

JOINT RESOURCE ALLOCATION FOR WLAN&WCDMA INTEGRATED NETWORKS BASED ON SPECTRAL BANDWIDTH MAPPING¹

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Abstract Next wireless network aims to integrate heterogeneous wireless access networks by sharing wireless resource. The spectral bandwidth mapping concept is proposed to uniformly describe the resource in heterogeneous wireless networks. The resources of codes and power levels in WCDMA system as well as statistical time slots in WLAN are mapped into equivalent bandwidth which can be allocated in different networks and layers. The equivalent bandwidth is jointly distributed in call admission and vertical handoff control process in an integrated WLAN/WCDMA system to optimize the network utility and guarantee the heterogeneous QoS required by calls. Numerical results show that, when the incoming traffic is moderate, the proposed scheme could receive 5%-10% increase of system revenue compared to the MDP based algorithms.

Key words Equivalent bandwidth; Spectral bandwidth mapping; Heterogeneous networks; Resource management

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I. Introduction

The future wireless network will support heterogeneous multi-radio access technology to provide “optimal connection”^[1,2], which improve the resource efficiency and guarantee the QoS for calls by sharing resources in different heterogeneous networks. In the resources management aspect, call admission control and vertical handoff control are used to reserve and allocate resources for incoming and handoff calls to satisfy QoS of all calls. There are relatively more researches in this filed for homogeneous networks. Refs. [3–5] present different schemes of cross-layer resource allocation for cellular networks. In recent years, some researches emphasize on resource allocation in heterogeneous

networks. Refs. [6,7] proposed a “WLAN-first” scheme, where WLAN is preferred by calls in the double coverage area of WLAN and cellular networks, and those calls rejected by WLAN will overflow to the cellular networks. In Ref. [8], a Markov decision process is introduced into the vertical handoff resource allocation for heterogeneous networks. Refs. [9–12] proposed an admission scheme based on maximizing the revenue or minimizing the resource occupation.

The admission and handoff control criterions in above researches are essentially based on the comparison of the spectral bandwidth available in the system with the bandwidth required by incoming or handoff calls. However, the wireless resources cannot always be simply quantified by certain amount of spectral bandwidth. For example, a single call in WCDMA systems occupies the entire system bandwidth through spreading spectrum. Similarly, a call in WLAN systems competes with other ones for the whole spectrum bandwidth rather than being allocated with a section of spectral bandwidth. In fact, the physical layer resources straightforwardly seen in the

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WCDMA and WLAN systems are “spreading code”, “power level”, and “equivalent transmission time”, respectively. From this point of view, the collective problem about above algorithms [3–9] is that the resources in heterogeneous networks are not uniformly expressed and properly quantified and therefore the heterogeneous resources can hardly be efficiently allocated for calls staying in different networks. For instance, Ref. [8] can not establish a unified state space for WCDMA/WLAN networks in the Markov decision process because of the difference of resources in WCDMA and WLAN networks, the vertical handoff decision in Ref. [8] is thereby made periodically rather than triggered by variations of the network states, which has been proved not being optimal in terms of resource efficiency.

An equivalent bandwidth mapping concept is initially proposed in the paper to uniformly express and quantify resources in heterogeneous networks. The algorithm is based on the following fact: The only transmission medium for wireless communication networks is electromagnetic wave. The diverse resource forms, such as code in WCDMA and time in WLAN networks, can be seen as the different partition of the electromagnetic spectrum in different orthogonal spaces, and can be somehow mapped into spectral bandwidth (equivalent bandwidth mapping). Based on the equivalent bandwidth mapping concept, a unified state space can be constructed for integrated WLAN/WCDMA networks in the Markov decision process, and the resources can be allocated to calls in the joint call admission and vertical handoff control process which is modeled as a Markov decision process.

