STUDY AND SIMULATION OF JOINT NETWORK-CENTRIC AND USER-CENTRIC POWER CONTROL GAME FOR WIRELESS DATA NETWORKS

A DISSERTATION

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requirements for the award of the degree
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(With Specialization in Communication Systems)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work, which is presented in this Dissertation report, entitled "**STUDY AND SIMULATION OF JOINT NETWORK-CENTRIC AND USER-CENTRIC POWER CONTROL GAME FOR WIRELESS DATA NETWORKS**", being submitted in partial fulfillment of the requirements for the award of the degree of MASTER OF TECHNOLOGY with specialization in COMMUNICATION SYSTEMS, in the Department of Electronics and Computer Engineering, Indian Institute of Technology, Roorkee is an authentic record of my own work carried out from June 2006 to June 2007, under guidance and supervision of **Mr.S.Chakravorty**, Assistant Professor, Department of Electronics and Computer Engineering, Indian Institute of Technology, Roorkee.

The results embodied in this dissertation have not submitted for the award of any other Degree or Diploma.

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CERTIFICATE

This is to certify that the statement made by the candidate is correct to the best of my Knowledge and belief.

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ABSTRACT

Power control is one of the most important aspects of radio resource management in CDMA systems. With the advent of multimedia services in wireless CDMA networks, power control has assumed greater significance. A good power control scheme ensures efficient use of radio resources, thereby increasing the capacity of the system, extending the battery life of mobile terminal and mitigating near far effect. The power control problem should be modeled such that various services meet their respective Quality of Service (QOS) requirements. QOS can be defined as achieving required target signal to interference plus noise ratio (SINR) or acceptable bit error rate in case of voice and maximizing the utility in case of data.

In this dissertation work, non co-operative game theoretic approach has been used to deal the power control problem for wireless CDMA data service. In the wireless CDMA network, all the users would like to have a high value of SINR, while transmitting at lower power. So, they have to satisfy conflicting objectives. Moreover, the output of each user depends on his decision as well as the decisions of other users. Therefore, power control problem can be modeled as a non cooperative game. In this game all users act selfishly to maximize their utilities with respect to power. We have considered joint network centric-user centric (NC-UC) power control game where users adjust their power to maximize their net utility and networks adjust their power to maximize the revenue. The net result is a tradeoff between the two seemingly conflicting user-centric and network-centric objectives, which implies that the solution lies between the two extreme solutions of pure network-centric and user-centric methods. Simulation studies are carried out for NC-UC scheme with throughput based utility function and gaussian channel capacity utility function for single cell and multi cell CDMA systems. In multi cell systems, two different types of pricing strategies have been considered and the performance under handoff is also evaluated.

In, NC-UC scheme for single cell using throughput based utility function, users with better channels obtain higher utility, transmit with lesser power but they pay proportionally more, compared to other users. For a multi cell system, we observe that network obtains its revenue mainly from few users with best channels at global pricing

and for mini-max pricing, network trades off revenue for a more even resource allocation. Considering the single cell situation using gaussian channel capacity utility function, we observe that all users obtain equal net utility, payment, SINR at equilibrium unit price. In multi cell system, we observe that network collects equal revenue from all users at global pricing and at mini-max pricing, equal revenue is obtained from few users with best channels and for other users revenue decreases with increasing distance from base station.

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INTRODUCTION

Radio resource management is one of the most challenging and important aspects of wireless communications. Radio resource management basically deals with the allocation of limited resources such as power, bandwidth, channels etc to satisfy the desires of users, service providers. An intelligent radio resource management system can significantly improve the capacity of the system. The capacity can be increased in many ways such as power control, frequency reuse etc. The capacity of the system is maximized if the transmitter's power is controlled so that the signal arrives at the base station with minimum signal to interference ratio. So power control is one of the most important aspects which can improve the capacity of the system by minimizing interference.

1.1 POWER CONTROL [1]

The primary objective of power control is to regulate the transmit power level of the mobile user so as to maintain certain quality of service for as many users as possible [1]. Because of Near Far Effect, the received power at Base Station receiver due to distant mobile may be low compared to near mobile users resulting in dropping of distant mobile call. Power control mitigates the near-far effect and extends the battery life of mobiles. Power control techniques must be designed in order to achieve certain QOS requirement regardless of the channel conditions by minimizing the interference and hence improving the overall system performance. Power control schemes must operate very fast to track the changes in the path gain factor which arise due to movement of mobiles. Another factor which affects the signal is multi path fading which is caused due to mobile movement and reflections from terrestrial objects. So power control must also track multi path fading.

1.2 CLASSIFICATION OF POWER CONTROL [1]

Power control can be classified as

(a) ***Open Loop and Closed Loop Power Control***: In open loop power control the transmitter attempts to estimate the path loss based on measurement of the received power [1]. It adjusts the transmitted power according to received forward link signal strength. Open loop is based on assumption that losses in forward and reverse link are same. But generally fading is independent on reverse and forward links and so power control needs further adjustment. This is accomplished by closed loop power control.

In closed loop power control, the mobile transmitted power is controlled by a signal from the base station. According to power level assigned by the system controller, each base station maintains the desired power level for each mobile that is active within that cell. To maintain independence of fading on forward and reverse link, the mobile will be controlled by power adjustment commands from the base station. So generally a combination of both open and closed loop is normally used.

(b) ***Centralized and Distributed Power Control:*** In a centralized system, there is a centralized controller that has all the information about established connections and channel gains and controls all the power levels in the network or that part of the network. Centralized power control is generally not used at it requires extensive control signaling. In distributed power control, each mobile station has its own controller and it controls the power of one single transmitter and the algorithm depends only on local information such as measured SINR and the channel gain of the specific user.

1.3 POWER CONTROL APPROACHES

Third generation and future wireless CDMA systems will have to support multimedia services such as voice, data, video and satisfy different QOS requirements. Voice traffic is tolerant to errors but intolerant to delay, while data traffic is tolerant to delay but intolerant to errors [2]. So power control approaches are different for voice and data. Most of the past approaches deals only with voice [3]-[7] but recently most of the attention has been focused on game theoretic approaches to Power control in CDMA data systems[2],[8], [9],[10], [11].

1.3.1 VOICE

Quality Of Service (QOS) for voice can be defined as minimum Signal-to-Interference-plus-Noise ratio (SINR), γ_k^* for a given mobile terminal *k*, and the QoS requirement may be expressed as [2]

$$\gamma_k \geq \gamma_k^* \quad \forall k \qquad \text{-------------} \quad (1.1)$$

The value γ_k^* is a threshold which ensures transmission quality for user *k* by providing an acceptable speech quality at receiver . In this case the target SIR is the same for all users in the system i.e $\gamma_k \geq \gamma_k^* \quad \forall k$ and depends on the desired quality of speech at the receiver. Algorithms for power control in wireless systems can be centralized or distributed. In distributed power control (DPC) algorithms only knowledge of a given terminal's link is needed in order to adjust its transmitted power independent of the other terminals. As a consequence DPC algorithms have lower complexity and require less computational power than Centralized Power Control (CPC) algorithms, and are preferred in practical implementations. Earlier Power control approaches for voice involved mainly the calculation of Eigenvalues and corresponding Eigenvector from link gain matrix [3]. The maximum achievable SINR is calculated from the maximum Eigen-value of the link gain matrix. If the maximum achievable SINR is greater than threshold, then the corresponding Eigenvector is calculated and is sent to Transmitters. This Eigenvector is used to calculate the transmit power of each Transmitter. A very simple DPC algorithm adjusts the transmitted power of mobile terminals independently at discrete time instances by increasing the transmitted power for a given terminal *k* if the corresponding SINR, γ_k, is below the specified target γ_k^*, or decreasing the transmitted power if the corresponding SIR γ_k is above the specified target γ_k^* [4]. The associated power update equations for Distributed Power Control (DPC) [4], Constrained Distributed Dower control (CDPC) [5], Second Order Power control (SOPC) [6] and Fast Convergence Distributed Power control algorithm (FCDPC) [7] are given by

$$\text{DPC} \;:\quad p_k^{(n)} = p_k^{(n-1)} * \frac{\gamma_k^*}{\gamma_k^{(n-1)}} \qquad 1 \le k \le K, n \ge 1 \qquad \text{-------------} \; (1.2)$$

$$\text{CDPC} :\quad p_k^{(n)} = \min(P_{\max}, p_k^{(n-1)} * \frac{\gamma_k^*}{\gamma_k^{(n-1)}}) \quad 1 \le k \le K, n \ge 1 \qquad \text{-------------} \; (1.3)$$

$$\text{SOPC} :\; p_k^{(n)} = \min(P_{\max}, \max(P_{\min}, w^n * p_k^{(n-1)} * \frac{\gamma_k^*}{\gamma_k^{(n-1)}} + (1-w^n) * p_k^{(n-2)})) \quad \text{-----------} \; (1.4)$$

$$\text{FCDPC} :\quad p_k^{(n)} = \min(P_{\max}, p_k^{(n-1)} * e^{\alpha(\gamma_k^* - \gamma_k^{(n-1)})}) \quad 1 \le k \le K, n \ge 1 \qquad \text{-------------} \; (1.5)$$

DPC and CDPC algorithms are first order algorithms. In CDPC algorithms, a maximum Power constraint is set. For faster convergence, SOPC algorithm is used where w is a relaxation factor. In FCDPC, α is convergence parameter and it should be optimized for faster convergence speed. We note that both the SOPC and FCDPC algorithms are power constrained, and that they behave similar to CDPC with respect to the target SINR's. When these are feasible they will converge to a point where equation (1.1) is satisfied for all terminals, otherwise equation (1.1) is satisfied for only a subset of terminals, while the other terminals will transmit at the maximum allowed Power level.

1.3.2 DATA

When the mobile terminal performs data transmission services, as it is the case in wireless networks, the above QOS definition is no longer appropriate because probability of error is directly related to SINR and concepts from microeconomics have been used lately to define QOS in wireless systems in terms of utility functions [9]. In general, the utility function measures the satisfaction of a given user with a specific service, and in wireless communication systems utility can be related to the SINR and transmitted power. Using a game theoretic approach, Distributed Power control is formulated as a non-cooperative game in which users adjust transmit powers to maximize their corresponding utility functions [9] i.e

$$\frac{\partial u_k}{\partial p_k} = 0 \;\text{ for } 1 \le k \le K \;\text{ where K is the Number of users} \qquad \text{-------------} \; (1.6)$$

So solving the above K equations simultaneously is Power Control update Algorithm for data. The resulting utility maximization algorithm has a power update similar to that of

DPC Algorithm for voice but with the difference that the users update powers only if their corresponding utility is not decreased by the power update, otherwise they keep their powers unchanged. The value of γ_k^* in this case is the SINR that corresponds to a Nash equilibrium point of the Non-Cooperative Power control Game .

The difference between power control algorithms used for voice and data is that in voice, users adjust their power to achieve minimum target SINR γ_k^* value, whereas in case of data, users adjust their power to maximize their Utility. No target equilibrium SINR γ_k^* is used in this case. The power control algorithms developed for voice cannot be used for data because Probability of Error is directly related to SINR and therefore the approach of Utility function has to be used [9]. In case of Power control algorithms for voice, at each iteration, constant γ_k^* is achieved so as to provide subjective speech quality. The power control algorithms developed for data cannot be used for voice because during the initial stages of iteration, the value of γ_k is very low and so it affects Speech quality.

1.4 STATEMENT OF THE PROBLEM

Power Control for data in wireless CDMA system can be modeled as a non cooperative game to study User centric, Network Centric, Joint Network Centric- User Centric methods. In the joint Network Centric- User Centric (NC-UC) Power control Game, users adjust their powers to maximize the net utilities whereas the network adjusts the unit price to maximize revenue. The aim of this dissertation is to study and simulate joint Network centric- User centric Power control Game in single cell and multi cell CDMA system using different utility functions. The utility function defined in references [9] and [10] will be used.

The major objectives of this Dissertation are

(a) To Study and review User Centric, Network Centric, Joint Network Centric-User Centric Power control Algorithms.

(b) Simulation and performance comparison of Joint Network Centric-User Centric Power control Game for Single cell CDMA System using two different Utility Functions. For this performance, Utility Functions defined in references [9] and [10] will be used.

(c) Simulation and performance comparison of Joint Network Centric-User Centric Power control Game for Multi cell CDMA System using two different Utility Functions.

(d) Evaluating the performance of handoff on Joint Network Centric-User Centric Power control Game for Multi cell system

1.5 ORGANIZATION OF THE DISSERTATION

Including this introductory chapter, the dissertation is organized in seven chapters. Chapter 2 discuss about game theory and its application to power control. In Chapter 3, Joint Network Centric-User Centric Power control game in single cell system is studied. Here we will be considering the situation with two different types of utility functions. Chapter 4 deals with Joint Network Centric-User Centric Power control game in multi cell system and the effect of handoff. The Net utility maximization algorithm gets changed here compared to earlier case due to base station assignment. Once again we will be dealing with two different utility functions and two different types of pricing strategies. Chapter 5 discusses about simulation parameters and the basic flowchart for Joint Network Centric-User Centric Power control game in single cell system. Results and their explanations will be dealt in Chapter 6.

GAME THEORY AND ITS APPLICATION TO POWER CONTROL PROBLEM

Game theory is often described as a branch of applied mathematics and economics that studies situations where multiple players make decisions in an attempt to maximize their returns. Game theory is used in many diverse fields such as Political Science, Biology, Business, Economics, Mathematics etc. Game theory has recently drawn attention from computer scientists because of its use in artificial intelligence and cybernetics. In other words, game theory studies choice of optimal behavior when costs and benefits of each option depend upon the choices of other individuals.

2.1 GAME THEORY [12]

Game theory is concerned with the actions of decision makers who are conscious that their actions affect each other [12]. Game theory does not play role when decisions are made that ignore the reaction of others. The essential elements of the game are players, actions, payoffs and information or PAPI for short. They are collectively known as the rules of the game.

Some of the important Definitions in Game Theory are

(a) ***Player:*** They are the individuals who make decisions. Each player's goal is to maximize his utility by his choice of actions.

(b) ***Nature:*** It is a pseudo-player who takes random actions at specified points of time in the game with specified probabilities.

(c) ***Action:*** It is a choice made by a player. An action combination is an Ordered set $a = (a_1, a_2, ..., a_n)$, of one action for each of the n players in the game.

(d) ***Payoff:*** Payoff $\pi_i(s_1, s_2, .. s_n)$ means the expected Utility, player i receives after all players and nature have picked their strategies and the game has been played out.

(e) ***Outcome:*** The outcome of the game is a set of the interesting elements that the modeler picks from the values of actions, payoffs and other variables after the game are played out.

(f) ***Utility:*** It quantifies the quality level i.e. the level of satisfaction of the player.

(g) ***Strategy:*** Strategies are action plans. Player i's strategy s_i is a rule that tells him which action to choose at each instant of the game, given his information set. Player i's strategy set $S_i=\{s_i\}$ is the set of strategies available to him. A strategy combination is an ordered set consisting of one strategy for each of the n players in the game. Information set includes whatever the player knows about the previous actions of other players, the strategy set tells him how to react to their actions.

(h) ***Equilibrium:*** The equilibrium $S^*=(s_1^*, s_2^*,.., s_n^*)$ is a strategy combination consisting of the best strategy for each of the n players in the game, which is picked by players in trying to maximize their individual payoffs.

(i) ***Nash Equilibrium:*** The strategy combination S^* is Nash equilibrium if no player has Incentive to deviate from his strategy given that the other players do not deviate. In other words he cannot maximize his utility function by changing his strategy given that the other players have kept their Strategies fixed.

$$\forall i \quad \pi_i(s_i^*, S_{-i}^*) \geq \pi_i(s_i', S_{-i}^*), \ \forall s_i'$$

where S_{-i}^* is the strategy combination of all the players at Nash Equilibrium except player i.

(j) ***Dominant Strategy:*** The strategy s_i^* is a dominant strategy if it is a player's strictly best response to any strategies that other players might pick i.e his payoff is highest with s_i^*.

$$\pi_i(s_i^*, S_{-i}) > \pi_i(s_i', S_{-i}) \forall S_{-i} \forall s_i' \neq s_i^*$$

(k) ***Pareto Efficiency:*** Efficiency is concerned with the optimum allocation of scarce resources. Efficiency is achieved when some specific criterion is maximized. The Nash equilibrium Point is said to be Pareto efficient when no other strategy combination increases the payoff of one player without decreasing that of the other.

In a non cooperative game each user selfishly tries to maximize its net utility. The outcome of each user is a function which depends on user own decisions as well as decision of other users. In game theory, a non-cooperative game is one in which players can cooperate, but any cooperation must be self-enforcing.

A cooperative game is a game where groups of players ("coalitions") may enforce cooperative behavior, hence the game is a competition between coalitions of players, rather than between individual players. The cooperation in Power control Game is in the form of exchange of power, SINR values etc.

2.2 APPLICATION TO POWER CONTROL

The cellular CDMA systems are interference limited since all users share the same frequency spectrum. Each user's transmit signal power acts as interference to other users. In CDMA each user tries to maximize his SINR value to reduce the bit error rate and at the same time transmit with low power [13]. If all others power levels are fixed, increasing one's power would increase SINR of that user but it increases the interference seen by other users, driving their SINR's down and inducing them to increase their power levels. The outcome for each user is a function that depends on user's own decisions as well as the decision of other users. The user will attempt to make a best choice taking into account that the other users are doing the same thing. At last rational users will choose an operating point that is stable i.e. Nash equilibrium point . The equilibrium point is that where maximum utility is obtained.

Let $G=[N,\{P_i\},\{U_i(.)\}]$ denote the non-cooperative power control game (NPG) where N is the number of users currently in cell, P_i is the strategy set and $U_i(.)$ is the utility of user i [9]. Each user selects a power level such that $p_i \in P_i$. The power vector $p=(p_1,p_2,...,p_N)$ denotes the outcome of the game in terms of selected power level of all users. The resulting utility function for the i^{th} user is given by $U_i(p)$. This can also be written as $U_i(p_i,p_{-i})$ where p_{-i} denotes the vector consisting of users of P other than i^{th} user.

2.3 UTILITY FUNCTION

In game theory, Utility is defined as level of satisfaction that a user derives from undertaking an activity. In cellular systems, Utility is defined as the measure of satisfaction or quality of service (QOS) that a user derives from accessing the wireless data network. For voice communications, the utility function is zero below the minimum SINR and one above the value of minimum SINR [2]. For data communications probability of error is directly related to SINR. High SINR value implies low probability of error, low delay and higher throughput. This implies that utility is generally a increasing concave function of SINR.

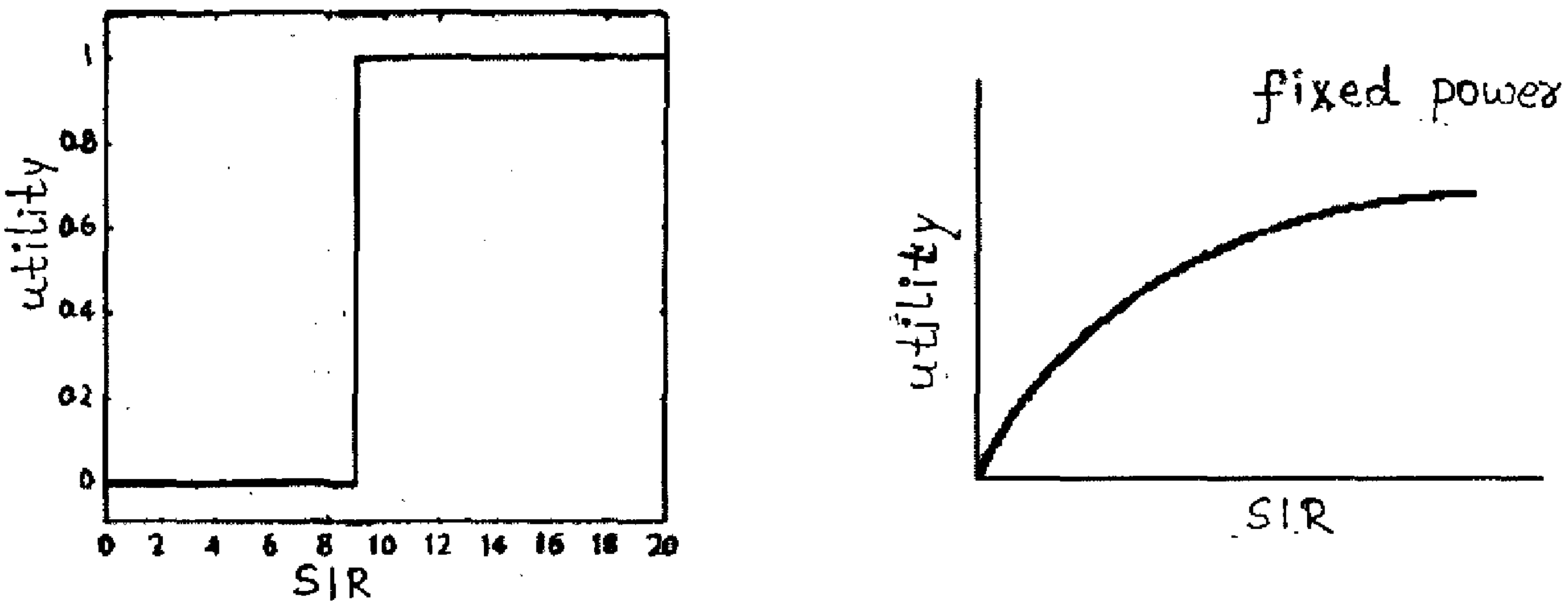


Figure 2.1

In Figure 2.1 we observe that Utility is a step Function for voice [2] whereas for data, Utility is a increasing concave function of SINR when power is fixed, for a Throughput Based Utility function [9].

2.3.1 DIFFERENT UTILITY FUNCTIONS [8],[9],[10],[11]

Some of the important Utility Functions which exist in Literature are listed below

(a) $$U=\frac{L*R*f(\gamma)}{M*p}$$

L : Number of information bits

M : Length of frame

p : Power of a given user

f(γ) : Efficiency function = $(1-2P_e)^M$

R : Rate in bits/sec

This utility function value depends on the details of data transmission, modulation, coding, interleaving, radio propagation and receiver structure. The properties of this utility function are

$U_i \to 0$ as $p_i \to 0$: zero utility when no usage

$U_i \to 0$ as $p_i \to \infty$: zero utility when power consumption is excessive

U_i is quasi-concave in p_i when BER (γ) decays exponentially in γ.

(b) $U = R * \log_2(1+\gamma)$

R : Rate of data in bits/sec

γ : SINR

This utility function value uses channel capacity as a figure of merit for the purpose of power control and leaves the decision as to whether the capacity will be fully exploited by coding/modulation.

(c) $U = u_i * \log(prob(\gamma_i \geq \gamma_i^*))$

$= u_i * \log(1 - O_i(\gamma_i^*))$

u : User specific utility parameter

$prob(\gamma_i \geq \gamma_i^*)$: Probability that SINR of a particular user is greater than threshold

$O_i(\gamma_i^*)$: Outage probability defined as the proportion of time that some SINR threshold γ_k^* is not met for sufficient reception at receiver.

(d) $U = \dfrac{1}{1+e^{-a(\gamma-b)}}$

a : Shape parameter

b : Shift parameter

The above given utility is a Sigmoid Utility function. The given utility function reaches a value of 1 at $\gamma = \infty$.

