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OPTIMUM CAPACITY WITH
LINEAR POWER ASSIGNMENT FOR
MULTIMEDIA CDMA NETWORKS

by

Sophie Vrzic

A thesis submitted to the Faculty of
Graduate Studies and Research in partial
fulfillment of the requirements for the
degree of

Master of Engineering

Ottawa-Carleton Institute for Electrical
Engineering

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OPTIMUM CAPACITY WITH
LINEAR POWER ASSIGNMENT
FOR MULTIMEDIA CDMA
NETWORKS

Submitted by

Sophie Vrzic

In partial fulfillment of the requirements
for the degree of Master of Engineering

Chair, Systems and Computer Engineering

Thesis Supervisor

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ABSTRACT

This thesis presents an optimum linear power assignment algorithm for a code division multiple access (CDMA) system supporting multimedia traffic. The new algorithm optimizes the cell capacity by minimizing the power transmitted by each user while satisfying the quality of service (QoS) requirements. In this thesis, the QoS includes satisfying a given probability of outage. The main advantage of this algorithm is its simplicity and robustness under all conditions including imperfect power control.

In deriving the theory for this optimum algorithm, a detailed mathematical analysis is performed on the previously developed linear power assignment algorithm. This analysis provides insight into how the parameters of the original algorithm affect the probability of outage. Two methods for achieving optimum capacity, based on the linear power assignment algorithm, are developed in this thesis. This mathematical analysis leads to the derivation of an optimum linear power assignment algorithm, referred to as the modified linear power assignment algorithm.

The theory is first developed for the simplified case where there is a single cell with only one class of users and perfect power control. It is then extended to the case where there are multiple cells with multiple classes of users and imperfect power control. Simulation results are also given that show a dramatic increase in capacity is obtained as compared to when the original linear power assignment algorithm is used.

Three call admission control procedures that use the modified linear power assignment algorithm are also developed. The first access control algorithm admits a new user if the desired probability of outage could be satisfied. The other two algorithms admit users if the desired probability of outage and the desired average signal to interference ratio could both be satisfied. The first of these algorithms is a simple, but sub-optimum method in capacity utilization, while the other is a more complex optimum solution.

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GLOSSARY

ARQ	Automatic Repeat Request
BER	Bit Error Rate
CDMA	Code Division Multiple Access
FEC	Frame Error Correction
LPA	Linear Power Assignment
MLPA	Modified Linear Power Assignment
QoS	Quality of Service
S/I	Signal to interference ratio
$\left(\frac{S}{I}\right)_{ij}$	Signal to interference ratio for the i^{th} mobile in cell j
$\left(\frac{S}{I}\right)_{ij}^+$	Target signal to interference ratio
$\left(\frac{S}{I}\right)_{ij}^*$	Required minimum signal to interference ratio for the i^{th} mobile in cell j
$\left(\frac{S}{I}\right)_{ave,ij}$	Minimum acceptable average signal to interference ratio for the i^{th} mobile in cell j
$\left(\frac{S}{I}\right)_{min,ij}$	Minimum signal to interference ratio for the i^{th} mobile in cell j
α_{ij}	Activity factor for the i^{th} mobile in cell j
γ_j^*	Optimal power coefficient for cell j
E_{bij}	Transmitted energy per bit value for the i^{th} mobile in cell j

h_{ij}	Path loss from the i^{th} mobile in cell j to its home base station
$h_{ij}^{(k)}$	Path loss from the i^{th} mobile in cell j to the base station in cell k
$I_{tot,j}^{(L)}$	Interference corresponding to the L^{th} percentile of the total interference to cell j
$I_{tot,j}$	Total interference to cell j
L	Outage probability threshold
M	Total number of cells in the network
N_j	Total number of users in cell j
P_{ave}	Total average transmitted power
P_{ij}	Received power for the i^{th} mobile in cell j
R	Channel transmission bit rate
$\bar{r}_{ij}$	Average bit rate for the i^{th} mobile in cell j
σ_j^2	Average inter-cell interference to cell j
σ_T^2	Average background noise power
W	Total available bandwidth

Chapter 1

INTRODUCTION

1.1 Motivation

During the last few years, there has been a dramatic increase in the demand for multimedia services. Wireless systems are now expected to accommodate various multimedia applications such as data, facsimile and video in addition to high quality voice users. These services have different bit rates, delay and error requirements and therefore a flexible network is necessary in order to accommodate each user's quality of service (QoS). For this reason, there has been a growing interest in using a code division multiple access (CDMA) system for multimedia personal communications. Because of its high bandwidth utilization and its resistance to multi-path fading, CDMA is one of the best air interfaces for multimedia applications.

As wireless systems evolve from accommodating only voice users to providing the variable QoS requirements of the different multimedia applications, the management of the available resources becomes increasingly important. The various QoS requirements can be satisfied by adjusting either the link bandwidth, the power of the transmitted signal or by using different signal processing algorithms for controlling the error rates. In this thesis, power assignment is used to satisfy the various QoS requirements.

Power assignment and power control are necessary in a CDMA environment. On the reverse link, signals originate from different locations. Signals from users close to the base station are received with a stronger signal than from users that are at a much farther distance from the base station. This is known as the

near/far problem. Power assignment and power control in a CDMA environment are necessary in order to reduce the effects of the near/far problem.

The power control law developed to mitigate the near/far problem, for single rate traffic, maintains the same received energy per bit for all users in the cell. However, since the information rate and the grade of service requirements for the different classes of users can vary considerably, this may no longer be appropriate for multimedia applications.

In a multimedia communication system, different types of media require different levels of error protection. Power assignment in a CDMA environment can not only control the near/far problem, it can also increase capacity and can be used to achieve the variable quality of services for the multimedia applications. Since increasing the power level for a given user relative to all other users results in a lower BER, error sensitive users can be accommodated. However, increasing the power of a particular user leads to performance degradation for all other users and results in reduced system capacity. Therefore, it is desirable to develop an optimum power assignment algorithm in order to maximize system capacity while satisfying the required QoS for each user.

Also, the time varying nature of the physical channel, as well as the low bandwidth and high error rates associated with wireless systems, make the QoS for the different applications difficult to guarantee with a high degree of certainty. As a result, it is beneficial if the power assignment algorithm can guarantee a given probability of outage for each user in the system.

1.2 Thesis Summary

In [21] a simple linear power assignment algorithm is developed which, when combined with an access control strategy, can be used to satisfy different quality of services for different classes of users. Although this algorithm is

computationally efficient, it is sub-optimal in capacity utilization. In this thesis, the linear power assignment algorithm is analysed mathematically to determine how best to modify the parameters in order to improve capacity. Two different methods, based on the linear power assignment algorithm, are developed that optimize capacity. Although the first method cannot easily be implemented, the second method is a robust and computationally efficient power assignment algorithm that can guarantee a given probability of outage. This second algorithm is referred to as the modified linear power assignment algorithm.

The modified linear power assignment algorithm optimizes the system capacity, while maintaining the required QoS for each user, without significantly increasing the computational complexity of the original linear power assignment algorithm. Compared to conventional power control algorithms, this new approach can not only satisfy a given probability of outage, but it can guarantee the QoS for each user in the cell even if a user has a low activity factor.

Three access control strategies that use the modified linear power assignment algorithm are also developed. The first access control procedure assumes that only the outage constraint needs to be satisfied, while the other two access control procedures assume that the average signal to interference ratio must be satisfied in addition to the probability of outage. The first of these two algorithms that satisfy both constraints is a simple but sub-optimum solution in capacity utilization, while the second algorithm is a more complicated optimum solution.

1.3 Thesis Outline

This thesis is organized as follows. A detailed review of current research in power assignment and call admission control is presented in Chapter 2.

The system models and definitions used throughout this thesis are described in Chapter 3.

Chapter 4 describes the, previously developed, sub-optimum linear power assignment algorithm and presents detailed mathematical analysis along with new simulation results showing under what conditions the algorithm fails to be a suitable power assignment algorithm. It also describes how the parameters can be modified in order to improve capacity.

In Chapter 5, the proposed modified linear power assignment algorithm is presented. This algorithm addresses the problems with the original linear power assignment algorithm while optimizing capacity. The algorithm is first developed for the simplified case where there is only a single cell with one class of users and perfect power control. It is then extended to the case where there are multiple cells with multiple classes of users and imperfect power control.

Chapter 6 describes three call admission control procedures using the modified linear power assignment algorithm. In this Chapter, the algorithm is further enhanced, by including an additional constraint that ensures the quality of the communication link.

The conclusions of this thesis and recommendations for future research are given in Chapter 7.

1.4 List of Contributions

The mathematical analysis of the previously developed linear power assignment algorithm, in Chapter 4, provides one method of guaranteeing the probability of outage for each user in the system.

The derivation of the new modified linear power assignment algorithm, in Chapter 5, provides another method of controlling the outage probability. This

simple and robust algorithm can also guarantee the QoS for users that have a low activity factor, which is a major problem with typical power control algorithms.

In Chapter 6, the modified linear power assignment algorithm is then extended to also satisfy the average signal to interference ratio. Two call admission control algorithms have been developed that can guarantee both the probability of outage and the average signal to interference ratio.

Chapter 2

STATE OF THE ART IN POWER ASSIGNMENT

An overview of the current published research on radio resource management and power assignment for multimedia CDMA is presented in this Chapter. The power assignment problem for CDMA networks is then stated in the form that it is addressed in this thesis.

2.1 Literature Review

Power assignment has been previously proposed as a method for satisfying the variable QoS requirements for different classes of users [1][2][12][28][39][34][43]. The QoS is usually defined by satisfying a given signal to interference ratio.

In [1], the cell capacity, on the reverse link, is defined as the maximum number of users of each class that can be admitted with the constraint of guaranteeing the QoS requirement of each user. In order to maximize capacity, different power levels are assigned to users of different classes. The target power level, for a given class of users, depends on the source rate and the QoS requirement. In this paper, capacity is optimized for the case where this is a single cell with multiple classes of users and perfect power control. The case with imperfect power control is addressed in [34]. However, the authors did not consider the case where there are multiple cells with multiple classes of users.

In [39], different error control schemes are used to satisfy the requirements of the different media. The error control schemes consist of frame error correction, diversity and automatic repeat request (ARQ). A power assignment algorithm,

which optimizes the capacity performance of the integrated system, is presented. This power assignment algorithm minimizes the total transmission power under the constraints of the QoS requirements and the transmission power limit. The different QoS requirements, which are either represented as a bit error rate or a codeword error rate, are mapped to different average signal to interference ratios depending on the error control scheme used. Linear programming techniques are then used to determine the optimum transmission power. A Gaussian approximation is used to model the multi-user and co-channel interference.

Another optimum power assignment algorithm is given in [28]. In this paper, capacities are derived for single code and multiple code DS-CDMA systems accommodating multiple classes of users in both single and multiple cell environments. These capacities are determined by deriving the necessary and sufficient conditions on the number of accepted calls of each class in order to satisfy the bit energy-to-interference power spectral density ratio. The optimal received power of a call of each class is also derived. This paper, however, does not discuss imperfect power control.

