Performance Analysis of Multi-Service Cellular Networks with Mobile Users

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Abstract-**Wireless cellular networks are fast evolving into multi-service networks supporting narrow-band, as well as, wide-band services. Capability to optimally partition the available radio frequency spectrum among competing services is key to the economical viability of these networks. An analytical model is developed, herein, to measure the performance of various bandwidth access control policies, in terms of call level QoS (Quality of Service) parameters such as call blocking probability, call dropping probability and throughput, in TDMA/FDMA (Time/Frequency Division Multiple Access) based multi-service cellular networks. The model also takes into consideration the impact of mobility on the QoS. Such models are essential for facilitating an effective optimization of bandwidth allocations in a cellular network supporting multiple services.**

Furthermore, requirements such as, adaptive updating of bandwidth allocations to track dynamical load variations, and preferential treatment for some services at the expense of others, due to revenue considerations, suggest applicability of priority based bandwidth access control policies. Some priority based bandwidth access control policies are, therefore, also proposed in this paper, and compared with conventional policies such as CS (Complete Sharing), CP (Complete Partitioning) and PS (Partial Sharing). Simulation results are presented that reflect upon the effectiveness of priority based policies.

The main contribution of this work is the precise formulations developed to predict call level QoS parameters in a multi-service cellular network with mobile users.

I. INTRODUCTION

The demand for mobile cellular communication services is increasing rapidly. With continuing growth in data and multimedia applications, service providers are actively engaged in offering high bandwidth services. Cellular network users can now subscribe to data, video-phone and other multi-media services, in addition to cellular phone services. These networks are, thus, fast evolving from voice only networks to multi-service multi-resource networks, supporting a heterogeneous mix of services with varying traffic characteristics, QoS constraints and bandwidth requirements. The main limitation to supporting a large number of subscribers continues to be the shortage of radio frequency spectrum. The number of subscribers per service per unit area that can be supported at some minimum QoS, is an important parameter. The challenge is to determine the optimum portions of the total cell capacity that should be reserved for each offered service to cater to the corresponding traffic load. In other words, the total cell capacity should be partitioned among various offered services or classes of users in such a way that the overall throughput or revenue is maximized, while ensuring that the QoS constraints are below some prescribed upper bound. As our focus is network planning and dimensioning, we are mainly interested in call level QoS constraints, that are achieved by bounding the blocking probability and/or dropping probability of the connections.

Essential to the aforementioned optimization problem is the availability of a suitable model that could be used to analytically evaluate various bandwidth reservation schemes in a multi-service wireless cellular network environment. In this paper, we develop a traffic model, and analytically investigate the effect of bandwidth reservation schemes, also known as bandwidth access control policies, on the QoS of stationary, as well as, mobile users in a cellular network. A number of bandwidth access control policies have been discussed in literature for wired telecommunication networks [5][6]. Notable among these are CS (Complete Sharing), CP (Complete Partitioning) and PS (Partial Sharing). These policies are analyzed under the context of wireless cellular networks for a single cell of a mobile system in [9]. We extend this analysis to a multi-cellular network using the proposed traffic model and taking mobility into account. In addition, we also propose some priority based bandwidth access control policies that can provide higher throughput for high priority services, and seem quite suitable for cellular networks.

The rest of the paper is organized as follows. Section II elaborates on the traffic model and the mathematical framework used for the analysis. An overview of bandwidth access control policies is provided, followed by performance evaluation of services in the presence of these policies. The analytical results are verified using computer simulations. The results of these simulations are presented in section III. Finally, section IV makes some conclusions and, once again highlights the main contributions of this work.