2.4 NASH EQUILIBRIUM AND PARETO EFFICIENCY [9]

Nash equilibrium for the non cooperative power control game is defined as the power vector p^* such that no single user can improve its utility by a unilateral change in its power. Mathematically Nash equilibrium is defined as power vector p^* such that

$$U_i(p_i^*, p_{-i}) \geq U_i(p_i^{'}, p_{-i}) \quad \forall p_i^{'} \in P_i \qquad \text{-------------(2.1)}$$

$i \in 1,2,\ldots N$ where p_{-i} is a power vector which contains the powers of all users except the ith user, P_i is the strategy space for user i and N is the number of users in cellular system.

A classical measure of the efficiency of an equilibrium solution is the Pareto efficiency. A power vector p^* is said to be Pareto efficient if and only if there exists no such vector $p^{'}$ such that at least one user achieves higher utility, while other user's utilities remains constant. In other words there exists no power vector $p^{'}$ such that

$$U_i(p_i^*, p_{-i}) < U_i(p_i^{'}, p_{-i}) \quad \forall p_i^{'} \in P_i,\ i \in 1,2,\ldots N. \qquad \text{-------------(2.2)}$$

The equilibrium analysis of the non cooperative power control game involving utility function is Pareto inefficient. In order to improve the inefficient equilibrium, the behavior of users is influenced by a pricing mechanism which will lead to a better equilibrium point.

2.5 PRICING FUNCTION

In the Non Cooperative Game (NPG), each terminal aims to maximize its own utility by adjusting its own power, but it ignores the cost (or harm) it imposes on other terminals by the interference it generates [9]. The self-optimizing behavior of an individual terminal is said to create an externality when it degrades the quality for every other terminal in the system. Among the many ways to deal with externalities, pricing (or taxation) has been used. Typically, pricing is motivated by two different objectives: 1) it generates revenue for the system and 2) it encourages players to use system resources more efficiently. A pricing policy is called incentive compatible if pricing enforces a

Nash equilibrium that improves social welfare. Roughly speaking, social welfare is defined as the sum of utilities. It is possible to use various pricing policies, such as flat rate, access-based, usage-based, priority-based, etc. In usage-based pricing, the price a terminal pays for using the resources is proportional to the amount of resources consumed by the user. In order to improve the equilibrium utilities of NPG in the Pareto sense, usage-based pricing schemes is widely used. Through pricing, system performance is increased by implicitly inducing cooperation and yet the non cooperative nature of the resulting power control solution is maintained.

2.5.1 DIFFERENT PRICING FUNCTIONS

Some of the important Pricing Functions are listed below

(a) Pricing proportional to power [9]:

Pricing Factor= C*p;

C : Cost per unit power

p : Power of user

In this method of usage based pricing, pricing is proportional to power transmitted by user. So net utility obtained by the above method is larger in value compared to utility obtained by NPG. Similarly Nash equilibrium power vector of users is less in value compared to power vector obtained by NPG.

(b) Pricing proportional to Throughput [14]:

Pricing Factor= C*T

C : Cost per unit throughput

T : Throughput of user

In this method of usage based pricing, pricing is proportional to throughput of user. Revenue is the product of price/unit service and amount of service provided. The amount of service provided by the network to any user is the amount of useful data bits that user sends to network over fixed time frame. This pricing factor is considered more natural when we are dealing with network centric situation.

2.6 RADIO RESOURCE MANAGEMENT (RRM) SCHEMES

(a) ***User centric (UC):*** This type of scheme tries to maximize the interest of individual users. The user centric management schemes tend to distribute quality of service more evenly to users. Quality of service can be achieved by achieving a specified threshold γ_k^* in case of voice or maximizing the net utility function with respect to power in case of data. In case of user centric situation all the users have fair distribution of throughput, utilities, power etc. Distributed power control [3], [15] and minimization of outage probability [16], [17] can be thought of as examples of user-centric resource management.

(b) ***Network centric (NC):*** This type of scheme optimizes network interests. Maximization of objectives like sum of network information capacity [18], [19] or sum of throughput [20] fall in this category. Network centric tend to provide most, if not all of the radio resources to the few users with the best channels. User centric and network centric are motivated by different interests and hence it results in dissimilar resource allocations.

(c) Network centric - User centric (NC-UC): In this scheme since the network has more access to global information than users and so it is more suitable for network to play the role of leader [14]. In this method users adjust their powers to maximize the net utilities where as the network adjusts the unit price to maximize revenue. The user-centric and the network-centric problems, though solved in a distributed fashion, are coupled with each other. Given any unit price, the output of the user-centric resource management is a set of equilibrium powers which is the input back to the network-centric problem. The net result is a tradeoff between the two seemingly conflicting user-centric and network-centric objectives, which implies that the solution lies between the two extreme solutions of pure network-centric and user-centric RRM.

JOINT NETWORK-CENTRIC AND USER-CENTRIC POWER CONTROL GAME IN SINGLE CELL CDMA SYSTEM

The importance of radio resource management (RRM) increases as the demand for higher data rates over radio links increases. Most Power control schemes can be classified as either user centric or network centric .User-centric schemes attempt to maximize the interests of individual users, while network-centric ones optimize network interests [14]. The Power control problem defined here, allows both Network-Centric and User-Centric objectives to compete. Here the network, being the leader, announces its decision to the other players, i.e., users who being the followers, take the network decision into account when designing their reactions. The network decides the unit price and users decide the transmitter power according to the price. In a realistic scenario, the network typically has access to more global information than the mobile users. Therefore, it is more suitable for the network to play the role of the leader instead of being another player in a common non cooperative game. Specifically, the utility function defined in references [14] and [10] is applied for the user-centric problem. For the network-centric objective, revenue is considered, which is defined as the sum of payments from all the users. In this method, pricing acts as a mediator between the possibly conflicting user and network objectives. According to the network-broadcasted unit price, users adjust their transmitter powers to maximize their net utilities .The network, on the other hand, adjusts its unit price to maximize its revenue.

3.1 THROUGHPUT BASED UTILITY FUNCTION

3.1.1 USER METRIC

The utility function is generic and orthogonal codes are assumed, so that there is no coupling among users [14]. Utility function is applied on reverse link of a CDMA system. Utility function for a wireless data user is defined as the average number of information bits transmitted correctly per Joule of battery energy. This utility function combines the two main criteria of wireless transmission: throughput denoted as T and transmitter power denoted as p. The utility U of the ith user is generally given by

$$U_i = \frac{T_i}{p_i} \qquad \text{------------------(3.1)}$$

We consider the uplink of a single-cell CDMA system with N mutually interfering users. Data bits are packed into M frames of bits containing L information bits per frame, where M-L bits are used for error detection. The signal of user is transmitted at the rate of R bits per second. The received signal-to-interference-plus-noise ratio (SINR) denoted as γ_i is equal to

$$\gamma_i = \frac{G * h_i * p_i}{\sum_{j=1, j \neq i}^{N} h_j * p_j + \sigma^2} \qquad \text{------------------(3.2)}$$

where h_i is the path gain of the user i, σ^2 is the additive white Gaussian noise (AWGN) power, G=W/R is the processing gain with W being the chip rate, $p = (p_1, p_2, \ldots p_N)$ is the transmitter power vector, and $I_i(p) = \sum_{j=1, j \neq i}^{j=N} h_j p_j + \sigma^2$ denotes interference plus noise level before de-spreading. Here, perfect error detection and automatic retransmission request (ARQ) is considered i.e. a frame with error is retransmitted until received correctly. If bit errors are independent of each other, then the throughput of user i can be rewritten as

$$T_i = \frac{L * R * f(\gamma_i)}{M} \qquad \text{------------------(3.3)}$$

where the efficiency function $f(\gamma)$ is defined as $f(\gamma_i) = (1 - 2 * BER(\gamma_i))^M$, with BER (.) being the bit-error rate (BER).

3.1.2 NETWORK METRIC [14]

With the existence of a pricing scheme, a natural metric of the network satisfaction is its revenue. Revenue is the product of price per unit service and the amount of service provided. The amount of service provided by the network to any user is the amount of useful data bits that the user sends to the network over a fixed time frame, which is proportional to the user's throughput in that time frame. Assuming a fixed time frame, the network charges any user i, in proportion to its throughput with a unit price λ_i. Hence, the payment by each user is

$$\rho_i = \lambda_i T_i \quad \forall i \qquad \text{------------------(3.4)}$$

So the revenue is given by $\rho = \sum_{i=1}^{N} \rho_i = \sum_{i=1}^{N} \lambda_i T_i$ ------------------(3.5)

3.1.3 JOINT USER AND NETWORK OPTIMIZATION

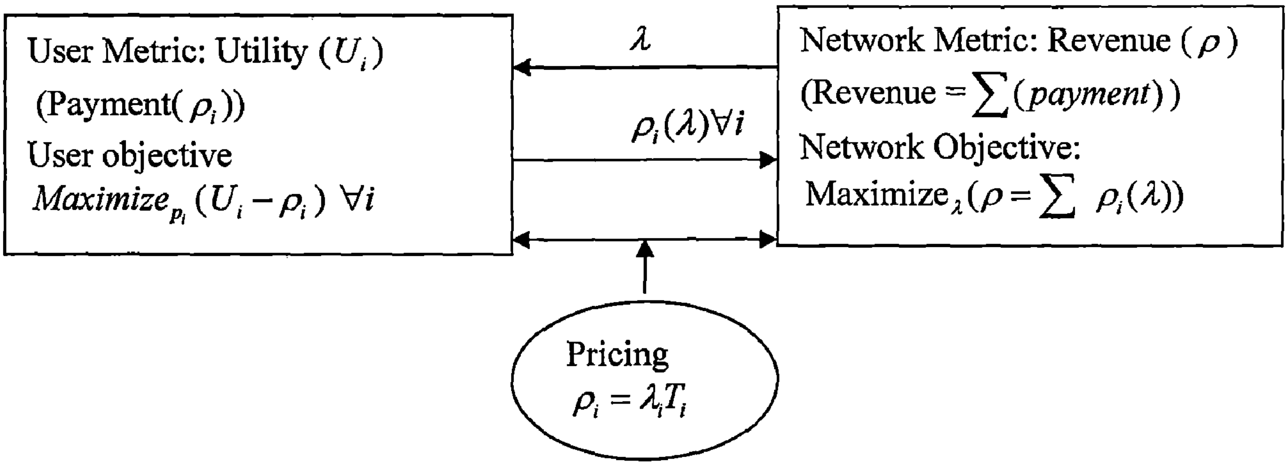


Figure 3.1

Pricing actually aims to accomplish user-centric goals. In this method, the pricing scheme not only explicitly characterizes the network-centric objective (Revenue=$\sum$ payment), but also mediates between the user and the network objectives. Each user optimizes its net utility, defined as its utility minus its payment. Therefore, the user and the network objectives interact with each other through the pricing mechanism. After adjusting for its payment, the net satisfaction or the net utility, U_i^{net} of user is

$U_i - \lambda_i * T_i$. The user's optimization attempts are essentially an iterative algorithm for distributed power control. In terms of the power vector at the *t*th iteration denoted by $p(t) = (p_1(t), p_2(t), \ldots, p_N(t))$, the power update rule for the next iteration is

$$p_i(t+1) = \arg\max_{\xi_i \in S_i} U_i^{net}(\xi_i, p(t)) \quad \forall i \qquad \text{------------------(3.6)}$$

A necessary condition for the Nash equilibrium is $\frac{\partial U_i^{net}}{\partial p_i} = 0 \quad \forall i$. The solution that satisfies it is given by [14]

$$1 - \lambda_i p_i = \frac{(e^{v * \gamma_i(p_i)} - 1)}{M * v * \gamma_i(p_i)} \qquad \text{------------------(3.7)}$$

$v = 0.5$ for non coherent FSK modulation and $v = 1$ for differential phase-shift keying (DPSK) modulation, respectively. Suppose that terminals update their powers at time instants given by $\mathrm{T} = \{\tau_1, \tau_2, \tau_3, \ldots\}$ with the update instances sorted in ascending order.

The Transmitted Power of each user is generated in the following way

1) Set the initial power vector **p** (0) = **p** where **p** is any vector in the strategy space P. Set $k = 1$.

2) For all k such that $\tau_k \in T$ and for all terminals, given $p(\tau_{k-1})$, compute

$$\hat{p}_l(\tau_k) = \arg\max_{p_l \in P_l} u_l(p_l, p_{-l}(\tau_{k-1})) \qquad \text{where } l = 1,2,3 \ldots N.$$

With the network-decided unit price vector $\lambda = (\lambda_1, \lambda_2, \ldots \lambda_N)$, the user objective is for each user to maximize its net utility, defined as the difference between its utility and its payment

$$\text{[User Problem]} \max_{p_i \in S_i} U_i^{net} = \max_{p_i \in S_i} U_i - \lambda_i * T_i \quad \forall i \qquad \text{------------------(3.8)}$$

where $S_i = (p_{\min} \le p_i \le p_{\max})$ is the strategy space of user, with $p_{\min}$ and $p_{\max}$ denoting the minimum and maximum transmitter power, respectively. The network aims to find its highest revenue by searching over a nonnegative price vector:

$$\text{[Network problem]} \max_{\lambda \ge 0} \rho(\lambda) = \max_{\lambda \ge 0} \sum_{i=1}^{N} \lambda * T_i(p^*(\lambda)) \qquad \text{------------------(3.9)}$$

where λ is the optimum price at which revenue is maximized.

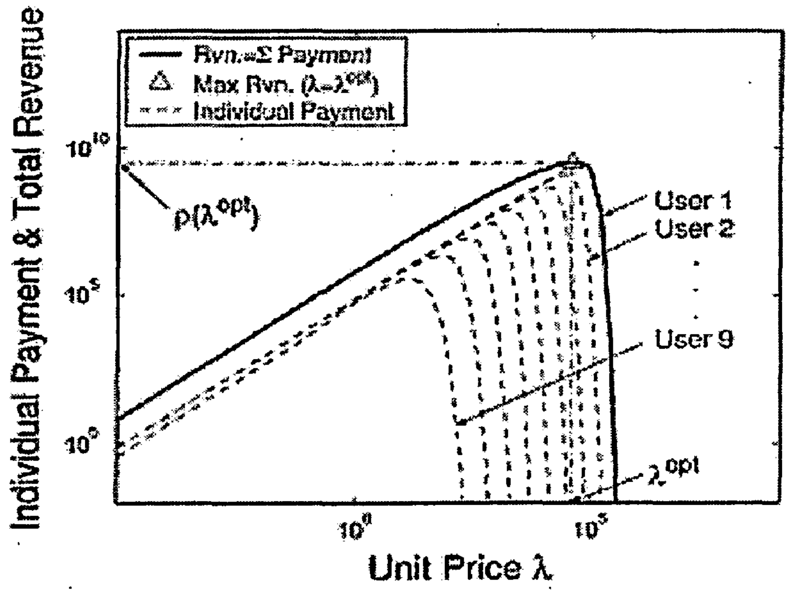


Figure 3.2

In figure 3.2, payment of each user is plotted against cost per unit throughput. Initially the payment increases with cost per unit throughput monotonically, reaches maximum at λ_{opt} and finally decreases. Similarly, the total revenue obtained by adding the individual payment of users, behaves in a similar fashion. Users close to Base Station obtain optimum higher cost per unit throughput compared to other users. The above simulation results are taken from [14].

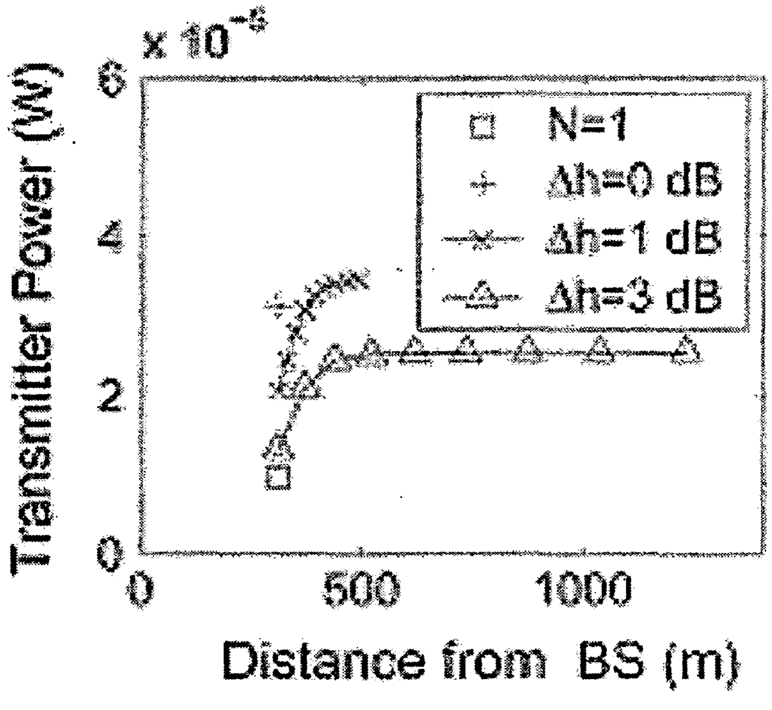


Figure 3.3

In figure 3.3, equilibrium transmitter power is plotted against Distance from BS. The equilibrium power is calculated at the point at which maximum revenue is obtained. The above figure is plotted in 4 different situations, (1) single user (2) 9 users with same distance from BS (3) 9 users with Δh=1db and (4) 9 users with Δh=3 db. The user close to BS requires less power compared to other users.

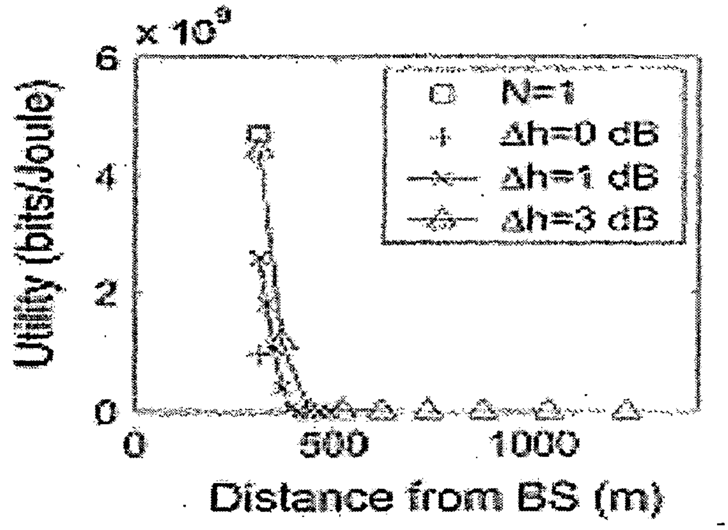


Figure 3.4

In figure 3.4, equilibrium utility is plotted against Distance from BS. The equilibrium utility is calculated at the point at which maximum revenue is obtained. The above figure is plotted in 4 different situations, (1) single user (2) 9 users with same distance from BS (3) 9 users with Δh=1db and (4) 9 users with Δh=3 db. The user close to BS has more utility compared to other users.

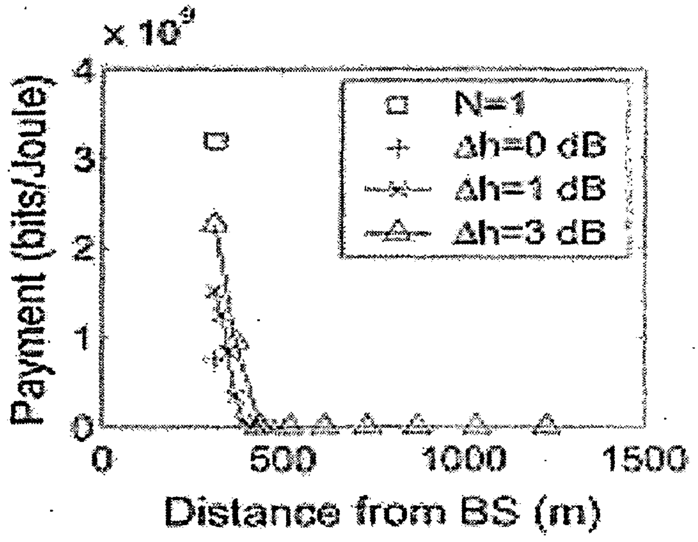


Figure 3.5

In figure 3.5, equilibrium payment is plotted against Distance from BS. The equilibrium payment is calculated at the point at which maximum revenue is obtained. The above figure is plotted in 4 different situations, (1) single user (2) 9 users with same distance from BS (3) 9 users with Δh=1db and (4) 9 users with Δh=3 db. The user who is close to BS obtains higher payment compared to other users.

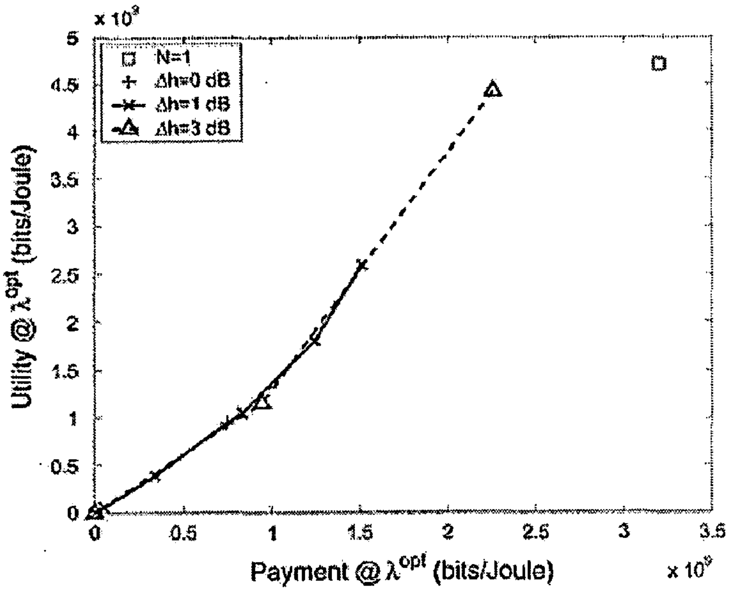


Figure 3.6

In figure 3.6, we observe that the proportionality holds between the user metrics and its payment, users with better channels get better QOS (higher utilities), but they pay proportionally more. This proportionality shows that this model is more sensible, compared with a flat-rate model, where the users are charged the same rate despite their uneven QOS. The flat rate model is obtained by using pure user centric method.

3.2 GAUSSIAN CHANNEL CAPACITY UTILITY FUNCTION

3.2.1 USER METRIC

The utility function is generic and orthogonal codes are assumed, so that there is no coupling among users. Utility function is applied on the reverse link of a CDMA system. User satisfaction is represented as a utility function, which is a strictly concave function, based on signal to interference ratio. The main objective is to formulate the game in terms of intrinsic properties of the channel (SIR and power), and thus decouple it from lower layer decisions such as modulation and coding. The utility of user i is given by [10]

$$U_i = R * \log_2(1+\gamma_i) \quad \forall i \qquad \text{-----------------(3.10)}$$

where R is the rate of data in bits/sec and γ is SINR ratio.