Optimum power assignment with integrated voice and data traffic is also considered in [35]. In this paper, the system is designed such that voice users satisfy the required frame error rate. The much lower data error rate is ensured by ARQ. A graphical method is used to obtain the optimum power assignment between voice and data users to maximize total system throughput.

The algorithm proposed in [12] addresses the problem of mobility. In this paper, an algorithm for combined cell site selection and power control is developed to maximize capacity. Mobility is also addressed in [2]. In this paper, a new method of modeling mobility is proposed and a method of calculating the instantaneous outage probability at different cell sites is also presented. However, the issue of power assignment is not discussed.

The power assignment problem has been extended to include rate assignment, for variable rate users, in [17][20][31][33][38] and [42]. The algorithm in [20] assigns different power levels and processing gains to different classes of users in order to maximize capacity, given the rate and QoS requirements. Only two classes of users are included and imperfect power control is not considered.

The algorithm proposed in [31] is a hybrid TDMA/CDMA access control mechanism where the channel is time-shared among the mobiles according to their instantaneous channel gains. This technique optimizes throughput of the non real-time users subject to the constraints on peak transmission power and maximum interference generated by the non-real-time users.

Although several of the above power assignment algorithms can minimize transmission power while satisfying a given signal to interference ratio, none of the algorithms, however, are designed to guarantee a given probability of outage. The probability of outage is usually guaranteed through a call admission control algorithm [3][8][9][14][29].

One of the first papers to consider the outage probability in a signal to interference ratio based call admission control algorithm is [29]. In this paper, the number of initial calls a base station can accept such that a system-wide outage probability will be guaranteed to be below a given level is calculated according to the reverse link SIR measured at the base station. However, this algorithm assumes that the received power at the base station is the same for each user and is therefore not suitable for a multimedia system.

In [3], a quality based call admission control policy is proposed for the integration of voice and data users. The data users are assigned a higher transmission power level over voice users to achieve a lower bit error rate. The admission policy accepts a call request based on its specified QoS and the network resources. A

Markov model is developed to analyse the blocking probability and the probability of outage. This paper does not discuss how to allocate power to voice and data users.

Call admission control algorithms can either be based on the interference level or on the total number of users. In [14], a comparison of the two strategies is performed using various propagation parameters, non-uniform traffic distributions and transmission rates. This paper describes a new method using simple expressions for the CDMA reverse link capacity that guarantees the loss probability and the blocking rate.

Capacity of the reverse link is also evaluated in [13][18] and [30]. An expression for capacity is derived in [18]. The reverse link capacity of an SIR-based power control system is obtained analytically in a multiple cell environment. This paper only considers one class of users and perfect power control.

In [30], capacity is evaluated by simulation. A packet DS-CDMA system model is proposed that supports integrated voice and data traffic with variable rates and different QoS requirements. Forward error correction and automatic repeat request are applied to data packets. The system supports constant bit rate voice and variable bit rate data. In order to analyse the single cell capacity, a fixed number of channels are assigned to data traffic while the remaining resources are assigned to voice traffic. It is determined that there is a linear relation between the capacity of voice users and that of data users in a single cell. This paper does not, however, consider the case where there are multiple cells and does not guarantee a given probability of outage.

In [8], a thorough review of the different approaches to handling the problem of other-cell interference is presented. This is then followed by a characterization of the interference in the form of an analytic expression for the interference

distribution function. The capacity of the system is analysed by modeling each cell as an $M/G/\infty$ queue. In this case, the number of users in a given cell is an independent Poisson random variable and the expression for outage probability is developed in terms of a compound Poisson random variable. Two techniques are applied to approximate the outage probability, the Chernoff bound and Gaussian approximation.

Call admission control for the analysis in [8] is addressed in [9]. In this paper, the received power is assumed to be directly proportional to the minimum signal to interference density ratio requirement for each user in the system. Capacity is then determined using the Chernoff bound and Gaussian approximation and comparisons are made to results obtained from a Monte Carlo simulation. The Gaussian approximation method usually overestimates capacity, while the Chernoff bound method is guaranteed to be conservative. Power assignment is not addressed in this paper.

An optimum power assignment algorithm is developed in [40]. This paper describes an optimum power control scheme that minimizes the probability of outage. The algorithm is an optimal user removal algorithm that removes users from the system until the desired signal to interference ratio is satisfied. However, this optimum power achieves the same signal to interference ratio for all mobiles in the system and is therefore not suitable for a multimedia communications system.

In multimedia CDMA systems, the variance of the probability distribution function of the signal to interference ratios for the different users is large. This is due to the large statistical variation in the users traffic and to the random changes in the mobiles power levels at the base station. As a result, it is noted in [22] that the quality of the communication link cannot be satisfactorily characterized by the average S/I ratio alone. In order to maximize capacity, the probability of outage

must also be considered at the power assignment level rather than at the call admission control level. The first algorithm to consider the probability of outage at the power assignment level is given in [22]. In this paper, a non-linear power assignment algorithm is proposed such that the average S/I ratio and the outage probability are both satisfied. Although this algorithm is an optimum technique in utilizing the cell capacity, the main disadvantage of this algorithm is that it is computationally complex.

A much simpler algorithm is developed in [27] where a joint power assignment algorithm and predictive call admission control procedure are used to guarantee the QoS for each mobile. In this work, a simple linear power assignment algorithm is developed that assigns a power level to each user that is proportional to its average S/I ratio and to its average bit rate. An access control algorithm [23][24][25][26] limits the number of users admitted in the cell to ensure the probability of outage is satisfied. The main advantage of this algorithm is its simplicity. However, it is sub-optimum in capacity utilization.

Power assignment in a CDMA environment has been proposed as an efficient technique in providing variable QoS for different classes of users. The QoS is usually defined by satisfying a given S/I ratio. Although many power assignment algorithms can satisfy this QoS requirement, an efficient technique is required to satisfy both the average S/I ratio and the probability of outage, while minimizing the average power transmitted by each user. The power assignment problem, as it is addressed in this thesis, is stated more precisely in the following section.

2.2 Power Assignment Problem

Consider a CDMA cellular network with M cells and N_j users in cell j . The power assignment problem is an optimization problem where the objective is to minimize the total average power transmitted by all users while satisfying the required QoS. The problem can be stated as follows.

Find a set of energy per bit values $\{E_{bij}\}$, ($i = 1, 2, \dots, N_p$, $j = 1, 2, \dots, M$) that minimizes the total average transmitted power given by

$$P_{ave} = \sum_{j=1}^M \sum_{i=1}^{N_j} E_{bij} \bar{r}_{ij} h_{ij} \quad (2.1)$$

subject to the constraints

$$\begin{aligned} E\left[\left(\frac{s}{I}\right)_{ij}\right] &\geq \left(\frac{s}{I}\right)_{ave,ij} \\ \Pr\left[\left(\frac{s}{I}\right)_{ij} \leq \left(\frac{s}{I}\right)_{ij}^*\right] &\leq L_{ij} \end{aligned} \quad (2.2)$$

where h_{ij} is the path loss encountered by user i in cell j , $\bar{r}_{ij}$ is the average bit rate of user i in cell j , $\left(\frac{s}{I}\right)_{ij}$ is the instantaneous signal to interference ratio, $\left(\frac{s}{I}\right)_{ave,ij}$ is the minimum acceptable average signal to interference ratio, $\left(\frac{s}{I}\right)_{ij}^*$ is the system outage threshold level and L_{ij} is the outage probability threshold.

Chapter 3

SYSTEM MODELS AND DESCRIPTION

This chapter describes the DS-CDMA cellular system model and the related assumptions used in this thesis.

The system considered in this thesis is an asynchronous cellular CDMA network with nine square cells. The total bandwidth, shared by all users, is 5 MHz. A DS-CDMA signaling scheme is assumed where separate frequency bands are used for the reverse and forward links. In this scheme the mobiles only experience interference from the base stations while the base stations only experience interference from the mobiles.

The base stations are assumed to be located in the centre of the cell, while an omni directional antenna is used at the receiver. The background noise power at the receiver is set to -128 dBm. Each mobile is assumed to be power controlled by only one base station.

Radio propagation is influenced by path loss due to distance and lognormal shadow fading. The radio propagation model used in this thesis is the generally accepted model also used in [8][15][18][19][29][36] and [40] where the path loss and shadow fading between a mobile and a given base station is given by the equation

$$h(d) = 10^{\epsilon/10} d^{-\alpha}$$

In this equation, the variable ξ is a Gaussian random variable with a zero mean and a standard deviation of σ , which ranges between 5 and 12 dB. The variable d is the distance between the mobile and the given base station, while e is the path loss exponent, which is typically between 2.7 and 4. In this thesis, σ is set to 0 dB, while the path loss exponent is set to 4. Any given mobile selects the base station that has the smallest radio propagation attenuation as its home cell. Handoff and user mobility are not modeled.

User traffic is generated using a Bernoulli traffic generator. In this traffic model, Bernoulli random variables are generated with the probability of success equal to the activity ratio.

Each class of users has a required average S/I ratio, a specified system outage threshold level, for the instantaneous signal to interference ratio, and a desired probability of outage, L_{ij} . The probability of outage is defined as the probability that the instantaneous signal to interference ratio is below the system outage threshold level and is given by the following constraint.

$$\Pr\left[\left(\frac{S}{I}\right)_{ij} \leq \left(\frac{S}{I}\right)_{ij}^*\right] \leq L_{ij}$$

where

- $\left(\frac{S}{I}\right)_{ij}$ is the instantaneous S/I ratio for user i in cell j ,
- $\left(\frac{S}{I}\right)_{ij}^*$ is the required minimum S/I ratio for user i in cell j ,
- L_{ij} is the desired probability of outage for user i in cell j .

The quality of the communication link is characterized by the required probability of outage as well as the desired average S/I ratio since the variance of the

probability distribution function for the S/I ratio can be quite large. If the link quality is characterized by the average S/I ratio alone, then it is more likely that the instantaneous S/I ratio will be well below the system outage threshold level as the variance increases.

The signal to interference ratio is chosen as a performance measure since there is a one to one correspondence between the bit error rate (BER) and the signal to interference ratio. For a given BER, the system outage threshold level can be determined as in [1] and [34] by the equation

$$BER_{ij} = Q\left(\left(\frac{s}{I}\right)_{ij}^*\right)$$

where BER_{ij} is the bit error rate for user i in cell j and

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-t^2/2} dt$$

Other equations for determining the required signal to interference ratio in order to satisfy a given BER are also given in [20][28] and [38].

Although a fixed processing gain is assumed, the algorithms developed in this thesis can easily be extended to use a variable processing gain.

LINEAR POWER ASSIGNMENT

4.1 Introduction

This chapter describes and analyses the linear power assignment algorithm developed in [21]. Although the algorithm was, intentionally, developed as a sub-optimum scheme in capacity utilization, the main advantage of the algorithm is its simplicity. The basic concept of the algorithm is to assign a received power level to each user based on the average bit rate and on a target S/I ratio for that user. In this algorithm, the target S/I ratio is set to the minimum acceptable average S/I ratio. However, since the variance of the total interference at a given base station can be quite large, it is likely that the assigned power level is not sufficient to maintain the desired probability of outage. An access control process [24][25][26] must then be used to regulate the users so that the required probability of outage is satisfied.