The rest of the paper is organized as follows: In Section II, the specific expressions of equivalent bandwidth in both WCDMA and WLAN networks are formulated in sequence; Section III proposes the system model, using the Markov Decision Process (MDP) based decision algorithm to realize the joint call admission and vertical handoff control in the heterogeneous networks; In Section IV, we set the priorities of different types of calls in the heterogeneous networks. Section V presents the numerical results and simulation analysis. Conclusions are stated in Section VI.

II. The Equivalent Spectral Bandwidth Mapping in WCDMA and WLAN Networks

1. The equivalent bandwidth in WCDMA networks

A WCDMA system with the chip rate W supporting several classes of multi-media traffic (denoted as Φ_m , for $m = 1, \dots, M$) is considered. For a class Φ_m , if a call is at the OFF state, no packets should be produced; if it is at the ON state, it can generate packets with a certain bit rate B_m . The relative amount of time for a call to stay in the ON state is called as activity factor and is denoted as η_m . The multi-code WCDMA scheme is adopted to support multi-rate services: the bit stream generated by a call will firstly split into C_m parallel sub-streams. These sub-streams with basic bit rate B were spread by C_m different codes and transmitted simultaneously.

Given R_m as the smallest desired energy to interference ratio for service class Φ_m , it follows that ^[22,23]:

$$\frac{GP_m}{\sum_{j=1, j \neq m}^M C_j N_j P_j \eta_j + N_m C_m P_m \eta_m - C_m P_m \eta_m + N_0} \geq R_m \quad (1)$$

where P_m is the received power at the base station for a code transmission, G is the processing gain, N_m is the number of active calls in class Φ_m , N_0 is the thermal noise.

Let:

$$\partial_m = \frac{C_m R_m \eta_m W}{C_m R_m \eta_m + G} \quad (2)$$

Substituting Eq. (2) into Eq. (1) yields:

$$P_m \geq \frac{\partial_m}{(C_m \eta_m W - N_m C_m \eta_m \partial_m)} \cdot \sum_{j=1, j \neq m}^M N_j C_j P_j \eta_j + \frac{\partial_m}{WC_m \eta_m - N_m C_m \eta_m \partial_m} N_0 \quad (3)$$

The minimum P_m is:

$$P_m^* = \frac{\partial_m}{(C_m \eta_m W - N_m C_m \eta_m \partial_m)}$$

$$\cdot \sum_{j=1, j \neq m}^M N_j C_j P_j \eta_j + \frac{\partial_m}{WC_m \eta_m - N_m C_m \eta_m \partial_m} N_0, \quad m=1, 2, \dots, M \quad (4)$$

After some algebraic manipulation, as shown in the Appendix, it follows:

$$P_m^* = \frac{\partial_m N_0}{\left(W - \sum_{j=1}^M N_j \partial_j \right) C_m \eta_m} \quad (5)$$

From Eq. (5), it is obvious that the minimum power exists if and only if $W - \sum_{j=1}^M N_j \partial_j > 0$, i.e.:

$$\sum_{j=1}^M \partial_j N_j < W \quad (6)$$

From Eq. (2), we can know that ∂_m is the transmission bit rate (C_m) weighed by the BER requirements (R_m). It can be considered as the weighed spectrum bandwidth occupied by a transmitting call in class Φ_m . We therefore name ∂_m as the equivalent bandwidth. $\sum_{j=1}^M \partial_j N_j$ is subsequently the total equivalent bandwidth occupied by all calls. Obviously, the physical meaning of Eq. (6) is: For the system to have the power solution, the total occupied equivalent bandwidth should be less than that provided by the system. In the Call Admission Control (CAC) level, this criterion converts the WCDMA method into a quasi Frequency Division Multiple Access (FDMA) method where each call occupies a part of system spectral bandwidth. Hence the dynamic distribution of bandwidth which will be used in CAC algorithm can be straightforward and flexible based on this criterion.

2. The equivalent bandwidth occupied by calls in WLAN

The wireless resources can be directly expressed as the equivalent transmission time in WLAN system, which is defined as the time required for a successful packet transmission. For an invested call, denote the equivalent transmission time as T_m , the network will undergo the following possible states during T_m [12]: Network idle, the call is at the detecting and waiting state; Network busy, other calls send packets successfully; Network busy, packets collision; Network busy, the invested call sends packets successfully.