3.2.2 NETWORK METRIC

With the existence of a pricing scheme, a natural metric of the network satisfaction is its revenue. Revenue is the product of cost per unit power and the transmitted power. In this method, the network charges any user i, in proportion to its transmitted power with a unit price λ_i. Hence, the payment by each user is

$$\rho_i = \lambda_i p_i \quad \forall i \qquad \text{-----------------(3.11)}$$

So the revenue is given by $\rho = \sum_{i=1}^{N} \rho_i = \sum_{i=1}^{N} \lambda_i p_i$ -----------------(3.12)

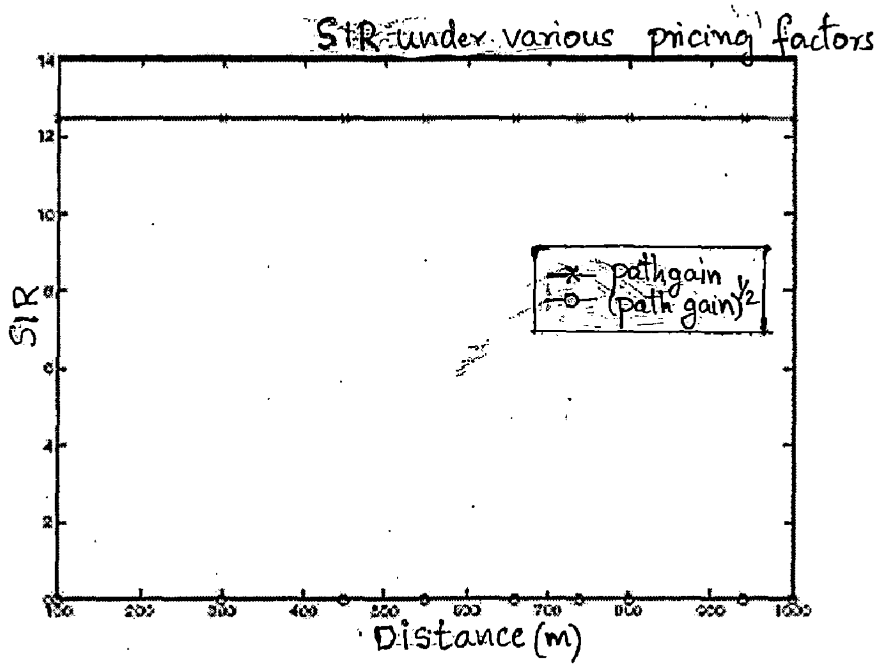


Figure 3.7

In figure 3.7, SINR of each user is calculated for two different pricing strategies [10]. In the first case, Pricing is proportional to path gain and in the other case; Pricing is proportional to square root of path gain. As seen from the above figure 3.7, when the pricing is proportional to the path gain the users receive a fairer allocation of SINR's than the other pricing strategy.

3.2.3 JOINT USER AND NETWORK OPTIMIZATION

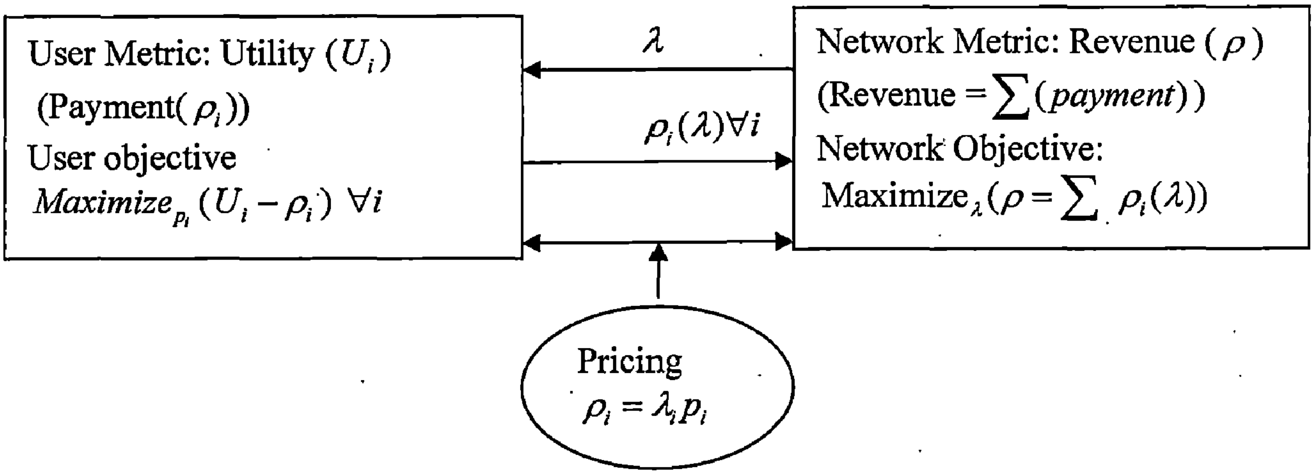


Figure 3.8

Pricing actually aims to accomplish user-centric goals. In this method, the pricing scheme not only explicitly characterizes the network- centric objective (Revenue=$\sum$ payment), but also mediates between the user and the network objectives.

Each user optimizes its net utility, defined as its utility minus its payment. Therefore, the user and the network objectives interact with each other through the pricing mechanism. After adjusting for its payment, the net satisfaction or the net utility, U_i^{net} of user is $U_i - \lambda_i * p_i$. Note that the user's optimization attempts are essentially an iterative algorithm for distributed power control. In terms of the power vector at the *t*th iteration denoted by $p(t) = (p_1(t), p_2(t), ..., p_N(t))$, the power update rule for the next iteration is

$$p_i(t+1) = \arg\max_{\xi_i \in S_i} U_i^{net}(\xi_i, p(t)) \quad \forall i \qquad \text{-----------------(3.13)}$$

A necessary condition for the Nash equilibrium is $\frac{\partial U_i^{net}}{\partial p_i} = 0 \quad \forall i$. The solution that satisfies it is [10]

$$\hat{p} = F(\tilde{p}) = F(Mp + b) \qquad \text{-----------------(3.14)}$$

where the matrix M $\in R^{n*n}$ and if at an instant terminal i updates its power then the *i*th row of the matrix is given by $m_{ii} = 0$ and $m_{ij} = -$ (B/W) $*\frac{h_j}{h_i}$ for i≠j and the *i*th component of the vector b $\in R^n$ is a constant given by $b_i = \frac{B}{a_i \ln 2} - \frac{B * \sigma^2}{W * h_i}$.

With the network-decided unit price vector $\lambda = (\lambda_1, \lambda_2, \ldots \lambda_N)$ the user objective is for each user to maximize its net utility, defined as the difference between its utility and its payment

$$\text{[User Problem]} \max_{p_i \in S_i} U_i^{net} = \max_{p_i \in S_i} U_i - \lambda_i * p_i \quad \forall i \qquad \text{------------------(3.15)}$$

where $S_i = (p_{\min} \le p_i \le p_{\max})$ is the strategy space of user, with $p_{\min}$ and $p_{\max}$ denoting the minimum and maximum transmitter power, respectively. The network aims to find its highest revenue by searching over a nonnegative price vector:

$$\text{[Network problem]} \max_{\lambda \ge 0} \rho(\lambda) = \max_{\lambda \ge 0} \sum_{i=1}^{N} \lambda * p_i^*(\lambda) \qquad \text{------------------(3.16)}$$

where λ is the optimum price at which revenue is Maximized.

JOINT NETWORK-CENTRIC AND USER-CENTRIC POWER CONTROL GAME IN MULTICELL CDMA SYSTEM

The Joint Network Centric-User Centric power control algorithm offers a more balanced solution between the two seemingly conflicting user and network objectives: the resulting operating points lie in between the two extreme solutions of purely network-centric and user-centric Power control game. Each user autonomously chooses a base station (BS) and a power level to maximize its utility is the user-centric objective, while the network chooses a unit price under network-centric objectives [21]. Specifically, for the network-centric optimization, we apply two approaches: one is global pricing, where the network seeks a unit price for global revenue maximization, and the other is mini-max pricing, where a unit price is assigned based on minimizing the local optimal price that maximizes the revenue at each Base Station.

When the mobile moves into a different cell while a conversation is in progress, the switching center automatically transfers the call to the new base station. This handoff operation not only involves identifying a new base station but also requires that signals can be allocated to the channel associated with the new base station [22]. Processing handoffs is an important task in any cellular mobile radio system. When a particular signal level is specified as the minimum acceptable, it is established as a threshold at which handoff is made. Hard handoffs are used in TDMA and FDMA cellular systems, in which different radio channels are assigned during handoff. CDMA cellular mobile radio systems provide handoff capability that cannot be provided with other wireless systems. In CDMA systems, the term “handoff” does not mean a physical change in the assigned channel but rather that several base stations handle the radio communication task. For the forward link transmission, while a mobile is tracking the pilot of a particular cell it is also searching for pilots of adjacent cells [22]. When a new pilot is detected and found to have sufficient signal strength, the mobile informs its original base station. This notifies the switching center, which orders the second cell’s base station to communicate with the given mobile in parallel with the first cell’s base station. When the first cell’s signal is too weak relative to the second it will be dropped.

For the reverse link, each base station demodulates and decodes the signals independently. By simultaneously evaluating the received signals from a user at several neighboring base stations, the switching center may decide on the version of the user's signal that is best. This technique exploits macroscopic space diversity provided by the different physical locations of the base stations and allows the switching center to make a soft decision. The soft handoff strategy has many advantages. It considerably increases the capacity of a multi cellular system. Soft handoff for the reverse link occurs throughout a range of distances from the two base stations. At any given time, the best of the receptions from the two base stations is used at the switching center. We assume for simplicity that this depends only on the path loss. Then the strongest, that is, with the lowest path loss, is used.

4.1 THROUGHPUT BASED UTILITY FUNCTION

4.1.1 USER METRIC

The quality of service (QOS) received by user can be translated quantitatively into a utility function [21]. In this method, one user is connected to only one BS at any time. The utility function $U_i(a_i, p)$ of user i when it is assigned to BS a_i is defined as the average number of information bits of user i received correctly at BS a_i per Joule of battery energy expended

$$U_i(a_i, p) = \frac{T_i(a_i, p)}{p_i} \qquad \text{--------------(4.1)}$$

where $T_i(a_i, p)$ is the throughput of user i received at BS a_i. Data bits are packed into frames of M bits containing L information bits per frame, where M-L bits are used for error detection. The signal of user i is transmitted at a rate of R_i b/s. The received signal-to-interference- plus-noise ratio (SINR) of user i at BS a_i is given as

$$\gamma_i(a_i, p) = \frac{G_i * h_{a_i,i} * p_i}{\sum_{j=1, j\neq i}^{j\neq N} h_{a_i,j} * p_j + \sigma^2} \qquad \text{--------------(4.2)}$$

where $G_i, h_{a_i i}$ and σ^2 represent the processing gain, path gain, and noise variance for the ith user, respectively. A frame in error is retransmitted until received correctly. Therefore, the throughput is equal to

$$T_i(a_i, p) = \frac{L}{M} * R_i * f(\gamma_i(a_i, p)) \qquad \text{-------------(4.3)}$$

4.1.2 NETWORK METRIC [21]

With the existence of a pricing scheme, a natural metric of the network satisfaction is its revenue. Revenue is the product of price per unit service and the amount of service provided. The amount of service provided by the network to any user is the amount of useful data bits that the user sends to the network over a fixed time frame, which is proportional to the user's throughput in that time frame. Assuming a fixed time frame, the network charges any user i, in proportion to its throughput with a unit price λ_i. The payment of user i is defined as

$$\rho_i = \lambda_i * T_i(a_i, p) \qquad \text{-------------(4.4)}$$

which is explicitly a function of the unit price vector $\lambda = (\lambda_1, \lambda_2, ..., \lambda_N)$, given a Base Station(BS) and Power Vector assignment. Further, if β_k denotes as the set of users connected to the Base Station k ($i \in \beta_k$ if and only if $a_i = k$), the revenue collected by the BS k is defined as

$$\rho^k(\lambda) = \sum_{i \in \beta_k} \lambda_i * T_i(a_i, p) \qquad \text{-------------(4.5)}$$

The revenue that the network collects is $\rho(\lambda) = \sum_{k=1}^{K} \rho^k(\lambda) = \sum_{i=1}^{N} \rho_i(\lambda)$, where K is number of cells and N is the number of mutually interfering users. The user's optimization attempts are essentially an iterative algorithm for distributed power control and BS assignment. The iterative algorithm for the user-centric optimization is for each user first to do the BS assignment based on maximizing its SINR, and then to find the transmitter power that optimizes its net utility.

$$a_i(t+1) = \arg\max_k \gamma_i(k, p(t)) \quad \text{--------------(4.6)}$$

$$p_i(t+1) = \arg\max_{\xi_i} U_i^{net}(a_i(t+1), \xi_i, p_{-i}(t), a_{-i}(t), \lambda) \quad \text{--------------(4.7)}$$

4.1.3 JOINT USER AND NETWORK OPTIMIZATION

With the network broadcasted unit price vector λ , the user objective is to unilaterally maximize its net utility, defined as the difference between its utility and its payment

$$\max_{p_i, a_i} U_i^{net}(a_i, p_i, p_{-i}, a_{-i}, \lambda) = \max_{p_i, a_i}\{U_i\ (a, p) - \lambda_i * T_i(a_i, p)\} \forall i \quad \text{-------------(4.8)}$$

Unlike the user-centric problem in a single-cell system where each user maximizes its net utility over its transmitter power only, the user-centric objective in multi cell is to optimize the net utility over two dimensions: its transmitter power and its BS assignment. U_i^{net} Monotonically increases with γ_i. Therefore, given an interference vector p_{-i}, the BS assignment based on the net utility maximization is equivalent to the one based on maximizing SINR.

$$a_i^* = \arg\max_k U_i^{net}(k, p_i, p_{-i}, a_{-i}, \lambda) \quad \text{--------------(4.9)}$$

$$= \arg\max_k \gamma_i(k, p) \quad \text{--------------(4.10)}$$

Therefore, the user problem can be solved by assigning the BS first, followed by power control. If all the users' optimization attempts settle down, the game achieves an equilibrium called a Nash equilibrium, with equilibrium power vector and BS assignment vector $(p^*(\lambda), a^*(\lambda))$, where the power and the BS assignment vectors are defined as $p^* = (p_1^*, p_2^*, ..., p_N^*)$ and $a^* = (a_1^*, a_2^*, ..., a_N^*)$, respectively. Formally, the Nash equilibrium power and BS assignment vector is the one at which no single user can improve its net utility by unilaterally changing its power and its BS assignment. Mathematically, for any user i

$$U_i^{net}(p_i^*, a_i^*, p_{-i}^*, a_{-i}^*, \lambda) \geq U_i^{net}(p_i, a_i, p_{-i}^*, a_{-i}^*, \lambda) \quad \text{-------------(4.11)}$$

The Nash equilibrium vector can also be written as

$$p_i^* = \arg\max_{p_i} U_i^{net}(a_i^*, p_i, p_{-i}^*, a_{-i}^*, \lambda) \qquad \text{--------------(4.12)}$$

$$a_i^* = \arg\max_k \gamma_i(k, p^*) \ \ \forall i \qquad \text{--------------(4.13)}$$

In this network optimization technique, two types of pricing have been used. In the first method we assume all the users belong to the same priority class, and hence, the network applies a common unit price to all the users.

(a) **Global Pricing:** The network aims to find its highest revenue by searching over $\lambda \geq 0$

$$\text{[Network Problem (G)]} \ \ \max_{\lambda>0} \rho(\lambda),$$

$$\text{where} \ \ \rho(\lambda) = \sum_{i=1}^{N} \lambda * T_i(a^*(\lambda), p^*(\lambda)) \qquad \text{--------------(4.14)}$$

(b) **Mini-max Pricing:** Here, the network chooses the unit price as follows. First, the optimum unit price that maximizes the revenue ρ^k at the kth BS is found. Then the unit price, called the mini max price λ_M, is chosen to be the smallest among the K optimum unit prices obtained at each of the Base Stations. Mathematically, the network problem in this case can be stated as

$$\text{[Network Problem (M)]} \ \min\{\arg\{\max_\lambda(\rho^1(\lambda)\}, \ldots, \arg\{\max_\lambda(\rho^K(\lambda)\}\} \qquad \text{----------(4.15)}$$

Mini max pricing results in a more even distribution of achieved QOS, compared with global pricing.

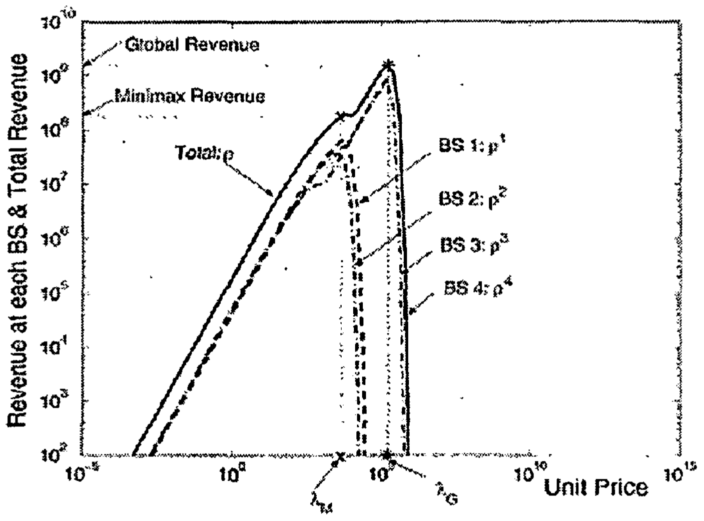


Figure 4.1

In figure 4.1, Revenue at each BS is plotted against cost per unit throughput [21]. Initially the revenue at each BS gradually increases with cost per unit throughput and then decreases. Similarly the total revenue obtained by adding the individual revenues at BS behaves in a similar fashion. The price at which maximum total revenue is obtained is called global pricing. Similarly the minimum price among the optimum prices where maximum revenue of the individual BS is obtained is called mini max pricing.

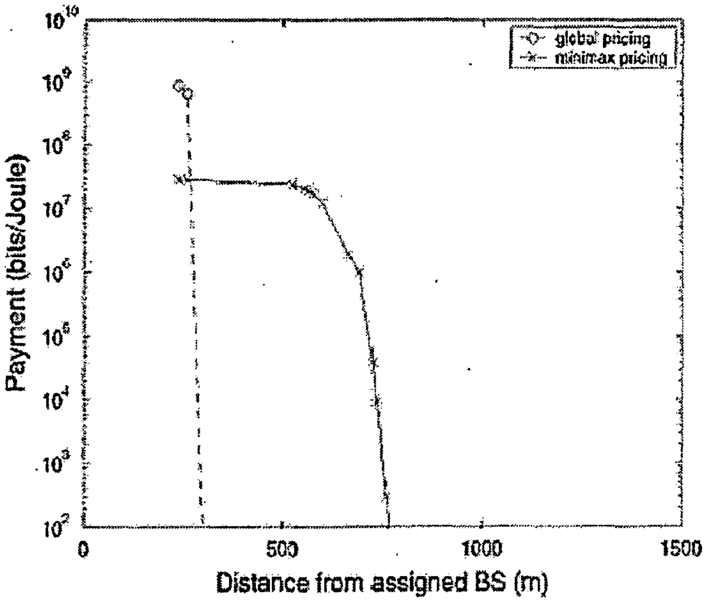


Figure 4.2

In figure 4.2, Equilibrium payment is plotted versus distance from assigned BS at two different pricing strategies. The network obtains its revenue mainly from the few users with the best channels when using global pricing, while the network collects nontrivial fractions of the revenue from more users when using mini max pricing.

4.2 GAUSSIAN CHANNEL CAPACITY UTILITY FUNCTION

4.2.1 USER METRIC

The following method has been proposed by me for a Gaussian channel capacity utility function in multi cell system. The quality of service (QOS) received by user can be translated quantitatively into a utility function. The utility function $U_i(a_i, p)$

of user i when it is assigned to BS a_i is defined as the average number of information bits of user i received correctly at BS a_i per second

$$U_i(a_i, p) = R_i * \log_2(1 + \gamma_i(a_i, p)) \qquad \text{---------------(4.16)}$$

The signal of user i is transmitted at a rate of R_i b/s. The received signal-to-interference-plus-noise ratio (SINR) of user i at BS a_i is given as

$$\gamma_i(a_i, p) = \frac{G_i * h_{a_i,i} * p_i}{\sum_{j=1, j\neq i}^{j\neq N} h_{a_i,j} * p_j + \sigma^2} \qquad \text{--------------(4.17)}$$

where $G_i, h_{a_i i}$ and σ^2 represent the processing gain, path gain, and noise variance for the ith user, respectively. We assume a frame in error is retransmitted until received correctly.

4.2.2 NETWORK METRIC

A natural metric of the network satisfaction is its revenue. Here in this method, the network charges each user proportional to its power. The payment of user i is defined as

$$\rho_i = \lambda_i * p_i \qquad \text{--------------(4.18)}$$

which is explicitly a function of the unit price vector $\lambda = (\lambda_1, \lambda_2, ..., \lambda_N)$, given a BS and power vector assignment. Further, if β_k denotes the set of users connected to the Base Station k ($i \in \beta_k$ if and only if $a_i = k$), the revenue collected by the BS k is defined as

$$\rho^k(\lambda) = \sum_{i \in \beta_k} \lambda_i * p_i \qquad \text{--------------(4.19)}$$

The revenue that the network collects is $\rho(\lambda) = \sum_{k=1}^{K} \rho^k(\lambda) = \sum_{i=1}^{N} \rho_i(\lambda)$, where K is number of cells and N is the number of mutually interfering users

4.2.3 JOINT USER AND NETWORK OPTIMIZATION

With the network broadcasted unit price vector λ , the user objective is to unilaterally maximize its net utility, defined as the difference between its utility and its payment

$$\max_{p_i,a_i} U_i^{net}(a_i,p_i,p_{-i},a_{-i},\lambda) = \max_{p_i,a_i}\{U_i(a\ ,p)-\lambda_i * p_i\}\forall i \qquad \text{-------------(4.20)}$$

Unlike the user-centric problem in a single-cell system where each user maximizes its net utility over its transmitter power only, the user-centric objective is to optimize the net utility over two dimensions: its transmitter power and its BS assignment. U_i^{net} is a logarithmic function of γ_i and therefore the net utility monotonically increases with γ_i. Given an interference vector p_{-i}, the BS assignment based on the net utility maximization is equivalent to the one based on maximizing SINR.

$$a_i^* = \arg\max_k U_i^{net}(k,p_i,p_{-i},a_{-i},\lambda) \qquad \text{-------------(4.21)}$$

$$= \arg\max_k \gamma_i(k,p) \qquad \text{-------------(4.22)}$$

Therefore, the user problem can be solved by assigning the BS first, followed by power control. If all the users' optimization attempts settle down, the game achieves an equilibrium called a Nash equilibrium, with equilibrium power vector and BS assignment vector $(p^*(\lambda),a^*(\lambda))$, where the power and the BS assignment vectors are defined as $p^*=(p_1^*,p_2^*,...,p_N^*)$ and $a^*=(a_1^*,a_2^*,...,a_N^*)$,respectively. Formally, the Nash equilibrium power and BS assignment vector is the one at which no single user can improve its net utility by unilaterally changing its power and its BS assignment. Mathematically, for any user i

$$U_i^{net}(p_i^*,a_i^*,p_{-i}^*,a_{-i}^*,\lambda) \geq U_i^{net}(p_i\ ,a_i\ ,p_{-i}^*,a_{-i}^*,\lambda) \qquad \text{-------------(4.23)}$$

The Nash equilibrium vector can also be written as

$$p_i^* = \arg\max_{p_i} U_i^{net}(a_i^*,p_i,p_{-i}^*,a_{-i}^*,\lambda) \qquad \text{-------------(4.24)}$$

$$a_i^* = \arg\max_k \gamma_i(k,p^*)\ \ \forall i \qquad \text{-------------(4.25)}$$

In this network optimization techniques two types of pricing have been used. In the first method, all the users belong to the same priority class, and hence the network applies a common unit price to all the users.

