

Performance Analysis of Cellular Mobile Communication Networks Supporting Multimedia Services *

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Abstract

This paper illustrates the development of an approximate analytical model for a communication network providing integrated services to a population of mobile users, and presents performance results to both validate the analytical approach, and assess the quality of the services offered to the end users. The analytical model is based on continuous-time multidimensional birth-death processes, and it is focused on just one of the cells in the network. The cellular system is assumed to provide three classes of service: the basic voice service, a data service with bit rate higher than the voice service, and a multimedia service with one voice and one data component. In order to improve the overall network performance, some channels can be reserved to handovers, and multimedia calls that cannot complete a handover are decoupled, by transferring to the target cell only the voice component and suspending the data connection until a sufficient number of channels becomes free. Numerical results demonstrate the accuracy of the approximate model, as well as the effectiveness of the newly proposed multimedia call decoupling approach.

1. Introduction

The ever increasing popularity of cellular and cordless telephone services is making wireless access and mobility two major components in the evolution of telecommunication networks.

In the design of the first and second generation cellular mobile telephony systems (such as ETACS and GSM in Europe), the technical approach mainly focused on increasing the capacity available for voice services, so as to cope with the explosive growth in the number of subscribers.

Today, the need for an increased system capacity is combined with the request for a wider spectrum of telecommunication services, in order to be able to offer data services in addition to plain telephony; this will pave the way to the introduction of wireless multimedia services for mobile users, including voice, data and images.

While the performance of cellular telecommunication networks offering mobile telephony services was investigated

by many authors under several different operating conditions, the same cannot be said of networks offering a variety of services to mobile users.

The performance of cellular telecommunication networks can be investigated by using either simulation or analytical models (or a combination of both). Though simulation is often preferred when aiming at the detailed study of the behaviour of a specific cellular system covering a given area, in recent years a number of analytical frameworks were developed to obtain more general results. Some examples of analytical approaches to the performance analysis of cellular telecommunication networks are found in [1, 2, 3, 4, 5, 6, 7, 8, 9].

In this paper we develop an analytical model based on continuous-time multidimensional birth-death processes, in order to evaluate the performance of a cellular system designed to provide three classes of service: the basic voice service, a data service with bit rate higher than the voice service, and a multimedia service with one voice and one data component, to be managed together (multimedia communication systems must be able to manage not only isolated connections, possibly belonging to different service classes, but also groups of connections that carry the different components of a multimedia service, such as voice and data, that in the simpler cases are set up at the same time, and terminate at the same time).

Furthermore, a new mechanism is proposed to decrease the probability that an active multimedia call is interrupted due to a handover failure: when the base station governing a cell cannot serve the handover request of a multimedia call, an attempt is made to serve at least the voice component. If this operation succeeds, the multimedia call is decoupled: the voice call is continued, while the data connection is suspended, and will be resumed as soon as possible.

2. Model description

The analytical model is based on a continuous-time multidimensional birth-death process, as we already mentioned; the model illustration is organized in four stages: i) discussion of the main assumptions and of the model parameters; ii) state definition and identification of the model driving processes; iii) derivation of the flow balance equations and computation of the equilibrium state probabilities; iv) evaluation of aggregate performance measures.

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2.1. Assumptions and parameters

The cellular telecommunication system comprises a large number of cells, and provides three classes of service to satisfy different kinds of users requests: **Class A** service is intended to support basic voice calls that require narrowband connections; **Class B** service satisfies the requirements of data calls (or slow video calls) with (moderately) wideband connections; **Class C** service is intended to support multimedia calls composed of a data component and a voice component, which are set up and terminated at the same time, and must be managed together.

Denoting with N the number of radio channels available in a given cell of the cellular telecommunication system, we assume that the establishment of connections of class *A* requires just one channel, that connections of class *B* require C_d channels, and finally that connections of class *C* require $C_d + 1$ channels.

A service request from a mobile user to a base station may be due either to the generation of a new call or to a handover request. Since handover failures force the termination of a call in progress, these events are considered to be worse than new calls blocking, whose effect is just to force the user to repeat his access request at a later time. Therefore, two mechanisms are introduced in the system in order to favor handover requests with respect to new call requests, under heavy traffic conditions. Priority is given to handover requests by reserving a small number of channels, denoted by C_h , for handovers ($C_h \geq 0$). Furthermore, when the handover of a multimedia call is requested, the base station tries to accommodate the entire call, but, if this is not possible, the two components of the call can be decoupled: the voice connection is accepted, if possible, while the data connection is temporarily suspended, waiting to be resumed as soon as enough channels are available in the cell to serve the entire multimedia call.

Decoupling a multimedia call because of a partially served handover can improve the quality of service, mainly because it allows the user to continue at least partly his communication. Furthermore, though the data connection is suspended, the user is given a chance to resume it later from the point it was interrupted; this can be a very useful feature for data applications, such as file transfer, for example. In fact, if the entire handover had been blocked, the whole multimedia connection would have been suddenly terminated, and all transferred data would have been lost.

