Admission Control in the Downlink of WCDMA/UMTS

S.-E. Elayoubi and T. Chahed

GET/Institut National des Telecommunications
{salah_eddine.elayoubi, tijani.chahed}@int-evry.fr

Abstract. In this paper, we develop a novel CAC algorithm that takes into account the mobility of users inside the cell with a focus on the downlink of third generation mobile systems. We first study the system capacity in a multiple cell setting and obtain effective bandwidth expressions for different calls as a function of both their positions in the cell as well as their classes of traffic (voice versus data). We then use this formulation to derive a mobility-based admission control algorithm which we analyze by Markov chains. We hence obtain several performance measures, namely the blocking probability, the dropping probability, both intra and inter-cell, as well as the overall cell throughput. We eventually investigate the performance of our CAC and show how to extend the Erlang capacity bounds, i.e., the set of arrival rates such that the corresponding blocking/dropping probabilities are kept below predetermined thresholds.

1 Introduction

Universal mobile Telecommunication System (UMTS) is designed to support a variety of multimedia services and its radio interface is based on Wideband Code Division Multiple Access (WCDMA). In such a context, the system is interference-limited and an efficient Connection Admission Control (CAC) is needed to guarantee Quality of Service (QoS) of the different multimedia classes.

Several CDMA-oriented CAC algorithms have been developed, considering the Signal-to-Interference Ratio (SIR) as the determinant parameter in accepting or not a new call; the idea being mainly that a new call is accepted if its contribution to the overall interference at the base station does not make the latter exceed a given value [9] , or alternatively if the new call does not make the SIR of an ongoing user fall below a target value [5][6][13]. However, these works did not compute exact values for the blocking probabilities, and hence cannot be used for an exact dimensioning of the system.

Yet, other works studied the capacity of CDMA systems using Markov chains, and obtained analytical values for the blocking probabilities, but they focused solely on the uplink [1][12]; it is well known, however, that the traffic in 3G systems is assymetric, with the major part of data traffic supported by the downlink. The only work, to our knowledge, that computed exact blocking rates

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in the downlink is [11], but it failed to consider the maximal transmission power of the base station as an additional CAC constraint.

Moreover, these works considered a static CDMA system, where the QoS of a user does not depend on its mobility and position in the cell. This assumption could be somehow acceptable in the uplink, where a perfect power control makes the SIR homogeneous in the cell until the maximal transmission power is reached [7]. This is not true in the downlink where the SIR is largely dependent on mobility. In fact, the level of interference at the mobile station in the downlink will depend largely on its position in the cell : the farther is the mobile terminal from the base station, the higher is the interference it experiences from adjacent cells [7]. This factor, i.e., distance r between the base station and the mobile terminal, plays a discriminating role between different users in the downlink.

Our aim in this work is then to develop an admission control algorithm that handles the mobility issue in the downlink of 3G wireless systems. It shall also account for the maximal transmission power of the base station. Our algorithm also handles priorities between voice and data traffic.

To take mobility into account, we develop expressions for the SIR in a multiple cell setting, and define a larger set of classes of users that implements, in addition to the traditional voice versus data cleavage, new levels of priorities based on the distance r. r is a random variable that changes with time accounting for the user's mobility. The idea is then to decompose the cell into a finite number of concentric circles, so-called rings, and to define an effective bandwidth expression relative to each ring.

This effective bandwidth formulation makes it possible to study the capacity of the system by Markov chains and to determine exact values of the blocking probabilities. Another important performance measure that we obtain is the dropping probability, i.e., the probability that an accepted user moving away from its base station sees its call dropped before reaching the adjacent cell, or has its handoff request blocked due to a lack of resources in the new cell.

Using these analytical tools, we associate to each ring and each class of multimedia calls a given acceptance ratio. We find out that if the aim is to reduce the dropping probability of ongoing calls at a low price in terms of blocking probability of voice calls, we need to prioritize the calls that have the lower effective bandwidth requirements. In this sense, data users near the base station may have higher priority over farther voice users.

We next study the Erlang capacity of our system and determine the set of arrival rates such that the corresponding blocking/dropping probabilities are below predetermined thresholds. We show how to extend the Erlang capacity region to include some additional arrival rates.

The remainder of this paper is organized as follows. In section II, we develop an effective bandwidth formulation for the different classes of users in the system where a class reflects both the user's type of traffic as well as its position in the cell. Based on these expressions, we define our CAC condition. In Section III, we present a Markovian analysis of our algorithm and determine the steady state probabilities. The performance measures in terms of blocking and dropping probabilities as well as cell throughput are calculated in Section IV. In Section V we investigate, through numerical applications, several CAC strategies so as to determine optimality of the algorithm. We also address the Erlang capacity issue and show the benefits of our CAC in extending it. Section VI eventually concludes the paper.

2 Model

2.1 Cell Decomposition

We consider a homogeneous DS/CDMA cellular system with hexagonal cells, of radius R, uniformly deployed, and numbered from 0 to ∞; the target cell being numbered 0 and containing K users.

