THE UNIVERSITY OF CALGARY

Optimal Algorithms for Indoor Handoff

by

Christopher Lau

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "**Optimal Algorithms for Indoor Handoff**", submitted by Christopher Lau in partial fulfillment of the requirements for the degree of Master of Science.

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Abstract

The fading characteristics of the indoor radio channel are analyzed and a model for estimating the probability of a signal outage in the radio channel is developed. Additionally, an expression for estimating the probability of handoff due to motion of a portable cellular transceiver is derived. These methods are used in enhancing an existing indoor cellular handoff algorithm. The new handoff algorithm utilizes signal outage probability and prioritization of call handoff requests. It is shown that the proposed handoff algorithm results in a significant improvment in terms of less blocking, fewer calls dropped and higher channel utilization than the currently available indoor handoff schemes.

Acknowledgements

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I wish to thank Mr. George Squires, Director of Wireless Research at TRLabs and TRLabs Calgary for providing funding, research facilities and support, without which this project would not have been possible.

Dedication

Ad majorem Creator gloriam,

hic opus,

quorum pars minima fui.

To the Creator's greater glory,

this work,

in which I played a small part.

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a	offered traffic in Erlangs
A	mean received signal amplitude (dB)
A_{min}	minimum received amplitude threshold (dB)
©	copyright
CT2Plus	second generation cordless telephone
dB	decibel
dBμV	decibel with respect to 1 microvolt
DECT	digital European cordless telephone
erf	the standard error function
EAMPS	extended advanced mobile phone service
FIFO	first-in, first-out
FSK	frequency shift keying
λ	call or handoff arrival rate (calls/hour)
LOS	line of sight
μ	mean value
MSE	mean square error
NLOS	non-line of sight
σ	Rayleigh parameter or standard deviation
s	system capacity in lines or channels
t	elapsed time on current channel (hours)
T_{cwr}	codeword reception timeout value (millisec)

TDMA	time division multiple access
Tremax	maximum time allowed for retry (millisec)
TRLabs	Telecommunications Research Laboratories

Chapter 1

Introduction

1.1 Cellular Radio

The cellular radio communication system provides a flexible means of long range, portable communications. Cellular systems consist of a number of small cells covering a wide geographical area. The fundamental principle behind cellular technology is the sharing of a common set of radio frequency channels and the ability of users to move between cells transparently and without interruption to communications; this system reduces both the bandwidth required and more importantly, the transceiver power required, making portability possible. The tremendous popularity of this system, which offers a relatively inexpensive and portable means of personal communications is evident in the growth of the cellular telephone industry. The great desire for personal communications shows itself in the many emerging standards for indoor cellular and other systems.

This amazing growth, however, has caused most systems to have reached their peak capacity as much as ten years ahead of predictions. As a result, the need for system upgrades and improvements is high. Because equipment upgrades are costly, there is great impetus for the development of techniques to increase the operating efficiency of current equipment so that greater levels of traffic can be handled, forestalling the need for new hardware expenditures. One of the areas targeted by researchers is the area of call handover. This is the mechanism which allows ongoing calls to be transferred between cells without interruption. Because of severe multipath interference and a limited number of channels, low efficiency of handoff procedures in indoor environments is particularly detrimental.

1.2 Literature Review

Since efficient handoff is crucial for optimum system performance, various methods for improving handoff must be studied.

Because indoor channel conditions are especially severe, handoff is much more critical. Studies of indoor channels improve understanding of fading effects, allowing effective means of dealing with fading to be developed.

At TRLabs, initial studies of the indoor radio channel were performed by Morrison, Fattouche and Zaghloul in 1990 [1]. Their research culminated in an extensive database of indoor channel measurements which can be used for analysis or simulation. The recent work of Hashemi et al [2][3], also at TRLabs, provided researchers with additional measurements of spatial and temporal variations of the indoor.channel.

Characterization of the multipath fading effects on the indoor channel by Hashemi, Tholl and Morrison [6] in 1992 yielded a log normal model. This was confirmed by other studies by Rappaport et al [4][5]. Later studies by Hashemi [2] indicated that in some cases, the Nakagami and Weibull distributions describe indoor fading effects slightly better than the log normal model.

Because handoffs may be caused by loss of signal due to fading, techniques which can estimate the likelihood of signal loss are desirable. Work by Sowerby and Williamson [7][8] based on initial work by Sachs [9] indicated that an expression for the probability of signal outage can be derived if the fading distribution of the channel is known. In an outdoor environment, this expression was used to determine coverage areas of cellular base stations.

Standards documents [11][12] and [13] describe the European DECT and the Canadian CT2Plus digital cellular radio systems. Both of these systems use a non-prioritized, non-queued handoff algorithm which can suffer large degrees of call loss under heavy traffic conditions. Hong and Rappaport describe several methods for call handoff in an outdoor system using first-in/first-out (FIFO) queuing and prioritization of call classes [17]. Tekinay and Jabbari propose a queuing handover scheme which arranges requests in order of signal strength [18][19]. This technique has been shown to produce lower call losses when used in an outdoor cellular radio system.

1.3 Research Focus

In order to develop an efficient handoff algorithm which is suited to conditions found in an indoor environment, the characteristics of the indoor channel must be understood, and an effective means of determining the necessity of handoff must be found. The focus of this research is to investigate fading effects on the indoor radio channel, and using this information, develop methods for determining handoff need and lastly, to use these methods to try to improve the performance of an existing indoor handoff algorithm. The investigation and results will be presented as follows:

1) Study and characterization of the indoor radio propagation channel,
2) Investigation of handoff determination criteria,
3) Simulation of handoff algorithms

Simulation results will be presented to show that marked improvements in the performance of existing handover schemes is possible. Problems encountered will be discussed as appropriate and summarized in the conclusion.

1.4 Thesis Overview

Chapter two introduces the indoor and outdoor cellular communication systems. The differences between the two operating environments are discussed, then the fading phenomenon on the indoor channel is characterized using channel measurements from the TRLabs channel measurement database.

Chapter three investigates two methods based on outage probability for determining the need for handoffs in an indoor cellular system. The indoor channel fading distribution found in chapter two is used to derive an expression for signal outage probability. Similarly, using a Guerin's model for channel occupancy time [10], an expression for the probability of handoff due to mobility of the portable transceiver in an indoor cellular system is developed. Simulation results are presented and conclusions drawn about the suitability of these methods as handoff criteria in a cellular radio network.

Chapter four examines the handoff algorithms in two existing indoor cellular standards: DECT and CT2Plus. The CT2Plus system is chosen for simulation because it is more sensitive to handoff and would benefit most from improvements. The simulator and the model used for simulation are introduced, and the measures used for gauging performance are discussed. The handoff algorithm is then simulated and results for varying levels of traffic are presented.

Finally, in chapter five, the major conclusions of thesis are summarized, recommendations for improving the performance of the CT2Plus are made based on simulation results and topics for further study are discussed.

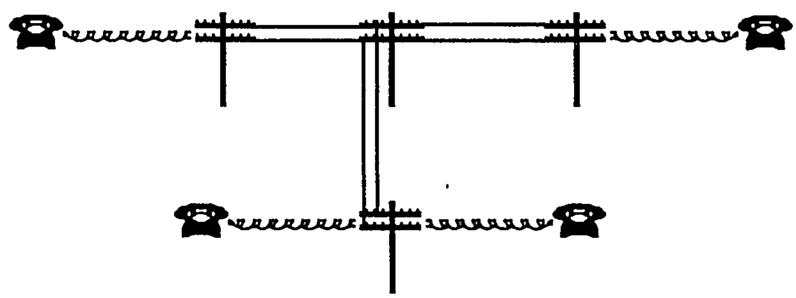
Chapter 2

The Cellular Communication System

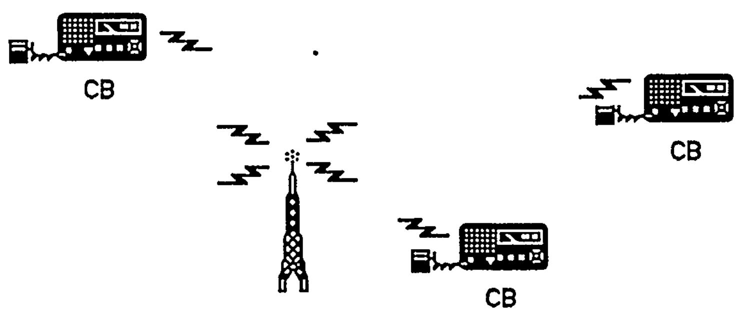
2.1 Introduction

Communication systems play an increasingly important role in society today. The two most widely used two-way communication systems are telephone and radio. Telephone systems use wires to relay messages between different people and places. Radio systems are used to allow communication at great distances without the need for wires and without being tied to a particular location. However, like telephone systems, the range of a radio communication system is limited by several factors: (i) transceiver power- the higher the transmitted power, the larger the coverage area and communications range, (ii) atmospheric and environmental conditions, which may cause interference and reflections, resulting in reduced communications range. Traditional radio communication systems increase their range by increasing the amount of power radiated. This is accomplished with bigger transmitters and better, more efficient antenna designs. However, because small size and portability are important requirements, the power output of a typical portable radio communication system is limited. Therefore the range of the system is also limited to just a few kilometers.

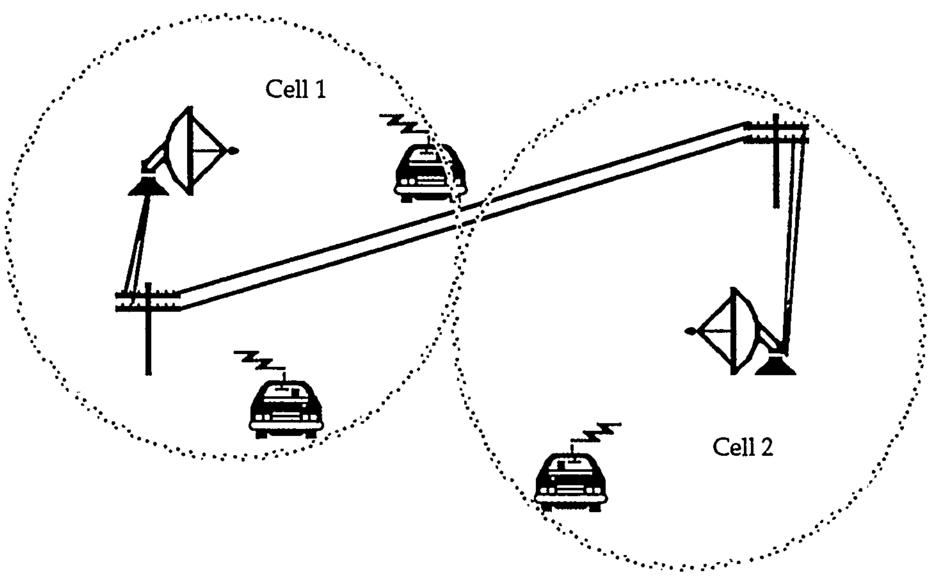
The cellular radio system is designed to allow a virtually unlimited communications range at modest transceiver power levels by utilizing aspects of both telephone and radio systems. A typical cellular system consists of several fixed transceivers (base stations) located adjacent to each other and linked to a central switching office or to each other with wires or even another radio transceiver, and a number of small, low-power portable calling units (terminals). The coverage areas of each of the base stations are referred to as cells. Because calls initiated in one cell (the home cell) can be transferred or handed off to another when the portable unit moves out of the cell, the effective coverage area of the system is much larger than that of any single base station or terminal. In addition, when the base stations are connected to a central telephone switching office, calls may also be made to and from fixed telephones in the existing telephone system. Figure 2.1 illustrates the three different systems discussed.



(a) Landline telephone system



(b) Radio communication system



(c) Cellular communication system

Figure 2.1- Three types of communication systems

2.2 Indoor and Outdoor Cellular Systems

Cellular systems may be used both indoors and outdoors. The outdoor system has been the subject of much study. However, comparatively little work has been done on indoor systems. The two systems are similar in that they both combine aspects of radio and telephone communication, but there are also some significant differences between the two.

The most obvious difference between the indoor and outdoor cellular systems is size, both physical and in terms of spectrum usage. The outdoor system is designed to cover a very large physical area, perhaps a city and its surrounding area, while an indoor system is designed to cover a comparatively small physical area- a home or an office building. Because of its large physical scale, an outdoor system also tends to require a greater share of the spectrum. The North American EAMPS outdoor cellular system allocates several hundred channels per cell, while an indoor cellular system such as the Canadian CT2Plus system only allocates forty channels per cell. Because the number of possible radio channels (and thus the number of calls possible in the system) is very limited, the perceived quality of service of a cellular system can be affected significantly if (i) a user's call cannot be connected or (ii) if a call in progress cannot be handed off and must be terminated when there are no free channels available. New calls which cannot be connected can be retried later, however, this is not desirable for calls in progress. Therefore, it is important to develop techniques to both improve the quality of handoffs and maximize the efficiency of channel usage, particularly for indoor systems.

Another obvious difference is in the names of the two systems- indoor and outdoor. Although signals in the indoor and outdoor environments suffer similar problems, the environments themselves are quite different. Radio signals in a typical outdoor urban environment may experience very large fluctuations in the channel gain due to the effects of multiple reflections from obstacles in the propagation path, both natural and man-made. In addition, these multiple reflections can also cause gain variations across the frequency spectrum. These two effects are known respectively as multipath induced fading and frequency selective fading. The same problems exist in an indoor system. This is illustrated by the fact that although a typical portable radio transceiver has more than enough output power to cover the area that a structure like an office building would take, performance of a standard radio system indoors is usually very poor because of severe signal attenuation. Signals in the indoor channel, like the outdoor radio channel, also suffer from reflection, refraction and scattering by various objects and structures, particularly the many partitions and walls in modern office building and also from the steel structure of the building itself. Because of this, multipath fading in the indoor environment tends to be much more severe than in the outdoor environment.

In either environment the construction and layout of the locale affects the channel characteristics because of different absorption and reflection properties of the building materials used. Additionally, motion of the transmitter/receiver or of objects in the vicinity also produce significant variations in the channel. These conditions can cause a transmitted signal to arrive by more than one path resulting in the phenomenon previously referred to as multipath fading. Although other effects including noise, co-channel interference and frequency selective fading can affect the quality of the received signal, multipath fading is considered the most severe and can seriously degrade the performance of both indoor and outdoor communication systems. The effect of multipath fading can be lessened through use of methods such as antenna diversity. However, the fading phenomenon cannot be eliminated entirely. If these fading effects can be characterized, techniques and processes for minimizing the severity of these disturbances can be developed.

2.3 The Indoor Radio Propagation Environment

2.3.1 Channel Characterization

Characterization of the channel and fading disturbances on the channel allows a better understanding of the channel impairments and provides the basis for the development of new fade-tolerant or fading-aware communications algorithms. For the case of handoff, a model of fading-induced amplitude variations is desired.

2.3.2 The TRLabs Channel Measurement Database

The work of Morrison et al [1] has provided TRLabs with an extensive database of over 12 000 indoor channel measurements. Hashemi et al [2][3], have made available an additional set of over 400 measurements of spatial and temporal variations of the indoor channel. These measurements are representative of conditions in typical modern office buildings and can be used to assist in characterization of the indoor radio channel as well as in performance simulation of indoor radio systems.

The measurements are grouped according to the distances at which they were made- 5, 10, 20 and 30 metres respectively. In addition, line-of-sight (LOS), non-line-of-sight (NLOS) and measurements with movement around the portable transceiver and the base station are available. Figure 2.2 shows an example of the amplitude variations of the channel at a range of 30 metres. Evident in this figure are many instances where the signal strength drops off rapidly. These are referred to as fades and are caused by the aforementioned multipath or selective fading and other effects, and if the fade is deep enough or long enough the signal may be degraded such that information may be lost, and in the worst case, the call may be disconnected. In an indoor cellular system, severe multipath fading is one of the primary causes of signal outage and efficient handoff and channel management strategies are needed to ensure uninterrupted communications.

