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*Research Article*

# Adaptive Bandwidth Management and Joint Call Admission Control to Enhance System Utilization and QoS in Heterogeneous Wireless Networks

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The coexistence of different cellular networks in the same area necessitates joint radio resource management for enhanced QoS provisioning and efficient radio resource utilization. We propose adaptive bandwidth management and joint call admission control (JCAC) scheme for heterogeneous cellular networks. The objectives of the proposed adaptive JCAC scheme are to enhance average system utilization, guarantee QoS requirements of all accepted calls, and reduce new call blocking probability and handoff call dropping probability in heterogeneous wireless networks. We develop a Markov chain model for the adaptive JCAC scheme and derive new call blocking probability, handoff call dropping probability, and average system utilization. Performance of the proposed adaptive JCAC scheme is compared with that of nonadaptive JCAC scheme in the same heterogeneous wireless network. Results show an improvement in average system utilization of up to 20%. Results also show that connection-level QoS can be significantly improved by using the proposed adaptive JCAC scheme.

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## 1. INTRODUCTION

The coexistence of different cellular networks in the same geographical area necessitates joint radio resource management (JRRM) for enhanced QoS provisioning and efficient radio resource utilization. The concept of JRRM arises in order to efficiently manage the common pool of radio resources that are available in each of the existing radio access technologies (RATs) [1, 2]. In heterogeneous cellular networks, the radio resource pool consists of resources that are available in a set of cells, typically under the control of a radio network controller or a base station controller.

Not many approaches to JRRM are available in the literature. The interest has been mainly focused on architectural aspects of JRRM, and not many specific algorithms have been provided to investigate JRRM among different RATs, even in simple scenarios [3]. Therefore, this paper focuses on joint call admission control (JCAC) algorithm which is one of the JRRM algorithms.

Call admission control (CAC) algorithm is one of the radio resource management (RRM) algorithms. The traditional call admission control (CAC) algorithms for homogeneous cellular network determine whether or not a user may be admitted into the network. Many CAC algorithms have been developed for homogeneous cellular network, and a review of these CAC algorithms appears in [4, 5]. However, homogeneous CAC algorithms do not provide a single solution to address the heterogeneous architectures which characterize next generation wireless network [6]. This limitation of homogeneous CAC algorithms necessitates the development of JCAC algorithms for heterogeneous wireless networks.

However, unlike homogeneous CAC algorithms, JCAC algorithms do not only decide whether an incoming call can be accepted or not. They also decide which of the available radio access networks is best suited to accommodate the incoming call. JCAC algorithms must manage individual services and technologies, and ensure that the QoS requirements of all admitted calls are satisfied while at the same time making the best use of the total resources available in the heterogeneous network.

Gelabert et al. [7] study the impact of load balancing among different RATs in heterogeneous cellular networks. However, handoff calls are not considered in the study. The algorithm deals with initial RAT selection only for new calls. Moreover, no analytical model is presented in the study.

Pillekeit et al. [8] propose a forced load balancing algorithm for heterogeneous UMTS/GSM network with colocated cells. In their approach, all the cells in the heterogeneous network are classified into two groups: over-loaded cells and under-loaded cells. The load balancing algorithm is triggered when a certain load threshold is exceeded in order to balance the traffic load in the heterogeneous network. However, the algorithm treats both new calls and handoff calls alike. In practice, it is necessary to keep handoff call dropping probability below new call blocking probability. Moreover, no analytical model is presented in the study.

Romero et al. [9] propose a service-based RAT selection policy for heterogeneous wireless networks. They illustrate the selection policy using heterogeneous network comprising GERAN and UTRAN, and a mix of voice and interactive users (e.g., www browsing). Examples of the service-based selection policies are defined in the following [9].

(i) VG (voice GERAN) policy: this policy has only the service class as input and allocates voice users into GERAN and other services into UTRAN.

(ii) VU (voice UTRAN) policy: this policy acts in the opposite direction as VG and allocates voice users to UTRAN and interactive users to GERAN.

In the previous works mentioned above, no analytical model has been developed for JCAC algorithms in order to investigate connection-level QoS parameters in heterogeneous cellular networks. Therefore, this paper models and analyzes a JCAC algorithm in heterogeneous cellular networks.

We propose adaptive bandwidth management and JCAC (AJCAC) scheme to enhance system utilization and connection-level QoS in heterogeneous cellular networks supporting multiple classes of calls such as voice and video. The proposed AJCAC scheme is designed to simultaneously achieve, the following objectives:

(1) distribute traffic load uniformly among available RATs to improve average system utilization,
(2) guarantee the QoS requirement of all admitted calls,
(3) prioritize handoff calls over new calls,
(4) adapt the bandwidth of ongoing calls to improve connection-level QoS and system utilization.

Uniform distribution of traffic load among multiple RATs in heterogeneous wireless network allows for a better utilization of the radio resources. QoS requirements of all admitted calls are guaranteed by allocating to each of the calls at least the minimum bandwidth needed. Handoff calls are prioritized over new calls by using different call rejection thresholds for new and handoff calls, and also by using different bandwidth adaptation mechanism for new and handoff calls. To the best of our knowledge, developing a scheme that achieves the above objectives at the same time in heterogeneous wireless network is a novel work.

The contributions of this paper are twofold. Firstly, we combine adaptive bandwidth management and JCAC scheme to enhance system utilization and connection-level QoS in heterogeneous wireless networks. Secondly, we develop an analytical model for the AJCAC scheme, derive average system utilization, new call blocking probability, handoff call dropping probability, and examine the tradeoff between new call blocking and handoff call dropping.

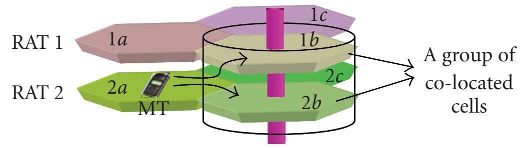


Figure 1: Two-RAT heterogeneous cellular networks with colocated cells.

The rest of this paper is organized as follows. Section 2 presents the system model for heterogeneous wireless networks. In Section 3, the components of the AJCAC scheme are described. Section 4 presents the Markov chain model of the AJCAC scheme. In Section 5, we investigate the performance of the AJCAC scheme through simulations.

## 2. SYSTEM MODEL AND ASSUMPTIONS

We consider a heterogeneous cellular network which consists of $J$ number of RATs with colocated cells, similar to [7, 8]. Cellular networks such as GSM, GPRS, UMTS, and so forth can have the same and fully overlapped coverage, which is technically feasible, and may also save installation cost [10]. Figure 1 illustrates a two-RAT heterogeneous cellular network.

