Call Admission Control for Voice/Data Integration in Broadband Wireless Networks

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Abstract

This paper addresses bandwidth allocation for an integrated voice/data broadband mobile wireless network. Specifically, we propose a new admission control scheme called EFGC, which is an extension of the well-known fractional guard channel scheme proposed for cellular networks supporting voice traffic. The main idea is to use two acceptance ratios, one for voice calls and the other for data calls in order to maintain the proportional service quality for voice and data traffic while guaranteeing a target handoff failure probability for voice calls. We describe two variations of the proposed scheme: EFGC-REST, a conservative approach which aims at preserving the proportional service quality by sacrificing the bandwidth utilization; and EFGC-UTIL, a greedy approach which achieves higher bandwidth utilization at the expense of increasing the handoff failure probability for voice calls. Extensive simulation results show that our schemes satisfy the hard constraints on handoff failure probability and service differentiation while maintaining a high bandwidth utilization.

Index Terms

Call admission control, voice/data integration, quality-of-service, broadband wireless networks.

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I. Introduction

Emerging wireless technologies such as 3G and 4G will increase the cell capacity of wireless cellular networks to several Mbps [1]. With this expansion of wireless bandwidth, the next generations of mobile cellular networks are expected to support diverse applications such as voice, data and multimedia with varying quality of service (QoS) and bandwidth requirements [2]. Wireless links bandwidth is limited and is generally much smaller than that of wireline access links. Therefore, for integrated voice/data mobile networks it is necessary to develop mechanisms that can provide effective bandwidth management while satisfying the QoS requirements of both types of traffic.

At call-level, two important quality of service parameters are the *call blocking probability* (p_b) and the *call dropping probability* (p_d). An active mobile user in a cellular network may move from one cell to another. The continuity of service to the mobile user in the new cell requires a successful handoff from the previous cell to the new cell. The probability of a handoff failure is called *handoff failure probability* (p_f). During the life of a call, a mobile user may cross several cell boundaries and hence may require several successful handoffs. Failure to get a successful handoff at any cell in the path forces the network to drop the call. The probability of such an event is known as the call dropping probability.

Since dropping a call in progress has a more negative impact from the user perspective, handoff calls are given higher priority than new calls in accessing the wireless resources. This preferential treatment of handoffs increases the probability of blocking new calls and hence may degrade the bandwidth utilization. The most popular approach to prioritize handoff calls over new calls is by reserving a portion of available bandwidth in each cell to be used exclusively for handoffs. Based on this idea, a number of call admission control (CAC) schemes have been proposed which basically differ from each other in the way they calculate the reservation threshold [3]–[8].

Bandwidth allocation has been extensively studied in single-service (voice) wireless cellular networks. Hong and Rappaport [3] are the first who systematically analyzed the famous *guard*

channel (GC) scheme, which is currently deployed in cellular networks supporting voice calls. Ramjee et al. [9] have formally defined and categorized the admission control problem in cellular networks. They showed that the guard channel scheme is optimal for minimizing a linear objective function of call blocking and dropping probabilities while the *fractional guard channel* scheme (FGC) [9] is optimal for minimizing call blocking probability subject to a hard constraint on call dropping probability. Instead of explicit bandwidth reservation as in GC, the FGC accepts new calls according to a randomization parameter called the *acceptance ratio*. One advantage of FGC over GC is that it distributes the new accepted calls evenly over time which leads to a more stable control [10].

Because of user mobility, it is impossible to describe the state of the system by using only local information, unless we assume that the network is uniform and approximate the overall state of the system by the state of a single cell in isolation. To include the global effect of mobility, *collaborative* or *distributed* admission control schemes have been proposed [4]–[8], [10], [11]. Information exchange among a cluster of neighboring cells is the approach adopted by all distributed schemes.

In particular, Naghshineh and Schwartz [4] proposed a collaborative admission control known as *distributed call admission control* (DCA). DCA periodically gathers some information, namely the number of active calls, from the adjacent cells to make, in combination with the local information, the admission decision. It has been shown that DCA is not stable and violates the required dropping probability as the load increases [10]. Levin et al. [5] proposed a more sophisticated version of the original DCA based on the *shadow cluster* concept, which uses dynamic clusters for each user based on its mobility pattern instead of restricting itself (as DCA) to direct neighbors only. A practical limitation of the shadow cluster scheme in addition to its complexity and inherent overhead is that it requires a precise knowledge of the mobile's trajectory. Recently, Wu et al. [10] proposed a stable distributed scheme (SDCA) based on the classical fractional guard channel scheme which can precisely achieve the target call dropping probability. A key feature of SDCA is the formulation of the time-dependent call dropping probability which can be computed by the diffusion approximation of the channel occupancy.

One of the challenges in considering multi-services systems is that the already limited bandwidth has to be shared among multiple traffics. Epstein and Schwartz [12] investigated complete sharing, complete partitioning and hybrid reservation schemes for two classes of traffic, namely

narrow-band and wide-band traffic. In general, complete sharing strategy achieves the highest bandwidth utilization [12].

Fixed and movable boundary schemes for bandwidth allocation in wireless networks were studied by Wieselthier and Ephremides [13]. They concluded that movable boundary schemes can achieve a better utilization than fixed boundary schemes for voice and data integration. Since then, a number of papers have been published focusing on the performance of fixed and movable boundary schemes given different assumptions and network configurations [14]–[20].

In particular, Haung et al. [18] proposed a bandwidth allocation scheme for voice/data integration based on the idea of movable boundaries (MB). In their scheme, bandwidth is divided into two portions that can be dynamically adjusted to achieve the desired performance. However, they completely neglected the prioritization of handoff calls over new calls and treated the two identically. Yin et al. [19] proposed a *dual threshold reservation* (DTR) scheme, which extends the basic guard channel to use two thresholds, one for reserving channels for voice handoff, and the other for limiting the data traffic into the network in order to preserve the voice performance. An extended version of DTR which implements queueing for data calls (DTR-Q) was proposed in [20]. In general, queueing of new/handoff calls, can further improve the performance of call admission control [21]. The main limitation of DTR (DTR-Q) is that it is static, i.e., the two reservation thresholds are fixed over time regardless of the state of the network. Interested readers are referred to [22] for a comparison between DTR and MB schemes.

This paper introduces an *extended fractional guard channel call admission mechanism* (EFGC) for integrated voice and data mobile cellular networks. EFGC maximizes the wireless bandwidth utilization while satisfying a target call dropping probability and a relative voice/data service differentiation. The main idea is to use two acceptance ratios for voice and data according to the desired dropping probability of voice calls and the relative priority of voice calls over data calls. Similar to [15]–[20], we assume that call dropping is not an important issue for data calls and treat handoff and new data calls in the same way. We define the extended MINBLOCK [9] problem as follows:

> *for a given cell capacity, maximize the bandwidth utilization subject to a hard constraint on the voice call dropping probability and relative voice/data call blocking probability.*

To the best of our knowledge, extending the basic fractional guard channel scheme to address the extended MINBLOCK problem is a novel work. We follow an approach similar to the stable

admission control algorithm proposed by Wu et al. [10] to derive the acceptance ratios for voice and data calls. The main features of EFGC are as follows:

1) EFGC is dynamic, therefore, adapts to a wide range of system parameters and traffic conditions.
2) EFGC uses separate acceptance ratios for voice and data calls, therefore, it is very straightforward to enforce a relative or even strict service differentiation between voice and data traffic.
3) EFGC is distributed and takes into consideration the information from direct neighboring cells in making admission decisions.
4) The control mechanism is stochastic and periodical to reduce the overhead associated with distributed control schemes. EFGC determines the appropriate control parameters such as the control interval length in order to restrict the impact of the network to the direct neighbors only.

The rest of the paper is organized as follows. Our system model, assumptions and notations are described in section II. Section III is dedicated to the proposed admission control algorithm and presents the analysis of the proposed algorithm in detail. In section IV, we discuss the estimation of control parameters such as arrival rates, then we address the multiple handoffs problem and control interval length. Extensive simulation results and their analysis are presented in section V. Finally, section VI concludes this paper.

II. System Model

As shown in Fig. 1, we consider a cellular system which carries both voice and data traffic. We assume that wireless bandwidth is channelized where a channel can be a frequency, a time slot or a code sequence. We define the basic bandwidth unit (BU) as the smallest amount of bandwidth that can be allocated to a call, e.g., a channel. In this paper we focus on call-level QoS parameters, therefore only call-level traffic dynamics are required for resource allocation and admission control. More specifically, we assume that the *effective bandwidth* [23]–[25] concept is applied to each call. When employing this concept, an appropriate effective bandwidth is assigned to each call and each call is treated as if it required this effective bandwidth throughout the active period of the call. The feasibility of admitting a given set of connections may then

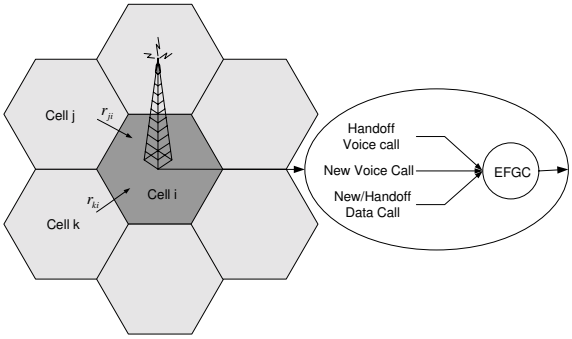


Fig. 1. Integration of voice and data at the base station of a cellular network.

be determined by ensuring that the sum of the effective bandwidths is less than or equal to the total available bandwidth, i.e. the cell capacity.