II. TRAFFIC MODEL

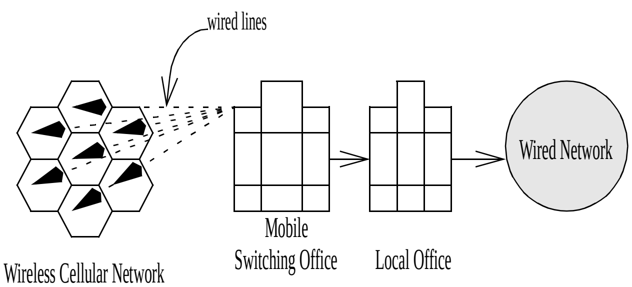

Fig. 1. Wireless Cellular Network

Consider a two dimensional cellular region with hexagonal cells and omni-directional antenna base stations, as shown in Fig. 1. Assuming FCA (Fixed Channel Assignment), let each cell be allocated with a total of C channels of bandwidth. The basic system model assumes that the new call origination rate is uniformly distributed over the entire mobile service area. A very large population of users is assumed, and thus the average call origination rate is independent of the number of calls in progress. The system may have both stationary and mobile users. A mobile is served by the base station in its current cell. When a new call gets a channel, it keeps the channel until the call is completed in the cell or the mobile moves out of the cell. When the mobile crosses a cell boundary into an adjacent cell while the call is in progress, a handoff procedure takes place. If no channel is available in the new cell into which the mobile moves, the handoff call is forced to terminate before completion. For clarity purposes, we assume non-prioritized handoffs i.e. handoff calls are treated same as new calls and, thus, no capacity is exclusively reserved in each cell to handle handoff calls [3][4].

A random movement model is assumed in which a mobile moves with a random speed v, uniformly distributed between $[0,V]$, and an independent moving direction, uniformly distributed between $[0,2\pi]$. The system is considered to be always in the state of mobility equilibrium i.e. the mean number of incoming mobiles in a cell is equal to the mean number of outgoing mobiles.

Consider that I different services are being offered in this cellular network. Each cell, thus, may support traffic from I services. The traffic corresponding to service s_i arrives, in each cell, at a Poisson rate λ_i with, exponentially distributed, channel holding time of mean $1/\mu_i$. It may be noted that $\lambda_i = \lambda'_i + \lambda''_i$, where λ'_i is the rate at which new calls belonging to service s_i originate in the cell; and λ''_i is the handoff call arrival rate for that service in the cell. Both are assumed to be Poisson. The channel service rate μ_i is the rate at which the carried calls belonging to service s_i are completed in the cell or are handed off to the other cells. Thus, $\mu_i = \mu'_i + \mu''$, where $1/\mu'_i$ is the mean call holding time given that either the call terminates in the cell it originated or no handoff fails, and μ'' is the outgoing handoff rate per terminal [3]. The handoff rate per terminal is a function of system parameters such as cell size, speed and direction of the mobiles etc., and is independent of the type of call a mobile has made. From [3], $\mu'' = \frac{E[v]L}{\pi S}$, where v is the velocity of the mobile unit, L is the perimeter of the cell, and S is the area of the cell. The average number of mobiles of each service type moving out of a cell, i.e. λ''_i, is then equal to $E[n_i]\mu''$, where n_i is the number of active users in the cell using service s_i [1].

Let each call belonging to s_i occupies m_i units of capacity for the duration of the call. For VBR sources m_i may be the peak rate or the equivalent bandwidth depending upon the cell level QoS guarantees [8]. This is an I-dimensional Birth-Death Markov process, with vector $\boldsymbol{j} = \{j_1, j_2, ..., j_i, ..., j_I\}$ representing the state of the cell, i.e. the number of connections from each service that are active in a cell at a given time. The objective now is to determine the probability of being in state $\boldsymbol{j}$ i.e. $P(\boldsymbol{j})$ and, then compute the blocking probability Pb_i and the dropping probability Pd_i for each service s_i. The blocking probability Pb_i is the probability that a call belonging to service s_i will be blocked in the cell. A BCC (Blocked Calls Cleared) system is assumed. The call dropping probability Pd_i is the probability that a non-blocked call is dropped. This usually happens due to handoff failure. The QoS of s_i is then better characterized as $QoS = \alpha Pb_i + (1-\alpha) Pd_i$ where $\alpha < 1$. Depending upon the relative importance of call blocking probability and call dropping probability for a service, a particular bandwidth access control policy could be deduced, or an existing one could be fine tuned.

Assuming that the call arrival process is stationary, $P(\boldsymbol{j})$ is obtained by solving the steady-state equilibrium equations of the I-dimensional Birth-Death Markov process. Subsequently, Pb_i is determined based on the constraints associated with the particular bandwidth access control policy.

