STATE UNIVERSITY OF NEW YORK AT STONY BROOK

COLLEGE OF ENGINEERING AND APPLIED SCIENCES

CEAS TECHNICAL REPORT NO. 693

TRAFFIC PERFORMANCE OF MOBILE CELLULAR COMMUNICATION SYSTEMS WITH MIXED SERVICES AND PLATFORM TYPES

Stephen S. Rappaport

Department of Electrical Engineering
State University of New York
Stony Brook, New York 11794-2350

NOTE:

This is a substantially revised and updated version of the following report:

S.S. Rappaport, "Traffic Performance of Cellular Communication Systems with Mixed Platform and Call Types," CEAS Technical Report No. 656, January 7, 1993, College of Engineering and Applied Sciences, State University of New York, Stony Brook, NY 11794.

file: rsrces94.ppr
ver. January 18, 1994

Traffic Performance of Mobile Cellular Communication Systems with Mixed Services and Platform Types

Stephen S. Rappaport

Department of Electrical Engineering
State University of New York
Stony Brook, New York 11794-2350

phone: (516) 632-8394
fax: (516) 632-8494
email: rappaport@sbee.sunysb.edu

ABSTRACT

The proliferation of mobile, portable and personal communication systems will bring a variety of offered services. Practical systems that are envisioned must support different types of calls. These may include voice only, mixed voice and data, high speed data, low speed data, image transmission and an array of intelligent network services. In addition there may be a mixture of platforms (such as persons, autos, buses, trains, boats and planes) having a range of mobility characteristics. In such environments, the bandwidth and/or resources needed for call sessions will not be identical. As a result, calls will generally encounter different blocking and hand-off constraints. These effects are in addition to differences in blocking and forced (call) termination probabilities that are attributable to differing platform mobilities and (resource) channel quotas.

A cellular system with mixed platforms and call types is considered. We identify a suitable state characterization for the problem and present a framework for performance analysis. The model is used to generate example performance characteristics. These show carried traffic, blocking probability, and forced termination probability for each platform type and for each call type. The example results are discussed.

The author is grateful to Gustavo MONTE and Hua JIANG whose skillful computer programming generated the performance characteristics shown.

The research reported in this paper was supported in part by the U.S. National Science Foundation under Grant No. NCR-9025131 and in part by BMDO/IST under Grant No. N0001491-J4063 administered by the U.S. Office of Naval Research.

INTRODUCTION

Practical cellular mobile communication systems that are currently envisioned must support a mixture of platform types having a range of mobility characteristics. In addition, a variety of services are foreseen. These include: voice only, mixed voice and data, image transmission, selectable data rates, call waiting, call-back queuing, phone mail, e-mail, hand-off priority, user (vehicle) location, conferencing, priority access, caller and/or calling ID, data base access and various other fee-for-service options. Call sessions will require different types and amounts of network resources such as radio bandwidth, buffer allocations, and performance monitoring and call supervising processors. As a result they will encounter different blocking and hand-off constraints. These differences are in addition to those that are attributable to differing mobilities of the various types of platforms that can be present in the system.

The formulation and evaluation of alternative network control strategies require characterization of communications traffic performance and the development of tractable models that can accommodate a fair amount of physical complexity. Heterogeneous call types and platform types in the same system are among these complexities. In recent work we have been developing a framework that is useful for teletraffic performance analysis and modeling for a broad class of problems that arise in cellular communication architectures. The approach, which is based on multidimensional birth-death processes, is rich enough to permit modeling of many practical issues and allows computation of theoretical performance characteristics. In particular we have devised models for cellular systems with the following features: single and multiple call platforms and hand-offs, priority and no priority for hand-off calls, mixtures of platforms having different mobility characteristics, lost call systems, delayed call systems, combined delay and loss systems, platform limits and quotas, channel limits and quotas, a broad class of platform mobility characteristics, and mixed macro and micro-cell configurations [1] - [9]. A central problem in traffic performance of mobile cellular communications is *hand-off.* The reader should note the nature of the hand-off issues which are considered here where the focus is on *resource allocation and availability*. A second facet of the hand-off problem is *how the hand-off process is initiated.* This has received some attention in the literature [10] -[14]. In addition, [15] and [16] consider the *exchange of supervisory messages* that are required for hand-offs. An approach to combining these various aspects of the problem is suggested in [6]. Incorporating intelligent network architectural features and resources in mobile telecommunications is discussed in [17]. Additional related work includes [18] - [24].

In this paper, we mathematically formulate the problem outlined (in the first paragraph) above in a format that makes it amenable to solution using the approach that we are developing. In particular we consider a cellular system with mixed platform and call types. As a communicating platform moves out of range of the base station to which it is linked, a hand-off to an alternative base must be made. A hand-off attempt which fails results in a forced termination of the session. Since forced terminations are more obtrusive than (new) call blocking we also consider priority for hand-off attempts using a cut-off priority scheme. Other priority schemes are possible. We identify a state characterization for the problem and we show how our framework can be applied. The model is used to generate theoretical performance characteristics. These show carried traffic, blocking probability, and forced termination probability for each platform type and for each call type. The example results are discussed.