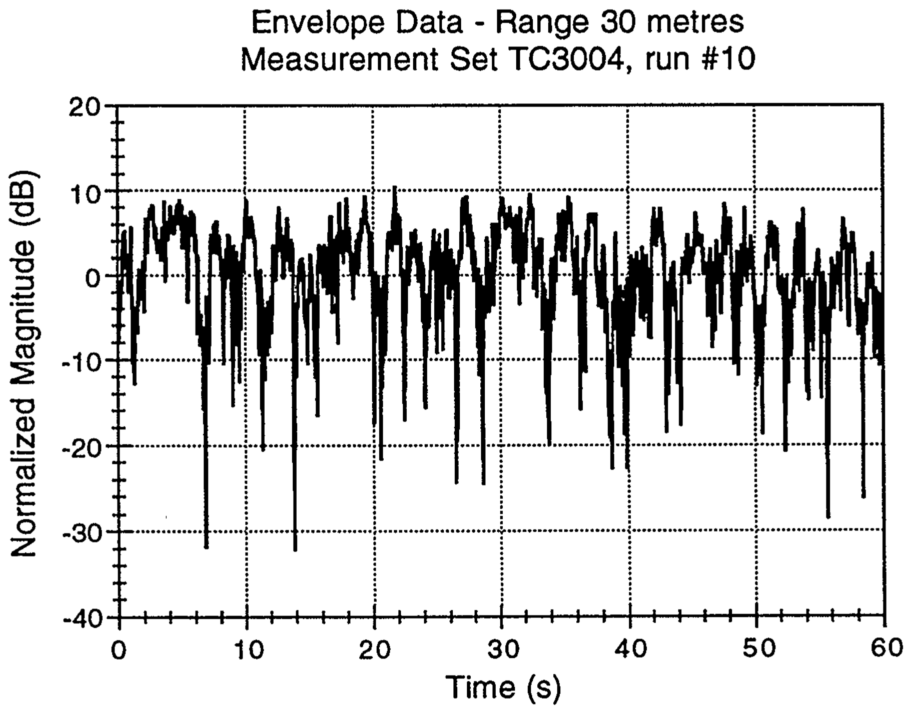


Figure 2.2- Indoor channel amplitude variations

2.3.3 Characteristics of the Indoor Channel

Discussed earlier were the two main effects which can cause outages in the cellular radio channel: (i) atmospheric effects and (ii) fading caused by the multipath phenomenon. Atmospheric effects are random and in general cannot be predicted, however, amplitude fading due to multiple reflections can be characterized and is the subject of much research. There are many models commonly used in the literature to describe the fading phenomena encountered on the radio channel. Most of these models are very complex or empirical models with no physical or theoretical basis. Since the purpose of this thesis is not to investigate the numerous models available, nor to undertake the extremely complex analysis of these models, they will be overlooked in favor of a standard model which is both simple to analyze yet describes fading effects accurately.

2.3.4 Model Selection

There are several standard distributions which are potential candidates for use in modeling fading-induced amplitude fluctuations in a radio channel. Of these distributions, the two most commonly used to account for multipath fading effects are:

- The Rayleigh distribution- This distribution is commonly used to explain small-scale local fading in outdoor environments. This distribution arises if the multiple reflections arriving at a receiver are assumed to combine additively. The probability density function (pdf) of the Rayleigh distribution is given by:

$$f(r)=\frac{r}{\sigma^2}e^{-\frac{r^2}{2\sigma^2}}, r\geq 0 \qquad (2.1)$$

where σ is called the Rayleigh parameter or the most probable value

and r is the amplitude of the received signal.

- The Lognormal distribution- This distribution is often used to explain large-scale variations in signal amplitude caused by the multipath environment. The theoretical explanation for encountering this type of distribution is that due to the multiple reflections in a multipath environment, the fading phenomenon can be characterized as a multiplicative process; thus multiplication of signal amplitude gives rise to a lognormal distribution. The pdf of the lognormal distribution is given by:

$$f(r)=\frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{(\ln r-\mu)^2}{2\sigma^2}}, r\geq 0 \tag{2.2}$$

where r is the amplitude of the received signal,
μ is the mean value of the distribution
and σ is the standard deviation.

Studies in literature show that for indoor channels, multipath components fade as lognormal distributions [4][5]. Analysis of indoor channel data by TRLabs researchers has also confirmed a lognormal fading distribution for the indoor channel [6]. Additional studies at TRLabs [2] have indicated good lognormal fit for LOS (line-of-sight) and short range (~30 metre) transmissions under moderate to heavy multipath conditions. The same study shows that for longer transmission ranges, both the Weibull and m- (or Nakagami) distributions were found to have slightly better fit, however the lognormal model was selected despite this fact because it displays good fit for transmission ranges that are typical of most indoor systems (<50 metre cell radius) and also due to the fact that it does not involve integral equations and is therefore much simpler to analyze.

2.3.5 Results of Indoor Channel Analysis

Assuming a lognormal distribution, several sets of data in the TRLabs channel measurement database described in the previous chapter were analyzed and the following statistics extracted:

Table 2.1- Indoor Channel Characteristics

Location	Mean Signal Amplitude	Average Std.Dev.	Max Std.Dev.	Average MSE	Max MSE
A	-58.6 dB	3.2 dB	4.9 dB	0.07	0.15
B	-72.8 dB	4.5 dB	5.5 dB	0.06	0.11
C	-34.6 dB	4.0 dB	5.3 dB	0.07	0.20
D	-60.2 dB	3.4 dB	5.6 dB	0.07	0.23

The data analyzed include a mixture of stationary LOS channel measurements and non-stationary, non-LOS measurements at various locations and ranges. Figure 2.3 shows an example of the results of a lognormal fit performed on one of the latter types of data (abcissa is in log scale, therefore, distribution appears normal or Gaussian on the plot). This measurement was taken at a range of

30 metres and the resulting mean-square error or MSE was 0.227. The low average mean-square error values shown in Table 2.1 indicate good lognormal fit. At 30 metres, the signal had a

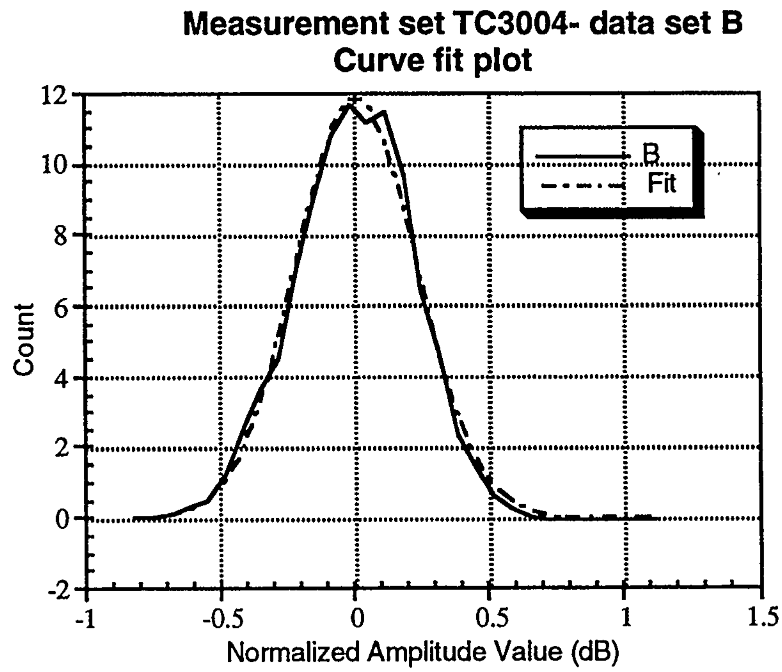


Figure 2.3- Sample curve fit data, lognormal distribution

maximum variance of 31.7 dB^2 and thus a maximum standard deviation of 5.63 dB (variance=sd^2). This indicates that signal amplitudes are expected to fluctuate up to a maximum of approximately 17 dB (in a normally distributed data set, 99.9999% of all values are expected to lie within three standard deviations of the mean: 3 * 5.63 dB = 16.9 dB) about the mean as the result of multipath fading.

2.4 Conclusions

The cellular radio system provides telecommunications services with great flexibility. Low power requirements also mean that the transceivers should be small and portable. However, because of the number of radio channels available is limited, the total number of calls allowed in the system is also limited. The amount of carried traffic is also reduced by effects such as multipath fading. This effect was shown to be particularly severe in indoor environments and is the primary cause of inefficiency of indoor cellular systems since such interference can effectively render a large percentage of channels unusable out of an already small channel pool. Because the quality of service that a user perceives is directly affected by (i) calls being blocked or (ii) calls in progress being terminated due to handoff failure, it is important to develop techniques which will reduce the probabilities of call blocking and premature call dropping.

Chapter 3

Handoff Determination Techniques

3.1 Introduction

Because of the negative impact slow and inefficient handoffs can have on a cellular communication system, there is great impetus for the development of methods which can improve both the quality and efficiency of handoffs.

Current outdoor cellular systems rely on signal strength measurements or calculation of signal-to-noise or carrier-to-interference ratios to determine the need for handoffs. This approach has proven to be fairly successful, however, designers of other cellular systems like the CT2Plus digital cellular system have chosen not to make use of physical measurements to determine the necessity of handoffs, (even though these statistics are available and are used by other mechanisms) but instead use a timeout-based approach. This approach has the drawback of the possibility of extremely long delays before handover is completed, and also, a timeout usually indicates that the connection has already been lost, which increases the possibility of handoff failure. Because of these drawbacks, a more efficient criterion for handoff is required.

Since handoffs are normally the result of signal outages due to range, fading, interference or other effects, techniques which can estimate the requirement or the necessity of handoffs due to signal outages are referred to as signal outage probability techniques. If handoffs occur with a particular frequency or within a particular distribution, then a second probability figure which will be referred to as handoff probability may be calculated. The first of these two types of techniques involves estimating the probability of loss of signal strength and the second attempts to estimate the need for handoff based on statistical criteria such as outage frequency or channel occupancy times. Such methods are especially attractive since they may be used both as an effective criterion for initiating handoff or as supplementary data for other handoff management techniques such as queue ordering information for a system using call queuing as part of its handoff algorithm.

3.2 Multipath Fading Induced Outage

Signal outage probability is defined as "a statistical measure that describes the probability of failing to achieve adequate reception of a signal". This type of outage probability has been commonly used to estimate coverage profiles (i.e., the effective communications range of a system in the presence of interference or other effects) in outdoor cellular radio systems [7][8][9]. A novel use of this technique is its application to estimating the probability of signal outages caused by the multipath fading phenomenon. Because handoffs in a cellular radio system are the result of signal outages caused by fading, the necessity of handoff may be estimated with this technique.

It has been shown in the literature that the probability of a signal outage can be calculated if the probability density function of the received signal envelope is known [7]. In the previous chapter, studies of the indoor channel have determined the probability density function of a signal experiencing multipath fading while propagating through the indoor channel to be approximately lognormal. The lognormal probability density function is:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma_x}\exp\left\{\frac{[\ln(x)-A]^2}{2\sigma_x^2}\right\} \tag{3.1}$$

where x is the amplitude of the received signal in microvolts, σ_x is its standard deviation and$A$ its mean value. Analysis is simplified by expressing (3.1) as the much less complicated normal or Gaussian distribution by simply converting the mean received signal, A into dB and expressing all other variables in dB relative to the mean.

If a radio receiver requires a received signal to have a minimum signal level of A_{min} dB in order to successfully extract the information in the signal, then the signal is defined to be lost when its field strengh drops below the minimum power threshold. Further, the probability of signal outage is defined as the probability of receiving a signal with strength less than the threshold level A_{min} dB:

$$P_{out} = P[x < A_{min}] = 1 - \int_{A_{min}}^{\infty} f(x)dx \tag{3.2}$$

Substituting expression (3.1) in (3.2) and evaluating results in an expression for the probability of fading induced signal outages in the indoor radio channel experiencing lognormally distributed multipath fading phenomena:

$$P_{out} = \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{A_{min} - A}{\sqrt{2}\sigma_P}\right) \tag{3.3}$$

where *erf()* is the standard error function, A_{min} is the minimum required signal amplitude and A is the mean signal amplitude, both expressed in dB.

Expression (3.3) may be used to calculate the percentage of the received signal strength which is below the threshold of A_{min} dB if the received signal has a mean field strength of A dB and standard deviation of σ_AdB. The value of A_{min} is determined mainly by the sensitivity of the radio receiver. The percentage of signal below threshold corresponds to the portion of the message which is lost due to multipath fading effects. Since voice messages can tolerate some degree of loss and still be intelligible, the outage threshold A_{min} is therefore also determined by the desired audio quality level; the threshold may be lowered if low voice quality is acceptable or raised if higher voice quality is desired. Both A and σ_A are determined by the multipath conditions. Typical values for these parameters were found previously by analysis of real channel data and listed in Table 3.1.

Table 3.1- Indoor channel parameters

Location	Mean Signal Amplitude	Average Std. Dev.	Max. Std. Dev.
A	-58.6 dB	3.2 dB	4.9 dB
B	-72.8 dB	4.5 dB	5.5 dB
C	-34.6 dB	4.0 dB	5.3 dB
D	-60.2 dB	3.4 dB	5.6 dB
Average	-56.6 dB	3.8 dB	5.3 dB

The percentage of signal below the outage threshold is directly related to the probability of signal outage: if 100% of the received field strength is found to be below the level necessary for maintaining communication, then obviously the probability of signal outage is one. Conversely, if 0% of the received signal is below the threshold, then there is no impediment to communication and the probability of outage must be zero. Therefore expression (3.3) can be used as an estimate of the probability of signal outage.

3.2.1 Signal Outage Probability Results

To observe the effectiveness of signal outage probability techniques, a series of simulations was performed. The software was written in the "C" language. The software first computes both local mean and variance for the input signal data. These parameters are then used in expression (3.3) to calculate the probability of signal outage. The TRLabs channel measurement database was used as a source of actual channel data for the simulations. Figure 3.1 shows a set of data measured on a stationary (i.e. no movement in the adjacent area) indoor channel. The light trace is the raw channel amplitude data and the dark trace is the data after an averaging filter with window length 25 has been applied. The averaging process is necessary to determine the "local mean" of the signal. This entails removing the short term variations which could confuse the outage probability calculation. The length of the averaging filter is important since if it is too short, excessive "noise" is passed to the probability estimator. Alternately, if too many averages are performed, the local mean information is destroyed and the output is delayed significantly with the possibility that the averaged output will not indicate a signal outage until well after the outage has already occurred. The length 25 was chosen arbitrarily since it produces a fairly clean output without introducing any significant delay.

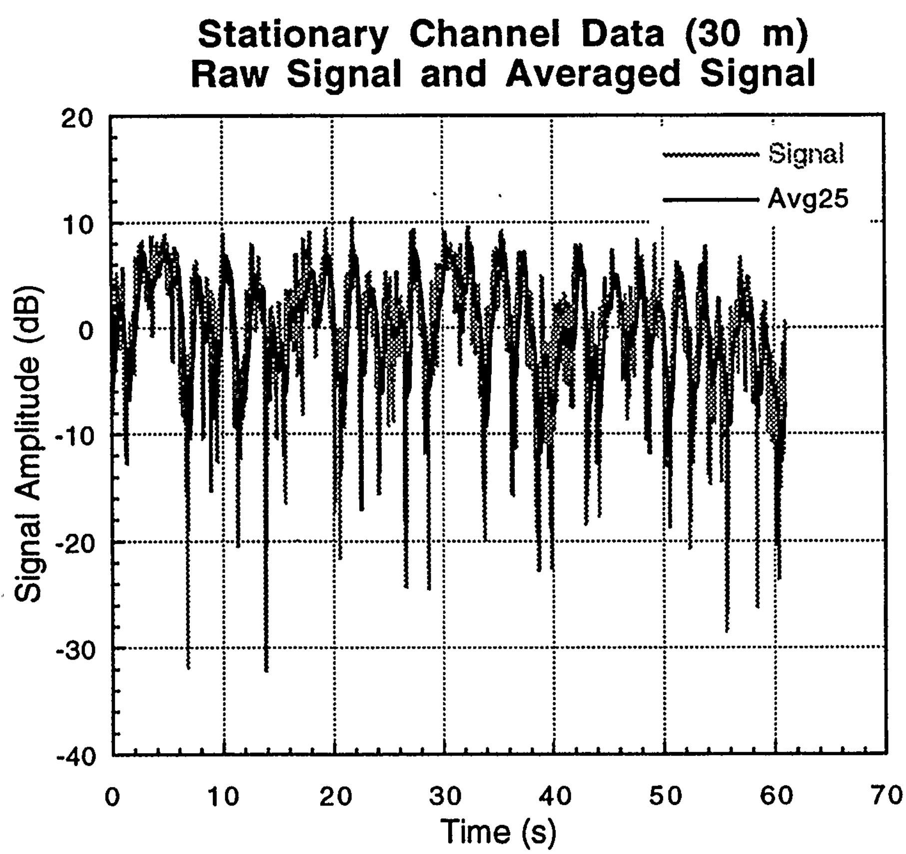


Figure 3.1- Channel data from the TRLabs channel measurement database

As stated earlier, standard handoff algorithms use signal strength measurements to determine the handoff requirement. Use of outage probability requires that the variance or standard deviation of the signal also be calculated. A good estimate of the variance of the signal may be calculated with:

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} \left(x_i - \bar{x} \right)^2 \tag{3.4}$$

Since both $\bar{x}$, the average signal strength and x_i, the instantaneous signal strength are available and the operations involved are simple multiplications and additions, the calculation of the variance does not add significant computational burden to the system. Figure 3.2 shows the averaged signal, the probability of signal amplitude calculated with expression (3.3) and the probable range of signal strength as determined by the variance (As mentioned previously, in a normally distributed data set, 99.9999% of all data values are expected to be within three standard deviations on either side of the mean, therefore, the probable range of signal strength is simply $\bar{x} \pm 3\sigma$. This measure gives both the maximum and minimum signal levels that the signal might have). The outage threshold for this simulation is set at -20.0 dB. Evident are the spikes in the outage probability value where the probable signal strength region (labeled "extent1" and "extent2" in Figure 3.2) extends below the outage threshold. Since the mean signal strength in this case is well above the threshold and the variance is relatively low, the signal outage

