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FREQUENCY HAND-OFF STRATEGIES IN CELLULAR LAND-MOBILE RADIO COMMUNICATION SYSTEMS

by

Esper Nadim Bitar

A thesis
Presented to the School of Graduate Studies
in partial fulfillment of the requirements
for the degree of
Master of Applied Sciences
in
The Department of Electrical
Engineering, Faculty of Sciences
and Engineering

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ABSTRACT

In cellular land-mobile radio-communication systems, mobiles may often traverse cell boundaries and move so far away from their local base stations that signal strength becomes inadequate during a call. Two solutions will be presented in this thesis in order to resolve this issue. The first solution is the hand-off procedure. Here, calls in progress, should be serviced by new voice-channels as they enter an adjacent cell. If such channels are available, the calls continue; otherwise they are terminated prematurely. The essense of the frequency hand-off procedure is to study methods for reducing the probability of these premature call terminations. In the second solution, by increasing the transmitter power the signal strength is increased, which helps eliminate problems of local attenuation. However, this creates the problem of co-channel interference.

This thesis presents a computer simulation study of a cellular, high capacity, land-mobile radio communications system with and without frequency hand-off stategies. We assume that there are cell boundary crossings for calls-in-progress. In the hand-off procedure, we have studied several strategies where channels are specifically reserved for hand-offs. These strategies have been evaluated in terms of the new-call rejection rate and the rate of premature terminations of calls in progress. In the second method, we have found the additional base station transmitter power required to service all the calls in progress without switching them to new channels. As well, the co-channel interference introduced by this method has been evaluated and studied by varying the additional transmission distance with different partitions of channels while maintaining a grade of service of 2%. Finally this co-channel interference was studied for different traffic intensities.

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CONTENTS

Appendix page

LIST OF FIGURES

Chapter I

INTRODUCTION

The ultimate objective of mobile communications is to enable any mobile user to communicate instantly and easily with anyone else.

Mobile telephone systems have been in use in the United States, Canada and other countries, for nearly 35 years. The modern systems of today are far superior to the earlier devices and offer advantages in communication ease as well as in size, weight and portability. The early radiotelephones were tube-type. Their operation necessitated the calling of a mobile operator. Basically, the user simply transmitted to a central operator station. Once in contact with the mobile operator, the various connections were made by hand, patching the mobile transmissions into the standard phone line. The voice from the person being called was patched from the phone line into a transmitter at the operator's station which broadcast this information back to the mobile receiver. Today, almost all radiotelephones in use feature completely solid-state circuit design, with integrated circuits used, wherever possible, instead of discrete devices. The principle of today's radiotelephone communication systems is very similar to the earlier one, except that the mobile operator is sometimes dispensed with. In some systems, a dial tone is heard by the mobile station when a channel is clear and a tone encoded (push-botton pad) is punched with the proper number combination. All of this is done by the mobile caller. Electronic circuitry at the central office automatically handles the patching work. It can be seen that, from a user's point of view, the mobile radiotelephone operation is about as simple as dialing a number from your home [28,2].

The last two decades have seen enormous increases in demand for mobile communication services. The growth in demand is projected to continue at a rate of 15 percent per annum. Various techniques have been proposed to cope with this increasing demand for mobile radio service. Among them, the cellular mobile radio is highly favoured [8]. In fact it has been considered of such importance that the Federal Communication Commussion (FCC) in the U.S.A. has allocated a 75MHZ bandwidth in the 800MHZ band to the common-carriers who would adopt the cellular structure to provide the public with mobile radio communication services. Out of the 75MHZ, 64MHZ is allocated for the land-mobile telephone service with the remaining 11MHZ reserved for the air-ground service. Developmental cellular systems have been put into operation in Chigago and Tokyo by AT&T and Nippon companies respectively [7,21].

Appreciation of the potential for cellular technology requires an understanding of existing mobile telephone systems and their inherent limitations.

In a conventional mobile telephone system the mobile units are frequency agile (i.e.,capable of operating on a range of channels) transceivers, and typically operate at 50-100 Watts of output. The base stations operate on the scale of tens or hundreds of watts. In "automatic" systems (the Bell system uses the terms IMTS for Improved Mobile Telephone Service), to initiate a call, the mobile station must first locate an idle radio channel. Then signals to and from the mobile unit are sent and received by a central base station, consisting of an antenna, a relatively high- power transmitter, and a receiver. In most systems, the base station has adequate power to send and detect signals over a distance of 20-50 miles.

In cellular mobile radio systems (CMRS), each cell base station broadcasts a relatively low power signal (100 watts is the maximum permitted by the FCC) on a specific set of pre-assigned frequencies. This signal is intended for communication with mobile units only within that particular cell. Therefore, transmission from a given cell is detectable over a shorter distance than in conventional systems, and potential interference is reduced. As well, the mobile units themselves are low power, with a maximum allowed output of seven watts, thereby further reducing the potential for interference. But this creates a problem which relates to the fact that when a mobile unit moves far away from the local base station, the signal strength becomes inadequate during a call. Indeed,the low-power nature of the various transmitters makes signal degradation more likely, and thus increases the probability that a call will be "lost" [22].

To solve this problem, two solutions have been proposed. First, increased signal strength can be achieved simply by greater transmitter power. This is, in fact, a feature of the AMPS system in Chicago, which employs variable-power transmitters at both the base station and the mobile units. This helps to eliminate problems of local attenuation, as both base station and mobile transmitters automatically adjust power output to maintain signal strength. Second, the mobile's movement into a new cell may require the need for a new base station, and the mobile telephone switching office (MTSO) must switch the call to a new channel associated with the new base station. This is called the "hand-off" procedure.

In this thesis we are concerned with the problem of frequency hand-offs in a cellular structured, high-capacity land-mobile radio communications system, and the problem of co-channel interference produced when the transmitter power of the base stations and the mobile units, is increased to service the calls-in-progress. This thesis first presents a simulation study of methods for reducing the probability of premature terminations of the calls in hand-off status. We also study the level of the base station's transmitter power needed to service all calls in the system without switching any of them from the service of one base station to another.

In chapter 2, various terms used in our study are introduced. The Erlang-B and Erlang-C as well as the Blocked-Calls-Held service discipline are discussed, and the corresponding queueing models, assuming a fixed number of servers, are presented.

Chapter 3 deals with the summary of the basic concepts, system considerations and system performance characteristics of a cellular-structured radio mobile system.

Chapter 4 discusses the basic channel assignment schemes. A way to allocate the radio channels of the assigned frequency band to the geographical cells is introduced. Three general categories of this method, using a fixed, a dynamic or a hybrid channel assignment schemes in a given cell, are treated from the standpoint of layout options and traffic handling capabilities.

Chapter 5 is concerned with the hand-off status of calls, system procedures, as well as the different channel assignment schemes for the hand-off calls.

The main part of this thesis lies in the simulation study of the frequency hand-off strategy in a cellular structured, high capacity land-mobile radio system with Erlang-B service. A description of the simulated system is given in chapter 6. Also, the increasing transmitter power simulation method will be discussed in this chapter and different simulation flow-charts will be presented.

Chapter 7 is addressed to the simulation results, regarding the performance of both methods concerning a system which allows the calls to cross the cell boundaries. The results of reserving channels for the hand-off calls, as well as the results of letting the boundary-crossing calls to keep being serviced by the same channels, will be discussed.

Finally, chapter 8 presents the general conclusions and remarks of this thesis. A detailed GPSS description of the simulation models, as well as the computer program, is included in the appendices.

Chapter II

TRAFFIC ANALYSIS FOR MOBILE RADIO SYSTEMS

2.1 INTRODUCTION

The term traffic used throughout the context of this thesis refers to telephone traffic rather than vehicular traffic. The study of traffic is a well-established discipline in telephone engineering.

Telephone calls are made by individual customers as they fit into their living or into the conduct of their business. The aggregate of customers' calls follows a varying pattern throughout the day, and facilities must be sufficient in quantity to satisfactorily handle the period of maximum demand, usually termed the busy hour. The basic factors involved in the provision of facilities are the call attempt rate, call holding time, grade of service and number of channels.

The traffic volume in telephone systems is measured in a unit called the Erlang. An Erlang is the amount of traffic one trunk can handle in one hour, if it is busy all the time. An Erlang is equal to 3600 call-seconds.

The number of Erlangs received is given by:

$$\frac{\text{No. of calls per hour x mean holding time per call (seconds)}}{3600}$$

The product of the call attempt rate and the call duration times is the "offered traffic", which denotes the amount of time that a quantity of callers desires the use of facilities. The offered traffic is usually expressed in term of Erlangs.

Grade of service may be described in terms of either the probability of blocking, that is the probability that all available channels are busy, or the average delay encountered by the calls [7,5,2].

2.2 BLOCKED-CALLS-CLEARED (ERLANG-B) DISCIPLINE

With this service discipline, an arrival that occurs when all channels are busy is blocked, leaves the system and does not return in the same period, say the busy hour.

The blocked-calls-cleared (BCC) discipline can be modelled by the M/M/m/m queueing situation shown in Fig. 2.1 in which there are m identical servers (channels) each having identical service times (call holding time) which are assumed to be independent according to a negative exponential distribution and have mean $1/\mu$ second. The calls

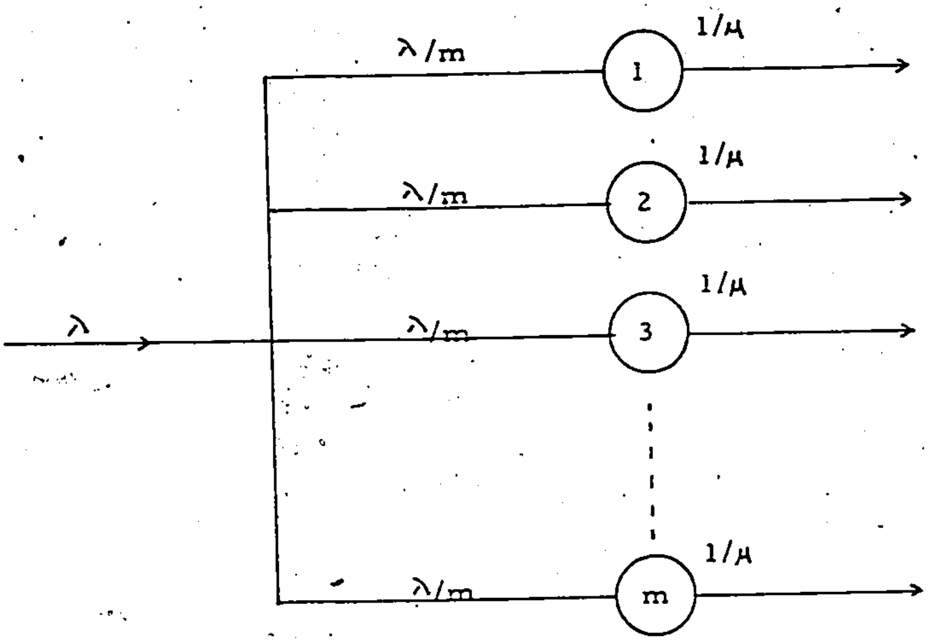

Fig. 2.1 A Queueing Model For The BCC Service Discipline.

arrive in a Poisson fashion with a mean arrival rate of λ calls/hr.

The utilisation factor ρ for the model is given by:

$$\rho = \frac{\lambda(\frac{1}{\mu})}{3600m}, \qquad (2\text{-}1)$$

or

$$m\rho = \frac{\lambda/\mu}{3600} \text{ (in Erlangs)} = \text{offered load} \qquad (2\text{-}2)$$

The Erlang-B blocking probability is given by the formula [2,7]:

$$P_B = \frac{\dfrac{(m.\rho)^m}{m!}}{\sum\limits_{k=0}^{m} \dfrac{(m.\rho)^k}{k!}} \qquad (2\text{-}3)$$

The average queueing delay is zero, since no queue is allowed to form in the Erlang-B model.

2.3 BLOCKED-CALLS-DELAYED (ERLANG-C) DISCIPLINE

The blocked-calls-delayed (BCD) or Erlang-C model arises when blocked calls are allowed to queue up and wait for service in order of arrival. More precisely, the system is composed of m channels and an unlimited waiting queue. Calls arriving to find a free channel are served immediately. Calls arriving when all channels are busy, queue up in order of arrival . If a channel becomes idle when calls are waiting, the channel serves the call at the head of the queue. Calls do not defect from the queue.

The (BCD) discipline can be modelled by a $M/M/m/\infty$ queueing situation shown in Fig. 2.2. This model consists of m servers (channels) having identical service times governed by the negative-exponential distribution with a mean of $1/\mu$ sec and call arrivals that occur according to a Poisson fashion with mean arrival rate of λ calls/hour.

Once again the utilization factor of each server is given by equation (2-1).

The probability of queueing is given by the Erlang-C formula as [2,7]:

$$P_c = \frac{1 - \left[\dfrac{\sum_{k=0}^{m-1} \frac{(m\rho)^k}{k!}}{\sum_{k=0}^{m} \frac{(m\rho)^k}{k!}}\right]}{1 - \rho\left[\dfrac{\sum_{k=0}^{m-1} \frac{(m\rho)^k}{k!}}{\sum_{k=0}^{m} \frac{(m\rho)^k}{k!}}\right]} \qquad (2-4)$$

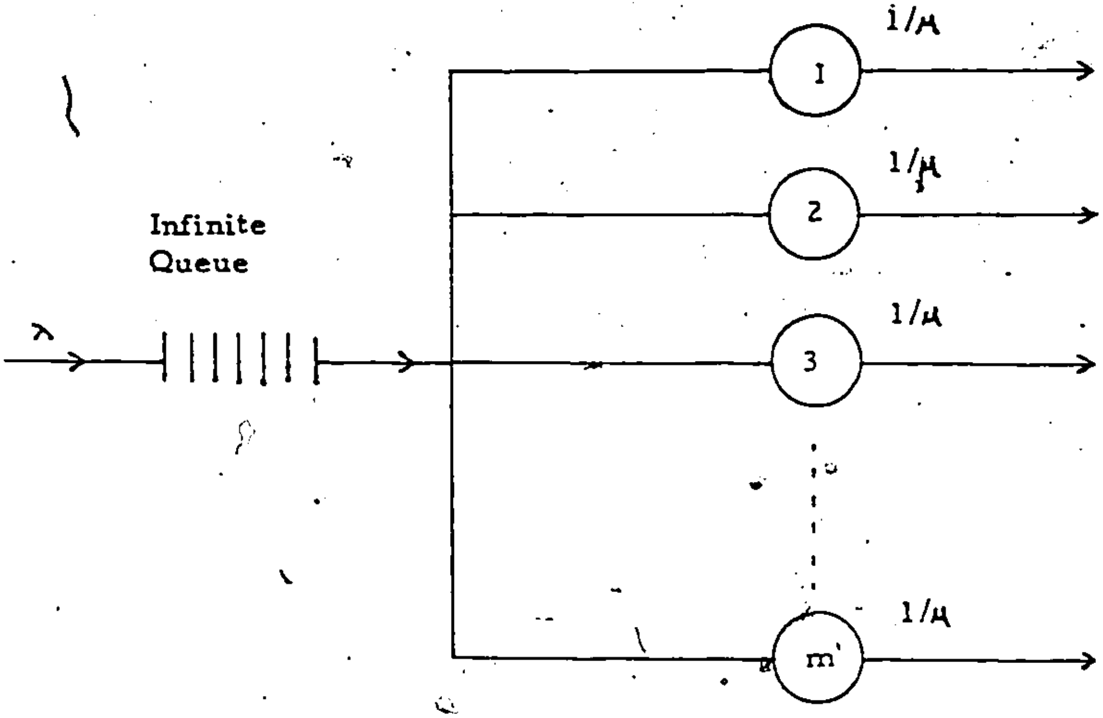

Fig. 2.2a A Multi-Server Queue With m Servers.

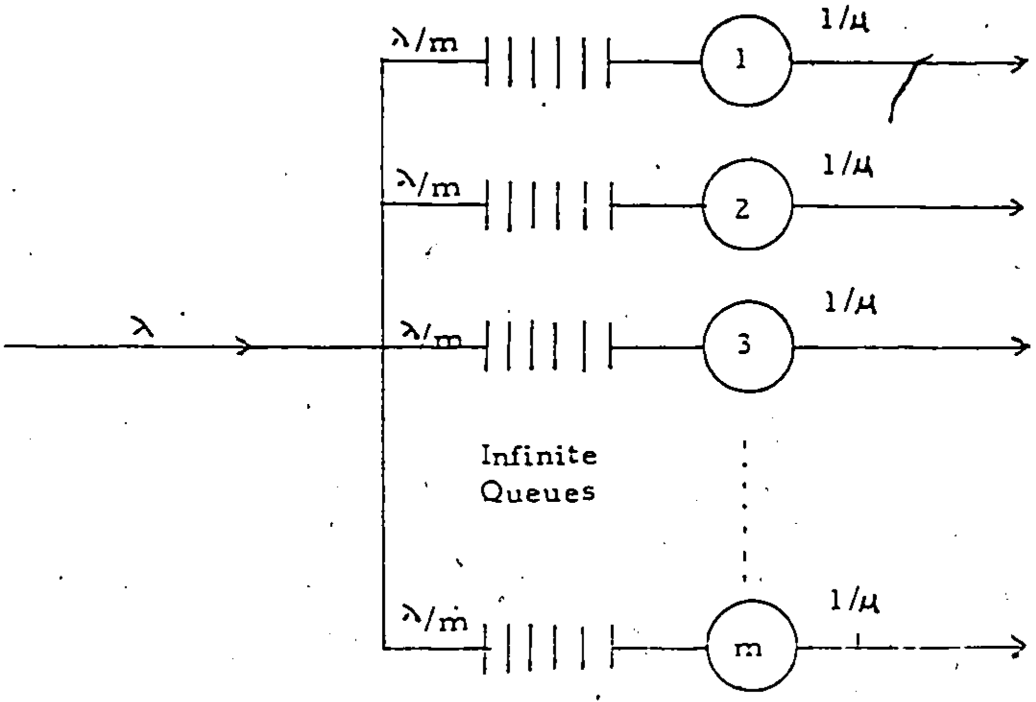

Fig. 2.2b m Single-Server Queues In Parallel.

Fig. 2.2a depicts the situation where the calls have no preferred servers, that is, they are served by the first server whoever becomes available. In Fig. 2.2b, the calls are to be served by their predetermined servers. The queueing time in the latter is found to be greater than if the calls were able to choose the first server who becomes free [13,2,7].

2.4 BLOCKED-CALLS-HELD (BCH) DISCIPLINE

The case of the Erlang-B where the number of channels is large may be approximate by another discipline referred as the BCH.

In such a system, calls arriving to find an idle channel are immediatly served. If an offered call upon finding no channel idle waits for, an interval of time exactly equal to its holding time, then it disappears from the system. In mobile radio telephone system, the call holding times (the times between call arrivals and call completions) are found to follow the negative-exponential distribution [2]. If a channel becomes available during the holding time, a waiting call will seize the channel for the portion of the holding time remaining.

With the same assumptions concerning the service time distribution and the call arrival pattern as in the previous two disciplines, the blocking probability ~~is~~ found to be: [2,7]:

$$P_H \doteq \sum_{k=m}^{\infty} \frac{(m.\rho)}{k!} e^{-m.\rho} \qquad (2\text{-}5)$$

where m is the number of servers and ρ is the utilization factor of each server as given by equation (2-1).

The way in which the blocked calls are disposed has different effects on the blocking probability. When the blocked calls are held, they occupy some channel time. If the probability of no idle channel is low, the blocked calls occupy nearly the full holding time. If blocked calls are delayed, they are allowed to wait in the system and occupy the full holding time. Hence the blocking probability is the highest of the three disciplines. In BCC model, the blocked calls do not occupy a channel and thus for a given load the probability of all channels found busy is the lowest among the three disciplines.

The mobile telephone service is closely described by the (BCC) assumptions. The International Consultative Commitee for Telegraphy and Telephony (CCITT) has recommended the use of Erlang-B. The Dispatcher service is closer to the (BCD) assumption. The Erlang-B discipline was considered in the simulation presented in this thesis [13,2,7,5](*).

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Chapter III

THE CELLULAR SYSTEM

3.1 INTRODUCTION

Historically, mobile radio engineers have sought the highest mountain or building within a proposed service area for their high-power antenna location, in order to "cover" the largest area possible. Since it was not practical to transmit the same power from the mobile units, additional receivers evantually had to be distributed within the area to service the mobile- to-base link in low-signal regions.

Because of large obstructions like hills or tunnels, holes in the radio coverage from the high base-station antenna sometimes existed within the primary coverage area. Attempts have been made to fill in some of the coverage holes by installing secondary transmitters and antennas. This solution creates problems in the coverage overlap because of frequency beats between the signals from the different transmitters. In addition, careful equalization of the delay in the baseband circuits to the different transmitters was required to keep distortion at acceptable levels (Fig. 3.1) [2,13,7].

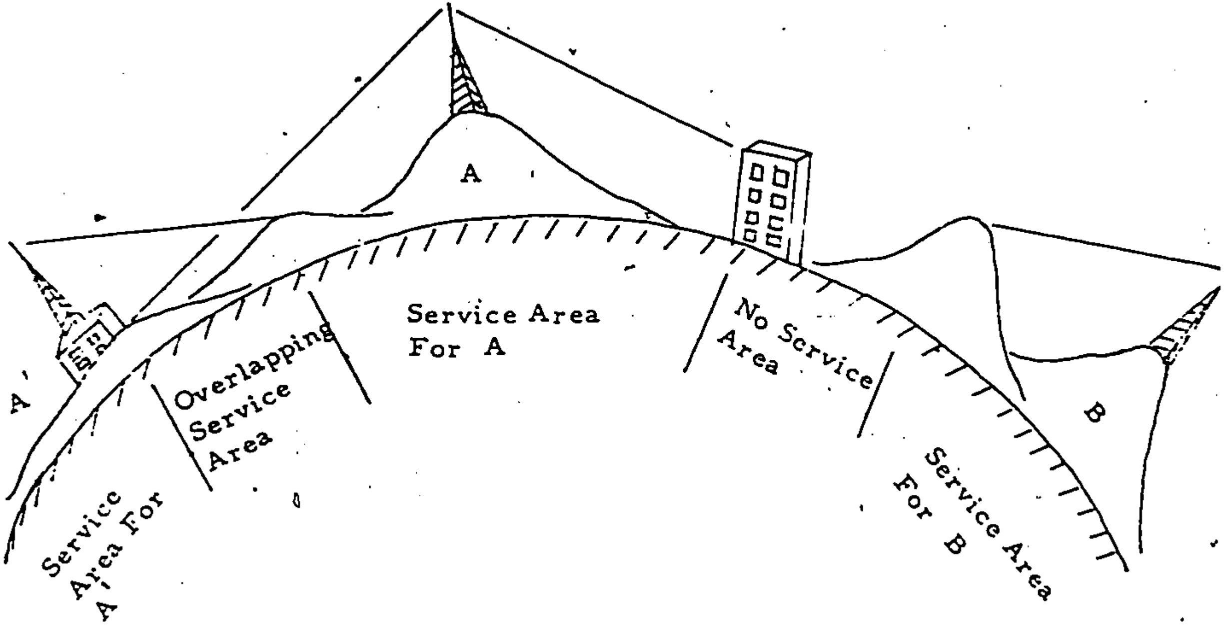


Fig. 3.1 A Global Coverage Radio System.

Due to the increasing demand for land-mobile communication service and the limited radio frequency spectrum available, in the global coverage system, one radio frequency channel can serve only one customer at a time in the whole geographical area in which the mobile telephone is permitted to operate. Different techniques have been studied in order to use that portion of the frequency spectrum efficiently. The cellular structure approach was first proposed and believed to be able to solve the channel shortage crisis and simultaneously cope with the rising demand for mobile radio service [13,25].

3.2 BASIC ELEMENTS OF THE CELLULAR SYSTEM

The most conspicuous attribute of a high-capacity system is its size. The heart of a high-capacity mobile communications system is the spectrum allocation. This system model assumes the availability of several hundred channels. In such a system, it has been proposed that a small zone approach be considered as a way to make efficient use of the radio spectrum for both land mobile telephony and dispatch services.

Basically, a plan was made to permit the reuse of the radio spectrum by limiting coverage, distributing the radio equipment into many small clustered cells or zones, and connecting into the land telephone plant at several points.

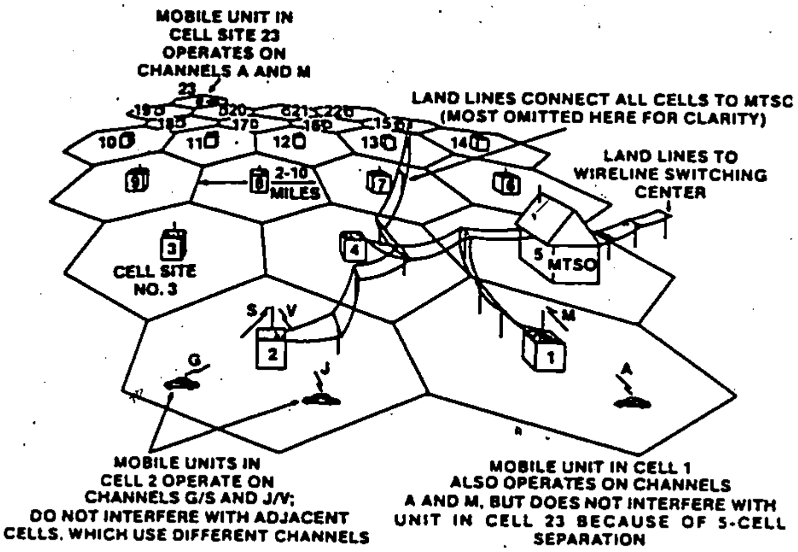
There are several reasons for going to a small-zone plan [17,15]:

1) Spectrum economy: Channels may be reused within the service area and also within contiguous service areas.
2) Flexible growth: After the initial installation of a system, growth can take place within the initial allocation, a) by shrinking zone size in the center of the system or b) by adding zones where there were none before.
3) Power: A small zone implies a lower transmitter power (or antenna height) at both mobile and base.
4) Balance: If base power and mobile power can be made equal, there is no need for more than one receiver per transmitter on the land.

The operation of a cellular system is illustrated in Fig. 3.2. The diagram shows the basic operating configuration of the cellular concept [22].

Any given area to be served by a CMRS can be imagined to be divided into discrete regions or cells. Each cell is equipped with its own radio frequency transmitter and receiver, and switching and control equipment. Collectively, this equipment is referred to as a "cell site".

In Fig. 3.2, we have assumed that available mobile frequencies are identified by letters of the alphabet. Thus,



MOBILE UNIT IN CELL SITE 23 OPERATES ON CHANNELS A AND M

LAND LINES CONNECT ALL CELLS TO MTSC (MOST OMITTED HERE FOR CLARITY)

LAND LINES TO WIRELINE SWITCHING CENTER

MOBILE UNITS IN CELL 2 OPERATE ON CHANNELS G/S AND J/V; DO NOT INTERFERE WITH ADJACENT CELLS, WHICH USE DIFFERENT CHANNELS

MOBILE UNIT IN CELL 1 ALSO OPERATES ON CHANNELS A AND M, BUT DOES NOT INTERFERE WITH UNIT IN CELL 23 BECAUSE OF 5-CELL SEPARATION

Fig. 3.2 Basic Operating Configuration of the Cellular Technology Concept. (diagram taken from [22]) for example, A/M represents a two-way channel operating mobile-to-land on frequency A and land-to- mobile on frequency M. If any two mobile units are far enough apart, they can both operate on the frequencies without suffering from co-channel interference.

The first problem with such a system is that several mobile units may desire service within the same cell at the same time. This creates a need for new frequencies or channels in each cell. This problem can be solved by some combination of two provisions: more channels, or frequency agility in the cell sites. Frequency agility means that the cell sites themselves would have the ability to broadcast on all channels allocated to a system, if necessary, to meet demand. Returning to Fig. 3.2, for example, if channel D/P is normally allocated to cell 3, but is currently idle, cell 1 could seize that channel and provide service to a new caller in cell 1. This solution is very important when calls are "lumped" geographically.

A second major problem relates to the fact that as transmitting units move about the terrain, signal strength is subjected to variation and degradation for several reasons. It may be that the mobile unit passes behind a tall building or over a metal bridge that attenuates the signal to and from the cell site. It may also happen that a mobile unit moves so far away from the local cell site that signal strength becomes inadequate during a call. Again, two solutions can be proposed. First, increased signal strength can be achieved simply by greater transmitter power which helps to eliminate problems of local attenuation. The second solution of distance attenuation is overcome by the unique feature that makes the cellular concept viable, that is the call "hand-off" procedure. This procedure will be explained in detail later on chapters 5 and 6.

3.3 CELLULAR CONCEPT AND SYSTEM DESCRIPTION

The urban area to be covered by this system is divided into a number of nonoverlapping cells or zones. In the center of each zone is a fixed base station and mobile units in the zone can communicate with this local base station which contains a group of low-power transmitters/receivers. All these base stations are connected via land lines to the mobile switching office (MSO) which, in turn is connected to the Direct Distance Dialing (DDD) network via land facilities as shown in Fig. 3.3. This allows for a complete connection between any mobile unit and any fixed subscriber. The MSO is equipped with an Electronic Switching System (ESS) with special data terminals, and trunking facilities and a unique program to achieve the required extensive centralized coordination and control to properly administer base station assignments,channel assignments and re-assignments and to interconnect the mobiles with each other and with the DDD network.

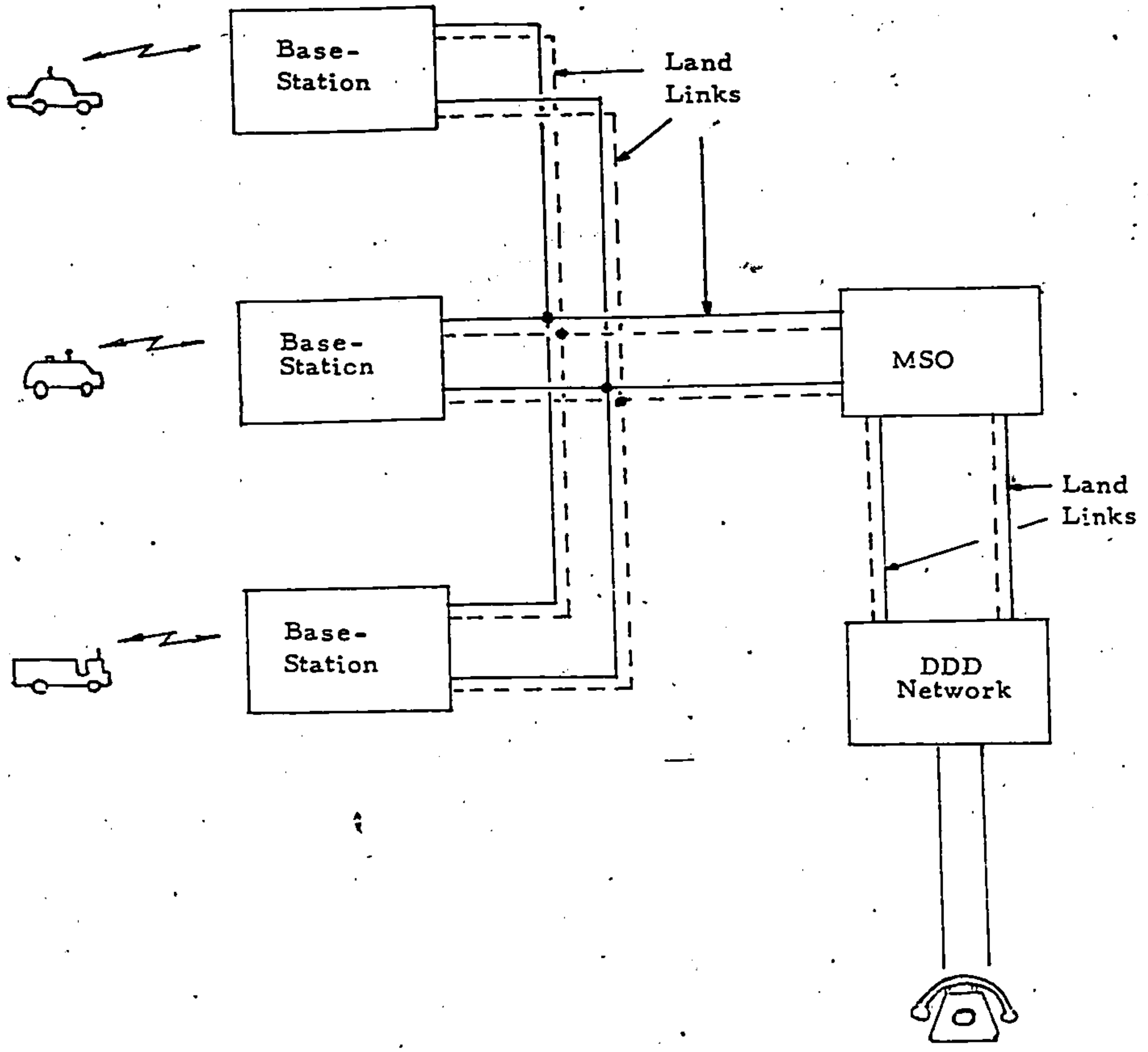


Fig. 3.3 Block Diagram Layout Of A Cellular Radio System.