We assume that each voice call requires b_v BUs and each data call requires b_d BUs for the whole duration of the call. In the system under consideration, voice handoff calls have the highest priority, then come new voice calls, and lastly the new and handoff data calls are considered. As mentioned earlier, there is no prioritization of handoff data calls, and hence handoff data calls are treated the same as new data calls.

The considered system is not required to be uniform. Each cell can experience a different load, e.g., some cells can be over-utilized while others are under-utilized. Let $k = \{v, d\}$ denote the type of traffic, i.e. $k = v$ for voice and $k = d$ for data traffic. Below is the notation which will be used throughout this paper.

- M: number of cells in the network
- $\mathcal{A}_i$: the set of the adjacent cells of cell i
- c_i: the capacity of cell i in terms of BUs
- $R_i(t)$: bandwidth requirements (used capacity) in cell i at time t in terms of BUs
- $p_{f\,i}$: voice handoff failure probability in cell i
- p_{QoS}: target voice handoff failure probability to be guaranteed
- k: the service index for voice and data with $k = v$ for voice and $k = d$ for data
- λ_i^k: type-k new call arrival rate into cell i
- $1/\mu_k$: type-k mean call duration
- $1/h_k$: type-k mean cell residency time

- T: length of the control period
- b_k: bandwidth requirement of type-k calls in terms of BUs
- $N_i^k(t)$: number of active type-k calls in cell i at time t
- r_{ji}: routing probability from cell $j \in \mathcal{A}_i$ to cell i
- b_i^k: type-k call blocking probability in cell i
- a_i^k: type-k call acceptance ratio in cell i
- α_i: relative priority of voice traffic over data traffic in cell i defined as $\alpha_i = a_i^v / a_i^d$
- α_{QoS}: target relative priority of voice traffic over data traffic to be guaranteed
- p_b^k: network-wide type-k call blocking probability
- p_d: network-wide voice call dropping probability
- $E[z]$: the mean of random variable z
- $V[z]$: the variance of random variable z
- $\tilde{z}$: time-averaged value of random variable z
- $\hat{z}$: measured (observed) value of random variable z

Let random variables t_{d_k} and t_{r_k} denote the call duration (call holding time) and cell residency time of a typical type-k call, respectively. Similar to [3], [9], [10], [12]–[22], we assume that t_{d_k} and t_{r_k} are exponentially distributed. In the real world, the cell residence time distribution may not be exponential but exponential distributions provide the mean value analysis, which indicates the performance trend of the system. Furthermore, our proposed admission control algorithm involves a periodic control where the length of the control period is set to much less than the average cell residency time of a call to make the algorithm insensitive to this assumption.

A. Multiple Handoffs Probability

As mentioned earlier, in order to make the optimal admission decision, distributed schemes regularly exchange some information with other cells in the network. Those cells involved in the information exchange form a *cluster*. Due to the intercell information exchange, base station interconnection network incurs a high signalling overhead. Moreover, as the cluster size increases the operational complexity of the control algorithm increases too. In particular, two major factors affect the overhead and complexity of distributed CAC schemes; (1) frequency of information exchange, and, (2) depth of information exchange, i.e. how many cells away information is exchanged.

To reduce the overhead, distributed CAC schemes typically have a periodic structure in which only at the beginning of control periods information exchange is triggered. Moreover, information exchange is typically restricted to a cluster of neighboring cells. Note that, if the control interval is too small then frequent communications increases the signalling overhead. On the other hand, if the control period is too long then the state information stored locally may become stale. Similarly, if the cluster is too small then the exchanged information will poorly reflects the state of the network. On the other hand, a big cluster will lead to higher overhead. An efficient CAC scheme must compromise between the frequency and depth of information exchange.

In this paper, we set the control interval in such a way that the probability of having multiple handoffs in one control period becomes negligible. Therefore, we can effectively assume that only those cells directly connected to a cell can influence the number of calls in that cell during a control period. In a sense, we reduce the control interval in favor of a smaller cluster size. We claim that using this technique, the signalling overhead will not increase, while the collected information on the network status will be sufficiently accurate for the purpose of a stochastic admission control. The reason is that: first, by decreasing the control interval, the probability of multiple handoffs decays to zero exponentially (see section IV-C); second, a cluster shrinks quadratically with decreasing the depth of information exchange (see below).

Without loss of generality, consider a symmetric network where each cell has exactly $\mathcal{A}$ neighbors. Consider cell i and all the cells around it forming circular layers as shown in Fig. 2. From cell i, all the cells up to layer n are accessible with n handoffs assuming that cell i forms layer 0. The number of cells reachable by n handoffs from cell i denoted by $M(n)$ is given by

$$\begin{aligned} M(n) &= 1 + \mathcal{A} + \cdots + n\mathcal{A} \\ &= 1 + \frac{1}{2}n(n+1)\mathcal{A}\,. \end{aligned} \tag{1}$$

Therefore, by slightly reducing the control interval, we essentially achieve the same control accuracy but with reduced signalling overhead. The problem of choosing the proper control interval will be further addressed in section IV-C.

B. Handoff Failure and Call Dropping Probabilities

Although call dropping probability is more meaningful for mobile users and service providers, calculating the handoff failure probability is more convenient. Therefore, our calculations in this

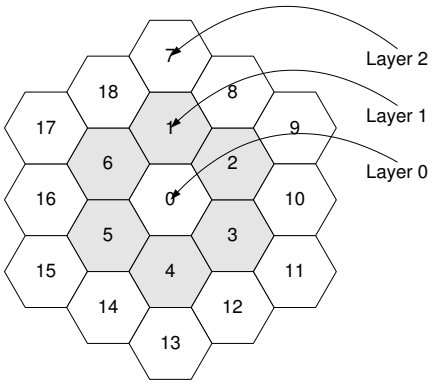


Fig. 2. A cellular system with 3 layers.

paper are based on the handoff failure probability, p_f, which can be related to the call dropping probability, p_d, as follows (refer to [3] for more details):

$$p_d = \sum_{H=0}^{\infty} (P_h^v)^H (1-p_f)^{H-1} p_f = \frac{P_h^v p_f}{1 - P_h^v (1-p_f)}, \tag{2}$$

where H is the number of possible handoffs during the life of a call, and P_h^v is the handoff probability of a voice call before the call completes which can be computed by the following equation:

$$\begin{aligned} P_h^v &= \Pr(t_{d_v} > t_{r_v}) \\ &= \int_{t=0}^{\infty} \Pr(t_{d_v} > t_{r_v} | t_{r_v}) \ \Pr(t_{r_v} = t)\, dt \\ &= \int_{t=0}^{\infty} h_v \exp(-\mu_v t) \exp(-h_v t)\, dt = \frac{h_v}{\mu_v + h_v} \end{aligned} \tag{3}$$

therefore,

$$p_f = \frac{p_d}{1-p_d} \left(\frac{\mu_v}{h_v} \right) . \tag{4}$$

It means that for a given p_d, the equivalent p_f can be easily computed based on (4). Therefore, in this paper it is assumed that a target handoff failure probability p_{QoS} must be guaranteed for voice calls. Notice that, exponential assumption is a necessary condition in deriving (3). Interested readers are referred to [26], [27] for the handoff probability under general call duration and cell residency distributions.

C. Time-Dependent Handoff and Stay Probabilities

We compute here some useful probabilities required for the rest of our discussion. Let $P_h^k(t)$ denote the probability that a type-k call hands off by time t and remains active until t, given that it has been active at time 0. Also, let $P_s^k(t)$ denote the probability that a type-k call remains active in its home cell until time t, given that it has been active at time 0. Then,

$$\begin{aligned} P_h^k(t) &= \Pr(t_{r_k} \leq t)\ \Pr(t_{d_k} > t) \\ &= (1 - \exp(-h_k t))\ \exp(-\mu_k t), \end{aligned} \tag{5}$$

and,

$$\begin{aligned} P_s^k(t) &= \Pr(t_{r_k} > t)\ \Pr(t_{d_k} > t) \\ &= \exp(-(\mu_k + h_k)t)\,. \end{aligned} \tag{6}$$

These equations are valid as far as the memoryless property of call duration and cell residency is satisfied. On average, for any call which arrives at time $t' \in (0, t]$, the average handoff and stay probabilities $\tilde{P}_h^k$ and $\tilde{P}_s^k$ are expressed as

$$\tilde{P}_h^k(t) = \frac{1}{t}\int_0^t P_h^k(t - t')\,dt', \tag{7}$$

$$\tilde{P}_s^k(t) = \frac{1}{t}\int_0^t P_s^k(t - t')\,dt'\,. \tag{8}$$

These integrals can be easily computed with respect to (5) and (6). Finally, let $P_{ji}^k(t)$ denote the time-dependent handoff probability and $\tilde{P}_{ji}^k(t)$ denote the average time-dependent handoff probability from cell j to cell i where $j \in \mathcal{A}_i$. It is obtained that

$$P_{ji}^v(t) = P_h^v(t)\, r_{ji}, \tag{9}$$

$$\tilde{P}_{ji}^v(t) = \tilde{P}_h^v(t)\, r_{ji}, \tag{10}$$

because voice handoff calls are always accepted if there is enough free bandwidth. Similarly,

$$P_{ji}^d(t) = a_i^d\big[P_h^d(t)\, r_{ji}\big], \tag{11}$$

$$\tilde{P}_{ji}^d(t) = a_i^d\big[\tilde{P}_h^d(t)\, r_{ji}\big], \tag{12}$$

because data calls are always subject to an acceptance ratio a_i^d in cell i.