In this chapter, other limitations, in addition to the sub-optimum capacity, are shown through simulation results as well as through mathematical analysis of the linear power assignment algorithm. It is also shown how the parameters affect the probability of outage and how the parameters can be adjusted in order to optimize capacity while satisfying the desired probability of outage.

This chapter is outlined as follows. The linear power assignment algorithm is described in section 4.2. In section 4.3, the algorithm is analysed mathematically and the limitations of the algorithm are revealed. Simulation results are also presented showing the failure of the algorithm under certain conditions. The

mathematical analysis illustrates how the parameters affect the probability of outage and how the algorithm can be improved in order to optimize capacity. The conclusions of this Chapter are summarized in section 4.4.

4.2 Algorithm Description

In the linear power assignment algorithm, each user is assigned a received power level, at the base station, that is proportional to its required target signal to interference ratio and to its average bit rate. The target S/I ratio, in this case, is set to the required average S/I ratio. The target received power for user i in cell j , P_{ij} , can then be written as

$$P_{ij} = \gamma_j^* \left(\frac{s}{I}\right)_{ij}^+ \bar{r}_{ij} \quad (4.1)$$

where

γ_j^* is the optimal power coefficient for cell j ,
 $\left(\frac{s}{I}\right)_{ij}^+$ is the target signal to interference ratio for user i in cell j , and
 $\bar{r}_{ij}$ is the average bit rate for user i in cell j .

The optimal power coefficient in the linear power assignment algorithm is derived from theorems given in [41] and by assuming that at capacity the value is the same for each cell. It is determined using the equation

$$\gamma_j^* = \frac{\frac{1}{W} [\sigma_j^2 + \sigma_T^2]}{1 - \frac{1}{W} \sum_{i=1}^{N_j} \left(\frac{s}{I}\right)_{ij}^+ \bar{r}_{ij}} \quad (4.2)$$

where σ_j^2 is the inter-cell interference to cell j , σ_T^2 is the background noise power, W is the system bandwidth and N_j is the total number of users in cell j .

The inter-cell interference is calculated as

$$\sigma_j^2 = \sum_{\substack{k=1 \\ k \neq j}}^M \gamma_k^* \left[\sum_{i=1}^{N_k} \left(\frac{S}{I} \right)_{ik}^+ \bar{r}_{ik} h_{ik}^{(j)} \right] \quad (4.3)$$

where $h_{ik}^{(j)}$ is the path loss parameter for user i in cell k with respect to the base station in cell j and M is the total number of cells in the network.

An iterative algorithm, which is run independently at each base station, can be used to determine the optimal power coefficients. The iterative algorithm is given by the following equations

$$\gamma_j^*(t_{n+1}) = \frac{\frac{1}{W} [\sigma_j^2(t_n) + \sigma_I^2]}{1 - \frac{1}{W} \sum_{i=1}^{N_j} \left(\frac{S}{I} \right)_{ij}^+ \bar{r}_{ij}} \quad (4.4)$$

where

$$\sigma_j^2(t_n) = \sum_{\substack{k=1 \\ k \neq j}}^M \gamma_k^*(t_n) \left[\sum_{i=1}^{N_k} \left(\frac{S}{I} \right)_{ik}^+ \bar{r}_{ik} h_{ik}^{(j)} \right] \quad (4.5)$$

t_n represents the time instant for the n^{th} update.

4.3 Analysis of the Linear Power Assignment Algorithm

The linear power assignment algorithm, as described in the previous section, is not optimal in terms of capacity utilization. Since the target S/I ratio is chosen as the required average S/I ratio, the amount of power assigned to each user might not be sufficient to satisfy the required probability of outage. In order to provide a better understanding of how the parameters affect the probability of outage, the linear power assignment algorithm is analysed mathematically, in this section. A simplified case where there is only a single cell with one class of users and perfect power control is considered. In this simplified case the probability of outage can

be calculated analytically, given the target signal to interference ratio and the total number of users.

Since there is no inter-cell interference and there is perfect power control, assuming the background noise power is constant, the probability distribution function for the S/I ratio is a discrete distribution function. Furthermore, the S/I ratio depends only on the number of users transmitting simultaneously. The probability of outage can then be calculated by determining the smallest number of interfering users, k , such that when transmitting simultaneously cause outage. In this case, the probability of outage is equal to the probability of having k or more interfering users transmitting at any given time and is given by

$$P(outage) = \alpha \sum_{i=k}^{n-1} \binom{n-1}{i} \alpha^i (1-\alpha)^{n-1-i} \quad (4.6)$$

where

- α is the activity factor,
- n is the total number of users in the system and
- k is the minimum number of users that cause outage when transmitting simultaneously.

Figure 4.1 shows a graph of the probability of outage, calculated using Equation (4.6), versus the total number of users and the target signal to interference ratio. In this case, the activity factor is set to 0.1 and the actual bit rate is set to 144 kbps. A contour plot for this graph is given in Figure 4.2. This contour plot can be used to identify the required target signal to interference ratio, given the number of users in the system, to achieve the required probability of outage. The graph also shows that the target signal to interference ratio needed to satisfy a given probability of outage decreases as the number of users increases.

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Figure 4.2: Contour plot of the three-dimensional plot in Figure 4.1 showing the target SIR versus the total number of users.

In order to determine what target S/I ratio is required to satisfy the system outage threshold level, $(\frac{s}{I})_{ij}^*$, the case where there is only one user in cell j is considered. In this case, the instantaneous signal to interference ratio for the given user is given by following equation

$$(\frac{s}{I})_{ij} = \frac{W}{R} \left[\frac{\gamma_j^* (\frac{s}{I})_{ij}^+ \bar{r}_{ij}}{\sigma_j^2 + \sigma_T^2} \right] \quad (4.7)$$

To ensure that there is no outage for this user, the right hand side of Equation (4.7) must be greater than or equal to the system outage threshold level. This is represented by the following inequality

$$\frac{W}{R} \left[\frac{\gamma_j^* (\frac{s}{I})_{ij}^+ \bar{r}_{ij}}{\sigma_j^2 + \sigma_T^2} \right] \geq (\frac{s}{I})_{ij}^* \quad (4.8)$$

Solving for the optimal power coefficient, γ_j^* , implies

$$\gamma_j^* \geq \frac{R(\sigma_j^2 + \sigma_T^2)}{W(\frac{s}{I})_{ij}^+ \bar{r}_{ij}} (\frac{s}{I})_{ij}^* \quad (4.9)$$

Substituting for γ_j^* , given by Equation (4.2), and solving for the target S/I ratio,

$(\frac{s}{I})_{ij}^+$, gives

$$(\frac{s}{I})_{ij}^+ \geq \frac{(\frac{s}{I})_{ij}^* R}{\bar{r}_{ij} \left(1 + \frac{R}{W} (\frac{s}{I})_{ij}^*\right)} = \frac{(\frac{s}{I})_{ij}^*}{\alpha_{ij} \left(1 + \frac{R}{W} (\frac{s}{I})_{ij}^*\right)} \quad (4.10)$$

where the activity factor, α_{ij} , is written as

$$\alpha_{ij} = \frac{\bar{r}_{ij}}{R}$$

If the above inequality is not satisfied, outage will occur each time the user is transmitting and the probability of outage will therefore be equal to the activity factor.

In the theoretical results given in Figure 4.1, the probability of outage decreases as the number of users increases. This decrease in the probability of outage can be explained by deriving the equation for the minimum instantaneous signal to interference ratio. The minimum S/I ratio occurs when all n users are transmitting simultaneously. It is given by the equation

$$\left(\frac{S}{I}\right)_{\min,ij} = \frac{\left(\frac{S}{I}\right)_{ij}^+ \alpha_{ij}}{1 - \frac{1}{W} \left(\frac{S}{I}\right)_{ij}^+ \bar{r}_{ij}} \quad (4.11)$$

Since the equation does not depend on the number of users in the system, the minimum S/I ratio is always the same for a given set of parameters. Although increasing the number of users in the system does not affect the minimum S/I ratio, it does affect the variance of the probability distribution function. Initially, as the number of users increases the variance also increases, however, since both the minimum SIR and the system outage threshold level remain the same, the probability of outage must then decrease. This is illustrated in Figure 4.3. The two probability distribution functions in the figure have the same minimum S/I ratio with different variances. The probability distribution function with the larger variance has a smaller probability of outage.

Figure 4.3: Two probability distribution functions with the same minimum S/I and system outage threshold level, but different variances.

Although changing the number of users in the system affects the shape of the probability distribution function, by modifying the variance, changing the target SIR causes a shift in the distribution function. Increasing the target SIR will increase the minimum SIR and will therefore shift the distribution function to the right. This causes the probability of outage to decrease. Conversely, decreasing the target SIR will cause the probability of outage to increase.

If the probability of outage decreases as more users are added to the system, then the target signal to interference ratio can be reduced to maintain a constant probability of outage. This is illustrated by the theoretical results given by the contour plot in Figure 4.2. Each contour line in the graph represents a constant probability of outage. The required target S/I ratio, for a given probability of outage, decreases as the number of users increases.

This is also confirmed by the following set of simulations where users, belonging to the same class, are uniformly distributed over a grid of nine square cells. The number of users is kept fixed during each simulation, while the results are averaged over one thousand different user locations. In this set of simulations, perfect power control is assumed.

Figure 4.4 shows a plot of the probability of outage versus the number of users in the system, for several different values of the target signal to interference ratio. In the simulation, the system outage threshold level is set to 4.5 dB, the activity factor is set to 0.1 and the bit rate is set to 144 kbps. For this set of parameters the required target S/I ratio, according to Equation (4.10), should be approximately 14.2 dB.

For each target signal to interference ratio in the graph below 14.2 dB the probability of outage decreases as the number of users increases. Also, when there is only a single user in the system the probability of outage is equal to the

activity factor whenever the target S/I ratio is less than 14.2 dB. This poses a problem for the access control strategy. If the target S/I ratio were below this optimum value then the call admission control procedure would either reject a new user when there are no users currently in the system or it would admit the user even though the probability of outage would not be satisfied.

Figure 4.4: Probability of outage versus the total number of users using the linear power assignment algorithm for different target S/I ratios.

The convergence percentage for the algorithm is given in Figure 4.5. As expected, increasing the target signal to interference ratio decreases the convergence percentage and, therefore, results in fewer users being accommodated in the system.

Figure 4.5: Convergence percentage of the linear power assignment algorithm versus the total number of users for different target S/I ratios.

The average optimal power coefficient for the centre cell versus the total number of users is given in Figure 4.6. This figure shows that for each target S/I ratio the optimal power coefficient increases and, therefore, the required received power for each user increases as more users enter the system. The graph also shows that the optimal power coefficient increases more quickly with a higher target S/I ratio.

Figure 4.6: Average optimal power coefficient for the centre cell versus the total number of users.

