Master's Thesis on
Performance Evaluation of Power Control Algorithms in Cellular Radio Communication Systems

by

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Abstract

Radio resources in wireless communication systems, implementing different multiple access techniques, must be wisely managed. This perspective is pivotal since the variations in propagation channel are very fast and the system is highly complex due to random and unpredictable movement of mobile users continuously. This complexity in the cellular system periodically contributes to different interference levels, high or low, resulting in the degradation of the system capacity. Transmitter power control is an efficient technique to mitigate the effect of interference under fading conditions, combat the Near-Far problem and conserve the battery life. Thus, an effective implementation of different power control algorithms in cellular radio communication systems can offer a significant improvement in the Quality of Service (QoS) to all the users.

Choice of an appropriate power control algorithm is of prime importance, as it should aim at increasing the overall efficiency of the system. In this thesis different distributed power control algorithms, each suited for implementation under different cellular technologies, were studied extensively. Specifically, six distributed power control algorithms are compared through simulations on the basis of performance metrics like Carrier to Interference Ratio (CIR) and Outage for the downlink case.

The work involves in finding the link gain matrix by modeling the cellular system in MATLAB and simulating different power control algorithms. The results obtained from the simulation work are used to evaluate the efficiency of the Distributed Power Control (DPC), Fully Distributed Power Control (FDPC), Improved Fully Distributed Power Control (FDPC+) and

Balanced Distributed Power Control (BDPC) algorithms on the basis of convergence speed and at the same time evaluating the limitations of the different algorithms. Also, with the results obtained on the basis of outage comparison between Fixed Step Power Control (FSPC) and Augmented Constant Improvement Power Control (ACIPC) algorithms, the quality of active link protection and cell removal procedures are demonstrated.

Acknowledgement

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Table of Contents

List of Abbreviations

TPC	Transmitter Power Control
CIR	Carrier to Interference Ratio
QoS	Quality of Service
BER	Bit Error Rate
FER	Frame Error Rate
FDMA	Frequency Division Multiple Access
TDMA	Time Division Multiple Access
CDMA	Code Division Multiple Access
WCDMA	Wideband Code Division Multiple Access
RRM	Radio Resource Management
GSM	Global System for Mobile Communications
SIR	Signal to Interference Ratio
MIMO	Multiple Input Multiple Output
CPCA	Centralized Power Control Algorithm
DPC	Distributed Power Control
FDPC	Fully Distributed Power Control
BDPC	Balanced Distributed Power Control
ACIPC	Augmented Constant Improvement Power Control
DFSPC	Distributed Fixed Step Power Control
MS	Mobile Station
BS	Base Station

List of Symbols

α	Path loss exponent
γ	CIR
γ_i	CIR at i^{th} mobile
p_i	Power at i^{th} mobile
λ^*	Largest Eigen value
P^*	Optimal power vector
γ^*	Optimal CIR
G	Gain matrix
A	Normalized gain matrix
g_{ij}	Link gain between i^{th} mobile and j^{th} base station
d_{ij}	Distance between i^{th} mobile and j^{th} base station
A_{ij}	Normalized gain between i^{th} mobile and j^{th} base station
s_{ij}	Shadowing between i^{th} mobile and j^{th} base station
C	Normalization constant
P_i^n	Power of i^{th} mobile at n^{th} iteration
P_i^{n+1}	Power of i^{th} mobile at $(n+1)^{th}$ iteration
P^0	Initial power vector
γ^T	Target CIR
γ_i^n	CIR of i^{th} mobile at n^{th} iteration
γ_i^{n+1}	CIR of i^{th} mobile at $(n+1)^{th}$ iteration
δ	Power control step size
α, β	Power balancing parameters
ε_1, ε_2	Instability detection parameters

E_b/N_o	Bit energy to noise ratio
D	Frequency reuse distance
R	Radius of the cell
N	No. of cells per cluster
t	No. of iterations

1 Introduction

Constraints on the available radio spectrum, owing to a continuous evolution and innovations in the field of Telecommunications affect adversely the development of Mobile Communications. The introduction of high data rate multimedia mobile services in the next generation Mobile Communication Systems such as MMS, video calls, TV on phone, Internet etc, require a huge amount of bandwidth. There is an ever-growing demand on the limited radio resources with the burgeoning number of mobile phone users. Consequently, an efficient use of radio resources has become an imperative global challenge.

Among different Radio Resource Management (RRM) techniques, power control, also known as TPC (Transmit Power Control), is one of the important ‘interference suppression’ techniques. The system capacity and performance are adversely affected and degraded by interference. Hence, power control plays a prominent role in an interference-limited system, which increases the efficiency by mitigating the adjacent and co-channel interference in the system.

There are several power control techniques and algorithms using the link quality measurements in both forward and reverse channels to adjust the power levels. There are also centralized and distributed power control algorithms. But the limited scope of this thesis is to consider only some of the important distributed power control algorithms for evaluation.

1.1 Objective

The primary objective of this thesis is to investigate the performance of some of the distributed power control algorithms in a multi-user cellular environment, which is almost close to the real time scenario. The multi-user cellular environment is created in MATLAB and the main parameter ‘G’ the gain matrix, which is random in nature, is obtained and utilized in all the algorithms by simulations. In total, six algorithms are considered for simulation and evaluation. In all these algorithms the Power and CIR variations are investigated.

Since convergence speed and outage are two important performance measures, the first four algorithms are compared on their speed of convergence which is the number of iterations the algorithm takes to obtain a steady state level and the remaining two on their outage, which is the ratio of number of users having a CIR less than the target CIR to the total number of users.

1.2 Motivation

Power control in cellular communications is a challenging task since the system is complex and mobiles randomly move all the time. Thus the channel is time varying and the various channel parameters affect the system performance considerably.

Power control is proved to be a potential technique for resource allocation, which balances the power levels of all the transmitters and receivers in the system. It also shows promising results in the capacity enhancements meeting the QoS requirements irrespective of the multiple access techniques.

In addition to this, power control also has an important role in reducing the battery power consumption, which is an essential factor for the next generation mobile phones. The previous research in power control [2-12] was on different power control algorithms proposed for various generations and situations. But there are quite few works done in [10-12] on the comparison of these algorithms, which could bring some useful conclusions and contributions in the Cellular Communications.

In this context, this thesis deals with the performance comparison of different power control algorithms to gain a better understanding of the different approaches in the field of Cellular Radio Mobile Communications.

1.3 Problem Statement

The basic power control problem can be termed as the ‘Near-Far effect’. In a general power control environment where all the mobiles in a system transmit with equal power levels, the power of the mobile closest to the base station dominates that of the mobile relatively further from the base station. This phenomenon is called ‘Near-Far effect’ and fig. 1 depicts the same explicitly.

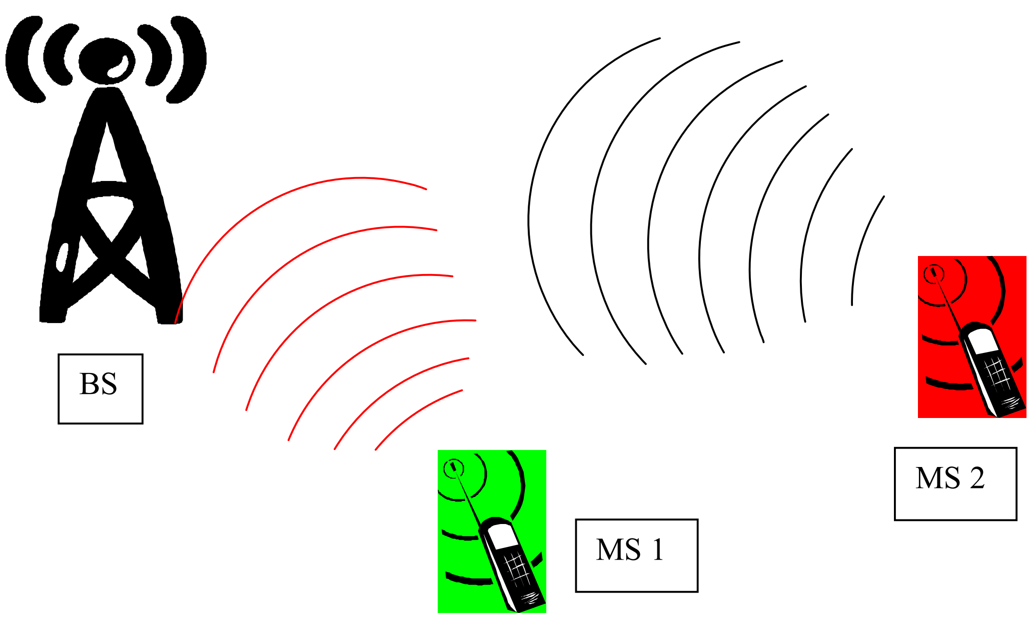

Figure. 1 The Near-Far Effect Scenario

To accommodate greater number of users, the available radio spectrum is divided among the users with some multiple access techniques and the same spectrum can be reused with different criteria. But, if the power levels of a user are not controlled, it may result in some interference to both co-channel and adjacent channel users.