(1) The average waiting time

Denote p_m as the collision probability of class Φ_m and the collision probabilities of different calls are independent from each other, then the average packet waiting time (in time slot unit) can be expressed as:

$$\overline{W}_m = \sum_{k=1}^{m_t+1} p_m^{k-1} (1-p_m) \sum_{n=1}^k \frac{CW_m(n)-1}{2} \quad (7)$$

where $CW_m(n)$ is the contention window size for class Φ_m , m_t is the retransmission limit. Collision probability p_m is given in Ref. [12]:

$$p_m = 1 - \left(1 - \frac{\lambda_m}{1-p_m} \right)^{N_m-1} \prod_{n=1, n \neq m}^S \left(1 - \frac{\lambda_n}{1-p_n} \right)^{N_n}, \quad m=1, 2, \dots, S \quad (8)$$

where λ_m represents the generation rate of the packets and $\lambda_m = B_m \eta_m / P_s$, P_s represents the size of the packet (bits / packet).

(2) The average transmission time of the other calls

For class Φ_m , the average number of packets generated by each call within time T_m is $\lambda_m T_m$, if the system is at equilibrium state, the number of packets generated by each call should be transmitted statistically and successfully, the transmission time needed is $\lambda_m T_m T_s$. T_s represents the time for transmitting a packet in the physical layer and $T_s = P_s / W$, where W represents the transmission bit rate supported by the physical layer. The total transmission time of all calls in the system except the investigated one is: $(N_m - 1) \lambda_m T_m T_s + T_m T_s \sum_{n=1, n \neq m}^S N_n \lambda_n$.

(3) The average collision time

Before a packet is transmitted successfully, it may undergo several possible collisions. The average collision time of the investigated call within time T_m can be expressed as:

$$\overline{T}_{c_m} = T_s \sum_{k=1}^{m_t+1} (k-1) p_m^{k-1} (1-p_m) \quad (9)$$

The sum collision time of the other calls in the system is:

$$\frac{1}{2} \left[\left(1 + (N_m - 1) \lambda_m T_m \right) \overline{T}_{c_m} + T_m \sum_{n=1, n \neq m}^S N_n \lambda_n \overline{T}_{c_n} \right]$$

Therefore the equivalent transmission time for a call in class Φ_m is:

$$\begin{aligned}
T_m &= (N_m - 1)\lambda_m T_m T_S + T_m T_S \sum_{n=1, n \neq m}^S N_n \lambda_n \\
&+ \frac{1}{2} \left[(\overline{T_{c_m}} + (N_m - 1)\lambda_m T_m \overline{T_{c_m}}) \right. \\
&\left. + T_m \sum_{n=1, n \neq m}^S N_n \lambda_n \overline{T_{c_n}} \right] + T_S + \overline{W_m} \quad (10)
\end{aligned}$$

In order to guarantee the stability of WLAN system, the following inequality should be meet:

$$\frac{\text{The generation rate of packets}}{\text{The equivalent transmission rate of packets}} < 1,$$

i.e. $\lambda_m T_m < 1$, $m = 1, \dots, S$.

Substitute Eq. (10) into the above inequality yields:

$$\begin{aligned}
\lambda_m T_m &= \frac{\lambda_m (2T_S + 2\overline{W_m} + \overline{T_{c_m}})}{2 + \lambda_m (2T_S + \overline{T_{c_m}}) - \sum_{n=1}^S N_n \lambda_n (2T_S + \overline{T_{c_n}})} \\
&< 1 \quad (11)
\end{aligned}$$

After some algebraic manipulation, we can get:

$$\sum_{n=1}^S N_n \lambda_n (2T_S + \overline{T_{c_n}}) < 2 - 2\lambda_m \overline{W_m} \quad (12)$$