(a) ***Global Pricing:*** The network aims to find its highest revenue by searching over $\lambda \geq 0$ i.e [Network Problem (G)] $\max_{\lambda>0} \rho(\lambda)$,

$$\text{where } \rho(\lambda) = \sum_{i=1}^{N} \lambda * p_i^*(\lambda) \qquad \text{--------------(4.26)}$$

(b) Mini-max Pricing: Here, the network chooses the unit price as follows. First, the optimum unit price that maximizes the revenue ρ^k at the kth BS is found. Then the unit price, called the mini max price λ_M, is chosen to be the smallest among the K optimum unit prices obtained at each of the Base Stations. Mathematically, the network problem in this case can be stated as

[Network Problem (M)] $\min\{\arg\{\max_\lambda(\rho^1(\lambda)\},\ldots,\arg\{\max_\lambda(\rho^K(\lambda)\}\}$ ------------(4.27)

4.3 HANDOFF FOR A GAUSSIAN CHANNEL CAPAPCITY UTILITY FUNCTION

The quality of service (QOS) received by user can be translated quantitatively into a utility function. The utility function $U_i(a_i, p)$ of user i when it is assigned to BS a_i is defined as the average number of information bits of user i received correctly at BS a_i per second [10]

$$U_i(a_i, p) = R_i * \log_2(1 + \gamma_i(a_i, p)) \qquad \text{-------------(4.28)}$$

Revenue is the product of price per unit service and the amount of service provided. The amount of service provided by the network to any user is the amount of useful data bits that the user sends to the network over a fixed time frame, which is proportional to the user's throughput in that time frame. Assuming a fixed time frame for our system, the network charges any user i, in proportion to its throughput with a unit price λ_i. The payment of user i is defined as

$$\rho_i = \lambda_i * p_i \qquad \text{--------------(4.29)}$$

which is explicitly a function of the unit price vector $\lambda = (\lambda_1, \lambda_2, ..., \lambda_N)$, given a BS and power vector assignment. Further, if β_k denotes the set of users connected to the BS k ($i \in \beta_k$ if and only if $a_i = k$), the revenue collected by the BS k is defined as

$$\rho^k(\lambda) = \sum_{i \in \beta_k} \lambda_i * p_i \qquad \text{--------------(4.30)}$$

The revenue that the network collects is $\rho(\lambda) = \sum_{k=1}^{K} \rho^k(\lambda) = \sum_{i=1}^{N} \rho_i(\lambda)$, where K is number of cells and N is the number of mutually interfering users. With the network broadcasted unit price vector λ , the user objective is to unilaterally maximize its net utility, defined as the difference between its utility and its payment,

$$\max_{p_i, a_i} U_i^{net}(a_i, p_i, p_{-i}, a_{-i}, \lambda) = \max_{p_i, a_i} \{U_i\,(a, p) - \lambda_i * p_i\} \forall i \qquad \text{--------------(4.31)}$$

The network aims to find its highest revenue by searching over $\lambda \geq 0$

$$\max_{\lambda > 0} \rho(\lambda), \text{ where } \rho(\lambda) = \sum_{i=1}^{N} \lambda * p_i^*(\lambda) \qquad \text{--------------(4.32)}$$

After the initial base station assignment a terminal updates its power to maximize the utility function. The power control and handoff algorithm is given as follows [10]

Suppose that terminal updates its power at time instants given by the set $T_i = \{t_{i1}, t_{i2}, ...\}$ where $t_{ik} < t_{i(k+1)}$ and t_{i0}=0 for all i. Define $T = \{\tau_1, \tau_2, ...\}$ as the set of update instances $T_1 \cup T_2 \cup ... \cup T_N$ sorted in ascending order. Similarly let T_{hi} be the set of instances when terminal i checks for handoff. Define $T_h = \{\tau_{h1}, \tau_{h2}, ...\}$ as the set of handoff instances $T_{h1} \cup T_{h2} \cup ... \cup T_{hN}$ sorted in ascending order. Consider a multi cell non cooperative power control game Γ_m. For all i=1,2...N initialize the power level of users to small values. The algorithm proceeds in the following way

Start

Step 1: If terminal is assigned to base station , then go to step 2. Else compute u_{ij}, the utility for terminal i at base station j, for all j. Find $j = \arg\max_j u_{ij}$. Assign terminal i to base station j.

Step 2: For all k such that $\tau_k \in T$ and for all terminals $l \in \{1,2...N\}$ such that $\tau_k \in T_l$ compute $\hat{p}_l(\tau_k) = \arg\max_{p_l \in P_l} u_{l\hat{l}}(p_l, p_{-l}(\tau_{k-1}))$, where $\hat{l}$ is the base station to which *lth* terminal is assigned at that instant.

Step 3: For all k such that $\tau_{hk} \in T_h$ and for all terminals $l \in \{1,2...N\}$ such that $\tau_{hk} \in T_{hl}$, calculate $u_{lj}(\tau_{hk})$ for all j. Let $j' = \arg\max u_{lj}(\tau_{hk})$ for all j. if $j' \neq \hat{l}$, where $\hat{l}$ is the base station to which terminal l was assigned to, hand-off terminal l to base station j'.

End

Once handoff occurs in the system, the network once again finds the value of optimum price at which revenue is maximized for Joint Network Centric- User Centric method.

SIMULATION PARAMETERS

The basic Joint network centric-user centric Power control game has been simulated for two different utility functions in this Dissertation. The Utility functions used are Throughput based Utility Function and Gaussian Channel Capacity Utility function. The results for Throughput based utility function are available in [14] and [21]. The results for Gaussian channel capacity utility function are new and for simulations in this case, appropriate changes have been made in the Simulation parameters. Both single cell and multi cell situations have been examined with handoff included in the latter case. All the simulations have been carried out in MATLAB 7.0.1.

5.1 SINGLE CELL CDMA SYSTEM

A single cell reverse link CDMA system is considered with 9 stationary data users, fixed frame size and no error correction. Users are uniformly distributed with in a distance of 300-500m from base station such that $\Delta d = 15$ m and the cell is modeled as a one dimensional cell.

5.1.1 THROUGHPUT BASED UTILITY FUNCTION

For the utility function defined in [14], first we consider a pure user centric situation where we try to maximize the sum of net utilities with respect to cost per unit throughput. In second situation, we consider a joint network centric- user centric method where we try to maximize the sum of payments (or revenue) with respect to cost per unit throughput. Next we compare the equilibrium powers, throughput and utility for the above two situations. The various simulation parameters are listed in Table 5.1.

Table 5.1

Simulation Parameters

Number of users	N	9
Maximum power constraint	$P_{\max}$	10^(-2)
Chip rate	W	10^7
Bit rate	R	10^5
Total frame length	M	96
Information bits	L	80
Noise power	σ^2	10^(-15)

5.1.2 GAUSSIAN CHANNEL CAPACITY UTILITY FUNCTION

For the utility function defined in [10] ,we consider a Joint network centric-user centric situation where we try to maximize the sum of payments with respect to cost per unit power. Next we plot the equilibrium powers, equilibrium net utility, equilibrium SINR for the above situation. In this method, cost per unit power is equal to a constant multiplied by path gain.

Table 5.2

Simulation Parameters:

Number of users	N	9
Chip rate	W	10^7
Bit rate	R	10^5
Noise power	σ^2	10^(-15)
Maximum power constraint	$P_{\max}$	10^(-1) W

5.2 MULTI CELL CDMA SYSTEM

We consider a multi cell CDMA system with 9 Base stations serving 45 users i.e 5 users with in each cell. Users are allocated randomly with in each cell .We assume that the path gain decays with the fourth power of the distance to BS. The modulation used is non coherent frequency-shift keying (FSK). Users are randomly located in a square grid (broken into nine quadrants) where each BS is in the center of a quadrant.

5.2.1 THROUGHPUT BASED UTILITY FUNCTION

For the utility function defined in [21], we consider a Joint network centric-user centric scheme where we try to maximize the total revenue with respect to cost per unit power. Next we plot the equilibrium payment of all users with respect to global pricing and mini max pricing.

Table 5.3

Simulation parameters

Maximum power constraint	$P_{\max}$	10^(-2)
Chip rate	W	10^7
Bit rate	R	10^5
Total frame length	M	96
Information bits	L	80
Noise power	σ^2	10^(-15)
Number of users	N	45
Number of Base stations	NB	9

5.2.2 GAUSSIAN CHANNEL CAPACITY UTILITY FUNCTION

In this method, cost per unit power is equal to a constant multiplied by path gain. For the utility function defined in [10], we consider a pure network centric-user centric situation where we try to maximize the total revenue with respect to cost per unit power. Next we plot the equilibrium payment of all users with respect to global pricing and mini max pricing.

Table 5.4

Simulation parameters

Maximum power constraint	$P_{\max}$	10^(-1)
Chip rate	W	10^7
Bit rate	R	10^5
Noise power	σ^2	10^(-15)
Number of users	N	45
Number of Base stations	NB	9

5.3 HANDOFF IN MULTI CELL SYSTEM

We consider a multi cell CDMA system with 4 Base stations serving 40 users i.e 10 users with in each cell. For the Gaussian channel capacity utility function defined in [10], we consider Joint network centric-user centric situation. Next we consider the scenario where the users are moving with constant speed and the path gains are varying. The mobility of the user i is modeled with a constant but random speed in the range 0-18 km/hr. The direction for the user is picked from a uniform distribution in $[-\pi, \pi]$. Handoff situation is considered for every 10 seconds. So in 10 seconds the distance covered by mobile will be in the range of 0-50 meters. After introducing mobility, handoff takes place where we will again consider joint Network Centric –User Centric situation. Next we compare the revenue at each BS and distribution of users before handoff and after handoff. We assume that the path gain decays with the fourth power of the distance to BS.

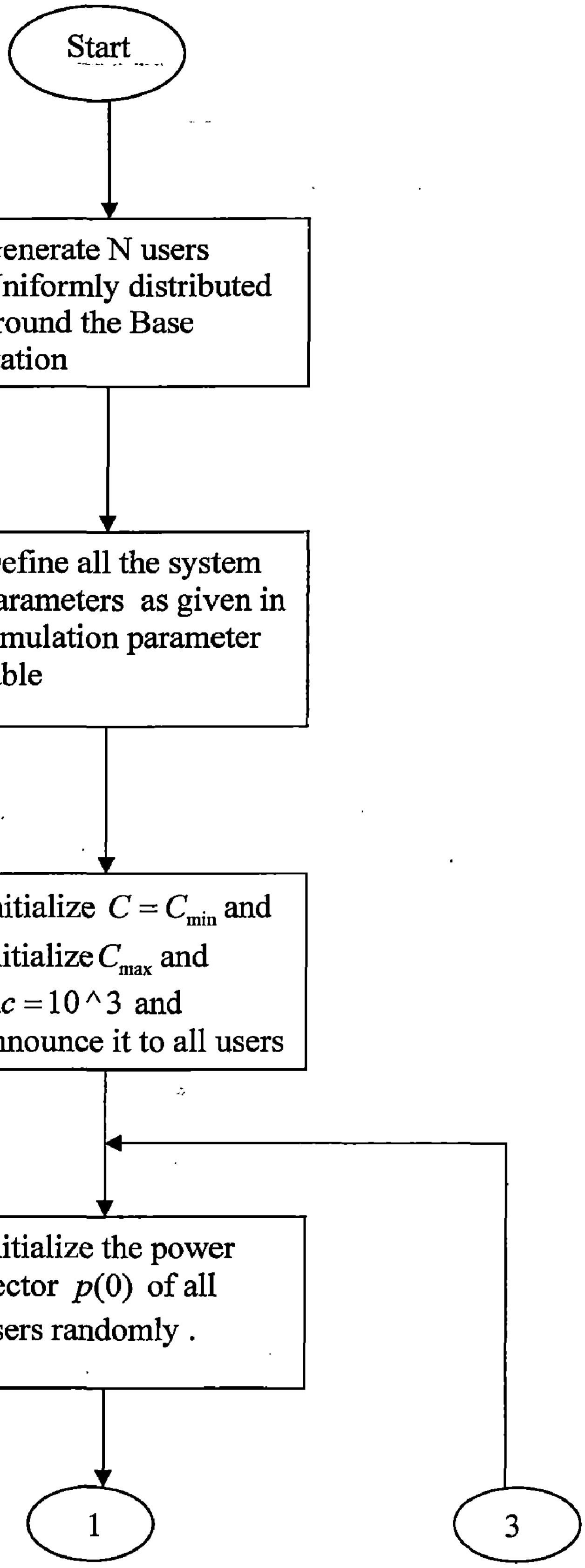
Table 5.5

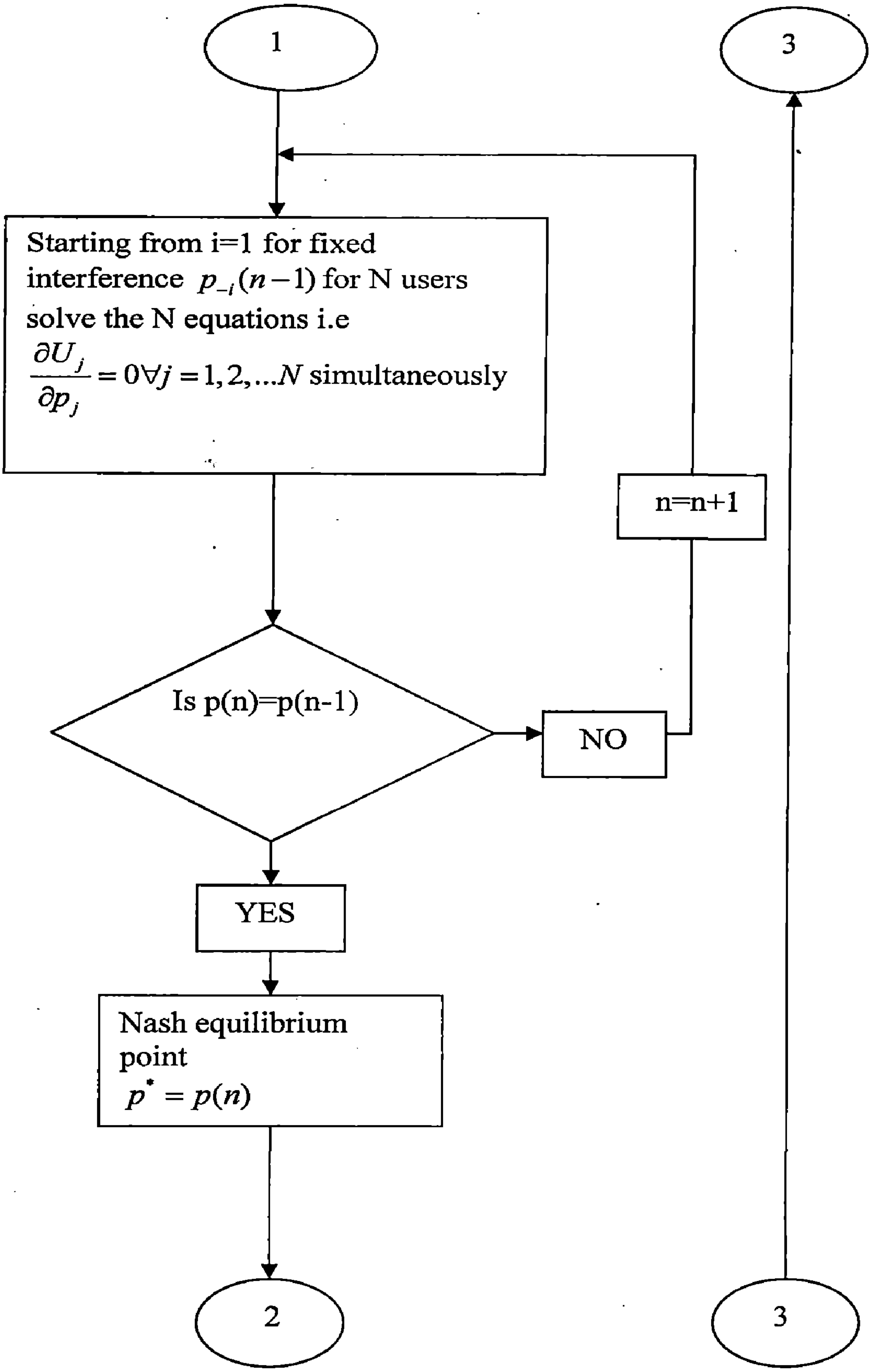
Simulation parameters

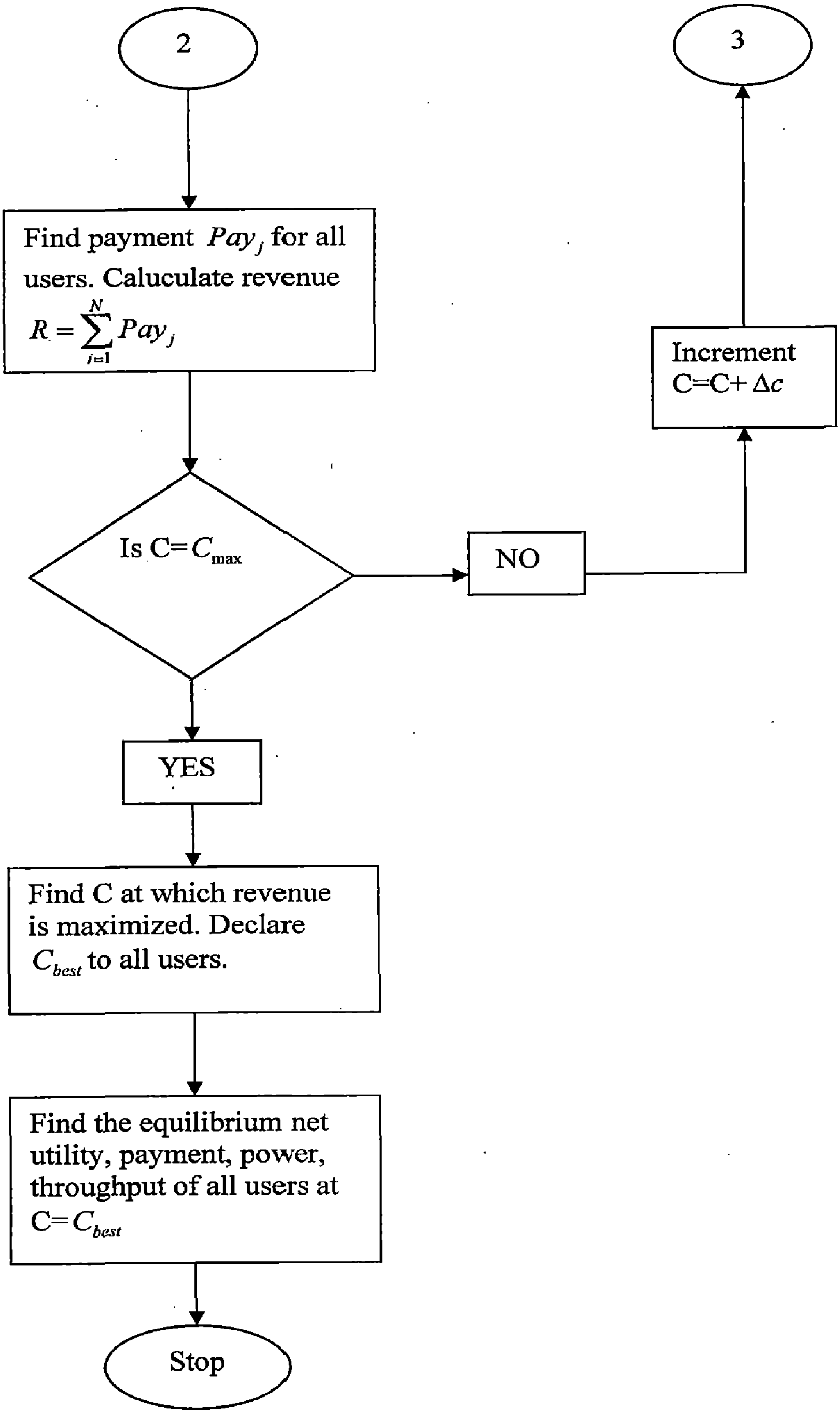
Maximum power constraint	$P_{\max}$	10^(-1)
Chip rate	W	10^7
Bit rate	R	10^5
Noise power	σ^2	10^(-15)
Number of users	N	40
Number of Base stations	NB	4

5.4 BASIC FLOWCHART FOR JOINT NETWORK CENTRIC-USER CENTRIC POWER CONTROL GAME

The Flowchart for Joint Network-Centric and User Centric is given below




1
3
Starting from i=1 for fixed interference $p_{-i}(n-1)$ for N users solve the N equations i.e $\frac{\partial U_j}{\partial p_j} = 0 \forall j = 1,2,...N$ simultaneously
n=n+1
Is p(n)=p(n-1)
NO
YES
Nash equilibrium point $p^* = p(n)$
2
3


2
3
Find payment Pay_j for all users. Caluculate revenue $R=\sum_{i=1}^{N} Pay_j$
Increment C=C+ Δc
Is C= $C_{\max}$
NO
YES
Find C at which revenue is maximized. Declare C_{best} to all users.
Find the equilibrium net utility, payment, power, throughput of all users at C= C_{best}
Stop

RESULTS AND DISCUSSIONS

From the simulations results discussed below, Equilibrium transmit powers, utilities, throughput, payment, SINR values are obtained. Simulation outputs plotted as a function of distance from the base station and as a function of cost per unit power/throughput constitute the results.

6.1 SINGLE CELL CDMA SYSTEM

6.1.1 THROUGHPUT BASED UTILITY FUNCTION

Figure 6.1.1.1 (a), (b) show the relationship between net Utilities of individual users and sum of net Utilities respectively versus cost per unit throughput for a throughput based function. As seen from the diagram, initially the net utility of each user increases monotonically with λ, reaches global maximum at λ_{opt}, where λ_{opt} varies for individual user depending on its distance from Base station and finally it decreases. Here, λ refers to cost per unit Throughput. The user nearest to Base station has larger net utility and higher value of λ_{opt} compared to other users.

