwidth allocation is set up and solved based on Shapley value. Section 5 presents the numerical evaluation results. Conclusions are stated in Section 6.

2 Proposed architecture for heterogeneous wireless networks

In NGWN, the available radio resources need to be used in a coordinated way to guarantee adequate satisfaction levels to all users, and to maximize the system revenues of all the networks. To achieve cooperative resource management among access networks, a novel JRRM integrated network architecture is proposed in this paper. Figure 1 shows the model of the proposed architecture, in which the functional entities user RRM (URRM), local RRM (LRRM) and global RRM (GRRM) are introduced to tackle the dynamic information of integrated networks and to achieve optimal bandwidth allocation for the users. The major functions of URRM, LRRM and GRRM are as follows.

URRM: functional module embedded in each MT, in charge of storing available network information, perceiving service type and requirements, and sharing the collected information with the attached LRRM.

LRRM: deployed in each access network, being responsible for interacting with the URRMs and the GRRM, collecting network resource information, i.e., the available bandwidth and the total bandwidth

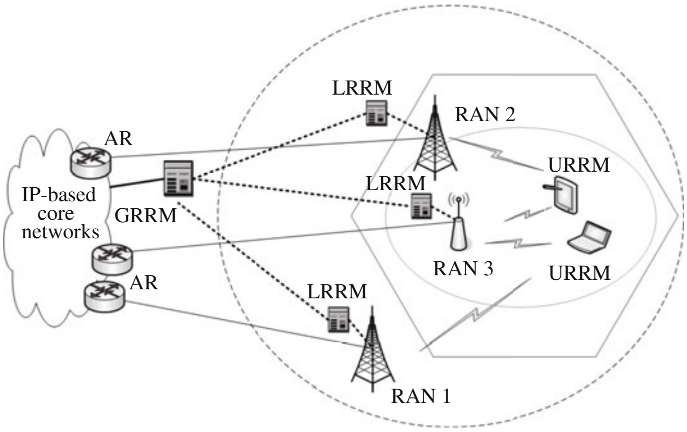

Figure 1 The architecture of interworking integrated network.

of the current network, and user information reported by URRMs, and reporting user and network information to GRRM. Given the allocated bandwidth for each particular type of service of one network, LRRM performs bandwidth allocation for each MT inside that network based on a bankruptcy game theory model, as will be discussed in Section 4.

GRRM: deployed outside all the access networks. Through interacting with the LRRMs, GRRM obtains the bandwidth information of all the networks and user service requirement information, and then conducts bandwidth allocation based on the joint utility optimization scheme, as will be discussed in Section 3.

3 Joint utility modeling for heterogeneous integrated networks

In this paper, we consider a heterogeneous integrated network scenario consisting of various wireless access networks. In particular, we focus on an overlapped geographic region with multiple networks, in which the MTs with multiple interfaces are able to freely access any available networks, and the access networks are allowed to provide services to any users. We denote the number of access networks in the region by M, and the number of service types provided by the networks in the region by K (i.e., the same number and type of services of all networks). Assuming that N is the total number of users in the region and N_k is the number of users that choose the kth type of service, under the common assumption that each user can request only one service at a given time, we obtain $\sum_{k=1}^{K} N_k = N$.

In this section, the optimal service bandwidth allocation problem for multi-network, multi-user and multi-service types is studied. To take into account the efficiency of bandwidth utilization, the QoS requirements for individual service types, and the balancing among service types, a utility function based optimization strategy is designed. By grouping the bandwidth requests for the same service type in one particular access network together, and introducing the variables of the amount of allocated bandwidth for each service type in each network, the joint network utility function is modeled and the optimal service bandwidth allocation scheme based on the criterion of joint utility maximization is proposed.

3.1 Joint network utility modeling

In this subsection, the utility function is applied to model the total revenue of the integrated access networks. The utility of one access network is closely related to the services provided to the users, which can be qualitatively characterized by the bandwidth resource allocated to the users. On one hand, while receiving communication services from access networks, users need to pay certain amount of service fees to the corresponding SP, and in general the amount of money users have to pay is monotonically increasing with the increase of user allocated bandwidth, which results in the increase of the network utility in turn. On the other hand, the more users accessing the system, and the more bandwidth resources users are occupying for their services, the higher competition for system resources, which may in turn deteriorate system performance and decrease system utility significantly. Furthermore, to offer accessing services to users, the SPs have to undertake certain infrastructure and people cost.