DESCRIPTION OF THE ANALYTICAL APPROACH

The approach that we use requires a suitable state characterization which allows the problem to be considered in the framework described in [3] - [6]. A cell state is specified by a concatenation of integer state variables. Permissible states correspond to those concatenations whose elements satisfy certain constraints determined by the system resources. The underlying driving processes are identified. In the present context these include new call arrivals, call completions, hand-off call arrivals to a cell and hand-off departures from a cell. These processes are in general multidimensional. In the problem under discussion, for example, each of the driving processes is subdivided according to platform type and call type. Markovian assumptions for the driving processes are invoked. Because of hand-offs, the states of adjacent cells are coupled. A more complete characterization of the system would require consideration of the *system state* as a concatenation of all the cell states. The dimensionality of the problem is prohibitive even for modest system parameters [4]. As part of the overall methodology this difficulty is circumvented by use of a *conservation law* which relates the mean hand-off arrival rates (to a cell) to corresponding mean hand-off departure rates from a cell. This allows a decoupling of driving processes and a reduction in the number of states needed to characterize performance. In particular it allows characterization of any cell without the mathematical encumbrance of accounting for the states of all cells simultaneously. The (cell) state transition flows are related to the underlying driving processes and the equilibrium state probability flow balance equations are formulated.

We devised a numerical algorithm to solve the resulting system of equations for the equilibrium state probabilities. Our algorithm used three levels of nested iterations based on Gauss-Seidel iteration, the bisection method, and successive substitutions. Details are given in [6]. Once the state probabilities are found for given system parameters, the various traffic performance measures are calculated.

PROBLEM DESCRIPTION

We present a brief description of the problem and then proceed with the mathematical formulation. We consider a large geographical region covered by cells that are defined by proximity to designated network gateways. The region is traversed by large numbers of mobile platforms that are of several types. Platform types differ primarily in their mobility characteristics. Pedestrians with hand-held devices and autos with cellular phones are example platform types. Communication with a mobile platform is via a wireless base station. This is a gateway node (or several nodes) which define and are identified with each cell. These base stations (or gateways) allow communications between the system's radio segment and its fixed or wireline segment. We use the word *cell* in its generic sense to describe a spatial region serviced by a wireless gateway. The essential problem considered here is the same whether this is a macro-cell, micro-cell, pico-cell, zone, sector, or satellite beam. The particular configuration is not very important in terms of demonstrating the applicability of the approach. Example configurations to which the analysis applies are suggested in [3] and [4]. In the development presented here, a platform can support at most one call. However, there are different call types each of which generally requires a different amount of communications resources when supported by the network. One of the resources is bandwidth (measured in appropriate units such as channels). Each supported call also needs access to a modem/radio at the supporting gateway. Buffer space, call supervising processors such as mobility managers/trackers, and directional antenna beam steering processors are examples of other resources that may be required.

The wireless links can employ radio, optical, infra-red or acoustic signaling, and the multiple access scheme can be FDMA, TDMA, CDMA, or any hybrid. Channels can be organized using any mixture of frequency, time, space, and code division techniques - including hybrid schemes. However, channels that are simultaneously used in the same zone must be sufficiently separated by the time-space-frequency-code multiplex to allow acceptable communications on each. Circuit or virtual circuit switching is used so that the system operates by reserving some communications resources for any call (session) in progress.

We assume that there are G platform types, labeled g=1,2,...G, and that there are C channels assigned to each gateway. A cut-off priority scheme is used. That is, each gateway keeps C_h channels for use by hand-off calls. Specific channels are not reserved, just the number. In this way hand-off calls have access to more channels than new calls do, and increasing C_h provides increasing priority for hand-offs at the expense of blocking new call originations. Similarly, for k=1,2,...K-1, each gateway has R_k units of resource type k, of which the amount R_{hk} is held for use by hand-off calls. Specific resources of each type are not held, only the amounts (of each type). Because hand-off calls have access to more resources than new call originations have, they receive (cut-off) priority. Thus, forced termination and blocking performance can be exchanged. For convenience we assume that the system is homogeneous. That is cells, gateways, and the respective driving processes that impinge upon each are statistically identical. Non-homogeneous systems can be considered essentially in the same way [3],[6]. At each gateway there may be channel *quotas*, so that no more than some given number of channels can be occupied by platforms of any given type at the same time in the same cell. Additional constraints on other network resources such as buffer space, directional radio beams, and call supervising processors may be present as well. Besides quotas, which constrain use of network resources according to platform and/or call type, there are also *limits* on the amounts of resources available at a gateway. There can be I call types, labeled i=1,2,...I, and K kinds of resources labeled k=0,1,2,...K-1.

NOTE: To characterize *resource* issues, in the following we use an *upper case italic* font to denote *resources*, an *upper case regular* font to denote *resource limits*, and an *upper case script* font to denote *resource quotas*.

EXAMPLE PROBLEM STATEMENT - SINGLE CALL HAND-OFFS, CUT-OFF PRIORITY, MIXED PLATFORM TYPES, MIXED CALL TYPES.