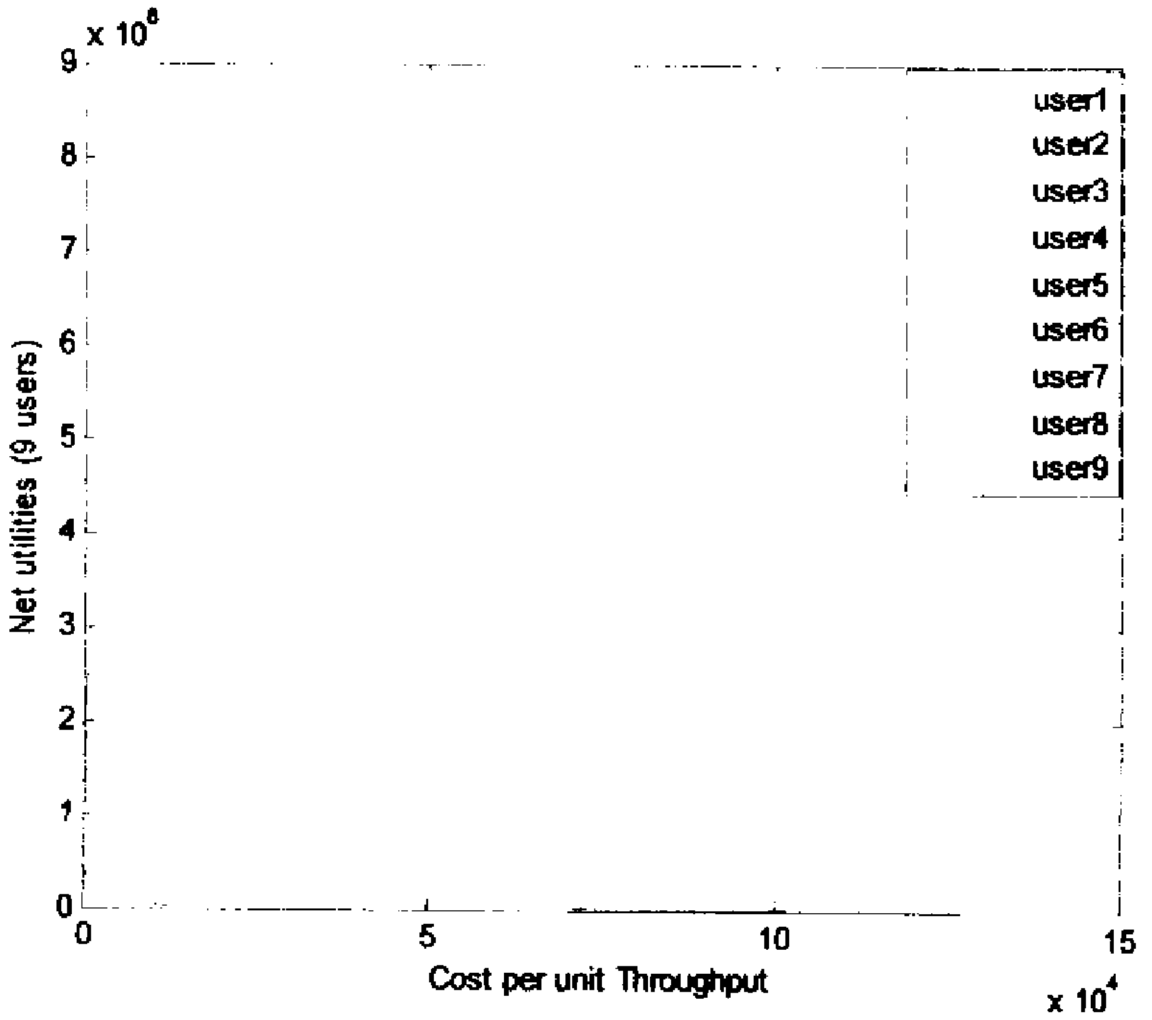


Figure 6.1.1.1 (a)

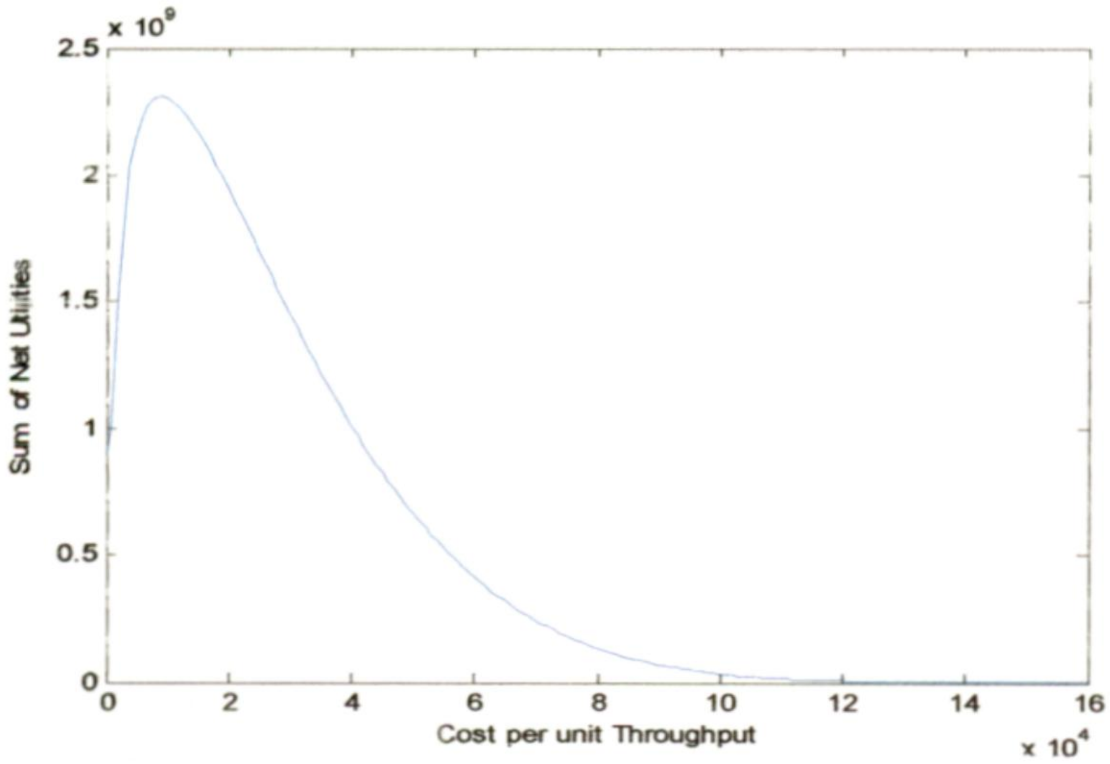


Figure 6.1.1.1 (b)

Figure 6.1.1.2 (a), (b) show the relationship between Payment of individual users and Revenue respectively versus cost per unit throughput. Revenue is obtained by individually adding the Payments of all users. The Payment of each user increases with λ where λ is cost per unit throughput and it decreases as $\lambda^{-(M-1)}$. Similarly, the Revenue obtains its maximum at λ_{opt} cost per unit throughput. The graphs obtained for Payment and Revenue are similar to those obtained in [14]. Maximization of Revenue is a joint Network centric-user centric Power control scheme. The user nearest to Base station has larger value of Payment and higher value of λ_{opt} compared to other users.

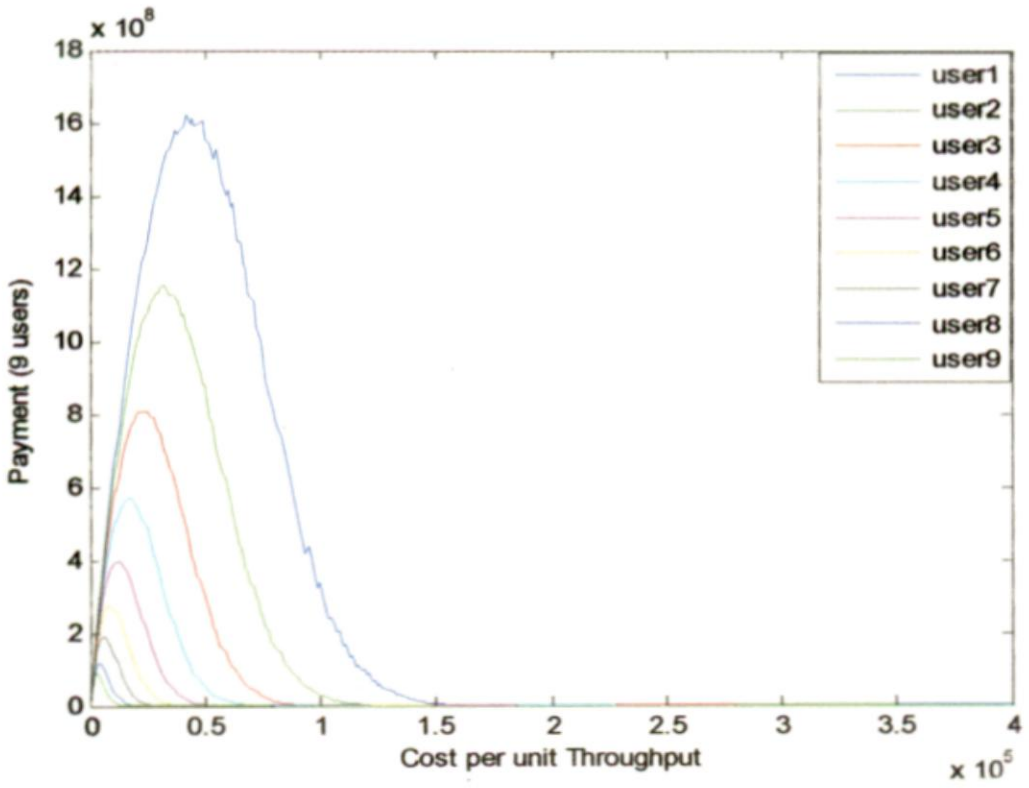


Figure 6.1.1.2(a)

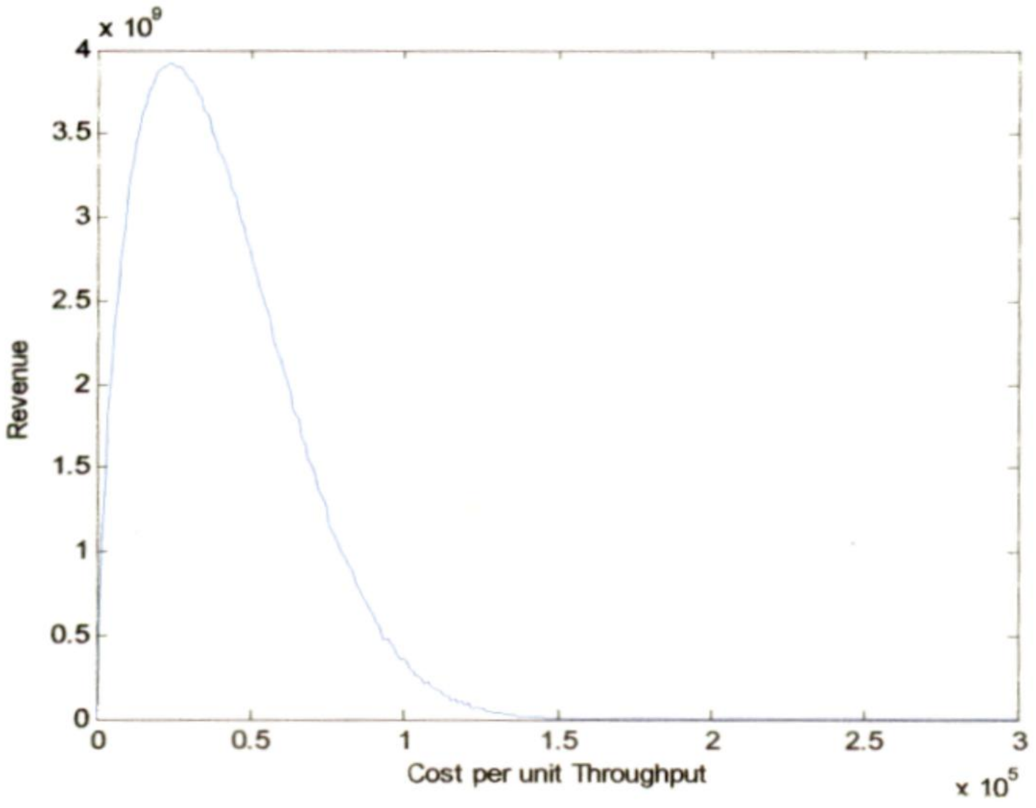


Figure 6.1.1.2 (b)

Figure 6.1.1.3 shows the relationship between Throughputs of individual users versus cost per unit throughput. The Throughput of each user decreases with λ and finally it becomes zero. For a given value of Cost per unit Throughput, the user nearest to Base station has larger value of Throughput compared to other users. Naturally, the user who is close to base station should obtain more QOS (i.e lower power, higher utility, higher throughput) compared to other users.

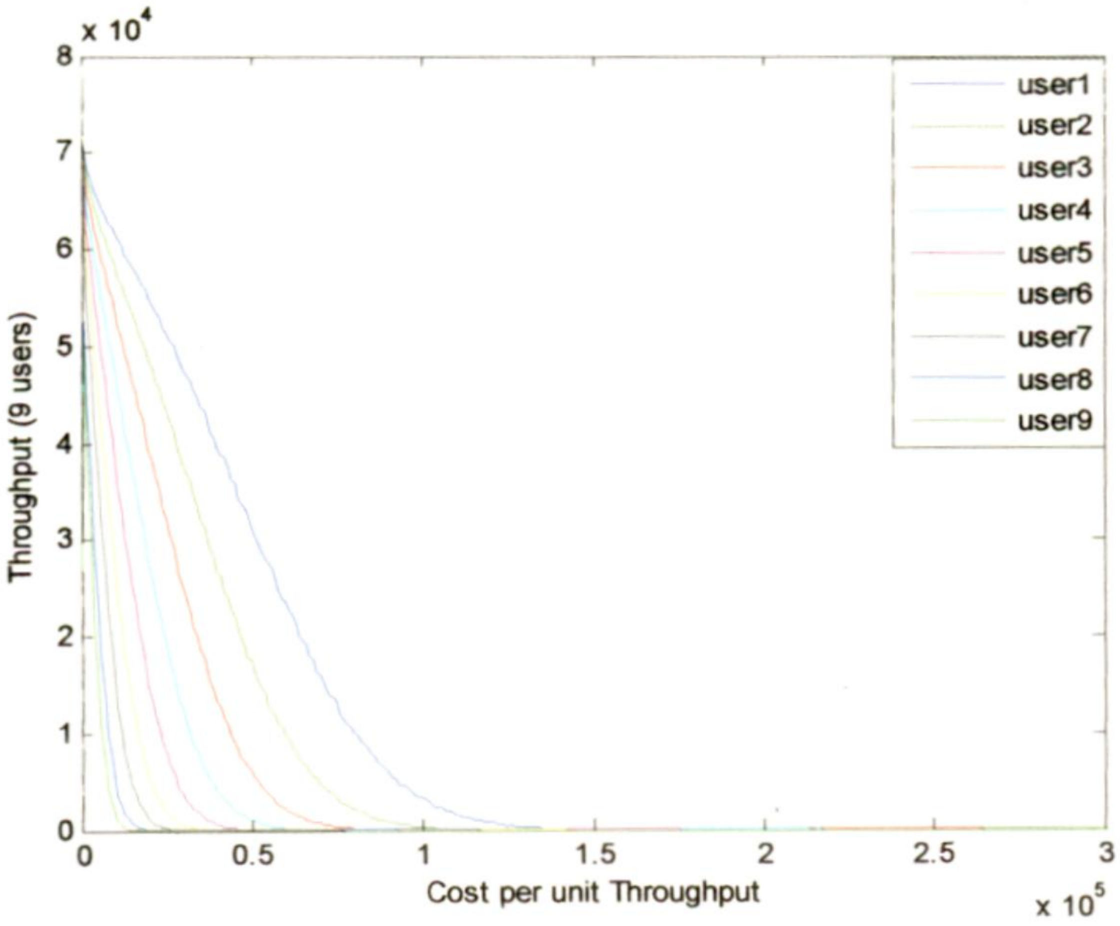


Figure 6.1.1.3

In Figure 6.1.1.4 (a), (b), Equilibrium net utility for NC-UC and Equilibrium net utility for UC of each user is plotted against its distance from Base station. Equilibrium net utilities decreases as the distance of the user from base station increases for Joint Network centric-user centric and pure user centric Power control game. The equilibrium net utility of each user is found at optimum cost per unit Throughput where the revenue gets maximized for joint network centric-user centric and sum of net utilities gets maximized for pure user centric power control game. The results obtained here are similar to the results obtained in [14].

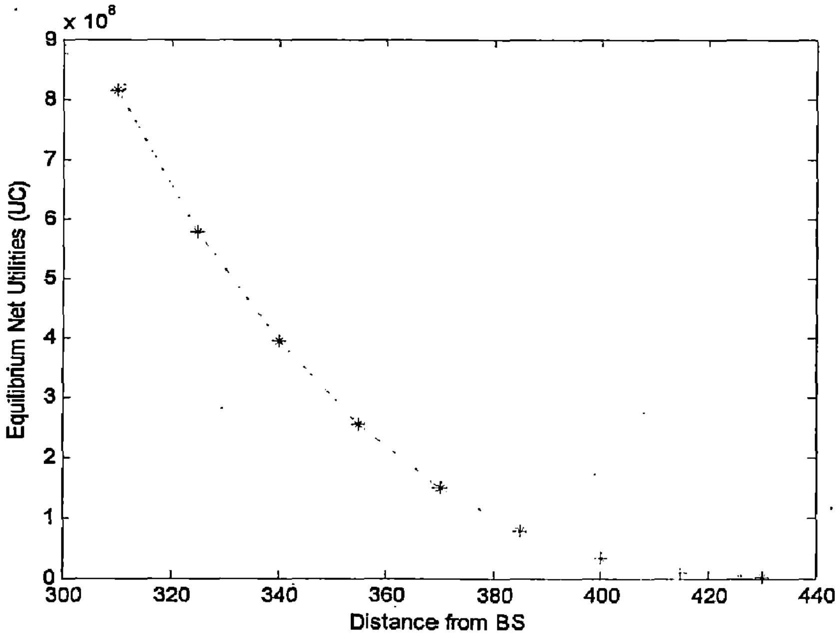


Figure 6.1.1.4 (a)

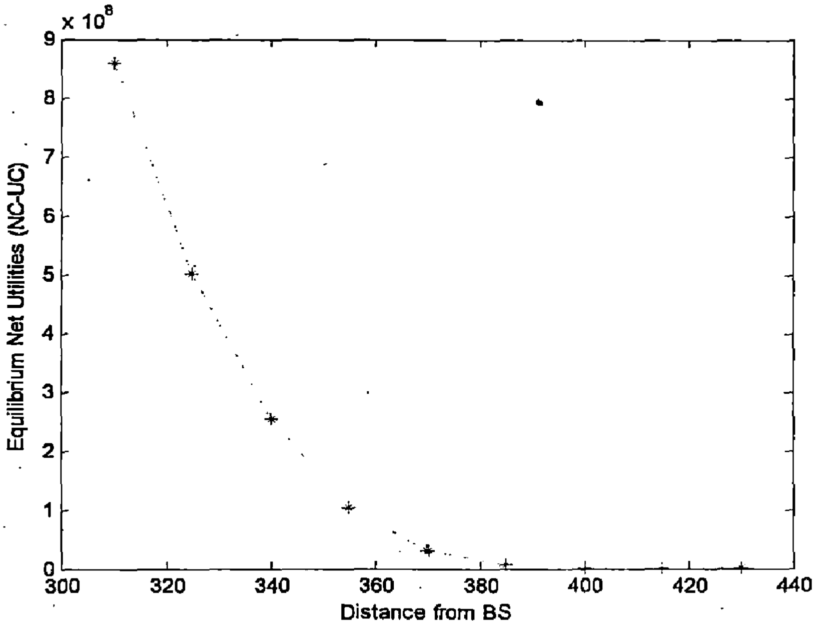


Figure 6.1.1.4 (b)

In Figure 6.1.1.5 (a), (b), Equilibrium payment for NC-UC and Equilibrium payment (UC) of each user is plotted against its distance from Base station. As seen from the diagram, Equilibrium payments of users are decreasing with increasing distance from base station. Similar behavior is exhibited in the results obtained for equilibrium payments in [14]. The values of Equilibrium payment obtained are greater in case of joint network centric-user centric game compared to pure user centric power control game.

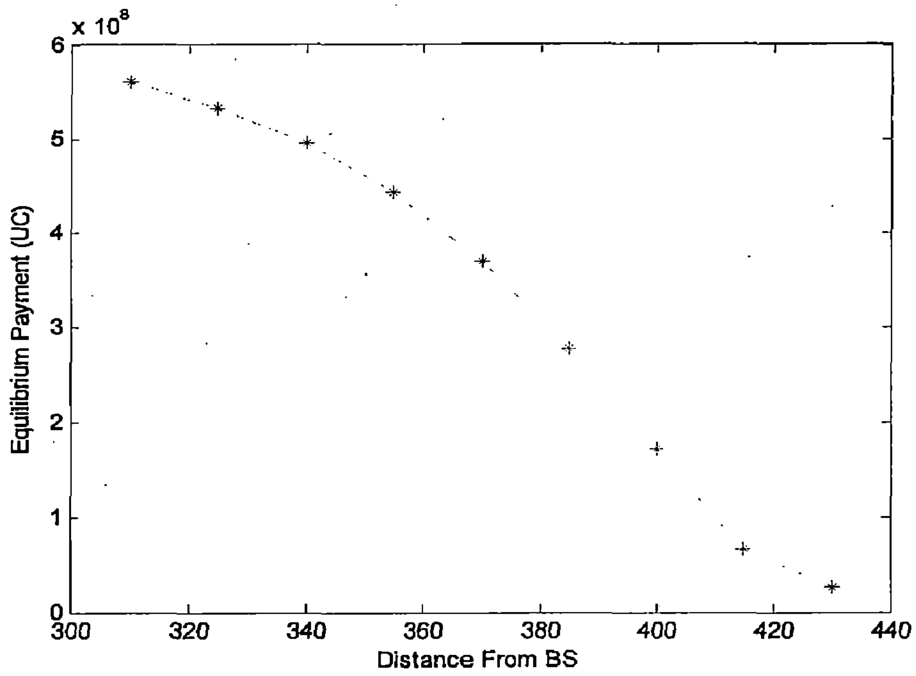


Figure 6.1.1.5 (a)

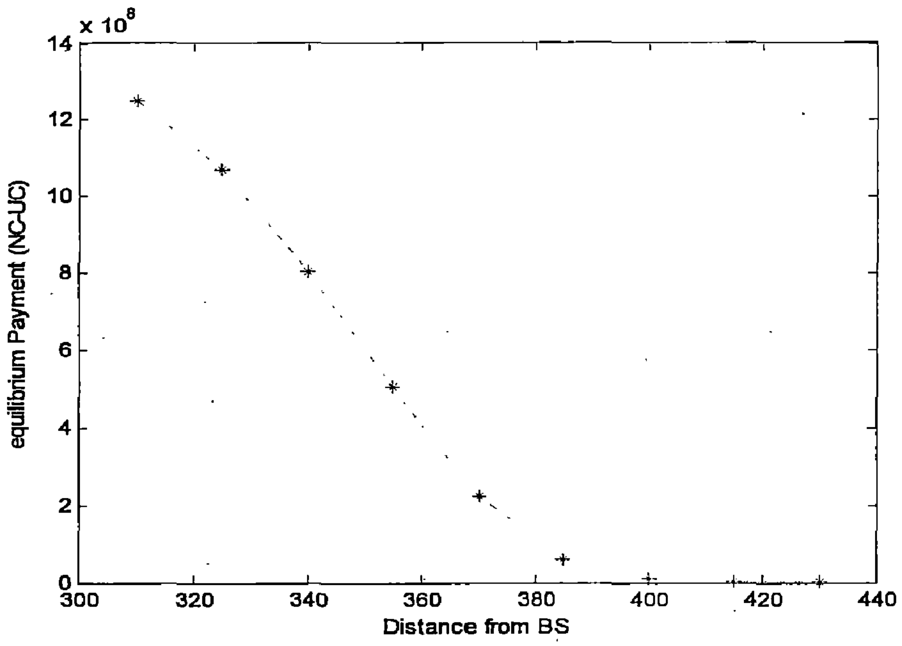


Figure 6.1.1.5 (b)

In Figure 6.1.1.6 (a), (b), Equilibrium Powers for NC-UC and Equilibrium Powers for UC of each user is plotted against its distance from Base station. Equilibrium Powers of users is increasing with increasing distance from base station. The values of Equilibrium powers obtained are higher in pure user centric power control game compared to joint network centric-user centric power control game. The results again are similar to the results obtained in [14].