Taking into account the above three major factors contributing to network utility, the utility function of an integrated access network can be expressed as

$$U(\boldsymbol{B}) = R(\boldsymbol{B}) + E(\boldsymbol{B}) + C(\boldsymbol{B}), \tag{1}$$

where $\boldsymbol{B} = [\boldsymbol{B}_1, \boldsymbol{B}_2, \ldots, \boldsymbol{B}_M]$ denotes the allocated bandwidth resource matrix of the integrated networks, $\boldsymbol{B}_m = [B_{1,m}, B_{2,m}, \ldots, B_{K,m}]^{\mathrm{T}}$ denotes the bandwidth allocation vector of K types of the service in the mth network, $m = 1, 2, \ldots, M$, $B_{k,m}$ denotes the allocated amount of bandwidth for the kth type of service in the mth network, $\boldsymbol{X}^{\mathrm{T}}$ denotes the transpose of vector or matrix $\boldsymbol{X}$, $R(\boldsymbol{B})$, $E(\boldsymbol{B})$, and $C(\boldsymbol{B})$ are defined as the network reward function, the bandwidth competition function and the network cost function, respectively. In the following, the utility components $R(\boldsymbol{B})$, $E(\boldsymbol{B})$, and $C(\boldsymbol{B})$ will be modeled in detail.

3.1.1 *Network reward function modeling*

The joint network reward of the access networks can be calculated as the sum of service fees received by each network for each individual service, i.e.,

$$R(\boldsymbol{B}) = \sum_{m=1}^{M} R_m = \sum_{m=1}^{M}\sum_{k=1}^{K} R_{m,k}, \tag{2}$$

where R_m denotes the reward of the mth network, $R_{m,k}$ denotes the reward received from the kth type of service in the mth network, and is characterized as a nonlinear function of service bandwidth and unit service fee:

$$R_{m,k} = \alpha_{m,k} p_{m,k} B_{k,m}^{\varepsilon_m}, \tag{3}$$

where $\alpha_{m,k}$ and $p_{m,k}$ denote the scale parameter of the reward function and the unit service fee corresponding to the kth type of service in the mth network, ε_m denotes the bandwidth revenue index of the mth network, $m = 1, 2, \ldots, M$, $k = 1, 2, \ldots, K$, ε_m is associated with multiple factors including the working mechanism and the capability of service provisioning of each individual network, and the serving policy of respective SPs. The larger ε_m, the higher revenue the SP can obtain by offering the bandwidth resources to users.

Substituting (3) into (2), and rewriting the equation in matrix form, we obtain

$$R(\boldsymbol{B}) = \sum_{m=1}^{M}\sum_{k=1}^{K} \alpha_{m,k} p_{m,k} B_{k,m}^{\varepsilon_m} = \mathbf{I}_{1\times K}(\boldsymbol{B}\cdot\boldsymbol{\Theta}), \tag{4}$$

where, $\mathbf{I}_{1\times K}$ denotes a $1 \times K$ unit row matrix, $\boldsymbol{\Theta}$ is defined as a joint network revenue operator, with the dimension of $M \times 1$, and is expressed as

$$\boldsymbol{\Theta} = [\theta_1(\cdot)\ \theta_2(\cdot)\ \cdots\ \theta_M(\cdot)]^{\mathrm{T}}, \tag{5}$$

where $\theta_m(\cdot)$ denotes the revenue operator of the mth network, and is defined as $B_{k,m}\theta_m(\cdot) = \alpha_{m,k} p_{m,k} \times B_{m,k}^{\varepsilon_m}$, $\boldsymbol{B}\cdot\boldsymbol{\Theta}$ is defined as applying the operator $\boldsymbol{\Theta}$ on each row of the matrix $\boldsymbol{B}$.