A decoupled multimedia call occupies only one channel, like a normal voice call; in the following we will refer to decoupled multimedia calls as **class D** connections.

To facilitate recombination of decoupled multimedia calls, new calls are not accepted as long as some active class *D* connections exist in the cell.

The amount of time that a Mobile Terminal (MT) with an ongoing call remains within the area covered by the base station of the cell under investigation is called *dwelt time*; if the call is still active after the dwelt time, the MT requests a handover toward an adjacent cell. The *unencumbered session duration* of a call is defined as the amount of time that the call would remain in progress if it could

continue to completion, without forced termination due to handover failure.

The analysis of the cellular telecommunication system focuses on just one cell, whose behavior is isolated from those of other cells, that are collectively described only through the handover request processes observed by the cell under investigation. Of course, if the network is highly symmetric, and the traffic is homogeneous, the analysis of one cell may suffice for the assessment of the quality of the services offered by the whole system; otherwise, several cells must be separately studied.

The following assumptions render the isolated cell analysis problem amenable to solution using the theory of multi-dimensional birth-death processes.

The new call request arrival processes for voice, data and multimedia services are modeled as Poisson point processes. The mean new voice call request arrival rate, denoted by λ_v , is the product of the mean new voice call request rate from one MT and the number of MTs in the cell. Mean call rates for data calls and multimedia calls, λ_d and λ_m , are obtained in a similar way.

The handover request arrival processes from adjacent cells follow Poisson point processes. The mean handover arrival rates corresponding to voice, data and multimedia calls, are denoted by λ_{hv} , λ_{hd} and λ_{hm} , respectively.

The dwell time of a MT in the cell is a random variable with negative exponential probability density function, with mean $1/\mu_{hv}$ in the case of a voice call, $1/\mu_{hd}$ for a data call, and $1/\mu_{hm}$ for a multimedia call.

The unencumbered session duration of a call is a random variable with negative exponential pdf whose mean value is $1/\mu_v$, $1/\mu_d$, and $1/\mu_m$, for voice, data and multimedia calls, respectively.

The values of the parameters can be derived from characteristics of the system such as the cell size and the speed of the mobile users.

2.2. State definition and driving processes

The cell state, in any instant, is determined by the number of currently active connections for each class of traffic, and it is therefore given by the vector $s = (v, d, m, r)$, where v is the number of active voice calls in the cell; d is the number of active data calls; m is the number of multimedia calls, composed by two components (voice and data), both of which are active; r is the number of active voice components of decoupled multimedia calls; if $r > 0$, some suspended data calls are waiting to be resumed as soon as a sufficient number of channels become available.

We denote with $n(s)$ the function giving the total number of channels allocated to active connections when the cell is in state s : $n(s) = v + d \cdot C_d + m \cdot (C_d + 1) + r$. We shall simply write n instead of $n(s)$ when no ambiguity arises.

Since the number of channels available in the cell is N , the maximum values of v , d and m are respectively N , $\lfloor N/C_d \rfloor$ and $\lfloor N/(C_d + 1) \rfloor$. Whereas these values are determined by the cell configuration, the maximum number of decoupled calls that can be active at the same time, r , is limited by a threshold r_{max} , that must be fixed by the operator of the cellular system; if no threshold is defined, r can grow

up to N . A permissible state s must satisfy the condition $n(s) \leq N$.

Let \bar{S} be the state space of the model we just described; it is convenient to order and number states from 0 to S_{max} .

The model dynamics is determined by a number of *driving stochastic processes* which cause state transitions at random instants.

Driving processes produce different kinds of events that must be processed by the network. In our case, with reference to the cell under investigation, they are the following: i) requests of new voice, data and multimedia calls; ii) incoming handover requests for voice, data, multimedia and decoupled calls; iii) outgoing handover requests for voice, data, multimedia and decoupled calls; iv) completion of voice, data, multimedia and decoupled calls.

Since only one cell is analysed, outgoing handover requests and call completions have the same effect on the model (i.e. some previously busy channels become free); on the contrary, new call requests and incoming handover requests have to be considered separately, because a handover request of a multimedia call can lead to a call decoupling, while a new call request cannot.

2.3. Flow balance equations and equilibrium probabilities

Since the Markovian model is homogeneous and irreducible, with finite state space, an equilibrium (or steady-state) distribution $\mathbf{p} = \{p(i)\}$, with $i = 0 \dots S_{max}$, exists, and can be computed through the matrix equation $\mathbf{p} \cdot \mathbf{Q} = 0$ where \mathbf{Q} is the infinitesimal generator matrix, together with the normalization condition $\sum_{i=0}^{S_{max}} p(i) = 1$.