It must be emphasized that all this equipment is far too expensive for any one user to afford. But the traffic carrying capacity of this system is so large that many users can share the system and equipment cost is divided among them. The MSO must be aware of the location of the mobile unit so that the call can be switched to the correct base station. In one realization of the system the "locating" function is accomplished with an "electronic fence" around each zone. Zones are laid out and zone boundaries slightly modified, so that zone boundary lines cut through streets near their centers. At each intersection of street and zone boundary line a short range sensor is installed. All mobile units have low-power transmitters that periodically emit the unit identity. When the unit gets within range (perhaps 100 feet) of a receiver this identity is picked up. By having two antennas, back-to-back, that look down the street in each direction, the receiver (with the aid of some internal storage) can, not only tell which vehicle crossed the boundary but also in which direction. All such receivers are connected to the MSO and transmit vehicle number and direction of crossing [4,27].

3.4 CELLULAR LAYOUT

In the cellular mobile radio telephone system, the prime mechanism for serving large subscriber groups with limited spectrum is the use of small radio coverage zones or cells. Where the area covered from a single base station is small, it is possible to reuse the radio channels of that base several times in the same region. Hexagonal cells are preferred because they nearly approach the circular pattern that can be easily produced by the base station omnidirectional antenna. Furthermore they fill a plane with no overlap. Each cell has its own base station located at the center of the cell.

A frequency modulation (FM) system with a reasonable modulation index has certain advantages over an amplitude modulation (AM) system [21]. A possible requirement for FM might be that for a mobile in the worst case position ,the (RF) signal-to- interference ratio should be better than 8 dB about 95 percent of the time. It will therefore be necessary to attempt to maintain a much higher average S-TO-I ratio to insure that the minimum requirements are surpassed most of the time.

Since each base station transmits within its own cell, the reuse of the same frequency channel in the other cells is feasible, thus providing many voice paths in a single urban area. Efficient use of frequency channels requires the simultaneous assignment of channels in radio coverage cells which are spaced as close together as possible without incurring excessive cochannel interference. However, there exists a minimum seperation (γ) within which the channel cannot be reused [17,5,6].

The minimum separation ratio cannot vary continuously but may assume discrete values consistent with the spacing between any two cell centers. This minimum separation is called the minimum reuse interval and given by :

$$\gamma = D/R \qquad (3\text{-}1)$$

Where D is the geographic separation between the two base stations using the same channel simultaneously and R is the cell radius. The ratio D/R is a function of the (SIR) ratio, the cell size, the antenna heights and gains, the propagation media, the frequency of operation as well as the modulation technique.

Using an acceptable value for γ, we must introduce enough sets of RF channels to provide each zone in an infinite plane with one set while preserving the established separation between zones using the same set. The minimum reuse distance is related to the number of channel sets N by the function:

$$N = 1/3\ (\ \gamma\ )^2 \quad \text{(Hexagonal Cells)} \qquad (3\text{-}2)$$

where possible values of N belong to the series: $i^2+j^2+i.j=N$; i and j called "shift parameters", must be positive integers [5,13]:

For any value of γ there is an interference cell group (ICG) associated with each cell. Channels assigned to a cell cannot be reused elsewhere within the ICG if already in use in that cell. The thick block contour, in Fig. 3.4, represents the boundary of the ICG of the shaded cell. There are 19 members in that ICG. The capital letter in each cell denotes the channel set allocated to be used there. As can be seen, any reuse of a channel set is prohibited within the ICG.

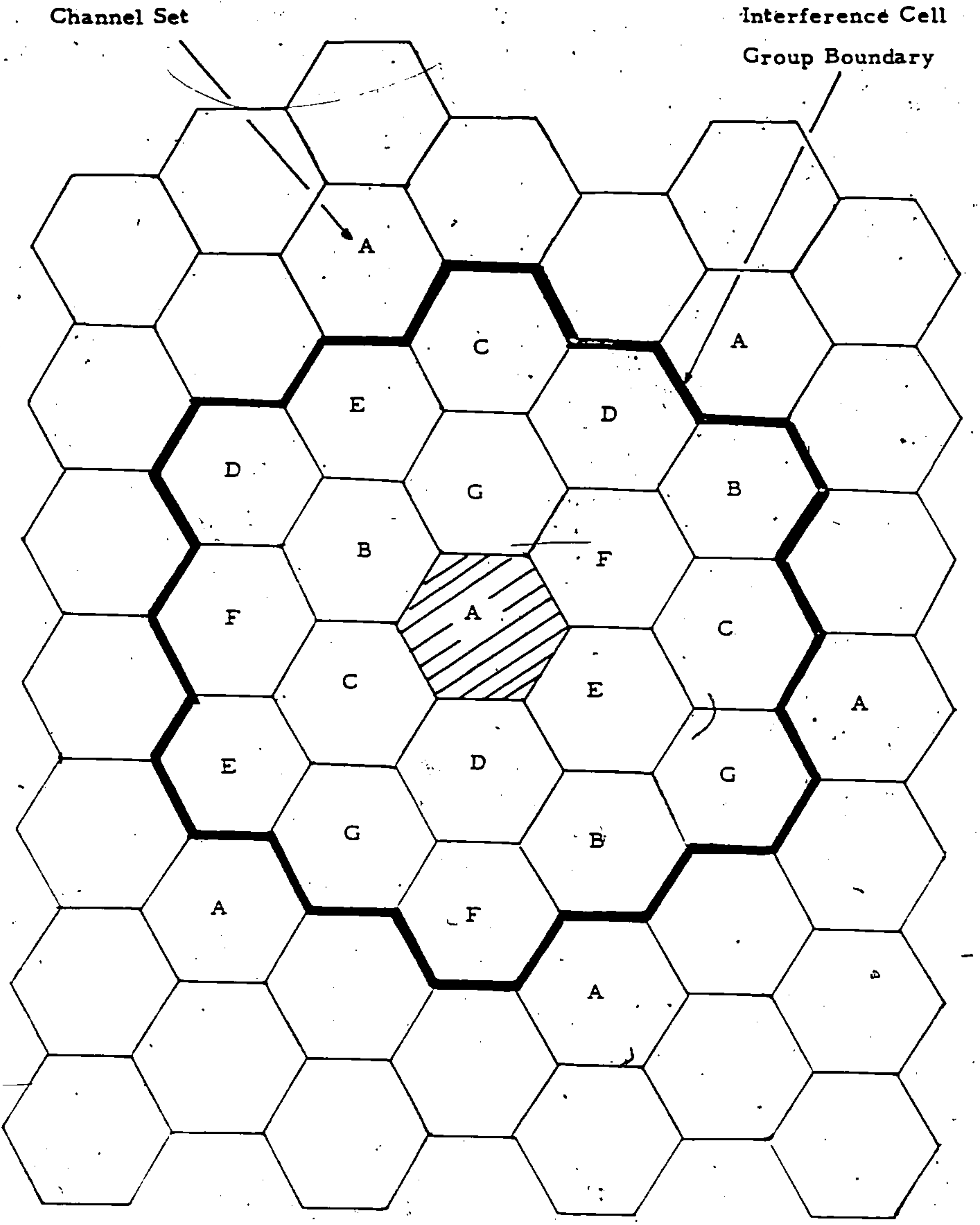


Fig. 3.1 A Cellular Layout of a High-Capacity Mobile Radio System.

3.5 CELL SIZE CANSIDERATION

What cell size should be used? Small cells are desirable for two reasons; the resulting large number of cells would permit considerable bandwidth conservation via channel reuse, and the power levels required of transmitters would be low. Reduced power levels reduce costs of mobile and base transmitters and lessen electromagnetic interference with other systems. However small cells require improved vehicle location accuracy and increase the probability that a call-in-progress will have to be transfered to another channel because of cell boundary crossings.

If the density of offered traffic were uniform over the entire service area of the mobile radio system, the design of a grid of small coverage areas would be straight forward. However, the traffic density usually decreases to much lower values at the outskirts of metropolitain areas than at the centers of cities. Also, base stations are expensive. therefore, in order to minimize system costs, larger cells are usually prescribed on the outskirts than around the city centers.

The lower bound on cell size is primarily controlled by the practical constraints on the amount of data processing required to keep track of moving vehicles and to switch voice paths as the mobiles move from cell to cell. Cells of about one mile radius are possible today and that even smaller cells may become feasible in the future due to the rapid advancement in microprocessing technology. The upper bound of cell size is a function of the mobile (or base) transmitter power, channel bandwidth, receiver design, antenna heights and gains, minimum required SNR and is also dependent on whether diversity is employed. Cells of about twenty-mile radius are possible today [26,17,7].

3.6 SYSTEM PERFORMANCE CHARACTERISTICS

3.6.1 Noise in a Mobile Radio Environment

In a conventional point-to-point analog AM communication system disturbed by additive white gaussian noise of power density $N_o/2$, the output signal-to-noise ratio (SNR) is given by :

$$SNR = P/N_o W \qquad (3-3)$$

Where P is the received information signal power and W is the audio bandwidth.

For conventional point-to-point above threshold FM transmission of a gaussian message in white gaussian noise :

$$SNR = (3/2)B^2 P/N_o W \qquad (3-4)$$

Where $B^2 = \overline{W^2c}/W^2$, and $\overline{W^2c}$ is the mean-square bandwidth of the transmitted FM signal.

In a mobile radio environment, SNR as given by equation (3-4) is often not applicable for one or more of the following reasons [2,21,26] :

1) Fast Rayleigh Fading: As the propagation characteristic between the mobile and the base station changes continuously as the vehicle moves, the multiple reflected waves transmitted from a single source may interfere destructively to varying degrees. This interference causes the signal envelope to vary in intensity in accordance with the Rayleigh distribution :

$$\Pr(\alpha) = \begin{cases} 0 & \alpha < 0 \\ \dfrac{\alpha}{r_o} \cdot e^{-\alpha^2/2r_o}, & \alpha \geq 0 \end{cases} \qquad (3\text{-}5)$$

Where r_o specifies mean power of the distribution.

2) Slower Log-Normal Fading: The actual value of the mean received power :

$$S = r_o\sqrt{\pi/2} \qquad (3\text{-}6)$$

varies slowly with respect to the wave length as the distance between the base station and the mobile changes. This slow variation is approximated by a

Log-Normal distribution. This r_o varies as R, where R is the distance between the base station and the mobile. The probability density $P_S(\alpha)$ is :

$$P_S(\alpha) = \frac{1}{\sqrt{2\pi}\,\sigma}.\exp[-\frac{(\alpha-\alpha_o)^2}{2\sigma^2}] \qquad (3\text{-}7)$$

The expected value (α_o) of "S" is :

$$\alpha_o = A - 10n.\log(R/R_o) \qquad (3\text{-}8)$$

Where the constant A depends on terrain and environment, antenna heights and gains and carrier frequency; R_o is a normalizing factor (the radius of the cell).

3) Co-channel interference: Reuse of an FM channel by mobile and base stations in geographically separated radio cells causes co-channel interference which is not normally present in conventional point-to-point communication links. The actual level of interference depends on the geographic reuse separation, the modulation index β, the propagation factor n, message statistics, and the receiver structure.

4) Adjacent channel interference: Information transmitted in channels adjacent in the spectrum to the local channel provides another source of interference. The level of interference depends on

the frequency separation of the local and adjacent channels, the modulation index, the propagation factor, geographic proximity and the receiver design.

5) Selective Frequency Fading: Because there are often several signal transmission paths between the mobile and the base station, the interference between these paths may, at any given moment, be either destructive, constructive or neither depending on the frequency of the transmitted signal. Since the instantaneous frequency of a modulated FM signal depends on the amplitude of the message signal, fluctuations is received signal strength may occur even if the mobile is stationary.

6) As a mobile moves about the instantaneous phase of the received signal changes abruptly due to sudden change in preferred signal paths. The result is output noise which is referred to as Random FM. It is proportional to:

$$f_m = \frac{V}{\lambda} \qquad (3-9)$$

where V and λ denote, respectively, vehicle velocity and the wavelength of the transmitted signal.

3.6.2 Output Signal to Noise Ratio

The discussion in the previous section suggests that determination of the SNR for a mobile radio channel subjected to fast Rayleigh fading, slower Log-normal signal level variation, co-channel or adjacent channel interference, frequency selective fading and Random FM, is not a simple matter. In one sense the availability of diversity receivers further complicates the problem of calculation of SNR which now depends not only on the various types of noise, but also on the detailed structure and amount of diversity employed. In another sense, diversity simplifies the problem of SNR calculations.

In the presense of co-channel interference and for good diversity and/or carrier-to-noise (CNR) ratio high enough to keep the signal above threshold, the minimum required SNR for a cell is given by [21]:

$$SNR = \{[\Gamma \sum_{i=1}^{I} (\frac{R}{D_i})^{\Omega} . \frac{P_i}{P}] \beta^{-3} + [\frac{1.5\beta^2}{R^{\Omega}} . CNR]^{-1} \}^{-1} \qquad (3\text{-}10)$$

where :

$\frac{P_i}{P}$ = ratio of the power of the ith co-channel interference to the radiated power of the signal in question.

D_i = geographic separation between the distant (ith) transmitter and the local receiver.

R = cell radius.

I = number of co-channel interferers.

Γ = constant depending on I, the amount of fading suffered by both the signal and the interference and on the average signal characteristics.

β = modulation index.

Ω = attenuation factor which lies between 2 and 4.

CNR = carrier-to-noise ratio at a unit distance from the transmitter ($=P/N_oW$).

W = audio bandwidth.

$N_o/2$= power spectral density of additive white Gaussian noise.

The first term of equation (3-10) accounts for the co-channel interference while the second one for the additive white gaussian noise. The quality range important to mobile radio is 15 to 30 dB SNR.

3.6.3 System Cost

System cost includes costs of all base stations and associated links, as well as supporting facilities such as license fees, design costs, equipment maintenance costs, etc. Total system costs can be represented as fixed plus variable costs. Fixed costs are those incurred in the establishment of a minimal facility. Variable costs are those additional costs required to provide an improved system which results from improved SNR, increasing numbers of base stations and increasing numbers of channels. The normalized system cost is expressed as follows [7,21]:

$$C = 1 + K(L)^{b-1} . \sum_{i=1}^{L} M_i^a (CNR_i)^c \qquad (3-11)$$

Where:

a,b,c= cost indices determining the rate of change in variable cost; a<1, b<1 and c>1.

K = variable cost factor normalized over the fixed cost.

L = number of cells.

M_i = number of channels in cell i.

CNR_i = carrier-to-noise ratio in cell i.

It follows immediately that if all base stations have identical values for CNR_i and M_i then with CNR_i = CNR and M = m:

$$C = 1 + KN^b m^a . (CNR)^c \qquad (3-12)$$

where m is the total number of radio channels.

3.6.4 Message Throughput

Message throughput Q for a mobile radio system is simply the product of the system call-completion rate and the average holding time L. The call-completion rate is the product of the observed call-attempt rate and 1-P, where P is the blocking probability :

$$Q = \lambda L(1-P) \qquad (3\text{-}13)$$

When each of N cells has a total call attempt rate λ_i then:

$$Q = \sum_{i=1}^{N} \rho_i (1 - P_i) \qquad (3\text{-}14)$$

where $\rho_i = \lambda_i L$ and P_i is the blocking probability for cell i.

3.7 DIVERSITY CONSIDERATIONS

The objective of diversity is to provide a path for reliable transmission of a radio signal between mobile and base station. In the limit, diversity can virtually eliminate the effects of both Rayleigh fading of the desired signal and effect of random FM and frequency selective fading.

The technique which is most often used in mobile telephone systems is space diversity, in which different site positions create a multiplicity of base-to-mobile paths, and in which the critical parameter is the degree of separation between paths that is necessary to achieve independence of path reliability [26,13].

Chapter IV

CHANNEL ASSIGNMENT SCHEMES

4.1 INTRODUCTION

In a high-capacity cellular mobile radio system that uses many base stations to provide radio service over a large geographical area, each base station is responsible for radio coverage within its assigned cell only. In order to make efficient use of the frequency spectrum, radio coverage from base stations would be limited to small zones and channels would be reused several times within a particular urban area under certain constraints. Various channel assignment schemes were developed, in order to increase the system efficiency. They were studied and their performances were evaluated by L.G. Anderson [16], T.J. Kawa and N.D. Georganas [24], D.C. Cox and D.O. Reulink [1,14], J.S. Engel [19], G. Nehme and N.D. Georganas [8] etc.

This chapter first presents different channel assignment methods. One such method is the fixed channel assignment scheme (FCAS) that assumes a definite relationship between the channels and the cells at any time. Another technique is the dynamic channel assignment scheme (DCAS) in which no definite relationship holds between cells and channels. All the radio channels available to the system belong to a central control. These channels can be temporarily borrowed by any cell to serve calls on a real time basis, provided that the minimum reuse distance is respected at the time of borrowing. Insight into these basic channel assignment schemes leads to the conception of the hybrid channel assignment scheme (HCAS) which is to be presented in this chapter.

4.2 FIXED CHANNEL ASSIGNMENT SCHEME (FCAS)

In cellular systems with fixed channel assignment, each frequency channel is permanently assigned to one or more specific radio cells. In this case, a subset of the channels available to the radio system is permanently reserved for use within each coverage cell. The channel subsets are reused in the coverage cells separated by a reuse interval. Only channels from the reserved subset can be used to serve a call in a particular coverage cell. If all channels from the reserved subset are in use, service will not be provided to another caller even though there may be vacant channels among those which are reserved for use in adjacent coverage cells.

In (FCAS), the total available radio channels are divided into a number of channel sets. There is a minimum number of channel sets required to serve the entire service area. This minimum number (N) of channel sets is governed by the minimum reuse distance in the following fashion :

$$N = 1/3(\gamma)^{2} \qquad (4-1)$$

where N can assume only integer values 3,7,9,...etc. as generally represented by the series $(i+j)^2-i.j$ with i and j being positive integers [2,7].

The N channel sets are then assigned to the cells in the system respecting the minimum reuse distance and are to be exclusively used in their nominal cells at any time. All the N channel sets will be of the same size if the customer offered traffic has a spatial uniform distribution; otherwise the number of channels in the channel sets can be appropriately 'tailored' to suit the traffic demands.

Efficient use of fixed channels requires simultaneous assignment (reuse) of a radio channel in cells that are spaced as close together as possible, without incurring excessive co-channel interference. If all fixed channels of a cell are in use, a new call initiated in that cell is immediatly blocked, and will be disposed of in a manner dictated by the service discipline adopted in the service area. Fig. 4.1 shows an example of the allocation of channel sets to various cells in the system with (γ) of 5 radii. The capital letter in each cell represents the nominal channel set while the superscript associated with each

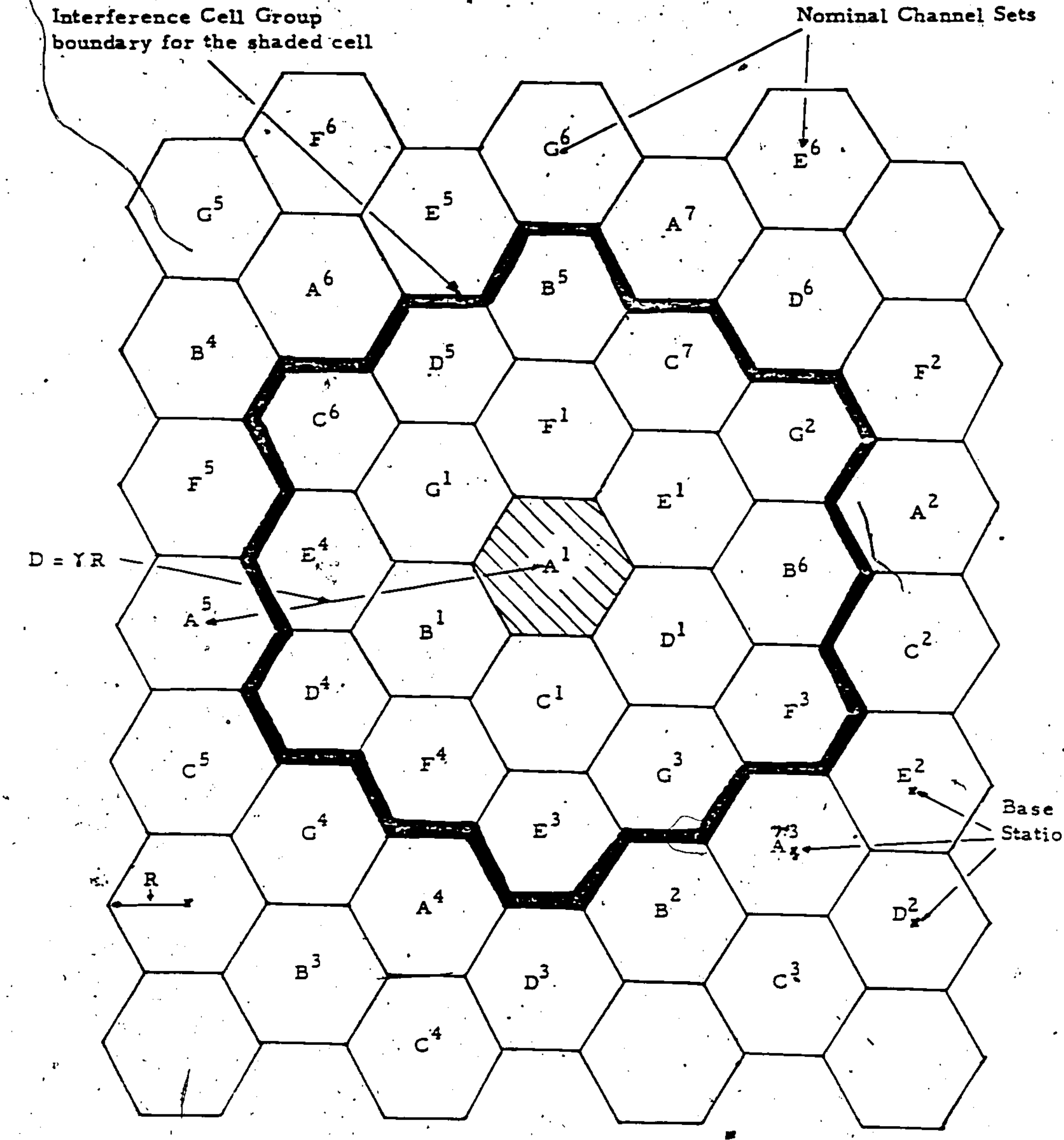


Fig. 4.1 Allocation Of Channel Sets With The Fixed Channel Assignment Scheme.

letter indicates the number of times that channel set is reused within the system [2,17,16,21,7].

4.3 DYNAMIC CHANNEL ASSIGNMENT SCHEME (DCAS)

In systems with dynamic channel assignment strategies, channels are available for assignment to any cell, provided adequate geographic separation between each channel is maintained. In this case, there is no need of assigning different channel sets to the different cells of an (ICG). Channels are assigned to serve calls in any cell in real time, provided such assignment respects the minimum spacing constraint γ . (The resulting average spacing between cells using the same channel depends on the criterion of borrowing, but it is usually larger than γ).

In (DCAS), channel search to assign in a particular cell at a particular time involves searching through all channels allocated to the central pool. If no such channel is found, service cannot be provided in the cell at that time.

Usually there are more than one channel in the central pool suitable for borrowing. Then one has to decide which channel, out of the eligible candidates, to borrow for use. The following schemes for a cell borrowing a free channel have been investigated [16,21,2] :

a) Borrow the very first channel found in the search that satisfies the interference constraint. That is, a channel not being used in any cell belonging to the interference cell group for the particular cell in question.

b) The second strategy is to choose for assignment that channel which is "in use" at a cell nearest to the assigned coverage cell, but still at least at reuse interval, away. That is, the channel which minimizes D over the available channels, where D is the distance to the first cell using that channel on either side of the assigned cell. If more than one channel has the same minimum D then the first channel encountered is assigned without regard to the distance to the first cell using that channel in the opposite direction.

c) Borrow a channel using the same criterion as in b) above, except using the minimum distance as $(\gamma+K)$, where K=1,2or3. This added distance between cells using the same channel is for the purposes of facilitating mobiles, which are currently receiving service, to go across cell boundaries and still keep the same channel. They would, if necessary, just change the base transmitters serving them.

d) This strategy is called the mean square (MSQ) assignment strategy, since it minimizes the quantity:

$$\left(\frac{1}{n}\right) \sum_{j=1}^{n} D_j^2 \quad , \qquad \gamma \le D_j \le 2\gamma \qquad (4-2)$$

for the available channels. Each channel is checked at cells in the interval (between γ and 2γ). D_i is the distance between the assigned coverage cell and the cell currently using the same channel within the specified interval and n is the number of cells using the same channel within the interval. If n=0 for some channel, that is, if the channel is not in use in any cell between γ and 2γ ,then the first such channel encountered is assigned to serve the call.

It has been shown that the very first channel philosophy gives the best overall performance in terms of blocking probability, system throughput and percentage of forced terminations [1,23].

4.4 FIXED VS DYNAMIC CHANNEL ASSIGNMENT SCHEMES

The two above cases have been studied quite extensively, and the results from system simulations have shown that for low blocking probabilities, the dynamic system performs much better than the fixed channel assignment system. But for very high blocking probabilities, the (FCAS) performs better [16,1,23,19,9]. At light traffic loadings the (DCAS) technique blocks fewer calls. However, the fixed system outperforms its counterpart at and above moderate offered traffic. This inferiority experienced by the dynamic system is a consequence of the fact that dynamic channels are assigned to serve random calls originating in cells which are spaced apart a distance generally greater than the minimum required reuse seperation distance. Thus the channels cannot be used most efficiently [24].

In addition, dynamic systems require a rather complex centralized control system, and are difficult to analyze. In fact, computer simulation seems to be required for analysis as well as for design and optimization [2,20].

4.5 HYBRID CHANNEL ASSIGNMENT SCHEME (HCAS)

In the (HCAS), we employ a mixture of the fixed and the dynamic channel assignment schemes. In this scheme, the total number (T) of available radio channel is first divided into N channel sets, where N is the minimum required number of channel sets governed by equation (4-1). Some of the channels available to the system are assigned on a fixed basis. That is, certain channels can be used only at specified base stations, assuming a static assignment scheme and observing the minimum reuse distance γ. If the spatial distribution of the offered traffic is uniform, then the average number of channels per cell will be given by :

$$M = T/N \qquad (4\text{-}3)$$

After the preliminary division of channels, each of the N channel sets is partitioned into a number of fixed channels (f) per cell and a number of dynamic channels (d) per cell such that [6,7,22]:

$$f + d = M \qquad (4\text{-}4)$$

The optimal channel partition ratio f:d which will yield the best system performance depends on the offered traffic loading. The channel set (d) contains channels that can be used in any cell in the system, to handle any statistical fluctuations in offered traffic, using the DCAS. Thus there are altogether Nd dynamic channels in the central pool, which can be temporarily borrowed for service by any cell in the system provided the co-channel interference constraint is respected there at the time of borrowing. All the (f) fixed channels are to be exclusively used in their nominal cells.

The partitioning of the channel sets yields an average number of channels per cell given by :

$$m = f + Ndj/I.C \qquad (4\text{-}5)$$

where I.C is the number of cells contained in the interference cell group (ICG) of the cell and j the number of times each dynamic channel can be reused within the ICG. Thus, the average number of channels per cell, after the division, is less than before the division.

In (HCAS), the search of a channel is first made through the fixed channels allocated to the assigned coverage area. If there is a fixed channel available in the assigned transmission area, that channel is assigned to serve the call attempt. If all fixed channels are in use, a channel search is made through the dynamically assignable channels and will borrow the eligible dynamic channels from the central pool to service the call, provided that the co-channel interference constraint is satisfied at the time of borrowing in the cell in question. If no such dynamic channel is available, the call will be disposed of according to the service discipline.

For Erlang-B traffic, a system adopting the (HCAS), and assuming that there are no cell boundaries crossings for all calls-in-progress, gives better overall performance than either the fixed or the dynamic channel assignment schemes at low to moderate traffic loading. As the system becomes heavily loaded the (FCAS) prevails over the other schemes [6,8].

Chapter V

THE "HAND-OFF" ACTION

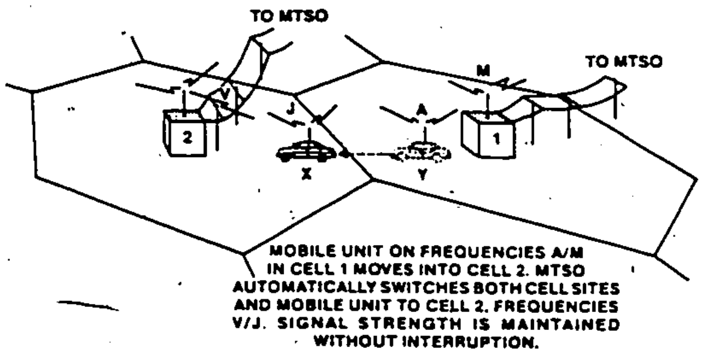
5.1 INTRODUCTION

All new high-capacity cellular mobile radio systems designs feature "hand-off", a method of providing continuous service to a mobile unit moving between cells while a conversation is in progress. The hand-off procedure is accomplished by instructing the mobile to change to an adjacent cell frequency, when the signal-to-noise ratio degrades to a predetermined level. This requires the MSO to know at all times during a call the vehicle's approximate location. Initially an appropriate channel is assigned to the mobile from the set of channels being used in the cell in which the mobile is temporarily located. When the mobile later changes cells, the MSO must assign to the mobile a channel from the new (adjacent) cell's set. However, since the mobile's movement may also require the need for a new base station, the MSO must be prepared to switch the call in midconversation, from the channel associated with the old base station to another channel associated with the new base station. This process, called a hand-off, must be closely synchronized with the channel retuning process in the mobile unit in order to reduce the customer's "break interval", i.e., interuption of the conversation, to a tolerable level, hopefully below that which he can bear [4,6].

5.2 HAND-OFF PROCEDURE

The hand-off procedure, as designed by the AMPS system in Chigago [22], is controlled by a powerful central computer, which AT&T calls a mobile telephone switching office (MTSO). Fig. 5.1 illustrates the hand-off method. The MTSO is first alerted by the cell site (in this case cell 1) that an in-progress call on channel A/M is operating at an unacceptable signal level. In Fig. 5.1, this has occured as mobile unit moved out of cell 1 (position Y) and into cell 2 (position X). The MTSO requests all cells adjacent to cell 1 to sample a supervision channel to determine which cell site is closest to the mobile unit. In this case, cell 2 wins. The MTSO signals both cell sites and the mobile unit to prepare for hand-off.

At a given instant, the MTSO switches the wire line connection away from the cell 1 landline to the cell 2 landline; cell 2 begins transmitting on channel V/J; cell 1 ceases transmitting on channel A/M, and the mobile unit retunes itself from channel A/M to V/J. The entire process, which takes place in a matter of milliseconds, in effect rerouting the call to a new cell site (or base station), on



MOBILE UNIT ON FREQUENCIES A/M
IN CELL 1 MOVES INTO CELL 2. MTSO
AUTOMATICALLY SWITCHES BOTH CELL SITES
AND MOBILE UNIT TO CELL 2. FREQUENCIES
V/J. SIGNAL STRENGTH IS MAINTAINED
WITHOUT INTERRUPTION.

Fig. 5.1 Block Schematic of the "Hand-off" Procedure (diagram taken from [22]) a different channel, with no perceptible interruption in the call.