In a previous work [7], we developed an expression for the SIR in UMTS. In the downlink, we obtained a lower bound for the SIR :

$$\beta_j \geq \gamma_j = \frac{P_j^{(B)}}{\sigma^2 q_j + \frac{I(r_j)}{N} + \frac{1-\epsilon}{N} \sum_{i=1}^{K} P_i^{(B)}} \tag{1}$$

with $P_i^{(B)}$ the signal emitted by the base station for user i, σ^2 is the power of the background Gaussian noise, N is the spreading factor and ϵ is the orthogonality factor. q_j is the path loss between mobile j and the base station given by :

$$q_j = L \times (r_j)^\alpha 10^{(-\xi_j/10)} \tag{2}$$

where r_j is the distance between mobile j and the base station and ξ_j is a random variable due to shadowing. α is usually equal to 4 and $L = 33.8$. $I(r_j)$ is the upper bound of the other-cell interference at mobile j that we calculated in [7] based on a log-normal approximation of this interference. We showed that this other-cell interference varies rapidly with the distance to the base station, while its variation with the angle with an arbitrary reference axis is not significant. It can then be considered as a function of r_j solely.

The downlink is limited by the maximum transmission power W^B that could be emitted by the base station [6][8] and so :

$$\sum_{i=1}^{K_0} P_i^{(B)} \leq W^B \tag{3}$$

Then, the CAC equation is :

$$\sum_{i=1}^{K} \gamma_i [\frac{(1-\epsilon)W^B}{N} + \sigma^2 q_i + \frac{I(r_i)}{N}] \leq W^B \tag{4}$$

This CAC equation is more constraining than classical ones where a call is accepted if it does not degrade the SIR of ongoing users [11][13], or if it does not make the system reach its pole capacity [1], i.e., the number of users that makes the power go to infinity. In fact, the maximal transmission power is not infinite and the pole capacity can thus never be reached.

Let us introduce the following notation :

$$\mathbf{g}(r,\xi) = \frac{(1-\epsilon)W^B}{N} + \sigma^2 r^\alpha 10^{-\xi/10} + \frac{I(r)}{N} \tag{5}$$

$\mathbf{g}(r,\xi)$ contains three interference terms. The first term, $\frac{(1-\epsilon)W^B}{N}$, due to the intra-cell interference, is a constant term that will be preponderant near the base station. The second term, $\sigma^2 r^\alpha 10^{-\xi/10}$, is due to the Gaussian noise. And the third term, $\frac{I(r)}{N}$, is generated by the other-cell interference and will have a larger effect near the cell border.

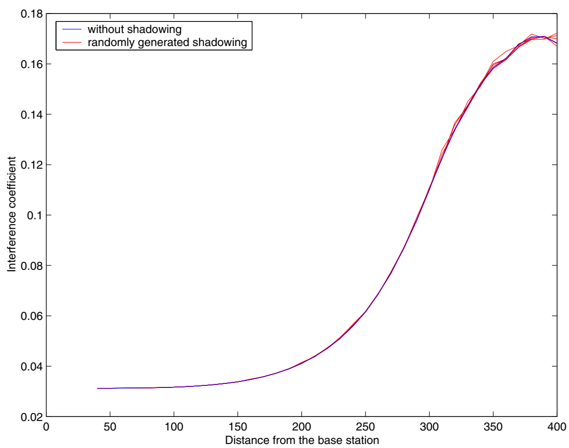

Fig. 1. Effect of the shadowing on the interference coefficient

However, the direct effect of the shadowing ξ in the noise term $\sigma^2 r^\alpha 10^{-\xi/10}$ is not significant as this term is small compared to the other parameters, as shown in Figure 1. The latter plots the interference coefficient $\mathbf{g}(r,\xi)$ as a function of the distance r, with and without shadowing in the noise term, for a cell of radius $R = 400$ meters. We can see that even for a large cell where the Gaussian noise has a relatively large mean value, the effect of shadowing is not significant in the overall interference coefficient and can thus be neglected in capacity calculations. Let us note that its effect remains however important as it increases the upper bound of the othercell interference factor ($P_i^d q_i$ in $I(r_i)$). We can then neglect the shadowing in the noise term, i.e.,

$$\mathbf{g}(r,\xi) \simeq g(r) = \frac{(1-\epsilon)W^B}{N} + \sigma^2 r^\alpha + \frac{I(r)}{N} \tag{6}$$

Without loss of generality, we limit our study to two classes of users : voice users requiring a SIR of γ^v and data users requiring a SIR equal to γ^d. For K^v and K^d voice and data users in the cell respectively, Eqn. (4) becomes :

$$\sum_{i=1}^{K^v} \gamma^v g(r_i) + \sum_{i=1}^{K^d} \gamma^d g(r_i) \leq W^B \tag{7}$$

We define the effective bandwidth of class-x users at distance r from the base station as

$$E^x(r) = \gamma^x g(r) \tag{8}$$

Let us now divide the cell into n concentric circles of radii R_k, $k = 1...n$, the last circle being the circumcircle of the hexagonal cell, and let us define ring Z_k as the area between the two adjacent circles of radii R_{k-1} and R_k (see Figure 2). The system is hence quantized. Let us note that the last ring will cover parts of the adjacent cells to include calls that are in the soft handover region and are then connected to both cells in the same time.