In heterogeneous cellular networks, radio resources can be independently or jointly managed. We consider a situation where radio resources are jointly managed in the heterogeneous network and each cell in RAT-$j$ ($j = 1, \ldots, J$) has a total of $Bj$ basic bandwidth units (bbu). The physical meaning of a unit of radio resources (such as time slots, code sequence, etc.) is dependent on the specific technological implementation of the radio interface [11]. However, no matter which multiple access technology (FDMA, TDMA, CDMA, or OFDM) is used, we could interpret system capacity in terms of effective or equivalent bandwidth [12–14]. Therefore, whenever we refer to the bandwidth of a call, we mean the number of bbu that is adequate for guaranteeing the desired QoS for this call, which is similar to the approach used for homogeneous networks in [14–16].

It is assumed that packet-level QoS is stochastically assured by allocating at least the minimum effective bandwidth required to guarantee a given maximum probability on packet drop, delay, and jitter [17].

Our approach is based on decomposing heterogeneous cellular network into groups of colocated cells. As shown in Figure 1, cell 1a and cell 2a form a groupof colocated cells. Similarly, cell 1b and cell 2b form another group of colocated cells, and so on. Based on the following assumptioncommonly made in homogeneous cellular networks, we assume that the types and amount of traffic are statistically the same in all cells of each RATs [14, 15, 18, 19]. Therefore, the types and amount of traffic are statistically the same in all groups of colocated cells.

A newly arriving call will be admitted into one of the cells in the group of colocated cells where the call is located. When a mobile subscriber using a multimode terminal and having an ongoing call is moving from one group of colocated cells to another group of co-located cells, the ongoing call must be handed over to one of the cells in the new group of colocated cells. For example (Figure 1), an ongoing call can be handed over from cell 2a to cell 2b or from cell 2a to cell 1b. Note that the handover consists of both horizontal and vertical handovers.

The correlation between the groups of colocated cells results from handoff connections between the cells of corresponding groups. Under this formulation, each group of co-located cells can be modeled and analyzed individually. Therefore, we focus our attention on a single group of colocated cells.

The heterogeneous network supports $K$ classes of calls. Each class is characterized by bandwidth requirement, arrival distribution, and channel holding time. Each class-$i$ call requires a discrete bandwidth value, $b_{i,w}$, where $b_{i,w}$ belongs to the set $B_i = \{b_{i,w}\}$ for $i = 1, 2, \dots, K$ and $w = 1, 2, \dots, W_i$. $W_i$ is the number of different bandwidth values that a class-$i$ call can be allocated. $b_{i,1}$ (also denoted as $b_{i,\min}$) and $b_{i,W_i}$ (also denoted as $b_{i,\max}$) are, respectively, the minimum and maximum bandwidth that can be allocated to a class-$i$ call. Note that $b_{i,w} < b_{i,(w+1)}$ for $i = 1, 2, \dots, K$ and $w = 1, 2, \dots, (W_i - 1)$.

The requested bandwidth of an incoming class-$i$ call is denoted by $b_{i,\text{req}}$, where $b_{i,\text{req}} \in B_i$. Let $m_{i,j}$ and $n_{i,j}$ denote, respectively, the number of ongoing new class-$i$ calls and handoff class-$i$ calls, in RAT-$j$ with $1 \le c \le m_{i,j}$ (for new calls) and $1 \le c \le n_{i,j}$ (for handoff calls). Let $b_{i,\text{assigned}\,c}$ denote the bandwidth assigned to call $c$ of class-$i$ in RAT-$j$ in the group of colocated cells, where $b_{i,\text{assigned}\,c} \in B_i$. A call $c$ of class-$i$ is degraded if $b_{i,\text{assigned}\,c} < b_{i,\text{req}}$ whereas the call is upgraded if $b_{i,\text{assigned}\,c} > b_{i,\text{req}}$.

If a class of calls (i.e., class-$i$ calls) requires a fixed number of bbu (i.e. constant bit-rate service), it becomes a special case in our model in which $b_{i,\min} = b_{i,\max}$ and the set $B_i$ has only one element. However, it will not be possible to upgrade or degrade this class of calls.

Following the general assumption in cellular networks, new and handoff class-$i$ calls arrive in the group of colocated cells according to Poisson process with rate $\lambda_i^n$ and $\lambda_i^h$, respectively. The call holding time (CHT) of a class-$i$ call is assumed to follow an exponential distribution with mean $1/\mu_i$ [18, 19].

To characterize mobility, the cell residence time (CRT), that is, the amount of time during which a mobile terminal stays in a cell (same as the time, it stays in a group of colocated cells) during a single visit, is assumed to follow an exponential distribution with mean $1/h$, where the parameter $h$ represents the call handoff rate. We assume that the CRT is independent of the service class.

The channel holding time is the minimum of the CHT and the CRT. Because minimum of two exponentially distributed random variables is also exponentially distributed [20], the channel holding time for new class-$i$ calls, and for handoff class-$i$ call, is assumed to be exponentially distributed with means $1/\mu_i^n$ and $1/\mu_i^h$, respectively.

Note that this set of assumptions has been widely used for homogeneous cellular networks in the literature, and is found to be generally applicable in the environment where the number of mobile users is larger than the number of channels [20].

## 3. PROPOSED AJCAC SCHEME

In this section, we describe the proposed AJCAC scheme which consists of the following three components: joint call admission controller, threshold-based bandwidth reservation unit, and bandwidth adaptation (BA) controller. These components are described in the following.

### 3.1. The joint call admission controller

The joint call admission controller implements the JCAC algorithm. The basic function of the JCAC algorithm is to make call admission decision and uniformly distribute traffic load among all the available RATs in the network.