In next section, we will use the computed probabilities to find the maximum acceptance ratios for voice and data calls with respect to the prespecified call dropping probability (p_{QoS}) and relative voice/data acceptance probability (α_{QoS}).

III. Admission Control Algorithm

The proposed distributed algorithm, EFGC, consists of two components. The first component is responsible for retrieving the required information from the neighboring cells and computing the control parameters. Using the computed control parameters, the second component enforces the admission control locally in each cell. The following sections describe these two components in detail.

A. Distributed Control Algorithm

As mentioned earlier, to reduce the signalling overhead EFGC has a periodic structure. All the information exchange and control parameter computations happen only once at the beginning of each control period of length T. Several steps involved in EFGC distributed control are described below:

1) At the beginning of a control period, each cell i sends the following information to its adjacent cells:
   a) the number of active voice and data calls presented in the cell at the beginning of the control period denoted by $N_i^v(0)$ and $N_i^d(0)$, respectively.
   b) the number of new voice calls, N_i^v, and new/handoff data calls, N_i^d, which were admitted in the last control period.
2) Each cell i receives $N_j^k(0)$ and N_j^k from every adjacent cell $j \in \mathcal{A}_i$.
3) Now, cell i uses the received information and those available locally to compute the acceptance ratios a_i^v and a_i^d using the technique described in section III-C.
4) Finally, the computed acceptance ratios a_i^v and a_i^d are used to admit call requests into cell i using the algorithm presented in section III-B.

Assume that all the cells have the same number of adjacent cells. Let $\mathcal{A}$ denote the number of adjacent cells. Also, assume that in one message all the required information can be sent from one cell to another cell. Then, the signalling overhead in terms of the number of exchanged messages in one control period is $\mathcal{A}$ messages per cell.

B. Local Admission Control Algorithm

Let (m, n) denote the state of cell i, where there are m voice calls and n data calls active in the cell. Define $\mathcal{S}_i$ as the state space of cell i governed by EFGC scheme. Then $\mathcal{S}_i$ can be

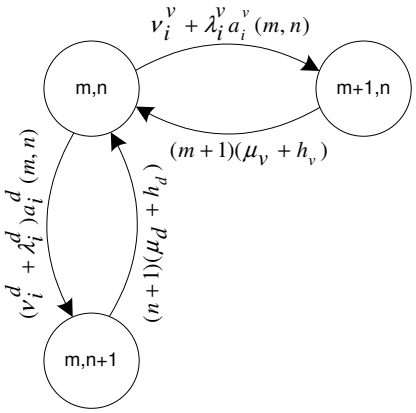


Fig. 3. Extended fractional guard channel transition diagram.

expressed as

$$\mathcal{S}_i = \{(m,n) | m b_v + n b_d \leq c_i\}\,. \tag{13}$$

Let $a_i^k(m,n)$ denote the acceptance ratio for type-k calls where the cell state is (m,n). Fig. 3 shows the state transition diagram of the EFGC scheme in cell i for a typical state $(m,n) \in \mathcal{S}_i$. In this figure, ν_i^k is the type-k handoff arrival rate into cell i. At each state there are two acceptance ratios for voice and data calls in such a way that

$$\begin{cases} a_i^v(m,n) = 0, & \text{if } (m+1,n) \notin \mathcal{S}_i \\ a_i^d(m,n) = \frac{1}{\alpha_i}\, a_i^v(m,n), & \text{if } (m,n) \in \mathcal{S}_i \end{cases} \tag{14}$$

There is a service differentiation (α_i) between voice and data calls that governs the relation between these two acceptance ratios. In this paper, we assume that this service differentiation is specified apriori (α_{QoS}) and EFGC should maintain it regardless of traffic conditions.

For an accurate control, the call blocking probability in each period is given by complementing the acceptance ratio. Therefore, by averaging acceptance ratios over a number of control periods, the call blocking probability is expressed as

$$b_i^k = 1 - E[a_i^k] \tag{15}$$

Consequently, the average network-wide call blocking probability for the considered network is given by

$$p_b^k = \frac{\sum_{j=i}^{M} \lambda_i^k b_i^k}{\sum_{j=i}^{M} \lambda_i^k}\,. \tag{16}$$

```
if (x_k is a voice handoff call) then
  if (R_i(t) + b_v ≤ c_i) then
    accept call;
  else
    reject call;
  end if
else /* new voice or new/handoff data call */
  if (R_i(t) + b_k ≤ c_i)&(rand(0,1) < a_i^k) then
    accept call;
  else
    reject call;
  end if
end if
```

Fig. 4. Local call admission control algorithm in cell i.

The pseudo-code for the local admission control in cell i is given by the algorithm of Fig. 4. In this algorithm, x_k is a type-k call requesting b_k BUs. The corresponding type-k acceptance ratio is a_i^k. Also, $\texttt{rand}(0,1)$ is the standard random generator function. In the next section, we will present a technique to compute the acceptance ratio vector $a_i = (a_i^v, a_i^d)$ in order to complete this algorithm.

C. Computing Acceptance Ratios

It is assumed that by setting the control interval T to an appropriate value, each call experiences at most one handoff during a control period (see section IV-C for more detail). Therefore, immediate neighbors of cell i, i.e. $\mathcal{A}_i$, are those which will affect the number of calls and consequently the bandwidth usage in cell i during a control period.

The proposed approach for computing the acceptance ratios includes the following steps:

1) Each cell i uses the information received from its adjacents and the information available locally to find the time-dependent mean and variance of the number of calls in the cell.
2) The computed mean and variance of the number of calls is used to find the mean and variance of the bandwidth requirement process in the cell.
3) Having the mean and variance of the bandwidth requirement process, the actual time-dependent bandwidth requirement process is approximated by a Gaussian distribution.
4) The tail of this Gaussian distribution is used to find the time-dependent handoff failure in each cell i.

5) Time-dependent handoff failure is averaged over control interval of length T to find an average handoff failure probability for the whole period.
6) Using the computed handoff failure probability and the prespecified QoS constraints, i.e. p_{QoS} and α_{QoS}, acceptance ratios a_i^v and a_i^d are computed.

The number of calls in cell i at time t is affected by two factors: (1) the number of background (existing) calls which are already in cell i or its adjacent cells, and, (2) the number of new calls which will arrive in cell i and its adjacent cells during the period $(0,t]$ ($0 < t \leq T$). Let $g_i^k(t)$ and $n_i^k(t)$ denote the number of background and new type-k calls in cell i at time t, respectively. A background type-k call in cell i will remain in cell i with probability $P_s^k(t)$ or will handoff to an adjacent cell j with probability $P_{ij}^k(t)$. A new type-k call which is admitted in cell i at time $t' \in (0,t]$ will stay in cell i with probability $\tilde{P}_s^k(t)$ or will handoff to an adjacent cell j with probability $\tilde{P}_{ij}^k(t)$. Therefore, the number of background calls which remain in cell i and the number of handoff calls which come into cell i during the interval $(0,t]$ are binomially distributed. For a binomial distribution with parameter q, the variance is given by $q(1-q)$. Using this property it is obtained that

$$V_s^k(t) = P_s^k(t)\,(1 - P_s^k(t)), \tag{17}$$

$$V_{ji}^k(t) = P_{ji}^k(t)\,(1 - P_{ji}^k(t)), \tag{18}$$

$$\tilde{V}_s^k(t) = \tilde{P}_s^k(t)\,(1 - \tilde{P}_s^k(t)), \tag{19}$$

$$\tilde{V}_{ji}^k(t) = \tilde{P}_{ji}^k(t)\,(1 - \tilde{P}_{ji}^k(t))\,. \tag{20}$$

where, $V_s^k(t)$ and $V_{ji}^k(t)$ denote the time-dependent variance of stay and handoff processes, and, $\tilde{V}_s^k(t)$ and $\tilde{V}_{ji}^k(t)$ are their average counterparts, respectively.

The number of type-k calls in cell i is the summation of the number of background calls, $g_i^k(t)$, and new calls, $n_i^k(t)$, of type k. Therefore, the mean number of type-k active calls in cell i at time t is given by

$$E[N_i^k(t)] = E[g_i^k(t)] + E[n_i^k(t)], \tag{21}$$

where,

$$E[g_i^k(t)] = N_i^k(0)P_s^k(t) + \sum_{j \in \mathcal{A}_i} N_j^k(0)P_{ji}^k(t), \tag{22}$$

$$E[n_i^k(t)] = (a_i^k \lambda_i^k t)\tilde{P}_s^k(t) + \sum_{j \in \mathcal{A}_i} (a_j^k \lambda_j^k t)\tilde{P}_{ji}^k(t)\,. \tag{23}$$

Similarly the variance is given by

$$V[N_i^k(t)] = V[g_i^k(t)] + V[n_i^k(t)], \tag{24}$$

where,

$$V[g_i^k(t)] = N_i^k(0)V_s^k(t) + \sum_{j \in \mathcal{A}_i} N_j^k(0)V_{ji}^k(t), \tag{25}$$

$$V[n_i^k(t)] = (a_i^k \lambda_i^k t)\tilde{V}_s^k(t) + \sum_{j \in \mathcal{A}_i} (a_j^k \lambda_j^k t)\tilde{V}_{ji}^k(t)\,. \tag{26}$$

Note that given the arrival rate λ_i^k and the acceptance ratio a_i^k, the actual new call arrival rate into cell i is given by $\lambda_i^k a_i^k$ (see section IV-B). Therefore, the expected number of call arrivals during the interval $(0, t]$ is given by $a_i^k \lambda_i^k t$.