5.3 CHANNEL ASSIGNMENT FOR THE "HAND-OFF" CALLS

Vehicles crossing cell boundaries and requiring new base station and radio channel assignments produce the following effects:

1. The average call duration experienced by each cell is shortened since a call exiting a cell vacates a channel prematurely.
2. The effective call attempt rate increases by the boundary crossing rate, since a call entering a cell requires a channel in the new cell just as a call attempt originating in the cell does.
3. Some calls are forced to terminate prematurely because channels are not available for their continuation after they enter new cells.

Items 1 and 2 considered together do not affect the traffic offered. The effect of item 3 can be minimized by giving priority to boundary-crossing calls in progress over new call attempts [6].

This section presents three channel assignment schemes namely the fixed, the dynamic and the hybrid channel assignment schemes, as applied to the hand-off calls.

5.3.1 Fixed Channel Assignment Scheme

In the fixed system, when the call-in-progress is crossing a cell boundary into an adjacent cell, it will have to be served by the base station of the new cell into which it is entering. Since the new cell has its own nominal channel set which is different from the channel set allocated to the former cell, a new fixed channel will have to be assigned to service that call. This switching of channels is called the "hand-off" and is performed while the call is still in progress. If no idle fixed channel is found in the new cell, the call-in-progress, on entering into the new cell, will be forced to a premature termination.

5.3.2 Dynamic Channel Assignment Scheme

In the dynamic system, if the vehicle has moved closer to another base station, that "now closer" station must be used to serve the call. The originally assigned dynamic channel is then checked at the new base station used and at all base stations within a reuse interval of the new one. If the channel passes this check, that is, is not in use at those stations, the new base station and old channel are assigned to serve the call and the old base station is cleared of the call. If the old channel is in use within a reuse interval of the new base station, then a whole new dynamic channel search is initiated, identical to the one used for new call-attempts. The only difference is that, if a substitude channel is not available, the call is forced to terminate instead of being refused [1,2].

5.3.3 Hybrid Channel Assignment Scheme

Just as in the case of new call attempts, the hybrid system is a mixture of the fixed and dynamic systems. Such system will be described later in detail when the system development will discussed.

Chapter VI

DEVELOPMENT OF THE SIMULATION MODEL

6.1 THE "HAND-OFF" PROCEDURE

6.1.1 Description of The Cellular Simulated System

The system to be simulated is illustrated in Fig. 6.1. It consists of an array of 37 hexagonal cells. Each cell contains one base station. The following general assumptions are made:

1. The mobiles are identifiable entities and can tune to any channel. The channels used are dictated by the base stations.
2. The base stations can transmit on any borrowed frequency at all times. The frequencies are assigned to them by the MSO.
3. The power level radiated from a base station antenna is sufficient to give an adequate SNR ratio at the cell's boundary. Thus the coverage limitation is due to the co-channel interference.
4. The service time per call is assumed to be exponentially distributed, with a mean of 120 secs.
5. All call arrival times are drawn from a Poisson process with the same arrival rate (λ calls/hr). Thus the loading will be:

$$\lambda \cdot \frac{120}{3600} = \frac{\lambda}{30} \text{ (Erlangs)} \qquad (6\text{-}1)$$

6. The first available channel in the search, that satisfies the spacing constraint γ, is borrowed for use.
7. For an hexagonal cellular layout the relationship between D/R and the number of distinct channel sets, N, required is given by:

$$\gamma = \frac{D}{R} = \sqrt{3N} \qquad (6\text{-}2)$$

   In the simulation model, N is taken to be 3 and consequently the minimum reuse distance is equal to 3 cell radii. Also, the number of members (IC) in the ICG equals 7.
8. All cells are of uniform size and shape.

The simulation model under development is based on the practical definition of a cell. The exact shape of the cell is not changed in this study, but the model itself can accommodate any shape of cell. A mobile is simply assigned to the nearest base station. If at some point while a call is in progress the mobile moves closer to some other base station, a boundary crossing is said to have occurred and this fact is noted.

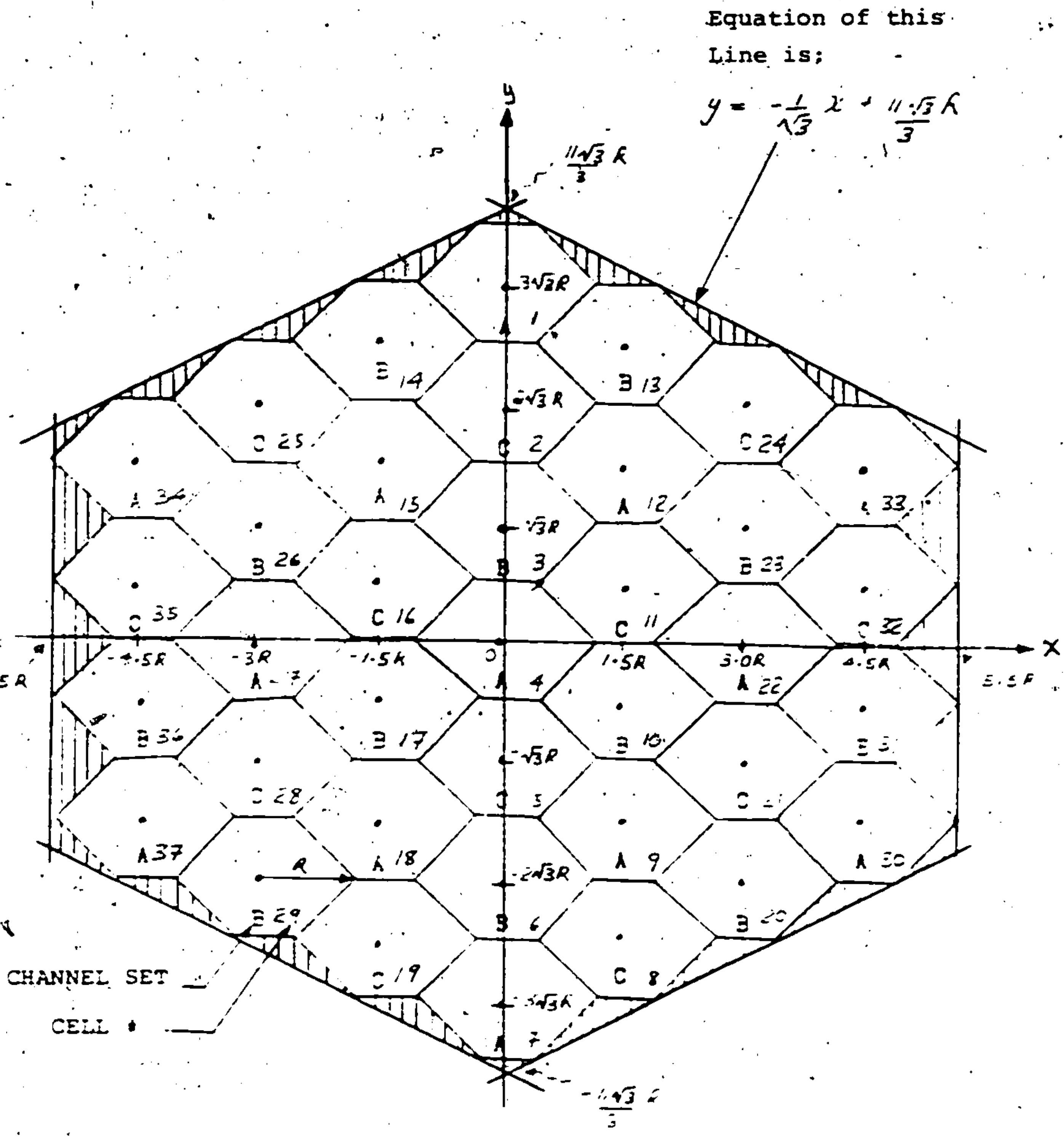


Fig 6.1 Hexagonal Cellular Configuration Utilizing Three Distinct Channel Sets

Transactions (XAC's) for the system as a whole are generated at time intervals specified by an exponential distribution (the XAC's represent mobiles). The XAC's pick up random (X,Y) coordinates and a velocity vector (V_x,V_y). The nature of the distributions for (X,Y) & (V_x,V_y) is detailed later. The following test is then performed 37 times:

$$d^2=(X-X_i)^2+(Y-Y_i)^2,\ i=1,2,.....,37. \qquad \text{Test 1}$$

where:

(X,Y)=current position of mobiles, and

(X_i,Y_i)=location of ith base station.

The minimum value assumed by d^2 is then used to assign the mobile to a base station.

Next a search is implemented to find a suitable fixed or dynamic voice channel. For this search GPSS coding developed in [13, pp. 55] can be used. If the search is successful, the mobile "picks up" a call holding time from the exponential distribution; otherwise, the call attempt is terminated according to Erlang-B discipline.

At regular intervals of simulated time (or cycle time, "T_c"), say 30 seconds, tests are performed on all calls which are still active. First, a new (X,Y) coordinate is computed using the old coordinates and the velocity vector; that is, if the new coordinate is (X',Y'), then:

$$X'=X+V_x T_c$$
$$Y'=Y+V_y T_c$$

Second, the following test is performed to determine if the mobile has moved outside the outer perimeter of the system:

$$d^2>1.1R^2? \qquad \text{Test 2}$$

where d is the separation of mobile from nearest base station, and R is the cell radius.

The premise upon which this test is based is that, while within the confines of the system, the mobile can never be further than a distance R from the nearest base station. If d^2 is 10% greater than R^2 then we say that the mobile has left the system. (The additional 10% allows some leeway for the cross-hatched areas of Fig. 6.1).

Third, test 1 is performed 37 times and a base station number assigned to the mobile. The new base station number is compared with the previous base station number to determine if a boundary crossing has indeed occurred. If so, a counter is incremented by one; if not, the counter remains unchanged. If the mobile has entered a new cell, a new channel search must be initiated. A counter is incremented by one if the search is successful; another counter is incremented by one if the search is unsuccessful.

Finally, in the assignment of velocity components V_x and V_y, currently, 50% of mobiles will have a V_x component and V_y component, 25% of mobiles will have a V_x component only and 25% of mobiles will have a V_y component only.

6.1.2 Generation of Random Position Coordinates ($\underline{X},\underline{Y}$)

The intention is to generate call attempts which are uniformly distributed in space and which constitute a Poisson process in time. For the call attempts to be uniformly distributed in space it is not merely sufficient that the X and Y coordinates be independent uniformly distributed random variables. This is a result of the shape of an individual cell and of the overall system of cells (both are hexagonal). As an explanation, consider the following illustration: if the X-coordinates were in fact uniformly distributed, then the probability that the random X value falls in a small range about X=0 would be identical to the probability that the X value falls in a small range of the same size centered about X=4.5R, for example (R=cell radius). Now if the X value were near zero and a uniformly distributed Y value were computed, then the call attempt could fall in any of the seven cells: 1,2,3,....,7. On the other hand, if the X value were near 4.5R, then the call attempt could only fall in one of the four cells: 30,31,32 or 33. As a result, when a simulation run was completed, there would be progressively more call attempts in those cells with larger X-coordinates.

The solution which has been implemented is to use a probability density function as shown in Fig. 6.2 for the X-coordinate while retaining a uniform distribution for the Y-coordinate.

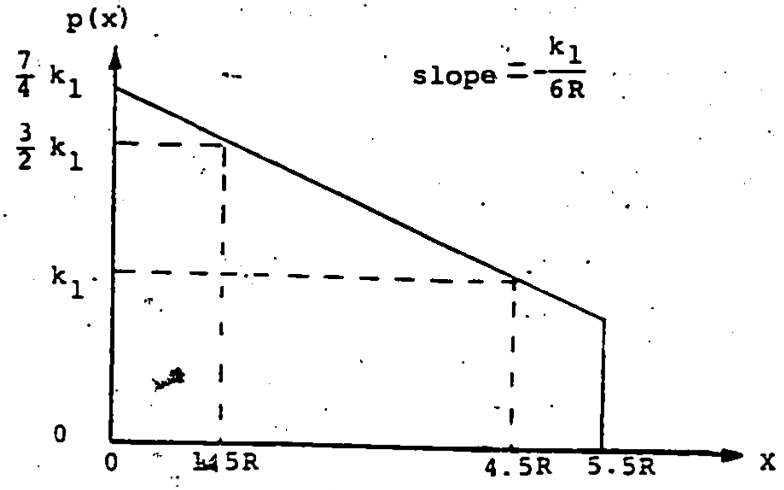


Fig 6.2 Probability Density Function of X-Coordinate

For example, the probability of choosing cells 11,12 or 13 which lie along $X=1.5R$, is 3/2 times as great as choosing cells 32 or 33 which lie along $X=4.5R$. From Fig. 6.2, we can write:

$$p(X) = -(K_1/6R)X + (7/4)K_1 \quad \text{for } 0<X<5.5R$$

Since $\int_{-\infty}^{\infty} p(X)dx = 1$, it is possible to determine K1:

$$K_1\int_0^{5.5R} p(X)dx = 1, \text{ therefore } K_1 = .1408/R.$$

Thus $p(X) = -(.02347/R^2)X + .2464/R,\ 0<X<5.5R$.

And finally: $P(X) = \int_0^X p(X)dx$, or:

$P(X) = -(.011735/R^2)X^2 + (.2464/R)X,\ 0<X<5.5R$.

The inverse comulative distribution function is found by solving the following equation for a given value of "U":

$$(.011735/R^2)X^2 - (.2464/R)X + U = 0$$

Where: U represents a random number uniformly distributed between 0 and 1. The numerical results for different values of R are tabulated in appendix A.

The steps followed in the initial assignment of a location to the mobile are:

1. Draw a random X value from the distribution tabulated (in Appendix B); call this value X_1.
2. Calculate $Y_1 = -(1/\sqrt{3})X_1 + \frac{11\sqrt{3}}{3}R$, for a given R (see Fig. 6.1).
3. Multiply Y_1 by a random number uniformly distributed between 0 and 1; label the new value of Y, Y_2.
4. Multiply X_1 by +1 or -1, and Y_2 by +1 or -1 such that the following ordered pairs are equally likely:

$$(X_1,Y_2);(-X_1,Y_2);(X_1,-Y_2);(-X_1,-Y_2)$$

6.1.3 GENERATION OF RANDOM VELOCITY COMPONENTS (V_x,V_y)

The V_x and V_y components of the velocity are truncated Gaussian random variables with means of zero metres/ses, standard deviations of 13 metres/sec and maximum values of 27 metres/sec (these values was used by Cox and Reudink [29]).

Because of the truncation, it is necessary to modify f(v) by some constant factor "c" in order that:

$$c\int_{-27}^{27} f(v)\,dv = 1, \text{ therefore :}$$

$$c = \frac{1}{\frac{1}{13\sqrt{2\Pi}}\int_{-27}^{27} e^{-s^2/338}\,ds} = 1.042$$

Thus :

$$F(v) = \frac{1.042}{13\sqrt{2\Pi}}\int_{-27}^{v} e^{-s^2/338}\,ds, \quad |v| \le 27$$

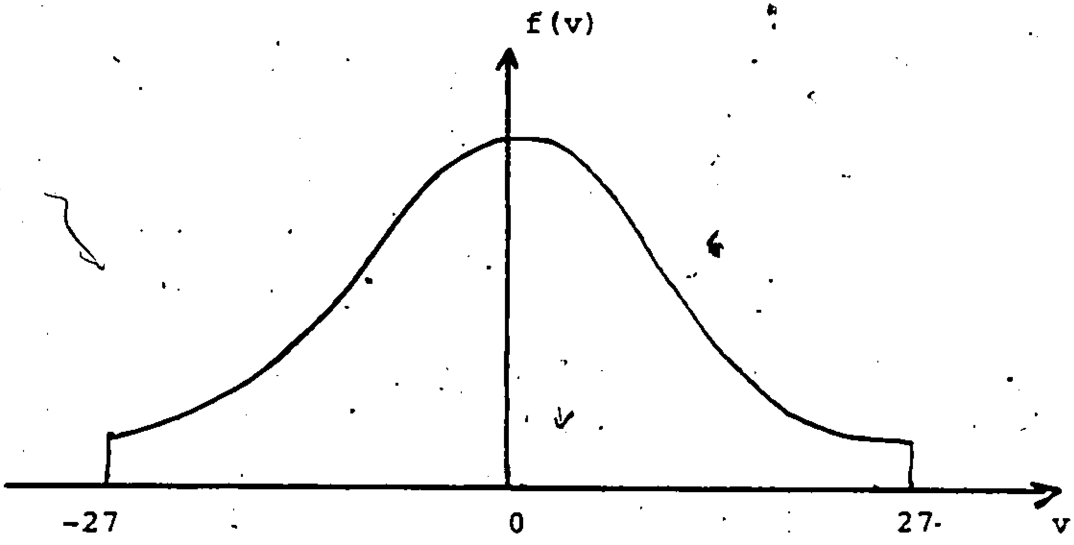


Fig 6.3 Probability Density Function of the Velocity Components

To tabulate the inverse cummulative distribution function for the random V and V components of the velocity, the following steps are performed:

i) Set F(v)=U

ii) Solve for "v" by using the error function table for the following values of U:

U=0,0.05,0.1,0.15,.......,1.0

Also the following assumptions are made:

1. All distances should be specified in meters. The reason is that after a random X or Y coordinate is generated, the values are automatically truncated to the nearest integer by GPSS. If the units are "metres", then the maximum error that would result from this truncation is 1 metre. In contrast, if the units were in kilometres, then the error could be as much as 1 km.
2. All the statistics should be calculated only for the central 19 cells. This eliminates "edge effects".

6.1.4 Channel Types and Reassignment Method

6.1.4.1 Channel Types

The simulation program has been made as flexible as possible and allows for four types of voice channels:

1. Nominal fixed channels: A channel assignment on a fixed basis to cell "i" (type A).
2. Fixed "hand-off" channels: A small group of channels in cell "i", assigned on a permanent basis, and to be used only for hand-offs and when a nominal fixed or nominal dynamic channel is not available (type B).
3. Nominal dynamic channels: A group of channels which may be used in any cell provided the co-channel interference constraint is met (type C).
4. Dynamic "hand-off" channels: A group of channels which may be used in any cell only when all the following conditions are met (type D):
    - i) May be used for hand-off purposes only. That is, for continuation of a call when a boundary crossing occurs.
    - ii) There are no nominal fixed channels available,
    - iii) There are no nominal dynamic channels available,
    - iv) There are no fixed "hand-off" channels available, and
    - v) The co-channel interference constraint is satisfied.

Previously, a typical channel division ratio might have been f:d=8:2 [13, pg.55], indicating 8 fixed channels per cell and 6 dynamic channels for use by the entire system. Now, in the most general case, "f" is further divided into types "A" and "B" and "d" is divided into types "C" and "D". As an example:

A:B:C:D=6:2:1:1

would signify 6, "type A" channels and, 2, "type B" channels per cell plus 3, "type C", and 3, "type D" channels available to the entire system.

6.1.4.2 Channel Reassignment Considerations

Channel reassignment must be carried out when:

1. A mobile, crossing a cell boundary, was using a fixed "hand-off" or nominal fixed channel in the old cell. Such a mobile must now find a new channel in the new cell and also release the old fixed channel. The released fixed channel can then be used to free a dynamic channel (if any) being used in the old cell.
2. A mobile using a nominal fixed channel or a fixed "hand-off" channel terminates its call.

The priorities during channel reassignment are:

a) A nominal fixed channel can free a nominal dynamic channel or a dynamic "hand-off" channel for further use.

b) A fixed "hand-off" channel can free a dynamic "hand-off" channel but not a nominal dynamic channel.

c) In all cases, an attempt is first made to free a dynamic "hand-off" channel for further use. If there are no dynamic "hand-off" channels in use in a particular cell, then an attempt is made to free a nominal dynamic channel.

The above channel reassignment policy is reflected in the flowchart of Fig. 6.4.

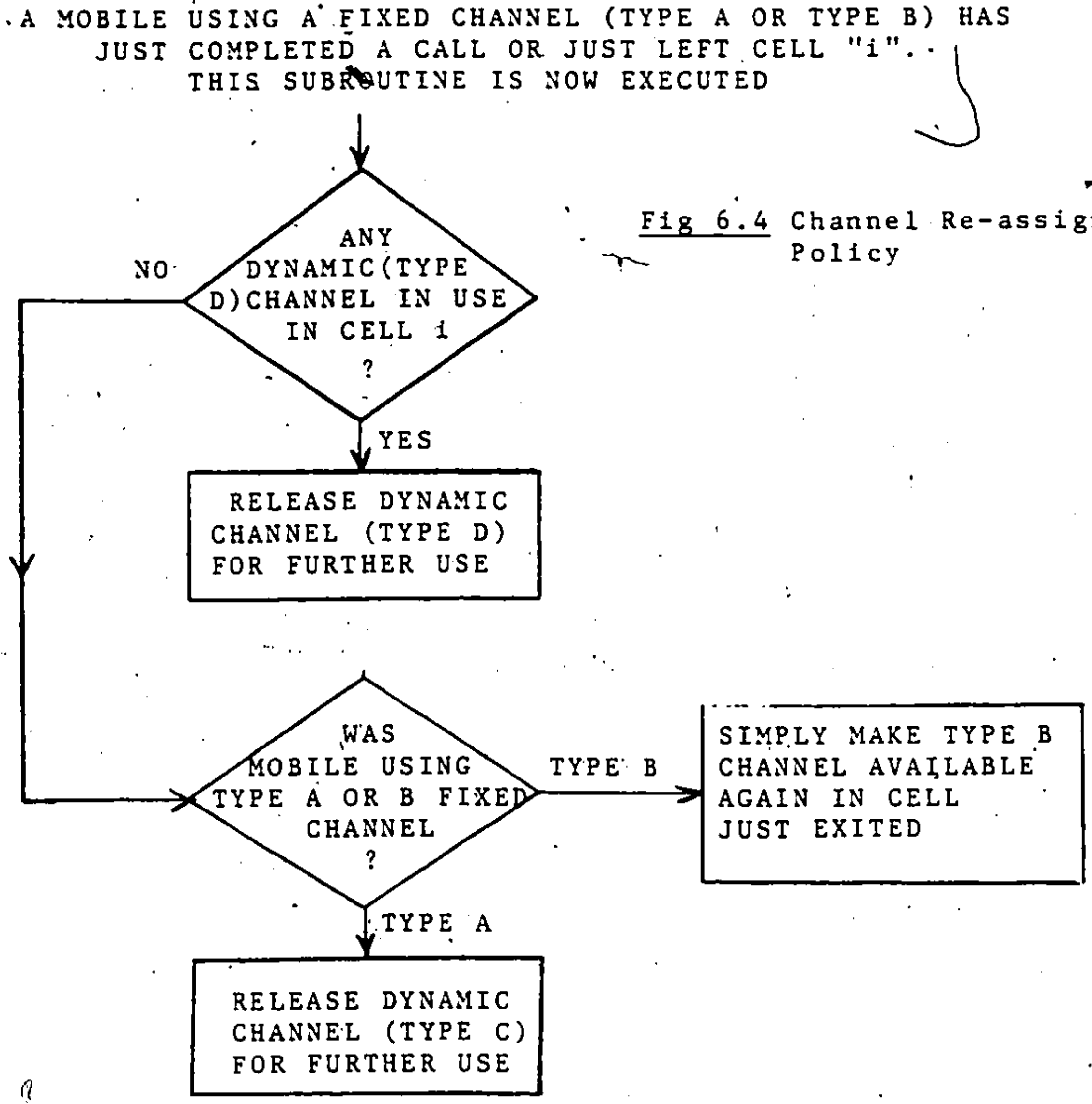


Fig 6.4 Channel Re-assignment Policy

6.1.5 The Statistics of Interest

1. Blocking probability (initial assignment):

$$P_b = \frac{\text{\# of Call attempts not finding a Channel}}{\text{Total Call attempts}}$$

2. Forced terminations, occuring when a mobile crosses a cell boundary and cannot find an available channel:

$$P_t = \frac{\text{\# of Calls forced to terminate when a boundary crossing occurs}}{\text{\# of boundary crossings}}$$

6.1.6 The Simulation Flow-Chart

The simulation model can be easily followed with the aid of the flow-chart's represented in Fig. 6.5 and Fig. 6.6. The first flow-chart represents the main program and the second flow-chart represents the subprogram for update of the mobile status. For the channel assignement flow-chart, please see the reference [13 pp. 55].

6.1.6.1 Main Program

The incoming calls arrive in the system according to the Poisson distribution. Each call is assigned an initial position in the system: a Random (X,Y) coordinate pair. In order for the call to be served, it is assigned to the nearest base station and given a velocity according to the truncated Gaussian distribution.

After the call completes these three steps, it searches for a nominal fixed channel. If none are available, then it searches for a nominal dynamic channel. This search is done in the same manner that was developed in the past for a hybrid system with Erlang-B discpline [13 pp. 55].

If the call fails to find a nominal channel, it will be rejected by the system. If it is successful in the search, it then enters the split box of the flow-chart in which a copy of the XAC's is made and sent to the advance block to serve out the holding time of its parent (the mean holding time is 2 minutes and its distribution is exponential). The copy unlinks its parent from the user chain, "ACTIV", once the call holding time has expired. The channel is then available again. The parent and copy are then terminated. The parent XAC was sent from the split box to be linked to the user chain "ACTIV".

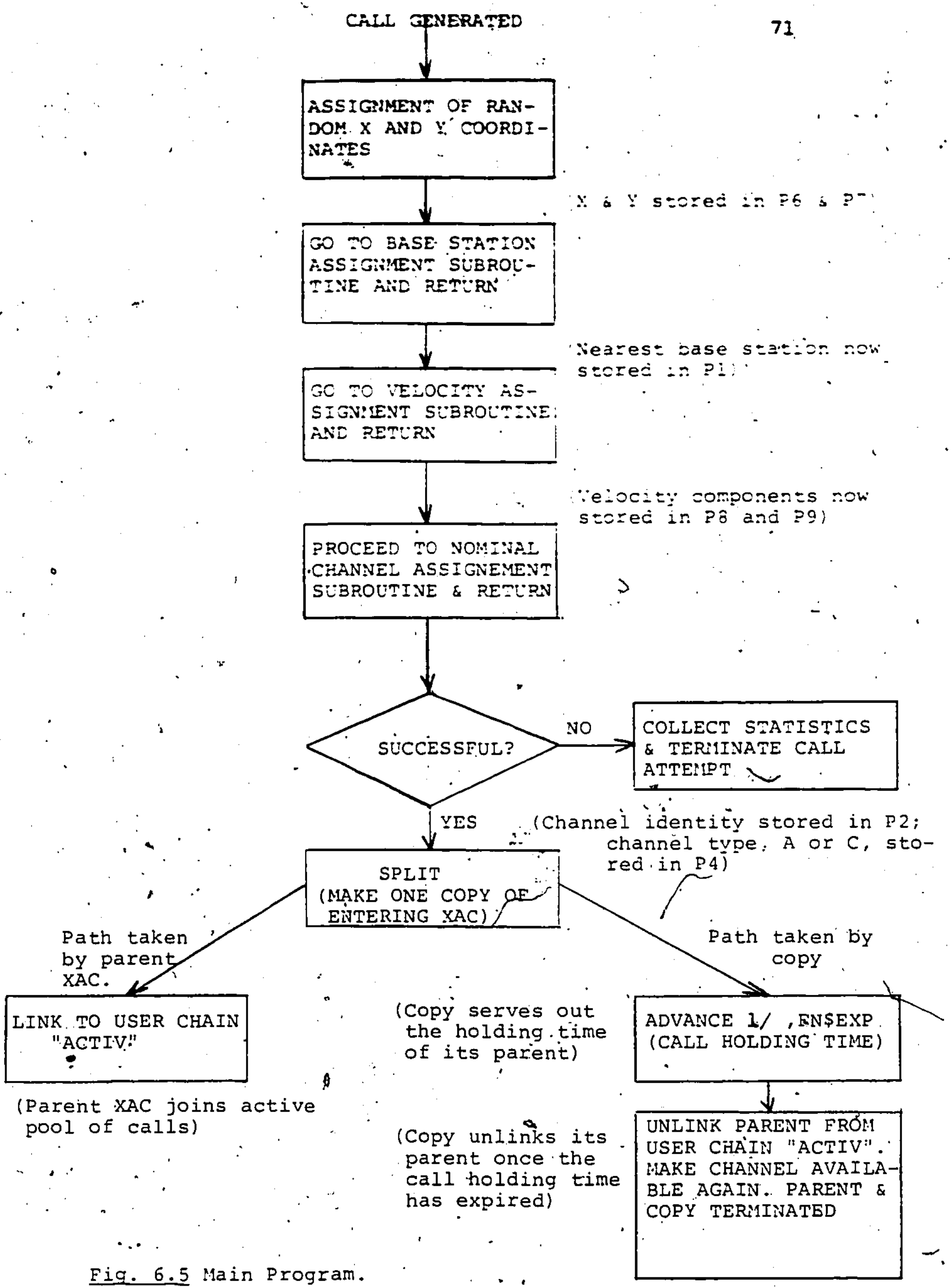


Fig. 6.5 Main Program.

6.1.6.2 Subprogram for Update of the Mobile Status

This subprogram is used to control the active mobiles (calls) for the successful continuation of their calls.

First, the calls will be sent one by one every 30 seconds, then all the collected calls will be withdrawn from the chain "ACTIV" to be sent one by one every 30 seconds to find the nearest base station.

The mobiles that find their base stations successfully are subjected to two tests. The first test verifies whether or not the mobiles are still in the system. If not, they must leave the system immediately. Otherwise, they are subjected to the second test. The second test involves determining if the mobiles are still in the same cell that were initially chosen. If the results of this test indicate that the mobiles always occupy their own cells, then the current channel assignment is acceptable. Next, a random selection of half of the active mobiles maintain their previous velocities. These mobiles are re-linked to the user chain "ACTIV" with no further processing. The remaining mobiles have their velocities re-initiated to zero and then have new values chosen for their velocities. They are then re-linked to the user chain "ACTIV".

If the results of the second test indicate that the mobiles are occupying new cells, then these mobiles are

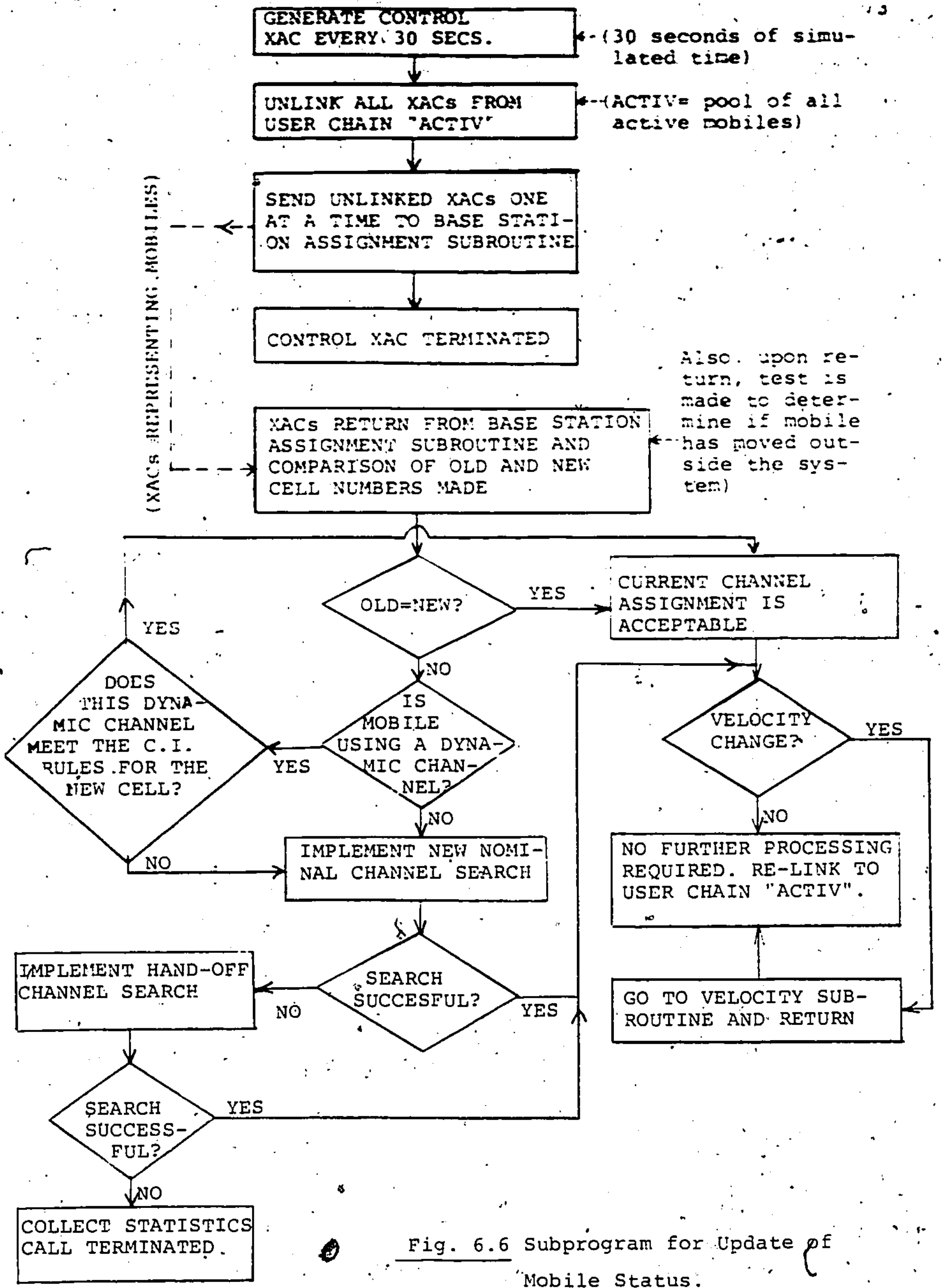


Fig. 6.6 Subprogram for Update of Mobile Status.

tested further to determine if they used dynamic channels in their old cells. If they were, then it must be shown that the interference rules are satisfied in the new cells. If the rules are satisfied, then the mobiles affected can be treated as though they didn't change cells. Mobiles that did not satisfy the interference rules must be handled separately. These mobiles will have to search for new nominal channels. If the search is successful, then these mobiles will verify their velocities and be grouped with mobiles that didn't change cells. If the search was not successful, then the calls will search for a new type of channel: A "hand-off" channel.