A. Call Blocking Probability

A wide spectrum of bandwidth access control policies have been discussed in the literature [5][6]. The simplest of all policies is a complete sharing (CS) policy, which permits an unrestricted sharing of total bandwidth among all the competing traffic types. On the other extreme is a complete partitioning (CP) policy, which permanently and statically partitions the bandwidth among the competing services. It is evident that the most desirable policy would lie between these two extremes. Partial sharing (PS) is one such class of schemes. According to partial sharing policy, total capacity can be partitioned into engineered capacity and shared capacity. The engineered capacity is intended to reserve proper capacity for accommodating the expected call arrivals whereas the shared capacity is used in reducing the impact of fluctuations in the arrival rate. Determination of accurate sizes of shared and engineering capacities, for every possible network configuration and load conditions, particularly when these conditions are dynamically varying, could become quite complex. Besides, for example, an argument could be made that though, in future, data traffic is expected to be dominant, it may not be as dominant from revenue generation perspectives. Dynamically varying network conditions, coupled with desire for preferential treatment of some services suggest potential for the use of priority based bandwidth access policies. Under these policies the competing services are assigned priorities. All the services have unrestricted access to the shared bandwidth, however, low priority calls may be dropped or preempted (PS with Call Preemption), or their arrivals could be blocked or discouraged (PS with Discouraged Arrivals) to make room for higher priority calls. The blocked or dropped calls are assumed to be lost.

Given a particular bandwidth access policy, Pb_i for a cell is derived as under. For simplicity, two service case i.e. $I = 2$ is assumed.

1) Complete Sharing

As mentioned earlier, complete sharing implies uncontrolled access to the cell's bandwidth by any of the services. Thus, as long as $m_1 (m_2)$ units of bandwidth are available, a call from $s_1 (s_2)$ is accepted. The acceptable states, as well as, state transitions of the cell are shown in Fig. 2(a). At equilibrium, the steady state balance equations are [6]:

$$\left[\lambda_1 \delta_{j_1+1, j_2} + \lambda_2 \delta_{j_1, j_2+1} + j_1 \mu_1 \delta_{j_1-1, j_2} + j_2 \mu_2 \delta_{j_1, j_2-1}\right] P(j_1, j_2) =$$

$$\lambda_1 \delta_{j_1-1, j_2} P(j_1-1, j_2) + \lambda_2 \delta_{j_1, j_2-1} P(j_1, j_2-1)$$

$$+ (j_1+1)\mu_1 \delta_{j_1+1, j_2} P(j_1+1, j_2) + (j_2+1)\mu_2 \delta_{j_1, j_2+1} P(j_1, j_2+1) \quad (1)$$

$$\sum_{(j_1, j_2) \in A} P(j_1, j_2) = 1 \quad (2)$$

for all $(j_1, j_2) \in A$, where A is the space of acceptable states, and

$$\delta_{k_1, k_2} = \begin{cases} 1 & if \quad (k_1, k_2) \in A \\ 0 & if \quad (k_1, k_2) \notin A \end{cases}. \tag{3}$$

Solving the above algebraic equations, we get the product-form solution [7] i.e.

$$P(j_1, j_2) = (P_A(0))^{-1} \times \frac{\rho_1^{j_1}}{j_1!} \times \frac{\rho_2^{j_2}}{j_2!} \tag{4}$$

where $P_A(0) = \sum_{(j_1, j_2) \in A} \frac{\rho_1^{j_1}}{j_1!} \times \frac{\rho_2^{j_2}}{j_2!}$; and ρ_i for i = 1, 2 is the traffic intensity i.e. λ_i/μ_i. The blocking probability is then the probability that the system will move out of the acceptable space A, and is given as

$$Pb_1 = \sum_{\left\{(j_1, j_2) \middle| 0 \le j_2 \le \left\lfloor \frac{C}{m_2} \right\rfloor, j_1 = \left\lfloor \frac{C - j_2 m_2}{m_1} \right\rfloor \right\}} P(j_1, j_2), \tag{5}$$

$$Pb_2 = \sum_{\left\{(j_1, j_2) \middle| 0 \le j_1 \le \left\lfloor \frac{C}{m_1} \right\rfloor, j_2 = \left\lfloor \frac{C - j_1 m_1}{m_2} \right\rfloor \right\}} P(j_1, j_2). \tag{6}$$