Apart from this, in the event of a random movement of the mobile user, the mobile tries to be connected to the nearest base station all the time, maintaining certain minimum signal. So, every time the mobile moves from place to place, its received power levels at the base station also vary. If the user is at the edge of the cell, the mobile tries to increase its power. This results in using up of the battery of the mobile quickly. Hence, power control has become extremely important not only for suppressing the interference and increasing the capacity of the system but also for enhancing the battery life.

1.4 Scope of the Thesis

As per the requirements and scope of the thesis, only basic power control algorithms are considered. The performance evaluation of these algorithms could be done on various parameters like Rate of Convergence, Bit Error Rate (BER), Frame Error Rate (FER) and Outage etc. But here only Rate of Convergence and Outage are compared since these two parameters judge any algorithm on its responsiveness and system availability. For simplicity no combined power control algorithms are dealt with here in this thesis. Since the cellular setup and simulation parameters considered, closely correspond to the real time situations, the results also are comparable to the real time measurements. The thesis work also can effectively be extended further to a comparison of the combined power control algorithms.

1.5 Outline

The thesis is organized into 6 chapters. The first of these gives a brief introduction to the scope and outline of the project. Chapter 2 deals with the background and related work along with some brief description of radio channel characteristics and power control. In chapter 3 all the details of the system model, propagation and path loss, which have been considered for the simulation and some of the performance parameters and their measures, are discussed. Chapter 4 illustrates six of the basic power control algorithms and their simulations in detail. In chapter 5 comparisons of algorithms are presented and discussed. Chapter 6 deals with the conclusions and future work.

2 Back ground and Related Work

2.1 Background

The basic problem in mobile communications is the efficient use of the radio spectrum. In overcoming, this problem, the mobile communications have evolved significantly from 1st generation (1G) to 3rd generation (3G) and now are heading towards the 4th generation (4G). The early cellular telephony system was based on the Frequency Division Multiple Access (FDMA), where the entire spectrum is divided among users and there are separate channels for uplink and downlink communications.

The First Generation cellular systems in the early 1980s basically catered to the requirements of voice communications only. The introduction of data communications and the development in digital communications by the end of 1980's, have led to the deployment of the 2nd generation systems which catered for both voice and data communications. The 2nd generation cellular systems are based on Time Division Multiple Access (TDMA) and also Code Division Multiple Access (CDMA). In TDMA, the user has the entire bandwidth for the allotted time-slot. This increased the system capacity tremendously. But with the greater demands on bandwidth and quality, the evolved 2.5-generation systems are based on higher level modulation techniques like 8PSK (Phase Shift Keying). In CDMA, all the users can avail the entire bandwidth for the entire time by using different spreading codes, which could further cater to the ever-increasing demands on bandwidth and quality.

In 3rd generation systems Wideband Code Division Multiple Access (WCDMA) has become the standard as it enhances the capacity much greater than FDMA and

TDMA. For all these systems, the cellular concept by V.H MacDonald [1] gives a detailed picture of the formation of the cellular system layout, which forms the basis for any cellular communications research or simulation. Along with the evolution of cellular systems, the usage and services of the same certainly raise the issues like interference and battery power consumption. The interference is caused mainly when all the users share a common channel for communications or if there is no proper frequency separation between users. The battery power consumption inevitably increases if power control is not employed.

Mainly, the interference in the uplink case is more serious than the downlink because the signals from different mobiles at various distances moving at different speeds experience different fades before reaching the base station. The interference in the downlink case is less compared to the uplink case because the signals coming from the base station experience similar fades before reaching the mobiles and moreover the base station transmitter is capable enough to transmit at stronger power levels. Since the channel fades are highly random and take place very quickly, the power control update should be faster than the fading rate. Otherwise, the power cannot be controlled. So, all these depend on the effectiveness and responsiveness of the power control algorithms.

2.2 Related Work

Research on power control and RRM was in progress ever since the advent of multiple access techniques. A huge number of papers [1-12] on power control have been presented at various conferences and journals advocating new algorithms since the early 1960's. Initially, these algorithms were proposed for satellite communication systems and later were applied to the cellular systems.

Many algorithms with different configurations were proposed for Global System for Mobile Communications (GSM), CDMA and WCDMA systems.

In the field of power control in cellular systems, initially, centralized algorithms based on balancing of the received power levels were proposed [5]. Since the centralized algorithms were not practically realizable, distributed algorithms, also aiming at balancing the power levels, have been substituted [6-8]. To match the demanding QoS requirements, many more algorithms were proposed [9-11] with different criteria like cell removal, call blocking etc., with multiple and fixed step power control.

All these algorithms [4-12] were proposed based on the Signal to Interference Ratio (SIR), Power step size, BER, FER etc., with different cellular setups. But there are few works like [9-12] which could bring out the essence of all the power control algorithms based on their performance. In [9-11] the algorithms are based on their speed of convergence and outage probability. Reference [12] compared quite a number of algorithms based on the speed of convergence but with a generalized gain matrix, solely for the purpose of comparing the algorithms.

In this thesis an attempt is made to generate a gain matrix, which is based on a randomly varying simulated radio channel. The gain matrix generated with this new code is more practical in nature as it attempts to create a practical cellular radio communication system. Hence, the results obtained would probably be more practical and can give a real picture on the performance of some of the algorithms.

2.3 Radio Channel

Radio communication channel is the propagation medium for electromagnetic waves between the transmitter and receiver. Designing a perfect radio channel in mobile communications would be practically an impossible task since the channel is stochastic in nature as the mobile terminals keep moving almost all the time with different speeds and the channel fades are unpredictable.

The signals in a radio channel undergo different propagation effects like reflection, refraction, scattering and shadowing. A smooth surface reflects the signals. But, when the signals encounter sharp edges of buildings, they are refracted, while a rough surface scatters them. When these signals are obstructed by big buildings, they pass through them causing the shadowing effect. All these effects cause the channel to be lognormal, rayleigh and rician distributed. Fig. 2 shows how the signals travel in different paths from transmitter to receiver.

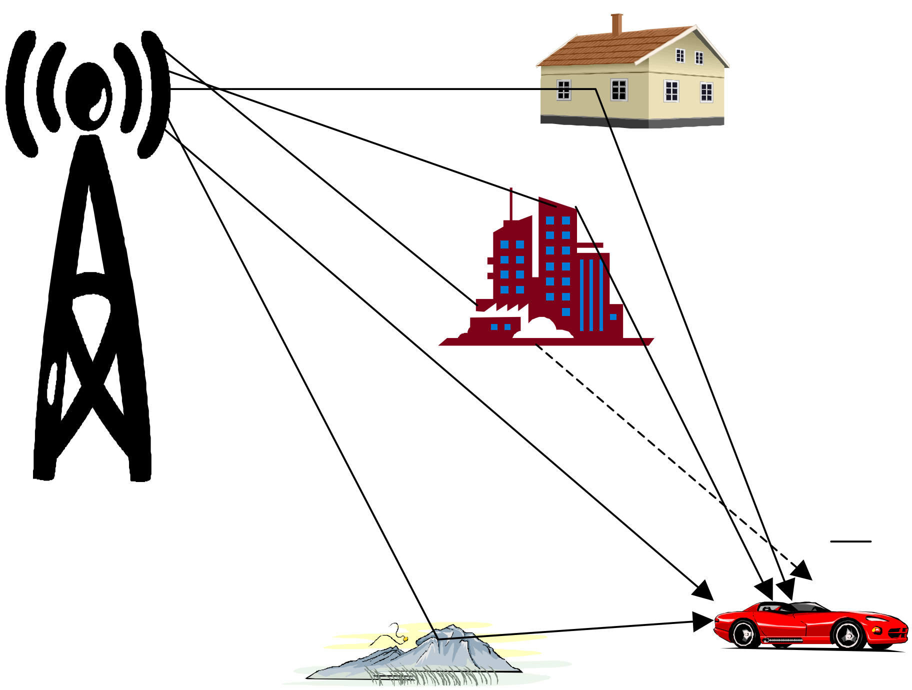

Figure 2. Multi-path Propagation

So, the receiver receives multiple copies of the same signal with variation in time and phase. These signals are either added constructively or destructively depending on the phase of the signals. The signals in the radio channel also undergo a path loss which depends on the distance between the transmitter and the receiver. Usually the path loss of a channel is given by an exponent ‘α’, which ranges from 2 to 5.