If hand-off channels are available, then these calls will be served. If hand-off channels are not available, then these calls will be forced to a premature termination.

6.2 THE INCREASING OF TRANSMITTER POWER METHOD

6.2.1 Method Description

A second solution to solve the problem of signal attenuation when a mobile unit is far away from the local base station, is the transmitter power method. This involves increasing the transmitter power of the base station, so that the mobile can retain it's original channel (and hence the original base station) as it crosses cell boundaries.

The model to be developed for this method is the same as was developed in the previous section with some modification.

Since the transmitter power of the base station in a cell is enough to service all the calls within that cell only, the power must be increased to service the calls in progress while the mobile is outside of the originating cell.

Since the mobile unit is to keep the same initial channel for the entire holding time of the call, "hand-off" frequencies are not needed. The question here is, what is the additional power needed so that the probability of "switching" frequencies is reduced to zero?. When the mobile unit enters an adjacent cell and is still being serviced by the same channel, the co-channel interference problem arises when the ICG of the new cell contains at least one busy channel. Hence, the average of the co-channel interfence must be also considered.

6.2.2 System Development

The model of transmitter power increasing method, is obtained by making a number of modifications to the flow-chart shown in Fig. 6.6.

When a call in progress crosses the boundary of the cell from where it originated, to an adjacent cell, its distance d from the old base station is compared to the distance (R+aR). The value "aR" is the additional distance (a percentage of the cell radius) given to the call so that the call can keep being serviced by the same initial channel. If the distance d is found to be greater than (R+aR), then this call will need to be switched to a new channel; that is the "hand-off" procedure will apply,

Otherwise, the existance of co-channel interference must be tested for. If the ICG of the cell in question contains any busy channel, a counter will be incremented by one. This increment of one represents one occurrence of co-channel interference. Another counter will be incremented by the number of the busy channels in the ICG. This second increment represents the number of channels interfering with the channel in question. The counters will remain unchanged if the ICG does not contain any busy channels.

At the end of the system simulation, two questions have to be answered: what is the additional power needed for the call to keep the same initial channel? and, what is the average of the co-channel interference produced?.

Chapter VII

SIMULATION RESULTS

The cellular system shown in Fig. 6.1 was simulated. The simulation was performed using the simulation package GPSS/360 on an AMDAHL 470/V7A computer. The simulation was started with no calls in the system. Statistics were collected at the end of each simulation run. The traffic is uniformly distributed over the cells. 37 cells were used because of the constraints imposed by GPSS [10,11,12]. The performance data is accumulated from the central portion of the system (19 middle cells) which is representative of an infinite system. The reason for using an infinite cellular layout is to overcome the edge effects. Using a finite system, cells near the edges of the system will have fewer neighbouring cells to induce co-channel interference. The cells around the edges have insufficient neighbouring cells to cause calls to be blocked, whereas the centrally located cells have numerous neighbouring cells. This results in a higher probability of co-channel interference in the calls originating from the central cells than those originating from cells at the edges.

7.1 THE "HAND-OFF" PROCEDURE SYSTEM PERFORMANCE

In this section, the results obtained by using a fixed system will be presented. Recall that a fixed system is one that contains no nominal dynamic channels.

The analysis only examines the performance of 19 central cells. This avoids the effects resulting from the boundary of the system. The number of fixed nominal channels was varied over four values while the number of "HAND-OFF" channels is increased from zero as starting value. Recall that a "HAND-OFF" channel is one reserved for a mobile call which has to change its frequency in crossing the cell boundaries. It is used when none of the nominal fixed channels are available. Three different situations are studied: First, a system with only nominal fixed channels, secondly, a system with fixed "HAND-OFF" channels added to the system, and finally, a system with dynamic "HAND-OFF" channels replacing the fixed "HAND-OFF" channels of the previous case.

7.1.1 SYSTEM WITH NOMINAL FIXED CHANNELS ONLY

This system assumes that each cell has an equal number of nominal fixed channels.

The simulation results of this system are presented in Tables 7.1-7.4 and Fig. 7.1-7.8. For four different partitions of channels (5:0:0:0,10:0:0:0,15:0:0:0,20:0:0:0) the probabilities of blocking the initial calls are approximately the same as those for calls coming from mobiles crossing the boundaries of adjacent cells. This is because a call crossing the boundary of a cell does not have any special priority in finding a channel in the new cell. It is considered to be a new call generated within a new cell. Therefore, such a call has an equal chance of being served by a voice channel as any "true" newly generated call.

These two types of the probabilities of blocking are compatible with the theoretical results for (Erlang-B) with some differences due to the fact that the mobiles were assigned velocities which allowed them to move across the boundaries of adjacent cells. However, the same system was simulated with velocities equal to zero and yielded results comparable to the theory.

7.1.2 System with Fixed "HAND-OFF" Channels

Here, the hand-off calls are given higher priority to be served than the initial calls. This priority comes about by adding a number of "HAND-OFF" channels in each cell. The results of simulation are shown in Tables 7.1-7.4 and Fig. 7.1-7.8. It can be found, from the results, that to make the probabilities of blocking of the calls in hand-off status acceptably small, a 20% of the total number of nominal fixed channels must be added to each cell, as fixed "HAND-OFF" channels. This applies to a system whose traffic gives a grade of service up to 2%. In other words, for 5 nominal fixed channels per cell, 1 fixed "HAND-OFF" channel is needed to avoid blocking of calls in hand-off status, where the traffic corresponds to a grade of service of 2%. With 10 nominal fixed channels per cell, 2 fixed "HAND-OFF" channels are needed,..etc. Experiments were made for the following partitions of channels: 5:1:0:0, 10:2:0:0, 15:3:0:0, 20:4:0:0.

Table 7.1

TRAFFIC [ERLANGS]	5:0:0:0 SIMULATION		5 FIXED CHANNELS ERLANG-B	5:1:0:0 SIMULATION	
	%Pb	%Pt	%Pb	%Pb	%Pt
1.0	.32	0	.34	.36	0
1.5	.94	1.4	1.4	1.27	0
1.7	1.86	1.56	2.2	1.96	0
1.88	1.97	2.27	3.0	2.65	.35

Table 7.2

TRAFFIC [ERLANGS]	10:0:0:0 SIMULATION		10 FIXED CHANNELS ERLANG-B	10:2:0:0 SIMULATION	
	%Pb	%Pt	%Pb	%Pb	%Pt
3.09	.11	.15	.1	.20	0
3.96	.26	.28	.5	.37	0
5.08	1.22	1.82	2.0	1.62	0
7.5	7.21	7.46	10.0	6.6	.7

Table 7.3

TRAFFIC [ERLANGS]	15:0:0:0 SIMULATION		15 FIXED CHANNELS ERLANG-B	15:3:0:0 SIMULATION	
	%Pb	%Pt	%Pb	%Pb	%Pt
7.38	.42	.8	.5	.4	0
9.00	1.77	2.26	2.0	1.49	0
10.00	2.74	2.68	3.5	2.87	0

TRAFFIC [ERLANGS]	15:2:0:0 SIMULATION	
	%Pb	%Pt
8.5	.93	.23
10.0	2.70	.55

Table 7.4

TRAFFIC [ERLANGS]	20:0:0:0 SIMULATION		20 FIXED CHANNELS ERLANG-B	20:4:0:0 SIMULATION	
	%Pb	%Pt	%Pb	%Pb	%Pt
12	.42	.53	1.0	.64	0
13.5	1.98	2.31	2.4	1.56	.13
14.0	2.70	2.67	3.0	2.16	0

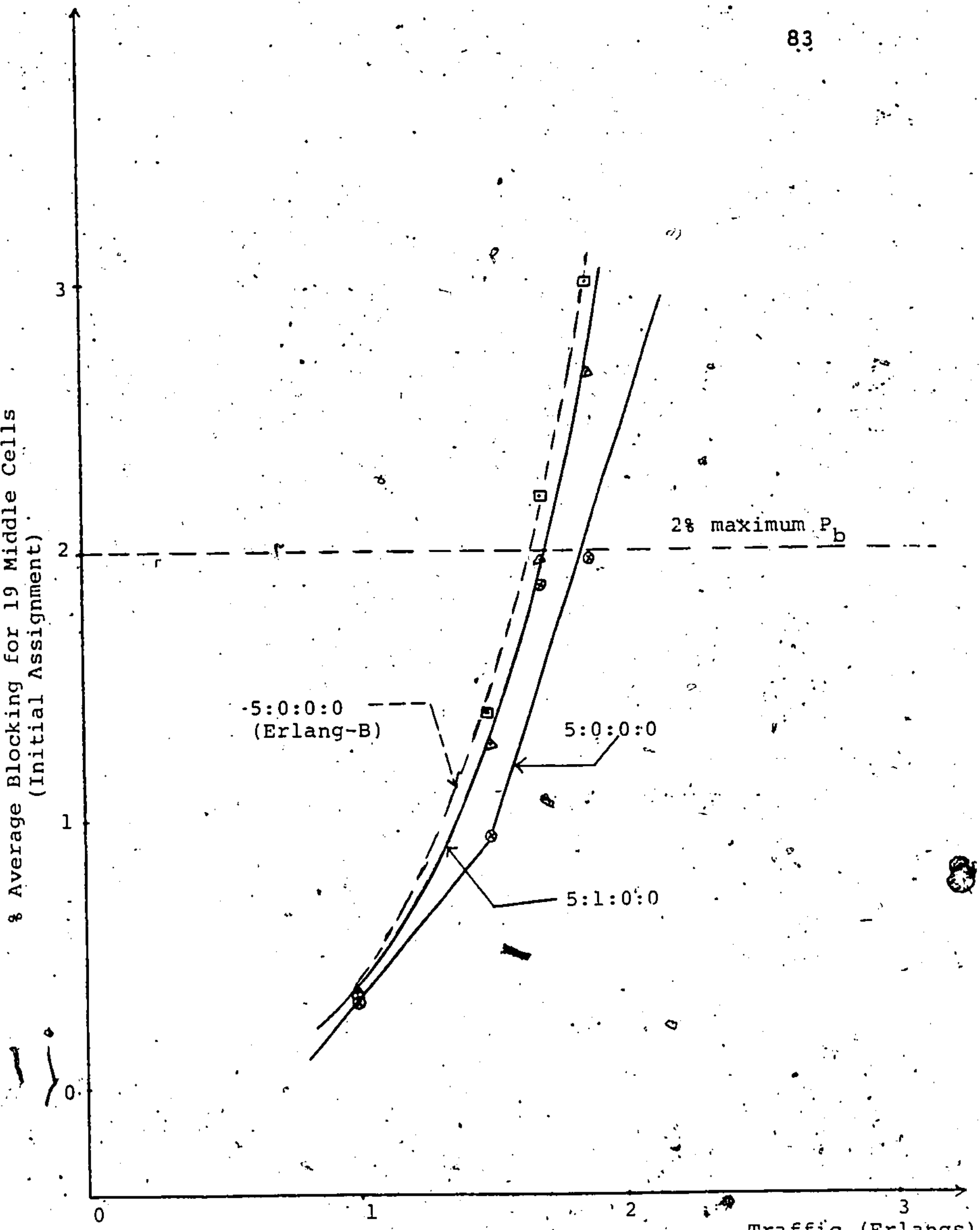


Fig 7.1 Performance of System with Initially 5 Nominal Fixed Channels per Cell, and with 5 Nominal fixed Channels Plus One Fixed Channel per Cell Reserved for the Hand-off Calls

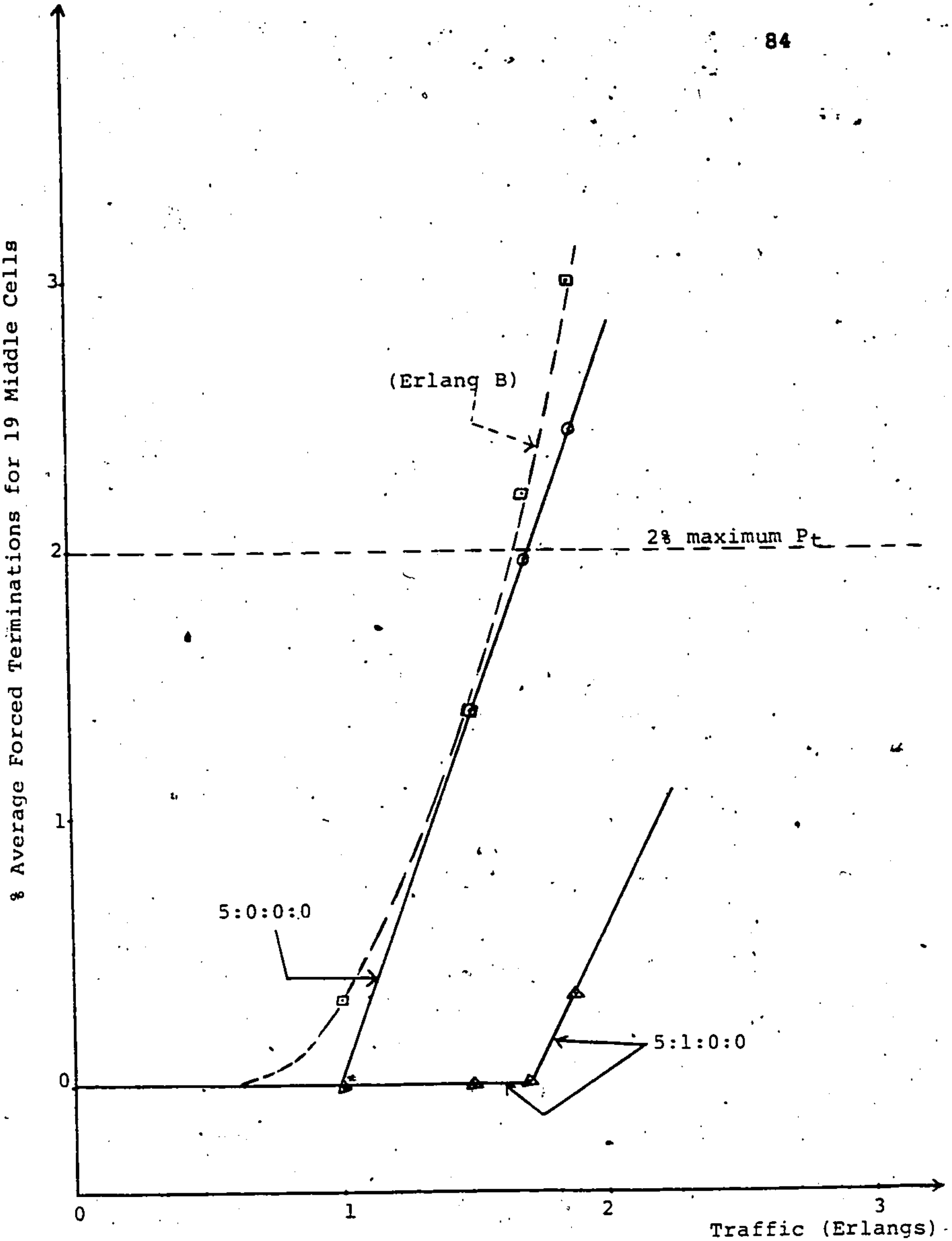


Fig 7.2 Performance of System with Initially 5 Nominal Fixed Channels per Cell , and with 5 Nominal Fixed Channels Plus One Fixed Channel per Cell Reserved for the Hand-off Calls

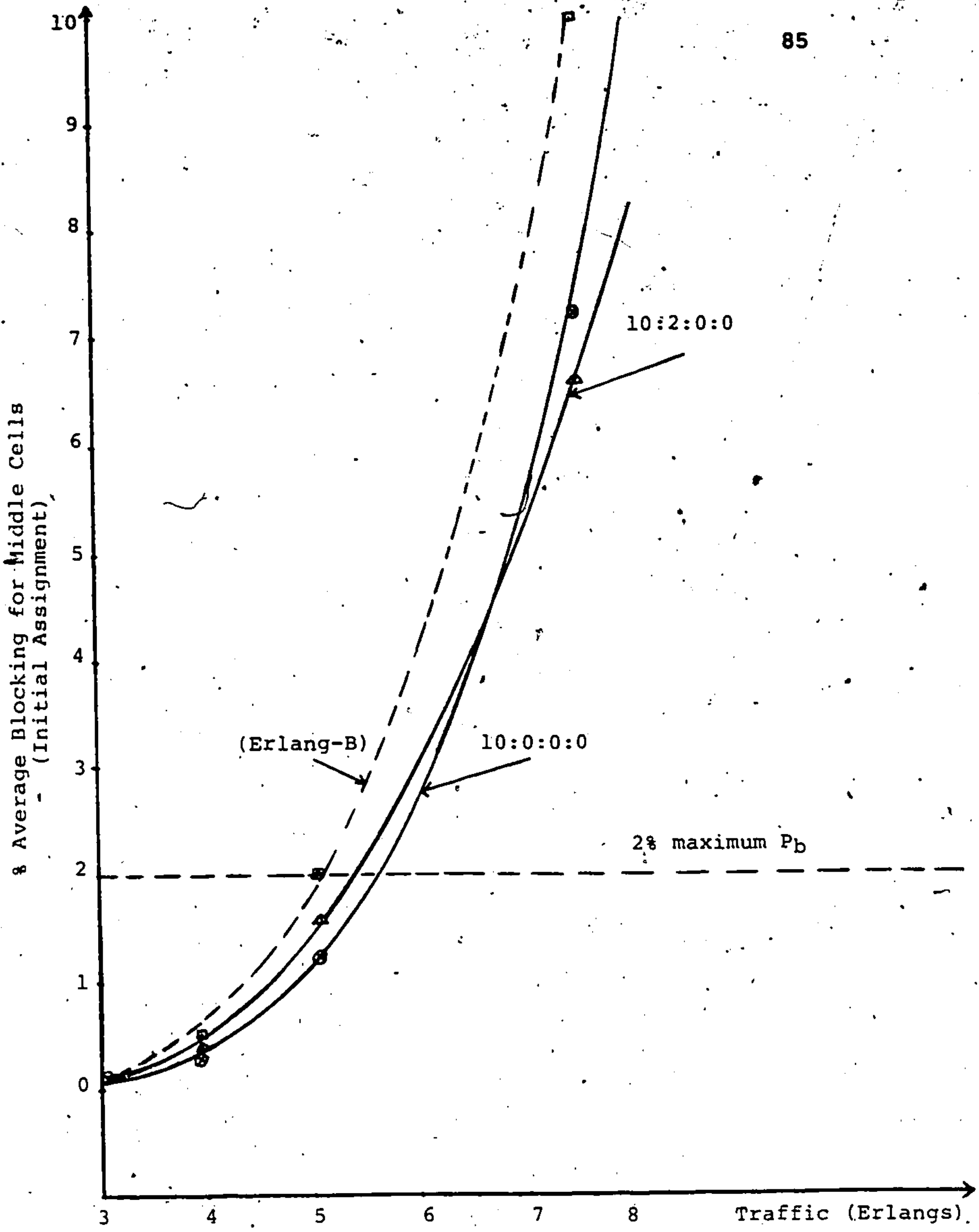


Fig 7.3 Performance of System with Initially 10 Nominal Fixed Channels, and with 10 Nominal Fixed Channels Plus 2 Fixed Channels per Cell Reserved for the Hand-off Calls

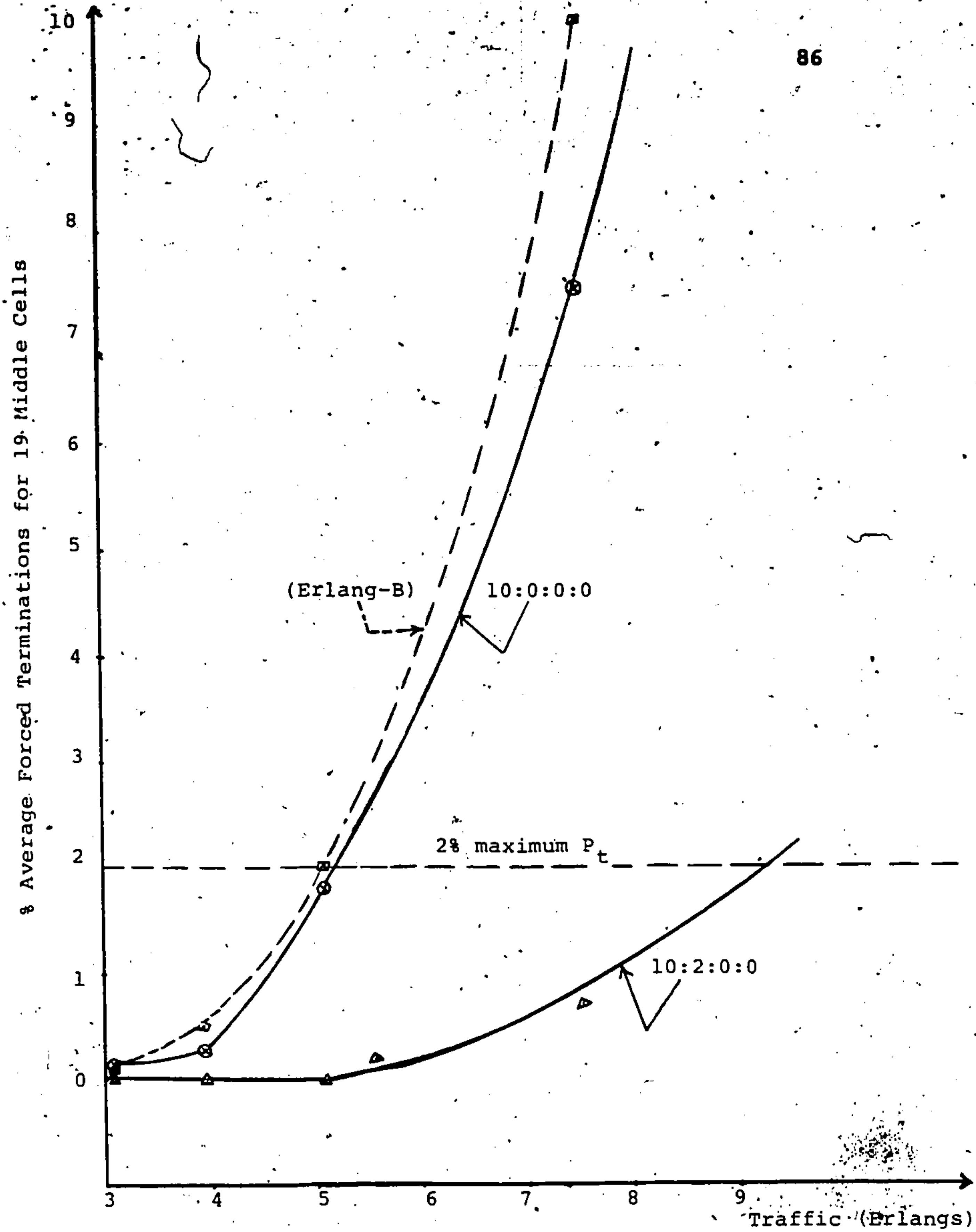


Fig. 7.4 Performance of System with Initially 10 Nominal Fixed Channels per Cell, and with 10 Nominal Fixed Channels Plus 2 Fixed Channels per Cell Reserved for the Hand-off Calls

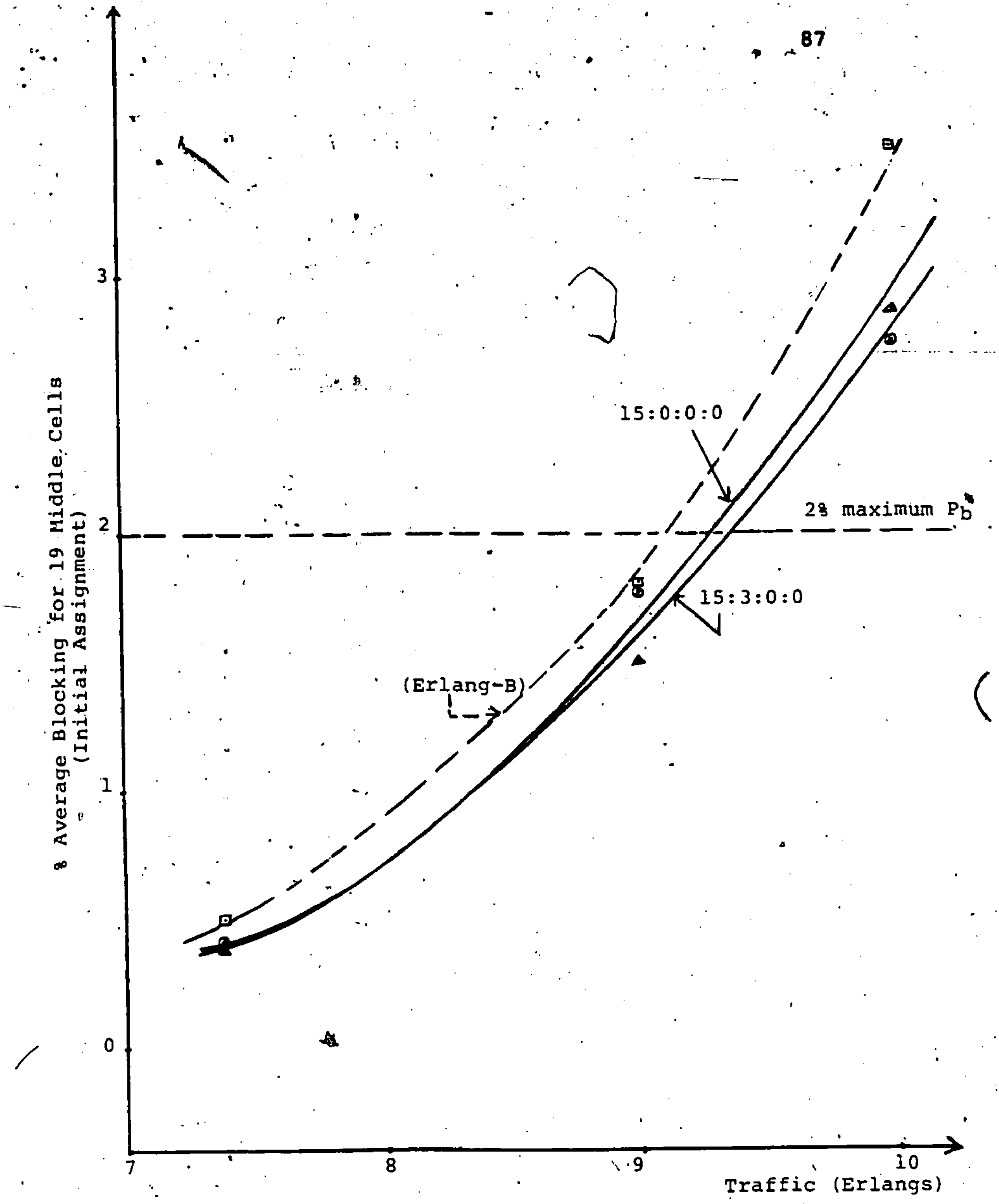


Fig. 7.5 Performance of System with Initially 15 Nominal Fixed Channels per Cell, and with 15 Nominal Fixed Channels Plus 3 Fixed Channels per Cell Reserved for the Hand-off Calls

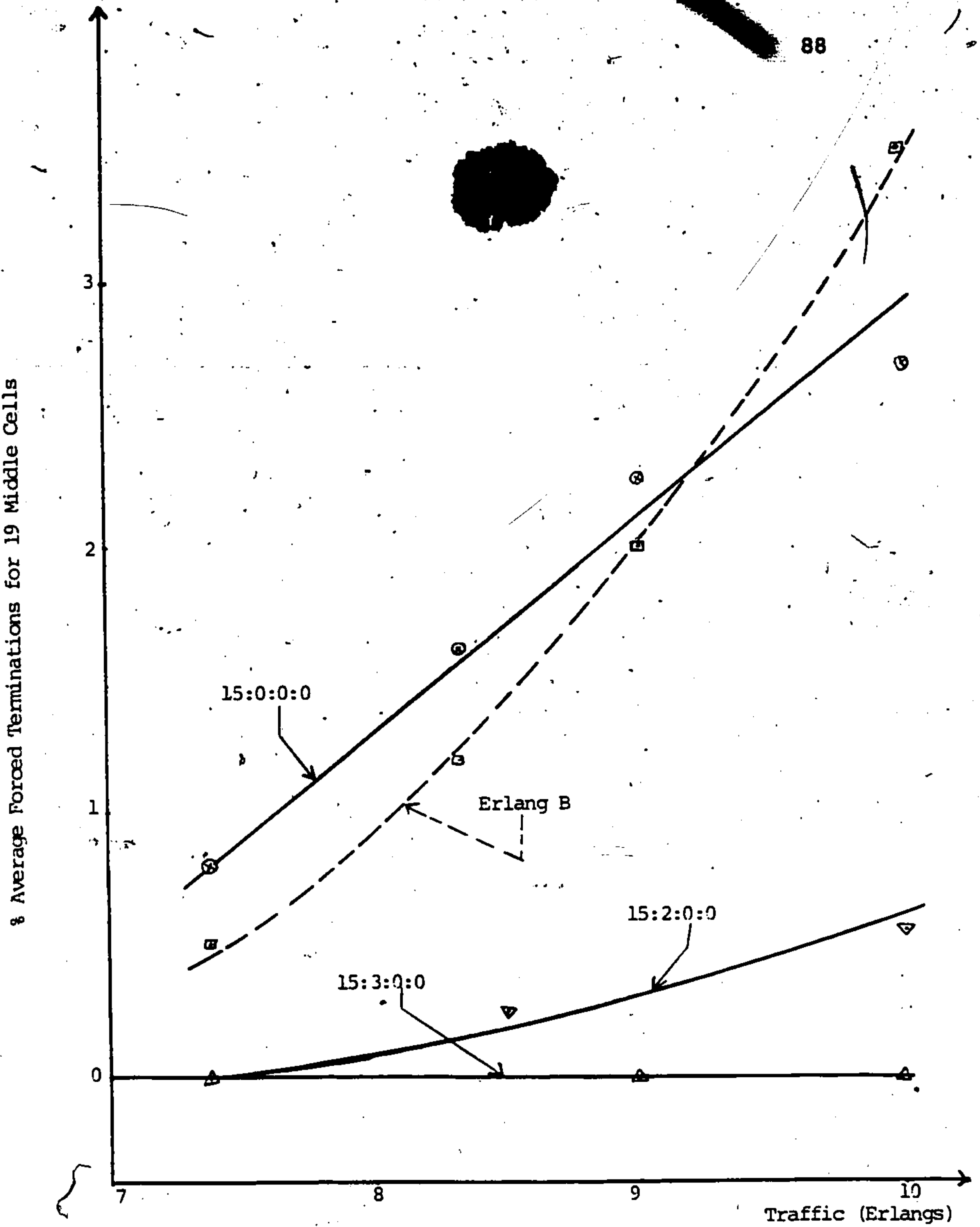


Fig 7.6 Performance of System with Initially 15 Nominal Fixed Channels per Cell, and with 15 Nominal Fixed Channels Plus 2 or 3 Fixed Channels per Cell Reserved for the Hand-off Calls

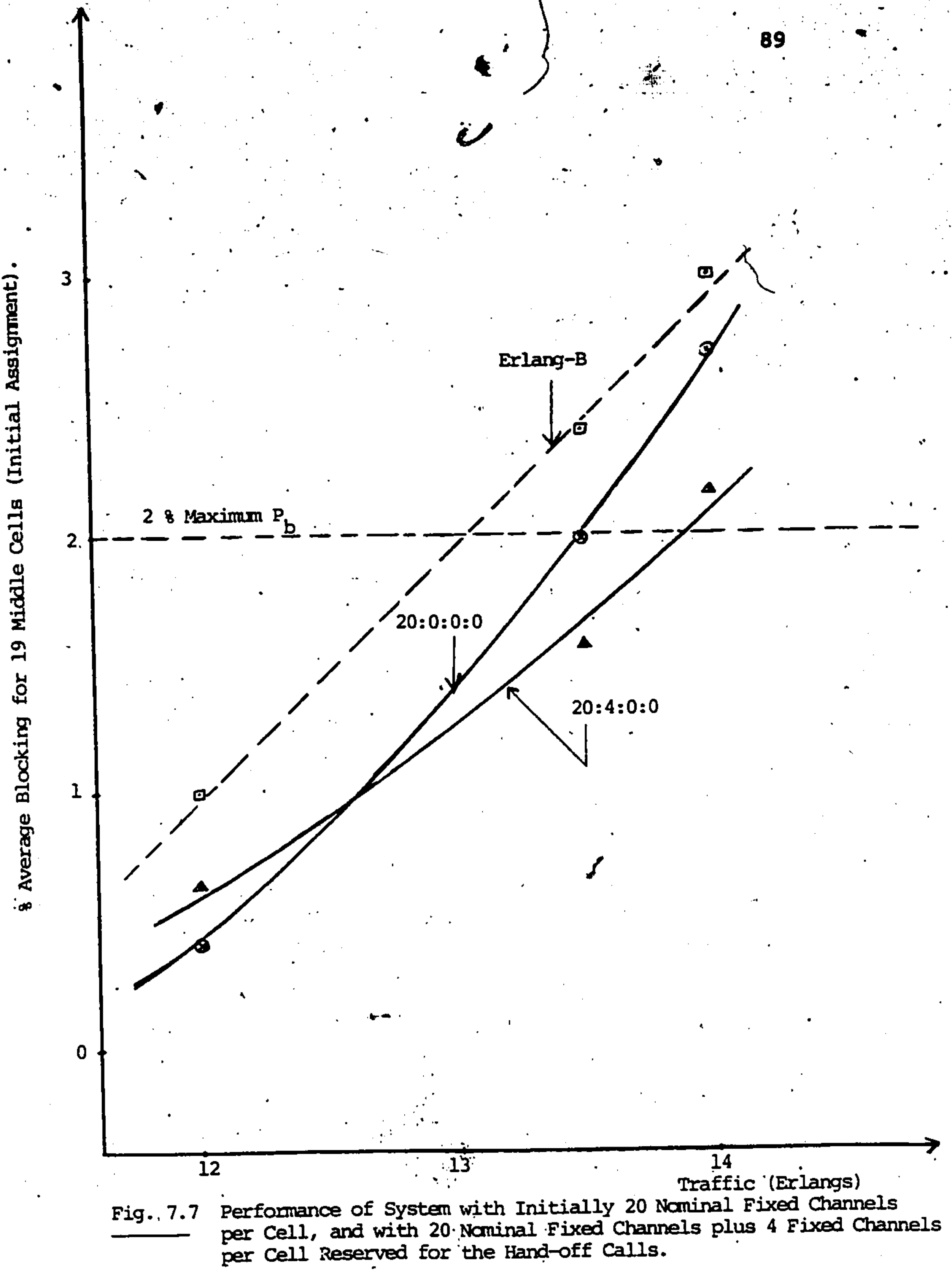


Fig. 7.7 Performance of System with Initially 20 Nominal Fixed Channels per Cell, and with 20 Nominal Fixed Channels plus 4 Fixed Channels per Cell Reserved for the Hand-off Calls.