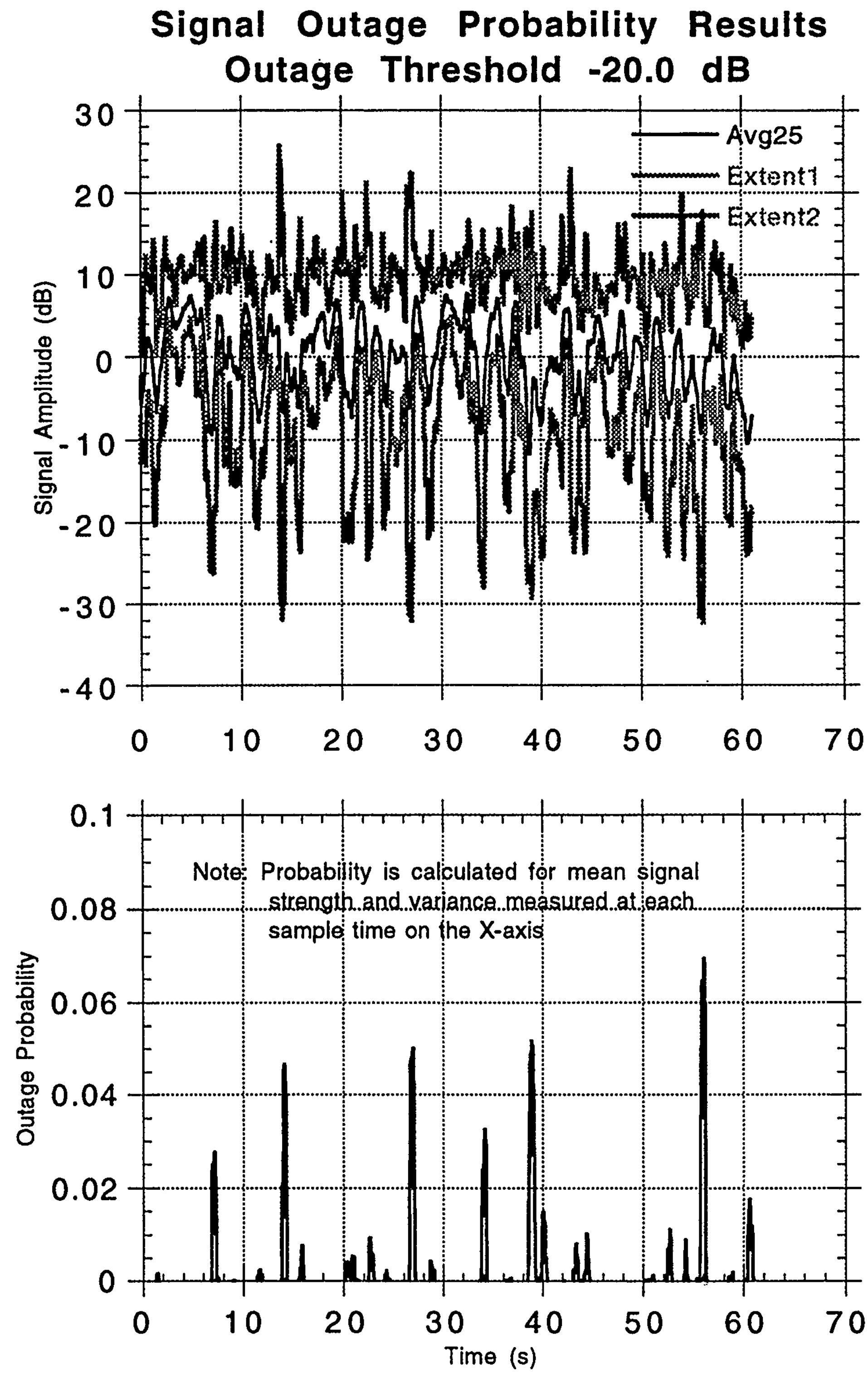


Figure 3.2- Signal outage probability results for stationary channel

probability is also low: the average probability of outage is only 0.24% and the maximum probability of outage is 6.9%. Therefore, no handoff is indicated. For this case, a signal strength based handoff algorithm would also conclude that no handoff is required, since neither the mean nor the minimum average signal strength is below the threshold. However, using only signal strength as a handoff criterion may not work for all signal conditions and may lead to poor handoff efficiency since signal strength does not give a significant enough indication of the need for handoff, especially in the indoor channel, where multipath fading may cause the signal strength to fluctuate widely. For example, in this case, where the channel is stationary, the averaged signal amplitude may still vary widely about the overall mean. A non-stationary channel can expect to have an even greater range. Because of the large fluctuations in signal amplitude, signal strength would make a very poor ranking criterion for a system using a prioritized queuing scheme as part of its handoff algorithm. In these cases, the variance of the signal can be an important indicator of channel conditions. Although there are conceivably many different ways to account for both the signal amplitude and signal variance, these methods may be purely empirical with little theoretical basis. Signal outage probability can take into account both these parameters.

Figure 3.3 shows the raw channel data and the averaged output for another set of indoor channel data, this time with path loss. This set of data reflects the signal a portable transceiver would see as the user moved steadily away from the base station. The light trace is the raw unaveraged data and the dark trace is the data after passing through a length 25 averaging filter. As with the stationary channel data, averaging the data removes the small amplitude variations while maintaining the local mean.

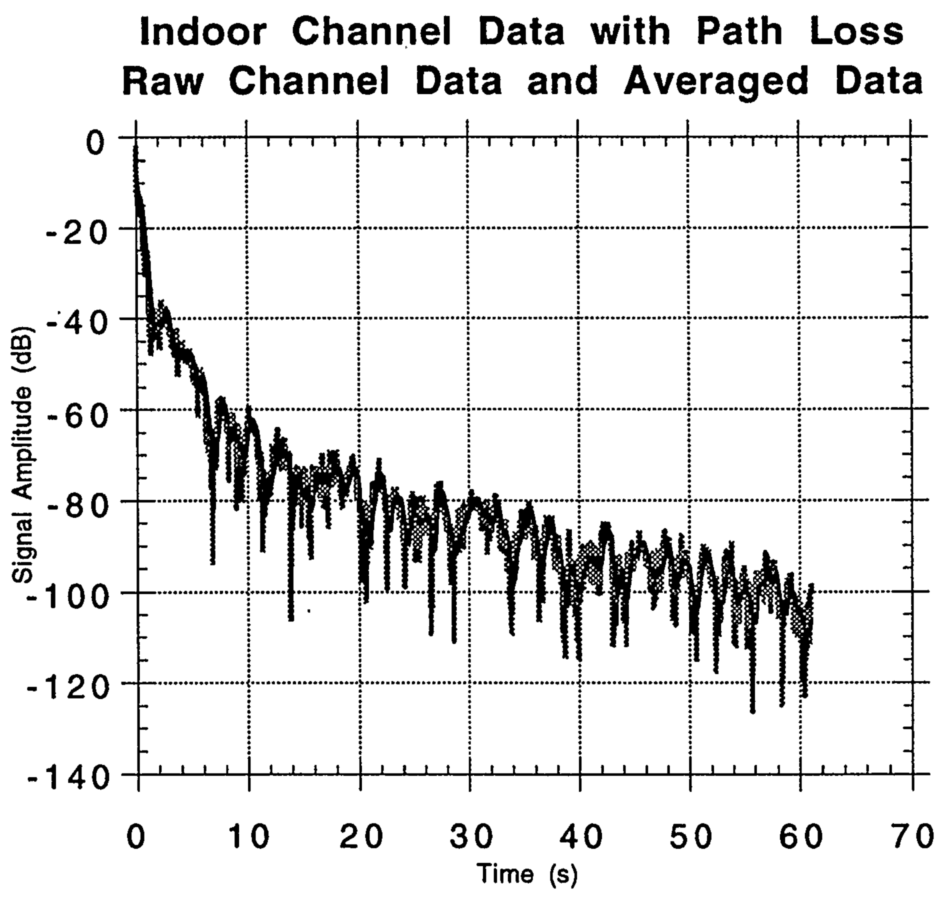


Figure 3.3 - Indoor channel data with path loss

Figure 3.4 shows the signal outage probability results and the probable range of signal strength for the data in Figure 3.3. The outage threshold for this example has been set at -80.0 dB. Therefore handoff algorithms based on signal strength measurements would initiate handoff if the signal strength dropped below -80.0 dB for a significant amount of time. In this case, a handoff would be initiated at around 20 seconds from the start of measurements, where the signal drops down to -90 dB. A system using signal outage probability would see an increasing probability of signal outage as the signal amplitude decreased. Since outage probability accounts for both signal amplitude and variance, in this example, a system using outage probability would know in advance that a signal outage is likely: the first indication as far back as about 12 seconds from the start, where the outage probability is about 38%. Also, at around the 15 second mark, where the amplitude drops to -80 dB for an instant, a signal measurement based handoff algorithm would probably not initiate a handoff because the average signal did not drop below the threshold for a long enough period. However outage probability shows a >50% probability of signal outage, indicating that although the average signal strength is not low enough for a signal strength based algorithm to justify handoff, the large variance increases the probability that a significant part of the signal will be below the outage threshold and thus the call may require handoff. When the outage does occur at the 20 second mark, the outage probability jumps to over 98%, indicating that the channel has "failed" and the call must be handed off. In this case however, because of the advanced warning given

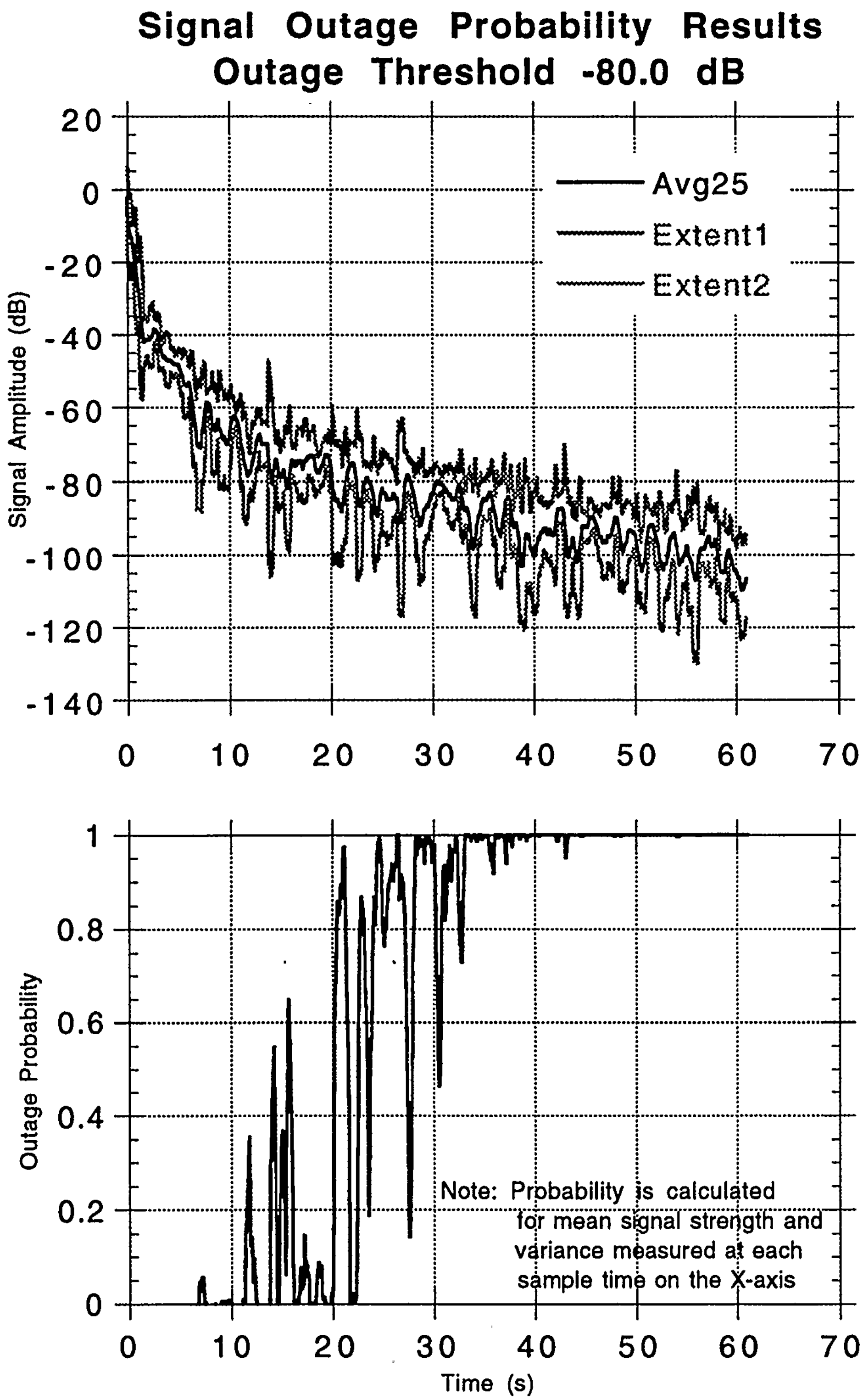


Figure 3.4 - Outage probability results for signal with path loss

by signal outage probability, a handoff may be initiated as far back as the 12 second mark, and depending on the handoff algorithm used, if a channel is not available immediately, the handoff may be queued in order of the outage probability.

3.3 Channel Occupancy Time

In a landline telephone system, a set of wires (the channel) is allocated to a caller when the call begins. Since landline telephones are fixed to a single location, the same wires are used for the duration of the call and therefore the channel occupancy time is equal to the length of the call. For typical voice calls the call duration is taken to have an exponential distribution with average call length being about three minutes.

In a cellular system, once a call has been initiated, the channel may change due to the user moving out of the cell or because of loss of signal due to fading or interference. Because of this, the probability of remaining on the same channel for the entire duration of the call is very low, and therefore the channel occupancy time is in general not equal to the call duration. A portable transceiver may also move through several cells and be handed off several times during the course of a single call. Thus the occupancy time on a given channel is only a fraction of the total length of the call, so even if the call duration is known to follow an exponential distribution, the channel occupancy time does not necessarily follow the same distribution.

If fading effects are ignored, the amount of time a call spends on a single channel will be determined solely by the movement of the portable calling unit. This is the period of time that a call will occupy a channel before the call is either handed off or terminated. Guerin [10] has found that for an outdoor cellular system, the channel occupancy time follows an exponential distribution. This study showed that the inverse of the mean occupancy time was equal to the sum of the inverse of the average call duration and the inverse of the average time spent in a given cell. The cell (and therefore the channel) occupancy time was found to be dependent on only three factors: (i) the size of the cell (i.e. the cell's effective radius), (ii) the speed at which the portable transceiver is moving and (iii) the average length of the call. It was also discovered that although the cell size and shape will affect the average channel occupancy time in a predictable way, neither the size nor the shape of the cell affect the shape of the distribution (it remains exponential), therefore, even though no similar studies have been performed to date on indoor cellular systems, it may be assumed that the exponential channel occupancy time distribution will hold for the smaller cell sizes and sometimes non-ideal cell shapes necessary in the indoor environment.

3.3.1 Handoff Probability

Since the channel occupancy time distribution is assumed to be known, it is possible to compute an estimate of the probabilty of requiring handoff based on the elapsed time on a given channel. This expression for the probability of handoff or call termination is derived in a manner similar to that used previously to find an expression fading induced outages. The channel occupancy time distribution is exponential, and the exponential distribution has a probability density function as follows:

$$f(t) = \lambda \exp(-\lambda t) \qquad \textit{for } t \geq 0 \tag{3.5}$$

The mean and variance of this distribution are respectively $\frac{1}{\lambda}$ and $\frac{1}{\lambda^2}$. Therefore, as before, this pdf may be used to derive an estimate for the handoff probability; expression (3.5) above, is substituted into expression (3.2) and evaluated, resulting in the following:

$$P_{Handoff} = 1 - \exp(-\lambda t) \tag{3.6}$$

where $\frac{1}{\lambda}$ is the mean time to handoff and t is the value of the elapsed time on the current channel.