There are G types of mobile platforms, indexed by g=1,2,...G.
No platform can support more than one call at any given time. There are I types of calls, indexed by i=1,2,...I.
There are K types of resources to support calls. These resources are labeled, $\mathcal{R}_k$, k=0,1,2,...K-1.
The new call origination rate *from a non-communicating g-type platform* is denoted $\Lambda(g,i)$.
We define $\alpha(g,i)= \Lambda(g,i) / \Lambda(1,i)$.
The number of *non-communicating* g-type platforms in any cell is denoted $v(g,0)$. The total rate at which new calls of type i are generated from platforms of type g *in a cell* is denoted $\Lambda_n(g,i)$. Thus, $\Lambda_n(g,i) = \Lambda(g,i) \cdot v(g,0)$.
It is assumed that $v(g,0) >> C$, so that overall the population of non-communicating g-type platforms in a cell generates $\Lambda_n(g)$ calls per second, where $\Lambda_n(g) = \Sigma_i \Lambda_n(g,i)$. This *infinite* population model is consistent with a large population of non-communicating g-type platforms in each cell, only a small fraction of which is served at any time. This is, in fact, usually the case.

CHANNEL LIMIT: Each cell or gateway has C channels.
RESOURCE LIMITS: Each cell or gateway has R_k units of resource k.

NOTE: Channels are in fact just another resource. So we can consider for example, R_0=C. *But in the present discussion, for the sake of clarity, we consider the channel resource by name.*

CHANNEL QUOTAS: At any gateway, the maximum number of channels that can be simultaneously used by g-type platforms with calls of type i, is $\mathcal{C}(g,i)$. Similarly, there may be quotas on resource use based only on platform type and on call type. For example the maximum number of channels that can be simultaneously used by g-type platforms is $\mathcal{C}(g,*)$ and the number of channels that can be simultaneously used by i-type calls is $\mathcal{C}(*,i)$.

RESOURCE QUOTAS: At any gateway, the maximum number of resources of type k, that can be simultaneously used by g-type platforms with calls of type i, is $\mathcal{R}_k(g,i)$. The k-th resource quota for g-type platforms is $\mathcal{R}_k(g,*)$, and that for i-type calls is $\mathcal{R}_k(*,i)$.

CUT-OFF PRIORITY: C_h channels in each cell are reserved for hand-off calls. Specific channels are not reserved, only the number C_h. New calls (of any type) will be blocked if the number of channels in use is C-C_h or greater. Hand-off attempts will fail if the number of channels in use is C. Similarly, certain amounts of each of the k resource types may be reserved for hand-off calls. Let R_{hk} denote the amount of resource k that is reserved for use by hand-off calls. Then, new calls of any type will be blocked if the amount of resource k in use is R_k - R_{hk}, but hand-off calls will have access to the full complement of resources of each type.

We define the unencumbered call (session) duration as the time a call would remain in progress if it were not forced to terminate. For a call of type i this is taken as a negative exponentially distributed (ned) random variable, $T(i)$, having a mean $\bar{T}(i)$.

The dwell time in a cell for a g-type platform is a ned random variable, $T_D(g)$ having a mean $\bar{T}_D(g)$.

The problem is to calculate relevant performance characteristics, including, for each platform type, and for each call type. Of special interest are blocking probability, hand-off failure probability, forced termination probability, carried traffic (or bandwidth utilization). Notice that we consider blocking probability to be the average fraction of ***new*** call originations that are denied access to a channel. Hand-off failure probability is the average fraction of hand-off "needs" that fail to gain access to a channel in the target zone. Forced termination probability is the probability that a call suffers a hand-off *attempt* failure some time in the "lifetime" of the call. *Hand-off activity*, which is the average number of hand-off attempts for a call that receives service, can also be determined.

The mathematical analysis is similar to that used in some of our previous work [3] - [6]. The differences are in definition of the state variables and state space, identification of the driving processes, and formulation of the equations that specify the state probability transition flows. In what follows we emphasize those aspects of the mathematical development that have important differences.

STATE CHARACTERIZATION

First consider a *single* cell. We define the state (of a cell) by a sequence of non-negative integers. This can be conveniently written as G n-tuples.

$$\begin{array}{l} v_{11}, v_{12}, v_{13}, \cdots v_{1I} \\ v_{21}, v_{22}, v_{23}, \cdots v_{2I} \\ \vdots \quad \vdots \quad \vdots \qquad \vdots \ \vdots \\ v_{g1}, v_{g2}, v_{g3}, \cdots v_{gI} \\ \vdots \quad \vdots \quad \vdots \qquad \vdots \ \vdots \\ v_{G1}, v_{G2}, v_{G3}, \cdot\cdot v_{GI} \end{array} \qquad (1)$$

where v_{gi} { $g=1,2,\ldots G$; $i=1,2,\ldots I$ } is the number of platforms of type g that have a call of type i in progress. It is convenient to order the states using an index $s=0,1,2,\ldots s_{max}$. Then the state variables v_{gi}, can be shown explicitly dependent on the state. That is, $v_{gi} = v(s,g,i)$. Let $r_0(s,g,i)$ denote the number of channels used by g-type platforms with i-type calls in progress when the cell is in state s. Also let $r_k(s,g,i)$ denote the amount of resources of type k that is used by g-type platforms with i-type calls in progress when the cell is in state s.

Then the following characteristics can be determined for a cell (gateway) that is in state, s.