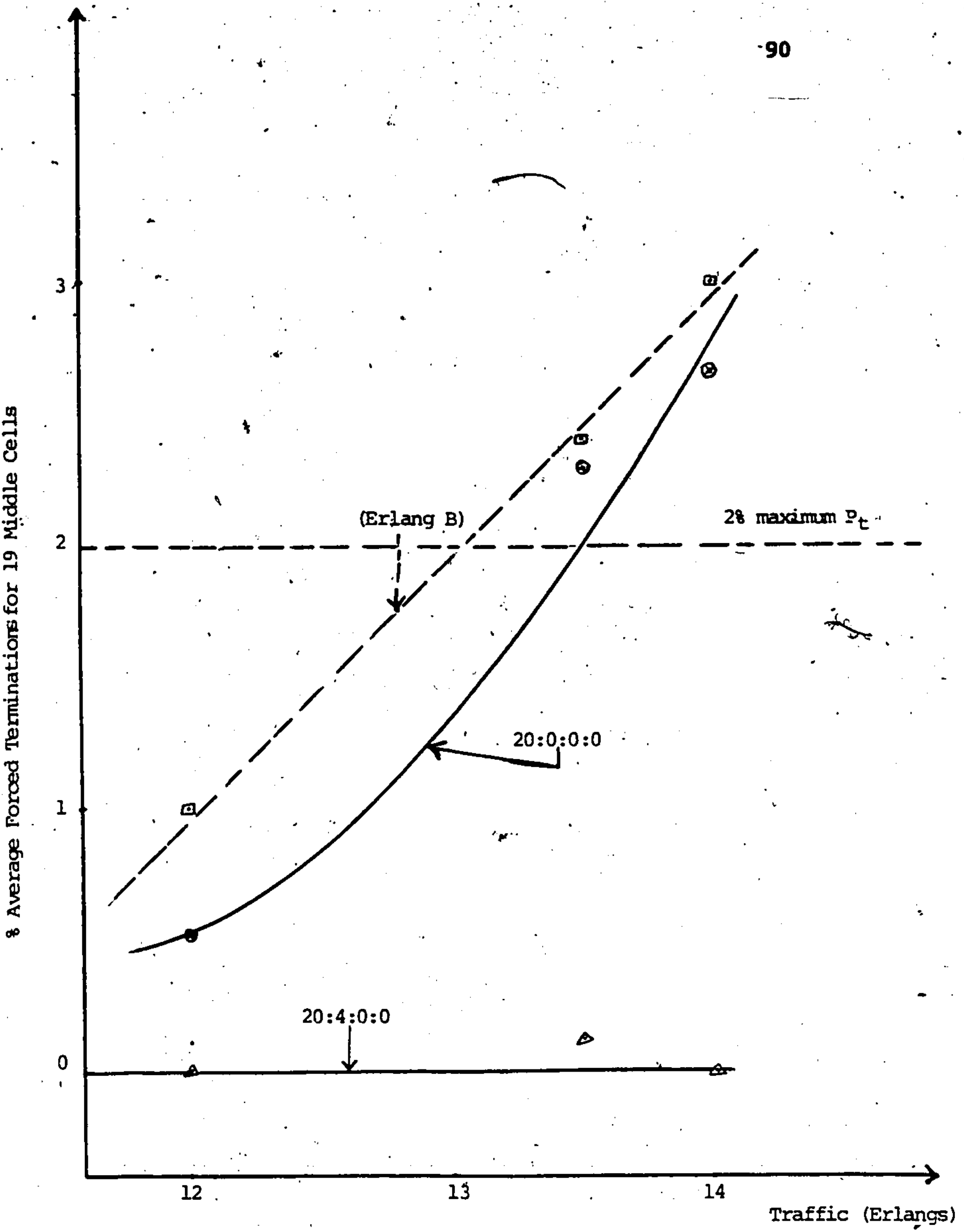


Fig 7.8 Performance of System with Initially 20 Nominal Fixed Channels per cell, and with 20 Nominal Fixed Channels Plus 4 Fixed Channels Reserved for the Hand-off Calls.

7.1.3 System with Dynamic "HAND-OFF" Channels

In this model, the fixed "HAND-OFF" channels are replaced by dynamic "HAND-OFF" channels. Such channels give higher priority to the hand-off calls than the initial calls. "HAND-OFF" channels of 20% of the number of nominal fixed channels per cell, were needed to eliminate blocking of the hand-off calls for a grade of service of 2%. In this case, the number of dynamic "HAND-OFF" channels required to attain this same objective is 26.7% of the number of nominal fixed channels per cell. For example 4 dynamic "HAND-OFF" channels per system (i.e. 4/3 channel per cell) are needed for the 5 nominal fixed channels per cell. For a system of 10 nominal fixed channels, 2 dynamic "HAND-OFF" channels per cell are not enough to reach the objective. However, 8 dynamic "HAND-OFF" channels per system (i.e. 8/3 channels per cell) are enough to eliminate the blocking of the hand-off calls. For systems with 15 and 20 nominal fixed channels per cell, 4 and 16/3 dynamic "HAND-OFF" channels per cell are needed respectively. In each case the number of dynamic "HAND-OFF" channels needed per cell represents 26.7% of the number of nominal fixed channels per cell. The simulation results are shown in Tables 7.5-7.8 and Fig. 7.9-7.12.

The addition of fixed "HAND-OFF" channels to the system yields a higher performance (in terms of reducing the blocking probabilities of the hand-off calls), than the system with dynamic "HAND-OFF" channels. The reason is that the dynamic channels cannot be used if the co-channel interference rules are not satisfied.

Table 7.5

TRAFFIC [ERLANGS]	5:0:0:0 SIMULATION %Pb	5:0:0:0 SIMULATION %Pt	5:0:0:3* SIMULATION %Pt	5:0:0:4* SIMULATION %Pt
1.0	.32	0	0	0
1.7	1.86	1.56	.99	0
2.16	2.9	2.76	1.16	.29

Table 7.6

TRAFFIC [ERLANGS]	10:0:0:0 SIMUL. %Pb	10:0:0:0 SIMUL. %Pt	10:0:0:6* SIMUL. %Pt	10:0:0:9* SIMUL. %Pt	10:0:0:8* SIMUL. %Pt
3.09	.11	.15	0	0	0
5.08	1.22	1.82	1.73	0	0
5.9	—	—	—	0	.35
7.5	7.21	7.46	3.93	.96	1.11

Table 7.7

TRAFFIC [ERLANGS]	15:0:0:0 SIMULATION		15:0:0:9* SIMULATION	15:0:0:12* SIMULATION
	%Pb	%Pt	%Pt	%Pt
7.38	.42	.8	0	0
9.00	1.77	2.26	.56	0
10.00	2.27	2.68		.34

table 7.8

TRAFFIC [ERLANGS]	20:0:0:0 SIMULATION %Pt	20:0:0:16* SIMULATION %Pt
12.0	.53	0
13.5	2.31	0
14.0	2.67	0

*: Number of dynamic hand-off channels in the system.

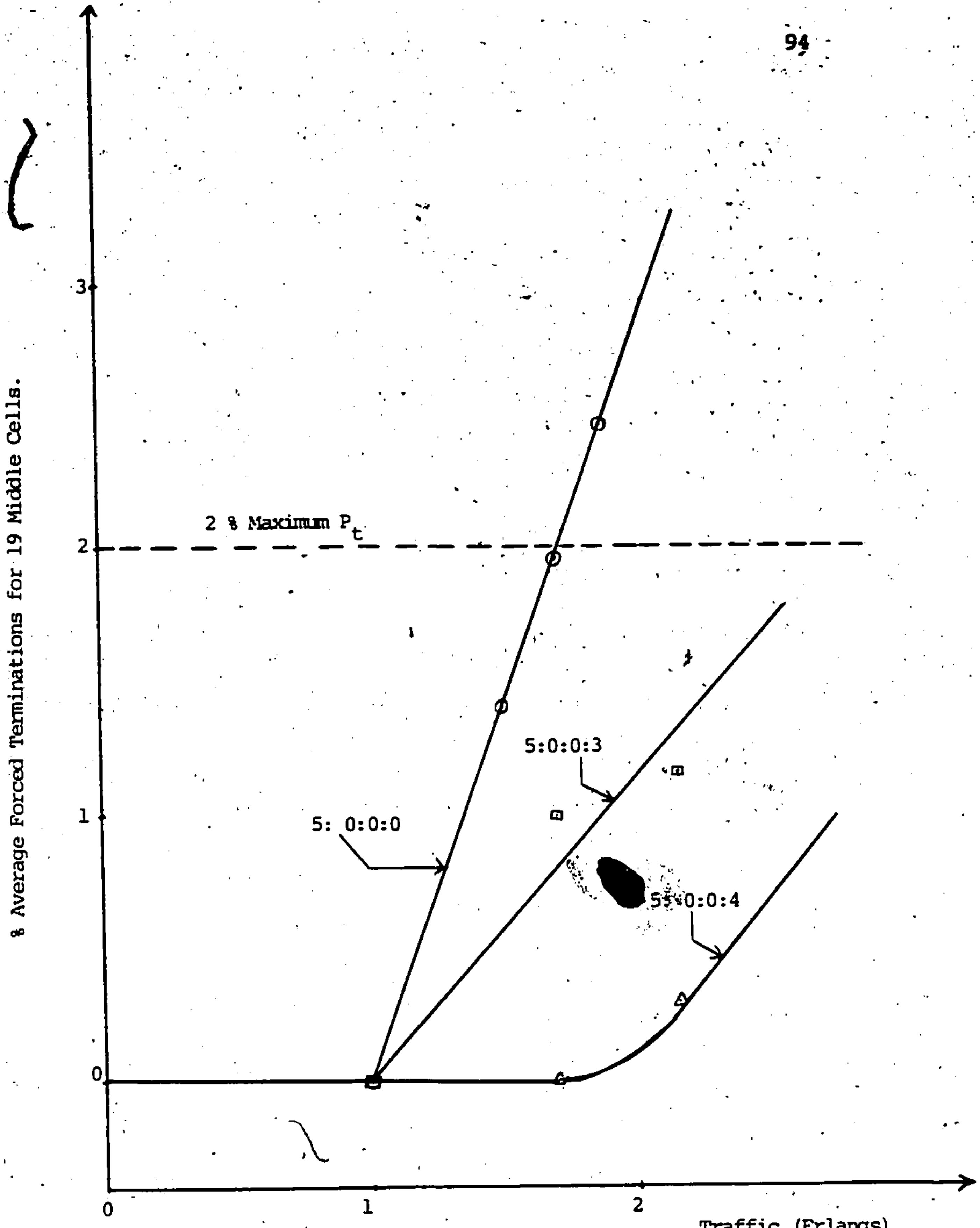


Fig. 7.9 Performance of System with Initially 5 Nominal Fixed Channels per Cell, and with 5 Nominal Fixed Channels per Cell plus 3 or 4 Dynamic Channels in the System (1 or 4/3 Channel per Cell) Reserved for the Hand-off Calls.

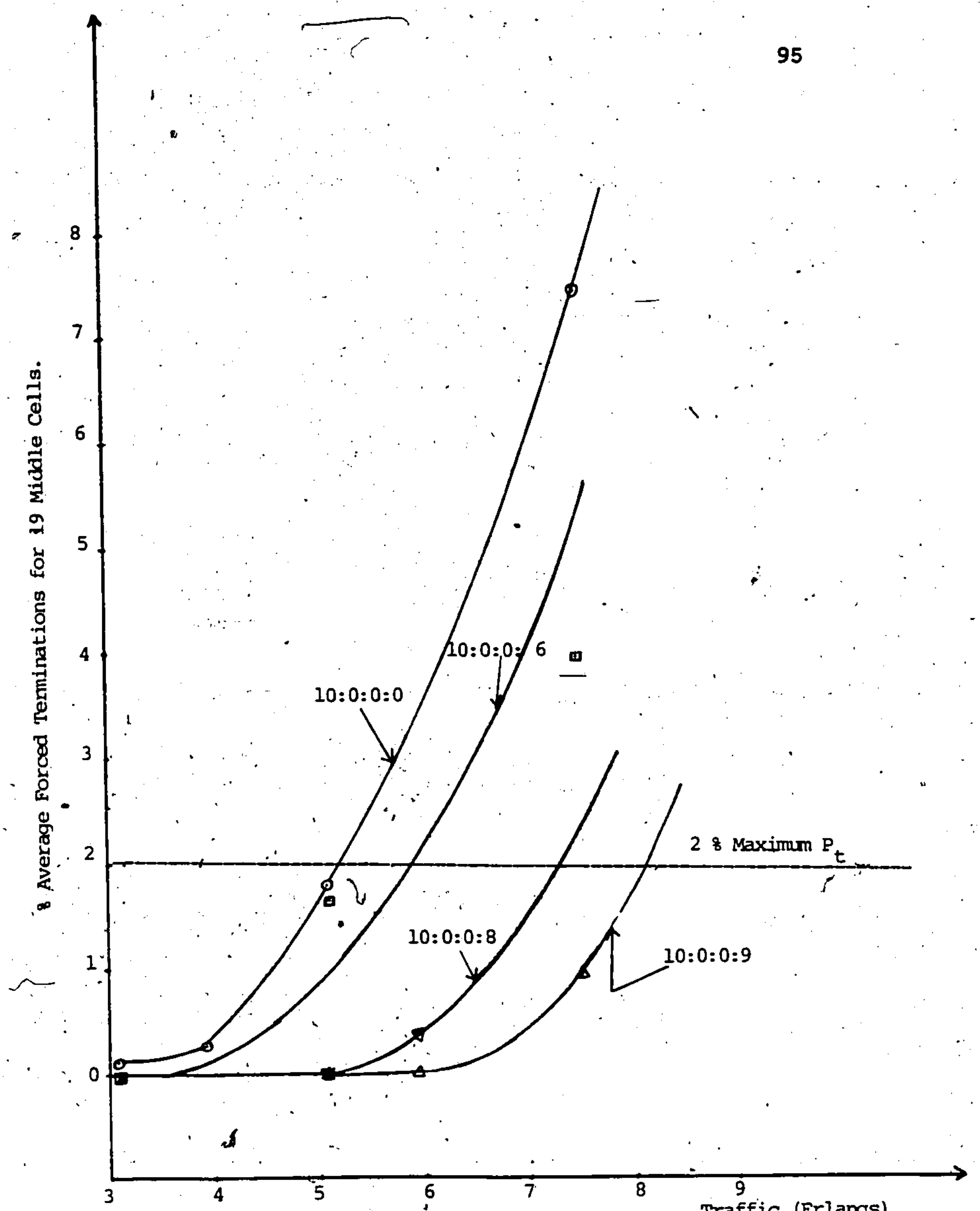


Fig. 7.10 Performance of System with Initially 10 Nominal Fixed Channels per Cell, and with 10 Nominal Fixed Channels per Cell plus 6,8, or 9 Dynamic Channels in the System (2,8/3,or 3 Channels per Cell) Reserved for the Hand-off Calls.

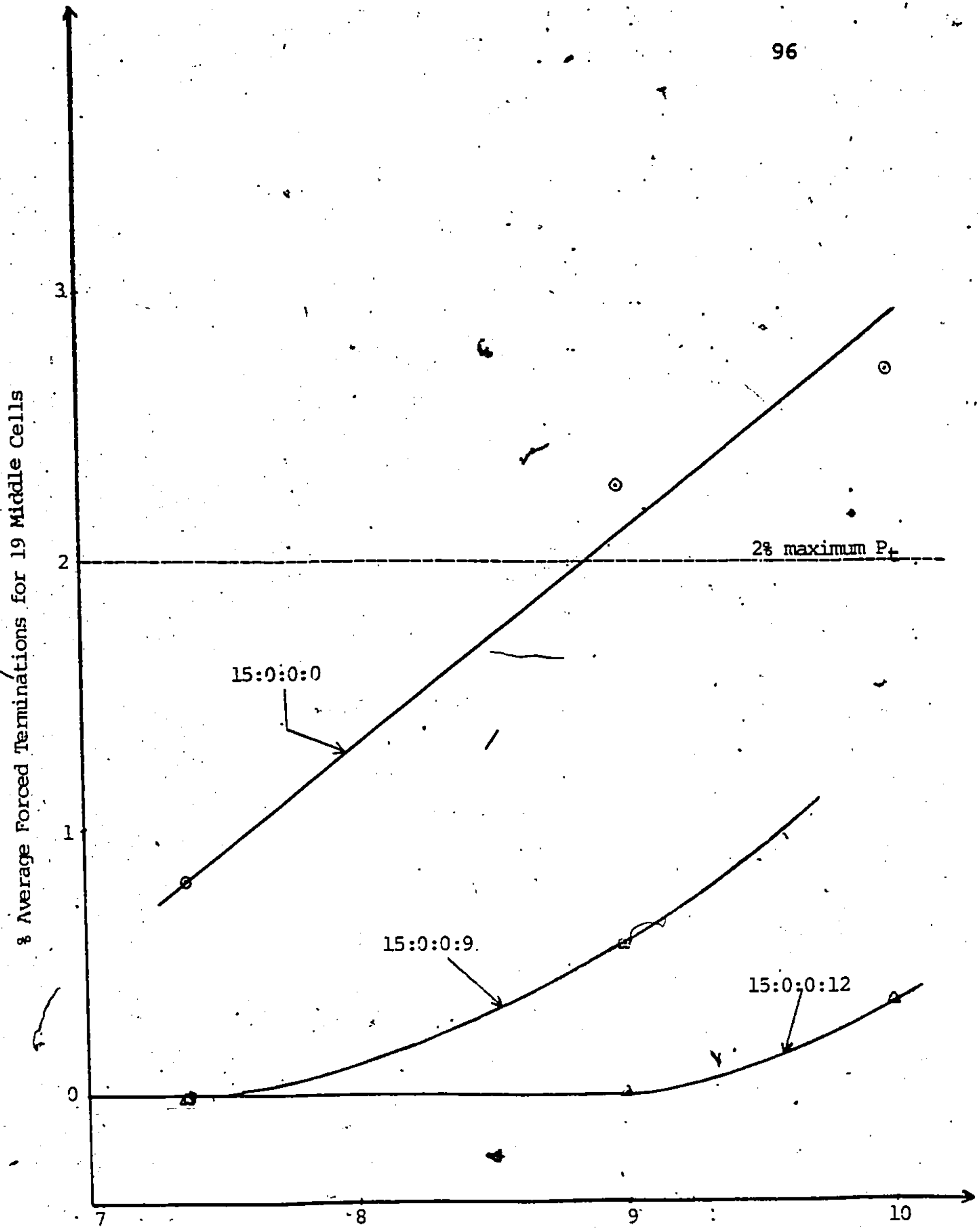


Fig 7.11 Performance of System with Initially 15 Nominal Fixed Channels per Cell, and with 15 Nominal Fixed Channels per Cell Plus 9 or 12 Dynamic Channels in the System (3 or 4 channels per cell) Reserved for the Hand-off calls.

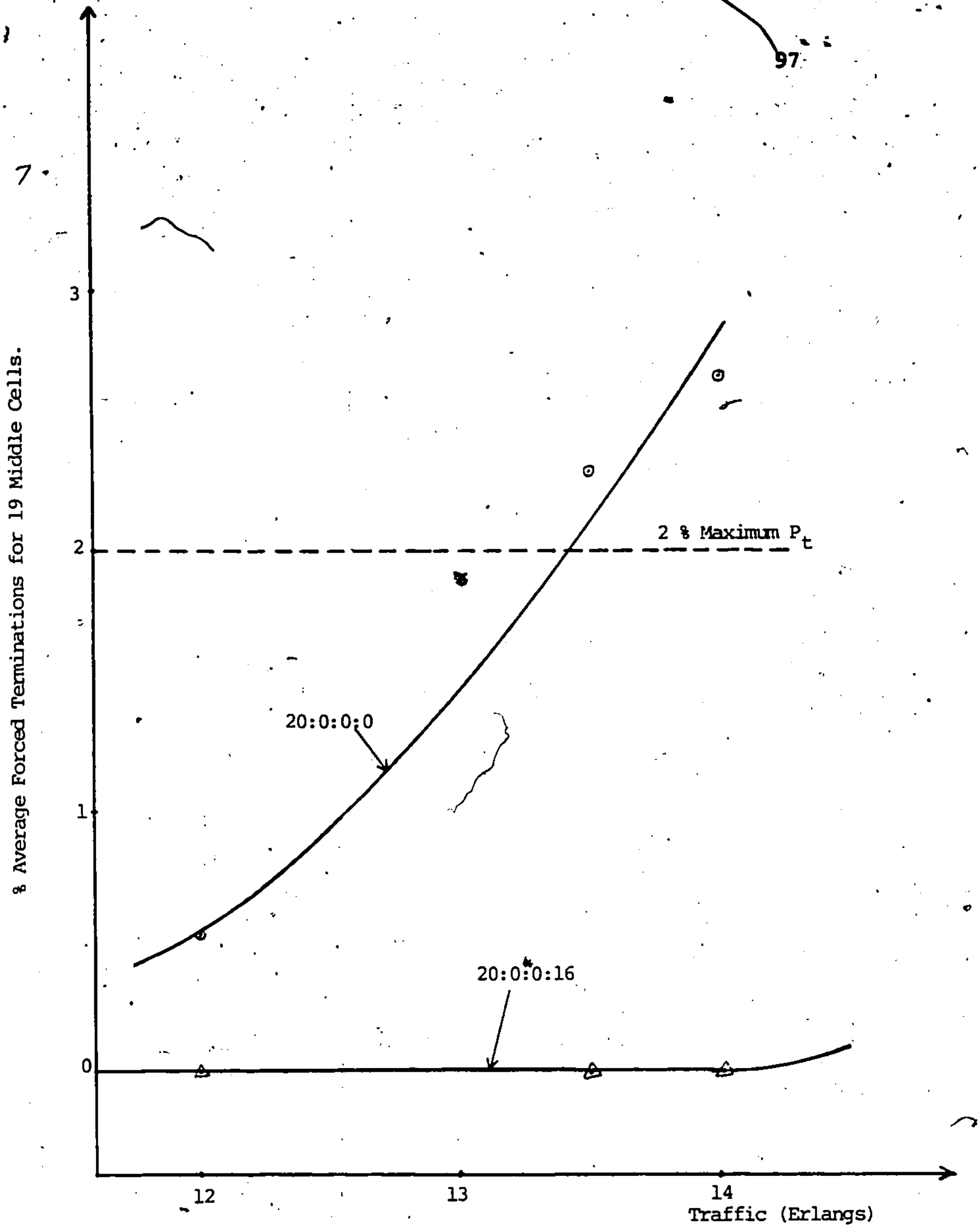


Fig. 7.12/ Performance of System with Initially 20 Nominal Fixed Channels per Cell, and with 20 Nominal Fixed Channels per Cell plus 16 Dynamic Channels in the System (16/3 Channels per Cell) Reserved for the Hand-off Calls.

7.2 THE INCREASING OF TRANSMITTER POWER METHOD SIMULATION RESULTS

The results of simulation for four partitions of channels are shown in Table 7.9-7.18 and plotted in Fig. 7.13-7.19. It is observed that the probability of hand-off calls decreases as the additional distance of transmission afforded by greater transmitter power is increased. This is due to the fact that when the additional transmission distance is increased, the cell radius seems to have increased and therefore the mobiles are more likely to stay within a given cell and be serviced by the same base station.

The probability of any call in the system to be in hand-off status decreases and becomes zero at a distance of 1.55R and a traffic whose grade of service is 2% minimum.

The corresponding base station transmitter power should be 2.4 times the initial transmitter power level. In the analysis of the co-channel interference results, it is found that:

1. The co-channel interference increases with increasing additional transmission distance. The reason behind it is that: by increasing the additional transmission distance, the interference region of the cell in question becomes larger resulting in more calls

falling in that region. This in turn produces more interference between the frequencies serving the calls in-progress and the frequencies in the ICG.

2. The co-channel interference increases with increasing traffic for any additional transmission distance and any partition of channels. this shown in Fig. 7.16-7.19. This can be explained as follows: as the traffic is increased, there will be more calls in the system and therefore more calls in the interference region which will cause the co-channel interference to increase.

Table 7.9

5:0:0:0 TRAFFIC*= 2 ERLANGS										
1*	2*	3*	4*	5*	6*	7*	8*	9*	10*	11*
0	853	50	0	0	0	0	0	0	0	0
10	166	20	217	336	11.4	43.4	2.3	17.7	67.2	3.5
20	72	9	333	539	17.5	66.6	3.5	28.4	108	5.7
30	29	4	343	556	18.1	68.6	3.6	29.3	111	5.9
40	6	1	303	503	16.0	60.6	3.2	26.5	101	5.3
50	0	0	345	545	18.2	69.0	3.6	28.7	109	5.7

Table 7.10

10:0:0:0

TRAFFIC*= 5.8 ERLANGS

1*	2*	3*	4*	5*	6*	7*	8*	9*	10*	11*
0	1838	47	0	0	0	0	0	0	0	0
10	428	22.3	540	869	28.4	54	2.8	45.7	86.9	4.6
20	173	10.6	809	1375	42.6	80.9	4.3	72.4	137.5	7.2
30	60	4.2	851	1396	44.8	85.1	4.5	73.5	139.6	7.4
40	19	1.4	865	1445	45.5	86.5	4.55	76.1	144.5	7.6
50	6	.5	866	1420	45.6	86.6	4.56	74.7	142.0	7.5
55	0	0	895	1459	47.1	89.5	4.7	76.8	145.9	7.7

Table 7.11

15:0:0:0

TRAFFIC*= 9.3 ERLANGS

1*	2*	3*	4*	5*	6*	7*	8*	9*	10*	11*
0	2035	50.8	0	0	0	0	0	0	0	0
10	503	21.9	758	1251	39.9	50.5	2.7	65.8	83.4	4.4
20	231	9.4	1129	1874	59.4	75.3	4.0	98.6	124.9	6.6
30	78	3.7	1254	2094	66.0	83.6	4.4	110.21	139.6	7.4
40	33	1.6	1260	2104	66.3	84.0	4.42	110.74	140.3	7.4
50	3	.2	1200	2016	63.2	80.0	4.2	106.1	134.4	7.1
55	0	0	1243	2088	65.4	82.9	4.4	109.9	139.2	7.3

Table 7.12

20:0:0:0 TRAFFIC*= 13.7 ERLANGS										
1*	2*	3*	4*	5*	6*	7*	8*	9*	10*	11*
0	2202	50.6	0	0	0	0	0	0	0	0
10	697	23.6	942	1573	49.6	47.1	2.5	82.8	78.6	4.1
20	272	10.0	1459	2437	76.8	73.0	3.84	128.3	121.9	6.4
30	118	4.4	1596	2665	84.0	79.8	4.2	140.3	133.3	7.0
40	38	1.5	1699	2854	89.4	85.0	4.5	150.2	142.7	7.5
50	6	.3	1554	2611	81.8	77.7	4.1	137.4	130.6	6.9
55	0	0	1710	2873	90.0	85.5	4.5	151.2	143.7	7.6

Table 7.13

5:0:0:0 TRAFFIC= 1 ERLANG								
1*	4*	5*	6*	7*	8*	9*	10*	11*
10	151	224	7.95	30.2	1.59	11.79	44.8	2.38
20	199	305	10.47	39.8	2.09	16.05	61.0	3.21
30	226	353	11.89	45.2	2.38	18.59	70.6	3.72

Table 7.14

<table>
<tr><th colspan="9">5:0:0:0
TRAFFIC= 2 ERLANGS</th></tr>
<tr><th>1*</th><th>4*</th><th>5*</th><th>6*</th><th>7*</th><th>8*</th><th>9*</th><th>10*</th><th>11*</th></tr>
<tr><td>10</td><td>217</td><td>336</td><td>11.42</td><td>43.4</td><td>2.28</td><td>17.68</td><td>67.2</td><td>3.54</td></tr>
<tr><td>20</td><td>333</td><td>539</td><td>17.53</td><td>66.6</td><td>3.51</td><td>28.37</td><td>107.8</td><td>5.67</td></tr>
<tr><td>30</td><td>343</td><td>556</td><td>18.05</td><td>68.6</td><td>3.61</td><td>29.26</td><td>111.2</td><td>5.85</td></tr>
<tr><td>50</td><td>345</td><td>545</td><td>18.16</td><td>69.0</td><td>3.36</td><td>28.68</td><td>109.0</td><td>5.74</td></tr>
</table>

Table 7.15

<table>
<tr><th colspan="9">5:0:0:0
TRAFFIC= 4 ERLANGS</th></tr>
<tr><th>1*</th><th>4*</th><th>5*</th><th>6*</th><th>7*</th><th>8*</th><th>9*</th><th>10*</th><th>11*</th></tr>
<tr><td>10</td><td>274</td><td>453</td><td>14.42</td><td>54.8</td><td>2.88</td><td>23.84</td><td>90.6</td><td>4.77</td></tr>
<tr><td>30</td><td>468</td><td>764</td><td>24.63</td><td>93.6</td><td>4.93</td><td>40.21</td><td>152.8</td><td>8.07</td></tr>
<tr><td>50</td><td>412</td><td>676</td><td>21.68</td><td>82.4</td><td>4.34</td><td>35.58</td><td>135.2</td><td>7.12</td></tr>
</table>

Table 7.16

10:0:0:0 TRAFFIC= 3.96 ERLANGS								
1*	4*	5*	6*	7*	8*	9*	10*	11*
10	471	784	24.79	47.1	2.48	41.26	78.4	4.13
30	760	1273	40.00	76.0	4.0	67.00	127.3	6.70
50	808	1379	42.53	80.8	4.25	72.58	137.9	7.27

Table 7.16

10:0:0:0 TRAFFIC= 5.8 ERLANGS								
1*	4*	5*	6*	7*	8*	9*	10*	11*
10	540	869	28.42	54	2.84	45.74	86.9	4.57
30	851	1396	44.79	85.1	4.48	73.47	139.6	7.35
50	866	1420	45.58	86.6	4.56	74.74	142.0	7.74

Table 7.17

10:0:0:0 TRAFFIC= 7.51 ERLANGS								
1*	4*	5*	6*	7*	8*	9*	10*	11*
10	562	947	29.58	56.2	2.96	49.84	94.7	4.98
30	890	1503	46.84	89.0	4.68	79.11	150.3	7.91
50	959	1616	50.47	95.5	5.05	85.05	161.6	8.51

TRAFFIC*: Traffic gives a maximum grade of service of 2%

1* : Additional transmission distance (%)

2* : # of crossing boundaries calls

3* : % probability that the calls are in hand-off status

4* : Total number of occurances of co-channel interference during the simulation time

5* : Total number of frequencies interfering during the simulation time

6* : Average number of occurrances of co-channel interference per base station

7* : Average number of occurrances of co-channel interference per channel

8* : Average number of occurrances of co-channel interference per base station per channel

9* : Average number of frequencies interfering per base station

10* : Average number of frequencies interfering per channel

11* : Average number of frequencies interfering per base station per shannel

N.B.: All the statistics calculations were made for the 19 middle cells.