The channel is also unpredictable due to fading of radio signals. Basically fading is the attenuation of the signal during its propagation in the medium. The fading of signals is categorized as fast or multi-path fading and slow or shadow fading. The fast fading of signals is due to the rapid change of the signal amplitude and phase due to the multi-path arrival of the signal. Similarly, the slow fading of the signals is due to the shadowing effects caused by the buildings, mountains, hoardings etc.

These fading channels are modeled by a log normally distributed random variable. In fact these fading problems can be used in a constructive way to boost the signal strength. For instance, multi-path fading is best utilized using Multi Input Multi Output (MIMO) antennas.

2.4 Power Control

The primary purpose of power control is to maintain the acceptable Carrier to Interference Ratio (CIR) by meeting some QoS requirements. So, it is obvious that all the transmitters should transmit with different power levels since every transmitter (Mobile station in our case) is at a different distance and the signals experience different fades before reaching the receiver. The determination of different transmitting power levels becomes an important issue here. There are some techniques involved in determining the power levels. They are:

Inner Loop Power Control

Outer Loop Power Control

Inner Loop Power Control is further classified into:

Open Loop Power Control

Closed Loop Power Control

Open Loop Power Control is generally used in combating the Near-Far and shadowing problems. As the name itself indicates, this power control does not have feedback mechanism as the mobile itself dynamically adjusts its transmitting power. The mobile tries to estimate the signal strength on the forward pilot channel (Base to Mobile) and decides its transmitting power. If the mobile senses a large power then, the mobiles assumes that the base station is near and reduces its power level and vice versa. Fig. 3 depicts the mechanism clearly.

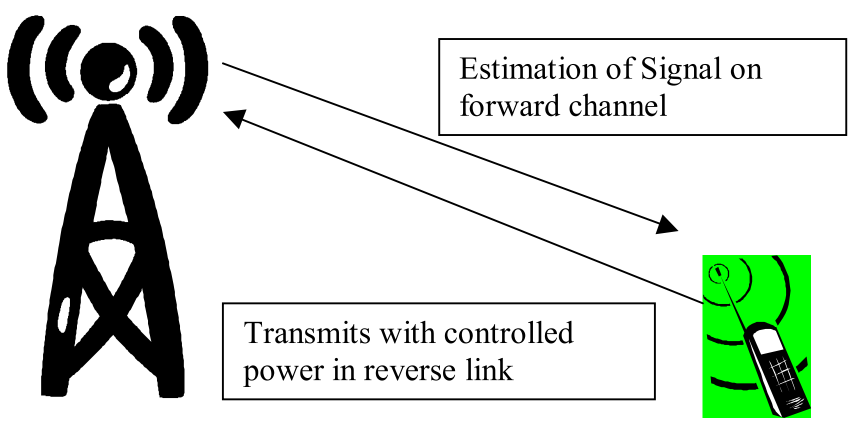

Figure 3. Open Loop Power Control

Closed Loop Power Control is used in combating the fast fading effects, generally caused by multi-path fading. This mechanism is also termed as ‘fast power control’ as it deals with the fast fading. Since the forward and reverse links are considered to be highly uncorrelated, the feedback mechanism is employed in this power control. The base station estimates the signal from the mobile in the reverse channel (Mobile to Base) and compares that signal-estimate with a predetermined signal level and sends the appropriate power control command to the mobile station as illustrated in fig. 4.

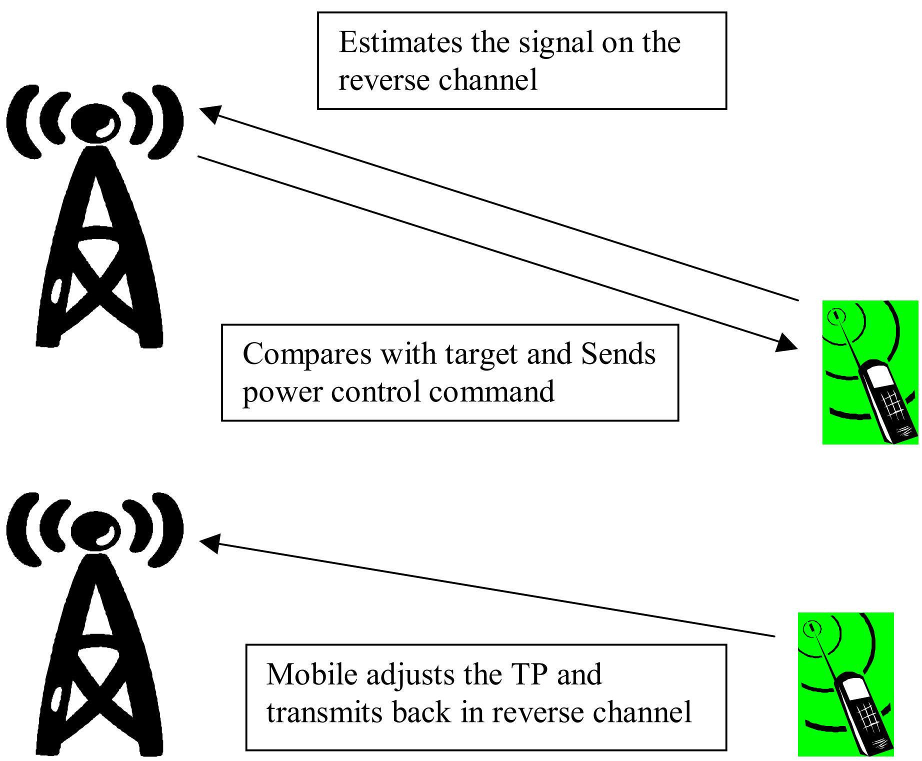

Figure 4. Closed Loop Power Control

Outer Loop Power Control is used to maintain different CIR levels depending on the QoS requirement. The signal from the mobile in the reverse link is measured and its frame error rate (FER), is calculated. This FER is compared with the predetermined FER depending on the QoS. If the measured FER is not equal to the predetermined FER, the outer loop power control adjusts its energy per bit to noise power spectral density (E_b/N_o) value to meet the desired FER. In practice the combination of open and closed loop power control is used for better performance.

Based on the type of the controller, power control is further divided into

- Centralized Power Control
- De-Centralized or Distributed Power Control

Centralized Power Control is a mechanism with a central controller having the information of all the link gains of the system. These link gains are utilized to find the optimal solution to control the power in all the links simultaneously. This type of power control is practically unrealizable, since the equipment is complex and the bandwidth is wasted due to the extreme signaling between base stations.

De-Centralized or Distributed power control is based on the local link gain measurements. Each base station measures its local parameters like link gain and CIR to control the power in that link. This type of power control is practically realizable since it does not involve complex signaling and is easier to implement.

Some of the advantages of power control can be briefly summarized as:

- Suppression of Near-Far problem
- Reduction of adjacent and co channel interference
- Improvement of QoS
- Enhancement of system capacity
- Enhancement of battery life

3 System Model

In this chapter, the simulation and channel models are discussed in detail and all the assumptions made for the simulations are clearly described. Then, the propagation model followed by the performance measure and system parameters is illustrated.

3.1 System Model

The basis for the cellular system concept is introduced in [1], by V.H. MacDonald. The simulation setup considered here is based on [1]. A cellular system model is developed here, where frequency reuse is implemented. The simulation was done in MATLAB. A cellular system model of 19 co-channel cells, which are spaced with a reuse distance D, has been considered on the assumption that each cell is a hexagon. The reuse distance is obtained from the formula

$$D = R\sqrt{3N} \qquad (1)$$

Where R is the radius of the cell taken as R=1Km. The frequency reuse factor is considered as N = 7 i.e., 7 cells per cluster. It is assumed that the base stations are at the center of the cells and use omni directional antennas. It is also assumed that the system is fully loaded with all the co-channel cells in use. For simplicity it is assumed that the adjacent channel interference and the noise in the system are negligible and are not considered in the simulations. All the assumptions considered for downlink case can also be applied for uplink case.