Because the value of $\lambda_m \overline{W_m}$ is much less than 1, Eq. (12) can be approximated as:

$$\sum_{n=1}^S N_n \lambda_n (2T_S + \overline{T_{c_n}}) < 2 \quad (13)$$

Take the equation of $\overline{T_{c_n}}$, T_S and λ_n into Eq. (13), it follows:

$$\sum_{n=1}^S N_n B_n \eta_n \left(\frac{2 - p_n}{2 - 2p_n} \right) < W \quad (14)$$

$$\partial_n = B_n \eta_n \left(\frac{2 - p_n}{2 - 2p_n} \right) \quad (15)$$

Then Eq. (14) can be modified as:

$$\sum_{n=1}^S N_n \partial_n < W \quad (16)$$

Eq. (16) is same as Eq. (6) with ∂_n being the equivalent bandwidth occupied by a call of class Φ_n in WLAN networks and $\sum_{n=1}^S N_n \partial_n$ representing the equivalent bandwidth occupied by all the calls in the system. The physical meaning of Eq. (16) can be consequently understood as: the prerequisite for guaranteeing the stability of WLAN system is that the equivalent bandwidth occupied by all the calls in the system should be less than the system bandwidth. Eq. (16) converts the resources of the statistical time-division-mul-

tiplexing mode into a quasi FDMA mode where each call occupies a part of system spectral bandwidth.

III. Joint Admission and Vertical Handoff Control under the Constraint of Equivalent Bandwidth

The double coverage area of WCDMA and WLAN networks is considered. Calls can selectively access into WLAN or WCDMA networks. Incoming and vertical handoff calls are Poisson distributed with the arriving rates $\lambda_{c,n,j}$ and $\lambda_{w,n,j}$ for incoming calls in WCDMA and WLAN networks, respectively. $\mu_{c,h,j}$, $\mu_{w,h,j}$ denote the probabilities of a Φ_j class call handoff from WCDMA to WLAN and from WLAN to WCDMA networks, respectively. Calls duration time is exponentially distributed with means of $1/\mu_{c,t}$, $1/\mu_{w,t}$ for WCDMA and WLAN networks respectively.

A Semi-Markov decision process, denoted by $\{t_k, X, a(x), \tau_x(a), p_{xy}(a), r(x, a)\}$, $x \in X$, is used to describe the joint admission/handoff control process, where t_k is the decision instant which is triggered by call arrival and departure events in the networks. $a(x)$ denotes the decision behavior based on the current state $x \in X$. $\tau_x(a)$ is the average duration time in the state x after adopting the behavior a . $p_{xy}(a)$ is the transferring probability from state x to state y after adopting the behavior a . $r(x, a)$ is the acquired profit after adopting the behavior a .

1. State space

The state space S is expressed by the number of active calls in the network. To ensure calls' QoS requirements, the number of active calls should be limited by the system resources, *i.e.* satisfying the effective bandwidth limit conditions. The space state satisfying QoS requirements of calls in WCDMA is: $X_C = \{n_{c,1}, n_{c,2}, \dots, n_{c,j}, \dots, n_{c,J}\}$, $j = 1, 2, \dots, J$. In which, $n_{c,j}$ is the number of activated calls in service Φ_j and is limited by the condition $\sum_{j=1}^J \partial_j n_{c,j} < W$ according to above bandwidth analysis. Similarly, the state space for WLAN network is $X_W = \{n_{w,1}, n_{w,2}, \dots, n_{w,j}, \dots, n_{w,J}\}$, $j = 1, 2, \dots, J$. In which, $n_{w,j}$ is constrained by $\sum_{j=1}^J n_{w,j} \lambda_j \beta_j < W$. The total space state of the decision process is:

$$X = [n_{w,1}, n_{w,2}, \dots, n_{w,J}, n_{c,1}, n_{c,2}, \dots, n_{c,J}] \quad (17)$$