The immediate consequence of this quantization is that each class of users is divided into n subclasses depending on their position in the cell. We then have $2n$ classes : n classes of voice calls, and n classes of data ones, and the effective bandwidth of class-x mobiles in ring Z_k can be considered as constant with value

$$E_k^x = \gamma^x g(\overline{R}_k) \tag{9}$$

where $\overline{R}_k = \sqrt{\frac{R_k^2 + R_{k-1}^2}{2}}$, for instance and $R_0 = 0$.

Note that Eqn. (7) can then be rewritten as

$$\sum_{k=1}^{n} (E_k^v K_k^v + E_k^d K_k^d) \leq W^B \tag{10}$$

This effective bandwidth formulation of the load makes an abstraction of the complexity of the WCDMA radio interface by a simple combination of a finite number of traffic classes, in a circuit-switched-like system.

3 Analysis

3.1 CAC Algorithm

Our CAC algorithm is based on the idea of handling the mobility of users for taking a CAC decision. The state of the system is then defined by the instantaneous number of calls in each ring. Priorities between handoff and new calls, as well as between voice and data, are assured by means of different acceptance ratios which we now define.

Calls arrive as new or handoff : voice handoff calls are given an absolute priority over all other calls, while data handoff calls (if present) are treated as new ones. Handoff voice calls are accepted if enough resources are available

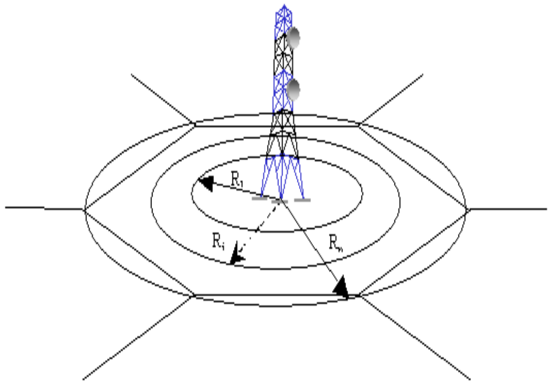

Fig. 2. Cell decomposition into rings

(i.e., condition (10) is verified taking into account that the handoff call is always situated in the last ring Z_n). For new calls of class x arriving in ring $Z_k, k = 1..n$, they are accepted, if condition (10) is verified, with an acceptance ratio $a_k^x \leq 1$, $k = 1...n$. In doing so, a new call request may be blocked, even though enough resources are available, in order to leave space to higher priority users. Handoff voice calls have an acceptance ratio of 1. Note that we treat handover calls, and generally calls in last rings, in a pessimistic way, giving that they may require lower power due to the macrodiversity. An alternative way to deal with these calls is to define lower effective bandwidth for them. The whole analysis of this paper will still hold.

3.2 Markovian Model

In what follows, we will make use of the following assumptions :

1. The arrival process of class-x new calls is Poisson with rate Λ^x uniformally distributed over the cell surface.
2. The arrival process of class-x handoff calls in Z_n is Poisson with rate λ_h^x.
3. Class-x calls migrate from ring Z_i to ring Z_j, $j = i \pm 1$, with rate $\lambda_{i,j}^x$.
4. The service time of a class-x call is exponential with mean $1/\mu^x$.

The arrival process of class-x new calls in ring Z_i is also Poisson with rate

$$\Lambda_i^x = \Lambda^x \frac{R_i^2 - R_{i-1}^2}{R^2} \qquad (11)$$

For K_i^v and K_i^d denoting the number of voice and data calls in progress within ring Z_i, respectively, the system state can be defined by a row vector $\overrightarrow{s}$

$$\overrightarrow{s} := (K_1^v, ..., K_n^v, K_1^d, ..., K_n^d)$$

In the remainder of this paper, we will use the following definitions :

Definition 1. A is the finite subset of $\mathbf{N}^{2n}$ for which condition (10) holds. This means that a state vector $\overrightarrow{s}$ is in A if and only if $\sum_{k=1}^{n}(E_k^v K_k^v + E_k^d K_k^d) \leq W^B$.

Definition 2. $\mathrm{A_k^x}$ is the subspace of A where any other new call of class x in ring Z_k will be blocked due to lack of resources. In other terms, $\overrightarrow{s} \in \mathrm{A_k^x}$ if and only if $\overrightarrow{s} \in$ A and $\sum_{k=1}^{n}(E_k^v K_k^v + E_k^d K_k^d) + E_k^x > W^B$. $\overline{\mathrm{A_k^x}}$ is the complementary subspace of $\mathrm{A_k^x}$ in A.