3.1.2 *Bandwidth competition function modeling*

More users competing for system bandwidth resources may result in the decrease of average resource occupation of users, thus directly affecting both user QoS and network performance, and resulting in the decrease of network utility in turn. In this paper, the quadratic utility function is applied to model the bandwidth competition function $E(\boldsymbol{B})$. The quadratic utility function was originally introduced in economics theory and has been used in communication area [19–21]. In our work, the function is modeled to characterize the effect of bandwidth competition on network utility when considering the competition among the wireless access networks and among the different users. It is apparent that due to limited capacity of the access networks, user competition for system resources exists inside one specific network, especially for systems with relatively high service load. Allocating a large amount of bandwidth to one user may affect QoS of other users significantly. As users in the overlapped area of various access networks tend to access or switch to the network with the best performance-cost-ratio (PCR), those users who experience deteriorated or unsatisfied QoS due to resource competition may choose to switch to other networks, resulting in a decrease of system utility in the previous network. Furthermore, the relatively small bandwidth occupation might not increase system load significantly, resulting in relatively small utility loss. However a large bandwidth occupation tends to increase system load and affect the resource allocation of other users significantly, which has a much higher impact on system utility. To characterize this property quantitatively, a quadratic utility function is a suitable candidate [19–21].

The bandwidth competition function $E(\boldsymbol{B})$ can be expressed as the sum of the utility decrease due to the competition from different sources, i.e.,

$$E(\boldsymbol{B}) = E_0 + E_m + E_k, \tag{6}$$

where E_0 denotes the network utility loss due to single service resource occupation, E_m and E_k denote the network utility loss due to resource competition among different networks, and different types of services in one network. E_0 , E_m and E_k can be respectively modeled as

$$E_0 = -\beta \sum_{m=1}^{M} \sum_{k=1}^{K} B_{k,m}^2, \tag{7}$$

$$E_m = -\rho \sum_{k=1}^{K} \sum_{m_1=1}^{M} B_{k,m_1} \sum_{m_2=1, m_2 \neq m_1}^{M} B_{k,m_2}, \tag{8}$$

$$E_k = -\varepsilon \sum_{m=1}^{M} \sum_{k_1=1}^{K} B_{k_1,m} \sum_{k_2=1, k_2 \neq k_1}^{K} B_{k_2,m}, \tag{9}$$

where β, ρ, ε are bandwidth competition factors [19–21], characterizing the impacts of different types of competition on system utility. Especially, $\beta \in [0,1]$ denotes the bandwidth competition factor for each type of services inside each network, $\rho \in [0,1]$ denotes the bandwidth competition factor for the same type of services among different networks, and $\varepsilon \in [0,1]$ denotes the bandwidth competition factor for the different types of services inside each network. Substituting (7)–(9) into (6), and rewriting $E(\boldsymbol{B})$ in matrix form, we obtain

$$\begin{aligned} E(\boldsymbol{B}) = &-\beta \mathbf{I}_{1\times K} \boldsymbol{B} [f_1' \ f_2' \ \cdots \ f_M']^{\mathrm{T}} \mathbf{I}_{M\times 1} \\ &-\frac{\varepsilon}{2} \sum_{m=1}^{M} \left(\mathbf{I}_{1\times K} \boldsymbol{B}_m \boldsymbol{B}_m^{\mathrm{T}} \mathbf{I}_{K\times 1} - \boldsymbol{B}_m^{\mathrm{T}} \boldsymbol{B}_m \right) - \frac{\rho}{2} \sum_{k=1}^{K} \left(\mathbf{I}_{1\times M} \boldsymbol{D}_k \boldsymbol{D}_k^{\mathrm{T}} \mathbf{I}_{M\times 1} - \boldsymbol{D}_k^{\mathrm{T}} \boldsymbol{D}_k \right), \end{aligned} \tag{10}$$

where $f_m'(\cdot)$ denotes a square operator, which is defined as $B_{k,m} f_m'(\cdot) = B_{k,m}^2$, and $\boldsymbol{D}_k = [0\ 1(k\text{th}) \ \cdots \ 0] \cdot \boldsymbol{B}$ is the kth row of matrix $\boldsymbol{B}$.