2) Complete Partitioning

This policy allocates a fixed bandwidth $C_1(C_2)$ to service $s_1(s_2)$ such that C_1+C_2 <= C. The acceptable states of this policy are a subset of the complete sharing case as illustrated in Fig. 2(b). This is a case of two independent queues, and the blocking probability is given by the well known Erlang-B formula [6] i.e.

$$Pb_i = \frac{\frac{\rho_i^{J_i}}{J_i!}}{\sum_{j=0}^{J_i} \frac{\rho_i^{j}}{j!}} \text{ where } J_i = \left\lfloor \frac{C_i}{m_i} \right\rfloor \text{ and } i = 1,2. \tag{7}$$

3) Partial Sharing

In partial sharing, some bandwidth $C_1(C_2)$ is allocated permanently to service $s_1(s_2)$, whereas a portion C_s could be shared by the two on a first-come-first-serve basis, such that C_1+C_2+C_s <= C. This is a special combination of the above two policies. The acceptable states are illustrated in Fig. 2(c). The blocking probabilities are

$$Pb_1 = \sum_{\left\{(j_1, j_2) \middle| 0 \le j_2 \le \left\lfloor \frac{C_s + C_2}{m_2} \right\rfloor, j_1 = min\left(\left\lfloor \frac{C_s + C_1}{m_1} \right\rfloor, \left\lfloor \frac{C - j_2 m_2}{m_1} \right\rfloor\right) \right\}} P(j_1, j_2) \tag{8}$$

$$Pb_2 = \sum_{\left\{(j_1, j_2) \middle| 0 \le j_1 \le \left\lfloor \frac{C_s + C_1}{m_1} \right\rfloor, j_2 = min\left(\left\lfloor \frac{C_s + C_2}{m_2} \right\rfloor, \left\lfloor \frac{C - j_1 m_1}{m_2} \right\rfloor\right) \right\}} P(j_1, j_2) \tag{9}$$

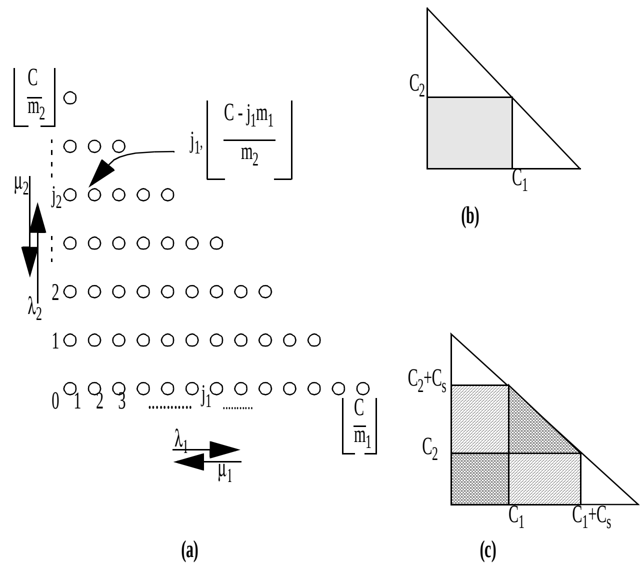

Fig. 2. (a) Two Dimensional Markov chain for Complete Sharing (b) Complete Partitioning (c) Partial Sharing.

The blocking probabilities for other variants of PS can similarly be derived [5]. The two priority based schemes are analyzed next.

4) PS with Call Preemption

In this case a call from a low priority service is accepted if enough capacity is available, however, the call could be dropped if a higher priority call arrives. We assume that s_2 is high priority broadband service and s_1 is low priority narrow-band service. The acceptable states, as well as, the state transitions are shown in Fig. 3(a). At equilibrium the steady state balance equations are:

$$\left[\lambda_1\delta_{j_1+1,j_2}+\lambda_2\delta_{j_1,j_2+1}+j_1\mu_1\delta_{j_1-1,j_2}+j_2\mu_2\delta_{j_1,j_2-1}+\lambda_2\Delta_{j_1,j_2+1}\right]P(j_1,j_2) =$$

$$\lambda_1\delta_{j_1-1,j_2}P(j_1-1,j_2)+\lambda_2\delta_{j_1,j_2-1}P(j_1,j_2-1)+(j_1+1)\mu_1\delta_{j_1+1,j_2}P(j_1+1,j_2)$$