Within the space of admissible states A, transitions are caused by :

1) Arrival of a new call in ring Z_k, $1 \leq k \leq n$.
2) Arrival of a handoff call in ring Z_n.
3) Termination of a class-x ongoing call in ring Z_k.
4) Migration of an ongoing class-x call from Z_k to Z_{k+1}, $1 \leq k < n$. Note that such a migrating call may be dropped if there are not enough resources.
5) Migration of an ongoing call from ring Z_k to ring Z_{k-1}, $2 \leq k \leq n$. Note that a call migrating from ring Z_k to ring Z_{k-1} is never dropped.
6) Departure of a class-x call from border ring Z_n to an adjacent cell.

3.3 Steady State Probabilities

Let $\pi(\overrightarrow{s})$ be the steady state probability of state $\overrightarrow{s}$. If we consider that the dwell time of class-x mobiles in ring Z_k (i.e., the time they spend in ring Z_k) is exponentially distributed with mean $1/\nu_k^x$, then the following theorem holds :

Theorem 1. *the system described above is a Markov chain and the steady state probabilities are given by*

$$\pi(\overrightarrow{s}) = \frac{1}{G}\prod_{k=1}^{n}\prod_{x=v}^{d}\frac{(\rho_k^x)^{K_k^x}}{K_k^x!}, \quad \overrightarrow{s} \in A \tag{12}$$

where ρ_k^x is the offered load of class-x calls in ring Z_k given by :

$$\rho_k^x = \frac{a_k^x \Lambda_k^x + a_h^x \lambda_h^x I_{k=n} + \lambda_{k+1,k}^x I_{k\neq n} + \lambda_{k-1,k}^x I_{k\neq 1}}{\eta_k^x} \tag{13}$$

where $\eta_k^x = (\nu_k^x + \mu_k)$ and G is the normalizing constant given by :

$$G = \sum_{\overrightarrow{s}\in \mathrm{A}}\prod_{k=1}^{n}\prod_{x=v}^{d}\frac{(\rho_k^x)^{K_k^x}}{K_k^x!} \tag{14}$$

Proof. Let V_k^x, X^x and Y_k^x be the random variables indicating the channel holding time of a class-x call in ring Z_k, the class-x call duration, and the dwell time in Z_k respectively. X^x and Y_k^x are independent as the first depends on the amount of data to be sent and the latter on the users' mobility. We then have $V_k^x = \min(X^x, Y_k^x)$ with cumulative distribution function (CDF) :

$$F_{V_k^x}(t) = F_{X^x}(t) + F_{Y_k^x}(t) - F_{X_k^x}(t)F_{Y_k^x}(t) = 1 - \exp(-(\mu^x + \nu_k^x)t) \tag{15}$$

V_k^x is then exponential and the load of calls (c, k) is given by Eqn. (13).

Our system corresponds to a BCMP network with a single node (corresponding to the cell), where class-x customers arrive from the outside to ring Z_k with rate Λ_k^x as new calls and λ_h^x as handoff ones. These rates must be multiplied by their corresponding acceptance ratios. These customers are served for a time equal to V_k^x and then either quit the queue (call termination or handoff), or reenter it after changing their class from (c, k) to $(c, k \pm 1)$, following certain routing probabilities [2] (migration from one ring to another). The total arrival rate of class-x calls in ring Z_k is then $a_k^x \Lambda_k^x + a_h^x \lambda_h^x I_{k=n} + \lambda_{k+1,k}^x I_{k \neq n} + \lambda_{k-1,k}^x I_{k \neq 1}$.

According to the BCMP theorem for multiple classes of customers with possible class changes (see [3] pp. 146-150), the steady state probabilities have the product form given in Eqn. (12).

Remark. It can be further shown that the formulae for the steady state probabilities extend also for the case where the dwell time for class-x calls in ring Z_k and/or the call duration time are not exponential, but have general distributions. The system is no more a Markov chain, but Eqn. (12) holds, as the steady state distribution in a multi-service loss system is insensitive to the call duration distribution and depends only on its mean [4]. This mean is derived via the resulting CDF of the channel holding time of calls (x, k) (Eqn. (15)).

3.4 Determination of Handoff and Migration Rates

In equilibrium, the overall system may be assumed homogeneous and a cell statistically the same as any other one. We can thus decouple a cell from the rest of the system by assuming that, for each class x of calls, the mean handoff arrival rate to the given cell is equal to the mean handoff departure rate from it [10][11], i.e., $\lambda_h^x = \lambda_{n,n+1}^x$.