During call setup, a multimode mobile terminal requesting a service sends a request to the joint call admission controller which implements the JCAC algorithm. The service request contains the call type, service class, and bandwidth requirements. The JCAC procedure is shown in Figure 2, where $x_{i,j}$ and $y_{i,j}$ denote, respectively, the residual bbu available in RAT-$j$ for new and handoff class-$i$ calls. Whenever a call arrives, the JCAC attempts to allocate the maximum bbu for this call (i.e., set $b_{i,\text{req}} = b_{i,\max}$) provided that the available bbu in the selected RAT is greater than or equal to $b_{i,\max}$. If the available bbu in the selected RAT is less than $b_{i,\max}$ but greater than or equal to $b_{i,\text{req}}$, the call will be assigned a bandwidth between $b_{i,\text{req}}$ and $b_{i,\max}$. If the available bbu is less than $b_{i,\text{req}}$ but greater than or equal to $b_{i,1}$ ($b_{i,\min}$), the call will be assigned a bandwidth between $b_{i,1}$ and $b_{i,\text{req}}$. If the available bbu in all the RATs is less than $b_{i,1}$, BA algorithm (BAA) will be invoked to reduce the bandwidth of some ongoing call(s) in the chosen RAT. If the available bbu is still less than $b_{i,1}$ for all available RATs, the call will be rejected.

For new class-$i$ calls, let $C_{i,j}^n$ denote the total bbu available in RAT-$j$, $\alpha_{i,j}$ the fraction of bbu available in RAT-$j$ over the summation of bbu available in all RATs, $x_{i,j}$ the residual bbu available in RAT-$j$, and $L_{i,j}^n$ the current load in RAT-$j$. For handoff class-$i$ calls, the corresponding values are $C_{i,j}^h$, $\beta_{i,j}$, $y_{i,j}$, and $L_{i,j}^h$. Then

$$\alpha_{i,j} = \frac{C_{i,j}^n}{\sum_{j=1}^{J} C_{i,j}^n} \quad \forall i, j, \qquad \sum_{j=1}^{J} \alpha_{i,j} = 1 \quad \forall i. \tag{1}$$

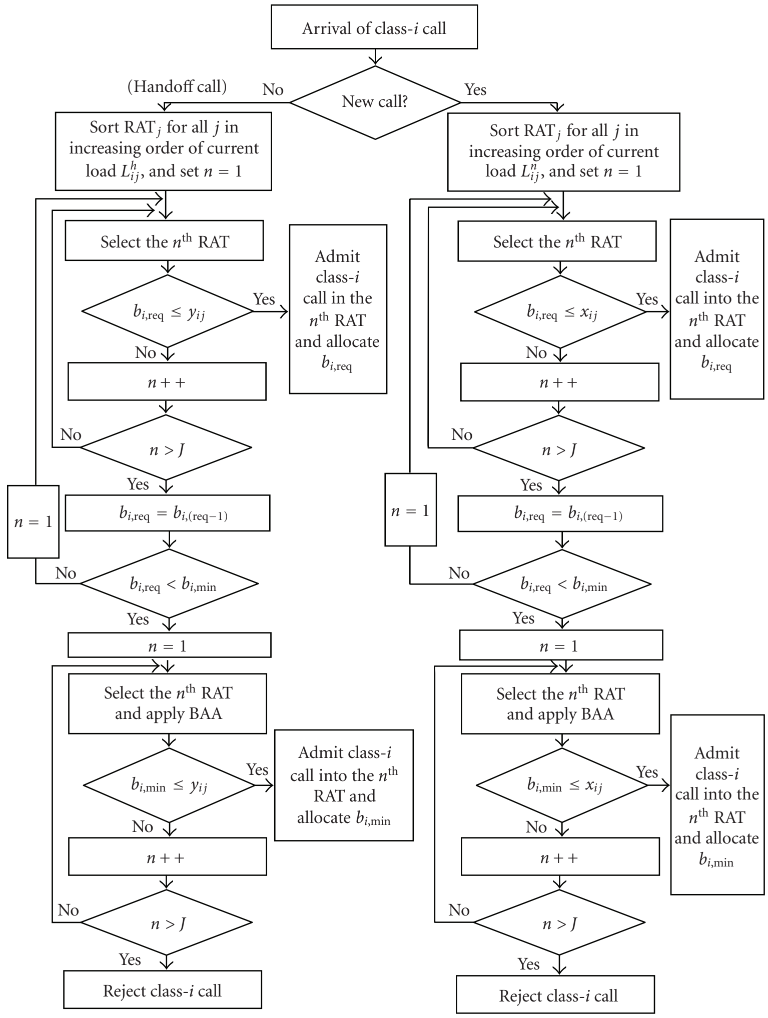


Figure 2: Proposed adaptive load-based JCAC algorithm.

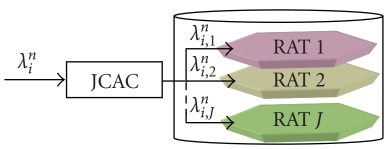


Figure 3: Splitting of the arraival process in the group of colocated cells.

Similarly,

$$\beta_{i,j} = \frac{C^h_{i,j}}{\sum_{j=1}^{J} C^h_{i,j}} \quad \forall i, j,$$
$$\sum_{j=1}^{J} \beta_{i,j} = 1 \quad \forall i. \tag{2}$$

When a new or handoff call arrives into a group of colocated cells, the JCAC algorithm selects the least loaded RAT available for the incoming call. The action of selecting a RAT for each arriving new or handoff call in the group of colocated cells leads to splitting of the arrival process. Figure 3 illustrates the splitting of the arrival among $J$ number of RATs in the group of colocated cells.

As shown in Figure 3, the arrival rate in the group of colocated cells is split among all the available RATs. Each RAT has a fraction of the arrival rate ($\lambda^n_i$). Due to the uniform-load-distribution action of the JCAC algorithm, the mean arrival rates of class-$i$ calls into each RAT in the group of collocated cells are as follows:

$$\lambda^n_{i,j} = \alpha_{i,j}\lambda^n_i \quad \forall i, j,$$
$$\lambda^n_i = \sum_{j=1}^{J} \lambda^n_{i,j} \quad \forall i. \tag{3}$$

Similarly

$$\lambda^h_{i,j} = \beta_{i,j}\lambda^h_i \quad \forall i, j,$$
$$\lambda^h_i = \sum_{j=1}^{J} \lambda^h_{i,j} \quad \forall i, \tag{4}$$

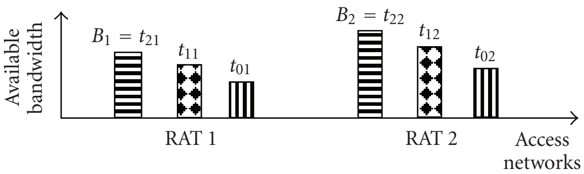


Figure 4: Accessible bandwidth for a two-class, two-RAT system.

where $\lambda_i^n$ and $\lambda_i^h$ denote the arrival rates of new class-$i$ calls and handoff class-$i$ calls, respectively, into the group of colocated cells. $\lambda_{i,j}^n$ and $\lambda_{i,j}^h$ denote the arrival rates of new class-$i$ calls and handoff class-$i$ calls, respectively, into RAT-$j$ in the group of colocated cells.