3.1.3 *Network cost function modeling*

To provide users with different types of services, each individual network has to undertake a certain amount of cost. In general, the cost each network pays is monotonically increasing with the increase of user QoS; thus it can be characterized by a function of service bandwidth. Therefore, we can obtain the joint network cost function and rewrite $C(\boldsymbol{B})$ in matrix form as

$$C(\boldsymbol{B}) = -\gamma_{m,k} \sum_{m=1}^{M} \sum_{k=1}^{K} C_{m,k} B_{k,m} = -\gamma_{m,k} \mathbf{I}_{1\times K} \cdot \boldsymbol{B} \cdot \boldsymbol{F} \cdot \mathbf{I}_{K\times 1}, \tag{11}$$

where $C_{m,k}$ denotes the unit bandwidth cost corresponding to the kth type of service in the mth network, $\gamma_{m,k}$ denotes the corresponding cost factor, $\boldsymbol{F}$ is defined as a joint network cost operator and is expressed as

$$\boldsymbol{F} = [f_1(\cdot)\ f_2(\cdot)\ \cdots\ f_M(\cdot)]^{\mathrm{T}}, \tag{12}$$

where $f_m(\cdot)$ denotes the cost operator of the mth network, and is defined as $B_{k,m} f_m(\cdot) = C_{m,k} B_{k,m}$. $\boldsymbol{B} \cdot \boldsymbol{F}$ is defined as applying the operator $\boldsymbol{F}$ on each row of the matrix $\boldsymbol{B}$.

3.2 Optimization constraints

To perform optimal bandwidth allocation, some optimization constraints have to be considered, such as the availability of the networks, the load status of the network, and the services bandwidth demands.

3.2.1 *General constraints*

Denoting by B_m^{av} the total available network bandwidth resource of the mth network, the sum of bandwidth resources allocated for different types of services in the mth network should be no larger than B_m^{av}, i.e., $\sum_{k=1}^{K} B_{k,m} \leqslant B_m^{\mathrm{av}}$, for $m = 1, 2, \ldots, M$. Furthermore, as in general different types of services pose various bandwidth requirements, denoting by $B_m^{\max}$ and $B_m^{\min}$ the maximal and minimal bandwidth requirements of users with the kth type of service, the bandwidth allocation should be subject to the following constraint:

$$B_k^{\min} \leqslant \sum_{m=1}^{M} B_{k,m} \leqslant B_k^{\max}. \tag{13}$$

3.2.2 *Supplementary optimization constraints*

Under different network load statuses, which can be characterized by the difference of the total user service requirements, i.e., $\sum_{k=1}^{K} B_k^{\min}$, $\sum_{k=1}^{K} B_k^{\max}$ and the network available bandwidth, i.e., $\sum_{m=1}^{M} B_m^{\mathrm{av}}$, different supplementary optimization constraints should be introduced, as discussed in the following.

(i) Sufficient network bandwidth resource.

In the case where the network bandwidth resource is relatively sufficient compared to user requirements, we have

$$\sum_{k=1}^{K} B_k^{\max} \leqslant \sum_{m=1}^{M} B_m^{\mathrm{av}}. \tag{14}$$

As the available network bandwidth of the integrated access networks is much larger than the sum of all types of the maximal services in this case, the maximal bandwidth requirement of all the service types should be satisfied. Thus the optimization constraint, i.e., $\sum_{m=1}^{M} B_{k,m} = B_k^{\max}$ should be applied for each type of service, so that the best service performance can be achieved by the users.

(ii) Limited network bandwidth resource.

In the case where the network bandwidth resource is limited compared to the user requirements, i.e.,

$$\sum_{k=1}^{K} B_k^{\min} \leqslant \sum_{m=1}^{M} B_m^{\mathrm{av}} \leqslant \sum_{k=1}^{K} B_k^{\max}, \tag{15}$$

the maximal bandwidth allocation for all the service types cannot be provided. In order to guarantee that no service type experiences unacceptable service provision, the fairness of bandwidth allocation among various service types should be considered. In this paper, the bandwidth allocation ratio of the kth service type is defined as

$$\tau_k = \frac{\sum_{m=1}^{M} B_{k,m}}{B_k^{\max}} = \frac{\mathbf{I}_{1\times M} \cdot \boldsymbol{D}_k^{\mathrm{T}}}{B_k^{\max}}, \quad k = 1, 2, \ldots, K. \tag{16}$$

The service fairness constraint is defined as

$$|\tau_{k_1} - \tau_{k_2}| \leqslant \delta, \quad k_1 \neq k_2,\ k_1, k_2 = 1, 2, \ldots, K, \tag{17}$$

where δ is a given constant characterizing the difference of the bandwidth allocation ratios corresponding to different types of services.