The migration rates from a ring Z_k to its adjacent rings Z_{k-1} and Z_{k+1} depend on the dwell times and the number of calls in ring Z_k. We then have

$$\lambda_{1,2}^x = \sum_{\overrightarrow{s} \in \mathrm{A}} \pi(\overrightarrow{s}) K_1^x \nu_1^x \tag{16}$$

$$\lambda_{i,i+1}^x + \lambda_{i,i-1}^x = \sum_{\overrightarrow{s} \in \mathrm{A}} \pi(\overrightarrow{s}) K_i^x \nu_i^x \tag{17}$$

$$\lambda_h^x + \lambda_{n,n-1}^x = \sum_{\overrightarrow{s} \in \mathrm{A}} \pi(\overrightarrow{s}) K_n^x \nu_i^x \tag{18}$$

On the other hand, if we assume that the trajectories followed by the different mobiles are randomly chosen, the migration rates are proportional to the perimeter of contact between two adjacent rings, which gives :

$$\lambda_{i,i+1}^x = \frac{R_i}{R_{i-1}} \lambda_{i,i-1}^x, \quad i = 2..n \tag{19}$$

One can see that these handoff/migration rates depend on the steady state probabilities, while the latter are themselves derived using the handoff/migration rates. To solve this problem, we use the following iterative algorithm that begins with an initial guess for handoff/migration rates.

Step 1 : Set initial values for the arrival/migration rates. To do so, we suppose that the dropping probabilities are negligible and that the blocking probabilities in Eqn. (22) are essentially due to the fact that the acceptance ratios a_k^x *may be strictly less than 1 :*

$$p_k^x \simeq 1 - a_k^x$$

If $p_{i,j}^x$ *is the probability that a call migrates from ring* i *to ring* $j = i \pm 1$ *:*

$$\lambda_{i,i+1}^x + \lambda_{i,i-1}^x \simeq (p_{i,i+1}^x + p_{i,i-1}^x)(\Lambda_i^x a_k^x + \lambda_{i+1,i} + \lambda_{i-1,i}^x) \tag{20}$$

The migration probability is the probability that the call quits ring Z_i *before termination. It is given by :*

$$p_{i,i+1}^x + p_{i,i-1}^x = P(Y_k^x < X^x) = \frac{\nu_k^x}{\nu_k^x + \mu^x} \tag{21}$$

The initial migration/handoff rates are then obtained by solving the set of equations (20), using Eqns. (19) and (21).

Step 2 : Obtain the steady state probabilities from Eqn. (12).

Step 3 : Calculate the migration rates corresponding to the obtained state probabilities using Eqns. (16)-(19).

Step 4 : Check the convergence of the migration rates using the relative error $e = \max |1 - \frac{\lambda_{new}}{\lambda_{old}}|$. *If* $e > \epsilon$, *where* $\epsilon > 0$ *is a predetermined constant, go to Step 2, otherwise, compute the performance measures given in the next section.*

4 Performance Measures

4.1 Blocking Probabilities

The first performance measure is the blocking probability.

Proposition 1. *The blocking probability* p_k^x *of a class-x call in ring* Z_k *is :*

$$p_k^x = 1 - a_k^x + a_k^x \sum_{\overrightarrow{s} \in \mathrm{A}_\mathrm{k}^\mathrm{x}} \pi(\overrightarrow{s}) \tag{22}$$

Specifically, the new call blocking probability is given by

$$p^x = \frac{1}{\Lambda^x} \sum_{k=1}^{n} p_k^x \Lambda_k^x \tag{23}$$

and the voice handoff call blocking probability is given by :

$$p_h^v = \sum_{\overrightarrow{s} \in A_n^v} \pi(\overrightarrow{s}) \tag{24}$$

Proof. A new connection of class-x in ring Z_k is always blocked if the system is in a state $\overrightarrow{s} \in \mathrm{A}_\mathrm{k}^\mathrm{x}$. Otherwise, it is blocked with probability $1 - a_k^x$. In total, the blocking probability is

$$p_k^x = (1 - a_k^x) \sum_{\overrightarrow{s} \in \overline{\mathrm{A}_\mathrm{k}^\mathrm{x}}} \pi(\overrightarrow{s}) + \sum_{\overrightarrow{s} \in \mathrm{A}_\mathrm{k}^\mathrm{x}} \pi(\overrightarrow{s}) = 1 - a_k^x + a_k^x \sum_{\overrightarrow{s} \in \mathrm{A}_\mathrm{k}^\mathrm{x}} \pi(\overrightarrow{s}) \qquad (25)$$

The overall blocking probability in the cell is directly derived by means of the relative arrival rates Λ_k^x / Λ^x.

For voice handoff calls, they arrive only at the last ring Z_n. They are then blocked when the system is in a state of the space A_n^v with probability :

$$p_h^v = \sum_{\overrightarrow{s} \in A_n^v} \pi(\overrightarrow{s})$$

Note that the blocking probability for handoff data calls is equal to that of new data ones at the cell border, i.e., $p_h^d = p_n^d$.

4.2 Dropping Probability

We now determine the dropping probability. In the literature [14], this term refers to the blocking of a handover call. We shall denote this particular event by inter-cell dropping. As we focus on intra-cell mobility, we should thus take into account the possibility of an intra-cell dropping event, i.e., a mobile station moving away from its base station experiences a higher interference figure and is thus dropped due to a lack of resources. The overall dropping probability is hence the result of both intra and inter-cell dropping probabilities.