$$+(j_2+1)\mu_2\delta_{j_1,j_2+1}P(j_1,j_2+1)+\lambda_2\sum_i\Delta_{j_1+i,j_2-1}P(j_1+i,j_2-1) \quad (10)$$

$$\sum_{(j_1,j_2)\in A} P(j_1,j_2) = 1 \quad (11)$$

$$\Delta_{k_1,k_2} = \begin{cases} 1 & if \quad 0\le k_2\le\left\lfloor\frac{C}{m_2}\right\rfloor \quad and \quad \left\lfloor\frac{C-k_2m_2}{m_1}\right\rfloor-b+1\le k_1\le\left\lfloor\frac{C-k_2m_2}{m_1}\right\rfloor \\ 0 & otherwise \end{cases} \quad (12)$$

for all $(j_1,j_2)\in A$, where A and δ_{k_1,k_2} are as defined above, and $b = \left\lfloor\frac{m_2}{m_1}\right\rfloor$. Solving (10) and (11) we get the state probabilities $P(j_1, j_2)$. The closed form solution for $P(j_1, j_2)$ does not exist, hence, $P(j_1, j_2)$ is solved using numerical methods. Since s_2 does not have to compete for bandwidth, its blocking probability is determined using the Erlang-B formula of (7), whereas the blocking probability for s_1 is, again, obtained using (5).

The probability that an s_1 can be preempted, on the other hand, is defined as:

$$Pp_1 = \frac{\text{average } s_1 \text{ calls preempted in an interval T}}{\text{total average } s_1 \text{ calls arrived in an interval T}} \quad (13)$$

It is clear from Fig. 3(a) that an s_2 call may drop upto b active s_1 calls. The average s_1 calls that could be dropped is then $D_s\sum_{i=1}^{b} iD_{s_i}$. The variable D_{s_i} is the probability that the cell is in the state where i number of s_1 calls would be preempted if an s_2 call arrives, and is given by

$$D_{s_i} = \sum_{\left\{(j_1,j_2)\middle|0\le j_2\le\left\lfloor\frac{C}{m_2}\right\rfloor-1,\, j_1=\left\lfloor\frac{C-j_2m_2}{m_1}\right\rfloor-b+i\right\}} P(j_1,j_2) \quad (14)$$

for i = 1, 2, .. b, whereas, D_s is the probability of being in any one of the preemptive states. Let $x_1(x_2)$ be the random variable representing the number of $s_1(s_2)$ calls arriving in an interval T, and x_{1_d} be the random variable representing the number of s_1 calls preempted in the interval T, then

$$E\left\{x_{1_d}\Big|_{x_2=a}\right\} = \left(aD_s\sum_{i=1}^{b} iD_{s_i}\right), \quad (15)$$

$$E\left\{x_{1_d}\right\} = E\left\{E\left\{x_{1_d}\Big|_{x_2}\right\}\right\} = E\{x_2\}D_s\sum_{i=1}^{b} iD_{s_i}, \quad (16)$$

and, therefore, from (13)

$$Pd_1 = \frac{E\left\{x_{1_d}\right\}}{E\{x_1\}} = \frac{\lambda_2 D_s\sum_{i=1}^{b} iD_{s_i}}{\lambda_1}. \quad (17)$$

5) PS with Discouraged Arrivals

In this case the arrival rate of low priority calls is reduced as the total number of connections in the cell grow. The Markov Chain process for this policy is shown in Fig. 3(b). At equilibrium the steady state balance equations are:

$$\left[\lambda_1(j_1,j_2)\delta_{j_1+1,j_2} + \lambda_2\delta_{j_1,j_2+1} + j_1\mu_1\delta_{j_1-1,j_2} + j_2\mu_2\delta_{j_1,j_2-1}\right]P(j_1,j_2) =$$
$$\lambda_1(j_1-1,j_2)\delta_{j_1-1,j_2}P(j_1-1,j_2) + \lambda_2\delta_{j_1,j_2-1}P(j_1,j_2-1)$$
$$+ (j_1+1)\mu_1\delta_{j_1+1,j_2}P(j_1+1,j_2) + (j_2+1)\mu_2\delta_{j_1,j_2+1}P(j_1,j_2+1) \qquad (18)$$

$$\sum_{(j_1,j_2)\in A} P(j_1,j_2) = 1 \qquad (19)$$

for all $(j_1, j_2) \in A$, where A and δ_{k_1,k_2} are as defined above. The arrival rate of s_1 is, thus, a function of the state (j_1, j_2) of the cell and is given as $\lambda_1(k_1,k_2) = \frac{\lambda_1}{1 + k_1 m_1 + k_2 m_2}$. Again the state probabilities $P(j_1, j_2)$ are obtained by solving the above set of algebraic equations, using numerical methods, and the blocking probabilities are obtained by substituting $P(j_1, j_2)$ in (5) and (6).