The transition rates, i.e. the elements of matrix \mathbf{Q} , are obtained from the analysis of the system driving processes. For each driving process, it is possible to determine what state transitions can happen, i.e. what are the possible *successor states* of a generic state $s = (v, d, m, r)$. This is what we discuss next, referring also to Table 1 which shows the conditions on the model state for a transition to be possible, the rate associated with the transition, and the successor state, for each type of new call (denoted with *new* in the table), of incoming handover request (*ho.in*), and of outgoing handover request (*ho.out*).

A new call is accepted in the cell if the number of free channels, excluding those reserved to handovers, is such that the call can be accommodated. Furthermore, new calls are refused if some class D connections are active, (i.e. if $r > 0$), in order to favour recombination of decoupled multimedia calls. Note that a new multimedia call is accepted only if the system can accommodate both the voice and the data components; decoupling a multimedia call is only permitted when the connection is already active.

The incoming handover request for a voice or data call is accepted if enough free channels to accommodate the request are available in the cell. In the case of an incoming handover request for a multimedia call (whether decoupled or not), two possible successor states are identified, corresponding to a handover that can either be completely served or produces a decoupled call (see row *mmedia*, *ho.in* in Table 1). In the first case, both the voice and the data com-

ponents can be accommodated. Otherwise, the handover results in the transfer of the voice component only, and in the decoupling of the multimedia call.

Both the completion of calls and the outgoing handover requests have the effect of freeing some channels in the cell; in some cases this leads to the recombination of a decoupled multimedia call. In fact, the data component of a decoupled call is resumed if, after channels are freed, at least C_d channels are available. The row of Table 1 denoted with *voice*, *ho.out* refers to the case of a voice call termination that is not followed by a recombination of a decoupled multimedia call. This event takes place if either $r = 0$ (no recombination is necessary) or $r > 0$ but $n > N - C_d$ (no recombination is possible). The following rows of the same table refer to the case in which a recombination follows a voice call completion and a data call completion. In the case of a multimedia call completion, $C_d + 1$ channels are freed in the cell, and it is possible that one, or even two decoupled multimedia calls can be recombined. Two suspended data connections are resumed if $r > 1$, and $n - (C_d + 1) \leq N - 2C_d$, since $2C_d$ channels are free after the multimedia call completion. The last two rows of Table 1 refer to the cases of completion of a decoupled multimedia call. For voice, data and multimedia calls, respectively, $M_v = \mu_v + \mu_{hv}$, $M_d = \mu_d + \mu_{hd}$, and $M_m = \mu_m + \mu_{hm}$.

The transition rate from a state s to a state k is computed by summing the contributions resulting from the driving processes that were just described. The state space size (hence the dimension of matrix \mathbf{Q}) depends on the values of C_d , r_{max} , and, most important, on the number of radio channels available in the cell, N . This last value can be rather large, so that in the computation of the equilibrium probability distribution it is essential to use a numerical algorithm that exploits the sparseness of the infinitesimal generator; choosing the best representation of \mathbf{Q} , in order to minimize computation time and memory requirements, is not a minor task.

2.4. Aggregate performance measures

The performance indices of interest can be defined as follows, for the cell under consideration.

The *average carried traffic AC* is the average number of channels in use in the cell, and it is given by

$$AC = \sum_{s=0}^{S_{max}} n(s) \cdot p(s)$$

where $n(s)$ is the number of busy channels when the system is in state s and $p(s)$ is the steady-state probability of state s . It is also possible to evaluate how channels are partitioned among the different kinds of service. AC_v , AC_d and AC_m are defined as the average number of channels respectively used by voice, data and multimedia connections.

The *new call blocking probability PB* is defined as the average fraction of new call requests that cannot be satisfied by the cell base station, due to the lack of free channels. This probability is computed separately for each class of service. A new voice call is blocked if $n > N - C_h - 1$, that is if the system is in one of the states belonging to the

type	condition	successor state	rate
voice, new	$(n \leq N - C_h - 1) \wedge r = 0$	$(v + 1, d, m, r)$	λ_v
data, new	$(n \leq N - C_h - C_d) \wedge r = 0$	$(v, d + 1, m, r)$	λ_d
mmedia, new	$(n \leq N - C_h - (C_d + 1)) \wedge r = 0$	$(v, d, m + 1, r)$	λ_m
voice, ho_in	$n \leq N - 1$	$(v + 1, d, m, r)$	λ_{hv}
data, ho_in	$n \leq N - C_d$	$(v, d + 1, m, r)$	λ_{hd}
mmedia, ho_in	$n \leq N - (C_d + 1)$	$(v, d, m + 1, r)$	λ_{hm}
	$N - (C_d + 1) < n \leq N - 1$	$(v, d, m, r + 1)$	λ_{hm}
voice, ho_out	$(r > 0 \wedge (n - 1 > N - C_d)) \vee r = 0$	$(v - 1, d, m, r)$	vM_v
	$r > 0 \wedge (n - 1 \leq N - C_d)$	$(v - 1, d, m + 1, r - 1)$	vM_v
data, ho_out	$r = 0$	$(v, d - 1, m, r)$	dM_d
	$r > 0$	$(v, d - 1, m + 1, r - 1)$	dM_d
mmedia, ho_out	$r = 0$	$(v, d, m - 1, r)$	mM_m
	$r = 1 \vee (r > 1 \wedge (N - 2C_d < n - (C_d + 1)))$	$(v, d, m, r - 1)$	mM_m
	$r > 1 \wedge (n - (C_d + 1) \leq N - 2C_d)$	$(v, d, m + 1, r - 2)$	mM_m
decoupled, ho_out	$r > 1 \wedge (n - 1 \leq N - C_d)$	$(v, d, m + 1, r - 2)$	rM_m
	$r = 1 \vee (r > 1 \wedge (n - 1 > N - C_d))$	$(v, d, m, r - 1)$	rM_m