Proposition 2. *The intra-cell dropping probability d^x of a class-x call due to mobility inside the cell is equal to :*

$$d^x = \frac{1}{\sum_{\overrightarrow{s} \in A} K^x (\nu_k^x + \mu^x) \pi(\overrightarrow{s})} \sum_{k=1}^{n-1} \sum_{\overrightarrow{s} \in \mathrm{A} / \overrightarrow{s}_{k,k+1}^x \notin \mathrm{A}} K_k^x \nu_k^x \frac{R_k}{R_k + R_{k-1}} \pi(\overrightarrow{s}) \qquad (26)$$

where $\overrightarrow{s}_{k,k+1}^x$ is the next state when a class-x call quits ring Z_k to ring Z_{k+1}.

Proof. If the system is in state $\overrightarrow{s}$, a migrating class-x call from ring Z_k to ring Z_{k+1} is dropped if the state $\overrightarrow{s}_{k,k+1}^x \notin \mathrm{A}$. However, not all mobiles migrate : only those whose dwell time in the ring is less then their call duration time do migrate. The rate of leaving the ring $K_k^x(\nu_k^x + \mu^x)$ must then be multiplied by the probability that an ongoing class-x call quits the ring :

$$P(Y_k^x < X^x) = \frac{\nu_k^x}{\nu_k^x + \mu^x}$$

Among these calls, only a fraction of $\frac{R_k}{R_k + R_{k-1}}$ try to migrate from ring Z_k to ring Z_{k+1}. These calls are dropped if $\overrightarrow{s}_{k,k+1}^x \notin \mathrm{A}$.

The intra-cell dropping probability d^x due to mobility within the cell is the sum of dropping rates at each ring Z_k, divided by the rate of leaving the system, which gives the proof.

Let us now determine the overall dropping probability.

Corollary 1. *The overall dropping probability f^x of an ongoing class-x call due to its mobility within the cell or between adjacent ones is equal to :*

$$f^x = d^x + \frac{1}{\sum_{\overrightarrow{s} \in A} K^x(\nu_k^x + \mu^x)\pi(\overrightarrow{s})} \sum_{\overrightarrow{s} \in A} K_n^x \nu_n^x \frac{R_n}{R_n + R_{n-1}} \pi(\overrightarrow{s}) p_h^x \qquad (27)$$

Proof. To the intra-cell dropping probability, we add the blocking rate of calls leaving the cell to adjacent ones, i.e., inter-cell dropping rate, divided by the rate of calls leaving the system. As the overall system is homogeneous in equilibrium, this blocking probability is equal to the handoff blocking probability calculated in Proposition 1. This leads to the expression (27).

Remark. It is envisaged that heavy loaded cells may be divided into three sectors by means of three directive transmitters, in order to limit the interference. This introduces the notion of softer handover between sectors of the same cell, which is present in all zones and not only in zone Z_n. The softer handoff blocking probability in zone Z_k is then equal to p_k^x. The same analysis can be applied to calculate the overall dropping probability. In particular, if λ_{sh}^x is the softer handover rate from zone Z_k in the target sector to the adjacent sectors, we have:

$$\frac{\lambda_{sh}^x}{2(R_k - R_{k-1})} = \frac{\lambda_{k,k+1}^x}{\frac{2\pi R_k}{3}} = \frac{\lambda_{k,k-1}^x}{\frac{2\pi R_{k-1}}{3}}$$

4.3 Throughput

Another important performance measure is the overall cell throughput :

$$T = \sum_{\overrightarrow{s} \in A} \{\sum_{k=1}^{n} (K_k^v D^v + K_k^d D^d)\} \pi(\overrightarrow{s}) \qquad (28)$$

where D^x is the throughput of a class-x single user.

5 Numerical Applications

The following parameters shall be used in the numerical applications:

- The cell has a radius of 400 meters, and the base station has a transmission power of 5 Watts.
- The mean call duration is equal to 120 sec.

– New calls arrive according to a Poisson process with rate Λ. A new call is randomly generated as a voice call with probability 0.75 or a data call with probability 0.25, that is, $\Lambda^v = 0.75\Lambda$ and $\Lambda^d = 0.25\Lambda$.
– Voice calls have a SIR requirement of 5 dB and a rate of 12.2 Kbps, while data calls require a SIR of 9 dB and have a rate of 64 Kbps.
– Medium mobility is studied for a mean dwell time in the cell equal to 300 sec, and the mean dwell time is proportional to the surface of each ring.