The number of channels being used by g-type platforms is

$$c(s,g,*) = \sum_{i=1}^{I} r_0(s,g,i) \qquad (2)$$

The number of channels being used by i-type calls is

$$c(s,*,i) = \sum_{g=1}^{G} r_0(s,g,i) \qquad (3)$$

The total number of channels in use is

$$c(s) = \sum_{g=1}^{G} c(s,g,*) \; . \qquad (4)$$

Generally, for a resource of type k, let $r_k(s,g,i)$ denote the quantity of resource (of type k) that is being used by g-type platforms with i-type calls when the cell is in state, s. Then the amount of resource of type k that is used by g-type platforms at a cell in state s is given by

$$r_k(s,g,*) = \sum_{i=1}^{I} r_k(s,g,i) \; . \qquad (5)$$

It is reasonable (but not necessary) that $r_k(s,g,i)$ be proportional to $v(s,g,i)$. That is, $r_k(s,g,i) = r_k(g,i) \cdot v(s,g,i)$, in which $r_k(g,i)$ is the amount of resource of type k used by *each* g-type platform with an i-type call in progress. If this is the case, $r_k(s,g,*)$ is a linear combination of certain state variables. For example

$$r_k(s,g,*) = \sum_{i=1}^{I} r_k(g,i)\, v(s,g,i) \; . \qquad (6)$$

The quantity of resources of type k being used by calls of type i is

$$r_k(s,*,i) = \sum_{g=1}^{G} r_k(s,g,i) \; . \qquad (7)$$

The total quantity of resources of type k that is being used is

$$r_k(s,*,*) \quad = \quad \sum_{g=1}^{G} r(s,g,*,k) \quad . \qquad (8)$$

Permissible states correspond to those sequences for which all constraints are met. For example, we have a *channel limit* which requires, $c(s) \leq C$, *channel quotas* (based on platform type) that require, $c(s,g,*) \leq \mathcal{C}(g,*)$, for $g=1,2,...G$; *and channel quotas* (based on call type) that require $c(s,*,i) \leq \mathcal{C}(*,i)$. These are in addition to the combined platform-call quotas, $c(s,g,i) \leq \mathcal{C}(g,i)$.

In addition there are *resource limits* that (for any permissible state, s) require

$$r_k(s,*,*) \quad \leq \quad R_k\,, \qquad k=1,2,...K-1, \qquad (9)$$

resource quotas on platform types that require

$$r_k(s,g,*) \quad \leq \quad \mathcal{R}_k(g,*)\,, \qquad g=1,2,...G;\ k=1,2,...K-1, \qquad (10)$$

resource quotas on call types that require

$$r_k(s,*,i) \quad \leq \quad \mathcal{R}_k(*,i) \qquad i=1,2,...I;\ k=1,2,...K-1, \qquad (11)$$

and combined platform-call quotas that require

$$r_k(s,g,i) \quad \leq \quad \mathcal{R}_k(g,i) \qquad \begin{array}{l} g=1,2,...G;\ k=1,2,...K-1; \\ i=1,2,...I. \end{array} \qquad (12)$$

There can also be additional limit and quota constraints. For example, the total number of communicating platforms of type g that can be supported at a cell at any time can be constrained by V_g, $g=1,2,....G$. If we let $w(s,g)$ denote the total number of g-type communicating platforms when the cell is in state s, we have

$$w(s,g) \quad = \quad \sum_{i=1}^{I} v(s,g,i) \qquad (13)$$

along with a constraint (on the state space) such that for any permissible state, s, the inequality $w(s,g) \leq V_g$ is satisfied. The set of permissible cell states corresponds to all possible sequences of variables of the form (1) which satisfy all of the limit and quota constraints. When the channel and resource contraints can be written as linear combination of the state variables, the set of permissible states is bounded by a set of hyperplanes in the multidimensional state space [21]. The dimension of this space is $G \cdot I$.

The general framework used in some of our previous work was extended to solve this problem. The underlying driving processes for this problem are new call arrivals, (successful) call completions, and the dwell time(s) in a cell for each platform type. The mean hand-off arrival rates to a cell for calls of type i on platforms of type g is dependent on these other processes. A thorough formulation which accounts for direct coupling of ***cell state*** transitions of adjacent cells that are involved in a hand-off is circumvented by relating the average hand-off arrival and departure rates. This avoids having to deal with an enormously (and usually intractably) larger number of ***system states*** represented by sequences of all simultaneously possible ***cell states***. Both *homogeneous* and *non-homogeneous* cellular systems can be treated in a similar way. The result is that we only have to consider a ***single cell*** and deal with the number of states needed to characterize its behavior [3], [4], [6], [9].

The solution approach as in [6], is to identify permissible cell states, relate the parameters of the underlying driving processes to the state probability transition rates, determine the state probability flow balance equations, and solve the resulting set of simultaneous nonlinear equations for the state probabilities. From these, the performance measures can be calculated. The approach requires an iterative solution because of the coupling between the underlying hand-off departure and hand-off arrival driving processes.

To find the statistical equilibrium (cell) state probabilities, we write the flow balance equations for the states. These are a set of smax+1 simultaneous equations for the unknown state probabilities, p(s). They are of the form

$$\begin{aligned} &\sum_{j=0}^{s_{max}} q(i,j)\ p(j) = 0 \quad , \qquad i = 0,1,2,\ldots smax-1 \\ &\sum_{j=0}^{s_{max}} p(j) = 1 \quad , \end{aligned} \tag{14}$$

in which, for i≠j, q(i,j) represents the net transition flow into state i from state j, and q(i,i) is the total transition flow out of state i. These equations express that in statistical equilibrium, the net probability flow into any state is zero and the sum of the state probabilities is unity. The index, i, in (14) can run up to smax to provide a redundant set that may be helpful in numerical computation. The state transition flows, q(i,j) for this problem can be found from the underlying driving processes in a manner similar to that described in [3] and [6].