3.3.2 Analysis of Handoff Probability

As before, a simulation was performed to observe the effectiveness of handoff probability estimation. In his work for outdoor systems, Guerin has determined the following expression for the rate of handoffs in a given circular/hex shaped cell [10]:

$$\lambda_H \cong \frac{6.46}{9\,\alpha}\ \textit{handoff / minute} \qquad (3.7)$$

where $\alpha = \frac{R\,\mu}{V}$ is a dimensionless unit, with R being the cell radius in metres, μ the average calling rate in calls per hour and V being the mean velocity of the portable transceiver in meters per second. Using (3.7), the mean handoff rate for a system using 50 metre cells where the call duration is exponentially distributed with a mean of three minutes and with average movement speed of about 0.3-0.4 metre/second is calculated to be about one handoff every 1.2 minutes. The 0.3-0.4 metre/second figure is arrived at by assuming an environment where about 60% of the users are stationary or where movement is limited (for example, within a cubicle or a single office) and the remaining 40% of the users are moving about in a larger area with an average speed of about one metre per second.

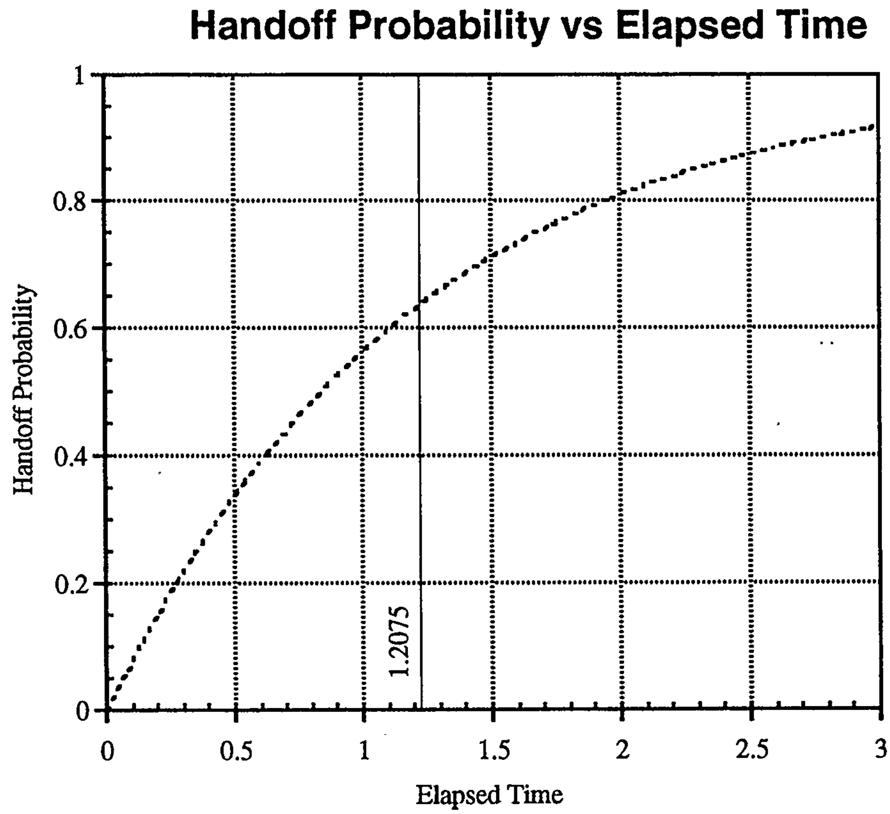


Figure 3.5 - Handoff probability vs. elapsed time on channel

Figure 3.5 illustrates the relationship between elapsed time and the probability of requiring handoff for a handoff rate of 1 per 1.2075 minutes. As expected, the probability estimate indicates an increasing probability of handoff requirement as the elapsed time on the current channel increases. However, because the handoff distribution is exponential, the time-to-handoff is not distributed evenly about the mean like a Gaussian variable: there is greater probability of handoff times less than the mean. Because of this, most handoffs are expected to occur when the handoff probability estimate is in the range of approximately 10% to 60%. This large range of values means that handoff probability is not too useful on its own as an indicator of handoff necessity, but should be used in conjunction with other methods to provide additional data about handoff need.

3.4 Conclusions

Two methods have been developed to determine the need for handoffs. The first, signal outage probability, attempts to estimate the probability of loss of signal strength due to fading effects based on the current channel conditions. When used as a handoff criterion, signal outage probability was seen to have significant benefits over simple signal strength threshold criteria that are currently in use; signal outage probability was found to be a more meaningful and useful indicator of signal outage which in certain conditions, is also able to give advanced warning of signal outage. The second method, handoff probability, utilizes the fact that channel occupancy times are exponentially distributed to determine the probability of requiring handoff due to the movement of the portable transceiver. Together, these two methods provide a better assessment of current cellular channel conditions and can be used in a handoff algorithm both as handoff criteria or as supplementary information for the handoff management strategy.

Chapter 4

Handoff Algorithms for Indoor Cellular Systems

4.1 Introduction

In a cellular communication system, the call traffic may be classified into two categories: (i) new call originations and (ii) handoff of calls in progress. Because it is clearly undesirable to terminate calls in progress, handoffs are most sensitive to loss and to a lesser extent, delay. New calls, however, are in general more tolerant to both loss and longer delays. The way the system deals with these two classes of calls greatly affects the perceived quality of service.

In previous chapters, it was reasoned that poor performance of a cellular communication system resulted mainly from poor handoff strategies. It was also illustrated how an effective method of determining the need for handoffs can be used to improve the quality of handoffs, particularly in an indoor environment where multipath effects are especially severe. In this chapter, an indoor handoff algorithm and modifications to it will be studied to find an effective solution for the handoff problems encountered in the indoor environment.

4.2 Existing Indoor Cellular Standards

There are several existing indoor cellular standards which vary in their approaches to dealing with the handoff problem. Two of the most well known standards are the "DECT" European telecommunications standard and the "CT2Plus" Canadian digital cellular standard.

4.2.1 The DECT Indoor Cellular Standard

DECT stands for "Digital European Cordless Telecommunications". This standard is available as [11] and describes a digital cellular system with ten channels with a nominal data rate of 1152 kbits/second each. Time-division multiple access (TDMA) techniques allow up to twelve calls per channel for a total system capacity of 120 calls per cell. The DECT standard does not specify a criterion for handoff but suggests using one or several of the following as the handoff criterion: (i) the packet CRC error detection codes, (ii) the synchonization pulse, (iii) clock jitter, (iv) signal strength or (v) some other measure of signal quality. The handoff procedure specified is of the "make-before-break" type, where a new channel must be allocated before the current channel is given up. This scheme improves the quality of voice communications since there will be no interruptions to conversation where the system is waiting for a new channel to be allocated. This scheme requires a relatively large number of channels to be efficient since it requires that two channels be occupied by a single call during the handoff. The handoff is not queued, which may lead to a significant number of premature call drops and call blockages when the traffic level is high.

4.2.2 The CT2Plus Indoor Cellular Standard

CT2Plus is the name of the Canadian Digital Cordless Telephone standard. The full specification is available as [12][13]. The standards documents describe a short range cellular system using two-level frequency-shift keying (FSK) for digital transmission. System capacity is forty time-division duplexed (data are transmitted and received in turn on the same channel) data channels per cell, with a nominal data rate of 72 kbits/second each and five common signalling channels which are used for call setup and identification purposes. Also specified are the schemes to be used for channel allocation and call handoff.

Channels are allocated on a first-free-channel basis. A channel is considered free if the field strength of that channel is below 40 dB relative to 1 μV/m for a period of time between 200 ms and 4 seconds. The decision on whether a channel is free is valid for a period of 2 seconds after the end of the monitoring period. No queueing of channel requests is possible if all channels are determined to be in use, although the unit may continue scanning for a maximum period of 3**Tremax*, where *Tremax* is defined to be 750 ms.

Call handoff is timeout based and may be initiated by either the portable unit or the base station- both the portable unit and the base station maintain a code word timer. The timer is reset on each reception of a good code word. If the code word is corrupted or lost due to interference or low signal power and a valid code word is not received before the timer expires (*Tcwr* =300 ms), a link re-establish is attempted. After the link re-establish message is sent, the portable unit must wait a period (*Tremax* =750 ms) for a reply from the base station. If after 750 ms, no reply is received, the portable unit may then scan for a free channel for a maximum of 3**Tremax* and attempt another link re-establish. If no free channel is found after the timer has expired, the call is dropped.

There are several deficiencies evident in the above specifications. The first is that because handovers and channel requests are not queued and not prioritized, an excessive percentage of handoffs and new calls will be blocked. In addition, because timeouts are used to initiate handoff, this system is relatively slow, and in the worst case, may have the possibility of causing handoff times greater than three seconds (300 ms + 4*750 ms = 3300 ms) which means that a conversation may be interrupted for up to 3 seconds, before it is re-connected or dropped. This poor handoff strategy combined with severe multipath conditions experienced indoors can result in very poor system performance. Lastly, because it is timeout based, this system must wait until the channel has failed before initiating a handoff. This precludes a make-before-break type of handover. Although make-before-break is desirable because it improves the perceived quality of service, the lack of this feature is not necessarily a severe deficiency in this case since this practice decreases the line utilization as two channels must be occupied during the handoff period. Because the CT2Plus system has an extremely limited number of channels, low line utilization can contribute significantly to poor overall system efficiency.

The algorithm chosen for study and enhancement is the handoff algorithm used in the CT2Plus telecommunications standard. The reasons for this choice are many: (i) the CT2Plus standard has been adopted as Canadian and North American standard. (ii) Unlike DECT, all aspects of the CT2Plus handoff algorithm are fully described in the standard, providing a firm starting foundation. (iii) With only ten radio frequency channels but an effective capacity of 120 calls, the DECT system is much less sensitive to the quality of the handoff algorithm used than the CT2Plus system. Therefore improvements in system performance due to enhancements of the handoff algorithm will be much more evident in the CT2Plus system.

4.3 System Performance Evaluation

Since cellular communication systems are extremely complex, system performance is evaluated using computer simulations. CACI Products Company's COMNET II.5 object-oriented communication system simulation package [14][15] was one of the tools used to assess handoff algorithm performance. The object-oriented nature of this package meant that no code had to be written; instead, graphical representations of the system components were laid out and connected together to form the system model. This shortened the development and debugging time considerably. Figure 4.1 shows the handoff algorithm used by the CT2Plus system that the simulations in this chapter are based on and Figure 4.2 shows the overall system model that was used. The system consists of an

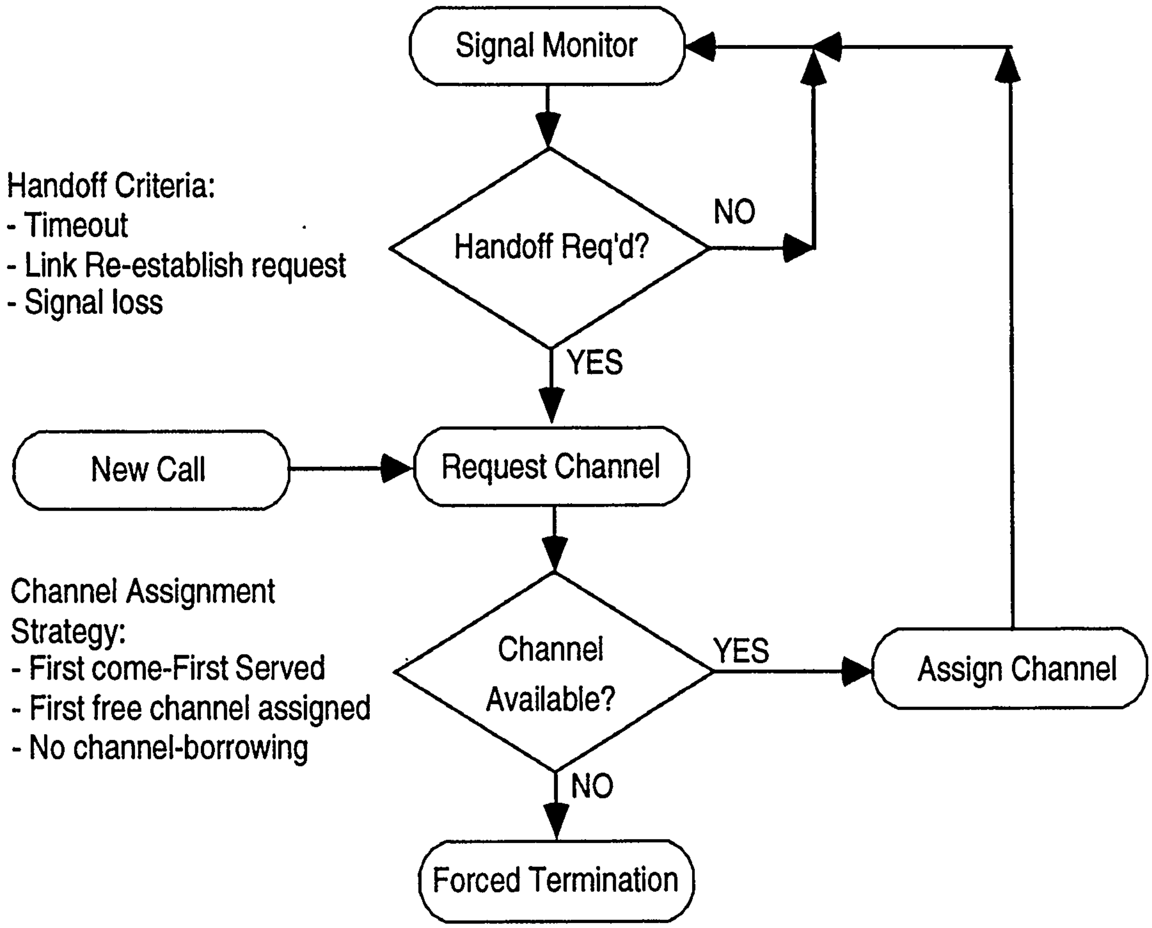


Figure 4.1 - Flowchart of the CT2Plus handoff algorithm

unspecified number of portable transceivers moving between two base stations with call traffic both to and from fixed telephones in the existing landline telephone system. The system uses three types of components: (i) nodes, (ii) links and (iii) traffic sources. The first type, nodes, represent system components where some type of

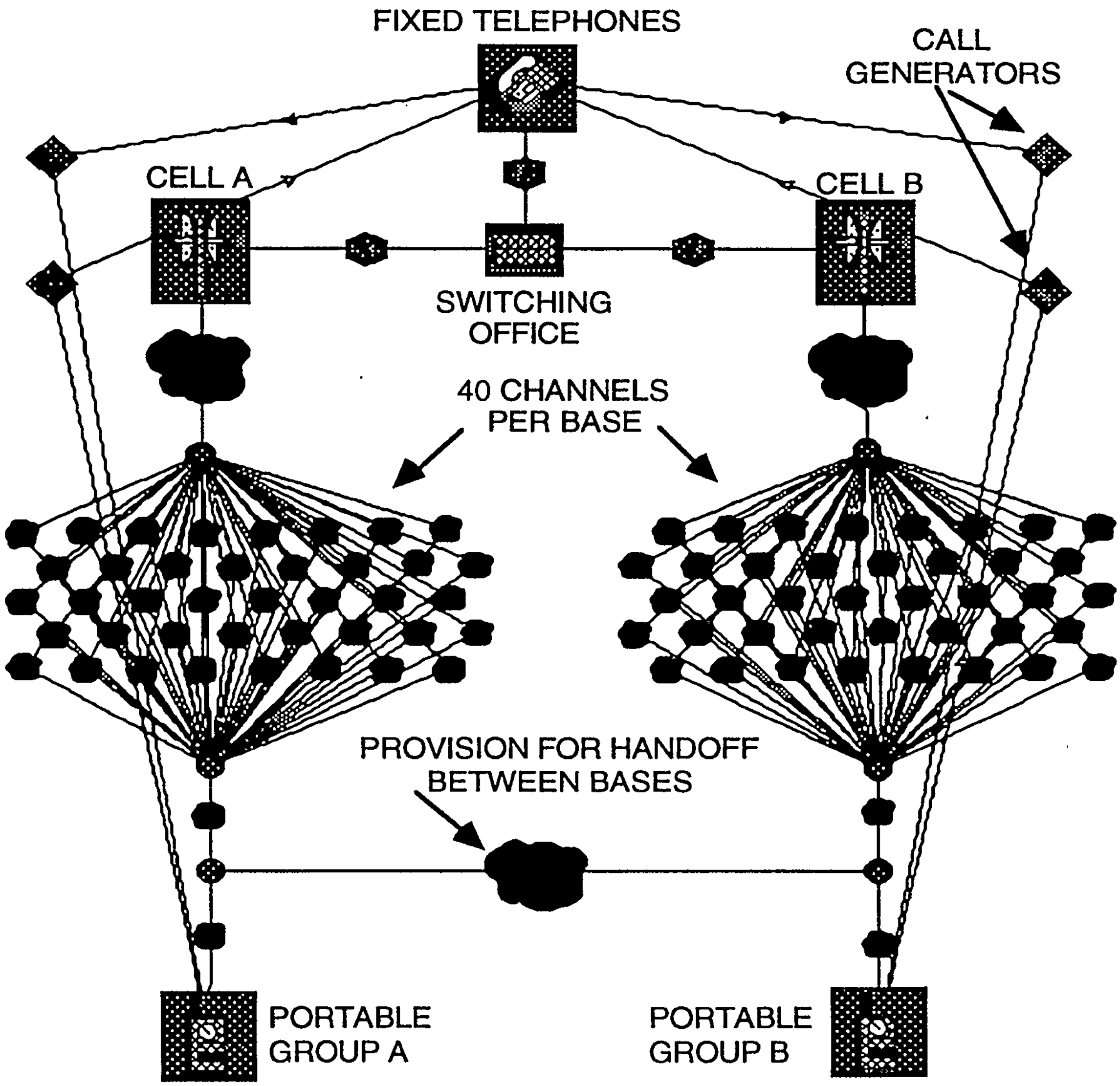


Figure 4.2 - The COMNET Model for a CT2Plus-based cellular system

processing can occur. This includes call initiation/reception and call routing. In Figure 4.2, the portable transceivers, the fixed telephones, the base stations and the central switching office are all represented as nodes. Nodes are connected together with the second component type, links. COMNET allows links to be specified in groups or as individual "wires". Forty separate links were used to represent the forty data channels of each base station of the CT2Plus system. The traffic generators are used to generate arbitrarily distributed call traffic and inject it into the system. The traffic model used for simulation is Poisson, with an average call length of three minutes. The system traffic is assumed to be composed of 50% incoming calls and 50% outgoing calls.