3.2 Hexagonal and Square Grid Setups

In this thesis simulation of a model close to the real time model is attempted. Usually there are two types of cellular system setups, the Hexagonal setup and the Square Grid setup, considered for simulations. Though they do not differ much technically, there is a difference in the consideration of the position of the cells. For the purpose of this thesis, Hexagonal setup alone is considered.

Hexagonal setup is the most commonly used one. In Hexagonal cellular setup, the co-channel cells are placed around a center reference cell as displayed in fig. 5.

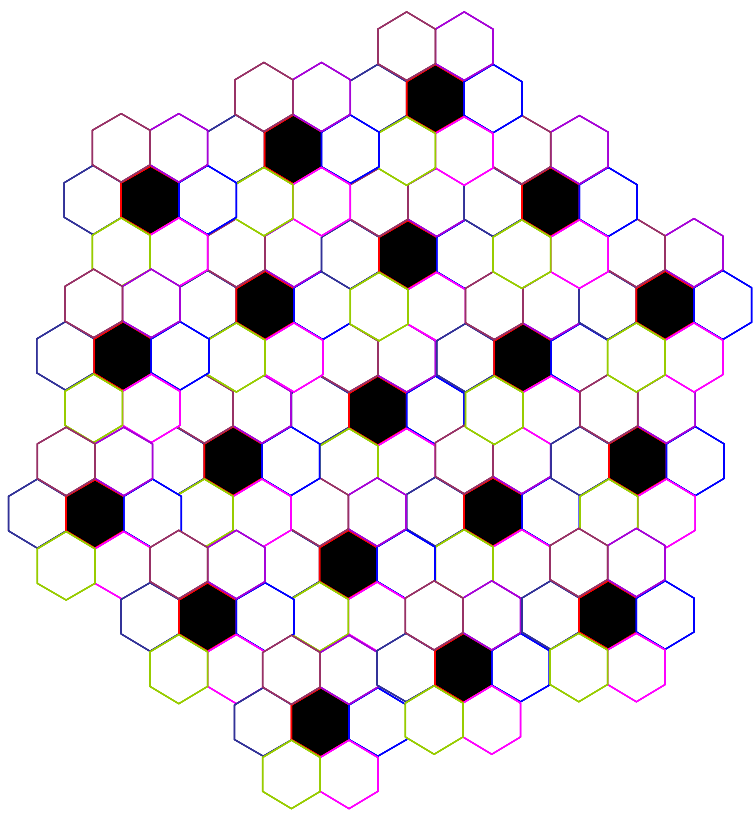

Figure 5. Hexagonal Cellular Setup

The square grid setup is cleared based on the work in [10]. Fig. 6 shows the Square grid arrangement of the cells.

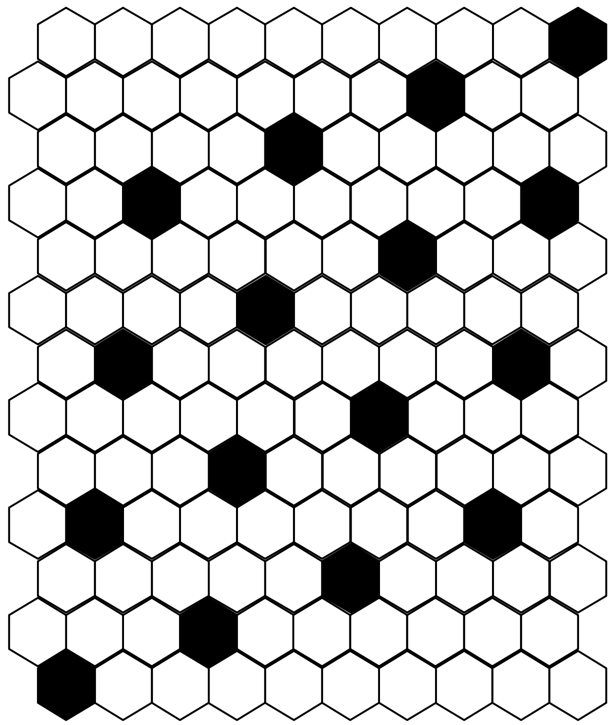

Figure 6. Square Grid Cellular Setup

3.3 Propagation and Path Loss Model

The channel is assumed to be noise free and interference limited. For instance, consider a mobile 'i' under a base station 'i' and mobile 'j' under a base station 'j'. The distance between j^{th} base station and i^{th} mobile is considered as d_{ij}. The channel link gain between j^{th} base station and i^{th} mobile station is given by g_{ij}, and is calculated from the formula

$$g_{ij} = s_{ij} / d_{ij}^{\alpha} \qquad (2)$$

Where s_{ij} the shadowing effect on the power level and 'α' is the path loss exponent which is an important simulation parameter varying from 2 to 5. In these simulations the value of 'α' is taken as 4 and the shadowing effect s_{ij} is a log normally distributed random variable with 0 dB mean and a variance of 6 dB. All the link gains of the system are calculated and together considered as a Gain Matrix. The code written in MATLAB calculates the G-Matrix for the system and is utilized for simulating different power control algorithms.

3.4 Performance Parameters and Measure

Rate of Convergence and Outage are important performance parameters. Rate of convergence measure gives us the responsiveness of an algorithm. It gives us the speed with which an algorithm can converge to the desired power level. Outage gives the ratio of number of mobiles having power levels lower than the required power level to the total number of mobiles in the system using same channel. It also gives the system availability for particular Quality of Service.

The performance of the system can also be tested under different load conditions. The load of the system could be changed by just increasing the number of users. But in these simulations the load is fixed at the time of power control. Another important system parameter that can be changed is the gain matrix. The distance of each user under each cell is random. So, the gain matrix changes in every run and the simulations can be effected for different gain matrices. The results obtained are the average results for 500 runs. The performance parameters are also explained in detail in chapter 5.

4 Power Control Algorithms and Simulations

4.1 Introduction

In this chapter the centralized power control algorithm and some of the commonly used distributed power control algorithms are discussed in detail.

Prior to the consideration of the mathematics involved in the power control, some of the parameters and terminologies used may be looked into. When there are N number of base stations and M number of mobile stations in a system, then the powers transmitted by the mobiles will be p = $[p_1, p_2,.....p_M]$ and the respective CIRs at the mobiles will be γ = $[\gamma_1, \gamma_2,...\gamma_M]$, . Let γ^T be the target CIR. The link gain between the base station $'i'$ communicating with the mobile station $'j'$ is given by g_{ij} . G is the gain matrix, where all the link gains from each and every mobile station to each and every base station are present.

4.2 Centralized Power Control Algorithm

The name is very explicit that the power control is done using a central controller. The Centralized Power Control Algorithm (CPCA) uses the global information to update the powers and balancing the CIRs. This CPCA reduces to a mathematical problem from which one can compute an optimum power vector. According to the matrix theory, if a matrix A exists such that

$$AX = \lambda X \qquad (3)$$

Then the scalar λ is the eigen value and X is its corresponding eigen vector.

In CPCA scheme the eigen vector corresponding to the largest eigen value is the optimal power vector. This optimal power vector is used by all the mobiles in the system to achieve the CIR balancing. The CIR balancing in CPCA is done in a single step. CPCA is dealt with extensively in [5]. The simple mathematical illustration is shown below.

In considering a down link case, as has been done throughout the thesis, and with the gain of the communication link between i^{th} base station and j^{th} mobile as explained above, the CIR at the mobile $'i'$ is given by

$$\gamma_i = \frac{p_i g_{ii}}{\sum_{\substack{i=1 \\ i \neq j}}^{M} p_j g_{ij}} \qquad (4)$$

After normalization, the equation can be written as

$$\gamma_i = \frac{P_i}{\sum_{j=1}^{N} A_{ij} P_j} \qquad (5)$$

Where $$A_{ij} = \begin{cases} \frac{G_{ij}}{G_{ii}} \cdots\cdots i \neq j \\ 0 \cdots\cdots\cdots i = j \end{cases}$$

The Centralized scheme always reduces to an eigen value problem as shown below.

According to the Perron-Frobenius, if A is an $M \times M$, normalized gain matrix, which is irreducible and non- negative with eigen values $\{\lambda_i\}_{i=1}^{M}$ then,

> One of its eigen value is positive and greater than or equal to all other eigen values

$$\text{i.e., } \lambda^* = \max\{|\lambda_i|\}_{i=1}^{M} \qquad (6)$$

There is a positive eigen vector P^* corresponding to the largest eigen value λ^*, which satisfies the equation

$$\lambda^* P^* = AP^* \qquad (7)$$

Where

$$\lambda^* = \frac{1}{\gamma^*} \qquad (8)$$

Therefore all the mobiles in the system would use the corresponding elements of the P^* as their transmitting powers to achieve γ^* for all the mobiles in the system.