The arrival rates of a split Poisson process are also Poisson [21]. Therefore, given that the mean arrival rate of class-$i$ calls into the group of colocated cells is Poisson, the mean arrival rates of the split class-$i$ calls into RAT-1, RAT-2, ..., RAT-$J$ are also Poisson.

### 3.2. Threshold-based bandwidth reservation unit

In order to maintain lower handoff dropping probability, the bandwidth reservation unit implements a bandwidth reservation policy that uses different thresholds for new and handoff calls. Figure 4 shows the bandwidth reservation policy for a two-class, two-RAT system.

The policy reserves bandwidth for aggregate handoff calls, thus gives them priority over new calls. The policy also prioritizes among different classes of handoff calls according to their QoS constraints by assigning a series of bandwidth thresholds $t_{1,j}, t_{2,j}, \ldots, t_{k,j}$, for handoff calls such that

$$t_{0,j} \leq t_{1,j} \leq \cdots \leq t_{i,j} \leq t_{(i+1),j} \leq \cdots \leq t_{k,j} = B_j \quad \forall j, \tag{5}$$

where $t_{0,j}$ denotes the total number of bbu available for all new calls in RAT-$j$, and $t_{i,j}$ denotes the total number of bbu available for handoff class-$i$ calls in RAT-$j$. $B_j$ denotes the total number of bbu available in RAT-$j$.

### 3.3. Bandwidth adaptation controller

The bandwidth adaptation controller executes the BAA which is triggered when a new call arrives or when a call is completed. Most multimedia applications are adaptive. For example, voice can be encoded at 16 kbps, 32 kbps, 64 kbps, and 128 kbps by choosing appropriate encoding mechanisms. Similarly, video applications can be made rate adaptive by using, for instance, a layered coding method. In layer coding method, the lowest layer (i.e., the base layer) contains the critical information for decoding the image sequence at its minimum visual quality. Additional layers provide increasing quality. All these encoded layers may be transmitted when the network is underutilized. However, when the network resources are being fully utilized, only based layer(s) which contain critical information may be transmitted.

As an illustration, if one would watch a 30-minute video clip encoded at 256 kbps and 64 kbps respectively. At 256 kbps, one will see better pictures with better resolution than at 64 kbps. Therefore, the bandwidth adaptation affects the quality of the real-time applications rather than the transmission time. However, the minimum requested QoS is maintained by ensuring that the bbu of the calls are not degraded below the required minimum.

In the proposed AJCAC scheme, when the system is underutilized, all arriving new and handoff class-$i$ calls are admitted by the JCAC algorithm with the highest bandwidth level (i.e., $b_{i,\max}$) for the calls. This approach increases bandwidth utilization for the heterogeneous wireless network. However, when the network resources are being fully utilized, bandwidth adaptation controller is invoked to execute BAA on arrival of a new or handoff call.

The BAA is triggered whenever there is a call arrival event or a call departure event. The BAA performs two main procedures: downgrades and upgrades ongoing calls. The downgrading procedure is activated in the arrival epoch (i.e., when a new or handoff arrives to an overloaded group of colocated cells). BAA reduces the bandwidth of some ongoing call(s) randomly selected in the system to free just enough bbu to accommodate the incoming call. Note that an adaptive class-$i$ call is never degraded below the minimum bbu necessary to guarantee its minimum QoS requirements. The upgrading procedure is activated in the departure epoch.

In the arrival epoch, the BAA downgrading procedure can be implemented in two ways. In the first implementation, only ongoing new calls can be downgraded to accommodate an incoming new call whereas both ongoing new and handoff calls can be downgraded to accommodate an incoming handoff call. This approach further prioritizes handoff calls over new calls, in addition to the prioritization obtained by using different rejection thresholds for new and handoff calls. In the second implementation, both new and handoff calls can be downgraded to accommodate an incoming new (or handoff) call. In this implementation, prioritization of handoff calls over new calls can only be achieved by using different rejection threshold for new and handoff calls.

In the departure epoch, when a call departs from a RAT in the group of colocated cells, some of the ongoing call(s) randomly selected in RAT of the group of colocated cells may be upgraded by the BAA algorithm.

## 4. MARKOV CHAIN ANALYSIS OF THE AJCAC SCHEME

The AJCAC policy described in Section 3 is a multidimensional Markov chain. The state space of the group of colocated cells can be represented by a $(2^*K^*J)$-dimensional vector given as

$$\Omega = (m_{i,j}, n_{i,j} : i = 1, \ldots, k, \ j = 1, \ldots, J). \tag{6}$$

The nonnegative integer $m_{i,j}$ denotes the number of ongoing new class-$i$ calls in RAT-$j$, and the nonnegative integer $n_{i,j}$ denotes the number of ongoing handoff class-$i$ calls in RAT-$j$. Let $S$ denote the state space of all admissible states of the group of colocated cells as it evolves over time. An admissible state $s$ is a combination of the numbers of users in each class that can be supported simultaneously in the group of colocated cells while maintaining adequate QoS and meeting resource constraints. The state $S$ of all admissible states is given as

$$S = \Big\{ \Omega = \left(m_{i,j}, n_{i,j} : i = 1,\dots,k,\ j = 1,\dots,J\right) : \\ \sum_{i=1}^{k}\sum_{c=1}^{m_{i,j}} b_{i,\text{assigned}_c} \le t_{0,j}^{n}\ \forall j \bigwedge \\ \sum_{c=1}^{n_{i,j}} b_{i,\text{assigned}_c} \le t_{i,j}^{h}\ \forall i,j \bigwedge \\ \sum_{i=1}^{k}\sum_{c=1}^{m_{i,j}} b_{i,\text{assigned}_c} + \sum_{i=1}^{k}\sum_{c=1}^{n_{i,j}} b_{i,\text{assigned}_c} \le B_j\ \forall j \Big\}. \tag{7}$$

The constraints simply state that the sum of the bandwidth units of all admitted class-$i$ calls cannot be more than the total bandwidth units available for that class of calls. Given that the system is in the current state, $s$, for the AJ-CAC scheme, the state transition could be triggered by any of the following events.