Channel outages due to multipath effects were simulated using COMNET's link failure feature. This feature causes links to fail according to a selected distribution or at user-specified times which are listed in a data file. When a link fails, any call using that link is automatically re-routed (handed-off) to the first free channel on the current cell, or to the first free channel on the adjacent cell if there are no free channels left on the current cell. If there are no free channels in either cell, the call is terminated. The link failure data file was generated by analyzing amplitude data from the TRLabs channel measurement database using the following decision criterion: *if signal strength is less than outage threshold for a period greater than 300 ms* (300 ms being the timeout period *Tcwr* in the CT2Plus system), *then a handoff is triggered.* In addition, mobility handoffs are simulated by generating exponentially distributed link failure events according to Guerin's model [10] assuming an average movement speed of 0.3 metres/second and a cell radius of approximately 50 metres, resulting in a mean of approximately 1.2 minutes between handoffs.

One of the limitations of the current version of the COMNET software is the lack of user-definable queuing routines (currently, only FIFO queuing is supported). Therefore custom software had to be developed to allow different queuing models and queue-ordering criteria to be used.

Because a simulation typically requires many tens of thousands of calculations, fast simulation speed is an extremely important requirement. For this reason, the "C" language was chosen as the programming language for the simulation. Once the system model described previously was developed and verified with COMNET, the model was re-coded in "C" and a custom simulation engine was written around it. The simulation engine was event-driven to increase simulation efficiency and speed; the custom simulator was found to be two to three times faster than a COMNET simulation of the same network, requiring only two to five minutes per traffic level (fourteen levels are simulated) on a DECstation 5000. Because it was event driven, an added benefit was that the same link failure data file used for the COMNET simulation could also be used to generate handoff events for the custom simulator.

Verification of correct operation of the new software was performed by simulating the same system in both the COMNET software and the custom software and comparing the results. The results generated were statistically identical, indicating proper operation.

4.4 Simulation Analysis of Handoff

As described earlier, the CT2Plus handoff algorithm is timeout based. If a handoff is needed, it may be initiated by either the base station or by the portable transceiver by transmitting a "link re-establish" request. The handoff is also non-prioritized and calls are not queued. The channel assignment strategy is likewise non-prioritized and no queuing is used. Table 4.1 shows the simulation parameters which are used for all the simulations throughout this chapter:

Table 4.1 - Simulation parameters

Parameter	Value
Number of cells	2
Number of data channels per cell	40
Call arrival distribution	Poisson, 10-2500 calls/hour
Traffic intensity range	0.5 through 125 Erlangs
Average call duration	3.0 minutes, exponential

Four main statistics may be used to evaluate the performance of a handoff algorithm: (i) the probability of blocking new calls, (ii) the probability of dropping calls in progress, (iii) the amount of traffic which is carried by the system and (iv) the percent utilization achieved by the system. Out of these four, (i) and (ii), the blocking and dropping probabilities are the most important. A cellular system can lose traffic from two sources: blocked new calls and prematurely terminated calls. Of these two sources, premature call termination is the most serious because a conversation or data transfer may be taking place; it is undesirable to terminate calls in progress because of handoff failure, therefore a low dropping probability is extremely important. Also, because a user expects that the majority of his calls will be connected on the first attempt, the perceived quality of service will go down if his calls are blocked because there are no free channels available. To maintain a good perceived quality of service, a low probability of new call blocking is also desired. The last two statistics, carried traffic and system utilization describe the efficiency of the system; a more efficient system will lose fewer calls due to blocking and call dropping and will be able to carry more calls. Because a greater amount of traffic is handled by an efficient system, there will also be fewer idle resources and hence a higher system utilization. Therefore the ideal system will have both low blocking and dropping probabilities and also a high degree of system utilization and a corresponding high level of carried traffic.

Another measure commonly used in the industry to gauge system performance is the "grade of service". This measure is a linear combination of the blocking and dropping factors of a system:

$$GOS = \alpha P_{block} + \beta P_{drop} \quad (4.1)$$

Where α and β are arbitrary weighting factors and P_{block} and P_{drop} are the blocking and dropping probabilities of the system. Smaller values of grade of service indicate better performance. Because good dropping performance is considered much more critical than blocking, P_{drop} is usually given a much heavier weighting than P_{block}. A typical ratio of α and β used in the industry to evaluate cellular system performance is 1:10, that is, P_{drop} is considered to be ten times more important than P_{block}.

Figure 4.3 shows the simulation results for the basic CT2Plus handoff algorithm. With traffic conditions as specified in Table 4.1, the maximum carried traffic of this system is approximately 60 Erlangs and the maximum system utilization is 86%. Although the probability of dropping a call in progress of the unmodified handoff algorithm is very low, the blocking probability versus offered traffic curve in Figure 4.3 reveals a significant deficiency in the CT2Plus handoff algorithm: there is no priority handling of different call types; because CT2Plus does not attempt to deal with new calls and handoffs differently, a very high blocking factor is realized, even at fairly low traffic levels. At a reference level of 100 Erlangs offered traffic, the grade of service of this system is 1(25.55% blocking) + 10(1.85% dropping) = 44.05.

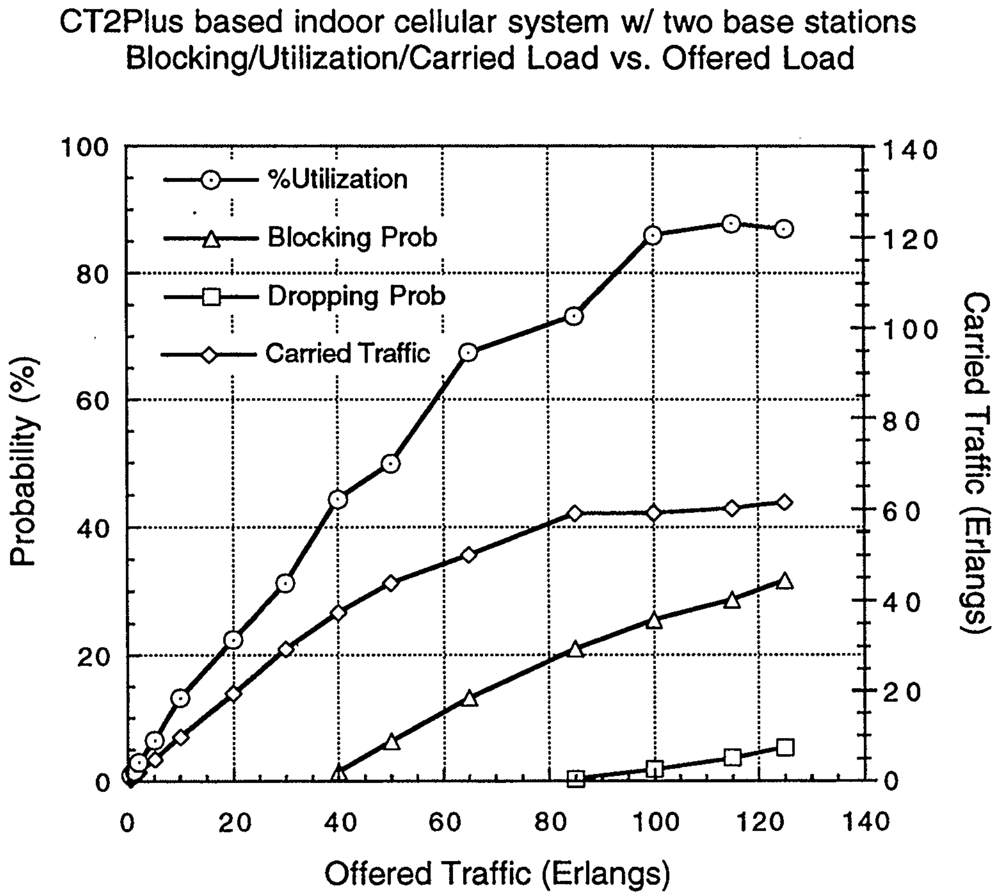


Figure 4.3 - CT2Plus system performance

Because calls in a cellular system may be handed off to a cell other than the current cell, call blocking and call dropping probabilities may not follow the well-known Erlang models which were developed for systems which do not require or allow handoffs. The Erlang B formula calculates the blocking probability for systems with Poisson arrivals and exponential call holding times where calls are lost if there are no free channels available [16]:

$$p_s = B(s,a) = \frac{a^s / s!}{\sum_{k=0}^{s} \left(a^k / k!\right)} \tag{4.2}$$

the quantity a is the offered traffic in Erlangs and s is the number of lines or channels available. The offered traffic for a typical land-based telephone system is simply $a = \lambda/\mu$, where λ is the call arrival rate and $1/\mu$ is the mean holding time per call. For a cellular system, this becomes $a = (\lambda_C+\lambda_H)/\mu$, where λ_C is the new call arrival rate, λ_H is the handoff rate and $1/\mu$ is the mean channel occupancy time. Note that λ_H accounts only for handoffs due to mobility; fading handoffs do not have a Poisson or any particular arrival distribution and therefore losses due to fading handoff failure cannot be estimated with the Erlang formula. Figure 4.4 shows a comparison between the probability of blocking versus offered load curves expected for a land telephone system using Erlang loss with 40 lines available and the probability of call loss that was encountered in the simulation of the CT2Plus cellular system which also has 40 channels but allows handoffs between cells. The call loss for a cellular system is the sum of all sources of lost traffic, which in this case is the sum of new call blocking and call dropping probabilities. Also shown is the expected call loss probability as calculated by the Erlang B formula. The results

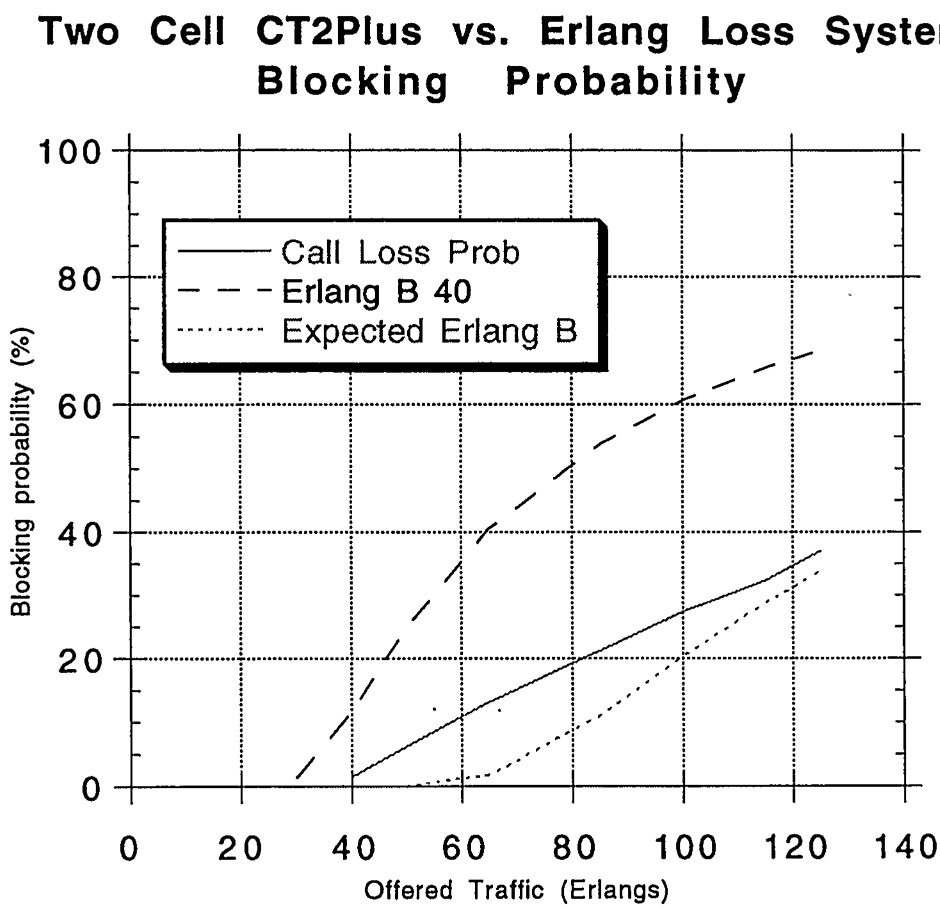


Figure 4.4 - CT2Plus vs. Erlang blocking probabilities

show fair agreement between the calculated call loss probability and the simulation results. The discrepancy is due, as stated previously, to the fact that only mobility handoffs were accounted for using λ_H; additional handoff traffic caused by fading results in more call losses than the Erlang model predicts. This extra call loss is reflected in the higher than expected loss probability. The large difference between the calculated and expected loss probabilities for the CT2Plus cellular system and the expected loss probability for the land telephone system indicate that because of its call handoff capability, a cellular system has more effective capacity available and therefore a higher traffic capacity than a fixed telephone system with the same number of lines.

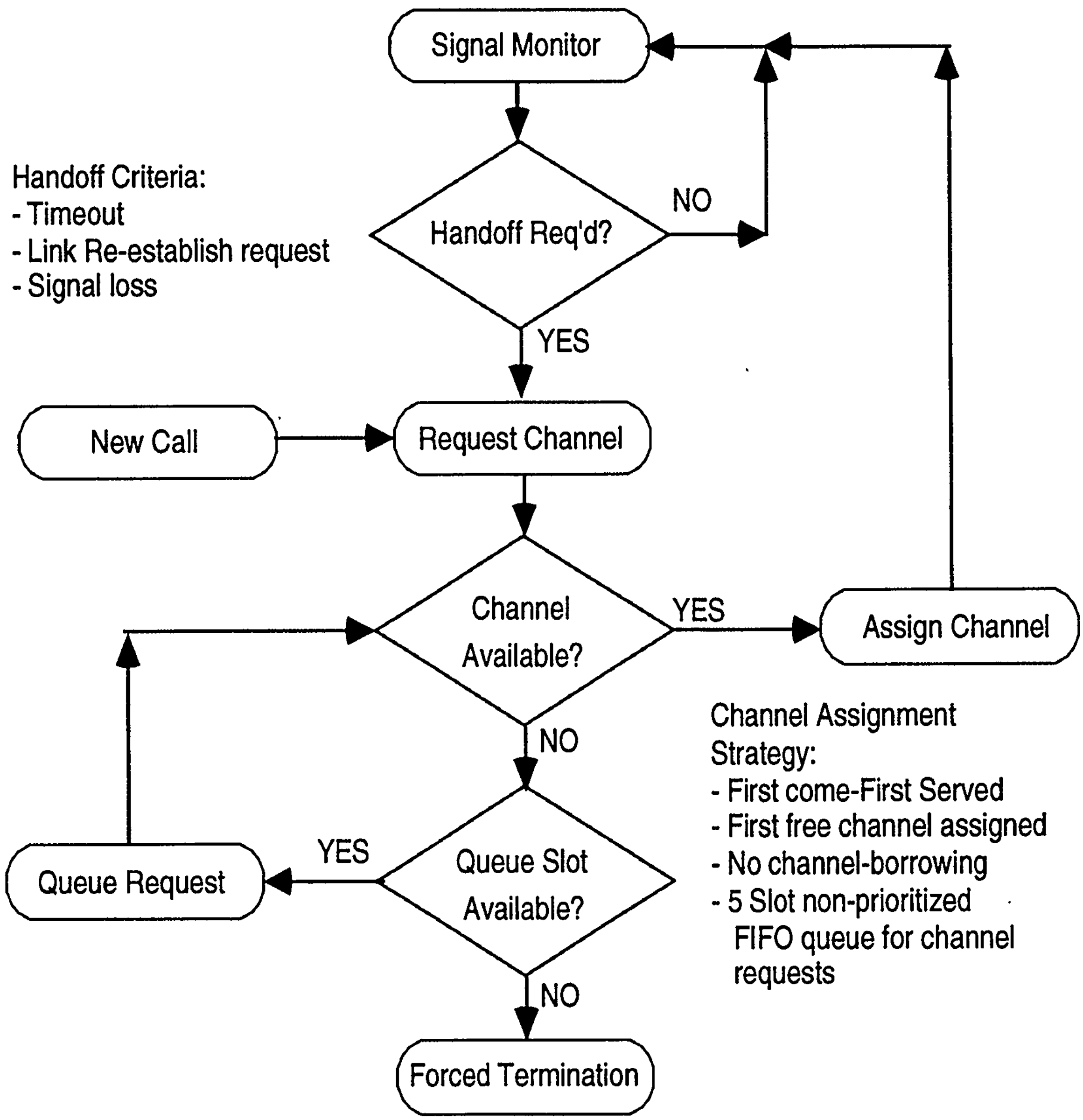


Figure 4.5 - Flowchart of the CT2Plus handoff algorithm with added FIFO queue

Studies have shown that significant benefits can be obtained when handover requests are queued and prioritized [17]. One of the simplest types of queue is the non-prioritized first-in-first-out or FIFO queue. As its name implies, in this type of queue, the request which entered the queue earliest will get served first. The queue is non-prioritized because all requests are treated the same- a particular request type is not given priority over other types. By adding simple non-prioritized FIFO queuing of both new calls and handoffs as shown in the flowchart of Figure 4.5 to the basic CT2Plus handoff algorithm, significant reduction of new call blocking is expected.