4.3 Distributed Power Control Algorithms

Unlike the CPCA, distributed power control algorithms use only the local information for the power updating and CIR balancing. There are different types of DPC algorithms suited for fulfilling different QoS requirements. These algorithms are iterative and generally each algorithm converges to the desired value after certain number of iterations. The iterations taken to converge to the desired value depends on the responsiveness of the algorithm. The system for which algorithms are considered may be CDMA, FDMA or TDMA system. Some of the DPC algorithms considered are given below.

1. Distributed Power Control Algorithm (DPC) [7]
2. Fully Distributed Power Control (FDPC) [8]
3. Improved Fully Distributed Power Control (Improved FDPC) [9]
4. Balanced Distributed Power Control (BDPC) [9]
5. Fixed Step Distributed Power Control (FSDPC) [10]

6. Augmented Constant Improvement Power Control (ACIPC) [11]

In the succeeding sections each of the above algorithms is explained in detail and all the necessary properties and parameters are discussed.

4.4 Distributed Power Control Algorithm

DPCA is one of the initial works done in the DPC scheme for the satellite communication systems and later on applied to cellular systems. The Power updating formula according to [7] is given below.

$$P^{(n+1)} = C^{(n)} A P^{(n)}, \quad n>0 \tag{9}$$

Here the present power is calculated using the previous power levels. In the above formula A is the normalized gain matrix and 'C' is a positive normalization constant and is generally chosen as

$$C = \frac{1}{\max\left\{P_i^{(n)}\right\}}, \quad i = \text{No. of mobiles} \tag{10}$$

The convergence speed of the algorithm depends on the value C. The algorithm converges to the optimal CIR, but the main disadvantage of this DPCA is its requirement of some global information for finding the normalization constant. Hence, it is not a fully distributed algorithm. In the simulation, the initial power is taken as 2 mW and the convergence is obtained to γ^* in less than 15 iterations. The results of the CIR convergence are shown clearly in fig. 7.

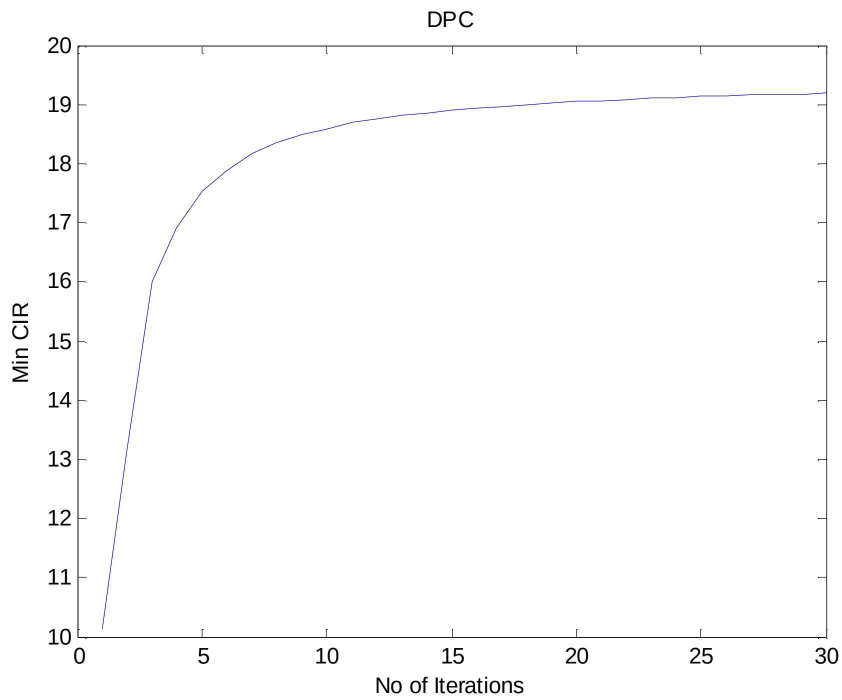

Figure 7. CIR convergence of DPCA

The pseudo code for the algorithm goes with calculating the gain matrix as given below:

1. *Initialize the No. of base stations, cluster size, and radius R.*
2. *Calculate the frequency reuse distance using D = R*sqrt(3*N)*
3. *Fix the position of the base stations.*
4. *First generate the relative positions of the mobiles in a reference cell and then fix the absolute positions of the mobiles in the respective cells.*
5. *Calculate the distance between the mobiles and base stations.*
6. *Calculate the link gain matrix using*

   gain =shadowing (mobile to base station distance)*$^{-\alpha}$
7. *Calculate the maximum eigen value of the above gain matrix (MxM) which is the optimum CIR.*

[The above calculated gain matrix is used by all the algorithms for the CIR calculations]

8. *Initialize the power for all the mobiles.*
9. *for 1 to No. of iterations*

for 1 to No. of mobiles

calculate and store the CIR

end

update the power using

$$P^{(n+1)} = C^{(n)} A P^{(n)}$$

calculate the normalization constant using

$$C = \frac{1}{\max\left\{P_i^{(n)}\right\}}$$

find the minimum CIR in each iteration

end

4.5 Fully Distributed Power Control Algorithm

FDPCA is one of the best-distributed power control algorithms, which achieves very good performance in cellular systems. As the name itself is self-explanatory, it is fully distributed because the algorithm uses only the local link information and does not depend on the global information for controlling the power.

Many interesting properties of this algorithm are discussed in [8] with their proofs. Here just a brief explanation of the power-updating step is given.

$$P_i^{n+1} = K_i^n \times P_i^n \quad (11)$$

Where $$K_i^n = \frac{\min\left(\gamma_i^n, \gamma^T\right)}{\gamma_i^n} \quad (12)$$

γ_i^n = The CIR of the i^{th} mobile in the n^{th} iteration.

γ^T = The target CIR.

Here the new power level is calculated by the product of the previous power level and the ratio of CIRs.

The algorithm has very good convergence properties and has shown good CIR convergence in the simulations. The CIR converges to the optimal CIR which is also the target in our simulations. The main drawback with this algorithm is as n tends to infinity the power p tends to 0; that is the power levels of all the mobiles tend to zero, which is highly undesired for any power control algorithm. The CIR and also the powers for all iterations were plotted and are shown in fig. 8 and fig. 9 respectively. The algorithm converges to the optimum CIR in approximately 30 iterations.