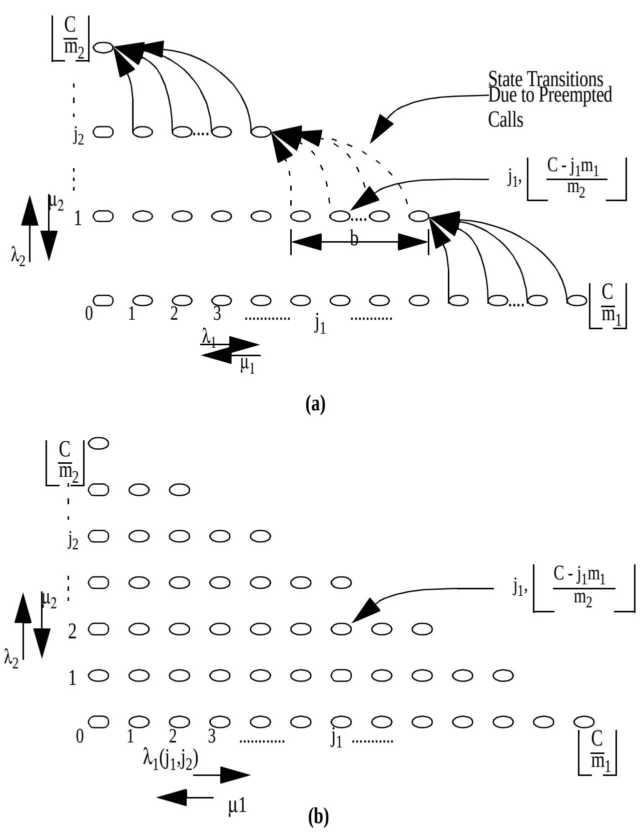

Fig. 3. Priority Based Policies (a) PS with Call Preemption (b) PS with Discouraged Arrivals

Once the call blocking probability of each service on every cell has been determined, the next step is to determine the call dropping probability.

B. Call Dropping Probability

The memoryless property of the exponential distribution of channel holding time and call holding time implies that the duration of a call after the handoff has same distribution as before the handoff. The probability that handoff occurs before a call completion can, therefore, be approximated as [1][2]:

$$h_i = \frac{\mu''}{\mu_i + \mu''} \qquad (20)$$

Since the whole service area is assumed to be much larger than the cell size, the likelihood that a mobile moves out of the service area during the call is negligible. The probability that a call belonging to service s_i does not complete and is dropped before k^{th} handoff is given by

$$Ph_i(k) = [h_i(1-Pb_i)]^{k-1} h_i Pb_i \text{, where } k=1,2,3... \qquad (21)$$

The dropping probability is therefore

$$Pd_i = \sum_{k=1}^{\infty} Ph_i(k) = \sum_{k=1}^{\infty} [h_i(1-Pb_i)]^{k-1} h_i Pb_i$$

$$= \frac{h_i Pb_i}{1 - [h_i(1-Pb_i)]} \qquad (22)$$

where Pb_i for a particular bandwidth access control policy, in use, is derived as in the last section.

For PS with Call Preemption policy, the dropping probability for lower priority calls will also include the probability of call preemption, given by (17), and thus, for this policy, the dropping probability of a lower priority service is given as

$$Pd_i = \frac{h_i Pb_i}{1 - [h_i(1 - Pb_i)]} + Pp_i \tag{23}$$

III. Results

Computer simulations were conducted to compare various bandwidth access control policies and, thus, verify the analysis of section II.A. A cellular network with two competing services, i.e. $I = 2$, was simulated. The overall capacity of each cell was assumed to be 48 channels of bandwidth. The other parameters such as (m_1,m_2), (λ_1,λ_2), and (μ_1,μ_2) were taken as (1,6), (20/21,1/21), and (1,0.05) respectively. The mean channel holding time of s_2 calls was, thus, 20 times more than that of s_1 calls, whereas, the bandwidth requirement of an s_2 call was 6 times more than that of an s_1 call. The call arrival rates (λ_1,λ_2) of both services were proportionally increased, and the effect of this increase in traffic on the call blocking probabilities was observed.