(iii) Severely insufficient network bandwidth.

In the case where the network bandwidth resource is severely insufficient compared to user requirements, i.e.,

$$\sum_{m=1}^{M} B_m^{\mathrm{av}} \leqslant \sum_{k=1}^{K} B_k^{\min}, \tag{18}$$

the QoS acceptable service provisioning for all the service types cannot be guaranteed. In this case, one possible solution is to grade user services into different levels according to various QoS sensitive factors, such as bandwidth, connection delay, etc., and then to jointly design the access control scheme with the resource allocation scheme, so that only services with high priorities can be admitted and allocated bandwidth.

In this paper, we mainly focus on the bandwidth allocation scheme design for the first two cases. For the third case, assuming a suitable access control mechanism is applied, similar bandwidth allocation schemes as for the first two cases can be applied for reasonably selected services.

3.3 Optimization problem modeling

In this paper, an optimal bandwidth allocation scheme which maximizes the joint utilities of access networks under the general and supplement constraints is proposed. The optimization problem can be expressed as

$$\begin{aligned} \max U(\boldsymbol{B}) \quad & \text{subject to} \\ & \mathbf{I}_{1\times K}\cdot \boldsymbol{B}_m \leqslant B_m^{\mathrm{av}}, \\ & B_k^{\min} \leqslant \mathbf{I}_{1\times M}\boldsymbol{D}_k^{\mathrm{T}} \leqslant B_k^{\max}, \\ & \mathbf{I}_{1\times M}\boldsymbol{D}_k^{\mathrm{T}} = B_k^{\max}, \quad \text{if } \sum_{k=1}^{K} B_k^{\max} \leqslant \sum_{m=1}^{M} B_m^{\mathrm{av}}, \\ & |\tau_{k_1}-\tau_{k_2}| \leqslant \delta, \quad \text{if } \sum_{k=1}^{K} B_k^{\min} \leqslant \sum_{m=1}^{M} B_m^{\mathrm{av}} \leqslant \sum_{k=1}^{K} B_k^{\max}. \end{aligned} \tag{19}$$

While the analytical solution of the optimization problem may not be accessible, the numerical solution can be obtained based on mathematical software, such as MATLAB. In calculating the optimal bandwidth allocated for different types of services of each networks, for given numbers of different type of services of each network, iterative searching for the particular bandwidth combination which corresponds to the optimal joint utility is conducted. By solving the optimization problem (19), the optimal bandwidth allocation for different types of services in individual networks, i.e., $B_{k,m}$, $k = 1, 2, \ldots, K$, $m = 1, 2, \ldots, M$, can be obtained. Then, the question that follows is how to further allocate the amount of bandwidth to individual users in each network in an efficient and fair manner, as will be discussed in Section 4.

4 Bankruptcy game modeling and Shapley value

In this section, the problem of user bandwidth allocation will be stressed based on the bankruptcy game theory. We demonstrate that the proposed user resource allocation problem can be modeled as a bankruptcy game. Following a brief introduction of bankruptcy game theory, the game model for user bandwidth allocation is established and the optimal solution is presented.

4.1 Bankruptcy game

The theory of bankruptcy game can be traced back to an estate allocation problem of a bankruptcy company. Assume that a company with estate E becomes bankrupt, it owes money to creditors, and

Table 1 Variable notations and descriptions

Variable	Bankruptcy game	User bandwidth allocation
$N_{k,m}$	The total number of creditors	The number of users employing the kth type of service in the ith network
S	The subset formed by creditors	The subset formed by the users
$B_{k,m}$	The estate of the company	The amount of bandwidth for the kth type of service in the ith network allocated
$d_j^{\max}$	The maximum claims of the jth creditor	The maximum bandwidth demand of the jth user
$d_j^{\min}$	The minimum claims of the jth creditor	The minimum bandwidth demand of the jth user
d_j	The actual money paid for the jth creditor	The actual allocated bandwidth for the jth user

the amount of the money claimed for all the creditors is d. Then the money E is needed to be divided among N creditors, but typically the sum of the claims from the creditors is larger than the money of the bankrupt company, i.e., $E \leqslant d$. This conflicting situation introduces an N-person cooperative game [22], where the optimal solution for dividing the money can be obtained through solving the game model.