5.1 Acceptance Strategy

In Section IV, we analyzed the performance of our algorithm under general assumptions for the acceptance ratios. We now study it under four specific acceptance strategies which are :

1. No priorities between classes : a new call is accepted if there are enough resources, it is blocked otherwise, i.e., $a_k^x = 1$, $k = 1...n$, $x = v, d$.
2. Voice calls are given absolute priority over data ones, i.e., $a_k^v > a_l^d$, $\forall k \leq n, l \leq n$.
3. Data calls are given absolute priority over voice ones, i.e., $a_k^d > a_l^v$, $\forall k \leq n, l \leq n$.
4. The priority of a class-x call is dependent on its effective bandwidth, i.e., $a_k^x > a_l^y$ if $E_k^x < E_l^y$. This will lead to a situation where data calls near the base station have higher priority than distant voice calls.

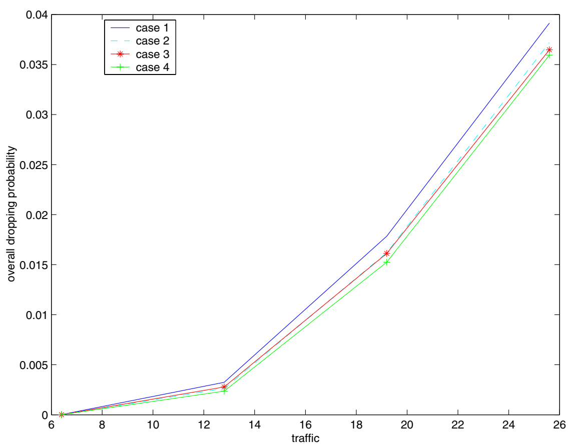

Fig. 3. Dropping probability for the four strategies in the Priority CAC

Our aim is to minimize the dropping probability, at low voice blocking probability. We plot in Figures 3 and 4 the dropping probability and the voice blocking probability for the four strategies, respectively.

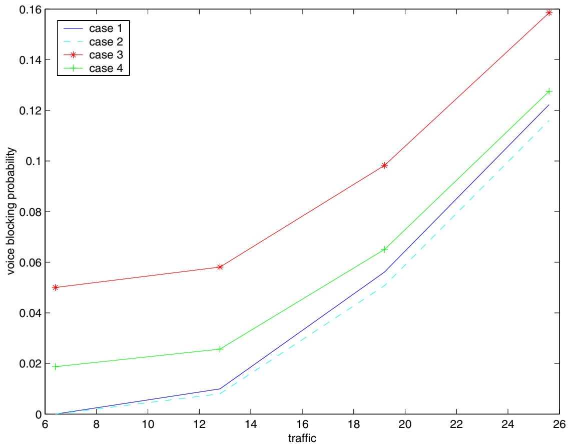

Fig. 4. Voice blocking probability for the four strategies in the Priority CAC

We observe that giving higher priority to data calls (strategy 3) decreases the dropping probability. However, it is very harmful to voice calls as they will experience a high blocking rate. The best lowest dropping probability is obtained when using strategy 4, where the blocking ratio is proportional to the effective bandwidth. This strategy achieves a low dropping probability at an acceptable blocking rate for voice calls. The only drawback is that this strategy results in a slightly lower throughput (see Figure 5) and may be unfair for users with large capacity demands. In the remainder of this work, we will adopt this strategy in our capacity calculations. However, the whole analysis holds for any strategy.

5.2 Investigating Erlang Capacity

The Erlang capacity is generally defined as the set of offered loads such that the corresponding blocking probability is smaller than a given $\epsilon > 0$ [1]. In this work, as we are also interested in the dropping probability, we will extend this definition to the following :

Definition 3. The Erlang capacity $EC(\epsilon_1, \epsilon_2)$ is defined as the set of offered loads such that there exists a set of acceptance ratios $(a_1^v...a_n^v, a_1^d...a_n^d)$ for which the dropping probability is less than a given $\epsilon_1 > 0$, and the blocking probability is less than $\epsilon_2 \geq \epsilon_1 > 0$.

In other words, we determine, if they exist, the acceptance ratios for each arrival rate that satisfy the constraints on blocking / dropping probabilities.

For illustration, we study the case where $\epsilon_1 = 3\%$ and $\epsilon_2 = 12\%$, and $a_{min}^v = (1 + a_{min}^d)/2$, i.e., the preventive blocking of data calls at the cell border occurs with a probability equal to $1 - a_{min}^d$, while voice calls in the same conditions are blocked in a preventive way only at a probability of $1 - a_{min}^v = (1 - a_{min}^d)/2$. We plot in Figures 6, 7 and 8 the voice blocking probabilities, the dropping proba-

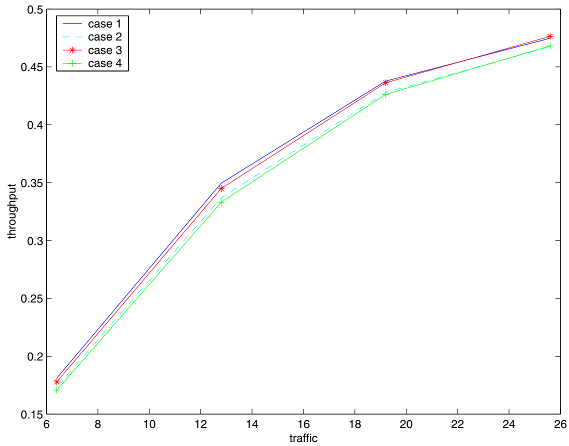

Fig. 5. Throughput achieved for the four strategies in the Priority CAC

bilities and the achieved throughput corresponding to those values, respectively, for six different arrival rates.