Knowing the bandwidth requirement of each type of calls, the mean and variance of bandwidth usage in cell i at time t are given by

$$E[R_i(t)] = b_v E[N_i^v(t)] + b_d E[N_i^d(t)], \tag{27}$$

$$V[R_i(t)] = b_v^2 V[N_i^v(t)] + b_d^2 V[N_i^d(t)]\,. \tag{28}$$

As we mentioned in section I, the cellular system considered in this paper is a broadband wireless system with a capacity of several Mbps. In practice, 3G systems and beyond can be considered as broadband wireless systems (for example a UMTS system can support up to 2 Mbps) [1], [2]. With this range of cell capacity it is reasonable to apply the central limit theorem. We will informally verify this in section V-C. Thus, the bandwidth usage in each cell can be approximated by a Gaussian distribution with mean $E[R_i(t)]$ and variance $V[R_i(t)]$. That is

$$R_i(t) \sim \mathbf{G}\big(E[R_i(t)],\ V[R_i(t)]\big)\,. \tag{29}$$

Therefore, the original problem of maintaining a target handoff failure probability p_{QoS} is reduced to maintaining the bandwidth usage below the available capacity c_i at any point in time $t \in (0, T]$. Approximating the handoff failure probability by the overload probability, the time-dependent handoff failure probability $P_{f_i}(t)$ can be computed as follows:

$$P_{f_i}(t) = \Pr\big(R_i(t) > c_i\big), \tag{30}$$

therefore,

$$P_{f_i}(t) = \frac{1}{2}\,\mathrm{erfc}\left(\frac{c_i - E[R_i(t)]}{\sqrt{2\,V[R_i(t)]}}\right), \tag{31}$$

where $\mathrm{erfc}(c)$ is the complementary error function defined as

$$\mathrm{erfc}(c) = \frac{2}{\sqrt{\pi}}\int_c^{\infty} e^{-t^2}\,dt\,. \tag{32}$$

Then the average handoff failure probability over a control period is given by

$$\tilde{P}_{f_i} = \frac{1}{T}\int_0^T P_{f_i}(t)\,dt\,. \tag{33}$$

Finally, to guarantee the target handoff failure p_{QoS}, we should have

$$\tilde{P}_{f_i} = p_{\mathrm{QoS}}\,. \tag{34}$$

To solve (34) for $a_i = (a_i^v, a_i^d)$ we need one more equation. This equation can be derived with respect to the required service differentiation. Given the service condition $a_d = f(a_v)$, the acceptance ratio vector $a_i = (a_i^v, a_i^d)$ can be found by numerically solving (34). Function f is such that $0 \le f(a_i^v) \le 1$ and $f(0) = 0$. In addition, f is uniformly increasing over $[0, 1]$. The boundary condition is that $a_i \in [0, 1] \times [0, 1]$, hence if $\tilde{P}_{f_i}$ is less than p_{QoS} even for $a_i^v = 1$ then a_i is set to $(1, f(1))$. Similarly, if $\tilde{P}_{f_i}$ is greater than p_{QoS} even for $a_i^v = 0$, then a_i is set to $(0, 0)$. In this paper, we only consider a constant service differentiation function denoted by α_i, where $a_i^d = a_i^v/\alpha_i$.

Finally, (34) can be solved using the bisection method [28]. Let ξ denote the required numerical precision. Then, the computational complexity of this technique is $O(\log 1/\xi)$, given that all mathematical operations (including exponentiation and integration) can be performed in $O(1)$.

IV. Control Parameters

In previous sections, we assumed that several parameters are known to the admission control algorithm apriori. Among these parameters are the call arrival rates, mean call durations, mean cell residency times and routing probabilities. In practice, all these parameters can be extracted from measured field data using an estimation technique. Measurement and estimation units are used for providing the required parameters to the admission control unit as shown in Fig. 5. One useful estimation technique is presented in the following subsection.

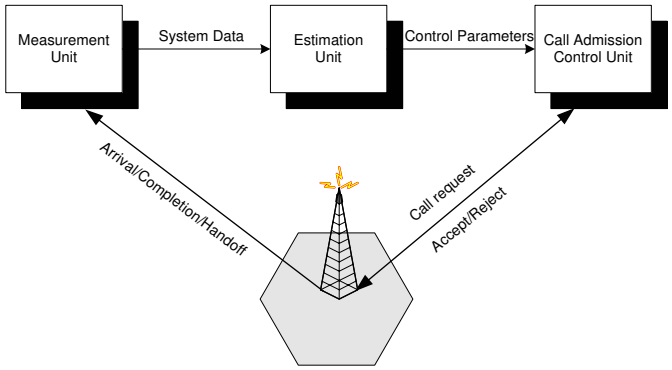


Fig. 5. Control unit diagram.

A. Parameter Estimation

A common technique for estimating the mean values from measurement data is the *exponentially weighted moving average* (EWMA) technique. Let z denote a control parameter to be estimated, e.g., arrival rate, and $\hat{z}$ its measured (observed) value. A moving average estimator for z at nth step is given by

$$z(n) = (1-\epsilon)\,\hat{z}(n-1) + \epsilon z(n-1) \tag{35}$$

where ϵ is a weighting factor that should be specified with respect to the sampled observations of z. In general, a small value of ϵ can keep track of the changes more accurately, but is too sensitive to temporary fluctuations. On the other hand, a large value of ϵ is more stable but could be too slow in adapting to real traffic changes. By using this estimator, it can be verified that $E[z] = E[\hat{z}]$. However, EFGC is independent of the estimation technique, and hence, it is possible to use more sophisticated estimation techniques to achieve more accurate estimations (refer to [29], [30]).

We now use the EWMA technique to compute the new call arrival rate λ into a cell of the network. To obtain a time series for the estimation, time is divided into intervals of length T. At the beginning of each interval i, we compute the estimated value $\lambda(i)$ for the arrival rate during that interval. Total experiment time is set to NT seconds. Let $\hat{\lambda}(i)$ denote the measured arrival rate during the ith interval. Using (35), it is obtained that

$$\lambda(i+1) = (1-\epsilon)\,\hat{\lambda}(i) + \epsilon\lambda(i)\,. \tag{36}$$

TABLE I

EFFECT OF ϵ ON MEAN SQUARED ERROR.

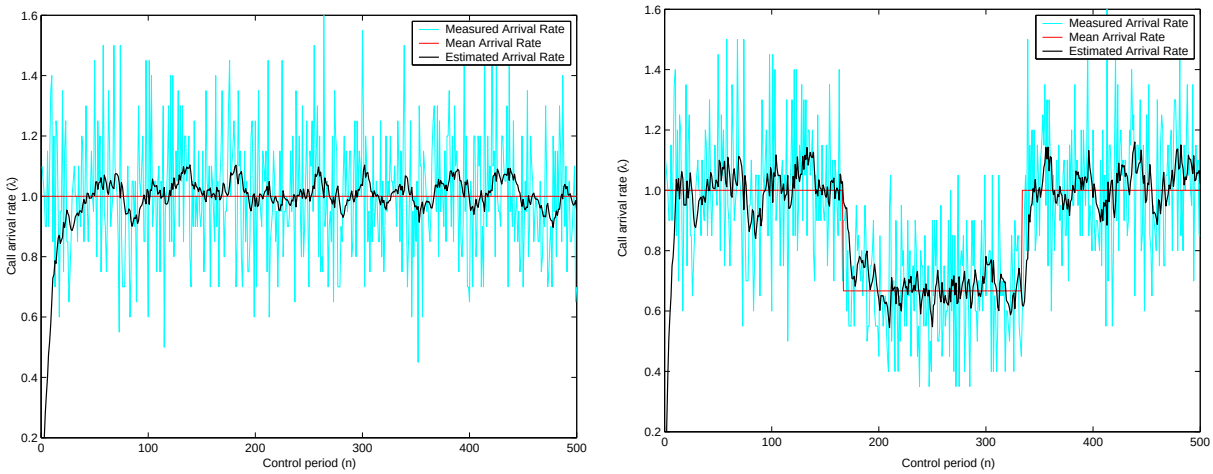
ϵ	MSE: Fixed λ	MSE: Variable λ
0.0	0.090	0.087
0.1	0.080	0.079
0.2	0.073	0.072
0.3	0.066	0.066
0.4	0.061	0.061
0.5	0.056	0.057
0.6	0.052	0.054
0.7	0.049	0.051
0.8	0.046	0.050
0.9	0.043	0.054

The only unknown parameters in (36) is the estimation coefficient ϵ. As mentioned before, the accuracy of the EWMA estimation depends on ϵ. The goal is to choose ϵ in such a way to minimize the estimation error. To measure the estimation error, we use the mean squared error (MSE) of the estimations as expressed by

$$\mathrm{MSE} = \frac{1}{N}\sum_{i=1}^{N}\Big(\lambda(i) - \hat{\lambda}(i)\Big)^2. \tag{37}$$

Two scenarios are simulated: (1) arrival rate is fixed at $\lambda = 1$ call/sec during the experiment; and (2) arrival rate varies two times during the experiment, from $\lambda = 1$ call/sec to $\lambda = 2/3$ call/sec and back to $\lambda = 1$ call/sec again. The initial value for the estimator is $\lambda = 0$. Table (I) shows the corresponding errors for a range of values of ϵ. Notice that, if ϵ is very close to 1 then the estimation becomes very sensitive to the initial value, hence must be avoided. Also, to avoid the transient part of scenario (1), values in Table (I) are computed using only the second half of experiment data.