The results from the above simulation indicate that it is possible to significantly increase the number of users by decreasing the target signal to interference ratio as the number of users increases such that the required probability of outage is satisfied. This is shown in Figure 4.7. The two curves in the graph indicate what target signal to interference ratio is required to achieve a probability of outage of 0.01 and 0.001 as the number of users is varied.

Figure 4.7: Required target S/I ratio versus the total number of users to achieve a probability of outage of 10^{-2} and 10^{-3} .

As shown by the graph, one hundred and twenty users can easily be accommodated if the target SIR is varied to maintain the desired probability of outage. Conversely, if the target SIR remains fixed as the number of users change, then it must be set to 14.2 dB to satisfy the outage constraint for all possible number of users. However, as illustrated by the graph of the convergence percentage given in Figure 4.5, setting the target SIR to this value results in fewer users being accommodated into the system.

The probability of outage is also affected by changes in the activity factor. From the equation for the minimum signal to interference ratio, given by Equation (4.11), it can be seen that increasing the activity factor decreases the probability of outage. Increasing the activity factor increases the average bit rate and therefore increases the minimum signal to interference ratio. Assuming all other parameters are the same, an increase in the minimum SIR results in a shift of the probability distribution function to the right such that it decreases the probability of outage.

This affect, of changing the activity factor, on the probability of outage is also verified by simulation. A set of simulations is performed where the activity factor is varied from 0.55 to 0.6. In this case, the system outage threshold level is 4.5 dB, the target SIR is 6.5 dB and the actual bit rate is 144 kbps. The plot of the probability of outage versus the number of users is given in Figure 4.7. The graph shows the probability of outage decreases as the activity factor increases. This indicates that the target S/I ratio should be chosen according to the activity factor. Users with a high activity factor should be assigned a small target S/I ratio, while users with a low activity factor should be assigned a larger target S/I ratio.

Figure 4.8: Probability of outage versus the total number of users for various activity factors using the LPA algorithm.

4.4 Summary

The previously developed linear power assignment algorithm is described and analysed in this Chapter. Several limitations of the linear power assignment algorithm are revealed. One limitation is that it is sub-optimum in capacity utilization. Additional users can be accommodated in the system if the target signal to interference ratio is varied as the total number of users in the system changes. Both theoretical and simulation results show that as the number of users increases the target S/I ratio can be decreased to maintain the same probability of outage.

Even though the linear power assignment algorithm was designed to be a sub-optimum scheme in capacity utilization, the target S/I ratio cannot be set arbitrarily. The simulation results show that for some values of the target S/I ratio the probability of outage decreases as the number of users increases. Also, the outage probability can be equal to the activity factor when only one user is in the system. An equation is derived for the target S/I that ensures the required probability of outage is satisfied for a single user in the system. This required target S/I ratio depends on the activity factor, the bit rate, the system outage threshold level and the system bandwidth.

From the equation for the required target S/I ratio, it is shown that the smaller the activity factor, the larger the required target S/I ratio. For users with a small activity factor, such as reverse link Internet traffic, capacity is dramatically reduced if the target S/I is to remain constant as the number of users varies since a much higher target S/I ratio is required.

The mathematical analysis of the algorithm, for the case where there is a single cell with only one class of users, provides insight into how the parameters affect

the linear power assignment algorithm. It is shown that increasing the target S/I ratio increases the minimum S/I and therefore shifts the probability distribution function to the right. However, increasing the number of users, while fixing the target S/I ratio, results in a change in the shape of the probability distribution function, without affecting the minimum S/I ratio. This occurs since increasing the number of users increases the variance.

Although the linear power assignment algorithm has been shown to be sub-optimal in terms of capacity, it can be modified to increase the total number of users by assigning enough power to maintain the required probability of outage. As shown in this Chapter, one way of maintaining the required probability of outage is by adjusting the target signal to interference ratio. However, another method of fixing the target signal to interference ratio and modifying the optimal power coefficient can also be used. This proposed modification to the linear power assignment algorithm is described in detail in the next chapter.

MODIFIED LINEAR POWER ASSIGNMENT

5.1 Introduction

The linear power assignment algorithm described in the previous chapter was not only shown to be sub-optimal in utilizing the cell capacity, it was also shown that under certain conditions the probability of outage would not be satisfied even when there are only a few users in the system. Although this problem can be corrected by selecting a higher target S/I ratio, capacity is significantly reduced if the target S/I ratio is not modified as the number of users changes. Increasing the target S/I ratio can result in maintaining the required probability of outage when fewer users are in the system, but as more users enter the system the probability of outage can be well below the desired value.

In this chapter, a new modified linear power assignment algorithm is developed. This algorithm optimizes the cell capacity by ensuring that the probability of outage is satisfied and is as close as possible to the desired probability of outage. The algorithm is first developed for the simplified case where there is only a single cell with one class of users and perfect power control. It is then generalized to the case where there are multiple cells with multiple classes of users and imperfect power control.

5.2 Algorithm Description

In the previous Chapter on the linear power assignment algorithm it is shown that a significant increase in capacity can be obtained by modifying the target

signal to interference ratio as the number of users increases. The target S/I ratio is chosen such that the desired probability of outage is maintained.

Although modifying the target signal to interference ratio as the number of users changes can optimize the total number of users in the system, it cannot easily be implemented. Another approach is to set the target signal to interference ratio so that the instantaneous S/I ratio is satisfied for the worst case, where all n users are transmitting simultaneously, and instead, change the equation for the optimal power coefficient to achieve the require probability of outage.

The equation for the instantaneous S/I ratio for the case where all n users are transmitting simultaneously is given by the following equation

$$\left(\frac{s}{I}\right)_{kj} = \frac{W}{R} \left[\frac{\gamma_j^* \left(\frac{s}{I}\right)_{kj}^+ \bar{r}_{kj}}{\sum_{\substack{i=1 \\ i \neq k}}^n \gamma_j^* \left(\frac{s}{I}\right)_{ij}^+ \bar{r}_{ij} + \sigma_j^2 + \sigma_T^2} \right]$$

where σ_j^2 is the average inter-cell interference to cell j and σ_T^2 is the average background noise power. Substituting for the optimal power coefficient given by Equation (4.2) gives

$$\left(\frac{s}{I}\right)_{kj} = \frac{W}{R} \left[\frac{\frac{1}{W} [\sigma_j^2 + \sigma_T^2] \left(\frac{s}{I}\right)_{kj}^+}{\left(1 - \frac{1}{W} \sum_{i=1}^n \left(\frac{s}{I}\right)_{ij}^+ \bar{r}_{ij}\right) \left(\frac{\frac{1}{W} [\sigma_j^2 + \sigma_T^2] \sum_{\substack{i=1 \\ i \neq k}}^n \left(\frac{s}{I}\right)_{ij}^+ \bar{r}_{ij}}{\left(1 - \frac{1}{W} \sum_{i=1}^n \left(\frac{s}{I}\right)_{ij}^+ \bar{r}_{ij}\right)} + (\sigma_j^2 + \sigma_T^2) \right)} \right] \quad (5.1)$$

After simplifying, the above equation becomes

$$\left(\frac{s}{I}\right)_{kj} = \frac{\left(\frac{s}{I}\right)_{kj}^+ \alpha_{kj}}{1 - \frac{1}{W} \left(\frac{s}{I}\right)_{kj}^+ \bar{r}_{kj}} \quad (5.2)$$

In order to satisfy the system outage threshold level, $\left(\frac{s}{I}\right)_{kj}^*$, the instantaneous signal to interference ratio must satisfy the following inequality

$$\frac{\left(\frac{s}{I}\right)_{kj}^+ \alpha_{kj}}{1 - \frac{1}{W} \left(\frac{s}{I}\right)_{kj}^+ \bar{r}_{kj}} \geq \left(\frac{s}{I}\right)_{kj}^* \quad (5.3)$$

This implies that the target S/I ratio must satisfy

$$\left(\frac{s}{I}\right)_{kj}^+ \geq \frac{\left(\frac{s}{I}\right)_{kj}^*}{\alpha_{kj} \left[1 + \frac{R}{W} \left(\frac{s}{I}\right)_{kj}^*\right]} \quad (5.4)$$

After setting the target signal to interference ratio to the expression on the right hand side of the above inequality, the probability of outage can be controlled by setting the optimal power coefficient using the equation

$$\gamma_j^* = \frac{\frac{1}{W}[\sigma_j^2 + \sigma_I^2]}{1 - \frac{1}{W}I_j^*} \quad (5.5)$$

where the parameter I_j^* is used to control the probability of outage. Setting I_j^* equal to

$$I_j^* = \sum_{i=1}^{N_j} \left(\frac{S}{I}\right)_{ij}^+ \bar{r}_{ij} \quad (5.6)$$

as in the original linear power assignment algorithm, will result in a probability of outage equal to zero, if the variance of the inter-cell interference and the background noise power are both equal to zero, since the minimum S/I ratio will be equal the system outage threshold level.

From the equation for the optimal power coefficient, given by Equation (5.5), it can be seen that decreasing I_j^* will decrease the optimal power coefficient. It is shown, in the next section, that this will also result in a shift in the probability distribution function for the S/I ratio. The distribution function shifts to the left, in this case, causing the probability of outage to increase.

The parameter I_j^* is a global parameter for cell j . This parameter is used to control the probability of outage for each user in cell j . If different classes of users require different values for I_j^* then the highest value can be used. However, this results in a higher QoS for those users that required a smaller value. To achieve the different outage requirements for different classes of users it might be necessary to further adjust the target S/I ratio.

Another way of achieving different outage requirements, which can be used for delay insensitive users only, is to select a smaller value for the parameter I_j^* . The

additional outage requirement that is necessary for the users that require a higher value for I_j^* can be obtained through ARQ.

In order to show the effect of changing the parameter I_j^* on the probability of outage and to determine the optimum value, the simplified case, where there is only one class of users in a single cell with perfect power control, is analysed in the next section.

5.3 Single Cell With One Class of Users

In the case where there is only a single cell with one class of users and perfect power control, the probability distribution function for the signal to interference ratio is a discrete distribution function. The S/I ratio, for this case, depends only on the number of users transmitting simultaneously and therefore the probability of outage can be obtained using Equation (4.6). This equation can be used to determine the value of the optimal power coefficient that is required to achieve the desired probability of outage.

The derivation of the modified linear power assignment algorithm for this simplified case is based on the following Lemma.

Lemma 1: If the target signal to interference ratio, for user i in cell j , is given by

$$\left(\frac{S}{I}\right)_{ij}^+ = \frac{\left(\frac{S}{I}\right)_{ij}^*}{\alpha_{ij} \left[1 + \frac{R}{W} \left(\frac{S}{I}\right)_{ij}^*\right]} \quad (5.7)$$

and the optimal power coefficient for cell j is set using

$$\gamma_j^* = \frac{\frac{1}{W}(\sigma_j^2 + \sigma_T^2)}{1 - \frac{1}{W} \sum_{i=1}^k \left(\frac{S}{I}\right)_{ij}^+ \bar{r}_{ij}}, \quad 1 \leq k \leq n \quad (5.8)$$

then $(\frac{s}{I})_{ij} \geq (\frac{s}{I})_{ij}^*$ whenever there are fewer than k users interfering at any given time.