(1) Admission of a new class-$i$ call into RAT-$j$ with the successor state $s_1^{+1}$ and transition rate $q(s, s_1^{+1})$. It follows that

$$q\left(s, s_1^{+1}\right) = \lambda_{i,j}^{n}, \quad s, s_1^{+1} \in S. \tag{8}$$

(2) Admission of a handoff class-$i$ call into RAT-$j$ with the successor state $s_2^{+1}$ and transition rate $q(s, s_2^{+1})$. It follows that

$$q\left(s, s_2^{+1}\right) = \lambda_{i,j}^{h}, \quad s, s_2^{+1} \in S. \tag{9}$$

(3) Departure of a new class-$i$ call from RAT-$j$ with the successor state $s_1^{-1}$ and transition rate $q(s, s_1^{-1})$. It follows that

$$q\left(s, s_1^{-1}\right) = m_{i,j}\mu_i^{n}, \quad s, s_1^{-1} \in S. \tag{10}$$

(4) Departure of a handoff class-$i$ call from RAT-$j$ with the successor state $s_2^{-1}$ and transition rate $q(s, s_2^{-1})$. It follows that

$$q\left(s, s_2^{-1}\right) = n_{i,j}\mu_i^{h}, \quad s, s_2^{-1} \in S, \tag{11}$$

where $s$, $s_1^{+1}$, $s_1^{-1}$, $s_2^{+1}$, and $s_2^{-1}$ are the following matrices:

$$s = \begin{bmatrix} m_{11} & \cdots & m_{1j} & \cdots & m_{1J} \\ \vdots & & \vdots & & \vdots \\ m_{i1} & \cdots & m_{ij} & \cdots & m_{iJ} \\ \vdots & & \vdots & & \vdots \\ m_{K1} & \cdots & m_{Kj} & \cdots & m_{KJ} \\ n_{11} & \cdots & n_{1j} & \cdots & n_{1J} \\ \vdots & & \vdots & & \vdots \\ n_{i1} & \cdots & n_{ij} & \cdots & n_{iJ} \\ \vdots & & \vdots & & \vdots \\ n_{K1} & & n_{Kj} & & n_{KJ} \end{bmatrix},$$

$$s_1^{\pm 1} = \begin{bmatrix} m_{11} & \cdots & m_{1j} & \cdots & m_{1J} \\ \vdots & & \vdots & & \vdots \\ m_{i1} & \cdots & m_{ij} \pm 1 & \cdots & m_{iJ} \\ \vdots & & \vdots & & \vdots \\ m_{K1} & \cdots & m_{Kj} & \cdots & m_{KJ} \\ n_{11} & \cdots & n_{1j} & \cdots & n_{1J} \\ \vdots & & \vdots & & \vdots \\ n_{i1} & \cdots & n_{ij} & \cdots & n_{iJ} \\ \vdots & & \vdots & & \vdots \\ n_{K1} & & n_{Kj} & & n_{KJ} \end{bmatrix}, \tag{12}$$

$$s_2^{\pm 1} = \begin{bmatrix} m_{11} & \cdots & m_{1j} & \cdots & m_{1J} \\ \vdots & & \vdots & & \vdots \\ m_{i1} & \cdots & m_{ij} & \cdots & m_{iJ} \\ \vdots & & \vdots & & \vdots \\ m_{K1} & \cdots & m_{Kj} & \cdots & m_{KJ} \\ n_{11} & \cdots & n_{1j} & \cdots & n_{1J} \\ \vdots & & \vdots & & \vdots \\ n_{i1} & \cdots & n_{ij} \pm 1 & \cdots & n_{iJ} \\ \vdots & & \vdots & & \vdots \\ n_{K1} & & n_{Kj} & & n_{KJ} \end{bmatrix}.$$

The decision epochs are the arrival or departure of a new or handoff call. Joint call admission decisions are taken in the arrival epoch. Every time a new or handoff class-$i$ call arrives in the group of colocated cells, the JCAC algorithm decides whether or not to admit the call, and in which RAT to admit it. Note that call admission decision is made only at the arrival of a call, and no call admission decision is made in the group of colocated cells when a call departs. When the system is in state $s$, an accept in RAT-$j$/reject decision must be made for each type of possible arrival, that is, an arrival of a new class-$i$ call, or the arrival of a handoff class-$i$ call in the group of colocated cells. The following are the possible JCAC decisions in the arrival epoch.

(1) Reject the class-$i$ call (new or handoff) in the group of collocated cells, in which case the state $s$ does not evolve.

(2) Admit the class-$i$ call into RAT-$j$ without adapting the bandwidth of ongoing call(s) in the RAT, in which case the state $s$ evolves.

(3) Admit the class-$i$ call into RAT-$j$ after adapting the bandwidth of ongoing call(s) in the RAT, in which case state $s$ evolves.

Thus, the call admission action space $A$ can be expressed as follows:

$$A = \{a = (a_1^n, \dots, a_k^n, a_1^h, \dots, a_k^h) : \\ a_i^n, a_i^h \in (0, \pm 1, \dots, \pm j, \pm (j+1), \dots, \pm J), \\ i = 1, \dots, k\}, \tag{13}$$

where $a_i^n$ denotes the action taken on arrival of a new class-$i$ call within the group of colocated cells, and $a_i^h$ denotes the action taken on arrival of a handoff class-$i$ call from an adjacent group of colocated cells. $a_i^n$ (or $a_i^h$) = 0 means reject the new class-$i$ (or handoff class-$i$) call. $a_i^n$ (or $a_i^h$) = +1 means accept the new class-$i$ (or handoff class-$i$) call into RAT-1 without adapting the bandwidth of existing call(s). $a_i^n$ (or $a_i^h$) = $-1$ means accept the new class-$i$ (or handoff class-$i$) call into RAT-1 after adapting (degrading) the bandwidth of existing call(s). $a_i^n$ (or $a_i^h$) = $+j$ means accept the new class-$i$ (or handoff class-$i$) call into RAT-$j$ without adapting the bandwidth of existing call. $a_i^n$ (or $a_i^h$) = $-j$ means accept the new class-$i$ (or handoff class-$i$) call into RAT-$j$ after adapting (degrading) the bandwidth of existing call(s).

In the departure epoch, the bandwidth adaptation unit makes the decision to adapt (upgrade) or not to adapt the bandwidth of ongoing call(s). Thus, the call departure action space $W$ can be expressed as follows:

$$W = \{w = (0, 1)\}, \tag{14}$$

where $w = 0$ means do not adapt the bandwidth of the ongoing call(s) and $w = 1$ means adapt the bandwidth of ongoing call(s).