According to Table (I), optimal values for cases (1) and (2) are $\epsilon = 0.9$ and $\epsilon = 0.8$, respectively. Using these values, Fig. 6 shows the estimated arrival rate versus the measured arrival rate for these two cases. As expected, the estimation process in Fig. 6(a) is more smooth while the estimation process in Fig. 6(b) is more adaptive to changes. Finally, Table (II) represents the average and variance of the estimated and measured arrival rates for case (1). It is observed



(a) Constant arrival rate.

(b) Changing arrival rate.

Fig. 6. EWMA.

TABLE II

FIXED ARRIVAL RATE.

Technique	Mean	Variance
Measurement ($\hat{\lambda}$)	1.005	0.203
Estimation (λ)	1.009	0.026

that the estimated value is very close to the actual value $\lambda = 1$ call/sec with a very small deviation.

B. Actual New Call Arrival Rate

In section III-C, we used products $a_j^k \lambda_j^k$ to compute the mean and variance of the number of calls in cell i ($j \in \mathcal{A}_i$). Let us define the *actual new call arrival rate* into cell j, denoted by $\bar{\lambda}_j^k$, as follows

$$\bar{\lambda}_j^k = a_j^k \lambda_j^k \,. \tag{38}$$

In order to compute a_i^k for the new control period we need to know $\bar{\lambda}_j^k$ for every adjacent cell j ($j \in \mathcal{A}_i$). Similarly, cell j needs to know $\bar{\lambda}_i^k$ in order to be able to compute a_j^k. Therefore, every cell depends on its adjacents and vice versa. To break this dependency, instead of using the actual value of $\bar{\lambda}_j^k$, each cell i estimates the actual new call arrival rates of its adjacents for the new control period.

Let $\bar{\lambda}_j^k(n)$ denote the actual new call arrival rate into cell j during the nth control period. Also, let $N_j^k(n)$ denote the number of new calls that were accepted in cell j during the nth control period. Similar to [4], [10], an estimator for $\bar{\lambda}_j^k$ is expressed as

$$\bar{\lambda}_j^k(n+1) = (1-\epsilon)\frac{N_j^k(n)}{T} + \epsilon\bar{\lambda}_j^k(n), \tag{39}$$

where, $\bar{\lambda}_j^k(n+1)$ is the actual new call arrival rate into cell j at the beginning of the $(n+1)$th control period. Note that $\bar{\lambda}_j^k(n)$ is known at the beginning of the $(n+1)$th control period. In our simulations we found that $\epsilon = 0.3$ leads to a good estimation of the actual new call arrival rate.

C. Control Interval

The idea behind at-most-one handoff assumption is that by setting control interval appropriately, the undesired multiple handoffs during a control period can be avoided. As discussed in section III, this minimizes the signalling overhead and operational complexity of EFGC. In this section, we address the control interval selection problem.

Consider a symmetric network where each cell has exactly $\mathcal{A}$ neighbors, and the probability of handoff to every neighbor is the same. Then, the routing probability r_{ij} from cell i to cell j is given by

$$r_{ij} = \begin{cases} 1/\mathcal{A}, & j \in \mathcal{A}_i, \\ 0, & j \notin \mathcal{A}_i\,. \end{cases} \tag{40}$$

Let $q(n)$ denote the probability that an active call experiences n handoffs during time interval T. Also, let $q_{ij}(n)$ denote the probability that a call originally in cell i moves to cell j over a path consisting of n handoffs during time interval T. Define δ as the multiple handoffs probability from cell i to cell j. We then can write

$$\delta = \sum_{n=2}^{\infty} q_{ij}(n)\,. \tag{41}$$

Our goal is to find a relation between T and δ in order to be able to control δ by controlling T.

For an effective control (p_f in the range of 10^{-4} to 10^{-2}) we can assume that p_f is effectively zero. Similarly, if $\delta \approx p_f$ for a given T, we can assume that the multiple handoffs probability is zero. Since cell residency is exponential, the number of handoffs a call experiences during

TABLE III

MULTIPLE HANDOFFS PROBABILITY FOR $T = 20\,s$.

n	Layer	$\max\{L_{j0}(n)\}$	$\max\{P_{j0}(n)\}$
0	0	1	0.73263
1	0	1	0.02442
2	0	6	0.00244
3	1	15	0.00007
4	0	90	0.00000
5	0	360	0.00000

an interval is Poisson distributed with mean hT, given that the call is active during the whole interval. Therefore, it is obtained that

$$q(n) = \frac{(hT)^n}{n!} e^{-(h+\mu)T}\,. \tag{42}$$

In order to compute $q_{ij}(n)$ based on (42), we need to find the probability of moving from cell i to cell j by n handoffs. Let $L_{ij}(n)$ denote the number of paths consisting of n handoffs from i to j, then

$$q_{ij}(n) = \frac{L_{ij}(n)}{\mathcal{A}^n}\, q(n)\,. \tag{43}$$

Consider the network depicted in Fig. 2. Let $T = 20\,s$, $1/\mu = 180\,s$, $1/h = 100\,s$ and $\mathcal{A} = 6$. Table (III) shows the maximum probability of multiple handoffs from any cell j to cell 0, $P_{j0}(n)$, based on the number of handoffs, n. For each n, we have also determined which layer has the maximum paths to cell 0. Interestingly, cell 0 has the most paths to itself through other cells. We have also illustrated in Fig. 7 the impact of the control interval T on the multiple handoffs probability δ for the same set of parameters.

Consider cell i and all the cells around it forming circular layers. From cell i, all the cells up to layer n are accessible with n handoffs assuming that cell i forms layer 0. It can be shown that

$$L_{ij}(n) \leq \mathcal{A}^{n-1}, \quad n \geq 1 \tag{44}$$

because for $n \geq 1$, at each level there are at least $\mathcal{A}$ cells which have the same number of paths to the destination cell i. Therefore

$$q_{ij}(n) \leq \frac{1}{\mathcal{A}} \frac{(hT)^n}{n!} e^{-(h+\mu)T}, \quad n \geq 1\,. \tag{45}$$

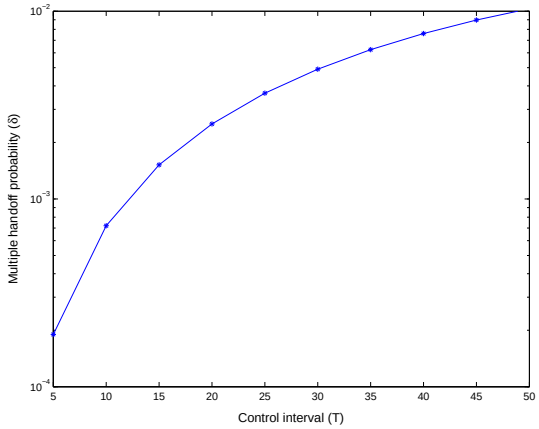


Fig. 7. Effect of T on multiple handoffs probability.

Using (41) and (45), it is obtained that

$$\begin{aligned}\delta &\leq \sum_{n=2}^{\infty} \frac{1}{\mathcal{A}} \frac{(hT)^n}{n!} e^{-(h+\mu)T} \\ &= \frac{e^{hT} - hT - 1}{\mathcal{A} e^{(h+\mu)T}} .\end{aligned} \tag{46}$$

Using the Taylor expansion of exponential terms for $\delta \ll \frac{1}{\mathcal{A}}(\frac{h}{\mu+h})$, it is obtained that

$$T \leq \frac{\mathcal{A}\delta(\mu+h) + h\sqrt{2\mathcal{A}\delta}}{\mathcal{A}\delta(\mu+h)^2 - h^2}, \tag{47}$$

which finally leads to the following simple relation

$$T \approx \frac{\sqrt{2\mathcal{A}\delta}}{h} . \tag{48}$$

V. Simulation Results

A. Greedy EFGC

The basic EFGC introduced in section III may seem to be too conservative about accepting data calls. We refer to this restrictive version of EFGC by EFGC-REST (or simply REST). REST is a conservative approach which aims at satisfying the specified priority function f over time. In other words, REST always uses the acceptance ratio $a_i = (a_i^v, f(a_i^v))$ regardless of the congestion situation to impose an exact priority function.

It is observed that in some states of the system it is possible to increase the acceptance ratio of data calls beyond the limit returned by the service differentiation function. For example when

the network is not congested (at light traffic loads), we found that by increasing the priority of data traffic the overall utilization of the wireless bandwidth is increased while the handoff failure remains almost untouched. This relaxed version is called EFGC-UTIL (or simply UTIL) due to its greedy behavior in maximizing the bandwidth utilization. To find the data acceptance ratio in cell i, UTIL follows the following steps:

1) Find a_i^v using (34),
2) If ($a_i^v == 1$) then find the maximum value of $a_i^d \in [f(1), 1]$ which satisfies (34),

It is worth noting that the computational complexity of EFGC-UTIL is the same as EFGC-REST, i.e. $O(\log 1/\xi)$.

B. Simulation Parameters

Simulations were performed on a two-dimensional cellular system consisting of 19 hexagonal cells (see Fig. 2). Opposite sides wrap-around to eliminate the finite size effect. It is assumed that mobile users move along the cell areas according to a uniform routing pattern. In other words, all neighboring cells have the same chance to be chosen by a call for handoff, i.e. $r_{ji} = 1/6$. For ease of illustrating the results, the simulated system is uniform, i.e. input load is the same for every cell, although EFGC as well as the simulation program are designed to handle the nonuniform case as well. Therefore, unless explicitly specified, the subscript i is omitted hereafter.