Table 1. Transitions from a state

subset B_v defined as $B_v = \{s : n > N - C_h - 1\}$. Thus, the blocking probability of new voice calls is

$$PB_v = \sum_{s \in B_v} p(s)$$

In a similar way it is possible to compute the blocking probabilities of new data calls (PB_d), and new multimedia calls (PB_m), using B_d and B_m , which are the subsets of states in which new data or multimedia calls cannot be accepted:

$$B_d = \{s : n > N - C_h - C_d\}$$

$$B_m = \{s : n > N - C_h - (C_d + 1)\}$$

Note that $B_v \subset B_d \subset B_m$ so that $PB_v \leq PB_d \leq PB_m$.

The *handover failure probability* PH is defined as the average fraction of incoming handover requests that cannot be satisfied, causing the forced termination of the call.

Incoming handover requests for voice, data and multimedia calls fail if the system is in one of the states belonging respectively to subsets H_v , H_d and H_m , defined as follows:

$$H_v = \{s : n > N - 1\}$$

$$H_d = \{s : n > N - C_d\}$$

$$H_m = \{s : n > N - C_d - 1\}$$

Therefore, handover failure probabilities are given by the aggregate probability of being in these subsets.

If some channels are reserved to handovers, i.e. if $C_h > 0$, handover requests are given higher priority with respect to new call requests; otherwise $PB = PH$.

PH_m is the probability that the system is not able to accommodate both components of a multimedia connection. However, if at least the voice component can be served, the call is decoupled, and the data component is suspended. This event happens when, at the time of the incoming handover request, the system is in one of the states of the subset $H_{dec} = \{s : N - C_d - 1 < n \leq N - 1, r < r_{max}\}$. We define the *decoupling probability* PH_{dec} as the probability that a multimedia call is decoupled after a handover request.

Finally, PH_r is defined as the probability that the handover request of the multimedia call completely fails, and

parameter	values
N	64
C_d	4 (8)
C_h	0 (4,8)
r_{max}	C_d (0)
$1/\mu_v = 1/\mu_d = 1/\mu_m$	100 s
$1/\mu_{hv} = 1/\mu_{hd} = 1/\mu_{hm}$	80 s

Table 2. Parameter values used in the presentation of numerical results

both components of the multimedia connection are forced to terminate: $PH_r = PH_m - PH_{dec}$.

The *probability of recovering a decoupled multimedia call*, P_{rec} , is defined as the probability that the data component of a decoupled multimedia call is resumed before the call is terminated by the user. P_{rec} is obtained as $P_{rec} = \frac{\bar{R}_{rec}}{AC_r}$.

In this expression, \bar{R}_{rec} is the relative rate of events that lead to the recombination of a multimedia call (normalized to the overall event rate R), and AC_r is the average number of decoupled calls in the cell:

$$\bar{R}_{rec} = \frac{1}{R} \cdot \sum_{s=0}^{S_{max}} R_{rec}(s) \cdot p(s)$$

$$AC_r = \sum_{s=0}^{S_{max}} r(s) \cdot p(s)$$

where $R_{rec}(s)$ is the recombination rate and $r(s)$ is the number of decoupled calls, when the system is in state s .

3. Results

This section consists of two parts. First we present some comparisons between analytical and simulation results in order to validate our approximate modeling approach; then we explore some alternate system configurations to assess

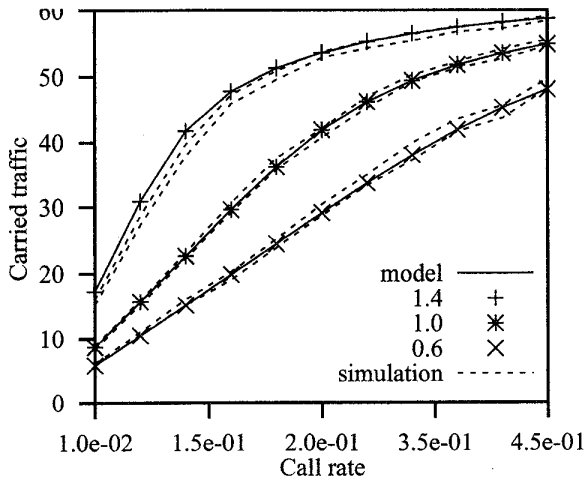


Figure 1. Simulation and analytical results for the average total carried traffic, with $\alpha = 1.4, 1.0, 0.6$ their effectiveness.