Based on its Markovian property, the proposed AJCAC scheme can be model as a $(2^*K^*J)$-dimensional Markov chain. Let $\rho_{\text{new}_{i,j}}$ and $\rho_{\text{han}_{i,j}}$ denote the load generated by new class-$i$ calls and handoff class-$i$ calls, respectively, in RAT-$j$. Then,

$$\rho_{\text{new}_{i,j}} = \frac{\lambda_{i,j}^n}{\mu_i^n} \quad \forall i, j, \\ \rho_{\text{han}_{i,j}} = \frac{\lambda_{i,j}^h}{\mu_i^h} \quad \forall i, j. \tag{15}$$

From the steady-state solution of the Markov model, performance measures of interest can be determined by summing up appropriate state probabilities. Let $P(s)$ denotes the steady-state probability that the system is in state $s$ ($s \in S$). From the detailed balance equation, $P(s)$ is obtained as

$$P(s) = \frac{1}{G} \prod_{i=1}^{k} \prod_{j=1}^{J} \frac{(\rho_{\text{new}_{i,j}})^{m_{i,j}}}{m_{i,j}!} \frac{(\rho_{\text{han}_{i,j}})^{n_{i,j}}}{n_{i,j}!} \quad \forall s \in S, \tag{16}$$

where $G$ is a normalization constant given by

$$G = \sum_{s \in S} \prod_{i=1}^{k} \prod_{j=1}^{J} \frac{(\rho_{\text{new}_{i,j}})^{m_{i,j}}}{m_{i,j}!} \frac{(\rho_{\text{han}_{i,j}})^{n_{i,j}}}{n_{i,j}!}. \tag{17}$$

### 4.1. New call blocking probability

A new class-$i$ call is blocked in the group of colocated cells if none of the available RATs has enough bbu to accommodate the new call with the minimum bandwidth requirement after degrading the ongoing new calls. Let $S_{b_i} \subset S$ denote the set of states in which a new class-$i$ call is blocked in the group of colocated cells. It follows that

$$S_{b_i} = \Bigg\{ s \in S : \Bigg( b_{i,\min} + \sum_{x=1}^{k} m_{x,j} b_{x,\min} > t_{0,j}^n \vee b_{i,\min} \\ + \sum_{x=1}^{k} m_{x,j} b_{x,\min} + \sum_{x=1}^{k} \sum_{c=1}^{n_{x,j}} b_{x,\text{assigned}_c} > B_j \Bigg) \ \forall j \Bigg\}. \tag{18}$$

Thus the new call blocking probability (NCBP), $P_{b_i}$, for a class-$i$ call in the group of colocated cells is given by

$$P_{b_i} = \sum_{s \in S_{b_i}} P(s). \tag{19}$$

### 4.2. Handoff call dropping probability

A handoff class-$i$ call is dropped in the group of colocated cells if none of the available RATs has enough bbu to accommodate the handoff call with the minimum bandwidth requirement after degrading the ongoing new calls and handoff calls. Let $S_{d_i} \subset S$ denotes the set of states in which a handoff class-$i$ call is dropped in the group of colocated cells. It follows that

$$S_{d_i} = \Bigg\{ s \in S : \Bigg( (1 + n_{i,j}) b_{i,\min} > t_{i,j}^h \vee b_{i,\min} \\ + \sum_{x=1}^{k} (m_{x,j} + n_{x,j}) b_{x,\min} > B_j \Bigg) \ \forall j \Bigg\}. \tag{20}$$

Thus the handoff call dropping probability (HCDP) for a class-$i$ call, $P_{d_i}$, in the group of colocated cells is given by

$$P_{d_i} = \sum_{s \in S_{d_i}} P(s). \tag{21}$$

### 4.3. Average system utilization

The average utilization of the heterogeneous wireless network can be obtained by summing up for all the admissible state $s$ ($s \in S$), the product of the system utilization in a particular state $s$ ($s \in S$), and the probability $P(s)$ of the system being in that state. The average utilization $U$ of the heterogeneous cellular network can be derived as follows:

$$U = \sum_{s \in S} P(s) \sum_{j=1}^{J} \sum_{i=1}^{k} \left( \sum_{c=1}^{m_{i,j}} b_{i,\text{assigned}_c} + \sum_{c=1}^{n_{i,j}} b_{i,\text{assigned}_c} \right). \tag{22}$$

## 5. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed AJCAC scheme with respect to new call blocking probability,

Table 1: Simulation parameters.

| Parameters | Class-1 call | Class-2 call |
|---|---|---|
| Class-$i$ call bbu set | $\{2, 3, 4\}$ | $\{3, 5, 7\}$ |
| Requested bbu ($b_{i,\text{req}}$) | 3 | 5 |
| $\lambda_i^n$ | [1,8] | [1,8] |
| $\mu_i$ | 0.5 | 0.5 |

Other parameters

| $B_1$ | $B_2$ | $t_{0,1}$ | $t_{0,2}$ | $t_{1,1}$ | $t_{1,2}$ | $t_{2,1}$ | $t_{2,2}$ | $h$ |
|---|---|---|---|---|---|---|---|---|
| 30 | 60 | 15 | 30 | 30 | 60 | 30 | 60 | 0.5 |

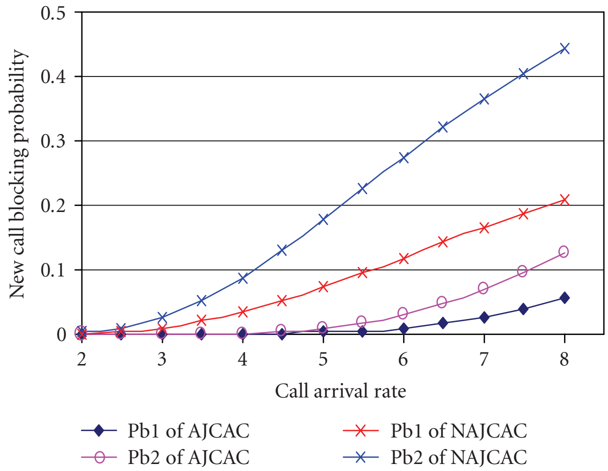


Figure 5: Effect of varying the call arrival rate on the new call blocking probability.