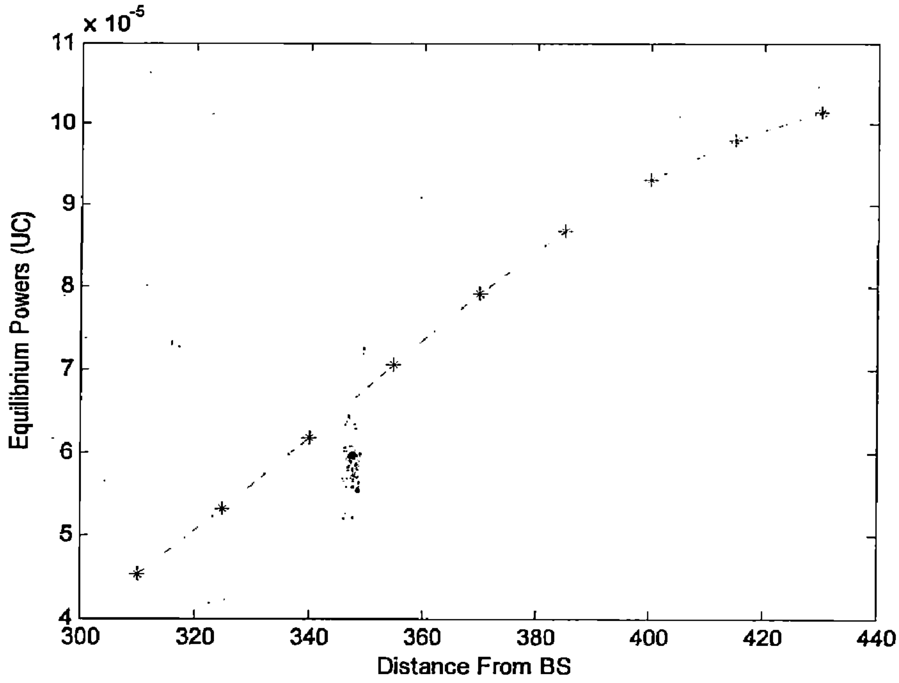


Figure 6.1.1.6 (a)

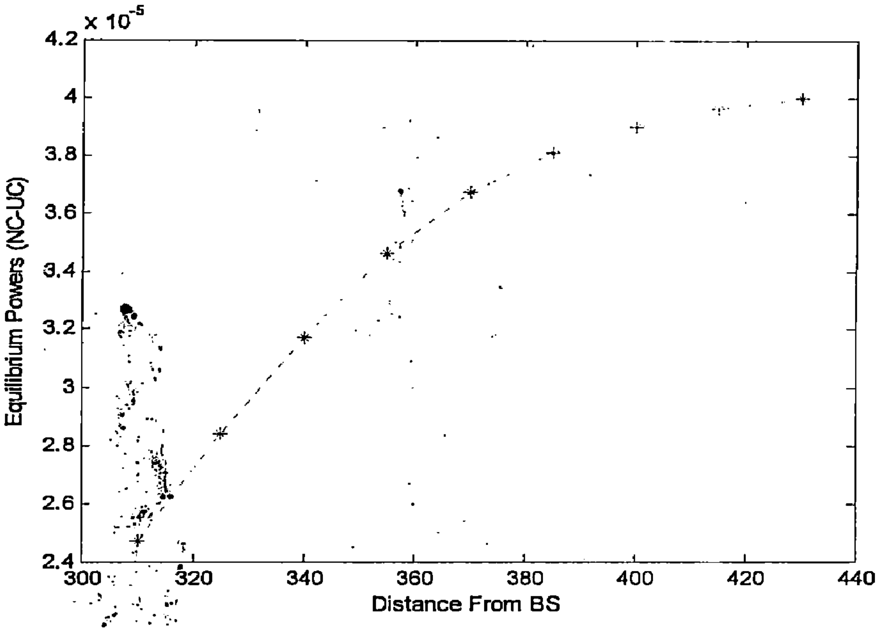


Figure 6.1.1.6 (b)

Figure 6.1.1.7 shows the relationship between Net utility and Payment of each individual user obtained at optimum unit price. The optimum unit price is the equilibrium price at which revenue gets maximized for joint network centric-user centric and sum of net utilities gets maximized for pure user centric power control game. In User Centric situation, the QOS (net utility) is distributed more evenly to users compared to Network Centric –User Centric scheme where users with best channels obtain high utility. In a Network Centric –User Centric scheme, users with better channels obtain more QOS but they pay proportionally more. In contrast for user centric, users close to base station obtain more QOS but their payment is nearly same. This shows that Network Centric – User Centric model is more sensible compared to flat rate model, where the users are charged the same rate despite their uneven QOS.

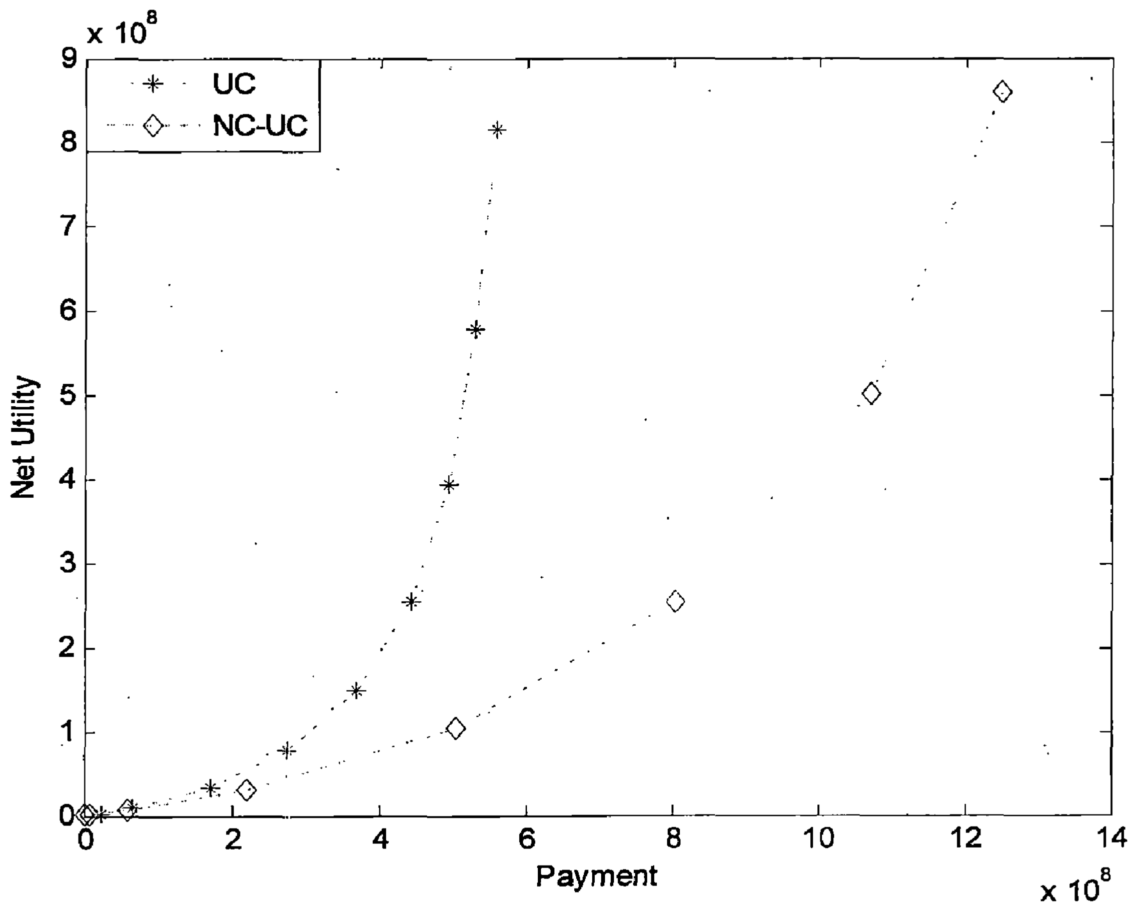


Figure 6.1.1.7

6.1.2 GAUSSIAN CHANNEL CAPACITY UTILITY FUNCTION

Figure 6.1.2.1(a), (b) show the relationship between Payment of individual users and Revenue respectively versus cost per unit Power for a Gaussian channel capacity utility function. The Payment of each user increases with λ where λ is cost per unit Power, reaches a global maximum and decreases very slowly. Similarly nature is exhibited by revenue. Maximization of Revenue is a joint Network centric-User centric Power control scheme. The user nearest to Base station has larger value of Payment compared to other users but the distant user has higher value of λ_{opt} compared to other users.

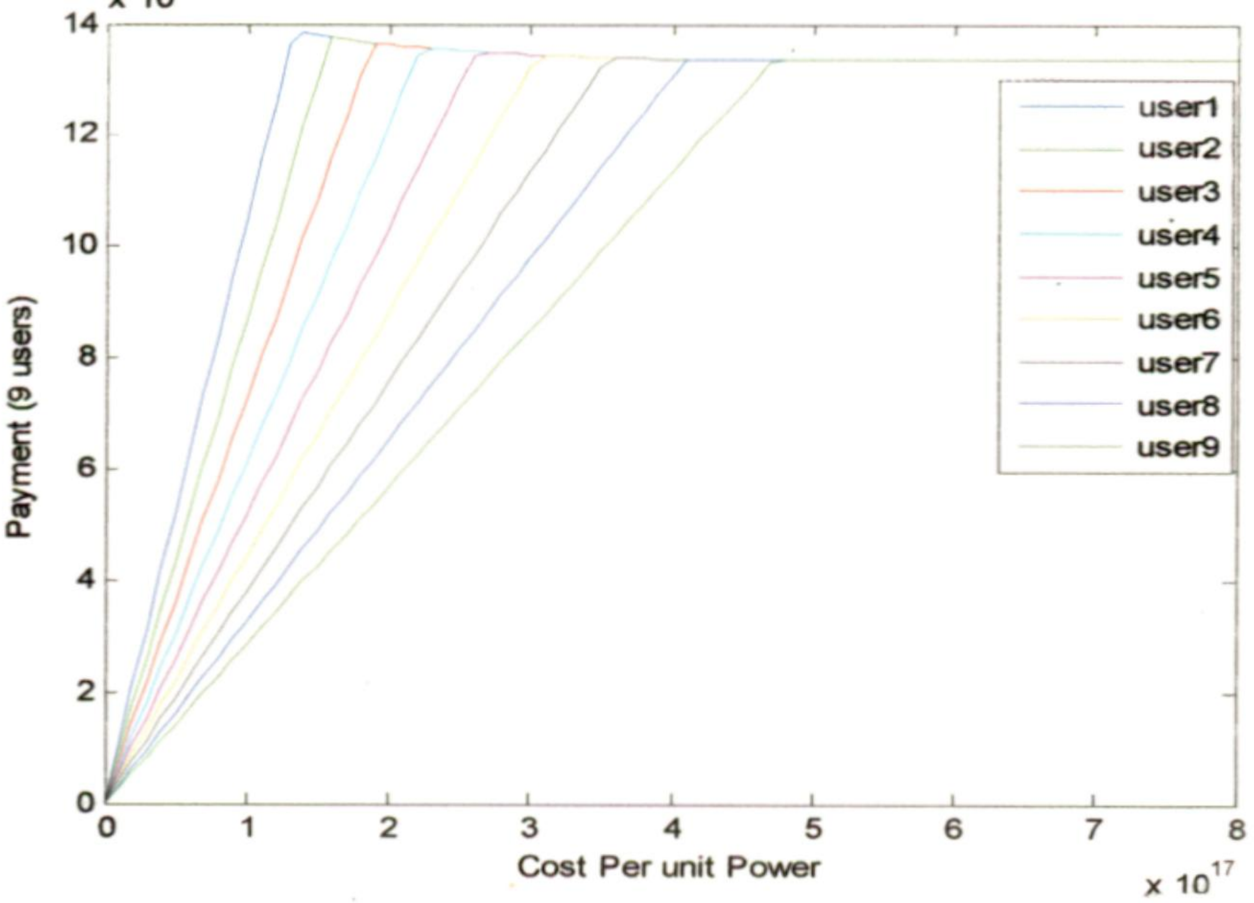


Figure 6.1.2.1 (a)

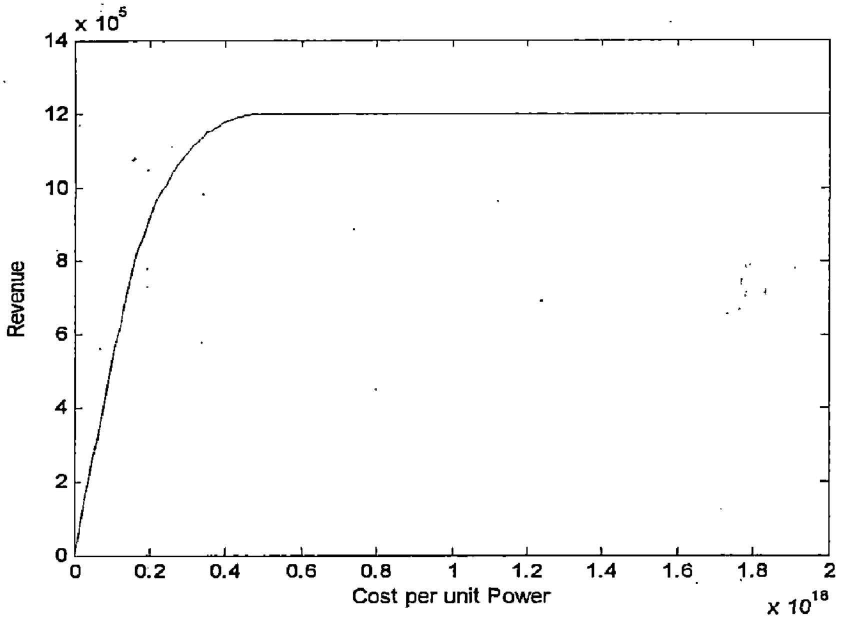


Figure 6.1.2.1 (b)

Figure 6.1.2.2 shows the relationship between Equilibrium SINR Values of each user plotted against its distance from Base station. As seen from the diagram, Equilibrium SINR is Constant for all users. Here, cost per unit power is taken proportional to path gain. The results shown in figure 6.1.2.2 match with the results obtained in [10].

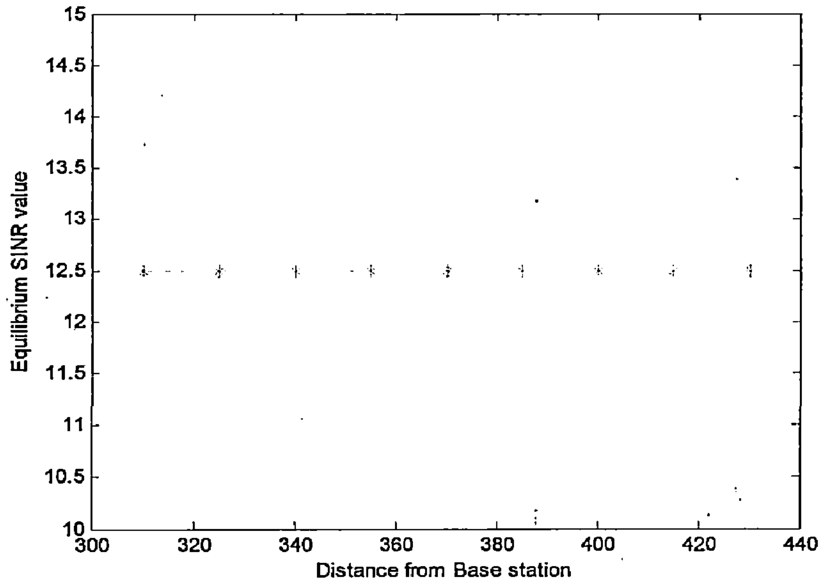


Figure 6.1.2.2

In Figure 6.1.2.3 (a), (b), Equilibrium net Utility and Equilibrium Payment of each user is plotted against its distance from Base station. Since the SINR of each user is constant, utility for all the users remain constant. Moreover at optimum unit price, payment is constant for all users. Therefore, the net utility is same for all users. This behavior is different compared to throughput based utility function. In this method, Equal QOS (net utility) and equal payment is obtained for all users.

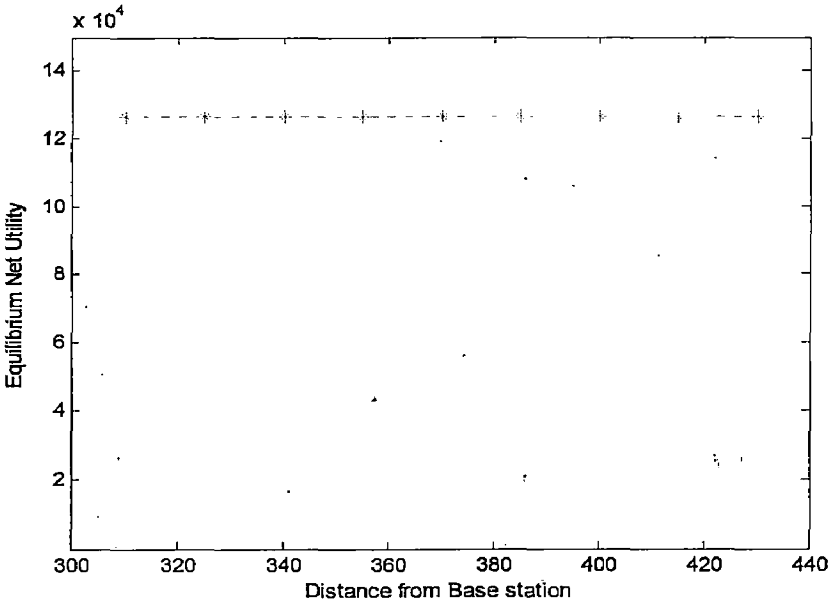


Figure 6.1.2.3 (a)

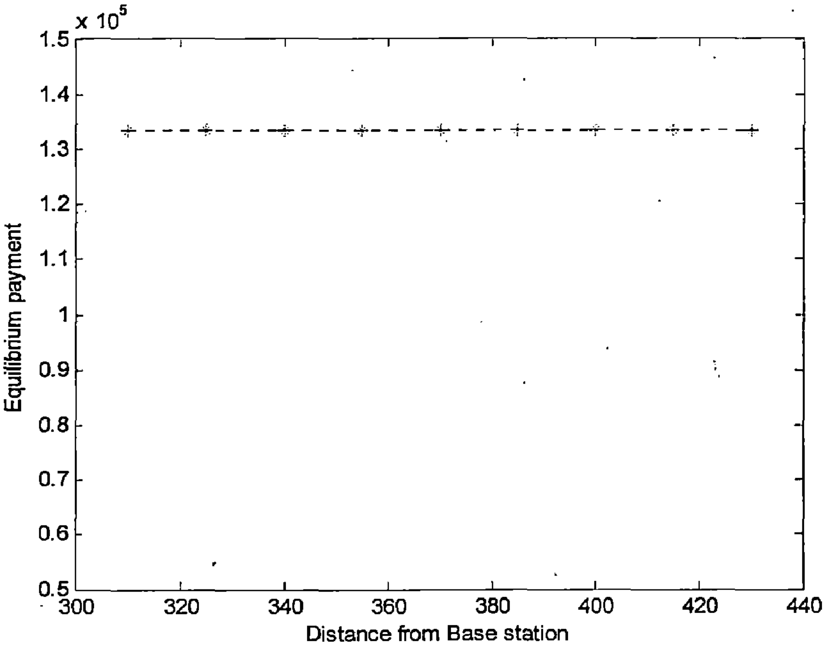


Figure 6.1.2.3 (b)

In Figure 6.1.2.4, Equilibrium Power of each user is plotted against its distance from Base station. Equilibrium Powers of users is increasing with increasing distance from base station. The user close to base station requires less power to transmit compared to all other users.

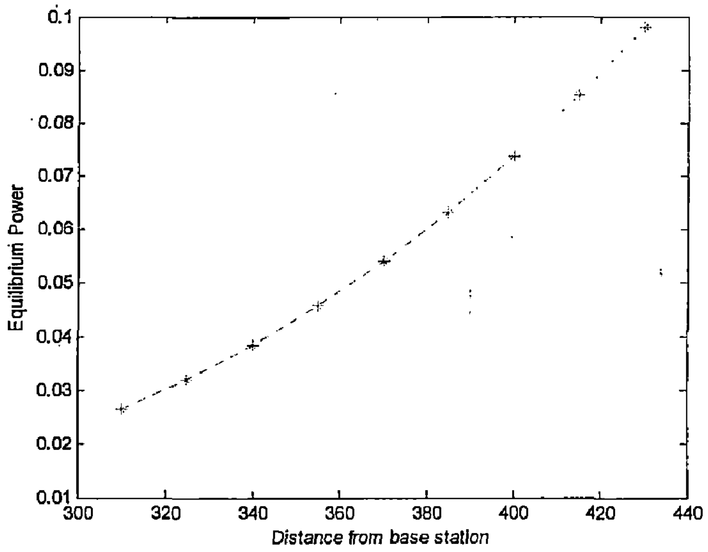


Figure 6.1.2.4

6.2 MULTI CELL CDMA SYSTEM

In figure 6.2.1, multi cell CDMA system with 9 Base stations serving 45 users i.e 5 users with in each cell is considered. Users are allocated randomly with in each cell such that the minimum distance is 50m. Users are randomly located in a square grid (broken into nine quadrants) where each Base Station is in the center of a quadrant. The dimensions of the square grid are 1000*1000 metres.

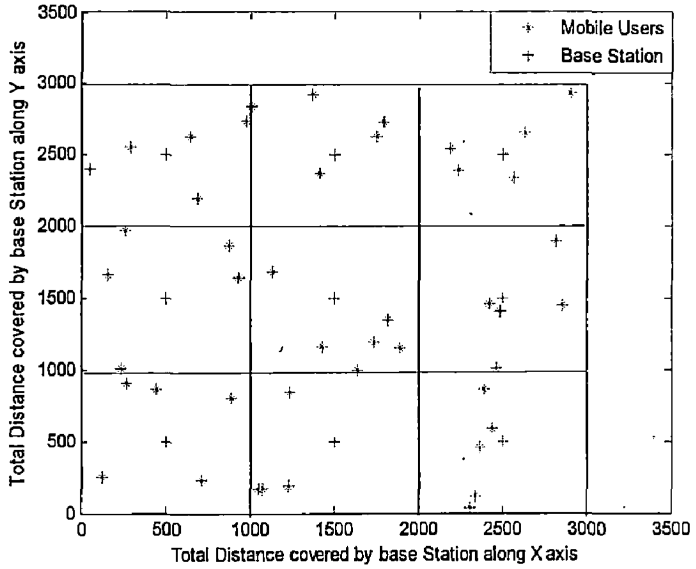


Figure 6.2.1 Distribution of users

6.2.1 THROUGHPUT BASED UTILITY FUNCTION

Figure 6.2.1.1 (a), (b) shows the relationship between Revenue of each base station and Total Revenue respectively versus cost per unit Throughput. Revenue of a particular base station is obtained by adding the payments of individual users assigned to that base station and total Revenue is obtained by adding the payments of all users. Initially the Revenue of each base station increases with λ, reaches a global maximum at λ_{opt} and finally it becomes zero. Similar behavior is exhibited by Total Revenue. The following result was obtained by taking the average of 25 simulations where, in each simulation, users were allocated randomly. These Results are similar to the results obtained in [21].