2. Decision behavior $a(x)$

At the decision instant t_k , the network chooses behavior $a(t_k)$ for incoming or vertical handoff calls:

$$a(t_k) = [a_{c,n}(t_k), a_{c,h}(t_k), a_{w,n}(t_k), a_{w,h}(t_k)] \quad (18)$$

where:

$$\begin{cases} a_{c,n}(t_k) = [a_{c,n,1}(t_k), a_{c,n,2}(t_k), \dots, a_{c,n,J}(t_k)] \in \{0,1\}^J \\ a_{c,h}(t_k) = [a_{c,h,1}(t_k), a_{c,h,2}(t_k), \dots, a_{c,h,J}(t_k)] \in \{0,1\}^J \\ a_{w,n}(t_k) = [a_{w,n,1}(t_k), a_{w,n,2}(t_k), \dots, a_{w,n,J}(t_k)] \\ \quad \in \{-1,0,1\}^J \\ a_{w,h}(t_k) = [a_{w,h,1}(t_k), a_{w,h,2}(t_k), \dots, a_{w,h,J}(t_k)] \in \{0,1\}^J \end{cases} \quad (19)$$

$a_{c,n,j}(t_k)$ and $a_{c,h,j}(t_k)$ denote the behaviors for incoming calls and vertical handoff calls, respectively, in the WCDMA network. Value 1 or 0 represents being admitted or rejected by the network; $a_{w,n,j}(t_k)$ and $a_{w,h,j}(t_k)$ denote the similar situation in the WLAN network. Since WLAN network is within the coverage of WCDMA network, incoming calls in WLAN can selectively access to the two networks. Therefore, -1 denotes WLAN incoming calls overflow to WCDMA network.

3. State duration time $\tau_x(a)$ and state transfer probability $p_{xy}(a)$

The call admission and departure events lead to the change of the system states, the change probability is the sum of probabilities of all these events, is given by:

$$\left[\sum_{j=1}^J (\lambda_{c,n,j} a_{c,n,j} + \mu_{w,h,j} n_{w,j} a_{c,h,j} + \lambda_{w,n,j} |a_{w,n,j}| + \mu_{c,h,j} n_{c,j} a_{w,h,j}) + \sum_{j=1}^J (\mu_{c,t,j} n_{c,j} + \mu_{w,t,j} n_{w,j}) \right]$$

State duration time $\tau_x(a)$ is the inversion of this state change probability.

Define:

$$\delta(x) = \begin{cases} 1, & \text{if } x > 0 \\ 0, & \text{if } x \leq 0 \end{cases} \quad (20)$$

The state transfer probability $p_{xy}(a)$ can be expressed as follows.

When an incoming call comes,

$$\begin{aligned} p_{xy}(a) = & \left[(\lambda_{c,n,j} a_{c,n,j} + \lambda_{w,n,j} \delta(-a_{w,n,j})) \delta(1-k) \right. \\ & \left. + \lambda_{w,n,j} \delta(a_{w,n,j}) \delta(k) \right] \tau_x(a), \\ \text{if } y = & [x_{w,1}, \dots, x_{i,j} + 1, \dots, x_{c,J}], \quad k \in \{0,1\} \end{aligned} \quad (21)$$

where, $k=0$ denotes an incoming call coming into the WCDMA network, then $x_{i,j} = x_{c,j}$. $k=1$ denotes the same in WLAN network, then $x_{i,j} = x_{w,j}$.

When there is a call handoff in the system,

$$\begin{aligned} p_{xy}(a) = & \left[(\mu_{w,h,j} n_{w,j} a_{c,h,j}) \delta(1-k) + \mu_{c,h,j} n_{c,j} a_{w,h,j} \delta(k) \right] \\ & \cdot \tau_x(a), \\ \text{if } y = & [x_{w,1}, \dots, x_{w,j} - 1, \dots, x_{c,j} + 1, \dots, x_{c,J}], \text{ when} \\ & k = 0 \end{aligned}$$

$$\begin{aligned} \text{or if } y = & [x_{w,1}, \dots, x_{w,j} + 1, \dots, x_{c,j} - 1, \dots, x_{c,J}], \\ \text{when } k = & 1 \end{aligned} \quad (22)$$

where, $k=0$ represents that there is a call switching into the WCDMA network; $k=1$, the situation reverses.