RESULTS

The approach was used to consider a problem with G=3 platform types, stationary platforms, low speed platforms, and high speed platforms. (Perhaps corresponding to stationary pedestrians, moving pedestrians and vehicles.) Mean dwell times were taken as ∞, 1000 s, and 200 s respectively. High speed platforms were assumed to move 5 times faster than low speed platforms. In addition we considered I=2 call types, low bandwidth calls, and high bandwidth calls. (Perhaps corresponding to low speed data, and voice plus high speed data.) High bandwidth calls were assumed to require 3 bandwidth units (channels) each, while low bandwidth calls require only one bandwidth unit each. The mean unencumbered session duration for all calls was taken as 100 s. The only resource considered was bandwidth (measured in channels). No quota constraints were considered. The only resource limit for this example is the number of channels, C, which was taken as C=24. Channel access can be any FDMA or TDMA arrangement or hybrid. With proper interpretation the model also represents CDMA systems. The parameter C would then be either the amount of base station resources (modems, codecs) that are available or the maximum number of users that can be accommodated at a base because of interference limitations (whichever is smaller) [22].

In the example chosen to demonstrate the approach, new call arrival rates for all *platform types* were assumed to be the same, and new call arrival rates for all *call types* were assumed to be the same. The parameter choices were taken only to demonstrate the applicability of the modeling approach and framework. The reader should not infer any loss in generality of the approach because of the example presented here.

Figure *1 shows overall blocking and forced termination probabilities for different platform types plotted as a function of demand (from a single platform). The possible exchange (increase) of blocking probability for a decrease in forced termination probability can be seen as C_h increases from 0 to 4. Of course blocking and forced termination probabilities increase as demand increases. The overall forced termination probabilities were determined by calculating the forced termination probability for platform-call types (g,i) and using a weighted average according to the fraction of carried traffic that is of type (g,i). Figure *2 shows *forced termination probabilities* for high speed and low speed platforms on a similar plot. The improvement attainable by increasing C_h is shown. Figure *3 shows *blocking probabilities* for different call types. Since high bandwidth calls need more resources to obtain service, they experience greater blocking probability when other parameters are the same. Also the increase in blocking (for each call type) as C_h is increased to favor hand-off calls can be seen. Figure *4 shows *forced termination probabilities* for different call types on a similar plot. The improvement obtainable by increasing C_h can be seen. Figure *5 shows bandwidth utilization by various traffic components as a function of call demand for several values of C_h, (C_h=0,2,4). Figure *6 shows blocking and forced termination probabilities as a function of dwell time means. Because the dwell times are held to a fixed ratio, one can consider the abscissa, which is labeled as dwell time, to be proportional to cell size (radius). The figure shows the impact on performance measures as the abscissa (envisioned either as dwell time or as cell radius) increases.

CONCLUSIONS

We have further extended the methodology of our previous work in several important directions. Specifically, by using an appropriate definition of state variables and formulation of the constraint equations that define the boundaries of the resulting state space, we show that the approach can be used to devise analytically tractable models for cellular communication systems that include a mixture of platform types and a mixture of services in the same system. We consider that the various services will in general require different types and amounts of various resources at each gateway. The effects of limits and quotas on the availability and use of these resources is included in the model. Priority access to the underlying resources for handoff calls is also considered. Again we see that the approach is rich enough to include many aspects of the complex physical context, yet it allows computational results to be relatively easily obtained without the need for extensive simulation studies. Example performance results are obtained showing traffic performance characteristics for a system with three types of mobile platforms (stationary, low speed, and high speed) and two types of services (requiring low bandwidth and high bandwidth) within a system that can provide priority access for handoffs. The class of problems that are discussed will undoubtedly become increasingly important as wireless, cellular, and personal communications services continue to spread rapidly in the years ahead.

REFERENCES

[1] D. Hong and S.S. Rappaport, "Traffic model and performance analysis for cellular mobile radiotelephone systems with prioritized and non-prioritized hand-off procedures," IEEE Trans. Vehic. Technol., vol. VT-35, pp. 77-92, Aug. 1986.

[2] D. Hong and S.S. Rappaport, "Priority oriented channel access for cellular systems serving vehicular and portable radio telephones," IEE (British) Proc., Part I, Commun., Speech and Vision, vol. 136, pt. I, no. 5, pp. 339-346, Oct. 1989.

[3] S.S. Rappaport, "The multiple-call hand-off problem in high-capacity cellular communications systems," IEEE Trans. Vehic. Technol., vol. 40, no. 3, pp. 546-557, Aug. 1991 .

[4] S.S. Rappaport, "Models for call hand-off schemes in cellular communication networks," in *Third Generation Wireless Information Networks*, ed. by S. Nanda and D.J. Goodman, Kluwer Academic Publishers: Boston, 1992, pp. 163-185.

[5] S.S. Rappaport, "Modeling the hand-off problem in personal communications networks," Proc. IEEE Vehicular Technology Conference, VTC '91, St. Louis, May 1991, pp. 517-523.