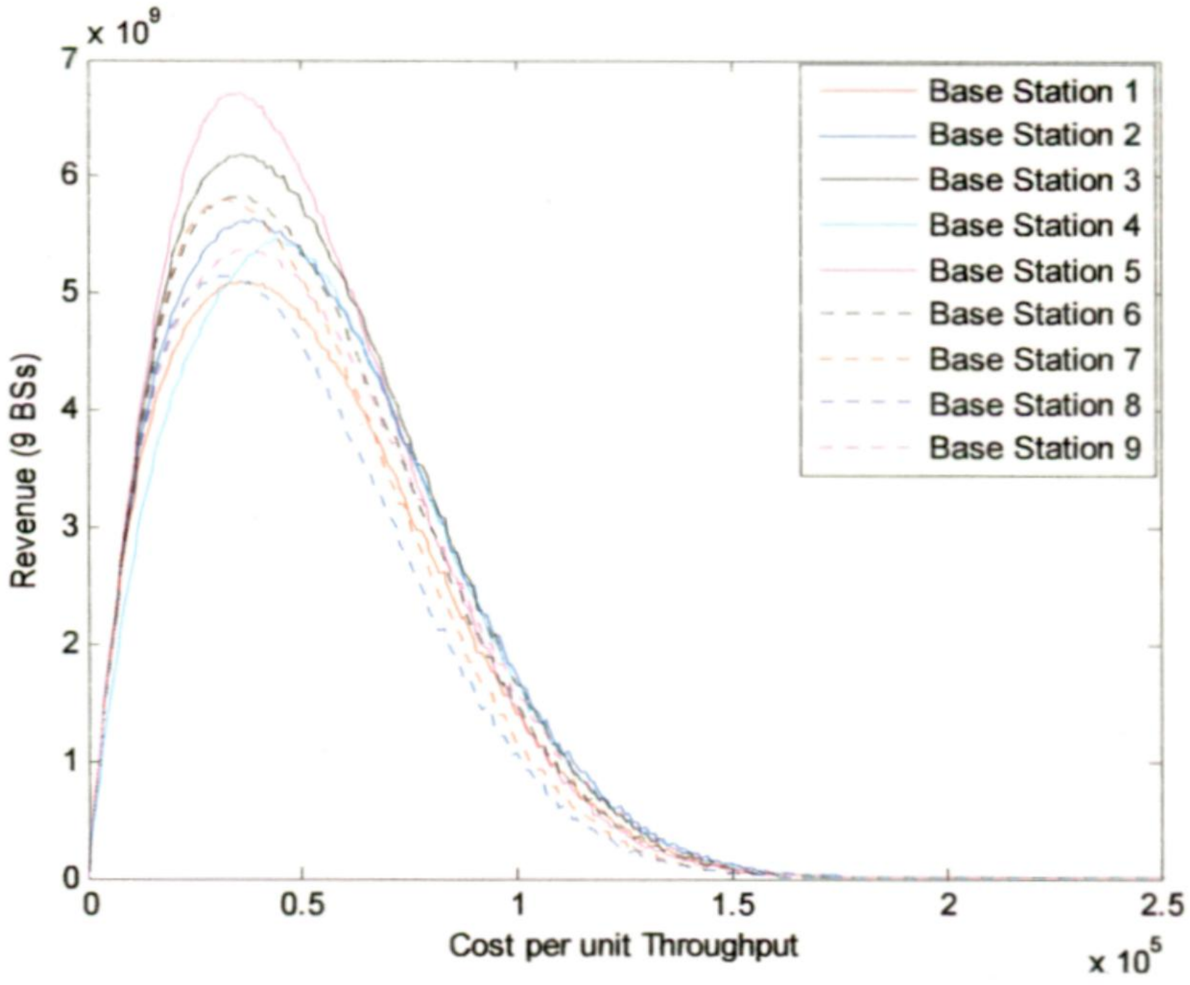


Figure 6.2.1.1 (a)

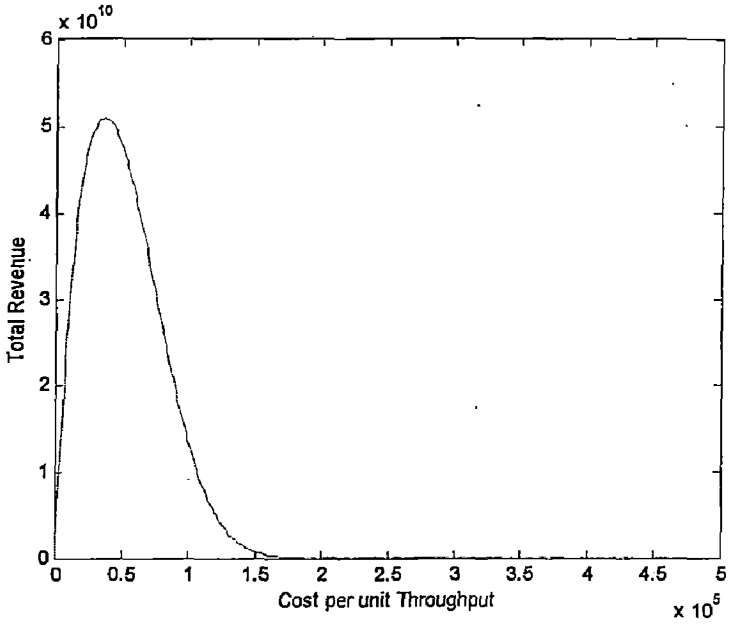


Figure 6.2.1.1 (b)

Figure 6.2.1.2 shows the relationship between Equilibrium payment of all users at Global Pricing versus distance from Base station. The network collects more revenue using the global pricing scheme. However, the network obtains its revenue mainly from the few users with the best channels when using global pricing. There are 8 users in this case who have a high value of payment at global pricing.

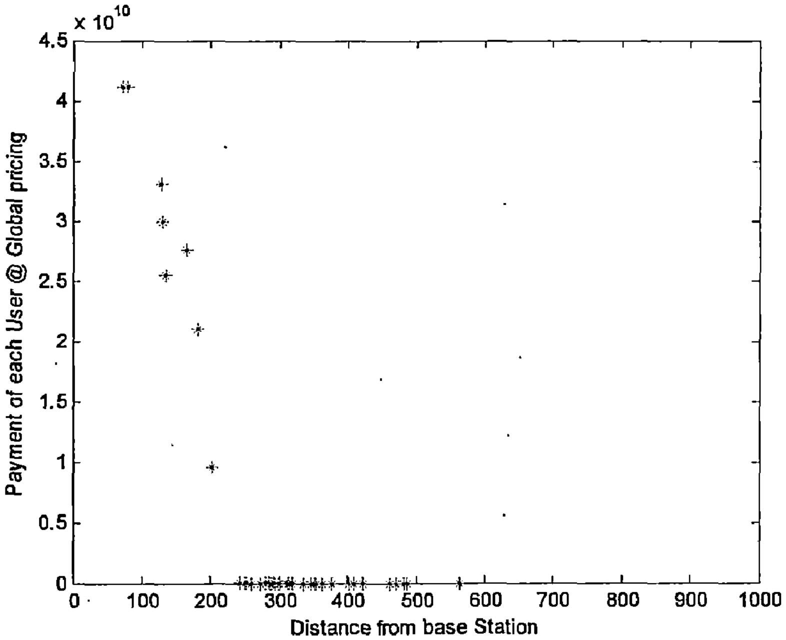


Figure 6.2.1.2

Figure 6.2.1.3 shows the relationship between Equilibrium payment of all users at Mini max Pricing versus distance from Base station. The network collects less revenue using the mini max pricing scheme compared to global pricing. However, the network collects nontrivial fractions of the revenue from more users when using mini max pricing. There are nearly 30 to 35 users in this case who have a high value of payment at mini max pricing

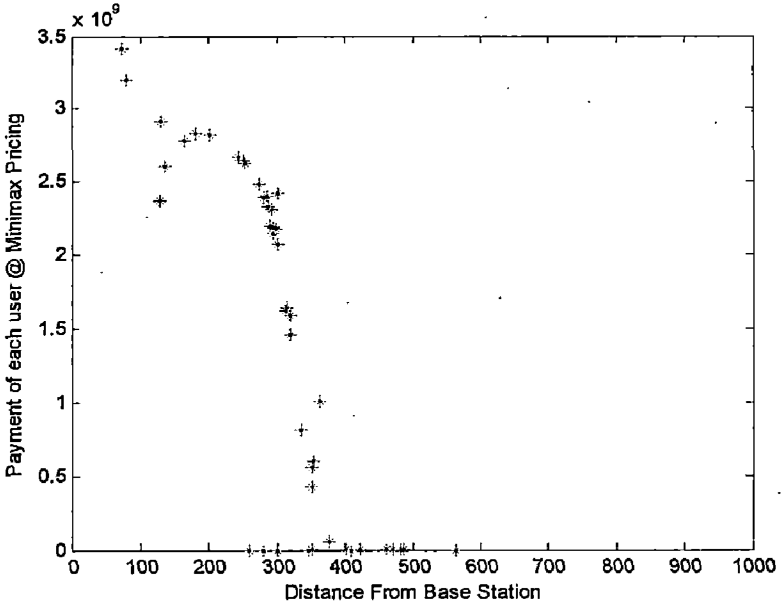


Figure 6.2.1.3

6.2.2 GAUSSIAN CHANNEL CAPACITY UTILITY FUNCTION

Figure 6.2.2.1(a), (b) shows the relationship between Revenue of each base station and Total Revenue respectively versus cost per unit Power. As seen from the diagram, initially the Revenue of each base station as well as the Total Revenue increases with λ, reaches maximum and decreases very slowly. The following result was obtained by taking the average of 35 simulations where, in each simulation, users were allocated randomly.

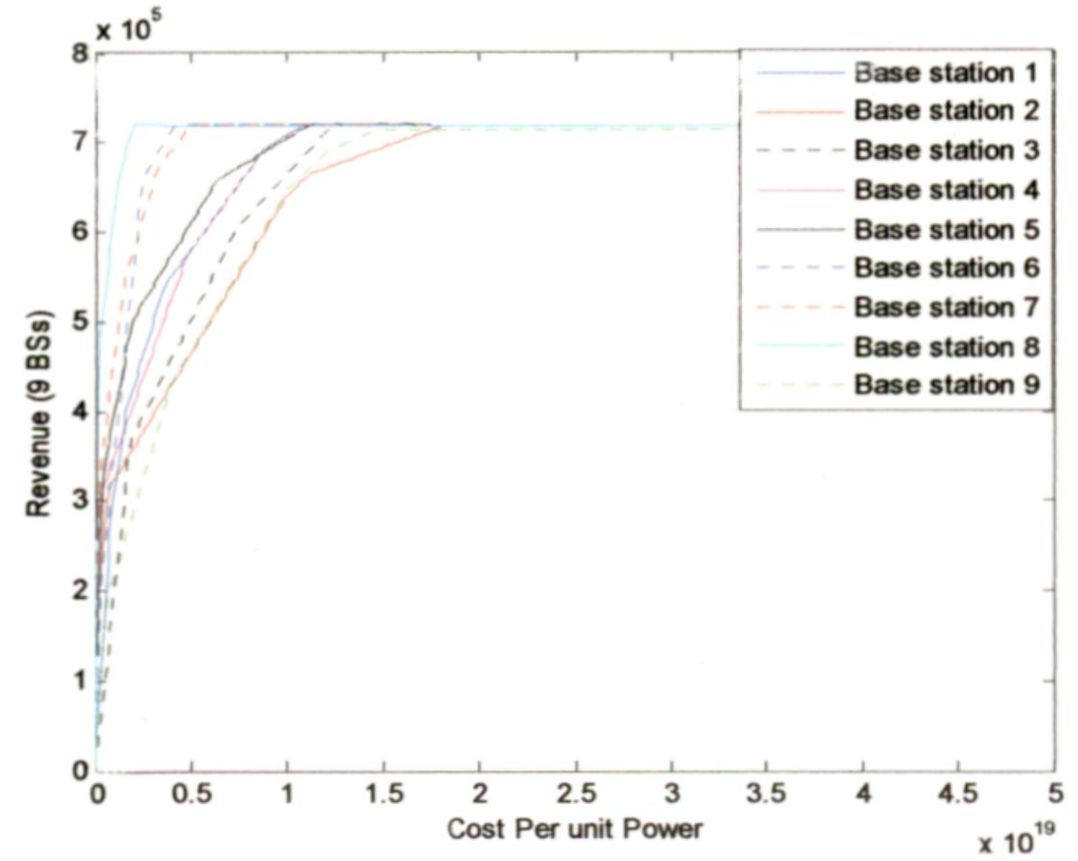


Figure 6.2.2.1 (a)

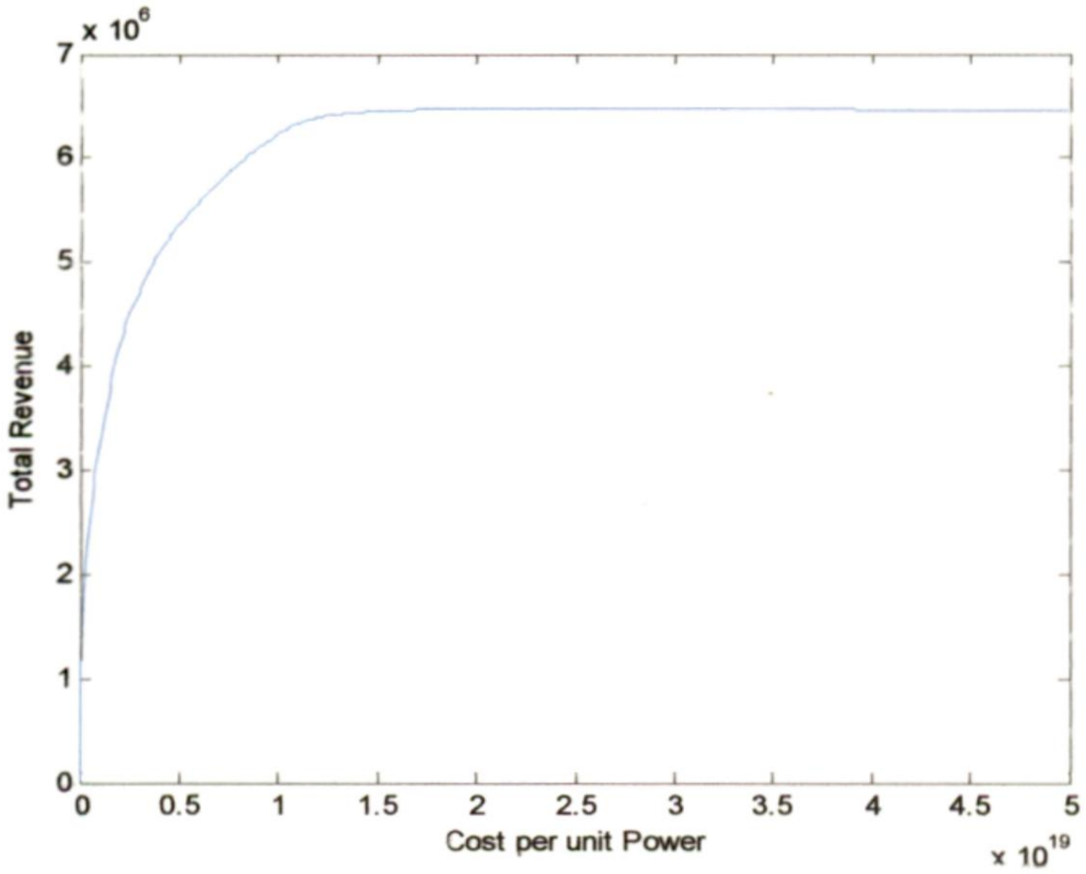


Figure 6.2.2.1 (b)

Figure 6.2.2.2 shows the relationship between Equilibrium payment of all users at Global Pricing versus distance from Base station. The network collects equal revenue from all users at global pricing scheme. However, the network obtains more revenue compared to mini max pricing. This result is similar to the result obtained in figure 6.1.2.3(b) .

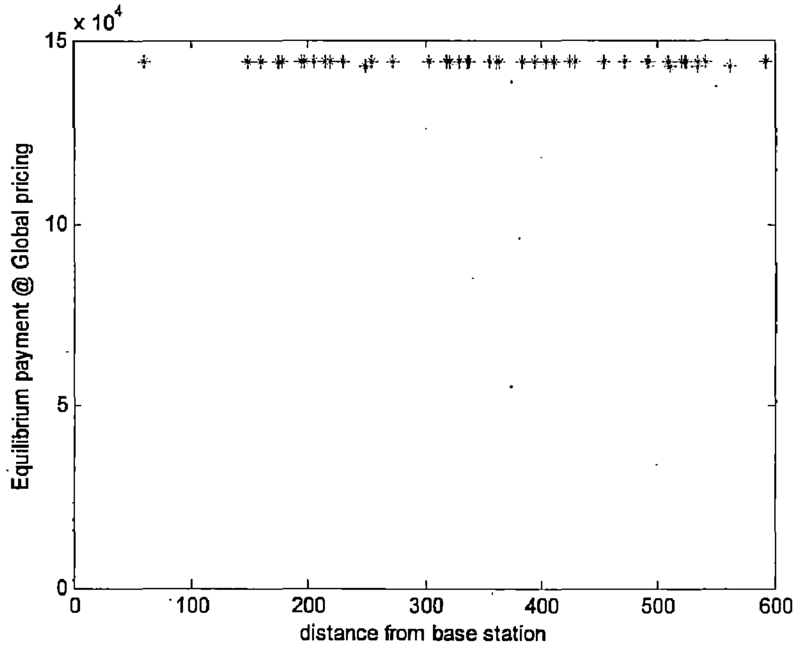


Figure 6.2.2.2

Figure 6.2.2.3 shows the relationship between Equilibrium payment of all users at Mini Max Pricing versus distance from Base station. Equal revenue is obtained from few users with best channels and for other users, revenue decreases as the distance of the user from base station increases. However, the network obtains less revenue compared to Global pricing.

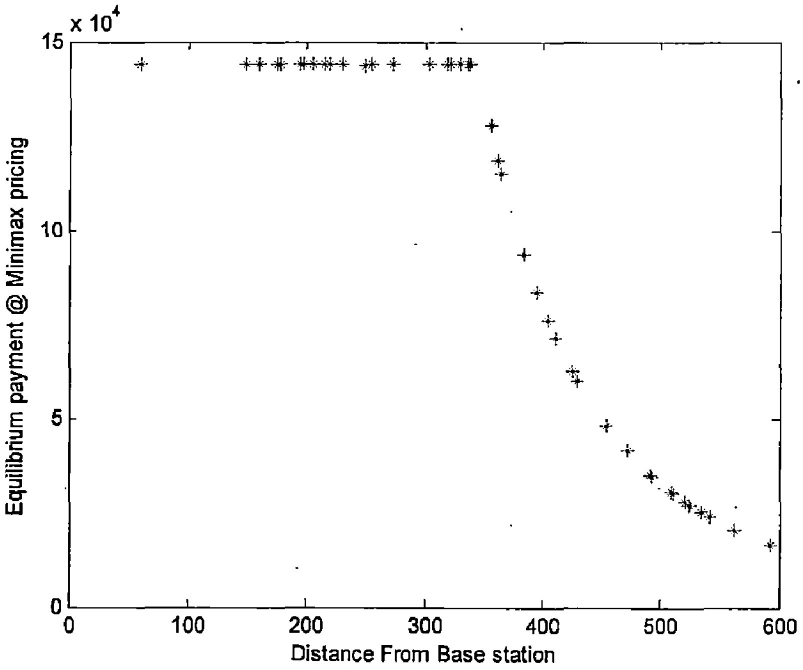


Figure 6.2.2.3

6.3 HANDOFF IN MULTI CELL SYSTEM USING GAUSSIAN CHANNEL CAPACITY UTILITY FUNCTION

Figure 6.3.1 (a), (b) represents the Revenue of each base station before handoff and Revenue of each base station after handoff respectively versus cost per unit power for a Gaussian channel capacity utility function. By introducing mobility in the system, the distance of users from base station and the number of users with in each Base station changes. So the revenue of each base station gets changed.

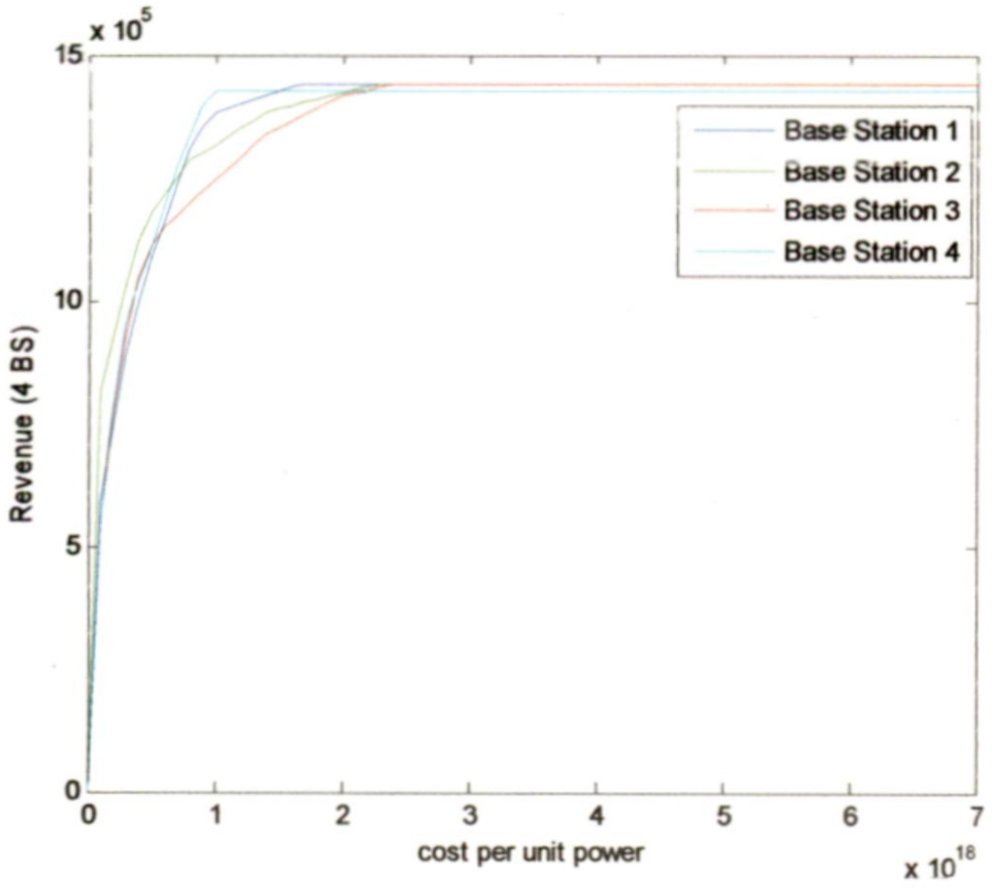


Figure 6.3.1(a)

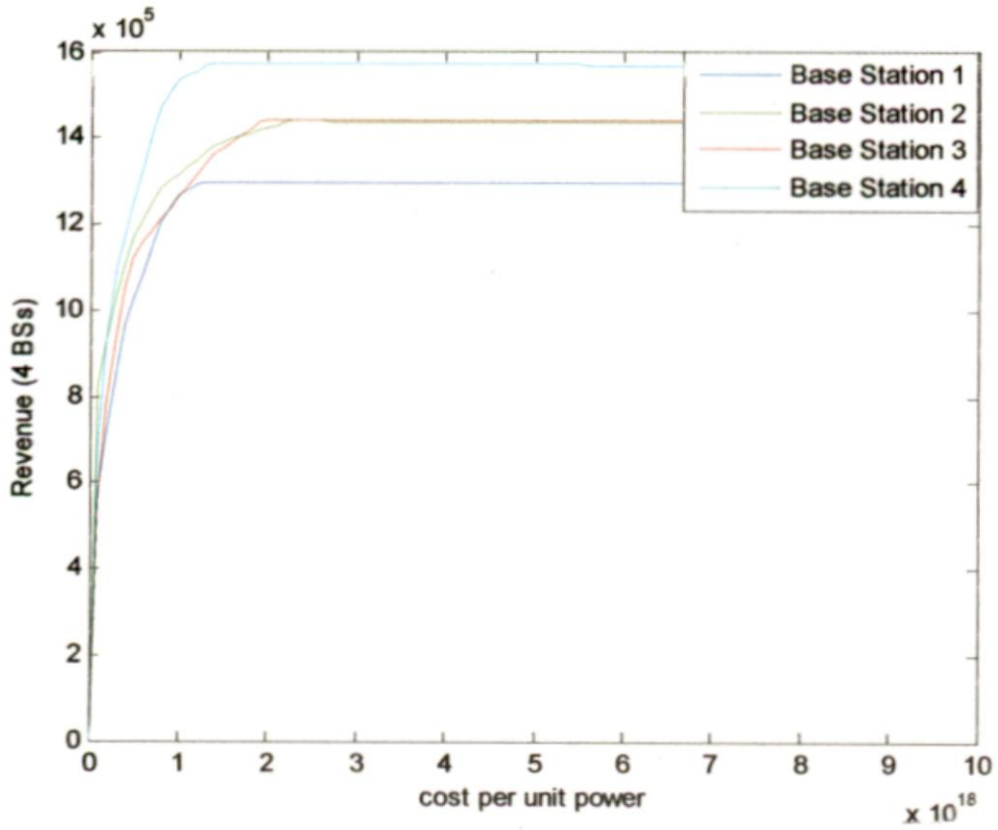


Figure 6.3.1(b)

Figure 6.3.2 (a), (b) represents the Total Revenue of the System before handoff and Total Revenue of the System after handoff respectively versus cost per unit Power. After handoff, revenue of a base station may increase or decrease depending on the number of users and the distance of users from that base station. But on an average, the total revenue of the system remains same.