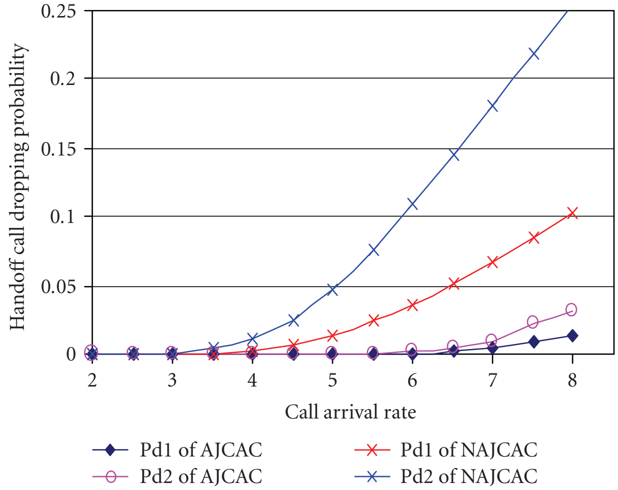


Figure 6: Effect of varying the call arrival rate on the handoff call dropping probability.

handoff call dropping probability, and average system utilization. The results of the proposed AJCAC scheme are compared with that of the NAJCAC scheme. The system parameters used are shown in Table 1.

The arrival rate of handoff class-$i$ calls in the group of colocated cells is assumed to be proportional to the arrival rate of new class-$i$ calls by $\lambda_i^h = (h/\mu_i)\lambda_i^n$ where $h$ is the handoff rate.

For comparison, we also model a JCAC algorithm without adaptive bandwidth allocation in heterogeneous cellular network and derive NCBP and HCDP for the nonadaptive JCAC scheme.

Figures 5 and 6 show the performance of the AJCAC scheme compared with that of NAJCAC. As shown in Figure 5, the NCBP of each class of calls increases with the call arrival rate. The NCBP, Pb1 is always less than the NCBP, Pb2 because class-2 calls require more bbu than class-1 calls. Thus class-2 calls may be blocked due to insufficient bbu to accommodate it whereas class-1 calls may still be accepted into the network. However, for both classes of calls, the NCBP for the AJCAC scheme is always less than the corresponding NCBP for the NAJCAC scheme. Note that lower NCBP of the AJCAC scheme implies that its connection-level QoS is better than that of the NAJCAC scheme. The reason why the NCBP of the AJCAC scheme is less than the NAJCAC scheme is as follows. When the total bbu allocated to new calls is being fully utilized, incoming new calls are rejected by the NAJCAC scheme whereas the AJCAC scheme adapts (degrades) the bandwidth of some of the ongoing adaptive calls to free just enough bbu to accommodate the incoming new calls. Consequently, the NCBP of the AJCAC is less than that of the NAJCAC. However, an adaptive class-$i$ call is never degraded below the minimum bbu necessary to guarantee its minimum QoS requirements.

Figure 6 shows a similar trend for the HCDP for each class of calls, which increases with the call arrival rate. The HCDP, Pd1 is always less than that the HCDP, Pd2, because class-2 calls require more bbu than class-1 calls. However, for both classes of calls, the HCDP for the AJCAC scheme is always less than the corresponding HCDP for the NAJCAC scheme. The reason why the HCDP of the AJCAC scheme is less than the NAJCAC scheme is as follows. When the system is being fully utilized, incoming handoff calls are rejected by the NAJCAC scheme whereas the AJCAC scheme adapts (degrades) the bandwidth of some of the ongoing adaptive calls to free just enough bbu to accommodate the incoming handoff calls. Consequently, the HCDP of the AJCAC is less than that of the NAJCAC.

Figures 7 and 8 compare NCBP and HCDP of the AJCAC for class-1 and class-2 call, respectively. One of the objectives of the AJCAC scheme is to prioritized handoff calls over new calls. Figure 7 shows that the HCDP, Pd1 of the AJCAC is always less than the Pb1. Similarly, it can be seen in Figure 8 that the HCDP, Pd2 is always less that the NCBP, Pb2. This shows that handoff calls are prioritized over new calls. This prioritization of the handoff calls over new calls is achieved by making the handoff call rejection thresholds higher than the new call rejection thresholds.

Figures 9 and 10 show the effect of varying the new call rejection threshold, $T_0$ on the NCBP and HCDP of the AJCAC and NAJCAC schemes for class-1 calls and class-2 calls, respectively. The additional system parameters used are as follows: $T_{01} = T_0$, $T_{02} = 2T_0$, $T_0 = [0, 30]$, $\lambda_1^n = \lambda_2^n = 8$. As

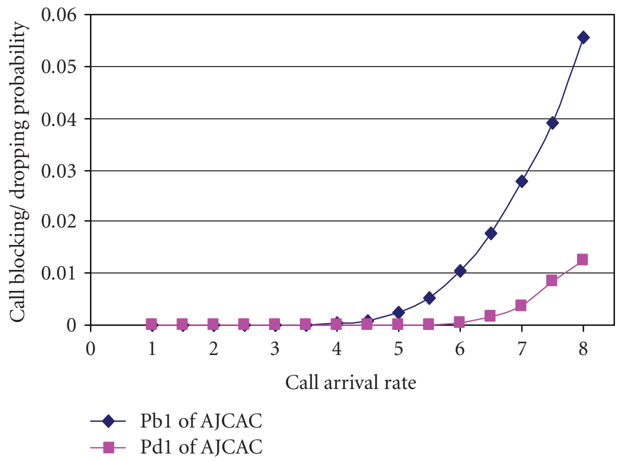


Figure 7: Effect of varying the call arrival rate on the new call blocking probability and handoff call dropping probability of class-1 calls.

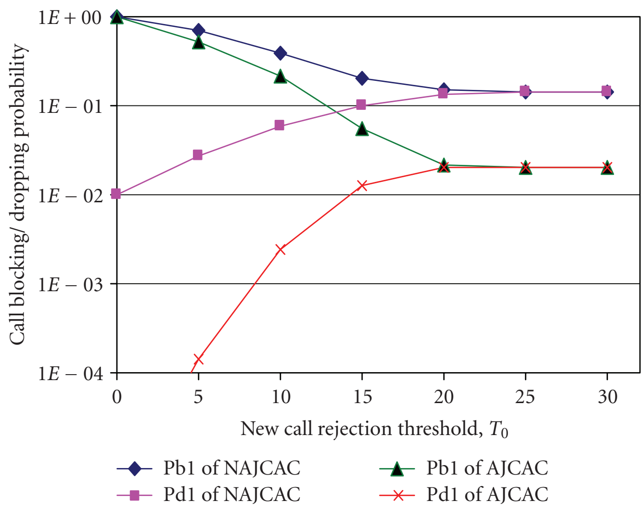


Figure 9: Effect of varying the new call rejection threshold, $T_0$ on the new call blocking probability and handoff call dropping probability of class-1 calls.