[6] S.S. Rappaport, "Blocking, hand-off and traffic performance for cellular communication systems with mixed platforms," IEE (British) Proceedings, Part I, Communications, Speech and Vision, Oct. 1993, vol. 140, no. 5, pp.389-401. See also: S.S. Rappaport, "Blocking, hand-off and traffic performance for cellular communication systems with mixed platforms and imperfect hand-off initiation," CEAS Technical Report no. 660, College of Engineering and Applied Sciences, State University of New York, Stony Brook, New York 11794-2350, November 26, 1991. Appendix.

[7] C. Purzynski and S.S. Rappaport, "Traffic Performance Analysis for Cellular Communication Systems with Mixed Platform Types and Queued Hand-Offs," Proc. IEEE Vehicular Technology Conference, VTC '93, Secaucus, New Jersey, May 18-20, 1993, pp. 172-175.

[8] L-R. Hu and S.S. Rappaport, "Micro-cellular communication systems with hierarchical macrocell overlays," Workshop Record, Winlab Workshop on Third Generation Wireless Information Networks, Rutgers University Winlab Workshop '93, New Jersey, Oct. 19-20, 1993., pp. 143-173.

[9] S.S. Rappaport, "Communications traffic performance for cellular systems with mixed platform types," in *Wireless Communications: Future Directions,* ed. by J. Holtzman and D.J. Goodman, Kluwer Academic Publishers: Boston, 1993, pp. 177-200.

[10] A. Murase, I.C. Symington, and E. Green, "Handover criterion for macro and microcellular systems," Proc. IEEE Vehicular Technology Conference, VTC '91, St. Louis, May 1991, pp. 524-530.

[11] S.T.S. Chia, "The control of handover initiation in microcells," Proc. IEEE Vehicular Technology Conference, VTC '91, St. Louis, May 1991, pp. 531-536.

[12] M. Gudmundson, "Analysis of handover algorithm," Proc. IEEE Vehicular Technology Conference, VTC '91, St. Louis, May 1991, pp. 537-542.

[13] O. Grimlund and B. Gudmundson, "Handoff strategies in microcellular systems," Proc. IEEE Vehicular Technology Conference, VTC '91, St. Louis, May 1991, pp. 505-510.

[14] J.M. Holtzman and R. Vijayan, "Analysis of hand-off algorithms using non-stationary signal strength measurements," Proc. IEEE Globecom '92, Orlando, Dec. 1992, pp. 1405-1409.

[15] K.S. Meier-Hellstern and E. Alonso, "The use of SS7 and GSM to support high density personal communications," in *Wireless Communications: Future Directions,* ed. by J. Holtzman and D.J. Goodman, Kluwer Academic Publishers: Boston, 1993, pp. 55-68.

[16] B. Jabbari, "Signalling System Number 7 for Fixed and Mobile Networks," Tutorial #405, IEEE International Communications Conference, ICC '92, June 1992.

[17] P.C. Mason, A.N. Brydon and J.M. Cullen, "UMTS handover requirements in the context of an intelligent network architecture," Proc. Symposium on Personal, Indoor and Mobile Radio Communications, Yokohama, Japan, Sept. 9-11, 1993, pp. 715-720.

[18] D.C. Cox and D.O. Reudink, "Layout and control of high-capacity systems," Chap. 7 in *Microwave Mobile Communications*, ed. by W.C. Jakes, Jr., Wiley:New York, 1974, pp. 545-622.

[19] S.A. El-Dolil, W-C. Wong, and R. Steele, "Teletraffic performance of highway microcells with overlay macrocell," IEEE J. Select. Areas Commun., vol. 7, no. 1, pp. 71-78, Jan. 1989

[20] R. Guerin, "Queueing-blocking system with two arrival streams and guard channels," IEEE Trans. Commun., vol. COM-36, pp. 153-163, Feb. 1988.

[21] J.M. Aein and O.S. Kosovych, "Satellite capacity allocation," Proceedings of IEEE, vol. 65, no. 3, pp. 332-342, March 1977.

[22] A.M. Viterbi and A.J. Viterbi , "Erlang capacity of a power controlled CDMA system," IEEE Journal on Selected Areas in Communications, vol. 11. no. 6, Aug. 1993, pp. 892-900.

[23] S.S. Rappaport, "Traffic performance of cellular communication systems with heterogeneous call and platform types," Proc. IEEE International Conference on Universal Personal Communications, Ottawa, October 12-15, 1993, pp. 690-695.

[24] S. Tekinay, B. Jabbari, and A. Kakaes, "Modeling of cellular communication networks with heterogeneous traffic sources," Proc. IEEE International Conference on Universal Personal Communications, Ottawa, October 12-15, 1993, pp. 249-253.