As a basic scenario we refer to a configuration similar to the one being considered by ETSI (the European Telecommunications Standards Institute) for the introduction of (moderately) high speed data services within the European wireless telephony network. We thus consider two classes of service only: class A (voice call) and class B (data call). Each data call requires the allocation of $C_d = 4$ channels.

The mean dwell time of voice or data calls is set to 80s, while the mean unencumbered session duration is taken to be 100s. The fraction of voice calls is assumed to be 75% of the total, the remaining 25% being data calls. The number of channels in the cell is taken to be 64. The number of users in the cell under investigation is taken to be 500. The performance indices will be presented as curves plotted versus the input load in terms of total call rate.

Table 2 provides the list of the parameter values that refer to the basic scenario (values given in the first position); additional values are given within brackets; when the used values differ from those of the basic scenario, this will be explicitly indicated in the figure caption.

3.1. Model validation

As we already mentioned, validating the analytical model by comparison with the results produced by a very detailed simulation of the wireless network is a necessity, because of the numerous simplifying assumptions adopted in the model development, in order to keep complexity under control. Recall that the major simplification stems from the choice of studying just one cell in isolation, instead of developing a detailed model of the entire network with the description of the interactions among adjacent cells. This also requires assuming that the average incoming handover flow is equal to the average outgoing handover flow.

The simulator that was used for the model validation shares only two features with the model: the description of users mobility, and the stochastic representation of the new

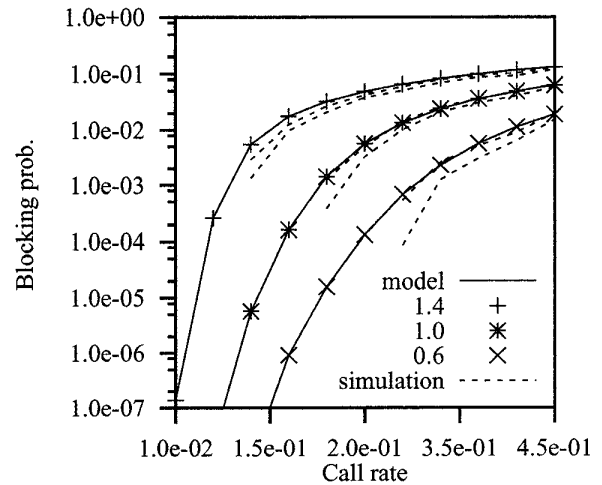


Figure 2. Simulation and analytical results for the average voice blocking probability, with $\alpha = 1.4, 1.0, 0.6$

call request traffic. All other system features are represented in detail in the simulator operations, with no simplification. In particular, the results that will be shown were obtained for a network comprising seven hexagonal cells, and the results of the central cell are compared with those obtained from the analytical model.

Confidence intervals are obtained for each simulation experiment by using the "batch means" technique, with confidence level equal to 0.95.

In order to extensively validate the model, we also consider situations where the incoming and outgoing handover flows are not balanced; this could be expected to induce non marginal perturbations on the accuracy of the analytical model. In particular, we assume that the relation between the average incoming and outgoing handover flows is $f_{in} = \alpha f_{out}$, where, of course, f_{in} and f_{out} respectively represent the incoming and outgoing handover flows. This kind of assumption can account for the particular type of traffic that a cell experiences in some period of time. For example, considering a cell covering the business district of a city, during the morning rush hour it can be expected that the incoming handover flow is significantly larger than the outgoing handover flow; thus the value of the parameter α should be set greater than 1. The opposite could be said in the evening rush hour period.

The first validation results are presented in Fig. 1, where we plot curves of the average carried traffic (number of occupied channels for both voice and data calls) in the cell with $\alpha = 1.4$, $\alpha = 1.0$ and $\alpha = 0.6$. Analytical results are presented as solid curves (one curve for each performance parameter), while simulation results are shown as three pairs of curves (one pair for each performance parameter), giving the upper and lower limits of confidence intervals.