Figure 4.6 shows the results of adding a five entry FIFO queue to each base station in the system. The differences between the modified system and the basic CT2Plus system are summarized below:

Table 4.2 - Results of adding FIFO queue at 100 Erlangs offered traffic

	Carried Traffic (Erlangs)	Utilization (%)	New Call Blocking (%)	Call Dropping (%)	Grade of Svc.
Basic FIFO	65.17	91.08	8.70	10.55	114.2
CT2Plus	59.04	85.95	25.55	1.85	44.05

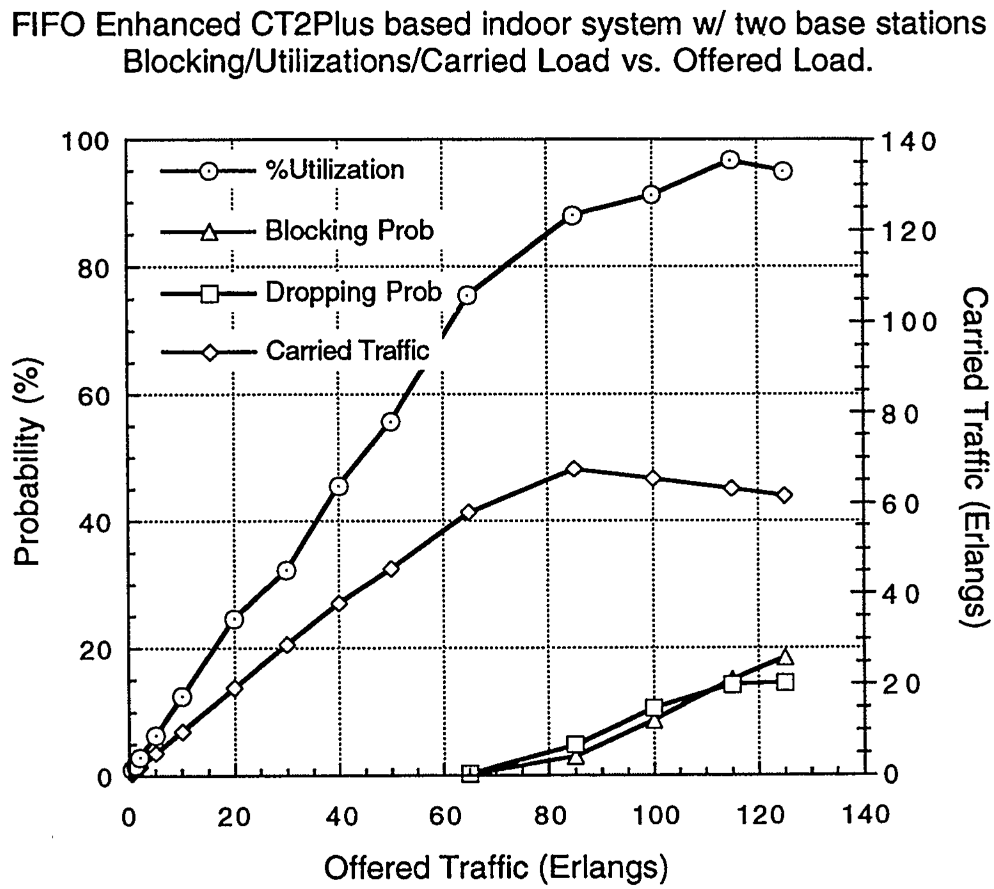


Figure 4.6 - System performance with added FIFO queue

As shown in Table 4.2, at a traffic level of 100 Erlangs, the new call blocking probability was reduced 66% from a previous value of over 25% probability of blocking to only about 9% with FIFO queuing in effect.

The Erlang combined loss and delay formula can be used to estimate the blocking for a system with a finite length queue; the blocking expression for the combined loss and delay system is [16]:

$$p_n = B_n(s,a) = \frac{a^n / \left(s! s^{n-s}\right)}{\sum_{k=0}^{s-1} \frac{a^k}{k!} + \frac{a^s}{s!} \frac{s}{s-a}\left[1 - \left(\frac{a}{s}\right)^{n-s+1}\right]} \tag{4.3}$$

where a is the offered load in Erlangs, s is the number of lines available and n is the total number of lines and queue slots available. Therefore, in the same manner as for the basic CT2Plus system in the previous section, the call loss probability for the system with a five entry FIFO queue is compared with the results obtained from the simulation; these are shown in Figure 4.7. These results show excellent agreement between the calculated and simulated results. As in the previous case, most of the discrepancy is due to fading handoff failures which are not accounted for by the Erlang model. The difference between simulated and calculated results is much smaller than found for the Erlang loss system simply because the queue does not distinguish between types of calls-handoffs are queued regardless if they are the result of mobility or of fading.

FIFO queuing also increased both the channel utilization and the carried traffic: from 85% previously to over 91% for channel utilization and from about 60 Erlangs to 65 Erlangs for carried traffic; these increases result simply because the queue reduces the number of calls lost and thus more calls are carried by the new system. The peak carried traffic of this system is almost 70 Erlangs for an offered load of 85 Erlangs. The price paid for the reduced blocking and higher utilization is a greatly increased number of premature call terminations: from less than 2% using the base

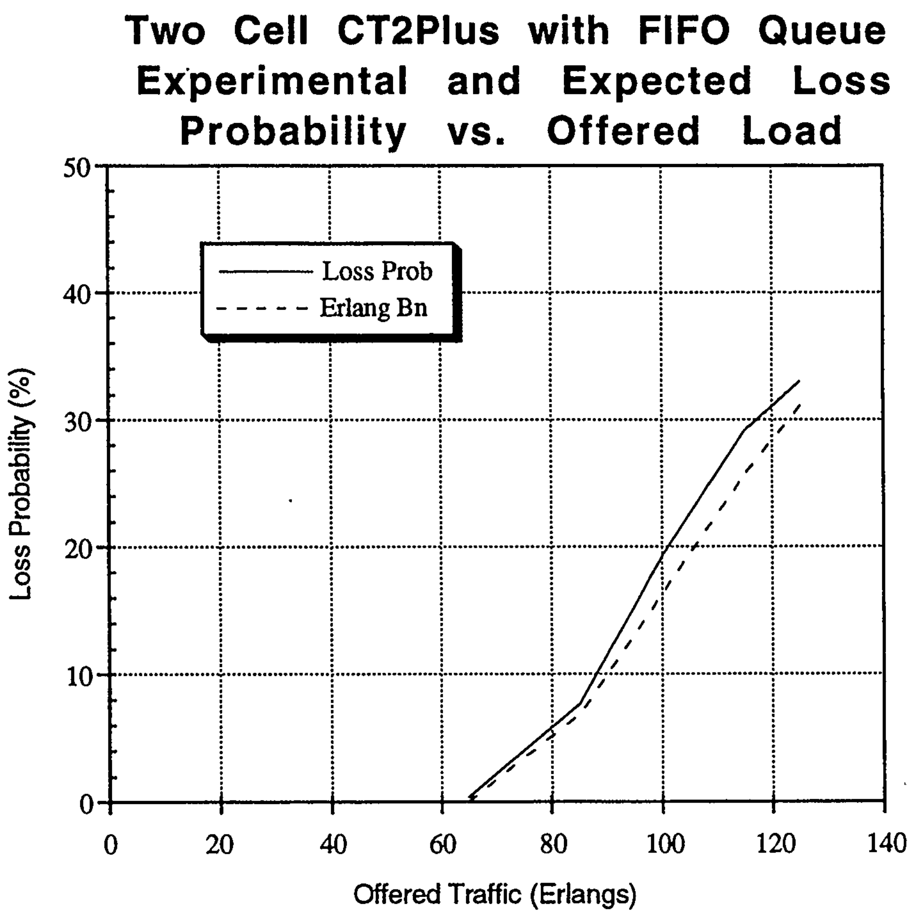


Figure 4.7 - CT2Plus with FIFO vs. Erlang combined call loss probabilities

CT2Plus system to over 10% with non-prioritized FIFO queuing. This increase is almost an order of magnitude; while both the increased utilization and reduced blocking probability are desirable characteristics, any increase in the number of premature terminations of calls in progress is not. The poor performance of this system is also reflected in the very high value of the grade of service calculated for this system. This illustrates the effect of weighting dropping level higher than blocking- the reduced blocking is not enough to offset the increased dropping, resulting in a poor grade of service. Therefore to improve the grade of service, methods to reduce the number of dropped calls while maintaining the reduction in new call blocking must be examined.

Priority techniques can be used to reduce the number of premature call drops by shifting call losses to a type which is more tolerant to loss. In this case, it is desired to allow more blocking of new calls in order to reduce dropping of calls in progress. In order to accomplish this, the simple FIFO queuing discipline used in the previous case is altered in the following fashion: (i) calls are identified as to their type (new call or handoff). (ii) Queue is still five entries in total, however, each type of call in the queue is handled in FIFO order. (iii) Handoffs are considered to have a higher priority than new calls and may therefore pre-empt new call entries as needed or until the queue is full, at which point further new calls are blocked and handoff calls dropped. An example of this type of queue is shown in Figure 4.8. The prioritized handling of requests means that handoffs requests will be served first and a reduction in the number of dropped calls is expected.

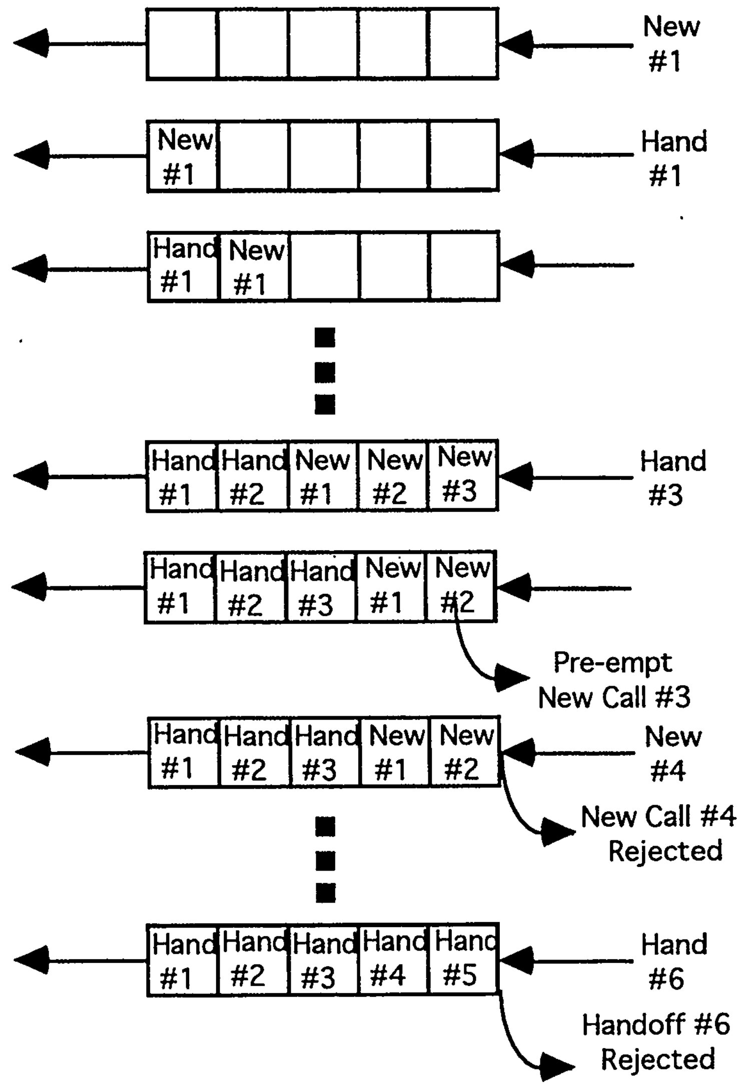


Figure 4.8 - Operation of FIFO queue with prioritized call handling

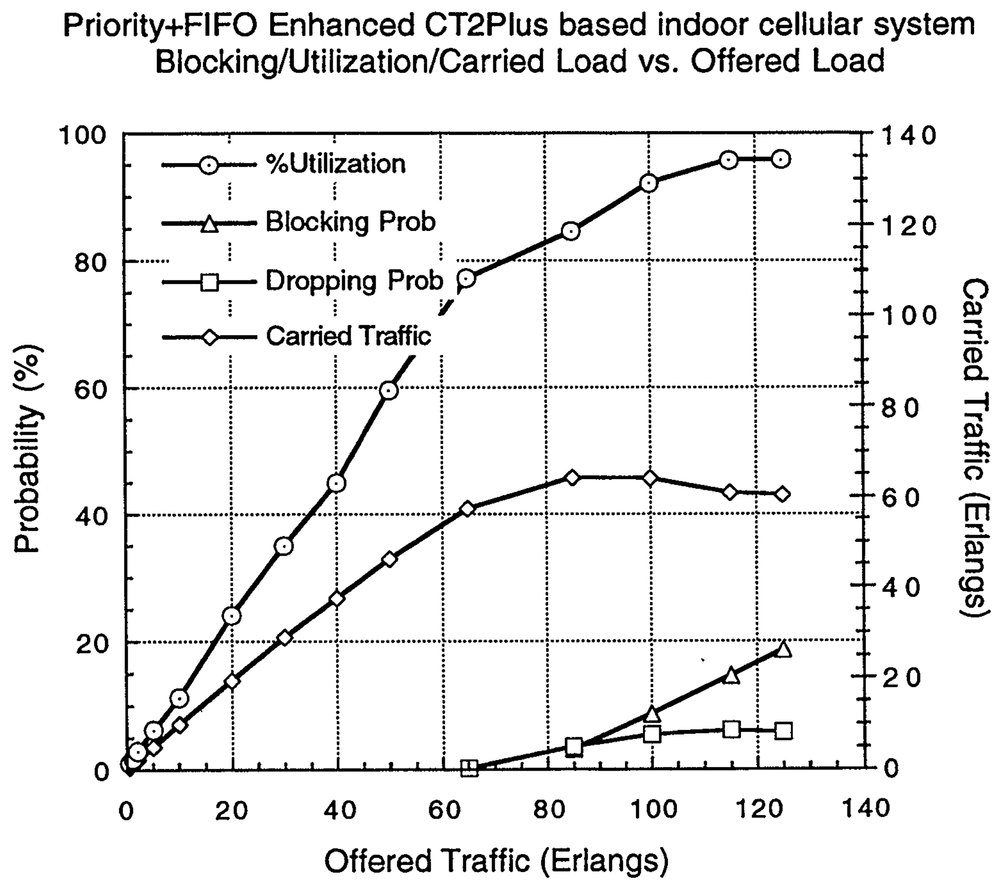


Figure 4.9 - System performance with priority FIFO queue

As is evident in Figure 4.9, modifying the FIFO system in the manner specified above to give queuing priority to call handoffs reduces the probability of premature call dropping by almost one half over the non-prioritized FIFO system. Table 4.3 shows a comparison of the results from the three systems studied thus far:

Table 4.3 - Results of adding priority to FIFO queue at 100 Erlangs offered traffic

	Carried Traffic (Erlangs)	Utilization (%)	New Call Blocking (%)	Call Dropping (%)	Grade of Svc.
Priority FIFO	65.05	92.29	9.20	5.20	61.2
Basic FIFO	65.17	91.08	8.70	10.55	114.2
CT2Plus	59.04	85.95	25.55	1.85	44.05

The addition of prioritized call handling resulted in a 5% probability of dropping calls in progress versus the 10% found previously. A surprising result was that there was no appreciable increase in blocking probability due to this modification: at an offered traffic of 100 Erlangs, blocking probability is only 0.5% higher than the case without prioritized call handling. The net result is that prioritized call handling in conjunction with a simple FIFO queue results in greater than 65% reduction of new call blocking over the unmodified CT2Plus system with no appreciable decrease in either carried load or line utilization.