4.2 User bandwidth allocation modeling

From Section 3, we can obtain the optimal allocated bandwidth results for the kth service type in the mth network, i.e., $B_{k,m}$. Denoting by $N_{k,m}$ the corresponding number of users, the amount of bandwidth $B_{k,m}$ should be allocated to $N_{m,k}$ users optimally. While different types of services may exhibit various sensitivities to service QoS factors. For instance, voice users are in general more sensitive to transmission delay, and interactive data users are more sensitive to system throughput. For users employing the same type of service, they may also require different service QoS due to different service preferences, cost sensitivities and specific service requirements. Thus a fair and efficient bandwidth allocation scheme for users with the same type of service within one network should be designed. Denoting by d_j the actual allocated bandwidth for the jth user, $j = 1, 2, \cdots N_{k,m}$, the service requirement of the jth user can be expressed as

$$d_j^{\min} \leqslant d_j \leqslant d_j^{\max}, \tag{20}$$

where $d_j^{\min}$ and $d_j^{\max}$ denote the minimal and maximal bandwidth requirements of the jth user, respectively. As in general, $\sum_{j=1}^{N_{k,m}} d_j^{\max} \leqslant B_{m,k}$, given $B_{k,m}$, $d_j^{\min}$ and $d_j^{\max}$, the problem of optimal allocation of d_j can be modeled as a bankruptcy game of $N_{k,m}$ persons. For comparison, the variable notations and the descriptions of the original bankruptcy game and the proposed bandwidth allocation algorithm are summarized in Table 1.

4.3 Shapley value

There are several methods available in the literature to solve the N-person cooperative game, e.g., Shapley value, nucleolus and τ-value [23]. Among these approaches, Shapley value method is more commonly applied for its relatively low computational complexity and high efficiency. According to the Shapley value method [24], assuming that the alliance formed by the $N_{k,m}$ users constitutes a finite set N , with S denoting a subset of N, i.e., $S \subset N$, the characteristic function $\nu(S)$ of the union S can be calculated as

$$\nu(S) = \max\Big(0, B_{k,m} - \sum_{j \notin S} d_j^{\max}\Big). \tag{21}$$

By (21), $\nu(S)$ holds the largest number of the allocated bandwidth for the union S, then the Shapley value of the proposed model can be defined as

$$\boldsymbol{\varphi} = [d_1, d_2, \ldots, d_{N_{k,m}}] = [\varphi_1(\nu), \varphi_2(\nu), \ldots, \varphi_{N_{k,m}}(\nu)], \tag{22}$$

Table 2 Parameters of access networks

	WLAN				Cellular			
	$\alpha_{1,k}$	$p_{1,k}$ (1/kbps)	$\gamma_{1,k}$	$C_{1,k}$ (1/kbps)	$\alpha_{2,k}$	$p_{2,k}$ (1/kbps)	$\gamma_{2,k}$	$C_{2,k}$ (1/kbps)
Voice 1	0.8	5	0.15	1	0.9	8	0.05	2
Video 2	0.9	10	0.20	2	0.8	9	0.10	3

where the value function $\varphi_j(\nu)$ represents the worth or value of the jth user in the game with characteristic function ν and can be obtained as

$$\varphi_j(\nu) = \sum_{S \subset N} \frac{(|S|-1)!(N_{k,m}-|S|)!}{N_{k,m}!}[\nu(S)-\nu(S-\{j\})], \tag{23}$$

where $|S|$ denotes the number of elements in the set S. Assuming that the jth user is in the coalition S, $\nu(S)-\nu(S-\{j\})$ represents the contribution that the jth user makes to the coalition and $(|S|-1)!(N_{k,m}-|S|)!/(N_{k,m}!)$ represents the weight of the contribution that the jth user makes to the coalition, which is dependent on the size of the S and the total number of game players. By (23), the Shapley value $\varphi_j(\nu)$ $(j = 1, 2, \dots, N_{k,m})$ which corresponds to the bandwidth allocation value d_j can be obtained.