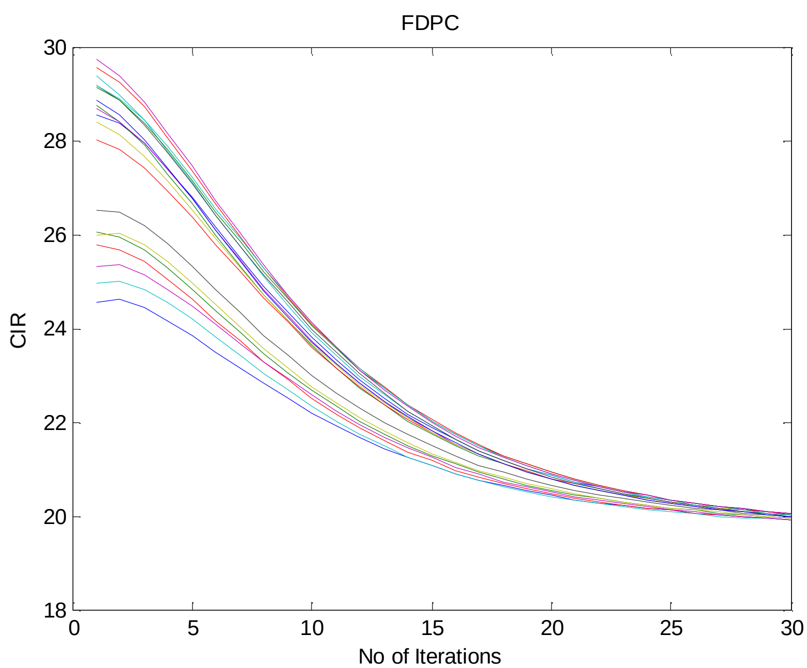

Figure 8. CIR convergence of FDPCA

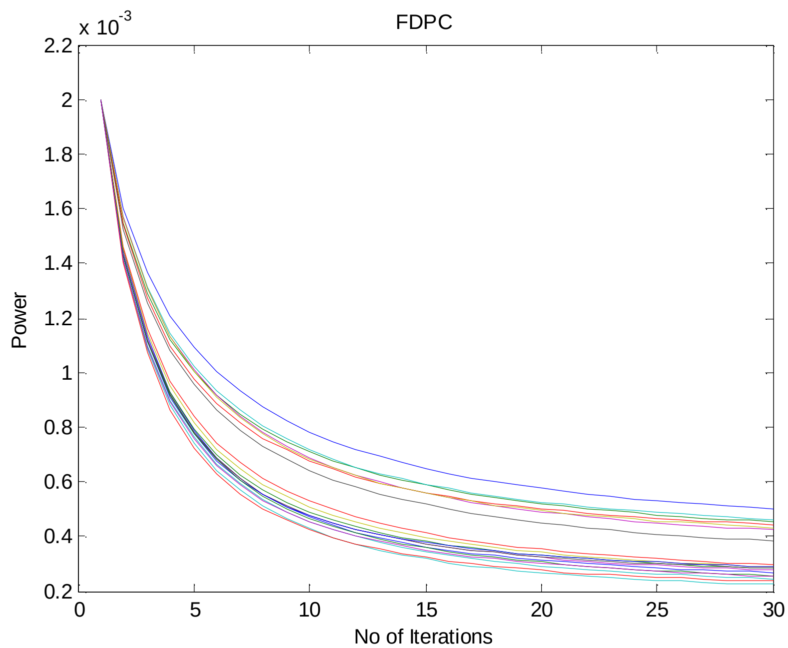

Figure 9. Powers in FDPCA

The pseudo code for the algorithm is as follows

1. *Initialize power values for all the mobiles.*
2. *for 1 to No. of iterations*

   for 1 to No. of mobiles

   calculate the CIR and update the power of all the mobiles using

$$P_i^{n+1} = K_i^n \times P_i^n$$

   End

   End

3. Plot CIR in each iteration against the iterations.

4.6 Improved Fully Distributed Power Control Algorithm

Improved Fully Distributed Power Control Algorithm is an improved version of the previous FDPC algorithm proposed in [9]. The previous algorithm considers the minimum value of the CIRs. The present algorithm differs from it in its consideration of the maximum value of the same.

All the properties of FDPC are also satisfied by Improved FDPC. The power updating is done according to the following equations:

$$P_i^{n+1} = K_i^n \times P_i^n \qquad (13)$$

Where

$$K_i^n = \frac{\max\left(\gamma_i^n, \gamma^T\right)}{\gamma_i^n} \qquad (14)$$

This algorithm also has good convergence properties. But its drawback is that as n tends to infinity, then P tends to infinity that is the power levels tend to increase to infinity, which is undesirable. The convergence and power levels are presented in fig. 10 and fig. 11. The pseudo code for the algorithm is the same as the previous algorithm with a slight modification. The CIR convergence is slower when compared to the FDPC and the power can be seen tending to infinity.

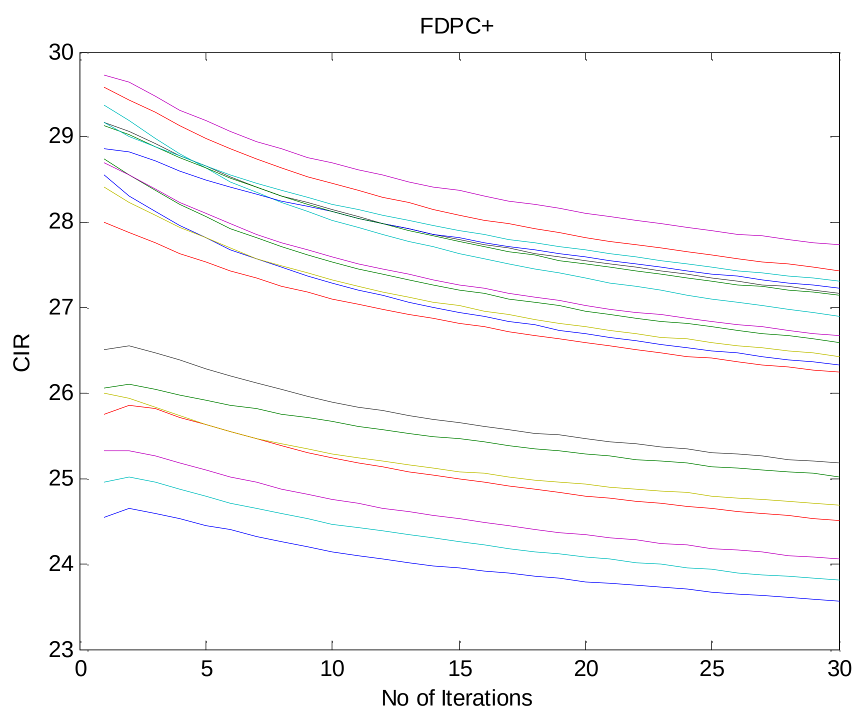

Figure 10. CIR convergence in Improved FDPCA

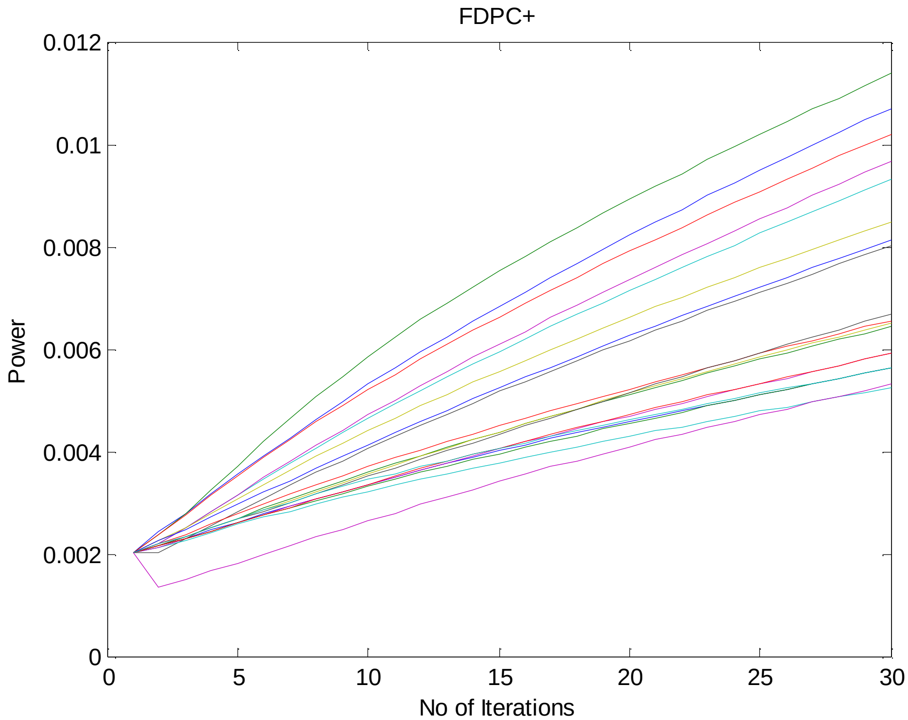

Figure 11. Powers in Improved FDPCA

4.7 Balanced Distributed Power Control Algorithm

BDPC is proposed by Wang et al. [9] for CDMA systems. The powers are balanced in this algorithm since it takes the advantage of the both FDPC and FDPC+. So, the power neither goes to infinity nor goes to zero. The power-updating step is given as follows:

$$P_i^{n+1} = K_i^n \times P_i^n \tag{15}$$

where

$$K_i^n = \begin{cases} \dfrac{\min\left(\gamma_i^n, \gamma^T\right)}{\gamma_i^n} \cdots\cdots\cdots\cdots\cdots\cdots P_i^n \geq P^U \\ K_i^{n-1} \cdots\cdots\cdots\cdots\cdots\cdots P^L < P_i^n < P^U \\ \dfrac{\max\left(\gamma_i^n, \gamma^T\right)}{\gamma_i^n} \cdots\cdots\cdots\cdots\cdots P_i^n \leq P^L \end{cases} \tag{16}$$

The algorithm sets upper and lower bounds for the power level to balance the power. If the power in any iteration is greater than the upper bound, then FDPC is implemented and if the power in any iteration is less than the lower bound, then Improved FDPC is implemented.

This algorithm also satisfies all the properties of the FDPC and Improved FDPC and the proofs are given in [9]. The convergence of BDPC in fig. 12 depends on the careful selection of the upper and lower bound power levels. The only drawback of this BDPC is that the convergence is a bit slower than the DPC and FDPC algorithms. Since the gain matrix varies with every run and as the plots have been averaged for 500 runs, the plot shows nearly a real picture of convergence.