Fig. 2 shows simulation and analytical results for the average blocking probability of new voice calls (results for the blocking probabilities of data calls are not shown, but the

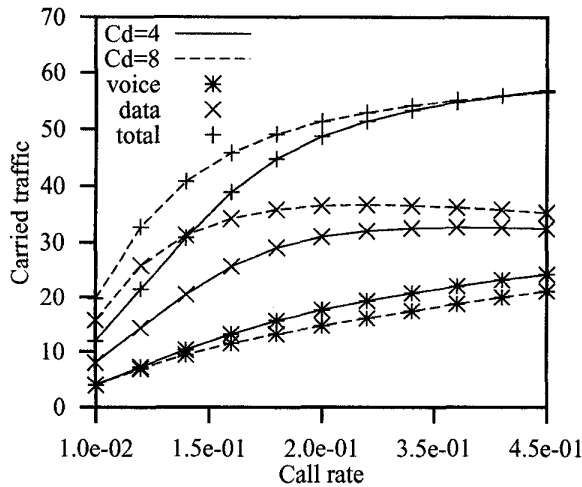


Figure 3. Average carried traffic (voice, data, and total) with $C_d = 4$ and $C_d = 8$

are quite similar to those presented for voice calls).

The curves presented in Figs. 1 and 2 clearly indicate that the approximations introduced in the model development do not alter significantly the numerical results with respect to those obtained with a detailed simulation of the system. It can be observed that the analytical model performance predictions are quite accurate in comparison with simulation, even for values of α different from 1, although some loss of accuracy with respect to that case can be noted.

As a preliminary conclusion we can thus state that the validation of the analytical results against those produced by quite a detailed simulation program was successful: the model can be considered to be accurate with respect to the experimented sets of values of system parameters.

3.2. Performance evaluation

In order to show how the approximate model can be used to study the performance of the cellular mobile communication network, we next illustrate some results that are obtained with different configurations of the cell under investigation.

In most of the figures of this subsection, numerical results explore variations with respect to the basic scenario that was introduced in the previous section, and used for the model validation.

In Figs. 3 and 4 we compare the average carried load and the voice and data blocking probabilities when the number of channels required for a data call is increased from $C_d = 4$ to $C_d = 8$. All other parameters are kept as in the basic scenario introduced in the previous section.

Increasing the number of channels allocated to each data call from $C_d = 4$ to $C_d = 8$ while keeping the same call rate significantly increases the data offered traffic, and also the data carried traffic when the channel occupancy is low. Differences in the data carried traffic tend to become smaller for higher call rates, and eventually the data carried traffic with $C_d = 8$ becomes smaller than with $C_d = 4$ for extremely high call rates (not shown). The carried voice

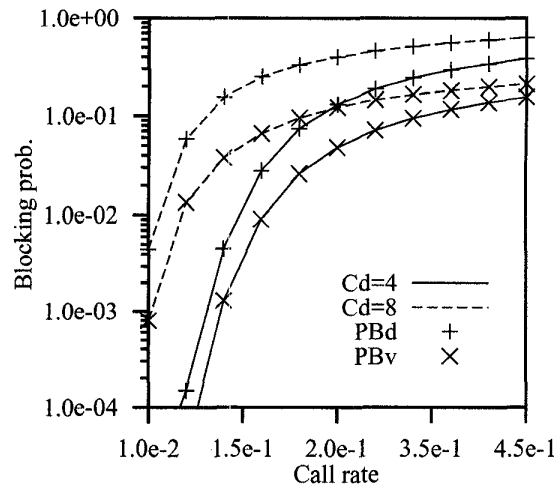


Figure 4. Voice and data call blocking probabilities with $C_d = 8$ and $C_d = 4$

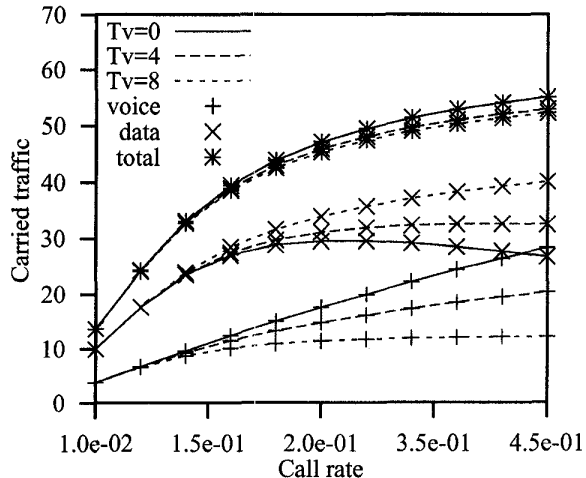


Figure 5. Average carried traffic (voice, data, and total) with $C_d = 8$ and $T_v = 0, 4, 8$

traffic instead is larger when $C_d = 4$, due to the larger average number of free channels in the cell. However, the total carried traffic always is larger when $C_d = 8$.

Moreover, as expected, the blocking probabilities for voice and data calls with $C_d = 8$ are much larger than with $C_d = 4$. In particular, the data call blocking probabilities quickly reach unacceptable values.