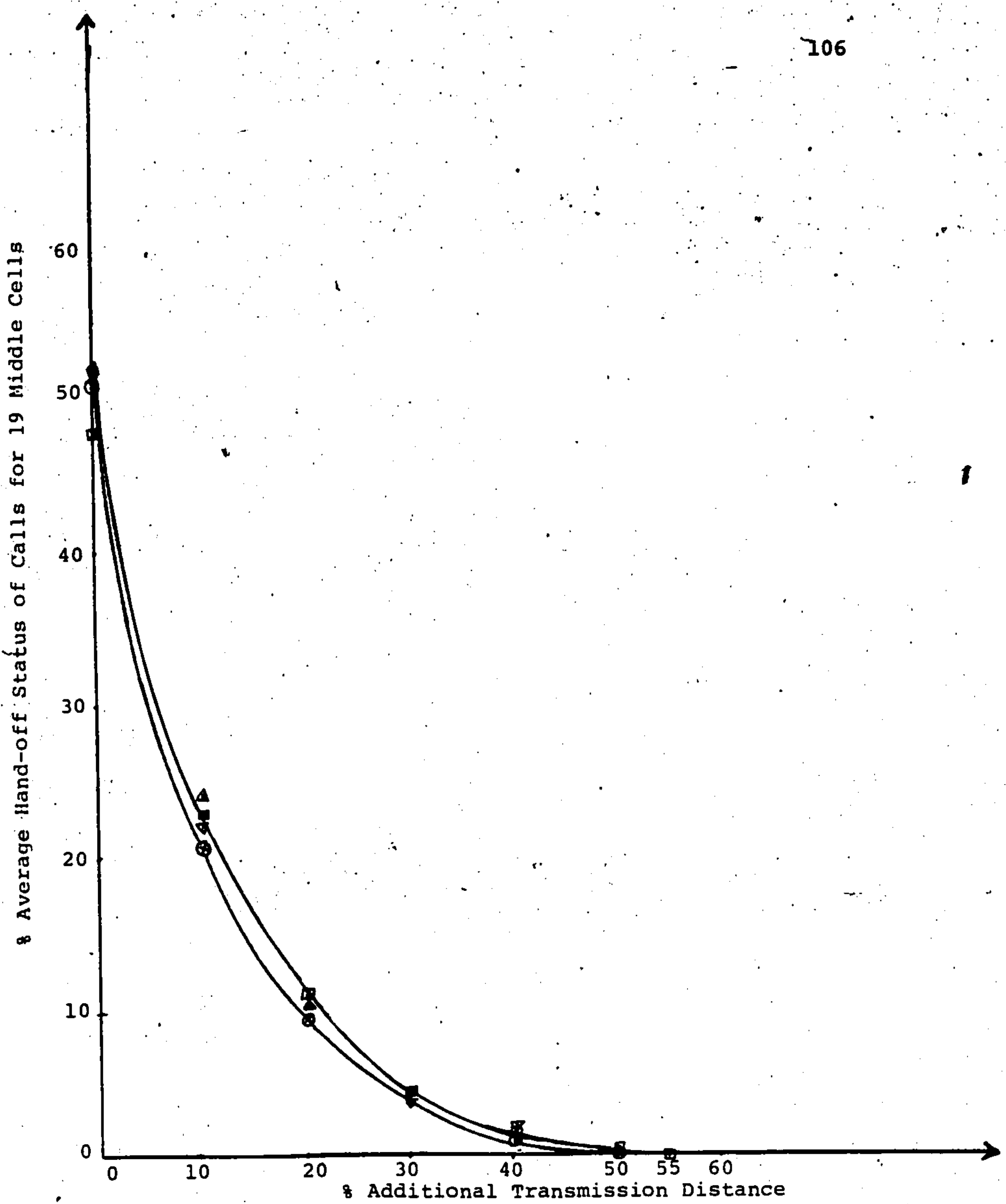


Fig. 7.13 Performance of System with Initially 5, 10, 15 and 20 Nominal Fixed Channels per Cell

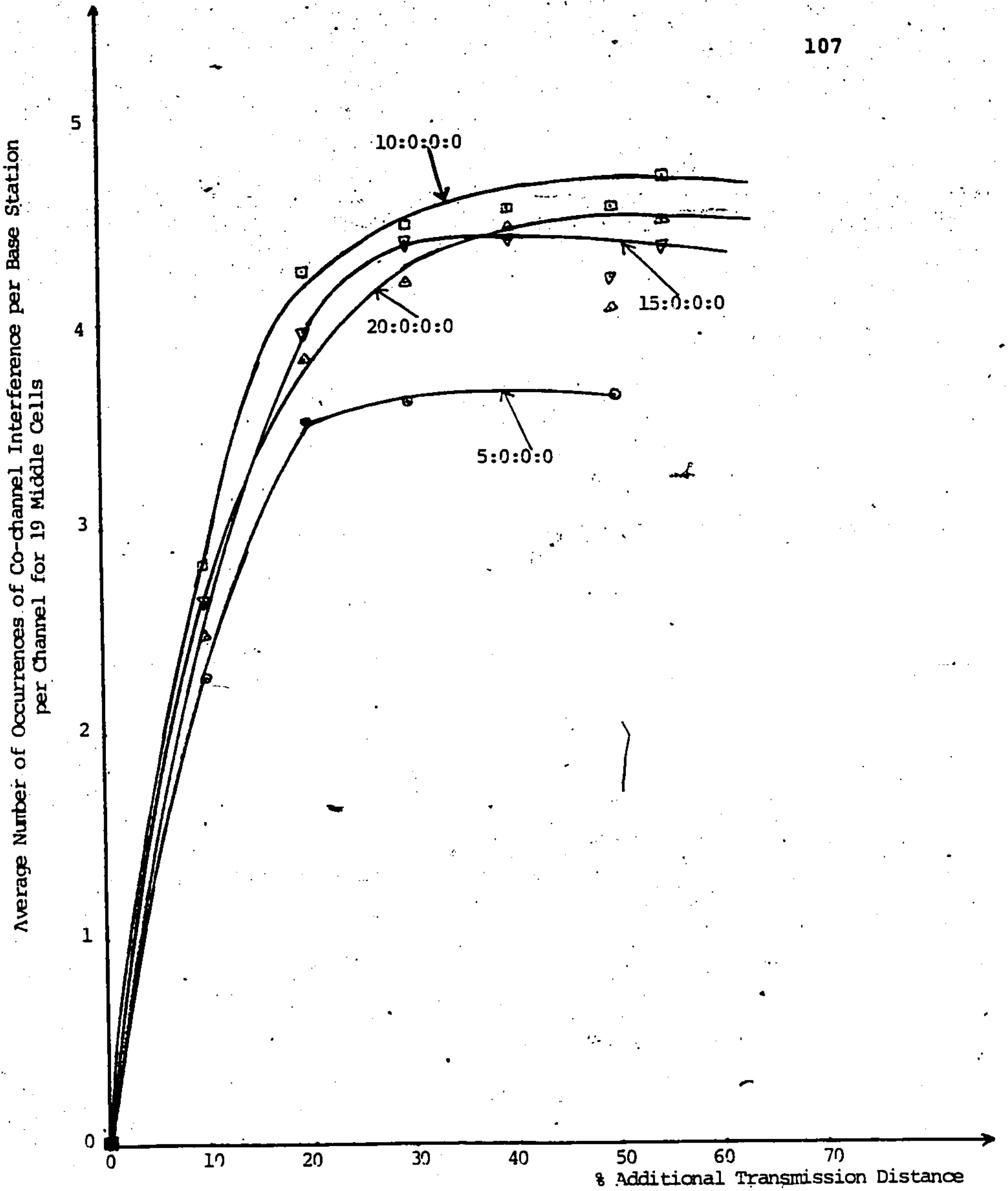


Fig 7.14 Performance of System with Initially 5, 10, 15 and 20 Nominal Fixed Channels per Cell

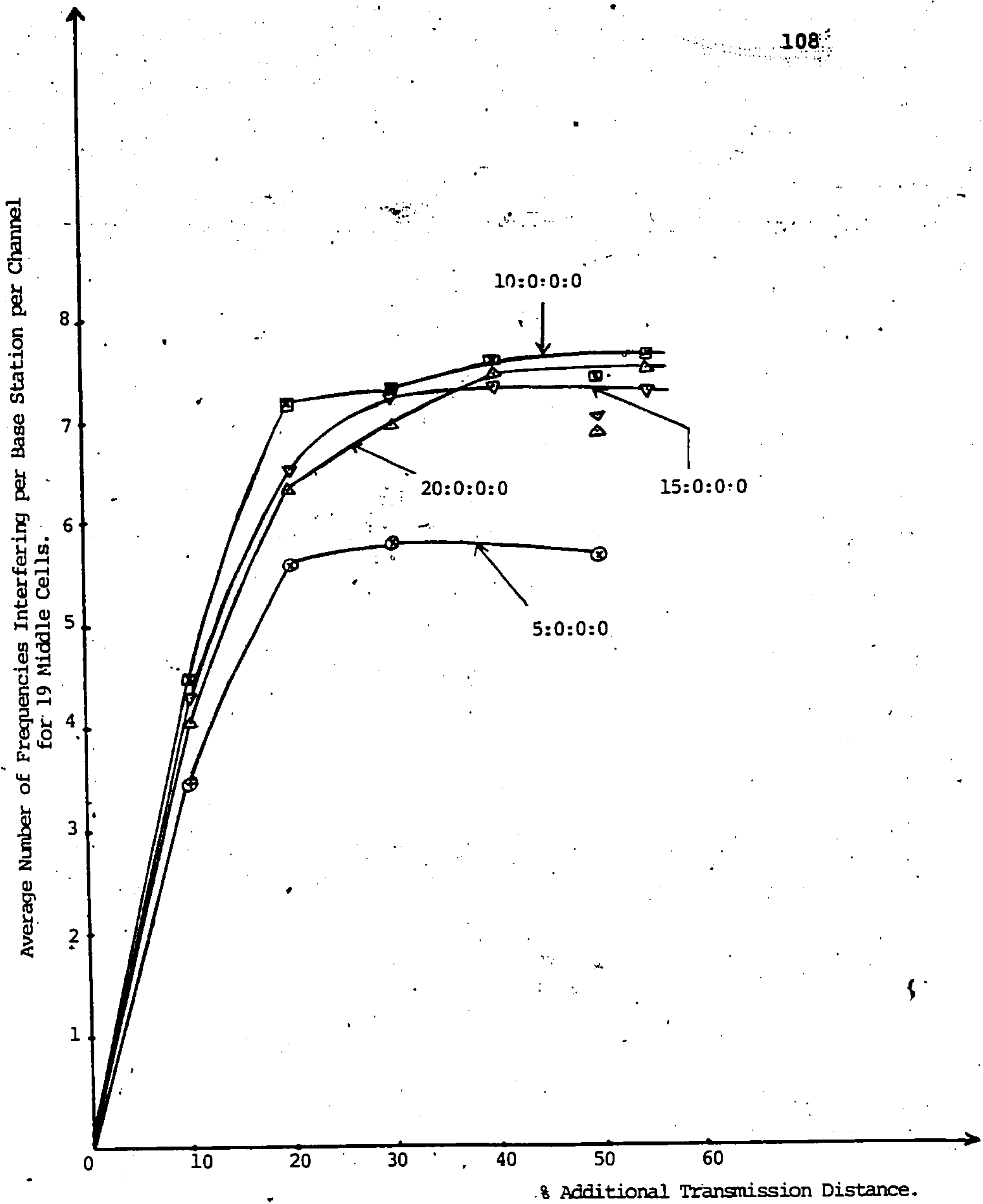


Fig. 7.15 Performance of System with Initially 5,10,15 and 20 Nominal Fixed Channels per Cell.

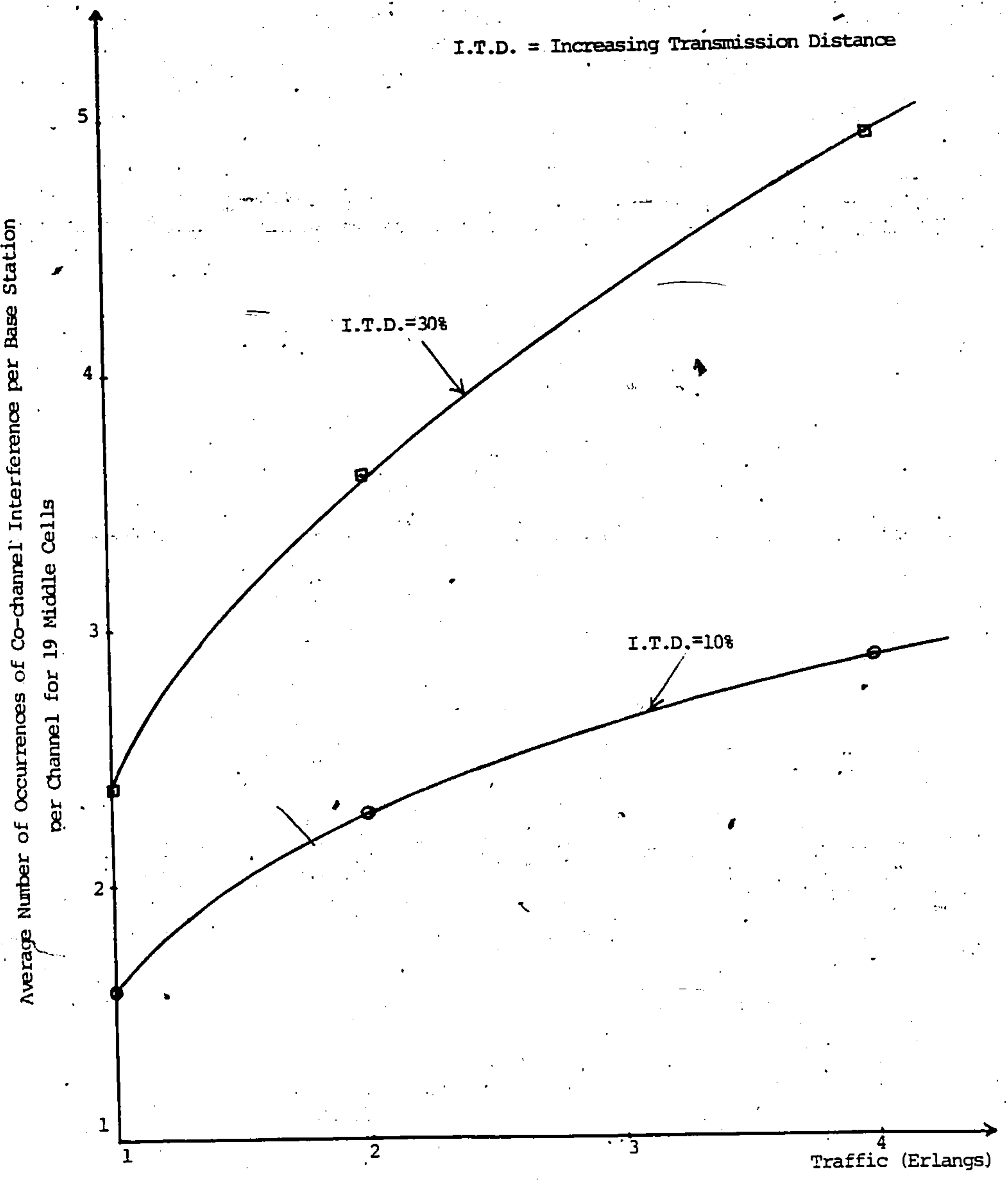


Fig. 7.16 Performance of System with Initially 5 Nominal Fixed Channels per Cell

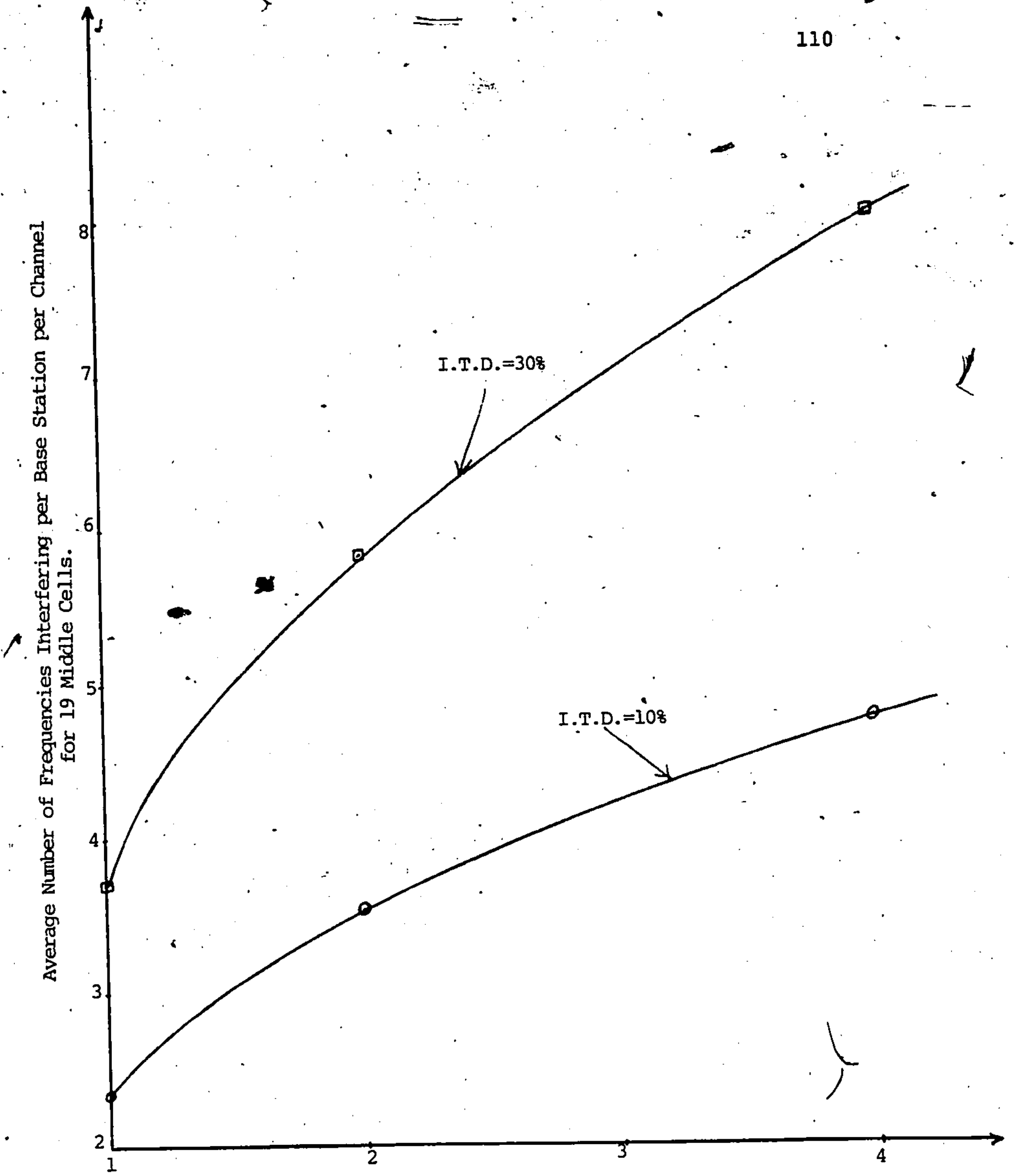


Fig 7.17 Performance of System with Initially 5 Nominal Fixed Channels per Cell.

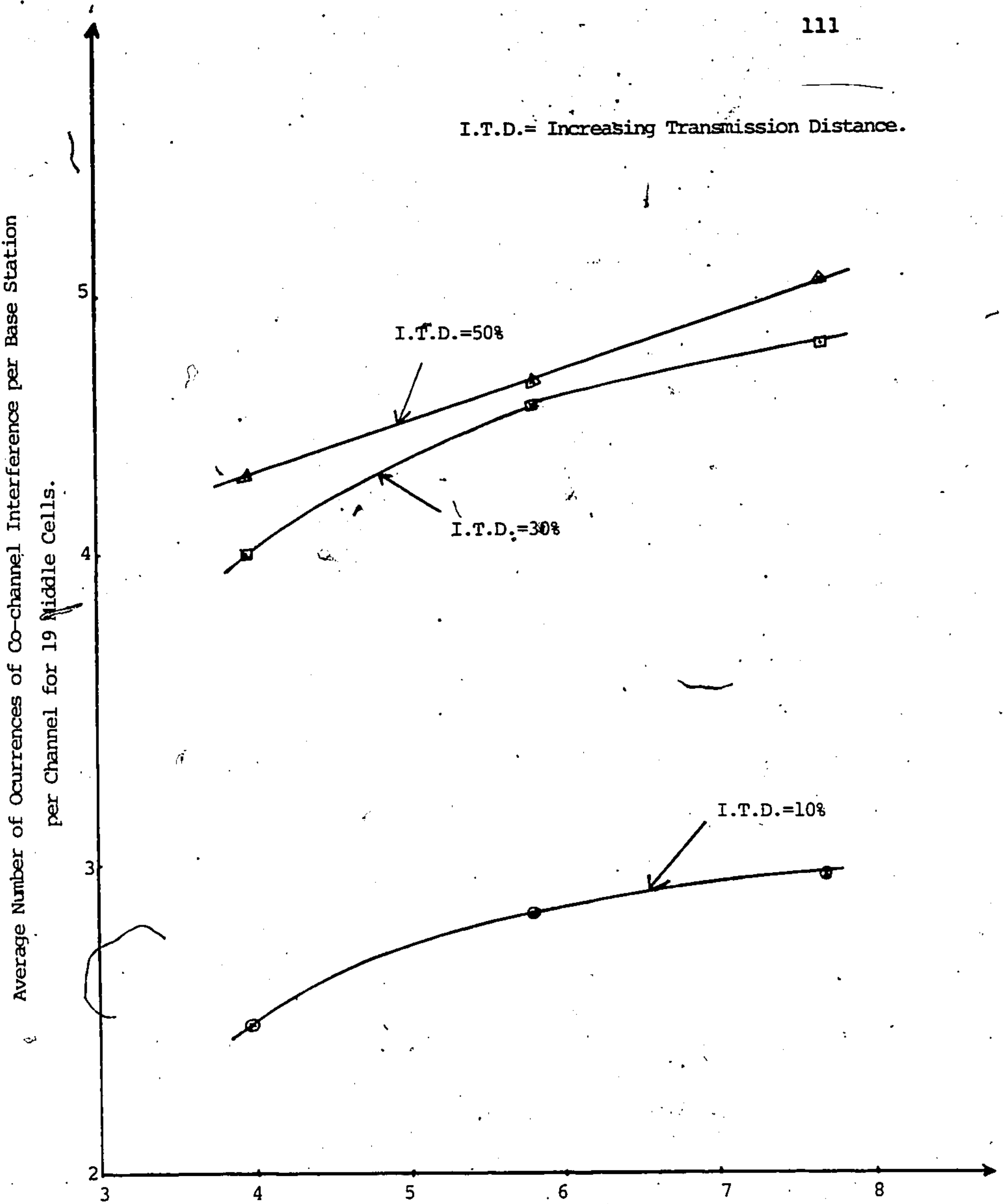


Fig. 7.18 Performance of System with Initially 10 Fixed Nominal Channels per Cell.

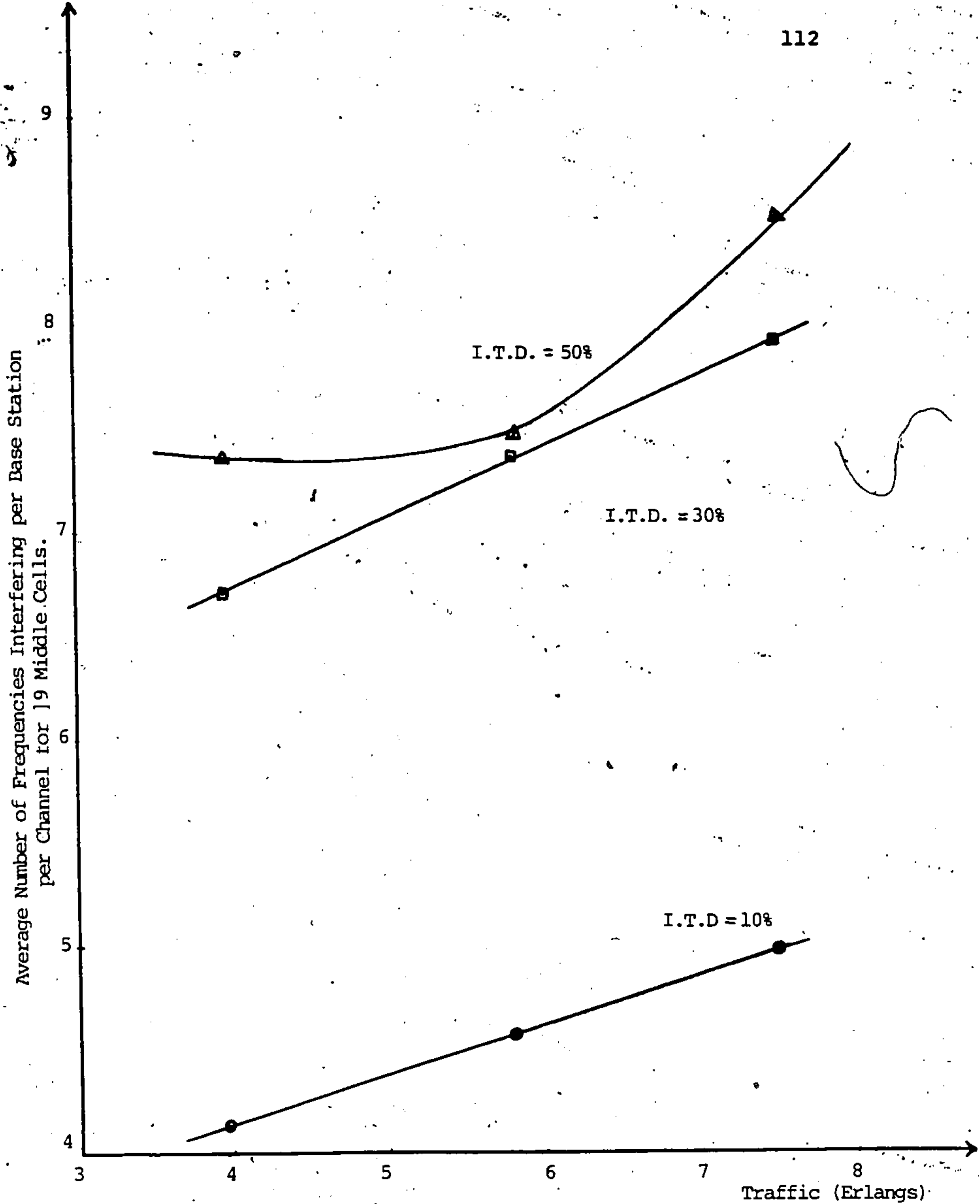


Fig. 7.19 Performance of System with Initially 10 Nominal Fixed Channels per Cell.

Chapter VIII

CONCLUSIONS

Previous simulations of cellular land-mobile radio communication systems did not include the case of mobiles crossing cell-boundaries. For the specific case of uniformly distributed traffic with the Erlang-B service discipline, Nehme and Georganas [8,24] found that the hybrid channel assignment scheme is superior to the fixed channel assignment scheme (in the sense of lower blocking probability for a 2% grade of service).

This thesis has extended previous work by simulating a cellular land-mobile system that permit mobiles crossing cell boundaries. For uniformly distributed traffic with the Erlang-B service discipline, it was found that the fixed channel assignment scheme is superior to the hybrid scheme (in the above sense). The reason behind that is as follows: in previous studies [8,24,6], without calls crossing cell boundaries, the hybrid scheme performed better than the fixed scheme for a grade of service of 2% (this is the result of the simulation studies of the hybrid scheme in cellular land-mobile radio systems); that is, more calls are permitted to continue into a new cell under the hybrid scheme. Therefore, the total number of calls entering a cell from its adjacent cells will be more with the hybrid scheme than if the fixed scheme was used. It then follows that the hand-off calls blocking probability will increase under the hybrid channel assignment scheme.

Two methods of handling the problem of mobiles crossing cell-boundaries were investigated in the simulation model:

1. The hand-off procedure, and
2. the transmitter power increasing method.

Using the hand-off procedure, the fixed system was first simulated by switching the nominal fixed channels when mobiles crossed cell-boundaries. The blocking probability of the hand-off calls was found to be unacceptable. Hand-off channels were added until the hand-off calls blocking probability was reduced to an acceptably small amount (in other words, all calls in-progress were serviced). If only fixed hand-off channels were added, then this point was reached when the number of channels added was equal to 20% of the nominal fixed channels per cell. If only dynamic hand-off channels were added, then 26.7% of the nominal fixed channel per cell were needed. The higher number of channels required by the dynamic hand-off type is because of the fact that dynamic channels are assignment to serve random calls originating from cells which are spaced apart by a distance generally greater than the minimum required reuse separation. Thus the dynamic channels cannot be used most efficiently.

On the other hand, in order to service all the calls in-progress, the simulation of the fixed channel assignment scheme, using the Increasing of Transmitter Power Method, indicated the following:

1. The transmitter power of the base station, required to maintain a grade of service of 2%, is at most 2.4025 times the power which is needed to service the calls within only one cell (or an additional transmitter power of the square of 55% of the original power).
2. The co-channel interference introduced (because of the increase distance of transmission) increases fairly linearly with traffic and piece-wise linearly with the additional distance.