Although prioritized call handling and FIFO queuing reduces blocking of new calls over a system using only FIFO queuing, the probability of dropping calls in progress and the corresponding grade of service is still higher than the basic CT2Plus system. Therefore additional methods for reducing call dropping must be considered. A popular technique for improving the quality of handoff by reducing the number of premature call terminations in the outdoor cellular system is called *measurement based prioritization*. This method requires that instead of simple

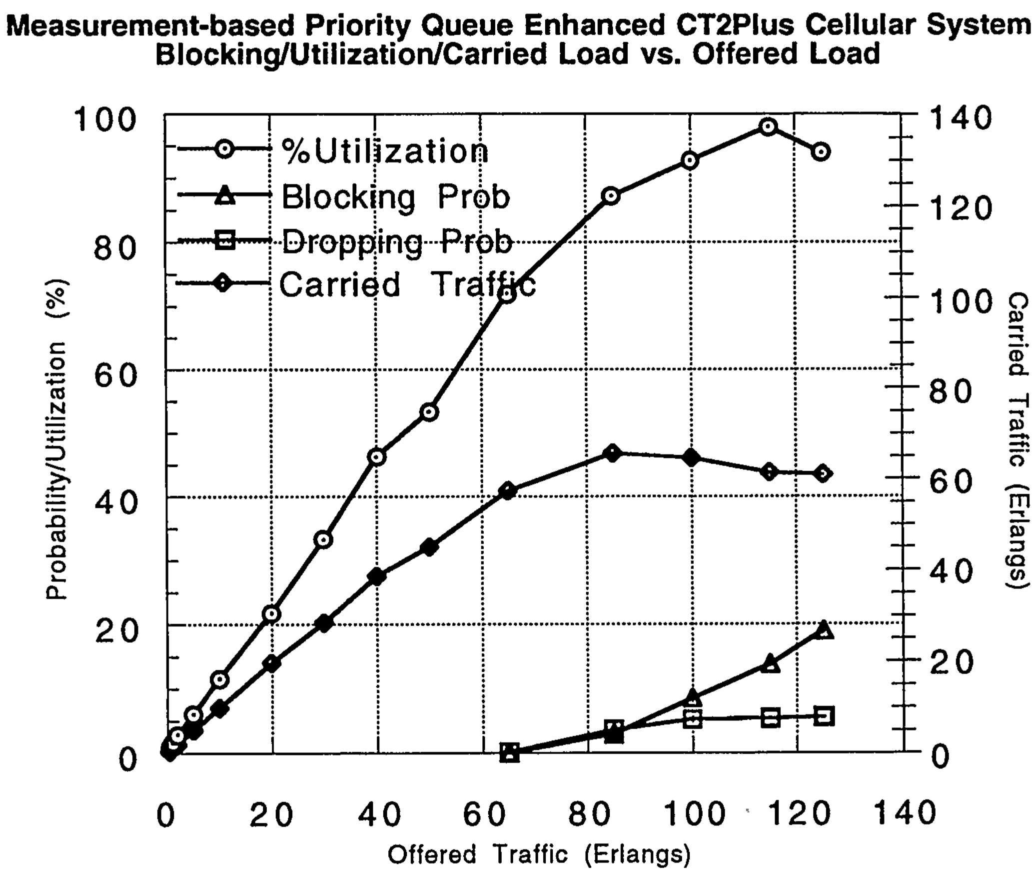


Figure 4.10 - Performance of measurement based priority queue

FIFO queuing, the queue entries are arranged in order of some measured parameter, usually the received signal strength [18][19]. The simulation results using signal strength as a queue ordering criterion are illustrated in Figure 4.10 and also summarized below in Table 4.4.

Table 4.4 - Results of signal strength based queue ordering at 100 Erlangs offered traffic

	Carried Traffic (Erlangs)	Utilization (%)	New Call Blocking (%)	Call Dropping (%)	Grade of Svc.
MBP Queue	64.79	92.74	8.45	5.25	60.95
Priority FIFO	65.05	92.29	9.20	5.20	61.2
Basic FIFO	65.17	91.08	8.70	10.55	114.2
CT2Plus	59.04	85.95	25.55	1.85	44.05

Using signal strength as a queue ordering criterion results in an 8% reduction in new call blocking over a FIFO with prioritized call handling, but also increased the number of dropped calls and reduced both the carried traffic and system utilization slightly. Although there is an improvement, the grade of service has not decreased significantly over prioritized FIFO handling, and is still worse than the unmodified CT2Plus system. As found in the previous chapter, this poor performance is due to the fact that in a multipath environment, there are large fluctuations in signal strength which can cause false outage indications. The indoor environment suffers moderate to heavy levels of multipath fading, therefore signal strength by itself is not a useful handoff criterion.

A solution for this problem based on outage probability estimates was proposed in the previous chapter. It was shown that because large signal variances in the indoor channel, outage measures must take both signal strength and signal variance into account. Signal outage probability is a figure which combines both the mean signal strength and the variance of the signal and has been found to be a more significant indicator of the channel conditions.

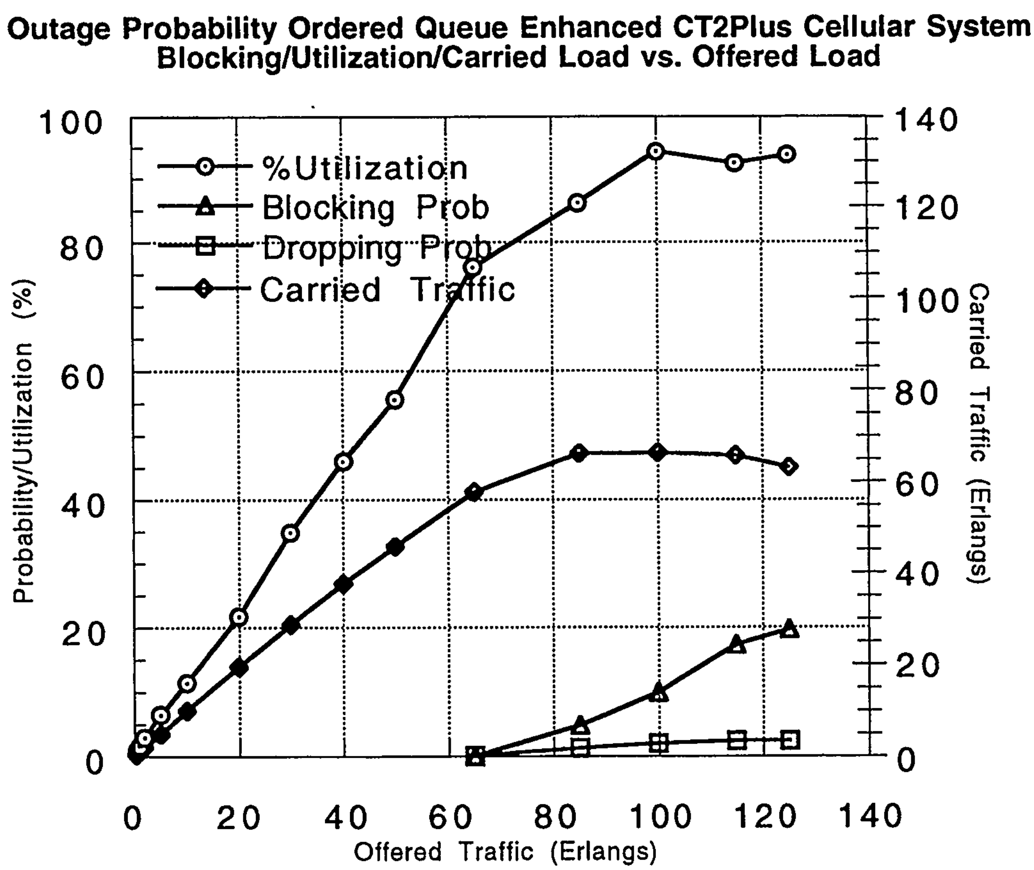


Figure 4.11 - Results of queue ordering based on outage probability

Figure 4.11 shows the results of the simulation using outage probability instead of signal strength only as the queue ordering criterion. The summary in Table 4.5 indicates that using outage probability to order the queue results in over 60% reduction in the probability of dropping of calls in progress; this brings the dropping probability down to 2.05%, which is almost as low as the 1.85% figure obtained with the unmodified CT2Plus system. At the same time, both the carried traffic and system utilization are greatly increased over the figures obtained with the previous queuing schemes and the unqueued base system. Although this new system results in slightly increased blocking over the other modifications, the blocking factor is still more than 60% lower than 25.5% blocking encountered in the original CT2Plus system. The excellent performance of this system is reflected by the marked improvement in the grade of service.

Table 4.5 - Results of outage probability based queue ordering at 100 Erlangs offered traffic

	Carried Traffic (Erlangs)	Utilization (%)	New Call Blocking (%)	Call Dropping (%)	Grade of Svc.
Outage Prob	66.27	94.38	9.95	2.05	30.45
MBP Queue	64.79	92.74	8.45	5.25	60.95
Priority FIFO	65.05	92.29	9.20	5.20	61.2
Basic FIFO	65.17	91.08	8.70	10.55	114.2
CT2Plus	59.04	85.95	25.55	1.85	44.05

The queuing of channel requests in order of outage probability results in a system with much less blocking than the original CT2Plus system and only a very small increase in the number of premature call terminations. To try to reduce the number of premature call terminations, priority techniques may be applied to the actual channel assignment as well; a common approach used in outdoor cellular systems is channel reservation.

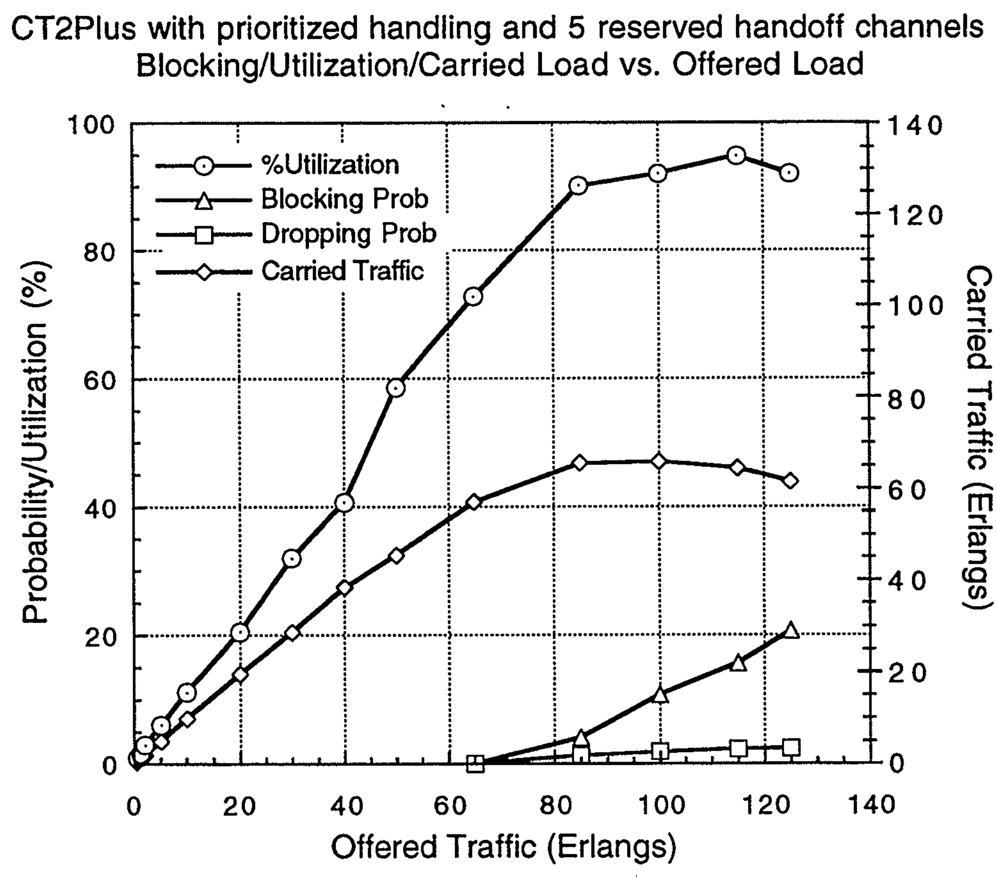


Figure 4.12 - System performance with channel reservation

This technique reserves a small number of channels for handoff use only. While this can reduce the number of failed handoff attempts, it is also expected to increase the number of new call blockages as fewer channels are now available for call initiations. Figure 4.12 shows the simulation results for a modified CT2Plus system which reserves five out of its forty channels (12.5% of total capacity) for handoffs; and, as in the last case, channel requests are also queued in order of outage probability. The results, summarized in Table 4.6 show that while reserving handoff channels reduces the dropping probability even further, there is increased new call blocking and both carried traffic and system utilization are reduced due to the unavailability of channels for new calls.

Table 4.6 - Results of channel reservation at 100 Erlangs offered traffic

	Carried Traffic (Erlangs)	Utilization (%)	New Call Blocking (%)	Call Dropping (%)	Grade of Svc.
Chn. Reserve	65.75	91.97	10.8	1.85	29.3
Outage Prob	66.27	94.38	9.95	2.05	30.45
MBP Queue	64.79	92.74	8.45	5.25	60.95
Priority FIFO	65.05	92.29	9.20	5.20	61.2
Basic FIFO	65.17	91.08	8.70	10.55	114.2
CT2Plus	59.04	85.95	25.55	1.85	44.05

4.5 Conclusions

Simulation analysis has revealed the deficiencies of the CT2Plus handoff algorithm: because it is non-prioritized and requests are not queued, low call termination is obtained at the expense of extremely high new call blocking.

Several methods were tried in order to improve the performance of the handoff: (i) simple first-in/first-out or FIFO queuing- both new calls and handoff requests are queued and served in order of arrival. (ii) Prioritized FIFO queuing- handoff requests are given queuing priority over new calls and may pre-empt new calls if the queue is full; each class of request is still handled in order of arrival. (iii) Signal strength measurement based priority queuing- this scheme is a variation of a popular outdoor technique; handoffs are still given priority over new calls, but in this case, the queue is arranged in order of signal strength, with the lowest signal strength given foremost position in the queue. (iv) Signal outage probability base priority queuing- as in (iii), but uses the outage probability expressions derived in chapter three instead of signal strength as the ordering criterion; the request with the highest probability of outage is given first position in the queue. (v) Handoff channel reservation with priority queuing- to reduce premature call terminations, a small subset of channels is reserved for handoff use only; queuing is handled as in (iv).

Simulation results indicate that call blocking is reduced significantly by the application of simple FIFO queuing. This method adds the least amount of complexity to the system, however, because call handling is not prioritized, the lower blocking comes at the expense of higher call dropping. Adding prioritized call handling to the FIFO queue reduces the call dropping significantly while the low blocking realized with the previous implementation is maintained. Although the call dropping is much lower with a prioritized FIFO queue than with a simple non-prioritized FIFO queue, it is still higher than what the unmodified CT2Plus system achieves.

Queue ordering based on some measured or calculated parameter has been shown to further improve handoff performance with little additional complexity. Measurement-based prioritization, a signal strength based technique which has produced significant improvement in handoffs for the outdoor environment performs poorly in the indoor environment because heavy multipath effects render signal strength measurements ineffective as an indicator of handoff need.

Queue ordering based on outage probability calculations as introduced in chapter three results in a significant reduction in call blocking and a dropping probability which is almost as low as the unmodified CT2Plus system. Applying priority to the channel assignment strategy by reserving a number of channels for handoff results in further reduction in the number of dropped calls, but at the expense of slightly increased blocking.

Although channel reservation in conjunction with priority queuing seems to produce the best results, the additional circuitry and computational resources needed to implement this scheme increases both cost and complexity unnecessarily; this additional cost and complexity may not be worth the small increase in performance gained with the method, especially since the simpler outage probability queue has similar performance with much less complexity and smaller computational requirements.

Chapter 5

Conclusions

5.1 The Cellular Communication System

The cellular radio system is a distributed system which provides portable, wide area communications. The system is extremely flexible as it may be used on its own or integrated into existing landline telephone systems. Cellular radio systems may be used both indoors and outdoors, however, analysis of the indoor radio environment indicates the presence of severe multipath fading effects on the indoor channel. These fading effects can seriously degrade the performance of the system by causing signal outages on the channel.

Examination of two typical short-range cellular standards, DECT and CT2Plus, reveals a major deficiency in the handoff algorithms used in indoor environments: severe multipath fading conditions can result in high handover traffic; lack of prioritized call handling and call queuing in these conditions can cause large numbers of permature call terminations and significant levels of call blocking.