Firstly, the CS policy was implemented in each cell. The results are presented in Fig. 4. As expected, due to unsymmetrical traffic load and heterogeneous service characteristics, CS exhibits unfairness. The narrow-band service s_1 monopolizes the available bandwidth, while starving the wideband service s_2. This effect becomes even more profound as the call arrival rates of both services increase. The CP policy was implemented next, where (C_1,C_2) were taken as (12,36) respectively. The blocking probability of s_2, in this case, improves significantly. The cell throughput, however, will deteriorate because of the bandwidth granularity. Fig. 4 also depicts the PS case with (C_1,C_2) being (18,12) respectively, and C_s being 18 channels. The PS policy can, therefore, be used to optimize the call blocking probability and throughput characteristics, by fine tuning the shared and engineered bandwidth. Determination of accurate sizes of shared and engineering capacities is anything but trivial as the networks and services are always ever evolving. The priority based schemes could be used in these situations. The priority based schemes achieve better gains in throughput for higher priority services. This is evident from Fig. 4(b) where the blocking probability of higher priority service s_2 is lower than the ones achieved through the conventional CS, CP or PS policies.

IV. Conclusions

A traffic model and mathematical framework has been developed to study the impact of various bandwidth access control policies on the call level QoS guarantees in a multiservice cellular network with mobile users. Precise formulations to compute call level QoS parameters such as, call blocking probability and call dropping probability have been derived. The model has potential application in network planning and bandwidth tuning of cellular networks.

Some priority based bandwidth access control policies have also been proposed, and compared with conventional policies. Simulation results indicate that the priority based policies can achieve better throughput for higher priority services. As the cellular networks and services continue to evolve, and the traffic load fluctuates dynamically, reserving bandwidth exclusively and statically for each service may not be efficient from revenue generation perspectives. The priority based policies may, therefore, be attractive alternative in these circumstances.

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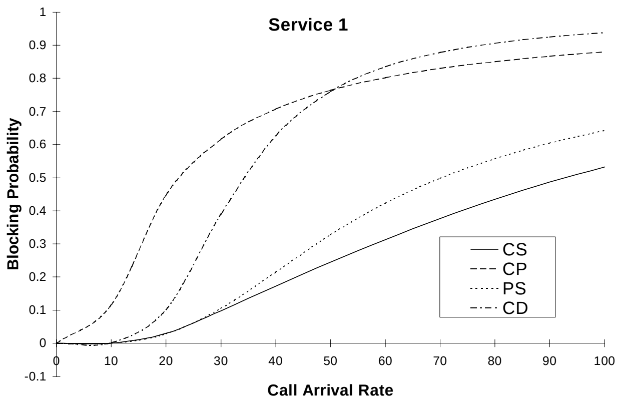
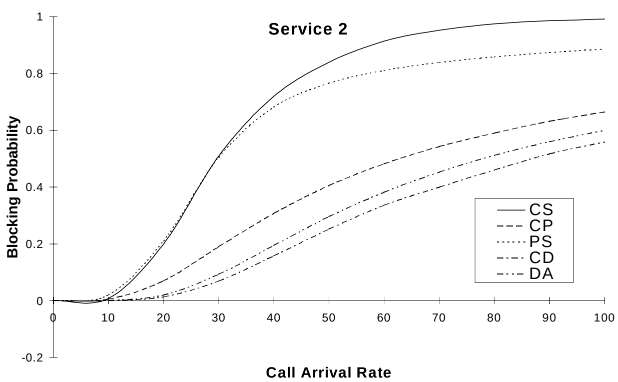


(a)



(b)

Fig. 4. (a) Blocking Probability of Service 1 for CS (Complete Sharing), CP (Complete Partitioning), PS (Partial Sharing), and CD (PS with Call Preemption) respectively. (b) Blocking Probability of Service 2 for CS, CP, PS, CD and DA (PS with Discouraged Arrivals) respectively.