Proof: As the number of users that are transmitting simultaneously increases, the instantaneous signal to interference ratio decreases monotonically. If there are k users transmitting simultaneously, then

$$(\frac{s}{I})_{ij} = \frac{W}{R} \left[\frac{\gamma_j^* (\frac{s}{I})_{ij}^+ \bar{r}_{ij}}{\sum_{i=1}^{k-1} \gamma_j^* (\frac{s}{I})_{ij}^+ \bar{r}_{ij} + \sigma_j^2 + \sigma_T^2} \right] = (\frac{s}{I})_{ij}^* \quad (5.9)$$

If there are $k+1$ users transmitting simultaneously then

$$(\frac{s}{I})_{ij} = \frac{W}{R} \left[\frac{\gamma_j^* (\frac{s}{I})_{ij}^+ \bar{r}_{ij}}{\sum_{i=1}^k \gamma_j^* (\frac{s}{I})_{ij}^+ \bar{r}_{ij} + \sigma_j^2 + \sigma_T^2} \right] = \alpha_{ij} (\frac{s}{I})_{ij}^+ < (\frac{s}{I})_{ij}^* \quad (5.10)$$

The above Lemma states that outage will occur if more than k users are transmitting simultaneously. In other words, if the probability of having more than k users transmitting at any given time is equal to L , then the probability of outage is equal to L . Therefore, in order to control the probability of outage, the value chosen for k in Equation (5.8) should be the smallest number of users such that the probability of having each user transmitting simultaneously is less than or equal to the desired probability of outage.

Equation (5.8) in the above Lemma can be rewritten in the form used by the modified linear power assignment algorithm, given by Equation (5.5), by setting the value for I_j^* using the equation

$$I_j^* = \sum_{i=1}^k \left(\frac{s}{I}\right)_{ij}^+ \bar{r}_{ij} \quad (5.11)$$

In order to determine the effect of changing the value for k and the total number of users in the system on the probability of outage, a three-dimensional plot of the probability of outage, calculated using Equation (4.6), versus k and the total number of users is given in Figure 5.1.

In this case, the system outage threshold level is set to 4.5 dB, the activity factor is set to 0.1 and the actual bit rate is 144 kbps. Since there is only a single class of users, the maximum value for k is determined using the following equation

$$k_{\max} = \max \left\{ k : k < \frac{W}{\left(\frac{s}{I}\right)^+ \bar{r}} \right\} \quad (5.12)$$

For the above chosen set of parameters $k_{\max}$ is equal to thirteen. This three dimensional plot in Figure 5.1 can be used to identify what value of k should be used to satisfy the required probability of outage for a given number of users.

The modified linear power assignment algorithm is simulated for the above set of parameters and the simulation results are compared to the theoretical results for a required probability of outage equal to 0.001. The required value for k that is needed to achieve this probability of outage is obtained from Figure 5.1.

Figure 5.1: Probability of outage versus the parameter k and the number of users.

Figure 5.2 shows the required value for k versus the number of users in the system. The actual probability of outage versus the total number of users, obtained from the simulation, is given in Figure 5.3. This graph shows that when the modified linear power assignment algorithm is used, the probability of outage remains below the required probability of outage of 10^{-3} .

Figure 5.2: Required value for k , to achieve a probability of outage of 10^{-3} , versus total number of users.

Figure 5.3: Probability of outage for one class of users in a single cell versus the number of users using the MLPA algorithm with a probability of outage of 10^{-3} .

The graph also shows that sixty-five users can be accommodated using the new algorithm. If the original linear power assignment algorithm is used, with the same target signal to interference ratio, the maximum number of users, given by Equation (5.12), is only thirteen. Capacity, for this set of parameters, has therefore, been increased by a factor of five. This increase in capacity decreases as the required probability of outage decreases. For a required probability of outage equal to zero, the two algorithms will be the same and the value for k will be equal to n .

The value for the optimal power coefficient versus the total number of users is given in Figure 5.4. This graph illustrates that as more users enter the system the optimal power coefficient increases and therefore the required received power for each user increases in order to maintain the same probability of outage.

The modified linear power assignment algorithm for the general case is discussed in the next section.

Figure 5.4: Optimal power coefficient versus the total number of users.

5.4 Multiple Cells With Multiple Classes of Users

The simplified case described in the previous section can be generalized to multiple cells and multiples classes of users. The modified linear power assignment algorithm for this case is based on the following Lemma.

Lemma 2: If the target signal to interference ratio, for user k in cell j , is given by

$$\left(\frac{S}{I}\right)_{kj}^+ = \frac{\left(\frac{S}{I}\right)_{kj}^*}{\alpha_{kj} \left[1 + \frac{R}{W} \left(\frac{S}{I}\right)_{kj}^*\right]} \quad (5.13)$$

and the optimal power coefficient for cell j is set using

$$\gamma_j^* = \frac{\frac{1}{W} [\sigma_j^2 + \sigma_T^2]}{1 - \frac{1}{W} I_j^*} \quad (5.14)$$

for some I_j^* , then $\left(\frac{S}{I}\right)_{kj} \geq \left(\frac{S}{I}\right)_{kj}^*$ whenever the total interference to cell j is less than or equal to $\gamma_j^* I_j^* + \sigma_j^2 + \sigma_T^2$. Furthermore, if I_j^* is chosen such that

$$I_{tot,j}^{(L)} = \gamma_j^* I_j^* + \sigma_j^2 + \sigma_T^2 \quad (5.15)$$

where $I_{tot,j}^{(L)}$ represents the L^{th} percentile of the total interference to cell j , then the probability of outage is equal to L .

Proof: As the total interference increases, the instantaneous S/I decreases monotonically. If the total interference to cell j is given by

$$I_{tot,j} = \gamma_j^* I_j^* + \sigma_j^2 + \sigma_T^2$$

where σ_j^2 is the inter-cell interference and σ_T^2 is the background noise power, then the instantaneous S/I is given by

$$\begin{aligned} \left(\frac{s}{I}\right)_{kj} &= \frac{W}{R} \left[\frac{\gamma_j^* \left(\frac{s}{I}\right)_{kj}^+ \bar{r}_{kj}}{\gamma_j^* I_j^* - \gamma_j^* \left(\frac{s}{I}\right)_{kj}^+ \bar{r}_{kj} + \sigma_j^2 + \sigma_T^2} \right] \\ &= \frac{W}{R} \left[\frac{\gamma_j^* \left(\frac{s}{I}\right)_{kj}^+ \bar{r}_{kj}}{\gamma_j^* \left(I_j^* - \left(\frac{s}{I}\right)_{kj}^+ \bar{r}_{kj}\right) + \sigma_j^2 + \sigma_T^2} \right] \\ &= \left(\frac{s}{I}\right)_{kj}^* \end{aligned}$$

In other words, if I_j^* is chosen such that $\gamma_j^* I_j^* + \sigma_j^2 + \sigma_T^2$ represents the L^{th} percentile of the total interference at cell j when user k is transmitting, then the probability of outage for any given user in cell j will be equal to L . The total interference, in this case, also includes the power received from user k as well as the inter-cell interference and the background noise power. A more detailed proof of the above lemma is given in Appendix A.

In order to calculate the L^{th} percentile of the total interference power at a given base station, an empirical density estimation method is required. There are a number of density estimation methods described in the literature. The main methods for density estimation are presented and compared in [21]. In this study, it was concluded that the kernel density estimator is the most reliable for estimating the L^{th} percentile. Although the kernel estimator is complex, as indicated in [21], it can be implemented using a DSP algorithm. In this thesis, a narrow bin histogram is used to estimate the L^{th} percentile.

Once the L^{th} percentile of the total interference is estimated, the value corresponding to the intra-cell interference, I_j^* , is determined by subtracting the

average inter-cell interference and the average background noise power. The value for I_j^* is then obtained by dividing by the optimal power coefficient. This is given by the equation

$$I_j^* = (I_{tot,j}^{(L)} - \sigma_j^2 - \sigma_T^2) / \gamma_j^* \quad (5.16)$$

where $I_{tot,j}^{(L)}$ represents the L^{th} percentile of the total interference to cell j .

Defining the value for I_j^* in this way will account for both the variance in the inter-cell interference and the variance in the background noise power. Since the modified linear power assignment algorithm accounts for only the average inter-cell interference and the average background noise power, it is necessary to include the variance of both of these quantities in the estimate of the L^{th} percentile of the intra-cell interference in order to satisfy the outage requirement. If either the variance in the inter-cell interference or the variance in the noise power increases the estimate for the L^{th} percentile also increases. This results in a larger value for I_j^* and therefore reduces capacity.

Equation (5.16) gives the theoretical value for the parameter I_j^* that is needed to achieve the desired probability of outage. However, since the actual L^{th} percentile of the total interference is not known, an approximation to this theoretical value is obtained, $\hat{I}_j^*$. Therefore, an adaptive algorithm is needed to update the value for $\hat{I}_j^*$ in order for the estimate to converge to the theoretical value. A gradient descent algorithm that minimizes the error between the average probability of outage and the desired probability of outage can be used to achieve this optimum solution. The equation for updating the estimate, using a simple gradient descent algorithm, is given by

$$\hat{I}_j^*(t_{n+1}) = \hat{I}_j^*(t_n) + \beta m (L - \bar{L}_j(t_n)) \quad (5.17)$$

where $\bar{L}_j$ is the average probability of outage for the users in cell j , L is the desired probability of outage, β is an adaptation coefficient and m is given by

$$m = \frac{\hat{I}_j^*(t_n) - \hat{I}_j^*(t_{n-1})}{\bar{L}(t_n) - \bar{L}(t_{n-1})} \quad (5.18)$$

The iterative algorithm for the modified linear power assignment algorithm is given by the following equations

$$\gamma_j^*(t_{n+1}) = \frac{\frac{1}{W} [\sigma_j^2(t_n) + \sigma_T^2]}{1 - \frac{1}{W} \hat{I}_j^*} \quad (5.19)$$

where

$$\sigma_j^2(t_n) = \sum_{\substack{k=1 \\ k \neq j}}^M \gamma_k^*(t_n) \left[\sum_{i=1}^{N_k} \alpha_{ik} \left(\frac{s}{T} \right)_{ik}^* \bar{r}_{ik} h_{ik}^{(j)} \right] \quad (5.20)$$

When the equations for the modified linear power assignment algorithm converge, the error in the probability of outage is measured and the value for $\hat{I}_j^*$ is updated using Equation (5.17). Then, the modified linear power assignment algorithm is iterated again using this updated value. As this process continues, the value for $\hat{I}_j^*$ converges to the theoretical value I_j^* and the measured probability of outage converges to the desired probability of outage. This adaptive algorithm is summarized in Figure 5.5 and is used in the simulations described in the next section.

Figure 5.5: Flow chart illustrating the adaptive modified linear power assignment algorithm.