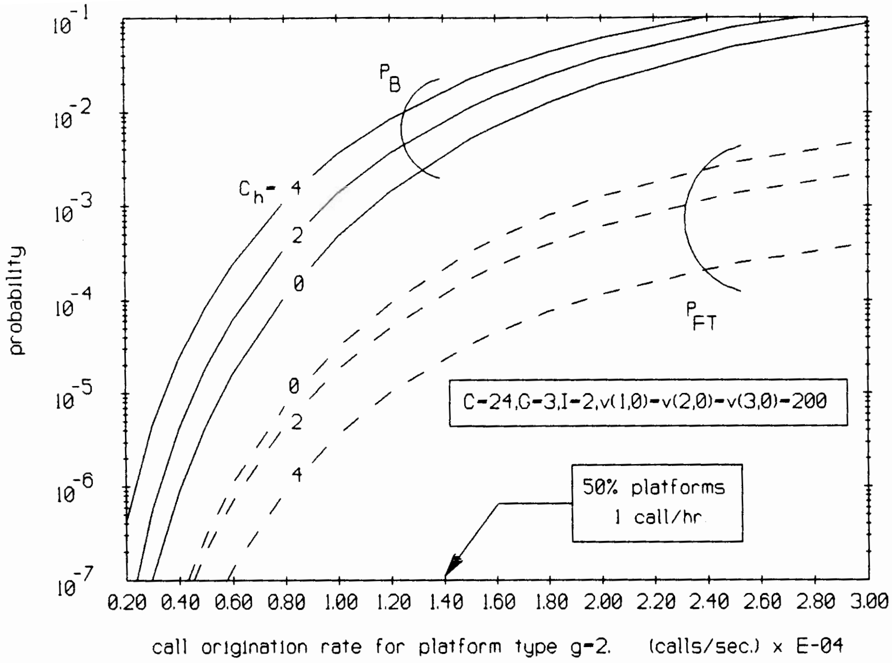

Figure *1. Overall Blocking and Forced Termination Probabilities

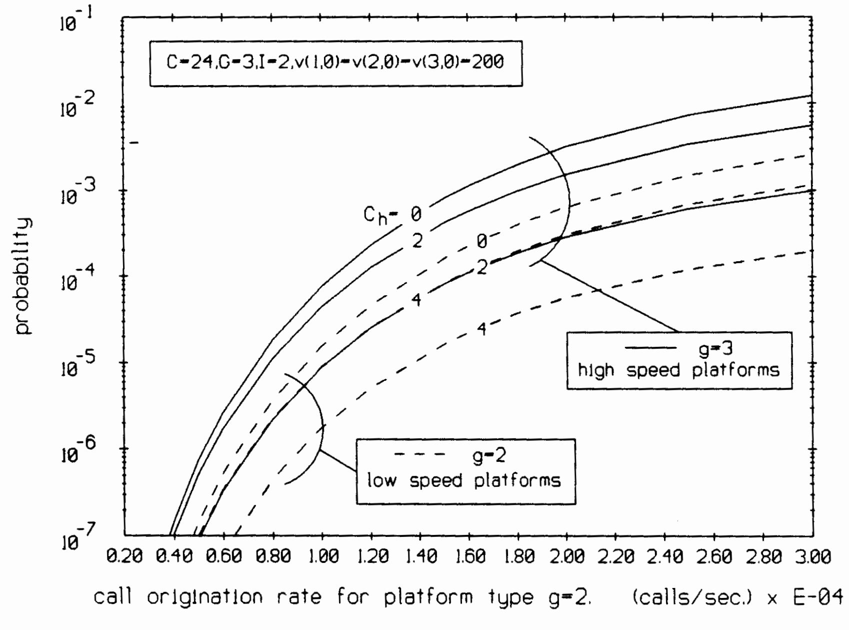

Figure *2. Forced Termination Probabilities for Different Platform Types

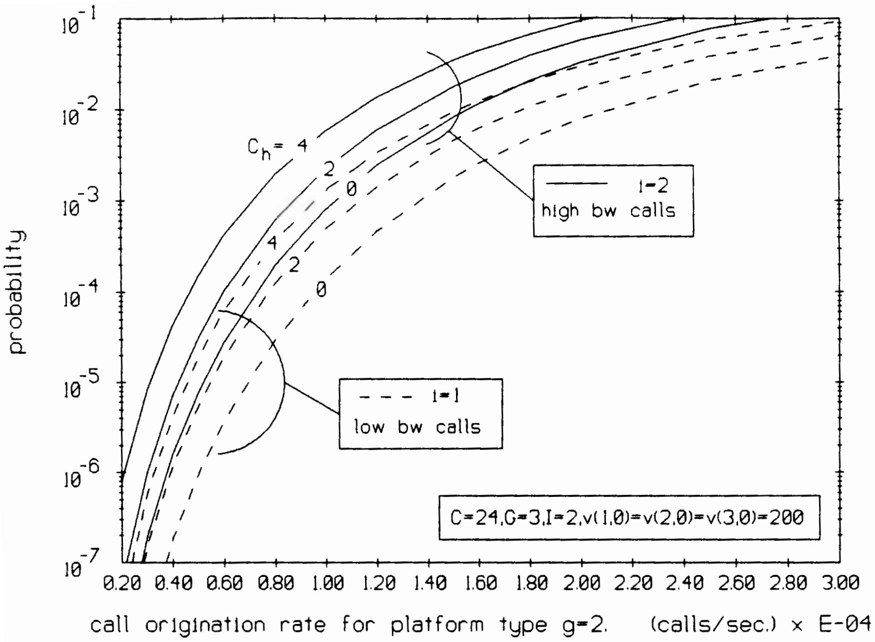

Figure *3. Blocking Probabilities for Different Call Types