One can see that for an arrival rate $\Lambda > 0.17$ calls per sec, we cannot satisfy the performance measures with any set of acceptance ratios. In fact, we cannot satisfy jointly the conditions on the blocking and dropping probabilities for any acceptance ratio (Fig. 6 and 7). The Erlang capacity region is than limited by $\Lambda_{max} = 0.17$ calls per sec.

On the other hand, when $\Lambda = 0.17$ calls per sec, the constraint on the dropping probability is satisfied for $a^v_{min} \leq 0.88$ (Figure 7), while the constraint for the blocking probability imposes that $a^v_{min} \geq 0.84$ (Figure 6). The best choice that maximizes the throughput is then $a^v_{min} = 0.88$ (Figure 8).

Note that if no priorities were implemented, an arrival rate of $\Lambda = 0.17$ calls per sec would have generate a dropping rate larger than 3% that is not acceptable. The priority-based CAC extends then the Erlang capacity region to include even larger arrival rates.

6 Conclusion

In this paper, we developed a mobility-based admission control for the downlink of third generation mobile networks. We first studied the system capacity and obtained effective bandwidth expressions based on both the class of traffic and the position of the user in the cell, hence accounting for its mobility pattern.

Based on this formulation, we attributed to each class of users an acceptance ratio to handle priorities between flows, and proved that the underlying system can be modeled as a Markov chain. We then obtained the steady state probabilities and gave an iterative algorithm to determine them explicitly.

As of the performance measures, we obtained the blocking probabilities and the dropping probabilities of ongoing calls, be they intra-cell due to their mobility

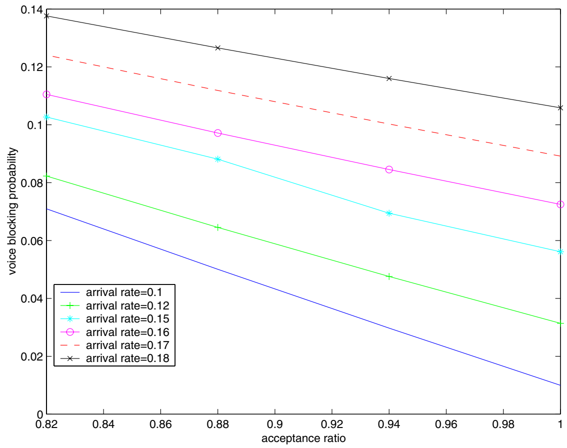

Fig. 6. Voice blocking probability for different arrival rates in the Priority CAC

or inter-cell due to handoff. We also determined the overall cell throughput. We next studied numerically our CAC algorithm and determined the Erlang capacity bounds, i.e. the set of arrival rates that satisfy predetermined constraints on blocking/dropping probabilities.

In a fucture work, we should introduce the effect of interaction between cells and show how downgrading elastic data calls affects the CAC algorithm.

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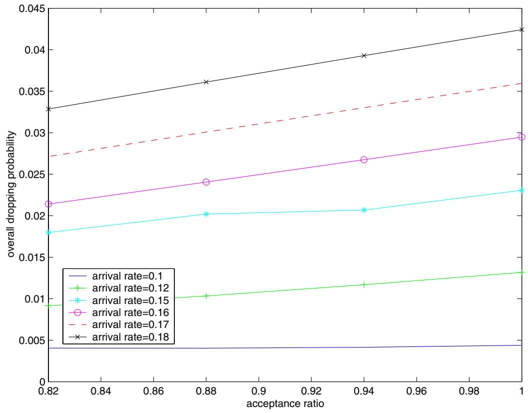

Fig. 7. Dropping probability for different arrival rates in the Priority CAC

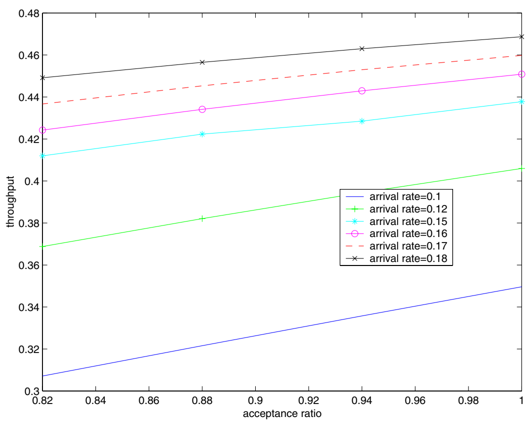

Fig. 8. Throughput for different arrival rates in the Priority CAC

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