When there are multiple classes of users in the system, it is possible that a different value for I_j^* is necessary to achieve the same probability of outage. This is a result of each class of users having a different probability distribution function for the total interference at a given cell. In this case, the class corresponding to the highest value of I_j^* can be used in the feedback for the gradient descent algorithm. When the gradient descent algorithm converges, the probability of outage for this class will be equal to the desired value. The probability of outage for the other classes of users will be below the desired value.

The target S/I ratio can be decreased for the classes that have an outage level below the required probability of outage in order to achieve the same of outage level for each class. If the exact probability of outage is not important, then all the users in the cell can be used in the feedback for the gradient descent algorithm. This may result in an outage level below the desired value for some users and an outage level above the required value for other users.

Simulation Results

The modified linear power assignment algorithm is simulated for the general case where there are multiple cells. In this simulation, the system outage threshold level is set to 4.5 dB, the activity factor is set to 0.1 and the bit rate is set to 144 kbps. The required probability of outage, in this case, is set to 10^{-3} . Figure 5.6 shows the probability of outage versus the total number of users in the network, which consists of nine square cells. A narrow bin histogram is used to initially estimate the L^{th} percentile of the total interference at each of the base stations, while the gradient descent algorithm, described in the previous section, is used to further refine the estimate. The graph in Figure 5.6 shows that the modified linear power assignment algorithm can successfully maintain the required probability of outage at the desired value as the number of users in the network changes.

Figure 5.6: Probability of outage versus the total number of users using the MLPA algorithm with a desired probability of outage of 10^{-3} . The results are for a multiple cell environment with perfect power control.

The graph also illustrates that the simple gradient descent algorithm can effectively achieve the desired optimum solution. Since a histogram is used to initially estimate the L^{th} percentile of the total interference, the value used for I_j^* is only an approximation to the theoretical value needed to achieve the exact probability of outage. If the value for I_j^* is over estimated, then the probability of outage will be lower than the desired value. Conversely, if the value for I_j^* is under estimated, then the probability of outage will be greater. In this case, the initial error in the estimate of I_j^* is quite large, but, as shown in Figure 5.6, the gradient decent algorithm is able to minimize the difference between the measured probability of outage and the desired value.

The convergence percentage of the modified linear power assignment algorithm is given in Figure 5.7. This graph illustrates that as the number of users increases the convergence percentage decreases. Although the graph in Figure 5.6 indicates that four hundred users can be accommodated in the network, as illustrated in Figure 5.7, the probability that the algorithm will converge in this case is only ten percent.

Figure 5.8 shows the average optimal power coefficient for the centre cell versus the total number of users. This graph illustrates that as the number of users increases the optimal power coefficient also increases. As a result, each user requires more power to maintain the same QoS.

Figure 5.7: Convergence percentage versus the total number of users using the MLPA algorithm with perfect power control

Figure 5.8: Optimal power coefficient versus the total number of users using the MLPA algorithm with perfect power control

5.5 Imperfect Power Control

The modified linear power assignment algorithm, for the general case described in the previous section, can also handle the case where there is imperfect power control. Power control errors affect the variance of the probability distribution function of the total interference for a given cell. As the power control errors increase the variance of the probability distribution function also increases. This results in an increase in the value for the parameter I_j^* and therefore results in an increase in the optimal power coefficient, which reduces capacity.

Figure 5.9 shows the probability of outage versus the total number of users when imperfect power control is included. The same traffic parameters and requirements are used as in the previous case with perfect power control. Since the activity factor is small, a closed loop power control algorithm cannot be used to control the users' power level at the desired value. In this case, the users' received power is controlled using only an open loop power control algorithm. However, since there is a 45 MHz separation in the forward and reverse links, in the IS-95 standard, the signals will fade independently. This results in relatively large power control errors compared to when a closed loop power control algorithm is implemented. A Gaussian distribution may no longer be a valid representation of the power control errors for this case. Therefore, uniform random variables in the range of -2 to 2 dB are used to represent the power control errors.

The results of the simulation are compared to the original sub-optimal linear power assignment algorithm. In both algorithms, the target S/I ratio is set to the same value, according to Equation (5.11), which in this case is 14.2 dB. From the graph, it can be seen that a significant increase in capacity is obtained by ensuring

that the probability of outage is as close as possible to the desired probability of outage. The graph also illustrates the affect power control errors have on capacity. With perfect power control four hundred users can be accommodated, whereas only three hundred users can be accommodated when the power control errors are uniformly distributed between -2 and 2 dB.

The convergence percentage of the modified linear power assignment algorithm versus the total number of users, for the case with imperfect power control, is given in Figure 5.10. The average optimal power coefficient for the centre cell versus the total number of users is given in Figure 5.11.

Figure 5.9: Probability of outage versus the total number of users using the LPA algorithm and the MLPA algorithm with a desired probability of outage of 10^{-3} . The results are for a multiple cell environment with imperfect power control.

Figure 5.10: Convergence percentage versus the total number of users using the MLPA algorithm with imperfect power control.

Figure 5.11: Optimal power coefficient versus the total number of users using the MLPA algorithm with imperfect power control.

5.6 Comparison of the MLPA Algorithm to a Traditional Power Control Algorithm

A typical power control algorithm for CDMA systems consists of two closed loops that set and maintain a target S/I ratio for a given user. An inner closed loop tracks short-term power level fluctuations while an outer closed loop determines the target S/I ratio that is required in order to satisfy the desired QoS. The outer loop first determines the QoS, such as the FER or BER, and maps the QoS to a target S/I ratio. This target S/I ratio is then compared to the measured S/I ratio in order to set the power control bits. The block diagram given in Figure 5.12 illustrates this closed loop power control algorithm.

Figure 5.12: Block diagram for a typical power control algorithm.

One disadvantage in using this algorithm is that it does not guarantee a given probability of outage. Although it can satisfy an average FER, it cannot guarantee

that the FER will not exceed a predefined threshold a specified percentage of time.

Another disadvantage to using this power control/assignment algorithm is that both power assignment and power control are applied to each user individually. If a particular user has a low activity factor then there is not enough information to either assign a target S/I ratio or to control the power level to satisfy the target S/I ratio. In this case, the user's QoS will not be satisfied.

The modified linear power assignment algorithm, developed in this Chapter, solves both of these problems. In this new approach, power assignment is applied to each class of users while power control is applied to each user individually. The power assignment portion uses statistics from an entire class of users to optimize the parameters for the entire cell in order to guarantee the probability of outage for each user in the cell. If a given user has a low activity factor, then a target power level can still be assigned to this user since the entire class of users may, collectively, have enough information to determine the target power level.

Once the received power levels are assigned to each class, each user is power controlled individually. The power control algorithm compares the measured received power of each user to the assigned power and adjusts the power control bits accordingly. A block diagram for this new approach is given in Figure 5.13.

Although a user with a low activity factor cannot be power controlled accurately with a closed loop power control algorithm, due to the infrequent feedback, the probability of outage can still be satisfied. This is confirmed by the simulation results in the previous section. The large power control errors result in a higher value for the optimal power coefficient and therefore a higher assigned power level. However, each user's probability of outage is still maintained.

Figure 5.13: Block diagram for the MLPA algorithm.

5.7 Summary

A modified version of the linear power assignment algorithm is developed in this Chapter. The new algorithm optimizes the cell capacity by ensuring that the required probability of outage is maintained through power assignment rather than through an access control algorithm, as in the case of the original sub-optimal linear power assignment algorithm.

The theory behind the algorithm is first derived for the simplified case where there is only a single cell with one class of users. This is then followed by simulation results where it is shown that the actual probability of outage remains consistently below the required probability of outage as the number of users in the system changes. The theory is then extended to include the general case where there are multiple cells with multiple classes of users as well as imperfect power control. This extended case is then verified by simulation. The simulation results show that a dramatic increase in capacity is obtained using the modified linear power assignment algorithm.

The main advantage in using this algorithm over the original linear power assignment algorithm is the increase in capacity obtained by requiring the probability of outage to be as close as possible to the desired probability of outage. This increase in capacity is obtained without significantly increasing the computational complexity of the original algorithm. Also, since the new algorithm guarantees the probability of outage at the power assignment level, the call admission control procedure, described in the next chapter, is simplified.

Another benefit in using the modified linear power assignment algorithm is that a solution can be obtained for any number of users as long as there is enough

available capacity. Previously, with the original linear power assignment algorithm, users may be rejected even if there are no users currently in the system.

In the comparison of the modified linear power assignment algorithm to a conventional power control algorithm, it is shown that this new approach can satisfy the QoS and guarantee the probability of outage for each user, even if the users have a low activity factor. The conventional power control algorithm cannot satisfy the QoS for users that have a low activity factor since there is not enough feedback for either adjusting the power level or for determining the required target S/I ratio.

Chapter 6

CALL ADMISSION CONTROL USING THE MODIFIED LINEAR POWER ASSIGNMENT ALGORITHM

6.1 Introduction

This Chapter describes three call admission control procedures that use the modified linear power assignment algorithm. The first call admission control method is developed with the assumption that only an outage constraint needs to be satisfied to ensure the quality of the communication link. The other two call admission control procedures are developed with the assumption that an average S/I ratio must be satisfied in addition to the outage constraint.

6.2 Access Control Satisfying the Outage Constraint

In the original linear power assignment algorithm, described in Chapter 4, a received power level is assigned to each user without taking into account whether or not the required probability of outage would be satisfied. Consequently, an access control method, such as the adaptive equivalent bandwidth technique developed in [21], must be used in order to ensure that the probability of outage is satisfied each time a new user enters the system. However, since the modified linear power assignment algorithm already ensures that the required probability of outage is satisfied, the call admission control procedure for this case is straightforward.

On the request for a new connection, the first step in this call admission control procedure is to calculate the required target S/I ratio for the new user. This is determined using Equation (5.13). An initial estimate for the parameter I_j^* is

then required. In Chapter 5, it is determined that the optimal value for I_j^* is given by the following equation

$$I_j^* = (I_{tot,j}^{(L)} - \sigma_j^2 - \sigma_T^2) / \gamma_j^* \quad (6.1)$$

where $I_{tot,j}^{(L)}$ represents the L^{th} percentile of the total interference to cell j . In order to obtain an approximation to this value, an empirical density estimation technique is required. However, since a gradient descent algorithm is used to further refine the initial estimate, the previous estimate of I_j^* , which is determined before the arrival of the new user, can be used as an initial estimate. If there are no users currently in the system before the request for a new connection, then the initial estimate of I_j^* is given by

$$\hat{I}_j^* = \left(\frac{S}{I}\right)_{kj}^+ \bar{r}_{kj} \quad (6.2)$$

The optimal power coefficients are then updated using the modified linear power assignment algorithm. If the algorithm does not converge the user is rejected, otherwise the error between the average probability of outage and the desired probability of outage is determined and the value for the estimate $\hat{I}_j^*$ is updated using Equation (5.17). The modified linear power assignment algorithm is then iterated again using this updated value. As this process continues, the estimate $\hat{I}_j^*$ will converge to the desired value of I_j^* . This call admission control procedure is summarized in Figure 6.1.