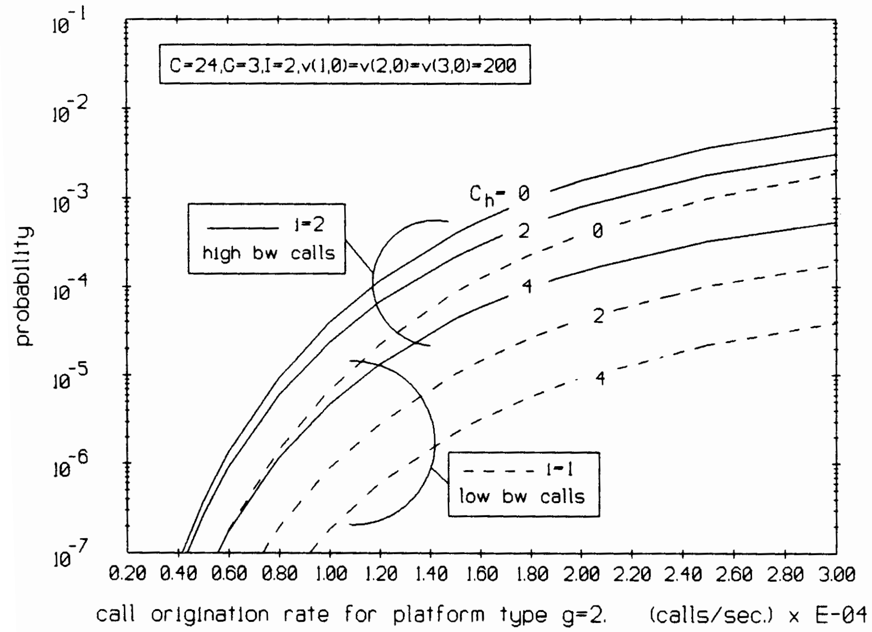

Figure *4. Forced Termination Probabilities for Different Call Types

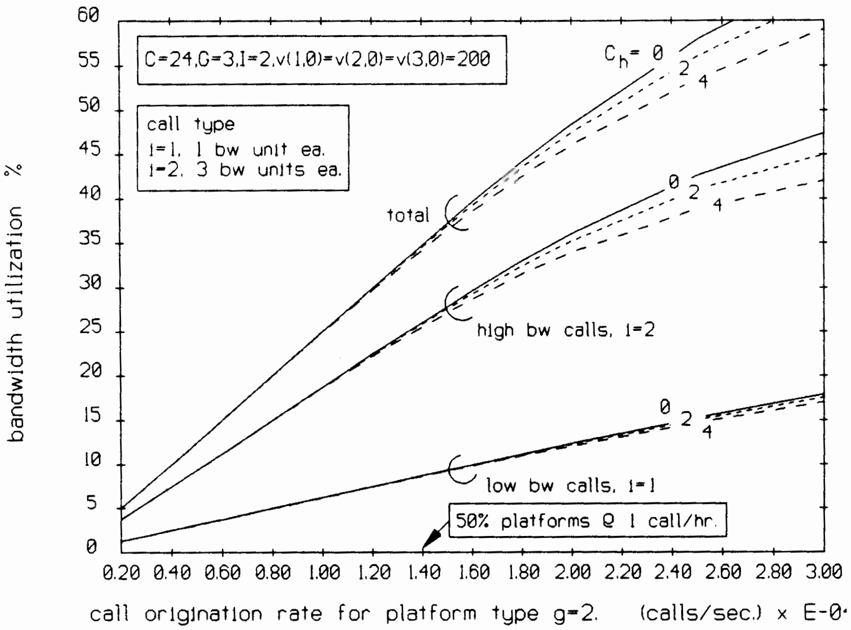

Figure *5. Bandwidth Utilization for Various Traffic Components (C_h 0,2,4)

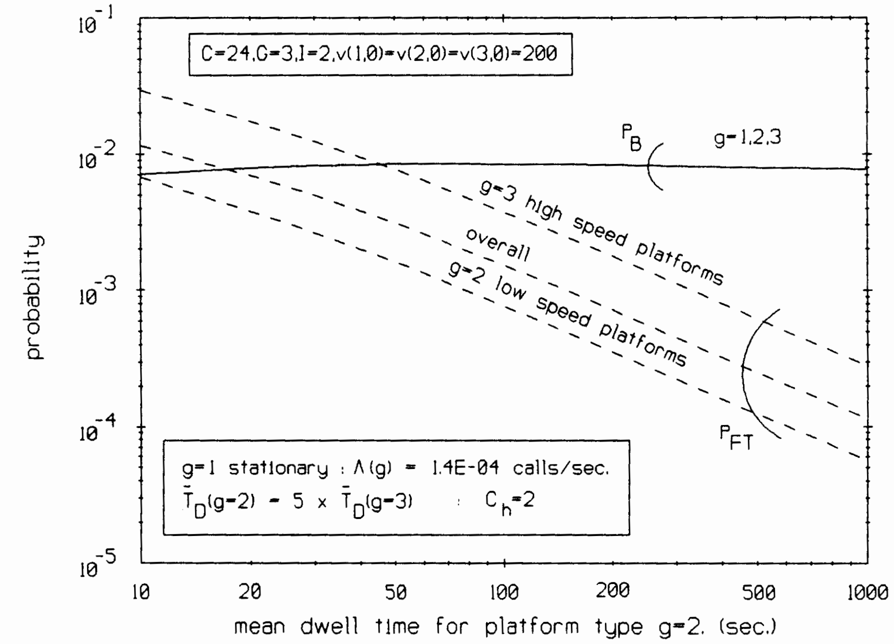

Figure *6. Blocking and Forced Teminations Depend on Dwell time Means (C_h =2)