When there is a call departing from the system,

$$\begin{aligned} p_{xy}(a) = & \left[\mu_{c,t,j} n_{c,j} \delta(1-k) + (\mu_{w,t,j} + \mu_{w,h,j} (1 - a_{c,h,j})) \right. \\ & \left. \cdot n_{w,j} \delta(k) \right] \tau_x(a), \\ \text{if } y = & [x_{w,1}, \dots, x_{i,j} - 1, \dots, x_{c,J}], \quad k \in \{0,1\} \end{aligned} \quad (23)$$

where, $k=0$ represents a call departing from the WCDMA network, then $x_{i,j} = x_{c,j}$; $k=1$ represents the same event happening in WLAN network, then $x_{i,j} = x_{w,j}$.

4. Revenue function

For Φ_j , the revenue weights allocated to incoming and vertical handoff calls in WCDMA and WLAN networks are denoted as: $w_{c,n,j}, w_{c,h,j}, w_{w,n,j}, w_{w,h,j}$, respectively. Given current state x and the behavior a , the network revenue is:

$$\begin{aligned} r(x, a) = & \sum_{j=1}^J [w_{c,n,j} a_{c,n,j} + w_{c,h,j} a_{c,h,j} + w_{w,n,j} \delta(a_{w,n,j}) \\ & + w_{c,n,j} \delta(-a_{w,n,j}) + w_{w,h,j} a_{w,h,j}] \end{aligned}$$

$$+ w_{c,n,j}(1 - a_{w,h,j}) \quad (24)$$

where, $w_{c,n,j}a_{c,n,j}$ and $w_{c,h,j}a_{c,h,j}$ denote the revenues obtained by the system when incoming calls and vertical handoff calls are admitted by the WCDMA network, respectively. $w_{w,n,j}\delta(a_{w,n,j})$ and $w_{w,h,j}a_{w,h,j}$ denotes the revenues of same situations for WLAN network, $w_{c,n,j}\delta(-a_{w,n,j})$ denotes the revenue when incoming calls access into WCDMA network after being rejected by WLAN. $w_{c,n,j}(1 - a_{w,h,j})$ denotes the revenue when vertical handoff calls are rejected by WLAN whereas continuously staying in WCDMA network.

The decision principle is maximizing the average revenue of the network during the whole call duration. That is:

$$\max_{z_{xa} \geq 0, x \in X, a \in A_x} \sum_{x \in X} \sum_{a \in A_x} r(x, a) \tau_x(a) z_{xa} \quad (25)$$

where, z_{xa} is the probability of selecting behavior a given the system in state x . By solving the linear system Eq. (25), z_{xa} which maximizes the average revenue, can be acquired. Calls can adopt their behaviors (access or handoff to a certain network) with the optimized probabilities z_{xa} and thereby make the resources be efficiently allocated in terms of maximizing the system revenue.

IV. The Priority Settings of Resources Usage

Since the sensitivity of rejecting a handoff call is higher than that of rejecting an incoming call. Higher priority of allocating resources should be set for handoff calls to decrease their rejection probability.

In order to digitize the “rejection” event and acquire the “rejection” probability, define $c_j^b(x, a) = 1 - |a_j(x)|$. When an incoming call is admitted by a certain network, $a_j(x) = 1$, hence $c_j^b(x, a) = 0$. When the call is rejected, $c_j^b(x, a) = 1$ ($a_j(x)$ can be extended to $a_{c,n,j}(x), a_{c,h,j}(x), a_{w,n,j}(x), a_{w,h,j}(x)$ representing the choice of different types of calls in different networks). Define $P_{c,n,j}^b$ as the average rejection probability of Φ_j new service in WCDMA networks during the call holding period, and it can be rewritten in the form of $P_{c,n,j}^b, P_{c,h,j}^b, P_{w,n,j}^b, P_{w,h,j}^b$ for other types of service in other networks. They can be expressed as:

$$\sum_{x \in X} \sum_{a \in A_x} (1 - |a_{c,n,j}(x)|) \tau_x(a) z_{xa}, \quad \sum_{x \in X} \sum_{a \in A_x} (1 -$$