Figure 6.1: Access control flow chart using the modified linear power assignment algorithm where only the outage constraint is satisfied.

6.3 Access Control Satisfying Both Outage and Average Constraints

In [21] it was noted that, in order to characterize the link quality more accurately, the average S/I ratio must also be considered, in addition to the probability of outage. This section describes two call admission procedures using the modified linear power assignment algorithm, where both the outage and average constraints are satisfied. The first method assumes that the target S/I ratio remains fixed to the value obtained from Equation (5.13) and modifies a global parameter so that each user satisfies the highest QoS from all the users in the given cell. Although this method is sub-optimal in capacity utilization it can easily be implemented and does not increase the computational complexity of the previous algorithm that only satisfies the outage constraint. The second method modifies the target S/I ratio for each class of users to achieve the different requirements for the different classes of users.

Fixed Target S/I Ratio

The average constraint for a given user in cell j is represented by the following inequality

$$\overline{\left(\frac{S}{I}\right)}_{kj} \geq \left(\frac{S}{I}\right)_{ave,kj} \quad (6.3)$$

where $\overline{\left(\frac{S}{I}\right)}_{kj}$ is the average S/I ratio for user k in cell j and $\left(\frac{S}{I}\right)_{ave,kj}$ is the required average S/I ratio for user k in cell j . One method of guaranteeing the average S/I ratio is to determine the constraint on the global parameter I_j^* that is used to control the outage probability in the equation for the optimal power coefficient given by Equation (5.14).

The average S/I ratio for user k in cell j is given by the following equation

$$\overline{\left(\frac{S}{I}\right)_{kj}} = \frac{W}{R} \left[\frac{\gamma_j^* \left(\frac{S}{I}\right)_{kj}^+ \bar{r}_{kj}}{\bar{I}_{kj} + \bar{\sigma}_j^2 + \bar{\sigma}_T^2} \right] \quad (6.4)$$

where $\bar{I}_{kj}$ is the average intra-cell interference for user k in cell j and is given by

$$\bar{I}_{kj} = \gamma_j^* \sum_{\substack{i=1 \\ i \neq k}}^{N_j} \alpha_{ij} \left(\frac{S}{I}\right)_{ij}^+ \bar{r}_{ij} \quad (6.5)$$

Substituting for the optimal power coefficient and the target S/I ratio, given by Equations (5.14) and (5.13) respectively, gives the following inequality

$$\overline{\left(\frac{S}{I}\right)_{kj}} = \frac{\frac{\left(\frac{S}{I}\right)_{kj}^*}{1 + \frac{R}{W} \left(\frac{S}{I}\right)_{kj}^*}}{\frac{1}{W} \sum_{\substack{i=1 \\ i \neq k}}^{N_j} \frac{\left(\frac{S}{I}\right)_{ij}^* \bar{r}_{ij}}{1 + \frac{R}{W} \left(\frac{S}{I}\right)_{ij}^*} + 1 - \frac{1}{W} I_j^*} \geq \left(\frac{S}{I}\right)_{ave,kj} \quad (6.6)$$

Solving for the parameter I_j^* implies

$$I_j^* \geq W + \sum_{\substack{i=1 \\ i \neq k}}^{N_j} \frac{\left(\frac{S}{I}\right)_{ij}^* \bar{r}_{ij}}{1 + \frac{R}{W} \left(\frac{S}{I}\right)_{ij}^*} - \frac{\left(\frac{S}{I}\right)_{kj}^*}{1 + \frac{R}{W} \left(\frac{S}{I}\right)_{kj}^*} \frac{W}{\left(\frac{S}{I}\right)_{ave,kj}} \quad (6.7)$$

If the above inequality is satisfied then the average constraint for user k in cell j will be guaranteed. Let $I_j^*(k)$ be the minimum value of I_j^* that is needed for user k in cell j to satisfy the average constraint. Then, in order to satisfy the average constraint for each user in cell j , the value for I_j^* should be set according to the following equation

$$I_j^* \geq \max\{I_j^*(k), k = 1, \dots, N_j\} \quad (6.8)$$

The above result is stated more precisely in the following Lemma.

Lemma 3: If the target signal to interference ratio, for user k in cell j , is given by

$$\left(\frac{S}{I}\right)_{kj}^+ = \frac{\left(\frac{S}{I}\right)_{kj}^*}{\alpha_{kj} \left[1 + \frac{R}{W} \left(\frac{S}{I}\right)_{kj}^*\right]}$$

and the optimal power coefficient for cell j is set using

$$\gamma_j^* = \frac{\frac{1}{W} [\sigma_j^2 + \sigma_T^2]}{1 - \frac{1}{W} I_j^*}$$

then $\overline{\left(\frac{S}{I}\right)_{kj}} \geq \left(\frac{S}{I}\right)_{ave,kj}$ whenever I_j^* is chosen such that

$$I_j^* \geq W + \sum_{\substack{i=1 \\ i \neq k}}^{N_j} \frac{\left(\frac{S}{I}\right)_{ij}^* \bar{r}_{ij}}{1 + \frac{R}{W} \left(\frac{S}{I}\right)_{ij}^*} - \frac{\left(\frac{S}{I}\right)_{kj}^*}{1 + \frac{R}{W} \left(\frac{S}{I}\right)_{kj}^*} \frac{W}{\left(\frac{S}{I}\right)_{ave,kj}}$$

Proof: As the value for I_j^* increases the average S/I ratio for any user in cell j also increases. If I_j^* is given by the equation

$$I_j^* = W + \sum_{\substack{i=1 \\ i \neq k}}^{N_j} \frac{\left(\frac{S}{I}\right)_{ij}^* \bar{r}_{ij}}{1 + \frac{R}{W} \left(\frac{S}{I}\right)_{ij}^*} - \frac{\left(\frac{S}{I}\right)_{kj}^*}{1 + \frac{R}{W} \left(\frac{S}{I}\right)_{kj}^*} \frac{W}{\left(\frac{S}{I}\right)_{ave,kj}}$$

then $\overline{\left(\frac{S}{I}\right)_{kj}} = \left(\frac{S}{I}\right)_{ave,kj}$.

In order to guarantee both the outage and average constraints, the parameter I_j^* must now satisfy both Equations (6.1) and (6.8).

The call admission control procedure developed in section 6.2 can easily be extended to include the average constraint by verifying the inequality given by Equation (6.8). If the condition is not satisfied then the value for I_j^* should be set to the expression on the right hand side of Equation (6.8).

The first step in this call admission control procedure is to estimate the value for I_j^* that is required to accommodate the new user. If there are users currently in the system before the request for a new connection, then the previous value for I_j^* can be used. This value should also satisfy the average constraint given by Equation (6.8). If the average constraint is satisfied the modified linear power assignment algorithm is iterated and the value for I_j^* is updated using the gradient descent algorithm described in the previous section. However, after each update of I_j^* the average constraint must be verified. If the average constraint is not satisfied the value for I_j^* is set to the expression on the right hand side of Equation (6.8) and the modified linear power assignment is iterated again. Once the algorithm converges, the outage probability must be determined to ensure that it is below the desired value. This call admission control procedure is summarized in the flow chart given in Figure 6.2.

Since the parameter I_j^* is set according to the class with the highest QoS requirements, this algorithm for including the average constraint is sub-optimal in capacity utilization. A better approach is to modify the target S/I ratio for each class of users in order to satisfy both the outage and average constraints. This method is described in the following section.

Figure 6.2: Access control flow chart using the modified linear power assignment where both outage and average constraints are satisfied.

Modifying the Target S/I Ratio

Modifying the target S/I ratio instead of the global parameter I_j^* can also ensure that the average constraint is satisfied. The average S/I ratio, given by Equation (6.4), can be written as

$$\overline{\left(\frac{s}{I}\right)} = \frac{W}{R} \left[\frac{\gamma_j^* \left(\frac{s}{I}\right)^+ \bar{r}}{\gamma_j^* \bar{I}_j^* + \sigma_j^2 + \sigma_T^2} \right] \quad (6.9)$$

The term $\gamma_j^* \bar{I}_j^*$ represents the average intra-cell interference. Substituting for the optimal power coefficient using Equation (5.5) and simplifying implies

$$\frac{\left(\frac{s}{I}\right)^+ \alpha}{1 - \frac{1}{W} (I_j^* - \bar{I}_j^*)} \geq \left(\frac{s}{I}\right)_{ave} \quad (6.10)$$

The target S/I ratio must therefore satisfy the following inequality

$$\left(\frac{s}{I}\right)^+ \geq \left[1 - \frac{1}{W} (I_j^* - \bar{I}_j^*) \right] \frac{\left(\frac{s}{I}\right)_{ave}}{\alpha} \quad (6.11)$$

In order to satisfy both the outage and the average constraints, the target S/I ratio must not only satisfy Equation (6.11) it must also satisfy the inequality obtained from the outage constraint given by Equation (5.4). This results in the following equation for the required target S/I ratio

$$\left(\frac{s}{I}\right)^+ = \max \left\{ \frac{\left(\frac{s}{I}\right)^*}{\alpha \left(1 + \frac{R}{W} \left(\frac{s}{I}\right)^*\right)}, \left[1 - \frac{1}{W} (I_j^* - \bar{I}_j^*) \right] \frac{\left(\frac{s}{I}\right)_{ave}}{\alpha} \right\} \quad (6.12)$$

where the first component corresponds to the outage requirement while the second component corresponds to the average requirement.

Since the average component in the above equation depends on the parameter I_j^* , the inclusion of the average constraint complicates the call admission control procedure. As the number of users changes the parameter I_j^* also changes. This will affect the difference between the parameter I_j^* and the mean intra-cell interference. As a result, it is possible that as the number of users vary the required target S/I ratio could also vary. Furthermore, the target S/I ratio might not be the same for the same class of users if the users belong to different cells, since the parameter I_j^* is likely to be different for different cells.

The first step in this access control method is to estimate the mean intra-cell interference and the parameter I_j^* . Then, the target S/I is calculated using Equation (6.12). Once these parameters are set, the modified linear power assignment algorithm is iterated using the gradient descent algorithm where only the users that have the target S/I ratio set according to the outage constraint are considered. If a solution exists, the user is temporarily admitted and the above steps are repeated until the target S/I and the value for I_j^* both converge. If both of these parameters converge the new user can then be admitted. This access control method is summarized by a flow chart given in Figure 6.3.

The extra iterations that are required in order for the target S/I ratio to converge increase the computational complexity of this access control method as compared to the previous method. However, these extra iterations only occur when the target S/I ratio is determined using the average constraint. Since the equation corresponding to the average constraint decreases as the variance of the total interference increases, the target S/I ratio decreases until it is determined by

the outage constraint. Therefore, as the number of users increases the target S/I ratio decreases until it stabilizes to the value obtained by the outage constraint. Once the target S/I ratio stabilizes, the extra iterations are no longer necessary when additional users enter the system. Extra iterations are, however, necessary in determining the optimal power coefficients as the number of users increases.

Figure 6.3: Access control flow chart satisfying both outage and average constraints..