In order to mitigate the difference in blocking probability between voice and data calls, a threshold T_v can be introduced on the number of free channels necessary for the acceptance of a new voice call. By so doing, if the number of busy channels is greater than $N - T_v$, no new voice call can be accepted. The performances achievable in this case, with $T_v = 0, 4, 8$, can be observed in Figs. 5 and 6, that report, respectively, the average carried traffic (voice, data, and total) with $C_d = 8$, and the voice and data call blocking probabilities. The proposed approach leads to better performance for data traffic, at the expense of a performance loss

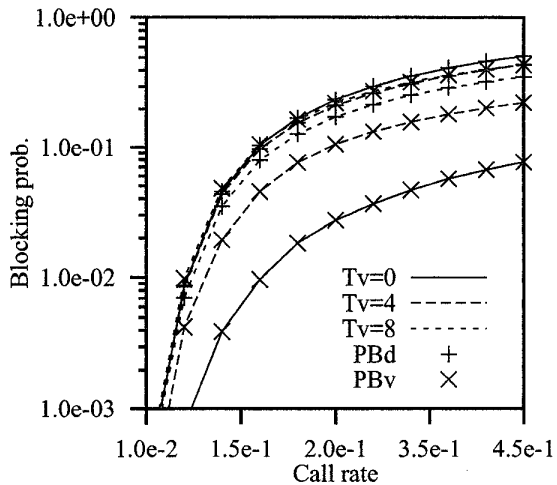


Figure 6. Voice and data call blocking probabilities with $C_d = 8$ and $T_v = 0, 4, 8$

for voice traffic.

We now explore the effect induced on system performance by the introduction of class C traffic, which is carried by multimedia connections comprising one voice and one data component. In the results we show next, the percentage of call requests referring to the three different classes of service is 60% for voice calls, and 20% each for data as well as multimedia calls.

In particular, we consider in this case the impact on performance indices of the reservation of a number of channels for handover calls (C_h). This is a common approach to favor the successful completion of call handovers, specially under high traffic conditions; when the number of busy channels in the cell is greater than C_h , new calls (whether voice, data, or multimedia) are blocked.

In Fig. 7 we plot curves of the handover failure probability for voice and data calls, with $C_h = 0, 4, 8$. As expected, the handover failure probability decreases with the increase of C_h . Note that this decrease is significantly different for voice and data connections: whereas for voice connections a large decrease is observed when C_h is increased from 0 to 4, and only a further minor improvement is obtained with $C_h = 8$, for data calls the largest gain is achieved by increasing C_h from 4 to 8. This is due to the fact that data connections use 8 channels, and thus they gain little from the availability of 4 channels reserved to handovers.

In the same scenario, Fig. 8 reports the curves of the probabilities that a multimedia call handover either completely fails, or results in a decoupled multimedia call, with $C_h = 0, 4, 8$. Recall that, as we noted before, a multimedia call must be decoupled when a handover is requested toward a cell in which the number of free channels is not sufficient for the acceptance of both components ($n > N - C_d - 1$), but sufficient for the acceptance of just the voice component ($n \leq N - 1$). Instead, the handover completely fails if no channel is free ($n = N$). With PH_{dis} we indicate the probability that a multimedia call is decoupled, while with PH_r we denote the probability that the handover request fails.

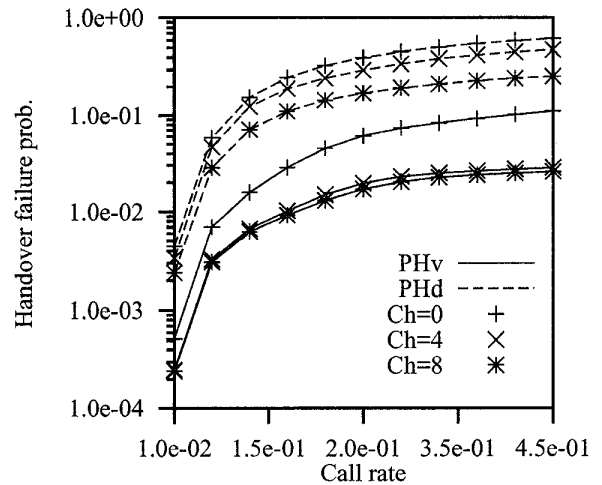


Figure 7. Voice and handover failure probabilities with three classes of service, and $C_d = 8$ and $C_h = 0, 4, 8$

Also in this figure we see that the effect of the reservation of channels to handovers is rather different on PH_{dis} and PH_r ; the reduction in the handover failure probability is significant when C_h is increased from 0 to 4, and only a further very minor improvement is obtained with $C_h = 8$. On the contrary, as regards the decoupling probability, very little is gained by letting $C_h = 4$, and even the gain obtained with $C_h = 8$ is not extraordinary. The justification of these results lies again in the difference between the number of channels necessary to serve the data and the voice components.