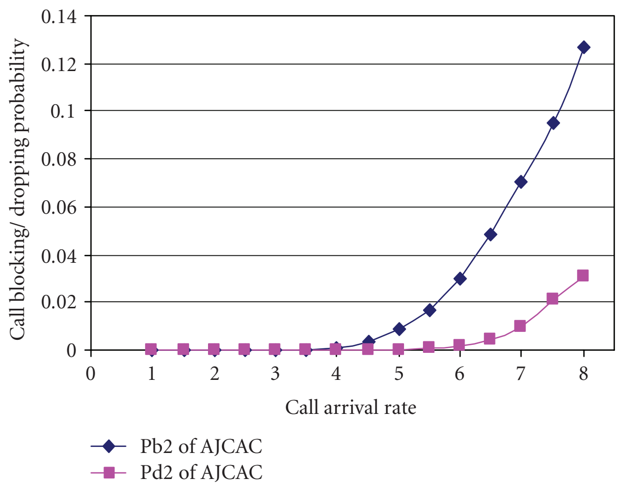


Figure 8: Effect of varying the call arrival rate on the new call blocking probability and handoff call dropping probability of class-2 calls.

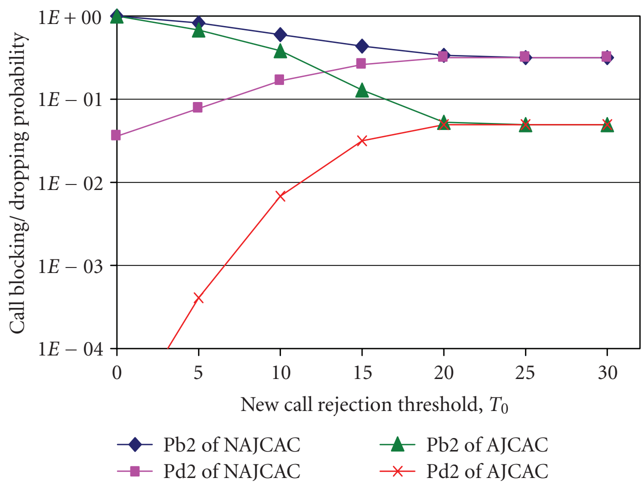


Figure 10: Effect of varying the new call rejection threshold, $T_0$ on the new call blocking probability and handoff call dropping probability of class-2 calls.

shown in Figure 9, at low threshold values, the NCPB, Pb1 for the two JCAC schemes is high whereas the HCDP, Pd1 is low. As the threshold value, $T_0$ increases, Pb1 decreases because new calls are given more access to the available bandwidth. On the other hand, the handoff dropping probability, Pd1 increases as a result of the higher degree of sharing between the new and the handoff calls. However, Pb1 and Pd1 of the AJCAC are always less than the corresponding Pb1 and Pd1 of the NAJCAC.

Figure 10 shows a similar trend for class-2 calls. At low threshold values, the NCPB, Pb2 for the two JCAC schemes is high whereas the HCDP, Pd2 is low. As the threshold value, $T_0$ increases, Pb2 decreases whereas handoff dropping probability, Pd2 increases. However, Pb2 and Pd2 of the AJCAC are always less than the corresponding Pb2 and Pd2 of the NAJCAC.

Figure 11 shows the normalized average system utilization for heterogeneous wireless network. The normalized average system utilization of the AJCAC is higher that the normalized average system utilization for the NAJCAC. The reason for improvement in system utilization of the AJCAC scheme over NAJCAC scheme is as follows. When the system load is low, the AJCAC allocates maximum bbu to all admitted calls, thereby improves the average system utilization whereas the NAJCAC allocates just the requested bbu to all admitted calls in the same class regardless of whether the traffic load is low or high. However, when the system is operating at the full capacity, the AJCAC algorithm degrades the bbu of some ongoing calls and frees just enough bbu to accommodate incoming new calls. Figure 11 shows that the AJCAC scheme improves the system utilization by up to 20% of the NAJCAC scheme.

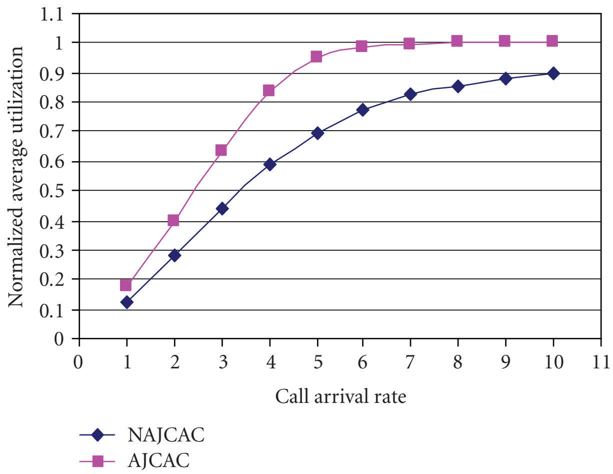


FIGURE 11: Impact of varying the call arrival rate on the normalized average system utilization.

## 6. CONCLUSIONS

We propose adaptive bandwidth management and JCAC scheme to enhance system utilization and connection-level QoS in heterogeneous cellular networks. The adaptive JCAC scheme improves average system utilization by adapting the bandwidth of calls based on current traffic condition and by uniformly distribute traffic load among the available RATs. The adaptive JCAC scheme guarantees the QoS requirements of all accepted call and reduces both new call blocking probability and handoff call dropping probability in the heterogeneous wireless networks. It prioritizes handoff calls over new calls by using different call rejection thresholds for new and handoff calls. We develop a Markov chain model which enables us to derive new call blocking probability, handoff call dropping probability, and average system utilization for the adaptive JCAC scheme. Performance of the adaptive JCAC scheme is compared with that of nonadaptive JCAC scheme in the same heterogeneous cellular network. Results show that new call blocking probability and handoff call dropping probability can be significantly reduced by using the adaptive JCAC scheme. Moreover, the adaptive JCAC scheme improves the system utilization by up to 20% of the nonadaptive JCAC scheme.

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