The common parameters used in the simulation are as follows. All the cells have the same capacity $c = 5$ Mbps, which is equal to 160 BU assuming each BU is equal to 32 Kbps (encoded voice using ADPCM requires 32 Kbps). Target handoff failure probability for voice calls is $p_{\mathrm{QoS}} = 0.01$ and $T = 20\,s$. We use normalized load in simulations which is simply the total arrival load per BU. Let ρ denote the total normalized arrival load into a cell, then

$$\rho = \frac{1}{c}\big(\rho_v + \rho_d\big), \tag{49}$$

where, ρ_v and ρ_d are, respectively, voice and data load given by

$$\rho_v = b_v\lambda_v/\mu_v, \tag{50}$$

$$\rho_d = b_d\lambda_d/\mu_d\,. \tag{51}$$

For each load, simulations were done by averaging over 8 samples, each for 10 hours of simulation time. Load distribution between voice and data traffic is fixed over time. At any

TABLE IV

VOICE/DATA SERVICE PARAMETERS.

Type	Priority	$1/\mu\ (s)$	$1/h\ (s)$	BU	Load
voice	1	180	100	1	60%
data	0.5	1000	800	2	40%

load, 60% of the load is due to voice calls and the remaining 40% is composed of data calls. Table IV summarizes service and traffic parameters for both traffic types. In this table, *priority* refers to the relative priority (service differentiation) of voice and data calls. It means that new voice calls have higher priority than data calls for the admission control algorithm. In particular, the probability of accepting a new voice call is at least twice the probability of accepting a data call (new/handoff) at any time and any load. Equivalently, this is achieved by setting $\alpha_{\mathrm{QoS}} = 2$. As mentioned earlier, this relative priority can be any service differentiation function. In our simulations, for the sake of simplicity we have chosen a constant service differentiation function.

We have also implemented the DTR scheme introduced in section I for comparison purposes. Since DTR is designed for a static traffic pattern, the handoff failure probability increases rapidly with the network load when the guard channels for handoff are few, but remains too low when the guard channels are many. Here, we choose the two thresholds in such a way that DTR achieves its objectives when the network starts to get overloaded. Hence, the voice threshold is set to 155 BUs and the data threshold is set to 151 BUs. Using these thresholds at load 2, p_f and $\alpha = a_v/a_d$ were found to be 0.01 and 2, respectively.

C. Gaussian Verification

When the network is not congested and each cell has only a few active calls, it is clear that Gaussian approximation is not good. However, at light loads the admission algorithm does not require a high precision estimation of the load since there is no congestion in the network. As the load increases the number of active calls in each cell increases rapidly until no more calls can be accepted. Due to the high capacity of broadband systems, it is expected to have enough active calls in each cell so that central limit theorem can be applied.

Other researchers have also successfully applied Gaussian approximation for similar purposes. Schwartz et al. [4], [7] used the same kind of approximation. The main difference is that we

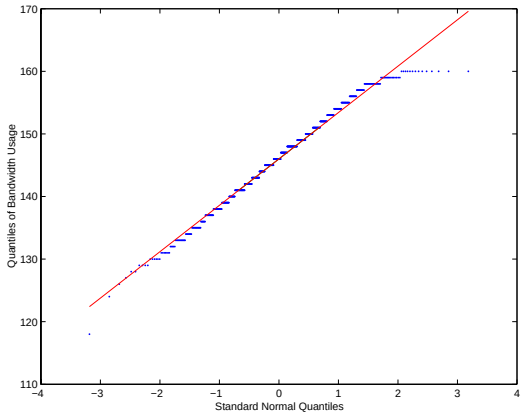


Fig. 8. QQ-plots of bandwidth usage in cell 0 at load 2.

extend their single point approximation at the end of the control period to a time dependent approximation over the whole control period. The authors of [10] also realized that for large system sizes, as is the case in this paper, the cell occupancy distribution evolves into a Gaussian distribution.

We further investigated this issue in our simulation. At the beginning of each interval, the bandwidth usage at cell 0 is recorded until the end of simulation for load 2 (which is not a very high load). To verify the normality of these samples, we used the standard QQ-plot. Fig. 8 depicts the QQ-plot of a sample of the bandwidth usage at cell 0 versus the quantiles of the standard normal distribution. This plot clearly shows that Gaussian approximation of the bandwidth usage in each cell is satisfactory for our stochastic control. Please note that QQ-plot only shows the non-tail part of the distribution. Investigating the tail behavior of the bandwidth usage distribution is beyond the scope of this paper, instead we rely on the results from other researchers [4], [7], [10], [23].

D. Results and Analysis

1) Effect of arrival load: The first set of simulation results show the main performance parameters of EFGC. Fig. 9 shows the handoff failure probability for the three schemes for a wide range of loads. Both UTIL and REST maintain a constant failure probability independent of the load. For DTR, it grows very rapidly with the load (which was expected). With light loads (load < 2), DTR and REST have almost the same handoff failure probability while UTIL

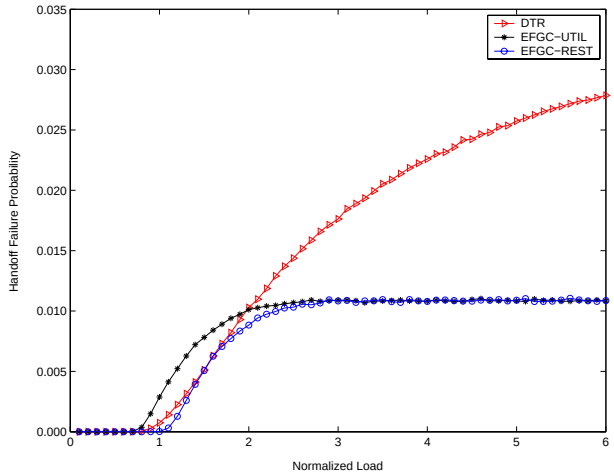


Fig. 9. Voice handoff failure probability.

has slightly higher handoff failure probability. But with high loads (load > 2), UTIL and REST converge to exactly the same handoff failure probability while DTR has much higher handoff failure probability. Fig. 11(b) shows that, although REST has better failure probability in light loads, this is accomplished at the expense of the data call blocking probability. However, even in this region (load < 2), UTIL satisfies the target handoff failure probability p_{QoS}.

One of the objectives of EFGC is to maintain the relative service priority between voice and data calls. In our simulations, this relative priority is fixed and indicates that the acceptance probability of new voice calls should be twice the acceptance probability of new data calls. Fig. 10 gives the service differentiation $\alpha = a_v/a_d$ for different loads. It shows that EFGC maintains an almost constant service priority between the two types of traffic. More precisely, REST preserves $\alpha = 2$ for the whole range of loads while UTIL has $\alpha = 1$ in light loads and $\alpha = 2$ in high loads as expected. This can be explained by the fact that in light loads UTIL accepts data calls as long as there is free bandwidth (without violating the target voice handoff failure probability). As the load increases, service priority of DTR increases rapidly. Fig. 11(b) shows that at high loads almost no data calls are accepted. In other words, DTR is not fair and leads to starvation of data traffic. It is worth mentioning that, although in this simulation the service differentiation is fixed, the EFGC can satisfy more complex priority disciplines such as state dependent priorities.

Fig. 11 shows the new voice and new/handoff data call acceptance probabilities respectively.

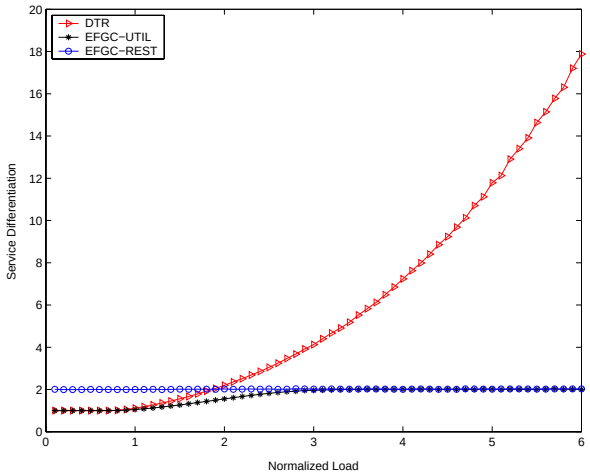
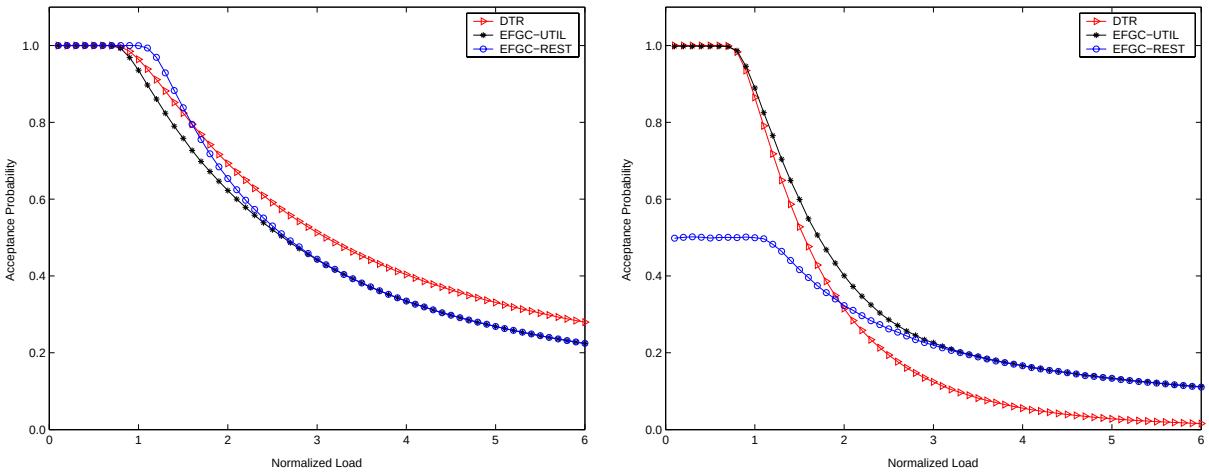


Fig. 10. Voice/Data relative acceptance probability (α).