Decoupled multimedia calls are recombined as soon as enough free channels are found within the cell; the curves reporting the probability that a decoupled multimedia call is recombined are presented in Fig. 9. For growing input traffic this probability obviously decreases, because of the smaller probability of finding C_d free channels in the cell before the completion of the call dwell time. The reservation of a subset of channels to handovers in this case has rather a beneficial impact, specially at high loads.

In order to assess the effectiveness of the multimedia decoupling approach, we finally show in Fig. 10, for $C_d = 4$, $C_h = 0$, and r_{max} equal to either C_d or 0, the probability that a multimedia call handover request is refused in the two cases in which a multimedia call can be decoupled ($r_{max} = C_d$), or is considered as an atomic entity ($r_{max} = 0$). Results clearly indicate that the decoupling approach allows the reduction of the handover failure probability by a factor between 5 and 10, depending on the cell traffic load.

4. Conclusions

In this paper we have illustrated the development of an approximate Markovian model for a communication network providing integrated services to a population of mobile users, and we have presented performance results to

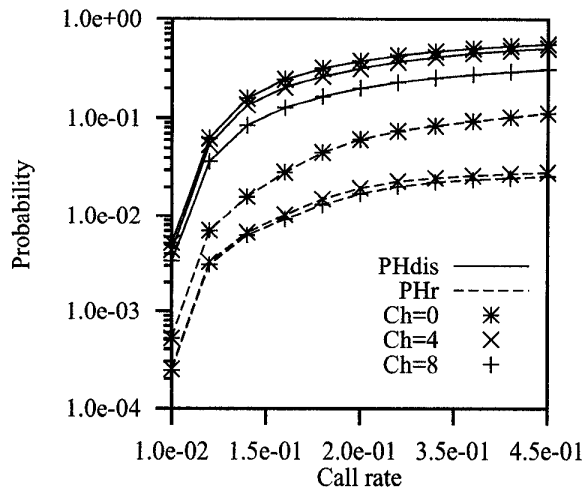


Figure 8. Decoupling and handover failure probabilities for multimedia calls with three classes of service, and $C_d = 8$ and $C_h = 0, 4, 8$

both validate the approximate analytical approach, and assess the quality of the services offered to the end users.

The cellular system is assumed to provide three classes of service: the basic voice service, a data service with bit rate four or eight times higher than the voice service, and a multimedia service with one voice and one data component.

In order to improve the overall network performance, some channels can be reserved to handovers, and multimedia calls that cannot complete a handover are decoupled, by transferring to the target cell only the voice component and suspending the data connection until a sufficient number of channels becomes free.

The analytical model is based on continuous-time multidimensional birth-death processes, and it is focused on just one of the cells in the network. The model solution is obtained with standard approaches for the solution of large Markovian systems, exploiting the sparseness of the infinitesimal generator.

Numerical results demonstrate the accuracy of the approximate model, as well as the effectiveness of the multimedia call decoupling approach, that is a novel contribution of this work.

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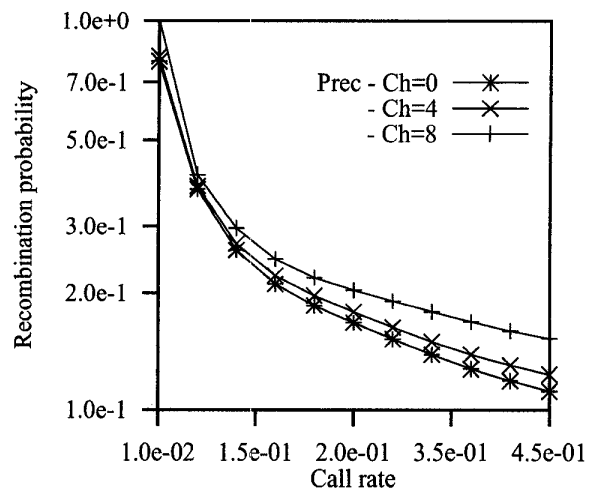


Figure 9. Recombination probability for multimedia calls with $C_d = 8$ and $C_h = 0, 4, 8$

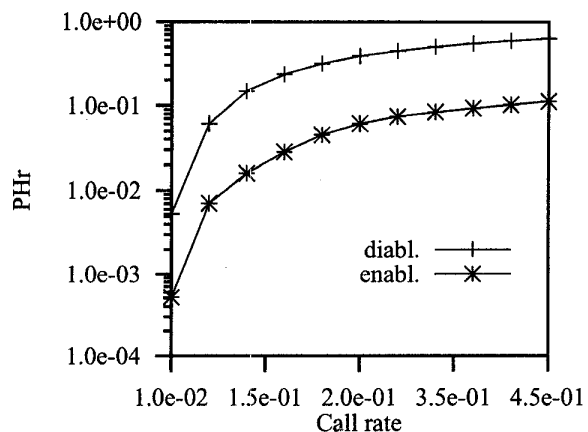


Figure 10. Handover failure probability for multimedia calls with $C_d = 8$, $C_h = 0$ and $r_{max} = 0$

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