6.4 Summary

Three call admission control procedures that use the modified linear power assignment algorithm are outlined in this Chapter. The first access control method requires that only the outage constraint be satisfied. Since the modified linear power assignment algorithm is designed to satisfy the outage constraint, the call admission control procedure for this case is straightforward. This call admission control method results in increased capacity, compared to when the original linear power assignment algorithm is used, without increasing the computational complexity of the original algorithm.

The second call admission control procedure requires that both the outage and average constraints be satisfied. In this method the target S/I ratio remains fixed to the value obtained in the derivation of the modified linear power assignment algorithm given in Chapter 5. However, a constraint is derived for the global parameter I_j^* . If the constraint is not satisfied the value is increased in order to satisfy the constraint. The inclusion of the average constraint provides a minimum bound for the parameter I_j^* and therefore does not increase the computational complexity of the algorithm. Although this call admission control algorithm is simple and can easily be implemented, it is sub-optimal in capacity utilization since a global parameter is modified so that each user satisfies the highest QoS from all the users in the cell. This sub-optimum approach, however, may not pose a major problem if the variance of the probability distribution function for the signal to interference ratio is large. In this case, satisfying the outage constraint will automatically satisfy the average constraint. If this variance increases when the number of users increases then the capacity of the system will not be affected.

The third call admission control procedure also requires that both the outage and average constraints be satisfied. This method is somewhat more complicated than the first two since the required target signal to interference ratio is likely to change as the number of users in the system varies. Therefore, it might be necessary to iterate the access control method until the target S/I ratio converges. Although the extra iterations increase the computational complexity of the access control method, the number of iterations decreases as the number of users increases. This occurs since the target S/I ratio stabilizes to the value determined by the outage constraint. The overall complexity of the algorithm, however, may not decrease as the number of users increase since, in this case, the number of iterations in determining the optimal power coefficients increases.

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this thesis, it is shown that power assignment can be used to provide the variable QoS requirements for mobiles supporting multimedia traffic. In particular, it is shown that power assignment can be used to guarantee a given probability of outage for each user in the system. The modified linear power assignment algorithm, developed in Chapter 5, provides a solution to the power assignment problem. This simple and robust algorithm can minimize the transmitted power of each mobile while satisfying the QoS requirements. The algorithm is therefore optimum in capacity utilization.

The detailed mathematical analysis of the previously developed sub-optimum linear power assignment algorithm, in Chapter 4, reveals another optimum power assignment algorithm that can guarantee a given probability of outage for each user in the system. This algorithm involves modifying the target S/I ratio as the number of users, or the variance of the total interference at the base station, changes. However, this algorithm cannot easily be implemented.

Three call admission control procedures using the modified linear power assignment algorithm are described in Chapter 6. The first algorithm ensures that an outage constraint is satisfied, while the other two algorithms ensure that both outage and average constraints are satisfied.

7.2 Summary of Contributions

The original linear power assignment algorithm is analysed, mathematically, in Chapter 4. This analysis provides insight into how the parameters affect the probability distribution function of the signal to interference ratio for a given class of users. In particular, it is shown how the target S/I ratio can affect the probability of outage. This also provides the motivation for modifying the linear power assignment algorithm in order to satisfy the required probability of outage.

A modified linear power assignment algorithm that guarantees the probability of outage is developed in Chapter 5. Compared to the original linear power assignment algorithm, the modified algorithm results in increased capacity, without increasing the computational complexity of the original algorithm.

The theory behind the modified linear power assignment algorithm is first proven for the simplified case where there is only a single cell with one class of users. This is then supported by simulation results that show that the algorithm maintains the desired probability of outage.

The theory is then extended to the general case where there are multiple cells with multiple classes of users and imperfect power control. Simulation results are also given showing that the algorithm works for a single class of users in a multiple cell environment with imperfect power control. The results show that a dramatic increase in capacity is obtained compared to when the original linear power assignment algorithm is used. It also shows that the algorithm is robust even under conditions such as imperfect power control.

In the comparison of the modified linear power assignment algorithm to a conventional power control algorithm, it is shown that this new approach can not only guarantee the required probability of outage, but it can also ensure the QoS for users with a low activity factor. The conventional power control algorithm

cannot guarantee a given probability of outage for any user and cannot ensure the QoS for users with a low activity factor.

Three access control methods that use the modified linear power assignment algorithm are developed in Chapter 6. The first method admits users only if the outage constraint can be satisfied for each class of users, while the other two methods admit users only if both the outage and average constraints can be satisfied. Each of these call admission control algorithms is more flexible and robust than either the original sub-optimum linear power assignment algorithm or the optimal non-linear power assignment algorithm developed in [21].

7.3 Recommendations

In Chapter 4 on the analysis of the original linear power assignment algorithm, it is shown that in order to satisfy a given probability of outage the target S/I ratio must be modified as the number of users or the variance in the probability distribution function of the total interference changes. Although the required target S/I ratio, in this case, is not determined, a gradient descent algorithm can be used to find the optimum value for each class of users. Other algorithms can also be investigated.

In order to improve the convergence of the gradient descent algorithm used by the modified linear power assignment algorithm, new and efficient algorithms for determining the L^{th} percentile of the total interference should be investigated. This can result in improving the initial estimate of the parameter used to control outage and, therefore, reduce the number of iterations that are needed for the gradient descent algorithm to converge. Several density estimation techniques are evaluated in [21] to determine the L^{th} percentile. However, other methods, not normally used for density estimation, can be used to approximate the parameters required to determine the optimal power coefficients. Investigating such algorithms is an area for further research.

In Chapter 6, the modified linear power assignment algorithm was extended to include the case where the average constraint is also satisfied. The proposed call admission control algorithms can be simulated to determine the affect of including the average constraint on capacity and on the convergence of the algorithm.

Although the modified linear power assignment algorithm, proposed in this thesis, is an optimum power assignment algorithm, other techniques can be used to further increase capacity. For example, reducing the variance of the total interference at a given base station can increase capacity. A technique such as delay scheduling can be used for delay insensitive users. Other techniques for reducing the variance could be investigated.

Since both the linear power assignment algorithm and the modified linear power assignment algorithm are simulated with the assumption that the users are uniformly distributed over the entire network area, further results should be obtained using a more realistic distribution.

The modified linear power assignment algorithm, described in this thesis, does not consider the transmitter power limit in determining the optimal power coefficients. This constraint can be added to the algorithm and simulated to determine the affect on capacity and on convergence of the algorithm.

APPENDIX A

Lemma 2: If the target signal to interference ratio, for user k in cell j , is given by

$$\left(\frac{s}{I}\right)_{kj}^+ = \frac{\left(\frac{s}{I}\right)_{kj}^*}{\alpha_{kj} \left[1 + \frac{R}{W} \left(\frac{s}{I}\right)_{kj}^*\right]} \quad (\text{A.1})$$

and the optimal power coefficient for cell j is set using

$$\gamma_j^* = \frac{\frac{1}{W} [\sigma_j^2 + \sigma_T^2]}{1 - \frac{1}{W} I_j^*} \quad (\text{A.2})$$

for some I_j^* , then $\left(\frac{s}{I}\right)_{kj} \geq \left(\frac{s}{I}\right)_{kj}^*$ whenever the total interference to cell j is less than or equal to $\gamma_j^* I_j^* + \sigma_j^2 + \sigma_T^2$. Furthermore, if I_j^* is chosen such that

$$I_{tot,j}^{(L)} = \gamma_j^* I_j^* + \sigma_j^2 + \sigma_T^2 \quad (\text{A.3})$$

where $I_{tot,j}^{(L)}$ represents the L^{th} percentile of the total interference to cell j , then the probability of outage is equal to L .

Proof: As the total interference increases, the instantaneous S/I ratio decreases monotonically. If the total interference to cell j is given by $\gamma_j^* I_j^* + \sigma_j^2 + \sigma_T^2$, then the instantaneous S/I is given by

$$\begin{aligned}
\left(\frac{S}{I}\right)_{kj} &= \frac{W}{R} \left[\frac{\gamma_j^* \left(\frac{S}{I}\right)_{kj}^+ \bar{r}_{kj}}{\gamma_j^* \left(I_j^* - \left(\frac{S}{I}\right)_{kj}^+ \bar{r}_{kj}\right) + \sigma_j^2 + \sigma_T^2} \right] \\
&= \frac{W}{R} \left[\frac{\frac{1}{W} [\sigma_j^2 + \sigma_T^2] \left(\frac{S}{I}\right)_{kj}^+ \bar{r}_{kj}}{\left[1 - \frac{1}{W} I_j^* \left[\frac{\frac{1}{W} [\sigma_j^2 + \sigma_T^2]}{\left[1 - \frac{1}{W} I_j^*\right]} \left(I_j^* - \left(\frac{S}{I}\right)_{kj}^+ \bar{r}_{kj}\right) + (\sigma_j^2 + \sigma_T^2) \right] \right]} \right] \\
&= \frac{W}{R} \left[\frac{\frac{1}{W} \left(\frac{S}{I}\right)_{kj}^+ \bar{r}_{kj}}{\left[1 - \frac{1}{W} I_j^* \left[\frac{\frac{1}{W} \left(I_j^* - \left(\frac{S}{I}\right)_{kj}^+ \bar{r}_{kj}\right)}{\left[1 - \frac{1}{W} I_j^*\right]} + 1 \right] \right]} \right] \\
&= \frac{W}{R} \left[\frac{\frac{1}{W} \left(\frac{S}{I}\right)_{kj}^+ \bar{r}_{kj}}{\frac{1}{W} \left(I_j^* - \left(\frac{S}{I}\right)_{kj}^+ \bar{r}_{kj}\right) + 1 - \frac{1}{W} I_j^*} \right] \\
&= \frac{W}{R} \left[\frac{\frac{1}{W} \left(\frac{S}{I}\right)_{kj}^+ \bar{r}_{kj}}{1 - \frac{1}{W} \left(\frac{S}{I}\right)_{kj}^+ \bar{r}_{kj}} \right]
\end{aligned}$$

Substituting for the target S/I ratio gives

$$\begin{aligned}
\left(\frac{S}{I}\right)_{kj} &= \frac{W}{R} \left[\frac{\frac{1}{W} \left(\frac{S}{I}\right)_{kj}^* \bar{r}_{kj}}{\alpha_{kj} \left[1 + \frac{R}{W} \left(\frac{S}{I}\right)_{kj}^* \left(1 - \frac{\frac{1}{W} \left(\frac{S}{I}\right)_{kj}^* \bar{r}_{kj}}{\alpha_{kj} \left[1 + \frac{R}{W} \left(\frac{S}{I}\right)_{kj}^* \right]} \right) \right]} \right] \\
&= \frac{W}{R} \left[\frac{\frac{1}{W} \left(\frac{S}{I}\right)_{kj}^* \alpha_{kj} R}{\alpha_{kj} \left[1 + \frac{R}{W} \left(\frac{S}{I}\right)_{kj}^* \right] - \frac{1}{W} \left(\frac{S}{I}\right)_{kj}^* \alpha_{kj} R} \right] \\
&= \left(\frac{S}{I}\right)_{kj}^*
\end{aligned}$$

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