(a) New voice calls acceptance probability. (b) New/handoff data calls acceptance probability.

Fig. 11. Acceptance probability of voice and data.

Again for high loads, UTIL and REST converge to the same result but the difference in their performance at light loads is significant. For data traffic at light loads the acceptance probability of UTIL is almost twice that of REST. This explains why the utilization of UTIL is superior to REST. It can be seen that DTR has slightly higher acceptance probability for voice but much lower acceptance probability for data in comparison to UTIL and REST.

Finally, Fig. 12 shows the wireless bandwidth utilization under the three bandwidth allocation mechanisms. Although DTR performs poorly in terms of handoff failure probability and service

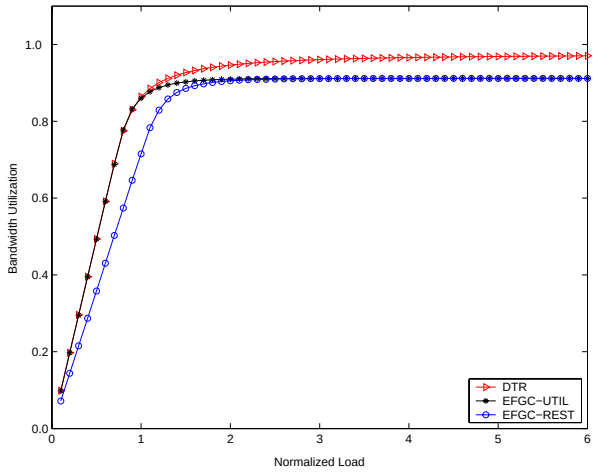


Fig. 12. Wireless bandwidth utilization.

priority, its utilization is slightly better than EFGC. Interestingly, UTIL has exactly the same utilization level as DTR at light loads but higher than that of REST. In this simulation, voice traffic constitutes the larger portion of the total load. As the percentage of data traffic increases, the utilization of DTR is expected to drop. This will be investigated next.

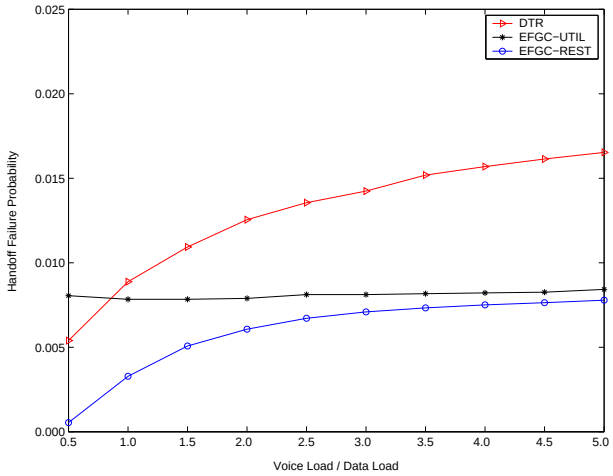
2) Effect of load sharing: In previous simulations, the load sharing factor $\beta(\beta > 0)$ is set to 1.5, where

$$\beta = \frac{\text{arriving data traffic load } (\rho_v)}{\text{arriving voice traffic load } (\rho_d)}. \tag{52}$$

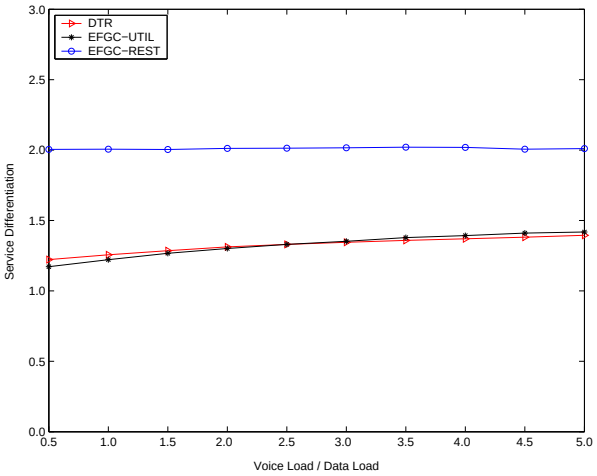
Due to the priority of voice calls over data calls, varying β will affect the behavior of EFGC. As shown in Fig. 13, EFGC is insensitive to the load sharing factor. In these plots, the X axis indicates the load sharing factor β. It is assumed that most of the traffic is composed of voice calls, hence β varies between 0.5 and 5.

For this set of simulations, normalized arrival load is set to 1.5 Erlang and voice priority is set to 2 ($\alpha = 2$). As expected, DTR is not able to adjust to changes in load shares although the total load is fixed. Interestingly as β increases, EFGC-UTIL and EFGC-REST converge to the same value for handoff failure probability. The reason is that by increasing β, voice traffic will dominate data traffic. Therefore, a larger portion of the available bandwidth is allocated to voice traffic in such a way that there is no extra free bandwidth to be assigned to data traffic (more than their guaranteed share).

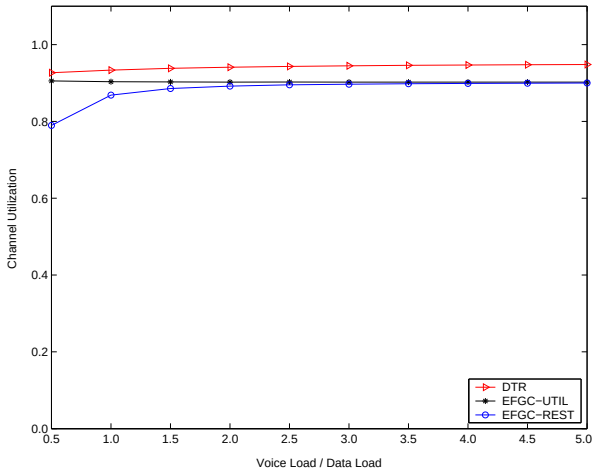
The primary goal of the following set of simulations is to show the stability of EFGC under



(a) Voice handoff failure probability.



(b) Relative acceptance probability (α).



(c) Wireless bandwidth utilization.

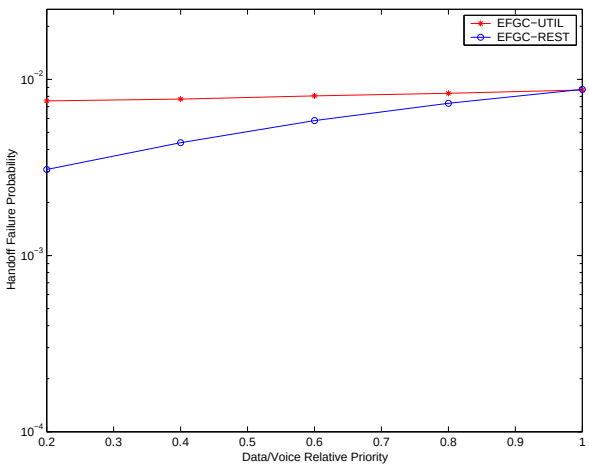
Fig. 13. Effect of load sharing (β).

various QoS requirements (p_{QoS} and α_{QoS}) and the insensitivity of EFGC to the exponential assumption we made about the cell residency time.

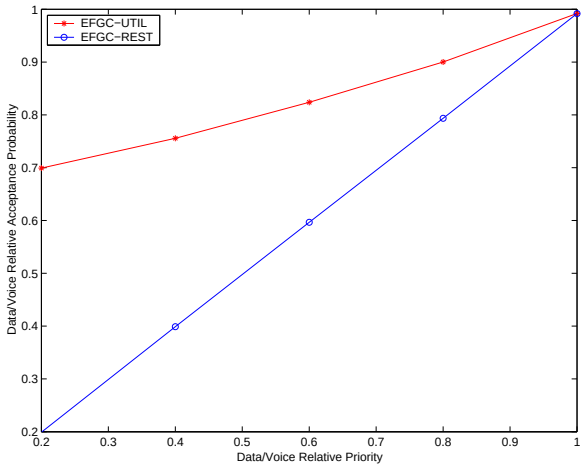
3) Effect of voice priority: Fig. 14 shows the effect of changing the relative priority of data calls and voice calls. In this set of plots, the X axis indicates the quantity $1/\alpha$, where

$$1/\alpha = \frac{\text{data calls acceptance probability } (a_d)}{\text{voice calls acceptance probability } (a_v)}. \tag{53}$$

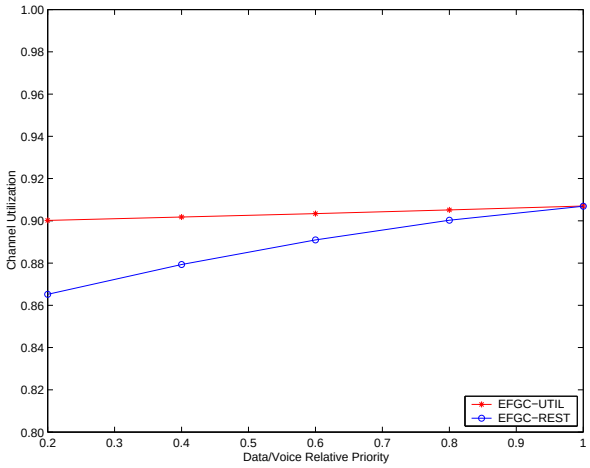
In the simulations, the total arrival load is set to 1.5 Erlang which consists of 60% voice traffic and 40% data traffic (i.e. a load sharing factor of 1.5). It is found that regardless of α, EFGC is able to satisfy the target α_{QoS} while providing the desired service differentiation. The straight



(a) Voice handoff failure probability.