5 Performance evaluation

In this section, numerical simulation is conducted to demonstrate the efficiency of the proposed scheme.

5.1 Parameter settings

In our numerical simulation, a heterogeneous wireless network with two access systems and two types of services, i.e., voice service and video service, is assumed. Although different wireless access networks are expected to be integrated in NGWN, among all possible combinations, the most commonly studied and deployed heterogeneous integrated system mainly consists of cellular system, and WLAN for both networks are relatively mature technologies and have been widely applied. Therefore, in our simulation, we mainly consider the system integrated scenario of cellular system and WLAN. The number of users in the overlapped area of the two networks are assumed to be 50. For simplicity, in the simulation, the bandwidth unit of 16 kbps is defined. The amount of user required bandwidth and the allocated bandwidth are then both represented as the number of bandwidth units as in [25]. The parameters chosen in the simulations are shown in Table 2 and Table 3, and β, ε and ρ in the bandwidth competition function are chosen as $\beta = \varepsilon = 0.6,\ \rho = 0.7$.

5.2 Numerical results

In our simulation, we calculate the optimal bandwidth allocated for different type of services and for different users in each network, and the corresponding network utility. For given numbers of users of different types of services in each network, iterative searching for the particular bandwidth combination which corresponds to the optimal joint utility is conducted. Figure 2 and Figure 3 plot the utility of the joint networks as a function of the number of voice service users, corresponding to the case of sufficient bandwidth resources (case 1 in Table 3) and insufficient bandwidth resources (case 2 in Table 3), respectively. The three curves in the figures represent network utility performance for different bandwidth revenue factors, i.e, ε_1, ε_2. To plot each curve, the total number of voice and video users are fixed at 50, and the number of voice users is chosen as the value in the horizontal axis. The optimal bandwidth allocation solution for both voice and video services in both of the two networks can be obtained by maximizing the joint network utility, and the corresponding maximal utility is plotted in the figure. In Figure 2, as the bandwidth resource is sufficient, the bandwidth is allocated to the users in the way such that the maximum bandwidth requirement of the kth type of service can be achieved. Figure 2 shows that with the increase of the number of voice service users, the utility of the joint network increases. This

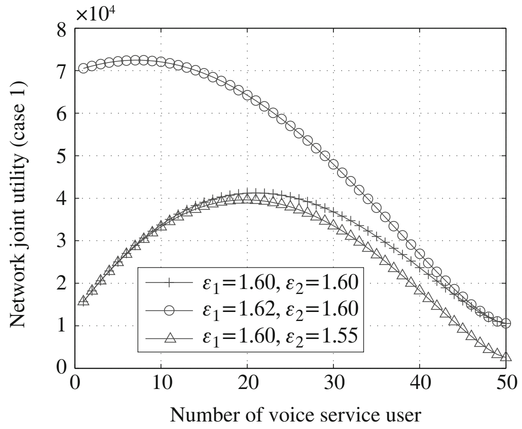

Figure 2 Utility function vs number of voice service users (case 1).

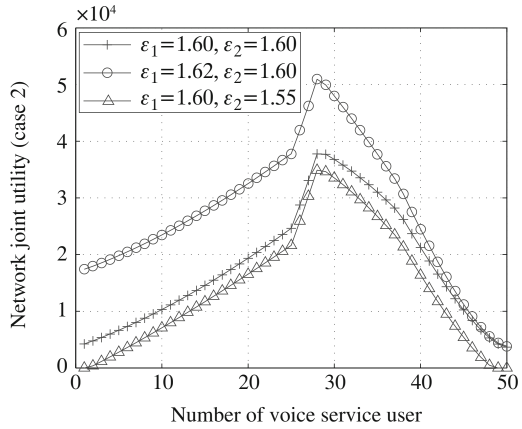

Figure 3 Utility function vs number of voice service users (case 2).