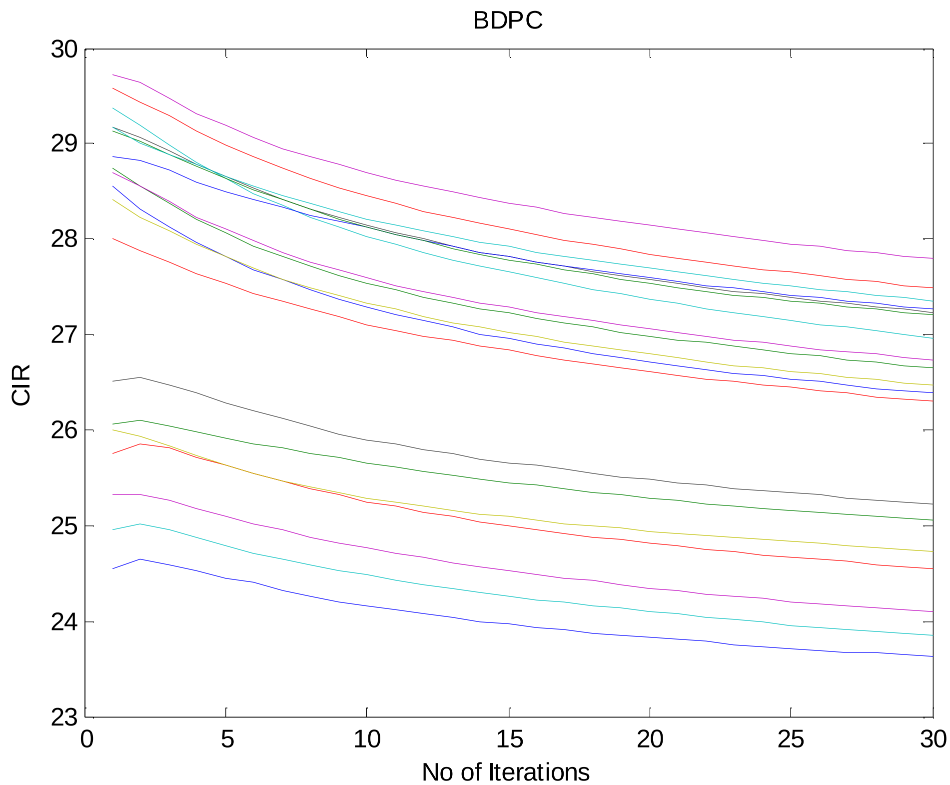

Figure 12. CIR convergence in BDPC

The pseudo code for the BDPC goes as follows:

1. *Initialize the power levels for all the mobiles.*
2. *for 1 to No. of mobiles*

   calculate initial CIR of all the mobiles

   end
3. *set the upper and lower bounds of power P^{ub} and P^{lb} respectively.*
4. *for 1 to No. of iterations*

   calculate the power using

$$P_i^{n+1} = K_i^n \times P_i^n$$

   if calculated power $\geq P^{ub}$

$$K_i^n = \frac{\min(\gamma_i^n, \gamma^T)}{\gamma_i^n}$$

   else if calculated power $\leq P^{lb}$

$$K_i^n = \frac{\max(\gamma_i^n, \gamma^T)}{\gamma_i^n}$$

   else

   no change

   end

   end
5. *Plot the CIR in every iteration against Iterations.*

4.8 Distributed Fixed Step Power Control Algorithm

Fixed step power control algorithm is a simple feedback adjustment algorithm proposed by Sung et al. [10]. This algorithm has many useful properties like built-in link quality protection, bandwidth efficiency etc. The algorithm uses quantized power levels and proof for the existence of the quantized power vector is given in [10]. The simple power-updating step is given as

$$P_i^{n+1} = \begin{cases} \delta P_i^n \cdots\cdots\cdots\cdots \gamma_i^n < \delta^{-1}\gamma^T \\ \delta^{-1} P_i^n \cdots\cdots\cdots\cdots \gamma_i^n > \delta\gamma^T \\ P_i^n \cdots\cdots\cdots\cdots Otherwise \end{cases} \qquad (17)$$

Where δ is the quantized step size and δ>1

γ^T is the target CIR.

The algorithm is based on the CIR measured and it sets a window for comparing the measured CIR. If the measured CIR is below the window then, a power up command is sent and if the measured CIR is above the window then, a power down command is sent; or else the CIR level remains the same. The algorithm is said to be bandwidth efficient since it uses only two bits for power controlling commands.

The algorithm maintains the link quality of the mobiles, which are already above certain target level. Generally the distributed algorithms in [6] and [7], tend to converge to the optimum CIR and if new mobiles are accepted into the cell then, the CIR of all the mobiles goes to a very low level and all the links become useless. But this does not happen in Distributed Fixed Step Power Control Algorithm (DFSPC) and it assumes that a new call is admitted with link having very low power. Then the mobile using this link tries to attain the target CIR for certain predetermined number of iterations and if the link does not gain the target level, the call is assumed to be dropped. The algorithm can be used to meet different QoS requirements. The only disadvantage of this algorithm is that the capacity of the system drastically decreases due to meeting the strict QoS requirements.

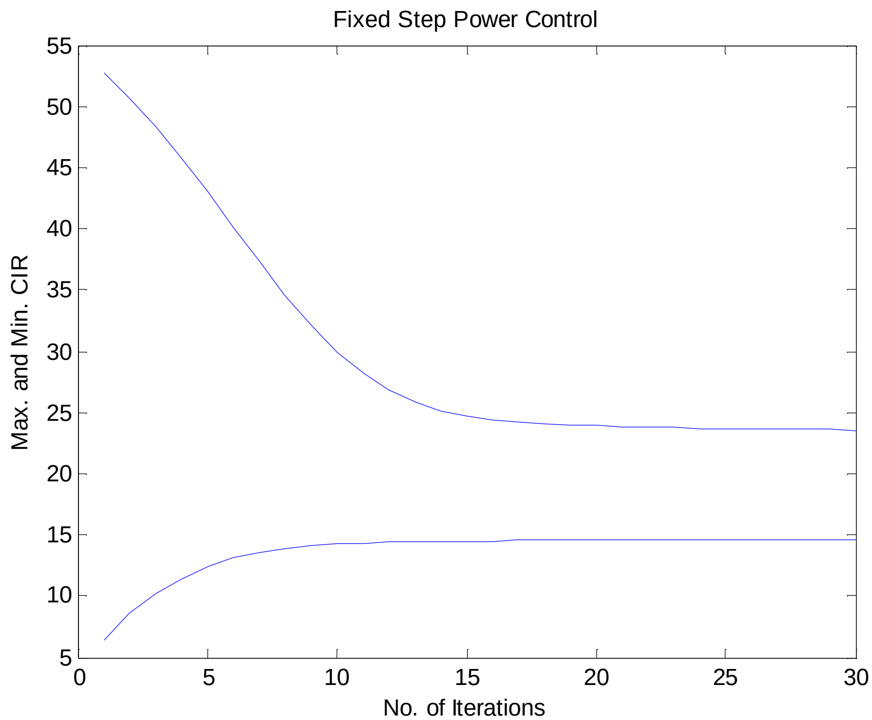

Figure 13. Link quality protection in DFSPCA

The maximum and minimum CIR in each iteration is plotted in fig. 13 and the link quality property is clearly visualized.

The pseudo code for the algorithm is as follows:

1. *Initialize the power for all the mobiles.*
2. *set the target CIR varying between any two levels.*
3. *set the step size* δ
4. *for 1 to No. of iterations*

    for 1 to No. of mobiles

        calculate the CIR

        if CIR > CIR +step size

$$P_i^{n+1} = \delta^{-1} P_i^n$$

        else if CIR < CIR-step size

$$P_i^n = \delta P_i^n$$

else $P_i^{n+1} = P_i^n$

end

end

end

5. Plot the max and min CIR in every iteration for different target CIRs.

4.9 Augmented Constant Improvement Power Control Algorithm

The ACIPC was proposed by Kim et al. [11], to increase the system performance in cellular mobile systems. The algorithm is complex in nature due to the cell removal procedure, which depends on the instability detection rule. The power-updating step for the algorithm is given by

$$P_i^{n+1} = \alpha P_i^n \left[1 + \beta \frac{\gamma^T}{\gamma_i^n} \right] \tag{18}$$

Where α and β are power balancing parameters.

Proposition: If a given target CIR is achievable and if power levels in each iteration are rescaled with $\alpha = \frac{1}{\beta} + 1$, then for any β >0 , the CIPC starting from any initial vector P^0 converges to an effective power vector P^* as t tends to infinity, with any gain matrix G.