Appendix A

NUMERICAL VALUES USED IN THE SIMULATION MODEL

A.1 BASE STATION LOCATIONS OF FIGURE 6.1

Table A.1.1: Exact base station location in term of R

CELL SITE #	X	Y	CELL SITE #	X	Y
1	0	$3\sqrt{3}\,R$	20	3R	$-2\sqrt{3}\,R$
2	0	$2\sqrt{3}\,R$	21	3R	$-\sqrt{3}\,R$
3	0	$\sqrt{3}\,R$	22	3R	0
4	0	0	23	3R	$\sqrt{3}\,R$
5	0	$-\sqrt{3}\,R$	24	3R	$2\sqrt{3}\,R$
6	0	$-2\sqrt{3}\,R$	25	-3R	$2\sqrt{3}\,R$
7	0	$-3\sqrt{3}\,R$	26	-3R	$\sqrt{3}\,R$
8	1.5R	$-(5\sqrt{3}/2)R$	27	-3R	0
9	1.5R	$-(3\sqrt{3}/2)R$	28	-3R	$-\sqrt{3}\,R$
10	1.5R	$-(\sqrt{3}/2)R$	29	-3R	$-2\sqrt{3}\,R$
11	1.5R	$(\sqrt{3}/2)R$	30	4.5R	$-(3\sqrt{3}/2)R$
12	1.5R	$(3\sqrt{3}/2)R$	31	4.5R	$-(\sqrt{3}/2)R$
13	1.5R	$(5\sqrt{3}/2)R$	32	4.5R	$(\sqrt{3}/2)R$
14	-1.5R	$(5\sqrt{3}/2)R$	33	4.5R	$(3\sqrt{3}/2)R$
15	-1.5R	$(3\sqrt{3}/2)R$	34	-4.5R	$(3\sqrt{3}/2)R$
16	-1.5R	$(\sqrt{3}/2)R$	35	-4.5R	$(\sqrt{3}/2)R$
17	-1.5R	$-(\sqrt{3}/2)R$	36	-4.5R	$-(\sqrt{3}/2)R$
18	-1.5R	$-(3\sqrt{3}/2)R$	37	-4.5R	$-(3\sqrt{3}/2)R$
19	-1.5R	$-(5\sqrt{3}/2)R$			

Table A.1.2: Approximate base station location for R=1600metres(*)

CELL SITE #	X (decm)	Y (decm)	CELL site #	X (decm)	Y (decm)
1	0	831	20	480	-554
2	0	554	21	480	-277
3	0	277	22	480	0
4	0	0	23	480	277
5	0	-277	24	480	554
6	0	-554	25	-480	554
7	0	-831	26	-480	277
8	240	-693	27	-480	0
9	240	-416	28	-480	-277
10	240	-139	29	-480	-554
11	240	139	30	720	-416
12	240	416	31	720	-139
13	240	693	32	720	139
14	-240	693	33	720	416
15	-240	416	34	-720	416
16	-240	139	35	-720	139
17	-240	-139	36	-720	-139
18	-240	-416	37	-720	-416
19	-240	-693			

(*): R=1600metres (or 1mile) is one of the cell radius used by AMPS. The 4 values of R correspond to the cell stages of development in the AMPS system are: 1mile, 2miles, 3milesand 8miles.

A.2 INVERSE CUMULATIVE DISTRIBUTION FUNCTION FOR X-COORDINATE

Table A.2: ICDF for the X-coordinates of the mobile locations in the system for R=1600metres

U	X (m)	U	X (m)
0	0	.55	4062
.05	328	.60	4498
.10	662	.65	4949
.15	1004	.70	5419
.20	1353	.75	5909
.25	1710	.80	6422
.30	2076	.85	6961
.35	2451	.90	7532
.40	2837	.95	8141
.45	3233	1.00	8795
.50	3641		

Appendix B

GPSS ENTITIES USED IN THE SIMULATION MODEL

B.1 TABLE OF DEFINITIONS

Time unit = 1msec

Distances unit = 1decamtre

B.2 STORAGES

The only storage used is called "SYSTM". All calls enter "SYSTM". After a steady state is reached all statistics collected up to that point are cleared and all transactions removed from the model except for those in "SYSTM". The simulation is then reatarted from the steady state point.

B.3 USER CHAINS

There is a single user chain called "ACTIV" which may be regarded as a pool of mobiles actively engaged in a call. At each update of the simulation clock the "mobiles" are unlinked from the chain one-by-one, their position, channel assignment etc. Updated and then returned to the user chain "ACTIV".

B.4 GROUPS

Group "i" (i=1,2,3,.....,37) contains all mobiles using a dynamic channel (nominal or hand-off) in the cell "i".

B.5 LOGIC SWITCHES

Logic switch "i" (i=1,2,3,.....,37), when set, indicates that there are no nominal fixed channels available in cell "i".

B.6 PARAMETERS

P1 -base station # (P1=1,2,...,37).

P2 -# of fixed channels per cell, either nominal alone or nominal + hand-off.

P3 -# of nominal fixed channels per cell.

P4 -type of channel being used by mobile (P4=0, 1,2,3):

  0: nominal fixed channel
  1: fixed hand-off channel
  2: nominal dynamic channel
  3: dynamic hand-off channel

P5 -used as temporary storage location during channel reassignment.

P6 -X-coordinate of mobile (P6<5.5R, R= cell radius,the unit is decametre).

P7 -Y-coordinate of mobile (P7<(11 3/3)R, unit is also decametre).

P8 -Vx component of velocity (P8 can have its values only between -27 and 27).

P9 -Vy component of velocity (the values of P9 is also between -27 and 27).

P10 -used as a loop index in base station assignment subroutine (P10=1,2,...,37).

P11 -used to store address when transferring back and forth from main program and subroutine.

P12 -used in co-channel interference subroutine to indicate the interference region.

B.7 SAVEVALUES

XH1 -# of fixed channels per cell (nominal+hand-off).

XH2 -# of fixed channels per cell (nominal).

XH3 -# of dynamic channels in system (nominal+hand-off).

XH4 -# of dynamic channels in system (nominal).

XH5 -simulation cycle time in msec (that is, time between updates).

XH6 -mean call holding time (msec).

XH7 -mean call interarrival time (msec).

XH8 -maximum simulation time (msec) (maximum simulated time, not CPU time).

XH9 -cell radius (decametre).

XF10 -used in base station assignment subroutine. It contains the smalest, most recent, computed distance (square) from a base station.

XH11 -used as temporary storage location in base station assignment subroutine. It contains identity of the nearest base station, XH11=1,2,3,....,37.

B.8 FUNCTIONS

EXPON	-this function is used to generate the poisson arrivals of calls and the exponential call holding times.
SPEED	-this function is used to generate the gaussian distribution of the mobile velocity components Vx and Vy.
XXX	-this function is used to generate the X-coordinates of the mobile locations in the system.
QUAD	-this function is used to multiply the coordinates of the mobile locations by +1 or -1 such that the following ordered pairs are equally likely: (X1,Y2);(-X1,Y2);(X1,-Y2);(-X1,-Y2)

B.9 MATRICES

MH1	-controls fixed channel assignent (both nominal and hand-off). Any position (x,y) in MH1 can only assume the values 0 or 1, indicating the vacant or busy status of fixed voice channel "y" in cell "x".
MH2	-controls dynamic channel assignment (both nominal and hand-off). Any position (x,y) in MH2 can only assume the values 0 or 1,

	indicating the non-use or use of dynamic channel "y" in cell "x".
MH3	-boundary crossing statistics. Any column "i" in row #1 represents the # of boundary crossings into cell "i". Any column "i" in row #2 represents the # of mobiles crossing a boundary into cell "i" and successfully obtaining a nominal channel. Any column "i" in row #3 represents the # of mobiles crossing a boundary into cell "i" and successfully obtaining a hand-off channel after finding no nominal channels available.
MH4	-blocking probability statistics (initial channel assignment). Any column "i" in row #1 represents the # of call attempts generated in cell "i" which successfully obtain a nominal channel. Any column "i" in row #2 represents the # of call attempts generated in cell "i" which are not successfully in obtaining a nominal channel.
MH5	-co-channel interference statistics. Any column "i" in row "j" represents the # of times of co-channel interference of channel "j" in cell "j" during the simulation time.
MH6	-matrix (37x37) used for assigning the

	interference regions of the cells.
MH7	-co-channel interference statistics. Any column "i" in row "j" represents the # of frequencies interferings of channel "j" in cell "i" during the simulation time.
MX1	-base station location. Columns 1 and 2 in row "i' contain, respectively, the x and y coordinates of base station "i".

B.10 VARIABLES

B.10.1 THE HAND-OFF PROCEDURE VARIABLES

1-37	-variable "i" gives the co-channel interference criterion whether or not a given dynamic channels may be used in a given cell.
37-63	-same as above, they are the combinations of the expressions for variables 1-37.

B.10.2 THE TRANSMITTER POWER INCREASING METHOD

11-373	-variable "i"(i=11,12,13,21,...373) is used to verify wether or not a given channel is used in a given cell in order to see if there is co-channel interference problem introduced by the increasing power method.

15 -the value of this variable gives the interference region #.

B.11 THE FLOATING-POINT VARIABLES

B.11.1 THE HAND-OFF PROCEDURE

64 -the Y-coordinates of the mobile locations

65 -the X-components of the distance between the base station and the mobile location.

66 -the Y-components of the distance between the base station and the mobile location.

67 -the new X-coordinates of the mobile locations after one cycle time.

68 -the new Y-coordinates of the mobile locations after one cycle time.

69 -the square of 1.1R

70 -the square of the distance between the base station and the mobile location.

B.11.2 THE TRANSMITTER POWER INCREASING METHOD

1 -same as the FV64 in the first procedure.

2 -same as the FV65 =====================.

3 -same as the FV66 =====================.

4 -same as the FV67 =====================.

5 -same as the FV68 =====================.

6 -same as the FV69 =====================.

7 -same as the FV70 =====================.

B.12 BOOLEAN VARIABLES

1 -controls the simulation run.

Appendix C

COMPUTER PROGRAM AND VALIDATION OF THE MODEL

C.1 VALIDATION OF THE SIMULATION

The computer simulation program, as shown later in this Appendix, makes use of 5 Random numbers (RNi) from the eight Random numbers available in GPSS. The validation of the simulation was done only for the case with 5 nominal fixed channels in the system. The program was executed 9 times, each with a different set of seeds. The results are presented in the following table:

Table C.1

TRAFFIC [ERLANGS]	MEAN VALUES OF P_t	STANDARD DEVIATIONS OF P_t	CONFIDENCE INTERVALS 95% *	90% *	80% *
1.5	1.32	.30	17.5	14.0	10.6
1.7	1.69	.41	18.7	15.0	11.3
1.88	2.00	.41	15.6	12.7	9.5

*: ± % of the mean value of P_t

C.2 COMPUTER PROGRAM

C.2.1 Hand-off Procedure

```
CREATE
REALLOCATE BLO,300,BVR,2,CHA,2,COM,180000,FMS,2
REALLOCATE FSV,7,FUN,5,GRP,41,HMS,5,HSV,7,LCG,41
REALLOCATE QUE,1,STC,2,TAB,1,VAR,80,XAC,1500
```

```
BLOCK
NUMBER   *LOC   OPERATION  A,B,C,D,E,F,G                COMMENTS
                SIMULATE
        *
        *INITIALIZATION
        *
                INITIAL    XH1,24         # OF FIXED CHAN/CELL (VOICE+HANDOFF)
                INITIAL    XH2,20         # OF FIXED CHAN/CELL (VOICE)
                INITIAL    XH3,0          # OF DYN CHAN IN SYSTEM (VOICE+HANDOFF)
                INITIAL    XH4,0          # OF DYN CHAN IN SYSTEM (VOICE)
                INITIAL    X1,30000       SIMULATION CYCLE TIME (MSECS)
                INITIAL    X2,120000      MEAN CALL HOLDING TIME (MSECS)
                INITIAL    X3,232         MEAN CALL INTERARRIVAL TIME (MSECS)
                INITIAL    X4,5400000     MAXIMUM SIMULATION TIME (MSECS)
                INITIAL    X5,160         CELL RADIUS (DECAMETRES)
        *
         1      MATRIX     H,37,24        FCA CONTROL, # OF COLUMNS=XH1
         2      MATRIX     H,37,6         DCA CONTROL, # OF COLUMNS=XH3
         3      MATRIX     H,3,37         BOUNDARY CROSSING STATISTICS
         4      MATRIX     H,2,37         INITIAL CHANNEL ASSIGNEMENT STATISTICS
         1      MATRIX     X,37,2         BASE STATION LOCATIONS
        *
                INITIAL    MX1(8-13,1),240/MX1(14-19,1),-240
                INITIAL    MX1(20-24,1),480/MX1(25-29,1),-480
                INITIAL    MX1(30-33,1),720/MX1(34-37,1),-720
                INITIAL    MX1(1,2),831/MX1(7,2),-831
                INITIAL    MX1(13-14,2),693/MX1(4,2),-693
                INITIAL    MX1(19,2),-693/MX1(2,2),554
                INITIAL    MX1(24-25,2),554/MX1(6,2),-554
                INITIAL    MX1(20,2),-554/MX1(29,2),-554
                INITIAL    MX1(12,2),416/MX1(15,2),416
                INITIAL    MX1(33-34,2),416/MX1(9,2),-416
                INITIAL    MX1(18,2),-416/MX1(30,2),-416
                INITIAL    MX1(37,2),-416/MX1(3,2),277
                INITIAL    MX1(23,2),277/MX1(26,2),277
                INITIAL    MX1(5,2),-277/MX1(21,2),-277
                INITIAL    MX1(28,2),-277/MX1(11,2),139
                INITIAL    MX1(16,2),139/MX1(32,2),139
                INITIAL    MX1(35,2),139/MX1(10,2),-139
                INITIAL    MX1(17,2),-139/MX1(31,2),-139
                INITIAL    MX1(36,2),-139
        *
        * EQUIVALENCE
        *
         QUAD   EQU        1,Z
         SYSTM  EQU        1,S
        *
        *FUNCTION DEFINITION
        *
         EXPON  FUNCTION   RN4,C24
        0,0/.1,.104/.2,.222/.3,.355/.4,.509/.5,.69/.6,.915/.7,1.2/.75,1.38
        .8,1.6/.84,1.83/.88,2.12/.9,2.3/.92,2.52/.94,2.81/.95,2.99/.96,3.2
        .97,3.5/.98,3.9/.99,4.6/.995,5.3/.998,6.2/.999,7/.9998,8
        *
         SPEED  FUNCTION   RN3,C25
        0,-27.0/.05,-19.31/.1,-15.541/.15,-12.69
```

```
.2,-10.3/.25,-8.27/.3,-6.43
.35,-4.78/.4,-3.13/.42,-2.43/.45,-1.47
.47,-0.91/.5,0/.52,0.644
.55,1.56/.57,2.30/.6,3.13/.65,4.87
.7,6.58/.75,8.37/.8,10.48
.85,12.78/.9,15.58/.95,19.58/.999,27
*
 XXX     FUNCTION    RN2,C21
0,0/.05,32.8/.1,66.2/.15,100.4/.2,135.3
.25,171.0/.3,207.6/.35,245.1
.4,283.7/.45,323.3/.5,364.1/.55,406.2
.6,449.8/.65,494.9/.7,541.9
.75,590.9/.8,642.2/.85,696.1/.9,753.2/.95,814.1/1.0,879.5
*
 QUAD    FUNCTION    RN1,D2
.5,-1/1,1
*
*VARIABLE  DEFINITION
*
 1       VARIABLE    MH2(1,P2)+MH2(14,P2)+MH2(2,P2)+MH2(13,P2)
 2       VARIABLE    MH2(2,P2)+MH2(15,P2)+MH2(3,P2)+MH2(12,P2)+V38
 3       VARIABLE    MH2(3,P2)+MH2(16,P2)+MH2(4,P2)+MH2(11,P2)+V39
 4       VARIABLE    MH2(4,P2)+MH2(17,P2)+MH2(5,P2)+MH2(10,P2)+V40
 5       VARIABLE    MH2(5,P2)+MH2(18,P2)+MH2(6,P2)+MH2(9,P2)+V41
 6       VARIABLE    MH2(6,P2)+MH2(19,P2)+MH2(7,P2)+MH2(8,P2)+V42
 7       VARIABLE    MH2(7,P2)+MH2(8,P2)+MH2(6,P2)+MH2(19,P2)
 8       VARIABLE    MH2(8,P2)+MH2(7,P2)+MH2(20,P2)+MH2(9,P2)+MH2(6,P2)
 9       VARIABLE    MH2(9,P2)+MH2(6,P2)+MH2(8,P2)+MH2(20,P2)+V43
 10      VARIABLE    MH2(10,P2)+MH2(5,P2)+MH2(9,P2)+MH2(21,P2)+V44
 11      VARIABLE    MH2(11,P2)+MH2(4,P2)+MH2(10,P2)+MH2(22,P2)+V45
 12      VARIABLE    MH2(12,P2)+MH2(3,P2)+MH2(11,P2)+MH2(23,P2)+V46
 13      VARIABLE    MH2(13,P2)+MH2(2,P2)+MH2(12,P2)+MH2(24,P2)+MH2(1,P2)
 14      VARIABLE    MH2(14,P2)+MH2(25,P2)+MH2(15,P2)+MH2(2,P2)+MH2(1,P2)
 15      VARIABLE    MH2(15,P2)+MH2(26,P2)+MH2(16,P2)+MH2(3,P2)+V47
 16      VARIABLE    MH2(16,P2)+MH2(27,P2)+MH2(17,P2)+MH2(4,P2)+V48
 17      VARIABLE    MH2(17,P2)+MH2(28,P2)+MH2(18,P2)+MH2(5,P2)+V49
 18      VARIABLE    MH2(18,P2)+MH2(29,P2)+MH2(19,P2)+MH2(6,P2)+V50
 19      VARIABLE    MH2(19,P2)+MH2(7,P2)+MH2(6,P2)+MH2(18,P2)+MH2(29,P2)
 20      VARIABLE    MH2(20,P2)+MH2(8,P2)+MH2(30,P2)+MH2(21,P2)+MH2(9,P2)
 21      VARIABLE    MH2(21,P2)+MH2(9,P2)+MH2(20,P2)+MH2(30,P2)+V51
 22      VARIABLE    MH2(22,P2)+MH2(10,P2)+MH2(21,P2)+MH2(31,P2)+V52
 23      VARIABLF    MH2(23,P2)+MH2(11,P2)+MH2(22,P2)+MH2(32,P2)+V53
 24      VARIABLE    MH2(24,P2)+MH2(12,P2)+MH2(23,P2)+V54
 25      VARIABLE    MH2(25,P2)+MH2(34,P2)+MH2(26,P2)+V55
 26      VARIABLE    MH2(26,P2)+MH2(35,P2)+MH2(27,P2)+MH2(16,P2)+V56
 27      VARIABLE    MH2(27,P2)+MH2(36,P2)+MH2(28,P2)+MH2(17,P2)+V57
 28      VARIABLE    MH2(28,P2)+MH2(37,P2)+MH2(29,P2)+MH2(18,P2)+V58
 29      VARIABLE    MH2(29,P2)+MH2(19,P2)+MH2(18,P2)+V59
 30      VARIABLE    MH2(30,P2)+MH2(20,P2)+MH2(31,P2)+MH2(21,P2)
 31      VARIABLE    MH2(31,P2)+MH2(21,P2)+MH2(30,P2)+V60
 32      VARIABLE    MH2(32,P2)+MH2(22,P2)+MH2(31,P2)+V61
 33      VARIABLE    MH2(33,P2)+MH2(23,P2)+MH2(32,P2)+MH2(24,P2)
 34      VARIABLE    MH2(34,P2)+MH2(35,P2)+MH2(26,P2)+MH2(25,P2)
 35      VARIABLE    MH2(35,P2)+MH2(36,P2)+MH2(27,P2)+MH2(26,P2)+V62
 36      VARIABLE    MH2(36,P2)+MH2(37,P2)+MH2(28,P2)+MH2(27,P2)+V63
 37      VARIABLE    MH2(37,P2)+MH2(29,P2)+MH2(28,P2)+MH2(36,P2)
 38      VARIABLE    MH2(13,P2)+MH2(1,P2)+MH2(14,P2)
```

```
          39    VARIABLE    MH2(12,P2)+MH2(2,P2)+MH2(15,P2)
          40    VARIABLE    MH2(11,P2)+MH2(3,P2)+MH2(16,P2)
          41    VARIABLE    MH2(10,P2)+MH2(4,P2)+MH2(17,P2)
          42    VARIABLE    MH2(9,P2)+MH2(5,P2)+MH2(18,P2)
          43    VARIABLE    MH2(21,P2)+MH2(10,P2)+MH2(5,P2)
          44    VARIABLE    MH2(22,P2)+MH2(11,P2)+MH2(4,P2)
          45    VARIABLE    MH2(23,P2)+MH2(12,P2)+MH2(3,P2)
          46    VARIABLE    MH2(24,P2)+MH2(13,P2)+MH2(2,P2)
          47    VARIABLE    MH2(2,P2)+MH2(14,P2)+MH2(25,P2)
          48    VARIABLE    MH2(3,P2)+MH2(15,P2)+MH2(26,P2)
          49    VARIABLE    MH2(4,P2)+MH2(16,P2)+MH2(27,P2)
          50    VARIABLE    MH2(5,P2)+MH2(17,P2)+MH2(28,P2)
          51    VARIABLE    MH2(31,P2)+MH2(22,P2)+MH2(10,P2)
          52    VARIABLE    MH2(32,P2)+MH2(23,P2)+MH2(11,P2)
          53    VARIABLE    MH2(33,P2)+MH2(24,P2)+MH2(12,P2)
          54    VARIABLE    MH2(33,P2)+MH2(13,P2)
          55    VARIABLE    MH2(15,P2)+MH2(14,P2)
          56    VARIABLE    MH2(15,P2)+MH2(25,P2)+MH2(34,P2)
          57    VARIABLE    MH2(16,P2)+MH2(26,P2)+MH2(35,P2)
          58    VARIABLE    MH2(17,P2)+MH2(27,P2)+MH2(36,P2)
          59    VARIABLE    MH2(28,P2)+MH2(37,P2)
          60    VARIABLE    MH2(32,P2)+MH2(22,P2)
          61    VARIABLE    MH2(33,P2)+MH2(23,P2)
          62    VARIABLE    MH2(26,P2)+MH2(34,P2)
          63    VARIABLE    MH2(27,P2)+MH2(35,P2)
          64    FVARIABLE   FN5+(0-5774/10000*P6+(6351/1000*X5))/1000
          65    FVARIABLE   P6-MX1(P10,1)
          66    FVARIABLE   P7-MX1(P10,2)
          67    FVARIABLE   P6+(P8*(X1/10000))
          68    FVARIABLE   P7+(P9*(X1/10000))
          69    FVARIABLE   (11/10)*X5*X5
          70    FVARIABLE   (V65*V65)+(V66*V66)
          1     BVARIABLE   C1'LE'X4*N$CALLS'LE'3000
         *
 1              GENERATE    X3,FN$EXPON,,,,15,F
 2        CALLS ENTER       SYSTM
 3              ASSIGN      6,FN$XXX
 4              ASSIGN      7,V64
 5              ASSIGN      6,P6,1
 6              ASSIGN      7,P7,1
 7              TRANSFER    SBR,VELOC,11
 8              TRANSFER    SBR,CELL,11
 9              TEST NE     XH5,0,EXIT
10              ASSIGN      1,XH5
11              TRANSFER    SBR,NORML,11
12              TEST NE     P2,0,FAIL1
13              MSAVEVALUE  4+,1,P1,1,H
14        PRI   PRIORITY    2
15              ASSIGN      3,N$PRI
16              SPLIT       1,HOLD
17              LINK        ACTIV,FIFO
18        HOLD  ADVANCE     X2,FN$EXPON
19              UNLINK      ACTIV,TYP23,1,5,,CHECK
20              TERMINATE
21        TYP23 TEST GE     P4,2,TYP01
22              REMOVE      P1
23              MSAVEVALUE  2,P1,P2,0,H
```

```
 24              TRANSFER     ,EXIT
 25       TYP01  TEST NE      G*1,0,VACAT
 26              SPLIT        1,FREE1
 27              TRANSFER     ,EXIT
 28       VACAT  MSAVEVALUE   1,P1,P2,0,H
 29              TEST E       P4,0,EXIT
 30       RESET  LOGIC R      P1
 31              TRANSFER     ,EXIT
 32       CHECK  TERMINATE
 33       FAIL1  MSAVEVALUE   4+,2,P1,1,H
 34              TRANSFER     ,EXIT
         *
         * CONTROL-TRANSACTION  GENERATION
         *
 35              GENERATE     X1,,,3,1,H
 36              UNLINK       ACTIV,UPDAT,ALL
 37              TERMINATE
         *
         * UPDATE  VEHICLE STATUS
         *
 38       UPDAT  ASSIGN       6,V67
 39              ASSIGN       7,V68
 40              TRANSFER     SBR,CELL,11
 41              TEST NE      XH5,0,EXIT
 42              TEST E       XH5,P1,CROSS
 43       MODFY  TRANSFER     .5,,CHANG
 44              LINK         ACTIV,FIFO
 45       CHANG  ASSIGN       8,0
 46              ASSIGN       9,0
 47              TRANSFER     SBR,VELOC,11
 48              LINK         ACTIV,FIFO
         *
         *BOUNDARY CROSSING
         *
 49       CROSS  TEST GE      P4,2,NOT23
 50              REMOVE       P1
 51              MSAVEVALUE   2,P1,P2,0,H
 52              ASSIGN       1,XH5
 53              MSAVEVALUE   3+,1,P1,1,H
 54              TEST E       P4,2,SEEK
 55              TEST E       V*1,0,SEEK
 56              MSAVEVALUE   2,P1,P2,1,H
 57              MSAVEVALUE   3+,2,P1,1,H
 58              JOIN         P1
 59              TRANSFER     ,MODFY
 60       NOT23  TEST E       G*1,0,SOME
 61              TEST E       P4,0,BYPAS
 62              LOGIC R      P1
 63       BYPAS  MSAVEVALUE   1,P1,P2,0,H
 64              TRANSFER     ,PLUS1
 65       SOME   SPLIT        1,FREE1
 66       PLUS1  ASSIGN       1,XH5
 67              MSAVEVALUE   3+,1,P1,1,H
 68       SEEK   TRANSFER     SBR,NORML,11
 69              TEST E       P2,0,FIND2
 70              TRANSFER     SBR,SPECL,11
 71              TEST E       P2,P3,FIND3
```

```
 72              TRANSFER    ,EXIT
 73       FIND2 MSAVEVALUE 3+,2,P1,1,H
 74              TRANSFER    ,MODFY
 75       FIND3 MSAVEVALUE 3+,3,P1,1,H
 76              TRANSFER    ,MODFY
          *
          * BASE STATION ASSIGNEMENT SUBROUTINE
          *
 77       CELL   SAVEVALUE   5,0,H
 78              ASSIGN      10,37
 79       RTN    TEST L      V70,V69,SKIP
 80              SAVEVALUE   5,P10,H
 81              ASSIGN      12,V70
 82       SKIP   LOOP        10,RTN
 83              TRANSFER    P,11,1
          *
          *VELOCITY ASSIGNMENT SUBROUTINE
          *
 84       VELOC TRANSFER     .25,XXX,YYY
 85       XXX    ASSIGN      6,FN$SPEED
 86              TRANSFER    .333,YYY,CONT
 87       YYY    ASSIGN      9,FN$SPEED
 88       CONT   TRANSFER    P,11,1
          *
          *NORMAL CHANNEL ASSIGNMENT SUBROUTINE
          *
 89       NORML  ASSIGN      2,XH2
 90              GATE LR     P1,DYN1
 91       FIXO   TEST E      MH1(P1,P2),0,SERCH
 92              MSAVEVALUE 1,P1,P2,1,H
 93              ASSIGN      4,0
 94              TRANSFER    P,11,1
 95       SERCH LOOP         2,FIXO
 96              LOGIC S     P1
 97       DYN1   ASSIGN      2,XH4
 98              TEST NE     P2,0,BACK1
 99       DYN2   TEST E      V*1,0,LOOK
100              MSAVEVALUE 2,P1,P2,1,H
101              ASSIGN      4,2
102              JOIN        P1
103              TRANSFER    P,11,1
104       LOOK   LOOP        2,DYN2
105       BACK1 TRANSFER     P,11,1
          *
          *SPECIAL HAND-OFF CHANNEL ASSIGNMENT SUBROUTINE
          *
106       SPECL ASSIGN       2,XH1
107              ASSIGN      3,XH2
108       FIX1   TEST E      MH1(P1,P2),0,NEXT1
109              ASSIGN      4,1
110              MSAVEVALUE 1,P1,P2,1,H
111              TRANSFER    P,11,1
112       NEXT1 ASSIGN       2-,1
113              TEST E      P2,P3,FIX1
114              ASSIGN      2,XH3
115              ASSIGN      3,XH4
116              TEST NE     P2,P3,BACK2
```

```
117        DYN3   TEST E       V*1,0,NEXT2
118               MSAVEVALUE 2,P1,P2,1,H
119               ASSIGN       4,3
120               JOIN         P1
121               TRANSFER     P,11,1
122        NEXT2  ASSIGN       2-,1
123               TEST E       P2,P3,DYN3
124        BACK2  TRANSFER     P,11,1
          *
          *CALLS LEAVE SYSTEM
          *
125        EXIT   LEAVE        SYSTM
126               TERMINATE
          *
          *CHANNEL REASSIGNMENT
127        FREE1  TRACE
128               UNTRACE
          *
129               SCAN         P1,4,3,2,5,HANDF
130        ALT    ALTER        P1,1,4,P4,2,5
131               ALTER        P1,1,2,P2,2,5
132               MSAVEVALUE 2,P1,P5,0,H
133               REMOVE       P1,1,,2,P2
134               TERMINATE
135        HANDF  TEST E       P4,1,FREE2
136               MSAVEVALUE 1,P1,P2,0,H
137               TERMINATE
138        FREE2  SCAN         P1,4,2,2,5,RESET
139               TRANSFER     ,ALT
          *
          *AUXILIARY CLOCK
          *
140               GENERATE     300000
141               TEST E       BV1,1,STOP
142               TERMINATE    1
143        STOP   TERMINATE    24
                  START        1,NP
                  RMULT        1,3,5,7,9,11,13,15
                  RESET        S1
                  INITIAL      MH3(1-3,1-37),0/MH4(1-2,1-37),0
                  START        25,,,
                  END
```