$|a_{c,h,j}(x)|) \tau_x(a) z_{xa}, \sum_{x \in X} \sum_{a \in A_x} (1 - |a_{w,n,j}(x)|) \tau_x(a) z_{xa}$, and $\sum_{x \in X} \sum_{a \in A_x} (1 - |a_{w,h,j}(x)|) \tau_x(a) z_{xa}$ respectively. Define the up-bound of the rejection probability as $\gamma_{c,n,j}, \gamma_{c,h,j}, \gamma_{w,n,j}$, and $\gamma_{w,h,j}$, thus Eq. (25) is modified into:

$$\max_{z_{xa} \geq 0, x \in X, a \in A_x} \sum_{x \in X} \sum_{a \in A_x} r(x, a) \tau_x(a) z_{xa}$$

Satisfying:

$$\begin{cases} \sum_{a \in A_y} z_{ya} - \sum_{x \in X} \sum_{a \in A_x} p_{xy}(a) z_{xa} = 0, & y \in X \\ \sum_{x \in X} \sum_{a \in A_x} \tau_x(a) z_{xa} = 1 \\ \sum_{x \in X} \sum_{a \in A_x} (1 - |a_{c,n,j}(x)|) \tau_x(a) z_{xa} \leq \gamma_{c,n,j}, & j = 1, 2, \dots, J \\ \sum_{x \in X} \sum_{a \in A_x} (1 - |a_{c,h,j}(x)|) \tau_x(a) z_{xa} \leq \gamma_{c,h,j}, & j = 1, 2, \dots, J \\ \sum_{x \in X} \sum_{a \in A_x} (1 - |a_{w,n,j}(x)|) \tau_x(a) z_{xa} \leq \gamma_{w,n,j}, & j = 1, 2, \dots, J \\ \sum_{x \in X} \sum_{a \in A_x} (1 - |a_{w,h,j}(x)|) \tau_x(a) z_{xa} \leq \gamma_{w,h,j}, & j = 1, 2, \dots, J \end{cases} \quad (26)$$

V. Numerical Results and Simulation Analysis

The following results are based on the joint WCDMA/WLAN networks supporting voice and data services where the minimal signal to noise ratios are $R_1=4.775$ and $R_2=6.916$ for voice and data services respectively. The process gain is $G=512$ for WCDMA networks; other parameters are shown in Tab. 1.

Fig. 1 shows the comparison of the revenues of different vertical handoff decision algorithms with the increase of arriving rate of voice calls in WLAN networks. It can be seen that the average revenue is consistently increasing with the arriving rate until it reaches a certain point. Reasons are presented as follows: every user in each access network has its own amount of occupancy of “equivalent bandwidth”. So, the maximum number of users that can be admitted into each system are ascertained, which constitutes the size of Markov state space. Therefore, when the arriving rate of new calls in WLAN increases, getting closer to its departing rate, more arriving calls can be admitted and occupy more bandwidth resources, thus counteracting more departing ones, and therein the time of