The instability detection rule proposed for cell removal is given by

$$\left[\frac{\gamma_i^{n+1} - \gamma_i^n}{\gamma_i^T}\right] < \varepsilon_1 \qquad \text{and} \qquad \gamma_i^{n+1} < (1 - \varepsilon_2)\gamma^T \qquad (19)$$

The first condition checks for the convergence of the power levels. It compares the difference between the CIR in all consecutive iterations and the second condition checks whether the target CIR can be achieved. If these two conditions are true then, the algorithm invokes the cell removal procedure. The instability detection rule depends on the values ε_1 and ε_2, which are to be chosen carefully.

The algorithm is as follows:

1. *Initialize the power levels for all the mobiles and calculate the CIRs.*
2. *Compare the CIRs of all the mobiles with target CIR. If CIR of all the mobiles is greater than target CIR, then stop, otherwise go to step 3.*
3. *Go for power updating for some 'T' number of iterations. If at some iteration below the 'T' number of iterations, the instability rule is true, then go to step 4.*
4. *Remove the cell having the mobile with least CIR and then go to 1.*

The algorithm can be applied to meet different QoS requirements. The cell removal procedure can be avoided by increasing the number of iterations but the convergence becomes slower. The main drawback with this algorithm is that, it involves a cell removal procedure, which is undesirable in cellular mobile systems.

5 Comparisons

In this chapter DPC, FDPC, Improved FDPC and BDPC with respect to their speed of convergence and the Fixed Step algorithm and ACIPC basing on their outage performance are compared.

5.1 Speed of Convergence

As the radio channel is highly stochastic, the channel characteristics vary very quickly. So, the power update by any power control algorithm should be fast enough to converge and stabilize the system quickly. So, the speed of convergence is an important performance comparison parameter that gives the responsiveness of the power control algorithm.

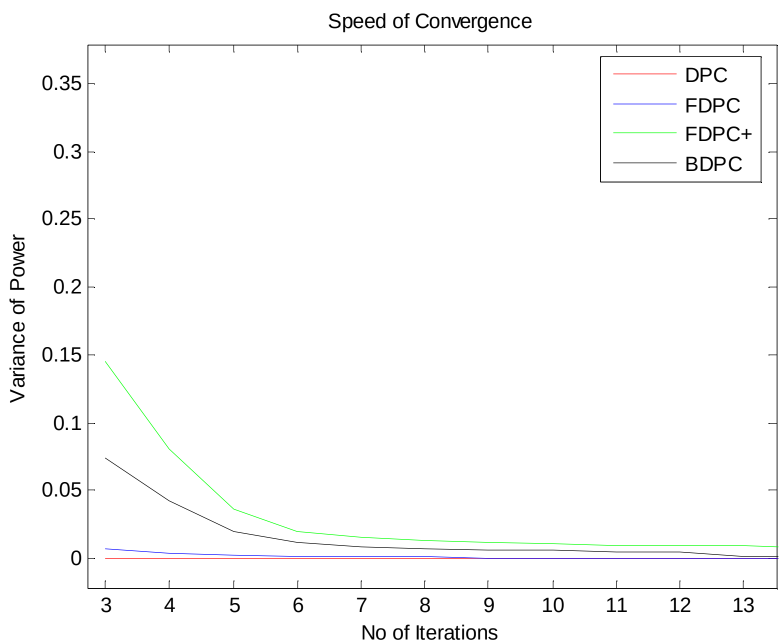

Figure 14. Convergence speed comparison of different power control algorithms

Fig. 14 depicts the variance of power levels in all consecutive iterations for the four algorithms. From the plot it is clear that DPC converges quicker than FDPC, BDPC and Improved FDPC. DPC almost converges instantly, but the lack of fully distributed quality makes it impractical for implementation.

Though the convergence of FDPC is slower than the DPC, the fully distributed property makes it effective than DPC. BDPC has a slow convergence but has a good power balancing property for consideration. The powers are balanced unlike FDPC and Improved FDPC which makes it more effective for practical implementation. Improved FDPC has the worst performance both in the convergence as well as power balancing, which makes it unsuitable for implementation.

5.2 Outage

System availability is also an important performance parameter that tells how efficient the system is. Fixed Step algorithms and ACIPC are compared on their outage performance since they can be implemented for satisfying different QoS requirements.

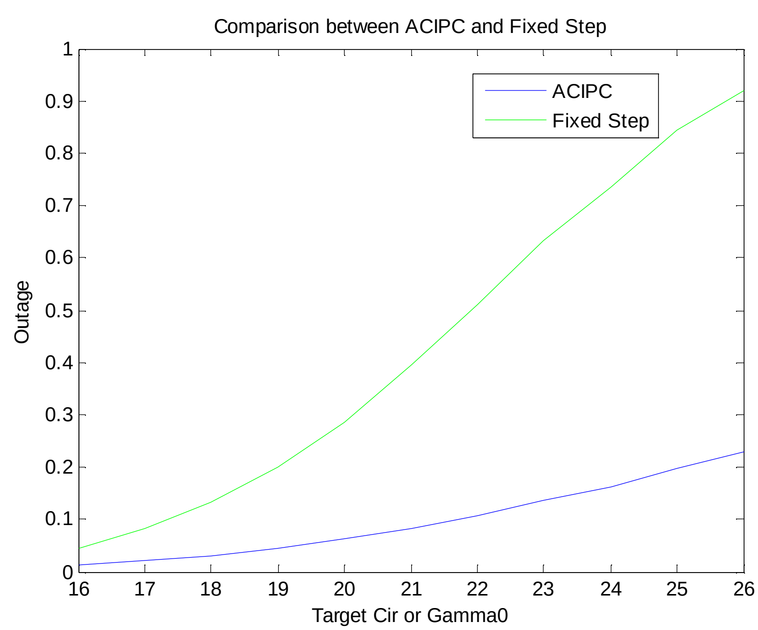

Figure 15. Outage comparison of ACIPC and DFSPCA

Fixed Step algorithm maintains the link quality depending on the target CIR and ACIPC involves in cell removal if the target CIR is not reached. The outage for these two algorithms in every iteration is plotted and shown in fig. 15.

From fig. 15, it is clear that Fixed Step has got worse outage performance compared to ACIPC. The link quality protection property of Fixed Step Algorithm makes it attractive for practical implementation and for satisfying QoS requirements than enhancing the capacity of the system. ACIPC has very good outage compared to Fixed Step, except that it involves in cell removal procedure. So, ACIPC can be a considerable choice for attaining better QoS requirements and capacity enhancements.

6 Conclusions and Future Work

6.1 Conclusions

In this thesis the concept of power control in cellular systems is extensively studied. The performance of different basic distributed power control algorithms is evaluated and compared on the basis of the simulations in MATLAB. Motivation for the thesis, problems in today's wireless communications, the advantages of RRM techniques mainly power control for enhancing the performance, background of power control, how and why power control is done, have been discussed in detail in the initial two chapters of the thesis.

The simulation work in the thesis is divided mainly into two parts. The first part is about the simulation of a Hexagonal cellular system model with 19 co-channel cells in MATLAB and how to find out the link gain matrix. The second part deals with the simulation of different distributed power control schemes for the downlink case and a comparison of their performance.

The theoretical study and simulation results presented in chapters 4 and 5 illustrate that each algorithm has different convergence speed and outage performance. From these results it can be concluded that the speed of convergence only partially evaluates the efficiency of an algorithm. Other factors like tremendous increase or decrease in the transmitting powers, call dropping probability and maintaining required QoS all the time, also need to be considered here.

Thus, it can be concluded, from the results obtained that each of these algorithms is at its best under certain operating conditions. In convergence DPC appears to excel the rest. BDPC stands its grounds in power balancing while ACIPC seems to surpass the others in QoS requirement. So, every algorithm has its own advantages and deficiencies.

6.2 Future Work

Several other issues have been encountered during the course of the thesis work, which can be studied further. The performance of different algorithms can also be compared on the basis of metrics like BER and FER. Further, the system model developed can be extended to accommodate more number of users randomly moving in and out of the cell area. Even when the users per cell continuously change, the model should be easily adaptable to the changes. Power control along with base station assignment and beam forming, generally termed as 'combined power control' is also an interesting area of research. Areas like performance comparison of these combined power control algorithms, power control in MIMO and adaptive antenna systems and power control in WCDMA can be further explored in the light of this thesis and the results can easily be extended also to them.

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