Table 3 Bandwidth parameters

Notation		WLAN ($m=1$)	Cellular ($m=2$)	Voice ($k=1$)	Video ($k=2$)
B_m^{av}	Case 1	800 units	400 units		
	Case 2	350 units	150 units		
$B_k^{\min}$				2 units	2 units
$B_k^{\max}$				4 units	16 units

is because high revenue can be obtained from the users. When the number of users reaches 8, 22, or 20, the utility of the joint network achieves its optimal value. When the number of users keeps increasing, the utility is decreasing. This can be explained by the fact that the cost for bandwidth competition and network service provision increases with an increase in the number of voice users, thus resulting in a decrease in network utility.

Similar results can be observed from Figure 3, where the case of insufficient bandwidth resources is considered. It can be seen that the utility of joint networks decreases significantly in Figure 3 compared to Figure 2. This is because less bandwidth resources can be allocated in this case, resulting in a decrease of network utility. In Figure 3, when the number of voice users increases from 1 to 28, the utility increases and reaches the maximum when the number of voice service users is 28. As the number of voice users is relatively small in this region, the number of video users is large, resulting in a high bandwidth requirement. Indeed, it can be verified that the available bandwidth of the access networks is smaller than the corresponding maximum bandwidth requirement of the services; thus, all the available bandwidth should be allocated to services so that the maximum joint utility can be achieved. When the number of voice users keeps increasing, the number of video users becomes smaller, leading to the decreased bandwidth requirement, and the available bandwidth of the networks then becomes sufficient for providing the maximum service requirement, as in Figure 2. As is evident in Figures 2 and 3, the impacts of the parameter ε_1 is larger than that of ε_2, indicating the first access network, i.e., WLAN, contributes more utility to the joint network utility than the cellular network. This is because WLAN is capable of providing user services with a large amount of bandwidth, which results in a relatively high utility.

In our simulation, we assume that the video service bandwidth offered by one network is 800 kbps, and there are 7 users employing video service, and we assume that the maximum bandwidth requests for each user are 150, 100, 190, 120, 140, 110, and 90 kbps, respectively. According to the Shapley value, the actual allocated bandwidth for each user can be calculated and compared with the user maximum bandwidth requirement as shown in Figure 4. It can be seen from Figure 4 that by applying the bankruptcy game model, a relatively fair bandwidth allocation with respect to user requirement can be achieved.

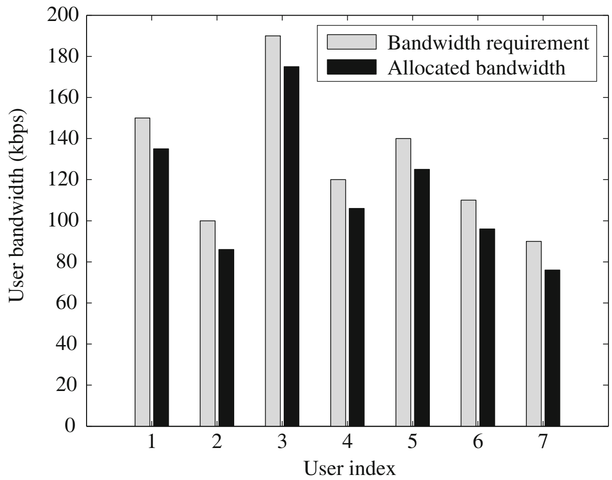

Figure 4 The comparison of user required bandwidth and allocated bandwidth.

6 Conclusions

In this paper, we propose a new JRRM system architecture for integrated wireless networks, which is in charge of monitoring the information status of the access networks and user service requirements, and executing the bandwidth allocation algorithm, as well as an optimal bandwidth allocation algorithm based on utility function and bankruptcy game. The utility of the joint access networks is modeled based on a quadratic utility function, and an optimal service bandwidth allocation scheme, which maximizes the joint network utility, is proposed under the constraints of bandwidth resource limitation, network load status and user service requirement. Finally, to optimally allocate user bandwidth among individual networks, a bankruptcy game model is applied. Numerical results demonstrate the efficiency of the proposed algorithm.

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