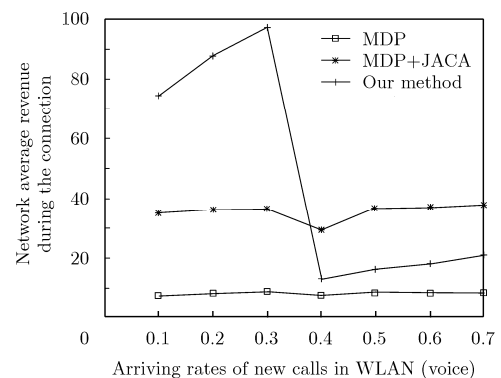
the system staying in one state increases. The more stable system is, the more revenue will be obtained. When the arriving rate reaches the saturation point where the arriving calls equal to the departing ones, the system has the maximum average revenue. At the instant that the arriving rate transcends the departing rate, system residual bandwidth start to decrease due to the arrival of more new WLAN calls, and the stable time as well as the steady-state probability of each state also decreases. So more incoming calls would be rejected because of the decreasing amount of total "equivalent bandwidth", the average revenue of the system thereby drops dramatically. However, with the increase of call arriving rate, part of the incoming calls rejected by WLAN will be admitted by WCDMA networks and make the value of WCDMA networks increase, thus contributing to the increase of value of the whole joint networks. From Fig. 1(b), the proposed algorithm has obvious advantage in realizing higher revenue compared to the MDP and MDP+JACA algorithms when the system has relatively moderate traffic. When the system traffic is heavy, this method is slightly inferior to the MDP-based JACA (equivalent to that shown in Fig. 1) but superior to MDP method.

Tab. 1 System parameters

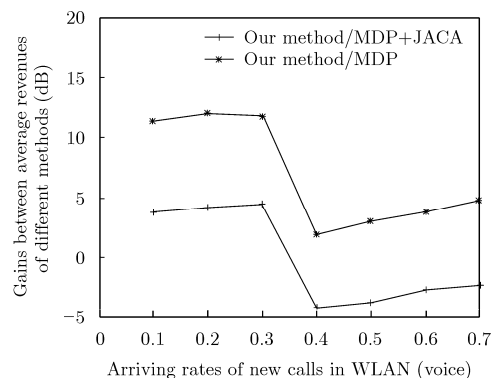
Parameters	Voice	Data
The arriving rates of new calls	WCDMA 0.045	WCDMA 0.03
	WLAN 0.03	WLAN 0.02
Departing rates of calls	0.01	0.001
Departing rates of handoff calls	WLAN 0.001	WLAN 0.0001
	WCDMA 0.005	WCDMA 0.0005
Weights	1	2
Active probability	0.35	0.1
Rejection probability up-bound	0.03	0.01

Fig. 2 shows the average revenue versus the call rejection probability up-bound. By loosing the up-bound limit of the handoff call rejection probability in WCDMA network, the saturation point of the call arriving rate increases and there will be more handoff calls being admitted into WCDMA net-

work thus increasing average revenue. When voice call arriving rate in WLAN reaches some certain value, WLAN network is saturated and the total average revenue decreases considerably. Most new calls to WLAN could be readmitted to WCDMA network according to its residual resource capacity, and thus the revenue start to increase slowly after the dramatic plunge, and finally the two revenue curves coincide.



(a) The average revenue of different methods



(b) The ratio of average revenue of different methods

Fig. 1 Comparison of the revenues of different vertical handoff decision algorithms

VI. Conclusions

A jointly optimized wireless resources distribution algorithm is presented in this paper. By mapping the heterogeneous wireless resources of different systems into the effective spectral bandwidth, call admission and vertical handoff control can be modeled as spectral bandwidth allocation with the Markov decision process. Simulation shows that this method has much better performance comparing with the MDP-based algorithms under the condition that new calls arriving

rate could not exceed certain threshold. When calls' incoming rate transcends the saturation point, the system revenue would decrease due to the scarcity of bandwidth resources.

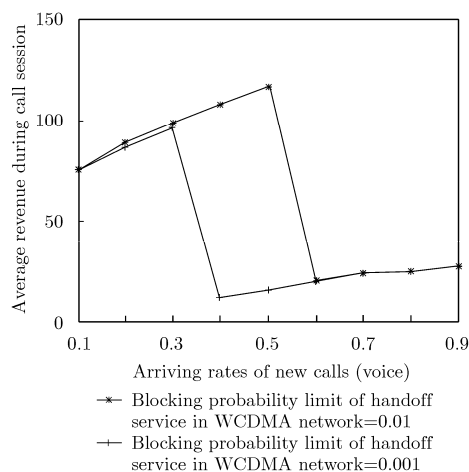


Fig. 2 Average revenue versus the call blocking probability up-bound

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