5.2 Handoff Determination

Methods of determining the necessity of handoff are useful for improving handoff procedures; these methods may be used directly as handoff criteria, alternately, they may be used as a queuing priority, where requests with the greatest need for handoff are given the highest priority. One such method is signal outage probability. Signal outage probability gives an estimate of the probability of failing to receive a transmitted signal due to the fading effects on the radio channel. Studies of the indoor radio channel done at TRLabs reveals that fading on the indoor channel is lognormally distributed. Using this fact, a simple expression for outage probability was derived. This expression is especially attractive for use in handoff algorithms because it only requires simple multiplication and addition operations; all other functions can be implemented very efficiently with table lookups, thus adding very little computational requirement to existing handoff schemes.

Simulations using actual channel data from the TRLabs channel meaasurement database indicate that in the indoor environment, signal outage probability provides a more accurate indicator of channel conditions than a simple signal strength measurement because both the signal strength and the variance of the signal strength are taken into account by the outage probability estimate. It was also found from simulation that in some cases, signal outage probability can even give advanced warning of a fading-induced signal outage.

Guerin has discovered in [10] that in an outdoor cellular system, the ability for users to move between cells and also hand over calls in progress to a different cell results in the channel occupancy time following an exponential distribution which is unaffected by cell shape. This property suggests that this channel occupancy time distribution is also applicable to indoor cellular systems, allowing a handoff probability expression to be derived in a similar manner as for the signal outage probability. It appears that the handoff probability figure is not as useful as the signal outage probability. the exponentially distributed occupancy time means that there is greater probability of handoff times which are less than the mean occupancy time than there are greater. Because of this, the handoff probability should not be used directly as a handoff criterion, but should be used in conjunction with signal outage probability or some other measure in order to provide a good assessment of current channel conditions.

5.3 Indoor Handoff

The CT2Plus handoff algorithm is described in [12] and [13], this algorithm was found to have a very low probability of premature call termination, but an inordinately high blocking probability. The following techniques were applied to the CT2Plus system in order to improve its performance: (i) simple non-prioritized FIFO queuing, (ii) prioritized FIFO queueing, (iii) signal strength measurement based priority queuing, (iv) outage probability based priority queuing and (v) channel reservation in combination with outage probability based priority queuing. Table 5.1 shows a comparison of the results of these modifications.

Table 5.1 - Results of modifications to the CT2Plus handoff algorithm at 100 Erlangs offered traffic

	Carried Traffic (Erlangs)	Utilization (%)	New Call Blocking (%)	Call Dropping (%)	Grade of Svc.
Chn. Reserve	65.75	91.97	10.8	1.85	29.3
*Outage Prob	66.27	94.38	9.95	2.05	30.45
MBP Queue	64.79	92.74	8.45	5.25	60.95
Priority FIFO	65.05	92.29	9.20	5.20	61.2
Basic FIFO	65.17	91.08	8.70	10.55	114.2
CT2Plus	59.04	85.95	25.55	1.85	44.05

* - Outage probability queuing is the optimal solution

These results show how even simple FIFO queuing may be used to improve the efficiency of the CT2Plus handoff algorithm. Also evident is how priority techniques can be used to shift losses from a loss-sensitive class to a class which is more loss-tolerant. Another important fact to note is that because of the difference in fading effects found in indoor and outoor environments, signal strength measurement based queue ordering, a technique which produces good results in the outdoor environment [18][19] performs very poorly in the indoor environment; whereas outage probability, a technique which has been developed specifically to handle indoor conditions produces excellent results. This difference in performance serves to illustrate the need for further study and development of techniques for indoor communication systems.

5.3.1 Recommendations

The two methods investigated which produce the lowest degree of call blocking and call dropping are channel reservation and outage probability based priority queuing. Although channel reservation produces the least amount of call dropping, the fewer number of channels available for new calls causes increased blocking and lower system efficiency. In addition, because of its need for both queuing and channel reservation circuitry, the channel reservation system is also the most complex of the modifications investigated. The system using outage probability for its queue ordering criterion achieves similar call dropping performance and lower blocking rates with much less complexity. Because this system offers higher efficiency for minimal additional complexity and is able to deliver both the low call dropping rates that are desired for a cellular communication system and also lower call blocking which can improve the perceived quality of service, this system is considered optimal and a modification to the CT2Plus handoff algorithm is recommended which adds prioritized call handling with queuing using outage probability as the ordering criterion.

5.4 Future Work

Other fading models for outage probability

The log normal fading model was chosen for the outage probability expression primarily for ease of analysis. Results show that the log normal model produces reasonable results, however, research into other more accurate models such as the Nakagami or Weibull distributed fading models for outage probability calculations may produce improved results. Application of outage probability techniques for outdoor channels is also another area for investigation.

Further investigation of channel occupancy time in an indoor environment

In [10] Guerin has shown an exponential channel occupancy time distribution for the outdoor cellular system. Given the current level of knowledge of the indoor radio environment, it is reasonable to assume a similar distribution in the indoor environment. However, because of the differences both in fading effects and cell shape and size between the two environments, further investigations and verification studies in this area are warranted.

Other handoff criteria for CT2Plus

Current simulations continue to use the timeout based handoff criteria specified by the CT2Plus standard. Although the blocking and dropping probabilities obtained with the simulations are good, better performance may be possible if outage probability or some other criterion is used as the handoff criterion. As found in chapter two, timeout based handoff tends to be very slow, thus significant improvement in the area of handoff speed are expected as a result of this change.

Simulation of the DECT system

Simulations were not performed on the DECT system for several reasons: (i) unlike the CT2Plus system, the handoff procedure was not fully described in the standards documents meaning that assumptions would have to be made which may not be compatible with an actual system. (ii) DECT uses multiple access techniques to accomodate multiple calls on a single channel- this type of system experiences different problems than the CT2Plus system which only allows a single call per channel. Concerns which need to be addressed include the need for multiple concurrent handoffs if a channel which is carrying many calls fails. In spite of these problems, because of its higher traffic capacity, there is increasing interest in this system, providing impetus for further research into DECT performance improvements.

Development of traffic analysis techniques for cellular communication systems

Currently there do not exist any simple techniques for determining the performance of cellular communication systems analytically. This means that the majority of system design is done via computer simulation studies and only very simple cases may be accounted for with classical telecommunications formulae such as the Erlang formulas which were used in chapter four. Development of uncomplicated analysis techniques for cellular or other distributed communications systems would improve understanding of these systems and lend justification to the simulation models now in use, therefore, development of analysis methods for cellular systems is warranted.

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Appendix

A. Models and Simulation

A *model* is a description of a system intended to predict the outcomes of certain actions. The process of driving the model with various inputs and observing the corresponding outputs is called *simulation*.

Two classes of simulations are possible: (i) continuous time simulations and (ii) discrete event simulations. Continuous time simulations are generally used for systems which can be modeled in terms of mathematical equations. Discrete event simulations are used examine behavior of systems where everything happens at finite time points. Both classes of simulation can be implemented on computers.

Simulations may be classified into two types: (i) synchrononous simulations, where time is advanced in fixed size increments and (ii) asynchronous simulations, where events can occur at arbitrary times. When applied to continuous time systems, synchronous simulations are conceptually easier to understand and design because if the time step is small enough, they effectively mimic our continuous time view of the world. On the other hand, if a system model is known to changes states only at certain time points, and the system is effectively idle during the periods between those time points, an asynchronous discrete simulation may be more effective for studying system behaviour. A synchronous simulation is still usable for this this but needs to recalculate the system state at every time step; if the times between changes are sufficiently large or the time step used by the simulator sufficiently small, then a great deal of time will be spent recalculating system states. For this reason, an asynchronous simulation is often more efficient than a synchronous simulation.

Depending on the information desired from the simulation of a model, different simulation strategies are needed. For example, in a telephone system, if very detailed information is needed about the condition of a voice signal as it travels down the telephone wire, then a continuous time synchronous simulation is probably most useful. However, if only information about the number of calls and their arrivals and departures is required and the system activity in between the arrival and departure events is unimportant, then an asynchronous simulation would be more useful and efficient since calculations only need to be performed when a call arrival or departure event occurs. For the handoff simulations presented in this thesis, the simulators used are of the asynchronous discrete event type.

B. Event-Driven Simulation

Asynchronous discrete simulations are normally undertaken using an "event-driven" simulator. The term "event-driven" refers to the fact that the calculation of the system state is triggered by the arrival of abitrarily spaced events; the state of the system between event arrivals is assumed to be static and only the stimuli of arriving events will cause changes in the system state. In this way, the events are said to "drive the system".

Normally, the events which are used by the simulator are generated before the simulation starts. This is possible if the events are defined in the system model to arrive according to a certain statistical distribution. For example, traffic into a telephone system may be defined in the simulation model as having a Poisson arrival distribution with a rate of 500 calls per hour. Events which cannot be generated beforehand may be generated during the simulation. New events may be created or existing events deleted as the result of other events. This allows the simulation to behave dynamically. This provision is used in the handoff simulation to remove call departure events for calls where a handoff or a new call initiation has failed.

C. Cellular Telephone System Simulation

A cellular communication system is very complex and certain simplifications and assumptions were made in the system model. Firstly, the call interarrival times are assumed to follow an exponential distribution with a mean equal to the inverse of the arrival rate. The arrival rate will vary with the desired offered load to be simulated. The call holding times are assumed to be exponentially distributed with a mean holding time of 3.0 minutes. Two cells are simulated, each with 40 available channels. These parameters are summarized in Table 4.1, which is duplicated below in Table A.1:

Table A.1 - Simulation parameters

Parameter	Value
Number of cells	2
Number of data channels per cell	40
Call arrival distribution	Poisson, 10-2500 calls/hour
Traffic intensity range	0.5 through 125 Erlangs
Average call duration	3.0 minutes, exponential

Because the traffic arrival and holding time distributions were defined in the model, an event list of the traffic arrival and departure times could be generated according to Figure A.1:

	Arrival Time	Departure Time
T2	t1	t1 + h1
	t2	t2 + h2
.	.	.
.	.	.
TN	tN	tN + hN

Figure A.1 - Call arrival/departure time generation

Where *t1..tN* are the arrival times, *Tk=tk-t(k-1), T0=0, k=1..N* are the interarrival times and *h1..hN* are the exponentially distributed holding times. In a similar manner, events for causing mobility handoffs are generated using Guerin's exponential channel occupancy time model [10]:

Arrival Time	Handoff Time
t1	t1 + c11
	.
	.
	t1 + c11 + ... + c1N
t2	t2 + c21
	.
	.
	t2 + c21 + ... + c2N
.	.
.	.
tN	tN + cM1
	.
	.
	tN + cM1 + ... + cMN

Figure A.2 - Handoff time generation

Where *cM1..cMN* are the exponentially distributed channel occupancy times for each channel (M=1..40). Mobility handoff events are generated for each call arrival such than $tN + cM1 + \ldots <= tN + hN$. That is, mobility handoffs are generated only for the period of time the call is in progress.

Lastly, fading handoff events are generated by analyzing amplitude data from the TRLabs channel measurement database, which is a database of over 12 000 frequency and time domain measurements of channel responses over a variety of ranges at several documented indoor locations. The time domain data was analyzed for fades which caused signal loss for the 300 ms period specified in the CT2Plus standard and handoff events were generated at each of these times. In addition, signal strength which fell below the CT2Plus requirements also caused a handoff event to be generated.

All of the above events were placed in a single list and the sorted in time order. Each event in the list is stored in a structure which includes the event time, the type of event (call arrival, call departure, handoff) and a call identification number. The simulator runs in a loop reading events from the list and taking the appropriate action for each event. The level of carried traffic, the system utilization achieved and the probabilities of call blocking and call dropping are calculated and summarized at the end of each simulation run. A simplfied flowchart of the simulator is show in Figure A.3:

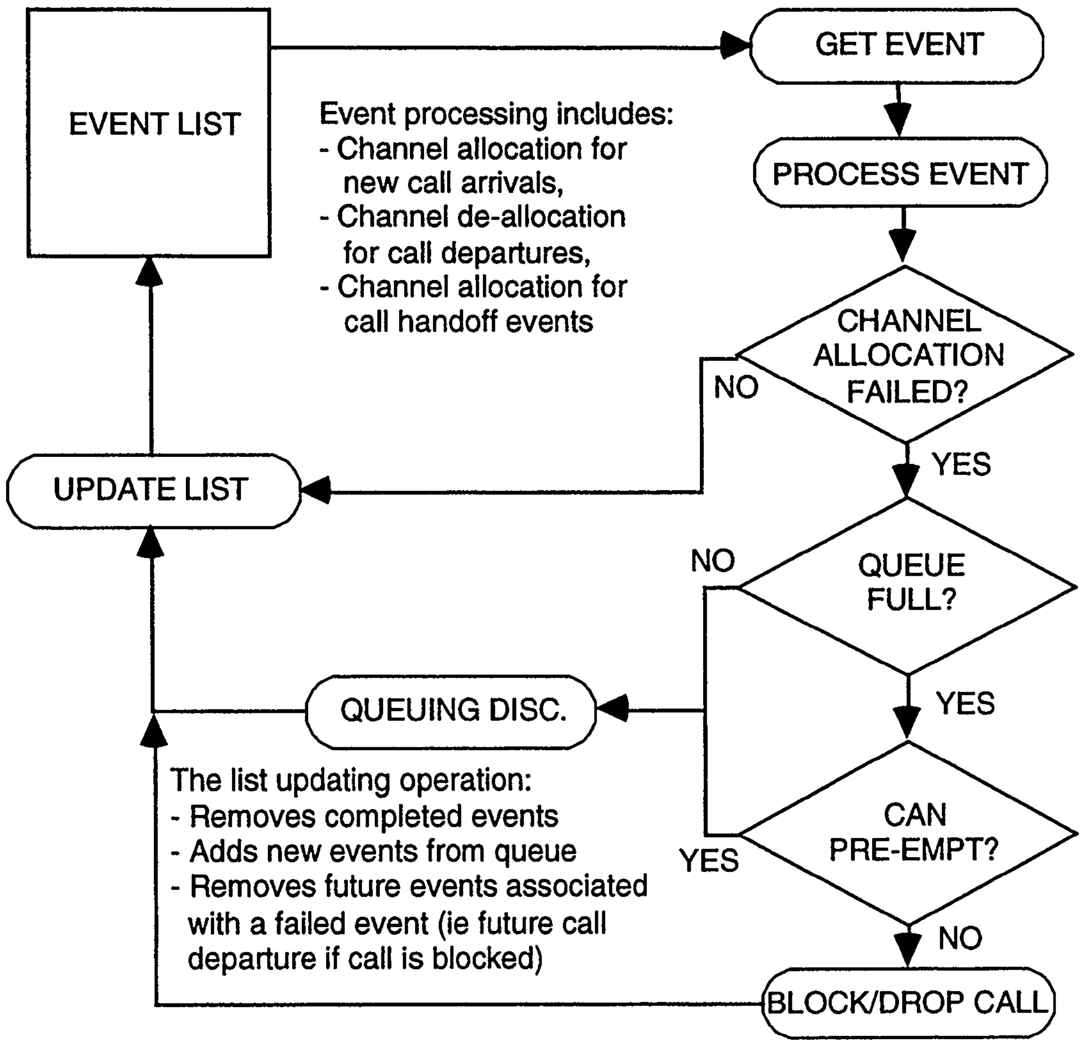

Figure A.3 - Simulator flowchart

To ensure that the system has reached a steady state condition, an additional 500 events are inserted at the beginning of the event list. After the system has processed these initial events, the calculation and collection of system statistics begins. Because of the efficient operation of the event-driven simulator, the simulation proceeds fairly quickly, taking between 2 to 5 minutes to complete a simulation of 5000 events on a Digital Equipment DECStation 5000 running Ultrix.

D. Comparison to Commercial Simulator

A commercial simulation package was also used to develop the initial model of the system. The commercial simulation package used is the CACI Product Company's COMNET II.5. COMNET is an object-oriented communication system simulation package written in the CACI's SIMSCRIPT simulation language. The object-oriented features and its event-driven simulation engine allowed quick development and testing of the model.

COMNET allows great flexibility for generating traffic events: a wide variety of arrival and holding distributions are available and user-defined functions or event-lists may also be specified for those which are not provided. The Poisson call traffic for a COMNET simulation is produced by the built-in traffic generator and the handoff event list was generated as described in section C of this appendix. This list was used to trigger "link failure" events in COMNET. A link failure is equivalent to a loss of signal, and COMNET automatically re-routes the call to a free channel, or drops the call if there are no channels available. This re-routing action is equivalent to the handoff action in a cellular system.

The custom simulator was written because the current version of COMNET does not have provision for user-defined queuing algorithms. Verification of the custom simulator was performed two ways: (i) comparison with established Erlang models and (ii) comparison with results obtained from the COMNET simulator. As discussed in Chapter 4, the simulation results showed good agreement with the Erlang loss and Erlang combined delay and loss systems, and comparison of the COMNET and custom simulator's results showed that they were statistically identical.