(b) Relative acceptance probability $(1/\alpha)$.



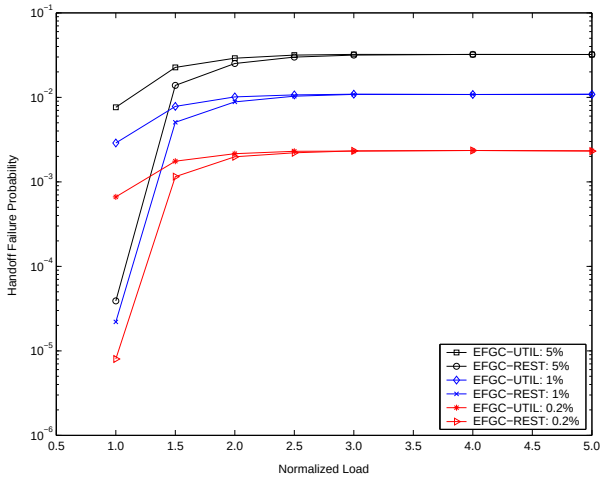
(c) Wireless bandwidth utilization.

Fig. 14. Effect of voice priority.

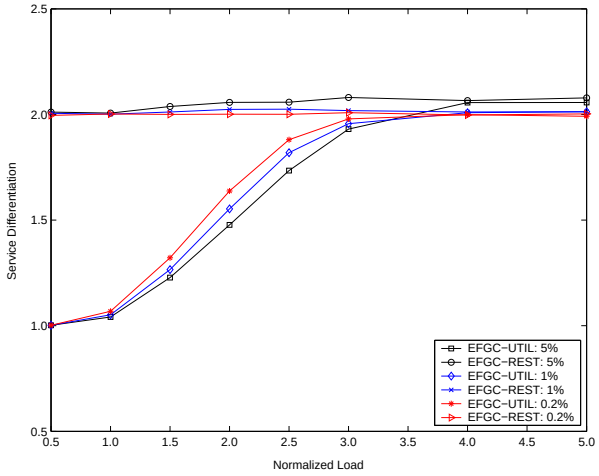
lines in Fig. 14(b) indicate that any value of service differentiation can be strictly guaranteed with EFGC.

As indicated in these figures, UTIL and REST converge to the same control policy as α tends towards 1. This was expected because the two schemes differ from each other with respect to α. In this case, available resources are completely shared among voice and data traffic and channel utilization is maximized. However, for large values of α (small values of $1/\alpha$), UTIL has a superior performance over REST. For example, at $\alpha = 1/0.2$, UTIL has 4% better utilization.

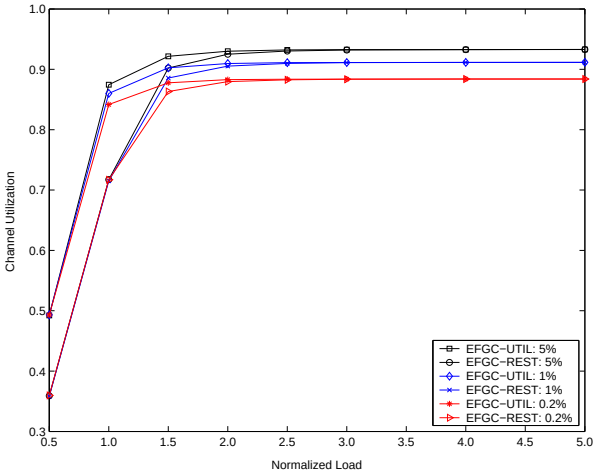
4) Effect of handoff failure probability (QoS): In cellular systems, the target p_{QoS} is typically set to 1%. To show the adaptiveness of EFGC, simulations were performed for $p_{\mathrm{QoS}} =$



(a) Voice handoff failure probability.



(b) Relative acceptance probability (α).

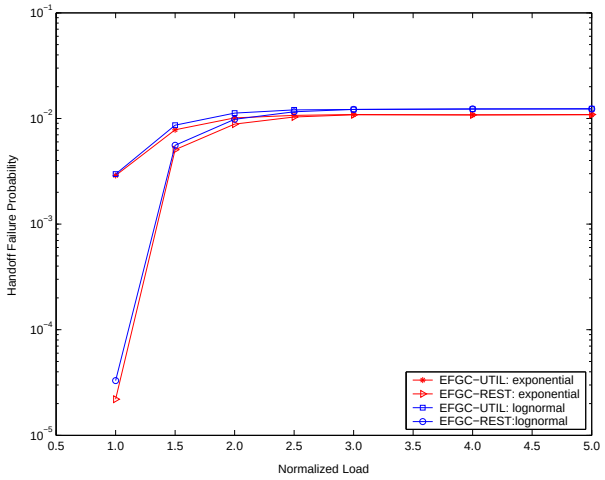


(c) Wireless bandwidth utilization.

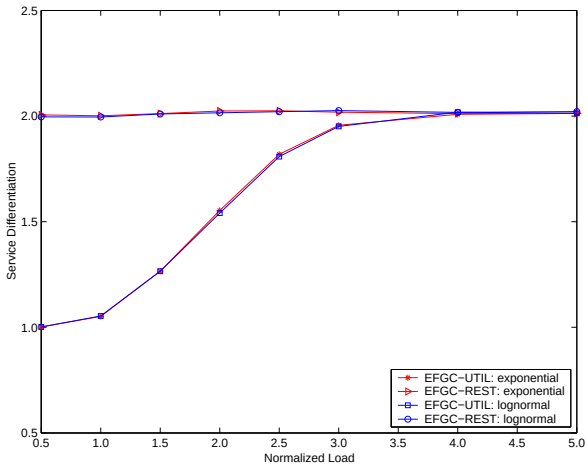
Fig. 15. Effect of handoff failure probability (QoS).

$[0.2\%, 1\%, 5\%]$. Notice that $p_{\mathrm{QoS}} = 0.2\%$ is an extremely low handoff failure probability. As shown in Fig. 15, handoff failure and service differentiation are fully satisfied regardless of the target QoS requirements. In particular, Fig. 15(a) shows the stability of EFGC under different target dropping requirements.

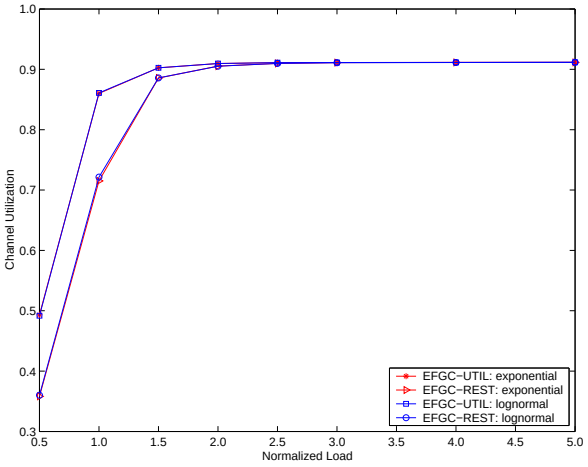
5) Effect of non-exponential cell residency: The first part of our analysis, which gives the equations describing the mean and variance of channel occupancy (i.e., number of busy channels in a cell), is based on the exponential cell residency time assumption. This assumption may not be correct in practice and needs more careful investigation as pointed out in [31]–[33] and references



(a) Voice handoff failure probability.



(b) Relative acceptance probability (α).



(c) Wireless bandwidth utilization.

Fig. 16. Effect of non-exponential cell residency.

there in. Although exponential distributions are not accurate in practice but the models based on the exponential assumption are tractable and do provide mean value analysis which indicates the system performance trend.

Using real measurements, Jedrzycki and Leung [31] showed that a lognormal distribution is a more accurate model for cell residency time. We now compare the results obtained under exponential distribution with those obtained under more realistic lognormal distribution. The mean and variance of both distributions are the same (refer to Table (IV)). Fig. 16 shows that the exponential cell residency achieves sufficiently accurate control. In other words, the control

algorithm is rather insensitive to this assumption due to its periodic control in which the length of the control interval is much less than the average cell residency time.

VI. Conclusion

In this paper, we proposed a new admission control algorithm for voice/data integration in broadband wireless networks. Our algorithm is a natural extension of the well-known fractional guard channel proposed for voice cellular systems. EFGC always achieves the predetermined call dropping probability for voice calls while keeping the relative blocking probability of voice and data calls within a target threshold. We then described two versions of the EFGC, namely EFGC-UTIL and EFGC-REST. EFGC-UTIL follows a greedy approach to maximize the bandwidth utilization while EFGC-REST maintains the relative service priority. Both versions converged to the same result for high traffic loads. The major advantage of EFGC is its insensitivity to network traffic load. The dropping probability of voice calls and relative blocking probability of voice and data calls is maintained at a stable level over a wide range of traffic loads. From the simulation results, we conclude that EFGC-UTIL is a better candidate for integrated voice/data cellular networks.

We are currently investigating the case of multiple classes of traffic where each class has its own QoS requirements in terms of call blocking and dropping probabilities. EFGC can readily support multiple classes of traffic by assigning a separate acceptance ratio to each class. However, computing these acceptance ratios in order to satisfy the desired QoS is not trivial.

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