C.2.2 Increasing Transmission Power Method

```
CREATE
REALLOCATE BLO,300,BVR,2,CHA,2,COM,180000,FMS,2
REALLOCATE FSV,7,FUN,5,GRP,41,HMS,6,HSV,7,LOG,41
REALLOCATE QUE,1,STC,2,TAB,1,VAR,400,XAC,1500
```

```
BLOCK
NUMBER   *LOC    OPERATION   A,B,C,D,E,F,G                COMMENTS
                 SIMULATE
         *
         *INITIALIZATION
         *
                 INITIAL     XH1,15      # OF FIXED CHAN/CELL (VOICE+HANDOFF)
                 INITIAL     XH2,15      # OF FIXED CHAN/CELL (VOICE)
                 INITIAL     XH3,0       # OF DYN CHAN IN SYSTEM (VOICE+HANDOFF)
                 INITIAL     XH4,0       # OF DYN CHAN IN SYSTEM (VOICE)
                 INITIAL     X1,30000    SIMULATION CYCLE TIME (MSECS)
                 INITIAL     X2,120000   MEAN CALL HOLDING TIME (MSECS)
                 INITIAL     X3,349      MEAN CALL INTERARRIVAL TIME (MSECS)
                 INITIAL     X4,5400000  MAXIMUM SIMULATION TIME (MSECS)
                 INITIAL     X5,160      CELL RADIUS (DECAMETRES)
         *
          1      MATRIX      H,37,10     FCA CONTROL, # OF COLUMNS=XH1
          2      MATRIX      H,37,1      THE INTERFERENCE FREQ. COUNTER
          3      MATRIX      H,3,37      BOUNDARY CROSSING STATISTICS
          4      MATRIX      H,2,37      INITIAL CHANNEL ASSIGNMENT STATISTICS
          5      MATRIX      H,37,10     THE INTERFERENCE TIMES COUNTER
          6      MATRIX      H,37,37     TO CONTROL THE IC LOCATIONS
          1      MATRIX      X,37,2      BASE STATION LOCATIONS
         *
                 INITIAL     MX1(8-13,1),240/MX1(14-19,1),-240
                 INITIAL     MX1(20-24,1),480/MX1(25-29,1),-480
                 INITIAL     MX1(30-33,1),720/MX1(34-37,1),-720
                 INITIAL     MX1(1,2),831/MX1(7,2),-831
                 INITIAL     MX1(13-14,2),693/MX1(8,2),-693
                 INITIAL     MX1(19,2),-693/MX1(2,2),554
                 INITIAL     MX1(24-25,2),554/MX1(6,2),-554
                 INITIAL     MX1(20,2),-554/MX1(29,2),-554
                 INITIAL     MX1(12,2),416/MX1(15,2),416
                 INITIAL     MX1(33-34,2),416/MX1(9,2),-416
                 INITIAL     MX1(18,2),-416/MX1(30,2),-416
                 INITIAL     MX1(37,2),-416/MX1(3,2),277
                 INITIAL     MX1(23,2),277/MX1(26,2),277
                 INITIAL     MX1(5,2),-277/MX1(21,2),-277
                 INITIAL     MX1(28,2),-277/MX1(11,2),139
                 INITIAL     MX1(16,2),139/MX1(32,2),139
                 INITIAL     MX1(35,2),139/MX1(10,2),-139
                 INITIAL     MX1(17,2),-139/MX1(31,2),-139
                 INITIAL     MX1(36,2),-139
                 INITIAL     MH6(1,2),1/MH6(1,13),2/MH6(1,14),3
                 INITIAL     MH6(2,1),1/MH6(2,3),2/MH6(2,12),3
                 INITIAL     MH6(2,13),4/MH6(2,14),5/MH6(2,15),6
                 INITIAL     MH6(3,2),1/MH6(3,4),2/MH6(3,11),3
                 INITIAL     MH6(3,12),4/MH6(3,15),5/MH6(3,16),6
                 INITIAL     MH6(4,3),1/MH6(4,5),2/MH6(4,10),3
                 INITIAL     MH6(4,11),4/MH6(4,16),5/MH6(4,17),6
                 INITIAL     MH6(5,4),1/MH6(5,6),2/MH6(5,9),3
                 INITIAL     MH6(5,10),4/MH6(5,17),5/MH6(5,18),6
                 INITIAL     MH6(6,5),1/MH6(6,7),2/MH6(6,8),3
                 INITIAL     MH6(6,9),4/MH6(6,18),5/MH6(6,19),6
                 INITIAL     MH6(7,6),1/MH6(7,8),2/MH6(7,19),3
                 INITIAL     MH6(8,6),1/MH6(8,7),2/MH6(8,9),3
                 INITIAL     MH6(8,20),4/MH6(9,5),1/MH6(9,6),2
```

```
          INITIAL     MH6(9,8),3/MH6(9,10),4/MH6(9,20),5
          INITIAL     MH6(9,21),6/MH6(10,4),1/MH6(10,5),2
          INITIAL     MH6(10,9),3/MH6(10,11),4/MH6(10,21),5
          INITIAL     MH6(10,22),6/MH6(11,3),1/MH6(11,4),2
          INITIAL     MH6(11,10),3/MH6(11,12),4/MH6(11,22),5
          INITIAL     MH6(11,23),6/MH6(12,2),1/MH6(12,3),2
          INITIAL     MH6(12,11),3/MH6(12,13),4/MH6(12,23),5
          INITIAL     MH6(12,24),6/MH6(13,1),1/MH6(13,2),2
          INITIAL     MH6(13,12),3/MH6(13,24),4/MH6(14,1),1
          INITIAL     MH6(14,2),2/MH6(14,15),3/MH6(14,25),4
          INITIAL     MH6(15,2),1/MH6(15,3),2/MH6(15,14),3
          INITIAL     MH6(15,16),4/MH6(15,25),5/MH6(15,26),6
          INITIAL     MH6(16,3),1/MH6(16,4),2/MH6(16,15),3
          INITIAL     MH6(16,17),4/MH6(16,26),5/MH6(16,27),6
          INITIAL     MH6(17,4),1/MH6(17,5),2/MH6(17,16),3
          INITIAL     MH6(17,18),4/MH6(17,27),5/MH6(17,28),6
          INITIAL     MH6(18,5),1/MH6(18,6),2/MH6(18,17),3
          INITIAL     MH6(18,19),4/MH6(18,28),5/MH6(18,29),6
          INITIAL     MH6(19,6),1/MH6(19,7),2/MH6(19,18),3
          INITIAL     MH6(19,29),4/MH6(20,8),1/MH6(20,9),2
          INITIAL     MH6(20,21),3/MH6(20,30),4/MH6(21,9),1
          INITIAL     MH6(21,10),2/MH6(21,20),3/MH6(21,22),4
          INITIAL     MH6(21,30),5/MH6(21,31),6/MH6(22,10),1
          INITIAL     MH6(22,11),2/MH6(22,21),3/MH6(22,23),4
          INITIAL     MH6(22,31),5/MH6(22,32),6/MH6(23,11),1
          INITIAL     MH6(23,12),2/MH6(23,22),3/MH6(23,24),4
          INITIAL     MH6(23,32),5/MH6(23,33),6/MH6(24,12),1
          INITIAL     MH6(24,13),27MH6(24,23),3/MH6(24,33),4
          INITIAL     MH6(25,14),1/MH6(25,15),2/MH6(25,26),3
          INITIAL     MH6(25,34),4/MH6(26,15),1/MH6(26,16),2
          INITIAL     MH6(26,25),3/MH6(26,27),4/MH6(26,34),5
          INITIAL     MH6(26,35),6/MH6(27,16),1/MH6(27,17),2
          INITIAL     MH6(27,26),3/MH6(27,28),4/MH6(27,35),5
          INITIAL     MH6(27,36),6/MH6(28,17),1/MH6(28,18),2
          INITIAL     MH6(28,27),3/MH6(28,29),4/MH6(28,36),5
          INITIAL     MH6(28,37),6/MH6(29,18),1/MH6(29,19),2
          INITIAL     MH6(29,28),3/MH6(29,37),4/MH6(30,20),1
          INITIAL     MH6(30,21),2/MH6(30,31),3/MH6(31,21),1
          INITIAL     MH6(31,22),2/MH6(31,30),3/MH6(31,32),4
          INITIAL     MH6(32,22),1/MH6(32,23),2/MH6(32,31),3
          INITIAL     MH6(32,33),4/MH6(33,23),1/MH6(33,24),2
          INITIAL     MH6(33,32),3/MH6(34,25),1/MH6(34,26),2
          INITIAL     MH6(34,35),3/MH6(35,26),1/MH6(35,27),2
          INITIAL     MH6(35,34),3/MH6(35,36),4/MH6(36,27),1
          INITIAL     MH6(36,28),2/MH6(36,35),3/MH6(36,37),4
          INITIAL     MH6(37,28),1/MH6(37,29),2/MH6(37,36),3
*
* EQUIVALENCE
*
 QUAD   EQU           1,Z
 SYSTM  EQU           1,S
*
*FUNCTION DEFINITION
*
 EXPON FUNCTION     RN4,C24
0,0/.1,.104/.2,.222/.3,.355/.4,.509/.5,.69/.6,.915/.7,1.2/.75,1.38
```

```
.8,1.6/.84,1.83/.88,2.12/.9,2.3/.92,2.52/.94,2.81/.95,2.99/.96,3.2
.97,3.5/.98,3.9/.99,4.6/.995,5.3/.998,6.2/.999,7/.9998,8
*
 SPEED FUNCTION    FN3,C25
0,-27.0/.05,-19.31/.1,-15.541/.15,-12.69
.2,-10.3/.25,-8.27/.3,-6.43
.35,-4.78/.4,-3.13/.42,-2.48/.45,-1.47
.47,-0.91/.5,0/.52,0.644
.55,1.56/.57,2.30/.6,3.13/.65,4.87
.7,6.58/.75,8.37/.8,10.48
.85,12.78/.9,15.58/.95,19.58/.999,27
*
 XXX    FUNCTION    FN2,C21
0,0/.05,32.8/.1,66.2/.15,100.4/.2,135.3
.25,171.0/.3,207.6/.35,245.1
.4,283.7/.45,323.3/.5,364.1/.55,406.2
.6,449.8/.65,494.9/.7,541.9
.75,590.9/.8,642.2/.85,696.1/.9,753.2/.95,814.1/1.0,879.5
*
 QUAD   FUNCTION    FN1,C2
.5,-1/1,1
*
*VARIABLE  DEFINITION
*
 1       FVARIABLE  FN5*(0-5774/10000*P6+(6351/1000*X5))/1000
 2       FVARIABLE  P6-MX1(P10,1)
 3       FVARIABLE  P7-MX1(P10,2)
 4       FVARIABLE  P6+(P8*(X1/10000))
 5       FVARIABLE  P7+(P9*(X1/10000))
 6       FVARIABLE  (11/10)*X5*X5
 7       FVARIABLE  (V2*V2)+(V3*V3)
 8.      FVARIABLE  P6-MX1(P1,1)
 9       FVARIABLE  P7-MX1(P1,2)
 10      FVARIABLE  (V8*V8)+(V9*V9)
 14      FVARIABLE  (144/100)*X5*X5
 15      VARIABLE   10*P1+MH6(P1,P3)
 16      VARIABLE   V*12-1
 11      VARIABLE   MH1(15,P2)+MH1(12,P2)+MH1(1,P2)
 12      VARIABLE   MH1(12,P2)+MH1(1,P2)
 13      VARIABLE   MH1(15,P2)+MH1(1,P2)
 21      VARIABLE   MH1(2,P2)
 22      VARIABLE   MH1(16,P2)+MH1(11,P2)+MH1(2,P2)
 23      VARIABLE   MH1(11,P2)+MH1(24,P2)+MH1(2,P2)
 24      VARIABLE   MH1(24,P2)+MH1(2,P2)
 25      VARIABLE   MH1(25,P2)+MH1(2,P2)
 26      VARIABLE   MH1(25,P2)+MH1(16,P2)+MH1(2,P2)
 31      VARIABLE   MH1(14,P2)+MH1(13,P2)+MH1(3,P2)
 32      VARIABLE   MH1(17,P2)+MH1(10,P2)+MH1(3,P2)
 33      VARIABLE   MH1(10,P2)+MH1(23,P2)+MH1(3,P2)
 34      VARIABLE   MH1(23,P2)+MH1(13,P2)+MH1(3,P2)
 35      VARIABLE   MH1(14,P2)+MH1(26,P2)+MH1(3,P2)
 36      VARIABLE   MH1(26,P2)+MH1(17,P2)+MH1(3,P2)
 41      VARIABLE   MH1(12,P2)+MH1(15,P2)+MH1(4,P2)
 42      VARIABLE   MH1(18,P2)+MH1(9,P2)+MH1(4,P2)
 43      VARIABLE   MH1(9,P2)+MH1(22,P2)+MH1(4,P2)
 44      VARIABLE   MH1(22,P2)+MH1(12,P2)+MH1(4,P2)
 45      VARIABLE   MH1(15,P2)+MH1(27,P2)+MH1(4,P2)
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46      VARIABLE    MH1(27,P2)+MH1(18,P2)+MH1(4,P2)
51      VARIABLE    MH1(11,P2)+MH1(16,P2)+MH1(5,P2)
52      VARIABLE    MH1(19,P2)+MH1(8,P2)+MH1(5,P2)
53      VARIABLE    MH1(8,P2)+MH1(21,P2)+MH1(5,P2)
54      VARIABLE    MH1(21,P2)+MH1(11,P2)+MH1(5,P2)
55      VARIABLE    MH1(16,P2)+MH1(28,P2)+MH1(5,P2)
56      VARIABLE    MH1(28,P2)+MH1(19,P2)+MH1(5,P2)
61      VARIABLE    MH1(10,P2)+MH1(17,P2)+MH1(6,P2)
62      VARIABLE    MH1(6,P2)
63      VARIABLE    MH1(20,P2)+MH1(6,P2)
64      VARIABLE    MH1(20,P2)+MH1(10,P2)+MH1(6,P2)
65      VARIABLE    MH1(17,P2)+MH1(29,P2)+MH1(6,P2)
66      VARIABLE    MH1(29,P2)+MH1(6,P2)
71      VARIABLE    MH1(9,P2)+MH1(18,P2)+MH1(7,P2)
72      VARIABLE    MH1(9,P2)+MH1(7,P2)
73      VARIABLE    MH1(18,P2)+MH1(7,P2)
81      VARIABLE    MH1(5,P2)+MH1(19,P2)+MH1(8,P2)
82      VARIABLE    MH1(19,P2)+MH1(8,P2)
83      VARIABLE    MH1(21,P2)+MH1(5,P2)+MH1(8,P2)
84      VARIABLE    MH1(21,P2)+MH1(8,P2)
91      VARIABLE    MH1(4,P2)+MH1(18,P2)+MH1(9,P2)
92      VARIABLE    MH1(18,P2)+MH1(7,P2)+MH1(9,P2)
93      VARIABLE    MH1(7,P2)+MH1(9,P2)
94      VARIABLE    MH1(22,P2)+MH1(4,P2)+MH1(9,P2)
95      VARIABLE    MH1(30,P2)+MH1(9,P2)
96      VARIABLE    MH1(30,P2)+MH1(22,P2)+MH1(9,P2)
101     VARIABLE    MH1(3,P2)+MH1(17,P2)+MH1(10,P2)
102     VARIABLE    MH1(17,P2)+MH1(6,P2)+MH1(10,P2)
103     VARIABLE    MH1(6,P2)+MH1(20,P2)+MH1(10,P2)
104     VARIABLE    MH1(23,P2)+MH1(3,P2)+MH1(10,P2)
105     VARIABLE    MH1(20,P2)+MH1(31,P2)+MH1(10,P2)
106     VARIABLE    MH1(31,P2)+MH1(23,P2)+MH1(10,P2)
111     VARIABLE    MH1(2,P2)+MH1(16,P2)+MH1(11,P2)
112     VARIABLE    MH1(16,P2)+MH1(5,P2)+MH1(11,P2)
113     VARIABLE    MH1(5,P2)+MH1(21,P2)+MH1(11,P2)
114     VARIABLE    MH1(24,P2)+MH1(2,P2)+MH1(11,P2)
115     VARIABLE    MH1(21,P2)+MH1(32,P2)+MH1(11,P2)
116     VARIABLE    MH1(32,P2)+MH1(24,P2)+MH1(11,P2)
121     VARIABLE    MH1(1,P2)+MH1(12,P2)
122     VARIABLE    MH1(15,P2)+MH1(4,P2)+MH1(12,P2)
123     VARIABLE    MH1(4,P2)+MH1(22,P2)+MH1(12,P2)
124     VARIABLE    MH1(1,P2)+MH1(12,P2)
125     VARIABLE    MH1(22,P2)+MH1(33,P2)+MH1(12,P2)
126     VARIABLE    MH1(33,P2)+MH1(12,P2)
131     VARIABLE    MH1(14,P2)+MH1(13,P2)
132     VARIABLE    MH1(14,P2)+MH1(3,P2)+MH1(13,P2)
133     VARIABLE    MH1(3,P2)+MH1(23,P2)+MH1(13,P2)
134     VARIABLE    MH1(23,P2)+MH1(13,P2)
141     VARIABLE    MH1(13,P2)+MH1(14,P2)
142     VARIABLE    MH1(3,P2)+MH1(13,P2)+MH1(14,P2)
143     VARIABLE    MH1(26,P2)+MH1(3,P2)+MH1(14,P2)
144     VARIABLE    MH1(26,P2)+MH1(14,P2)
151     VARIABLE    MH1(12,P2)+MH1(1,P2)+MH1(15,P2)
152     VARIABLE    MH1(4,P2)+MH1(12,P2)+MH1(15,P2)
153     VARIABLE    MH1(1,P2)+MH1(15,P2)
154     VARIABLE    MH1(27,P2)+MH1(4,P2)+MH1(15,P2)
155     VARIABLE    MH1(34,P2)+MH1(15,P2)
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156     VARIABLE    MH1(34,P2)+MH1(27,P2)+MH1(15,P2)
161     VARIABLE    MH1(11,P2)+MH1(2,P2)+MH1(16,P2)
162     VARIABLE    MH1(5,P2)+MH1(11,P2)+MH1(16,P2)
163     VARIABLE    MH1(2,P2)+MH1(25,P2)+MH1(16,P2)
164     VARIABLE    MH1(28,P2)+MH1(5,P2)+MH1(16,P2)
165     VARIABLE    MH1(25,P2)+MH1(35,P2)+MH1(16,P2)
166     VARIABLE    MH1(35,P2)+MH1(28,P2)+MH1(16,P2)
171     VARIABLE    MH1(10,P2)+MH1(3,P2)+MH1(17,P2)
172     VARIABLE    MH1(6,P2)+MH1(10,P2)+MH1(17,P2)
173     VARIABLE    MH1(3,P2)+MH1(26,P2)+MH1(17,P2)
174     VARIABLE    MH1(29,P2)+MH1(6,P2)+MH1(17,P2)
175     VARIABLE    MH1(26,P2)+MH1(36,P2)+MH1(17,P2)
176     VARIABLE    MH1(36,P2)+MH1(29,P2)+MH1(17,P2)
181     VARIABLE    MH1(9,P2)+MH1(4,P2)+MH1(18,P2)
182     VARIABLE    MH1(7,P2)+MH1(9,P2)+MH1(18,P2)
183     VARIABLE    MH1(4,P2)+MH1(27,P2)+MH1(18,P2)
184     VARIABLE    MH1(7,P2)+MH1(18,P2)
185     VARIABLE    MH1(27,P2)+MH1(37,P2)+MH1(18,P2)
186     VARIABLE    MH1(37,P2)+MH1(18,P2)
191     VARIABLE    MH1(8,P2)+MH1(5,P2)+MH1(19,P2)
192     VARIABLE    MH1(8,P2)+MH1(19,P2)
193     VARIABLE    MH1(5,P2)+MH1(28,P2)+MH1(19,P2)
194     VARIABLE    MH1(28,P2)+MH1(19,P2)
201     VARIABLE    MH1(6,P2)+MH1(20,P2)
202     VARIABLE    MH1(6,P2)+MH1(10,P2)+MH1(20,P2)
203     VARIABLE    MH1(10,P2)+MH1(31,P2)+MH1(20,P2)
204     VARIABLE    MH1(31,P2)+MH1(20,P2)
211     VARIABLE    MH1(5,P2)+MH1(8,P2)+MH1(21,P2)
212     VARIABLE    MH1(11,P2)+MH1(5,P2)+MH1(21,P2)
213     VARIABLE    MH1(8,P2)+MH1(21,P2)
214     VARIABLE    MH1(32,P2)+MH1(11,P2)+MH1(21,P2)
215     VARIABLE    MH1(21,P2)
216     VARIABLE    MH1(32,P2)+MH1(21,P2)
221     VARIABLE    MH1(4,P2)+MH1(9,P2)+MH1(22,P2)
222     VARIABLE    MH1(12,P2)+MH1(4,P2)+MH1(22,P2)
223     VARIABLE    MH1(9,P2)+MH1(30,P2)+MH1(22,P2)
224     VARIABLE    MH1(33,P2)+MH1(12,P2)+MH1(22,P2)
225     VARIABLE    MH1(30,P2)+MH1(22,P2)
226     VARIABLE    MH1(33,P2)+MH1(22,P2)
231     VARIABLE    MH1(3,P2)+MH1(10,P2)+MH1(23,P2)
232     VARIABLE    MH1(13,P2)+MH1(3,P2)+MH1(23,P2)
233     VARIABLE    MH1(10,P2)+MH1(31,P2)+MH1(23,P2)
234     VARIABLE    MH1(13,P2)+MH1(23,P2)
235     VARIABLE    MH1(31,P2)+MH1(23,P2)
236     VARIABLE    MH1(23,P2)
241     VARIABLE    MH1(2,P2)+MH1(11,P2)+MH1(24,P2)
242     VARIABLE    MH1(2,P2)+MH1(24,P2)
243     VARIABLE    MH1(11,P2)+MH1(32,P2)+MH1(24,P2)
244     VARIABLE    MH1(32,P2)+MH1(24,P2)
251     VARIABLE    MH1(2,P2)+MH1(25,P2)
252     VARIABLE    MH1(16,P2)+MH1(2,P2)+MH1(25,P2)
253     VARIABLE    MH1(35,P2)+MH1(16,P2)+MH1(25,P2)
254     VARIABLE    MH1(35,P2)+MH1(25,P2)
261     VARIABLE    MH1(3,P2)+MH1(14,P2)+MH1(26,P2)
262     VARIABLE    MH1(17,P2)+MH1(3,P2)+MH1(26,P2)
263     VARIABLE    MH1(14,P2)+MH1(26,P2)
264     VARIABLE    MH1(36,P2)+MH1(17,P2)+MH1(26,P2)
```

```
        265     VARIABLE     MH1(26,P2)
        266     VARIABLE     MH1(36,P2)+MH1(26,P2)
        271     VARIABLE     MH1(4,P2)+MH1(15,P2)+MH1(27,P2)
        272     VARIABLE     MH1(18,P2)+MH1(4,P2)+MH1(27,P2)
        273     VARIABLE     MH1(15,P2)+MH1(34,P2)+MH1(27,P2)
        274     VARIABLE     MH1(37,P2)+MH1(18,P2)+MH1(27,P2)
        275     VARIABLE     MH1(34,P2)+MH1(27,P2)
        276     VARIABLE     MH1(37,P2)+MH1(27,P2)
        281     VARIABLE     MH1(5,P2)+MH1(16,P2)+MH1(28,P2)
        282     VARIABLE     MH1(19,P2)+MH1(5,P2)+MH1(28,P2)
        283     VARIABLE     MH1(16,P2)+MH1(35,P2)+MH1(28,P2)
        284     VARIABLE     MH1(19,P2)+MH1(28,P2)
        285     VARIABLE     MH1(35,P2)+MH1(28,P2)
        286     VARIABLE     MH1(28,P2)
        291     VARIABLE     MH1(6,P2)+MH1(17,P2)+MH1(29,P2)
        292     VARIABLE     MH1(6,P2)+MH1(29,P2)
        293     VARIABLE     MH1(17,P2)+MH1(36,P2)+MH1(29,P2)
        294     VARIABLE     MH1(36,P2)+MH1(29,P2)
        301     VARIABLE     MH1(9,P2)+MH1(30,P2)
        302     VARIABLE     MH1(22,P2)+MH1(9,P2)+MH1(30,P2)
        303     VARIABLE     MH1(22,P2)+MH1(30,P2)
        311     VARIABLE     MH1(10,P2)+MH1(20,P2)+MH1(31,P2)
        312     VARIABLE     MH1(23,P2)+MH1(10,P2)+MH1(31,P2)
        313     VARIABLE     MH1(20,P2)+MH1(31,P2)
        314     VARIABLE     MH1(23,P2)+MH1(31,P2)
        321     VARIABLE     MH1(11,P2)+MH1(21,P2)+MH1(32,P2)
        322     VARIABLE     MH1(24,P2)+MH1(11,P2)+MH1(32,P2)
        323     VARIABLE     MH1(21,P2)+MH1(32,P2)
        324     VARIABLE     MH1(24,P2)+MH1(32,P2)
        331     VARIABLE     MH1(12,P2)+MH1(22,P2)+MH1(33,P2)
        332     VARIABLE     MH1(12,P2)+MH1(33,P2)
        333     VARIABLE     MH1(22,P2)+MH1(33,P2)
        341     VARIABLE     MH1(15,P2)+MH1(34,P2)
        342     VARIABLE     MH1(15,P2)+MH1(27,P2)+MH1(34,P2)
        343     VARIABLE     MH1(27,P2)+MH1(34,P2)
        351     VARIABLE     MH1(25,P2)+MH1(16,P2)+MH1(35,P2)
        352     VARIABLE     MH1(16,P2)+MH1(28,P2)+MH1(35,P2)
        353     VARIABLE     MH1(25,P2)+MH1(35,P2)
        354     VARIABLE     MH1(28,P2)+MH1(35,P2)
        361     VARIABLE     MH1(26,P2)+MH1(17,P2)+MH1(36,P2)
        362     VARIABLE     MH1(17,P2)+MH1(29,P2)+MH1(36,P2)
        363     VARIABLE     MH1(26,P2)+MH1(36,P2)
        364     VARIABLE     MH1(29,P2)+MH1(36,P2)
        371     VARIABLE     MH1(27,P2)+MH1(18,P2)+MH1(37,P2)
        372     VARIABLE     MH1(18,P2)+MH1(37,P2)
        373     VARIABLE     MH1(27,P2)+MH1(37,P2)
        1       BVARIABLE    C1'LE'X4*N$CALLS'LE'8000
       *
  1             GENERATE     X3,FN$EXPON,,,,15,F
  2     CALLS   ENTER        SYSIM
  3             ASSIGN       6,FN$XXX
  4             ASSIGN       7,V1
  5             ASSIGN       6,P6,1
  6             ASSIGN       7,P7,1
  7             TRANSFER     SBR,VELCC,11
  8             TRANSFER     SBR,CELL,11
  9             TEST NE      XH5,0,EXIT
```

```
10               ASSIGN       1,XH5
11               TRANSFER     SBR,NORML,11
12               TEST NE      P2,0,FAIL1
13               MSAVEVALUE   4+,1,P1,1,H
14        PRI    PRIORITY     2
15               ASSIGN       5,N$PRI
16               SPLIT        1,HOLD
17               LINK         ACTIV,FIFO
18        HOLD   ADVANCE      X2,FN$EXPON
19               UNLINK       ACTIV,TYP23,1,5,,CHECK
20               TERMINATE
21        TYP23  TEST GE      P4,2,TYP01
22               REMOVE       P1
23               MSAVEVALUE   2,P1,P2,0,H
24               TRANSFER     ,EXIT
25        TYP01  TEST NE      G*1,0,VACAT
26               SPLIT        1,FREE1
27               TRANSFER     ,EXIT
28        VACAT  MSAVEVALUE   1,P1,P2,0,H
29               TEST E       P4,0,EXIT
30        RESET  LOGIC R      P1
31               TRANSFER     ,EXIT
32        CHECK  TERMINATE
33        FAIL1  MSAVEVALUE   4+,2,P1,1,H
34               TRANSFER     ,EXIT
          *
          * CONTROL-TRANSACTION  GENERATION
          *
35               GENERATE     X1,,,,3,1,H
36               UNLINK       ACTIV,UPDAT,ALL
37               TERMINATE
          *
          * UPDATE  VEHICLE STATUS
          *
38        UPDAT  ENTER        SYSTM
39               ASSIGN       6,V4
40               ASSIGN       7,V5
41               TRANSFER     SBR,CELL,11
42               TEST NE      XH5,0,EXIT
43               TEST E       XH5,P1,CROSS
44        MODFY  TRANSFER     .5,,CHANG
45               LINK         ACTIV,FIFO
46        CHANG  ASSIGN       8,0
47               ASSIGN       9,0
48               TRANSFER     SBR,VELOC,11
49               LINK         ACTIV,FIFO
          *
          *BOUNDARY CROSSING
          *
50        CROSS  TEST GE      P4,2,NOT23
51               REMOVE       P1
52               MSAVEVALUE   2,P1,P2,0,H
53               ASSIGN       1,XH5
54               MSAVEVALUE   3+,1,P1,1,H
55               TEST E       P4,2,SEEK
56               TEST E       V*1,0,SEEK
57               MSAVEVALUE   2,P1,P2,1,H
```

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58                 MSAVEVALUE 3+,2,P1,1,H
59                 JOIN       P1
60                 TRANSFER   ,MODFY
61          NOT23  TEST E     G*1,C,SOME
62                 TEST E     P4,0,BYPAS
63                 LOGIC R    P1
64          BYPAS  MSAVEVALUE 1,P1,P2,0,H
65                 TRANSFER   SBR,INTER,11
66                 TRANSFER   ,PLUS1
67          SOME   SPLIT      1,FREE1
68          PLUS1  ASSIGN     1,XH5
69                 MSAVEVALUE 3+,1,P1,1,H
70          SEEK   TRANSFER   SBR,NORML,11
71                 TEST E     P2,0,FIND2
72                 TRANSFER   ,EXIT
73          FIND2  MSAVEVALUE 3+,2,P1,1,H
74                 TRANSFER   ,MODFY
75          FIND3  MSAVEVALUE 3+,3,F1,1,H
76                 TRANSFER   ,MODFY
           *
           * BASE STATION ASSIGNEMENT SUBROUTINE
           *
77          CELL   SAVEVALUE  5,0,H
78                 ASSIGN     10,37
79          RTN    TEST L     V7,V6,SKIP
80                 SAVEVALUE  5,P10,H
81          SKIP   LOOP       10,RTN
82                 TRANSFER   P,11,1
           *
           *VELOCITY ASSIGNMENT SUBROUTINE
           *
83          VELOC  TRANSFER   .25,XXX,YYY
84          XXX    ASSIGN     8,FN$SPEED
85                 TRANSFER   .333,YYY,CONT
86          YYY    ASSIGN     9,FN$SPEED
87          CONT   TRANSFER   P,11,1
           *
           *INTERFERENCE ASSIGNMENT SUBROUTINE
           *
88          INTER  TEST LE    V10,V14,MARO
89                 MSAVEVALUE 1,P1,P2,1,H
90                 ASSIGN     3,XH5
91                 ASSIGN     12,V15
92                 TEST G     V*12,1,FAR1
93                 MSAVEVALUE 5+,P1,P2,1,H
94                 MSAVEVALUE 2+,P1,1,V16,H
95          FAR1   ASSIGN     1,P3
96                 TRANSFER   ,MODFY
97          MARO   TRANSFER   P,11,1
           *
           *NORMAL CHANNEL ASSIGNMENT SUBROUTINE
           *
98          NORML  ASSIGN     2,XH2
99                 GATE LR    P1,CYN1
100         FIXO   TEST E     MH1(P1,P2),0,SERCH
101                MSAVEVALUE 1,P1,P2,1,H
102                ASSIGN     4,0
```

```
103              TRANSFER    P,11,1
104       SERCH  LOOP        2,FIX0
105              LOGIC S     F1
106       DYN1   ASSIGN      2,XH4
107              TEST NE     P2,0,BACK1
108       DYN2   TEST E      V*1,0,LOOK
109              MSAVEVALUE  2,P1,P2,1,H
110              ASSIGN      4,2
111              JOIN        P1
112              TRANSFER    P,11,1
113       LOOK   LOOP        2,DYN2
114       BACK1  TRANSFER    P,11,1
         *
         *SPECIAL HAND-OFF CHANNEL ASSIGNMENT SUBROUTINE
         *
115       SPECL  ASSIGN      2,XH1
116              ASSIGN      3,XH2
117       FIX1   TEST E      MH1(P1,P2),0,NEXT1
118              ASSIGN      4,1
119              MSAVEVALUE  1,P1,P2,1,H
120              TRANSFER    P,11,1
121       NEXT1  ASSIGN      2-,1
122              TEST E      P2,P3,FIX1
123              ASSIGN      2,XH3
124              ASSIGN      3,XH4
125              TEST NE     P2,P3,BACK2
126       DYN3   TEST E      V*1,0,NEXT2
127              MSAVEVALUE  2,P1,P2,1,H
128              ASSIGN      4,3
129              JOIN        P1
130              TRANSFER    P,11,1
131       NEXT2  ASSIGN      2-,1
132              TEST E      P2,P3,DYN3
133       BACK2  TRANSFER    P,11,1
         *
         *CALLS LEAVE SYSTEM
         *
134       EXIT   LEAVE       SYSTM
135              TERMINATE
         *
         *CHANNEL REASSIGNMENT
         *
136       FREE1  SCAN        P1,4,3,2,5,HANDF
137       ALT    ALTER       P1,1,4,P4,2,5
138              ALTER       P1,1,2,P2,2,5
139              MSAVEVALUE  2,P1,P5,0,H
140              REMOVE      P1,1,,2,P2
141              TERMINATE
142       HANDF  TEST E      P4,1,FREE2
143              MSAVEVALUE  1,P1,P2,0,H
144              TERMINATE
145       FREE2  SCAN        P1,4,2,2,5,RESET
146              TRANSFER    ,ALT
         *
         *AUXILIARY CLOCK
         *
147              GENERATE    300000
```

```
148              TEST E      BV1,1,STOP
149              TERMINATE   1
150         STOP TERMINATE   24
                 START       1,NP
                 RMULT       1,3,5,7,9,11,13,15
                 RESET       S1
                 INITIAL     MH3(1-3,1-37),0/MH4(1-2,1-37),0
                 START       25,,,
                 END
```

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