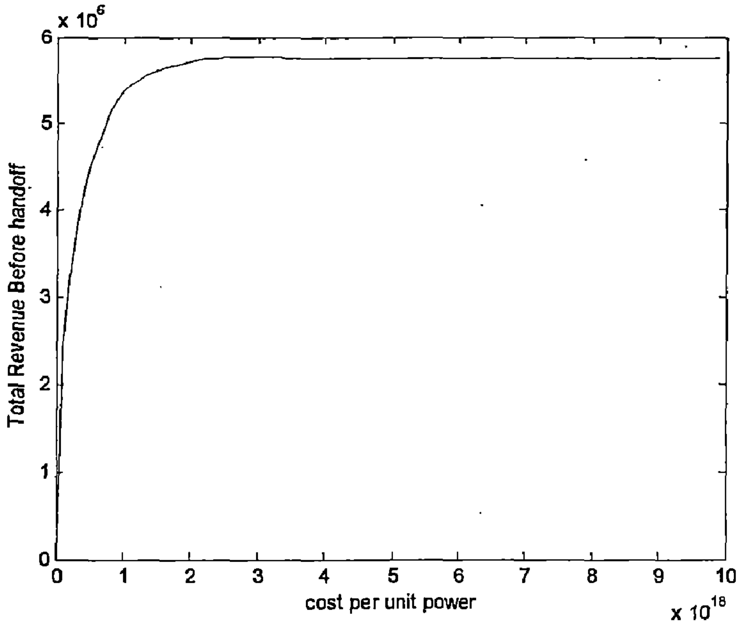


Figure 6.3.2 (a)

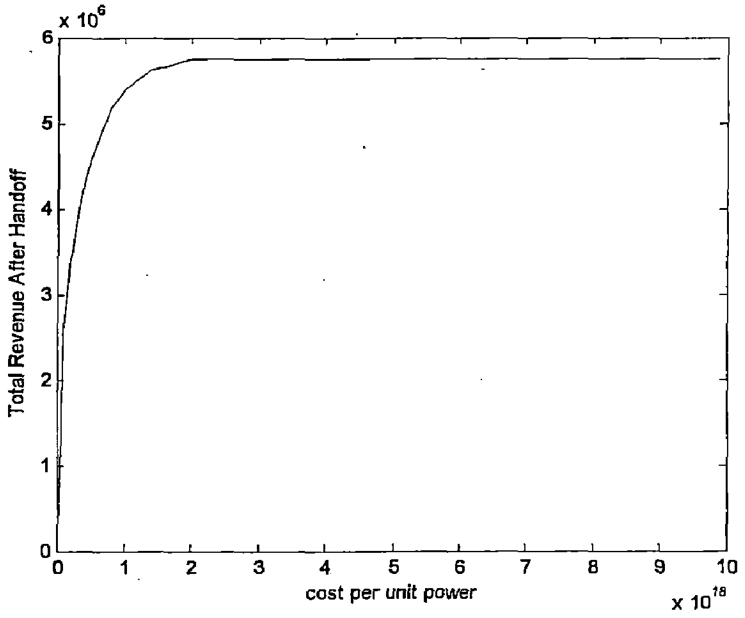


Figure 6.3.2 (b)

Figure 6.3.3(a), (b) represents the distribution of users before handoff and distribution of users after handoff respectively. Here, we consider a multi cell CDMA system with 4 Base stations serving 40 users i.e 10 users with in each cell. Users are allocated randomly with in each cell such that the minimum distance is 50m. Users are randomly located in a square grid (broken into four quadrants) where each Base Station is in the center of a quadrant. The dimensions of the square grid are 1000*1000 meters. The number of users in each Base Station varies, after handoff due to mobility.

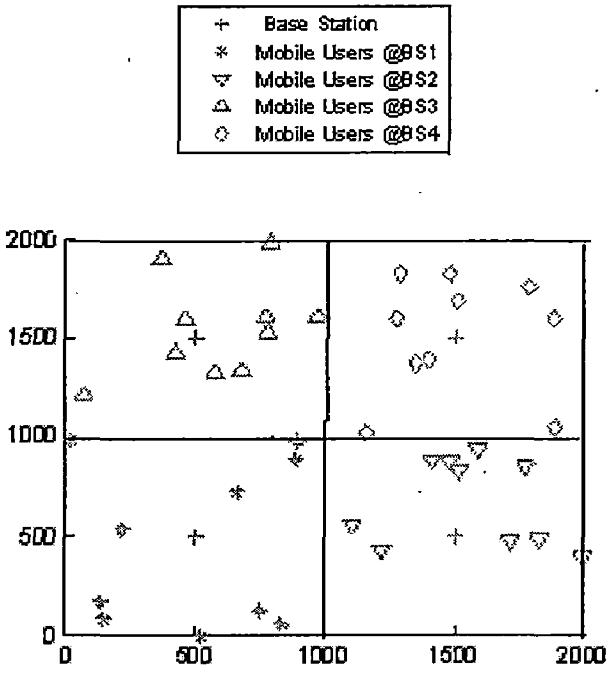


Figure 6.3.3 (a) Distribution of users before Handoff

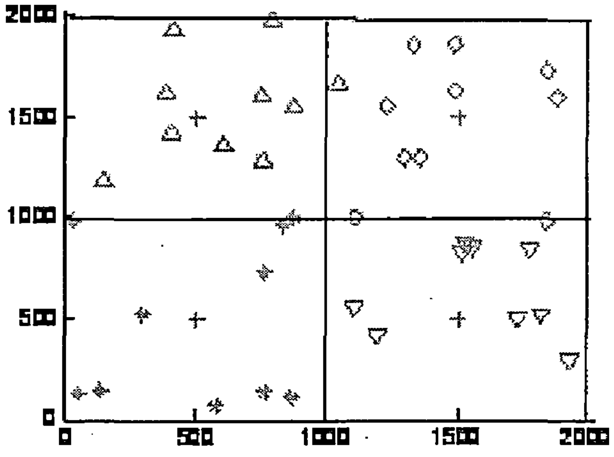


Figure 6.3.3 (b) Distribution of users after Handoff

CONCLUSION

It is evident from the simulation results for Joint Network Centric-User Centric Power Control Game for single cell using Throughput based Utility Function that users with better channels obtain Higher Utility, transmit with Lesser Power but they pay proportionally more, compared to other users. If we consider a pure user centric Power Control Game for the same situation, Quality of Service (QOS) is distributed evenly to all users. Moreover, the payment is same despite their uneven QOS. There exists an Equilibrium Unit Price at which Net Utility is maximized for User Centric Power Control Game and Revenue is maximized for Joint Network Centric –User Centric Power Control Game. In this single cell situation, for Gaussian Channel Capacity Utility Function there exists an optimum price at which Revenue is maximized for Network Centric-User Centric Power Control Game. All the users obtain the same value of Net Utility, Payment, SINR at Equilibrium unit price.

In a multi cell System using Throughput based Utility Function, we observe that network obtains its Revenue mainly from few users with best channels at Global pricing. At Mini-max pricing, network trades off revenue for a more even resource allocation i.e the network collects non trivial fractions of the Revenue from more users. Considering the above situation for a Gaussian Channel Capacity Utility Function, we infer that the network collects equal Revenue from all users at Global pricing. At Mini-max pricing, equal revenue is obtained from few users with best channels and for other users Revenue decreases with increasing distance from Base station. Next, by introducing Handoff in the multi cell system, we observe that the individual payment of each base station gets changed due to change in the number of users assigned to each base station. Moreover, there is marginal change in the total revenue, but on an average the total Revenue remains same.

7.1 FUTURE WORK

The following problems are proposed for future work :

1. We have used only linear pricing. Other pricing functions can also be considered.
2. In all our models we have considered the number of users are fixed. Work can be done by considering that the arrivals and departures of users are random and number of users varies from time to time.
3. Power allocation in forward link multi cell system subject to total power constraint can be evaluated.
4. Power control Game can be modeled for mixed Voice and Data services.
5. Performance evaluation of Power management in Adhoc Networks, MIMO-OFDM using Game theoretic approach can be considered..

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APPENDIX

Source code for Joint Network Centric-User Centric Power control game using a Throughput based Utility Function:

```
clc;
% Declaration Of variables
W=10^7;
R=10^5;
G=W/R;
M=96;
L=80;
N=10^(-15);
pmin=10^(-7);
pmax=10^(-3);
Cmin=10^0;
Cmax=10^5;

% distance from base station
d=[310 325 340 355 370 385 400 415 430];

% Path Gains
h=0.097./((d).^4);

h1=h(1);h2=h(2);h3=h(3);h4=h(4);h5=h(5);h6=h(6);h7=h(7);h8=h(8);h9=h(9);

j=1;
for C=Cmin:10^3:Cmax % Cost Per unit Throughput

% Initial Power vector

p1(j,1)=0.0012; p2(j,1)=0.0034; p3(j,1)=0.0056; p4(j,1)=0.0078;
p5(j,1)=0.0043; p6(j,1)=0.0091; p7(j,1)=0.0038; p8(j,1)=0.0056; p9(j,1)=0.0084;

% Power Update  Algorithm
 for i=2:10
 p=pmin:10^(-7):pmax;
 F1=1-C*p;

 % first user%

     y11=G*p*h1/((p2(j,i-1)*h2)+(p3(j,i-1)*h3)+(p4(j,i-1)*h4)+...
         (p5(j,i-1)*h5)+(p6(j,i-1)*h6)+(p7(j,i-1)*h7)+(p8(j,i-1)*h8)...
         +(p9(j,i-1)*h9)+N);
     F11=(exp(y11/2)-1)./((y11/2)*M);

    % Finding Intersection of Two curves
for k=1:length(p)
    if ((F11(k)-F1(k))<=10^(-5))
        F11eq=F1(k);

    end
end
p1(j,i)=(-F11eq+1)/C;


  %second user%

     y12=G*p*h2/((p1(j,i-1)*h1)+(p3(j,i-1)*h3)+(p4(j,i-1)*h4)+...
         (p5(j,i-1)*h5)+(p6(j,i-1)*h6)+(p7(j,i-1)*h7)+(p8(j,i-1)*h8)...
     +(p9(j,i-1)*h9)+N);
```

```
       F12=(exp(y12/2)-1)./((y12/2)*M);

       for k=1:length(p)
      if ((F12(k)-F1(k))<=10^(-5))
          F12eq=F1(k);

      end
  end
  p2(j,i)=(-F12eq+1)/C;


    % third user%

       y13=G*p*h3/((p2(j,i-1)*h2)+(p1(j,i-1)*h1)+(p4(j,i-1)*h4)+...
           (p5(j,i-1)*h5)+(p6(j,i-1)*h6)+(p7(j,i-1)*h7)+(p8(j,i-1)*h8)...
           +(p9(j,i-1)*h9)+N);
      F13=(exp(y13/2)-1)./((y13/2)*M);

       for k=1:length(p)
      if ((F13(k)-F1(k))<=10^(-5))
          F13eq=F1(k);

      end
       end

  p3(j,i)=(-F13eq+1)/C;



    % fourth user%

       y14=G*p*h4/((p2(j,i-1)*h2)+(p3(j,i-1)*h3)+(p1(j,i-1)*h1)+...
           (p5(j,i-1)*h5)+(p6(j,i-1)*h6)+(p7(j,i-1)*h7)+(p8(j,i-1)*h8)...
           +(p9(j,i-1)*h9)+N);
      F14=(exp(y14/2)-1)./((y14/2)*M);

       for k=1:length(p)
      if ((F14(k)-F1(k))<=10^(-5))
          F14eq=F1(k);

      end
       end

  p4(j,i)=(-F14eq+1)/C;


    %fifth user%

       y15=G*p*h5/((p2(j,i-1)*h2)+(p3(j,i-1)*h3)+(p1(j,i-1)*h1)+...
           (p4(j,i-1)*h4)+(p6(j,i-1)*h6)+(p7(j,i-1)*h7)+(p8(j,i-1)*h8)...
           +(p9(j,i-1)*h9)+N);
      F15=(exp(y15/2)-1)./((y15/2)*M);

       for k=1:length(p)
      if ((F15(k)-F1(k))<=10^(-5))
          F15eq=F1(k);

      end
       end

  p5(j,i)=(-F15eq+1)/C;
```

```
 % sixth user%

     y16=G*p*h6/((p2(j,i-1)*h2)+(p3(j,i-1)*h3)+(p1(j,i-1)*h1)+...
         (p5(j,i-1)*h5)+(p4(j,i-1)*h4)+(p7(j,i-1)*h7)+(p8(j,i-1)*h8)...
         +(p9(j,i-1)*h9)+N);
    F16=(exp(y16/2)-1)./((y16/2)*M);

     for k=1:length(p)
    if ((F16(k)-F1(k))<=10^(-5))
        F16eq=F1(k);

    end
     end

p6(j,i)=(-F16eq+1)/C;

     % seventh user%

     y17=G*p*h7/((p2(j,i-1)*h2)+(p3(j,i-1)*h3)+(p1(j,i-1)*h1)+...
         (p5(j,i-1)*h5)+(p6(j,i-1)*h6)+(p4(j,i-1)*h4)+(p8(j,i-1)*h8)...
         +(p9(j,i-1)*h9)+N);
    F17=(exp(y17/2)-1)./((y17/2)*M);

     for k=1:length(p)
    if ((F17(k)-F1(k))<=10^(-5))
        F17eq=F1(k);

    end
     end

p7(j,i)=(-F17eq+1)/C;

      % eight user%

     y18=G*p*h8/((p2(j,i-1)*h2)+(p3(j,i-1)*h3)+(p1(j,i-1)*h1)+...
         (p5(j,i-1)*h5)+(p6(j,i-1)*h6)+(p7(j,i-1)*h7)+(p4(j,i-1)*h4)...
         +(p9(j,i-1)*h9)+N);
    F18=(exp(y18/2)-1)./((y18/2)*M);

     for k=1:length(p)
    if ((F18(k)-F1(k))<=10^(-5))
        F18eq=F1(k);

    end
     end

p8(j,i)=(-F18eq+1)/C;


 %ninth user%

     y19=G*p*h9/((p2(j,i-1)*h2)+(p3(j,i-1)*h3)+(p1(j,i-1)*h1)+...
         (p5(j,i-1)*h5)+(p6(j,i-1)*h6)+(p7(j,i-1)*h7)+(p8(j,i-1)*h8)...
         +(p4(j,i-1)*h4)+N);
    F19=(exp(y19/2)-1)./((y19/2)*M);

     for k=1:length(p)
    if ((F19(k)-F1(k))<=10^(-5))
        F19eq=F1(k);

    end
     end
```

```
p9(j,i)=(-F19eq+1)/C;

    % check if Power Of users Exceed The Maximum value
  if(p1(j,i)>pmax)
    p1(j,i)=pmax;

     else
         p1(j,i)=p1(j,i);
end
if(p2(j,i)>pmax)
    p2(j,i)=pmax;

         else
             p2(j,i)=p2(j,i);
end
if(p3(j,i)>pmax)
    p3(j,i)=pmax;

         else
             p3(j,i)=p3(j,i);
end
if(p4(j,i)>pmax)
    p4(j,i)=pmax;

         else
             p4(j,i)=p4(j,i);
end
if(p5(j,i)>pmax)
    p5(j,i)=pmax;

         else
             p5(j,i)=p5(j,i);
end
if(p6(j,i)>pmax)
    p6(j,i)=pmax;

         else
             p6(j,i)=p6(j,i);
end
if(p7(j,i)>pmax)
    p7(j,i)=pmax;

         else
             p7(j,i)=p7(j,i);
end
if(p8(j,i)>pmax)
    p8(j,i)=pmax;

         else
             p8(j,i)=p8(j,i);
end
if(p9(j,i)>pmax)
    p9(j,i)=pmax;
         else
             p9(j,i)=p9(j,i);
end

 end

 %  Payment OF 9 Users

   pay1(j)=L*C*(R/M)*((1-exp((-0.5*G*p1(j,10)*h1)/((p2(j,10)*h2)+...
```

```
          (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
          (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

      pay2(j)=L*C*(R/M)*((1-exp((-0.5*G*p2(j,10)*h2)/((p1(j,10)*h1)+...
          (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
          (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

      pay3(j)=L*C*(R/M)*((1-exp((-0.5*G*p3(j,10)*h3)/((p2(j,10)*h2)+...
          (p1(j,10)*h1)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
          (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

      pay4(j)=L*C*(R/M)*((1-exp((-0.5*G*p4(j,10)*h4)/((p2(j,10)*h2)+...
          (p3(j,10)*h3)+(p1(j,10)*h1)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
          (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

      pay5(j)=L*C*(R/M)*((1-exp((-0.5*G*p5(j,10)*h5)/((p2(j,10)*h2)+...
          (p3(j,10)*h3)+(p4(j,10)*h4)+(p1(j,10)*h1)+(p6(j,10)*h6)+...
          (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

      pay6(j)=L*C*(R/M)*((1-exp((-0.5*G*p6(j,10)*h6)/((p2(j,10)*h2)+...
          (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p1(j,10)*h1)+...
          (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

      pay7(j)=L*C*(R/M)*((1-exp((-0.5*G*p7(j,10)*h7)/((p2(j,10)*h2)+...
          (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
          (p1(j,10)*h1)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

      pay8(j)=L*C*(R/M)*((1-exp((-0.5*G*p8(j,10)*h8)/((p2(j,10)*h2)+...
          (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
          (p7(j,10)*h7)+(p1(j,10)*h1)+(p9(j,10)*h9)+N)))^M);

      pay9(j)=L*C*(R/M)*((1-exp((-0.5*G*p9(j,10)*h9)/((p2(j,10)*h2)+...
          (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
          (p7(j,10)*h7)+(p8(j,10)*h8)+(p1(j,10)*h1)+N)))^M);

      3 Throughput OF 9 Users

      t1(j)=L*(R/M)*((1-exp((-0.5*G*p1(j,10)*h1)/((p2(j,10)*h2)+...
          (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
          (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

      t2(j)=L*(R/M)*((1-exp((-0.5*G*p2(j,10)*h2)/((p1(j,10)*h1)+...
          (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
          (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

      t3(j)=L*(R/M)*((1-exp((-0.5*G*p3(j,10)*h3)/((p2(j,10)*h2)+...
          (p1(j,10)*h1)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
          (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

      t4(j)=L*(R/M)*((1-exp((-0.5*G*p4(j,10)*h4)/((p2(j,10)*h2)+...
          (p3(j,10)*h3)+(p1(j,10)*h1)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
          (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

      t5(j)=L*(R/M)*((1-exp((-0.5*G*p5(j,10)*h5)/((p2(j,10)*h2)+...
          (p3(j,10)*h3)+(p4(j,10)*h4)+(p1(j,10)*h1)+(p6(j,10)*h6)+...
          (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

      t6(j)=L*(R/M)*((1-exp((-0.5*G*p6(j,10)*h6)/((p2(j,10)*h2)+...
          (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p1(j,10)*h1)+...
          (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

      t7(j)=L*(R/M)*((1-exp((-0.5*G*p7(j,10)*h7)/((p2(j,10)*h2)+...
          (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
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     (p1(j,10)*h1)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M);

 t8(j)=L*(R/M)*((1-exp((-0.5*G*p8(j,10)*h8)/((p2(j,10)*h2)+...
     (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
     (p7(j,10)*h7)+(p1(j,10)*h1)+(p9(j,10)*h9)+N)))^M);

 t9(j)=L*(R/M)*((1-exp((-0.5*G*p9(j,10)*h9)/((p2(j,10)*h2)+...
     (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
     (p7(j,10)*h7)+(p8(j,10)*h8)+(p1(j,10)*h1)+N)))^M);

 %  Net Utility of 9 users

 unet1(j)=(L*(R/M)*((1-exp((-0.5*G*p1(j,10)*h1)/((p2(j,10)*h2)+...
     (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
     (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M))...
     *((1/(p1(j,10)))-C);

 unet2(j)=(L*(R/M)*((1-exp((-0.5*G*p2(j,10)*h2)/((p1(j,10)*h1)+...
     (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
     (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M))...
     *((1/(p2(j,10)))-C);

 unet3(j)=(L*(R/M)*((1-exp((-0.5*G*p3(j,10)*h3)/((p2(j,10)*h2)+...
     (p1(j,10)*h1)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
     (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M))...
     *((1/(p3(j,10)))-C);

 unet4(j)=(L*(R/M)*((1-exp((-0.5*G*p4(j,10)*h4)/((p2(j,10)*h2)+...
     (p3(j,10)*h3)+(p1(j,10)*h1)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
     (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M))...
     *((1/(p4(j,10)))-C);

 unet5(j)=(L*(R/M)*((1-exp((-0.5*G*p5(j,10)*h5)/((p2(j,10)*h2)+...
     (p3(j,10)*h3)+(p4(j,10)*h4)+(p1(j,10)*h1)+(p6(j,10)*h6)+...
     (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M))...
     *((1/(p5(j,10)))-C);

 unet6(j)=(L*(R/M)*((1-exp((-0.5*G*p6(j,10)*h6)/((p2(j,10)*h2)+...
     (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p1(j,10)*h1)+...
     (p7(j,10)*h7)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M))...
     *((1/(p6(j,10)))-C);

 unet7(j)=(L*(R/M)*((1-exp((-0.5*G*p7(j,10)*h7)/((p2(j,10)*h2)+...
     (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
     (p1(j,10)*h1)+(p8(j,10)*h8)+(p9(j,10)*h9)+N)))^M))...
     *((1/(p7(j,10)))-C);

 unet8(j)=(L*(R/M)*((1-exp((-0.5*G*p8(j,10)*h8)/((p2(j,10)*h2)+...
     (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
     (p7(j,10)*h7)+(p1(j,10)*h1)+(p9(j,10)*h9)+N)))^M))...
     *((1/(p8(j,10)))-C);

 unet9(j)=(L*(R/M)*((1-exp((-0.5*G*p9(j,10)*h9)/((p2(j,10)*h2)+...
     (p3(j,10)*h3)+(p4(j,10)*h4)+(p5(j,10)*h5)+(p6(j,10)*h6)+...
     (p7(j,10)*h7)+(p8(j,10)*h8)+(p1(j,10)*h1)+N)))^M))...
     *((1/(p9(j,10)))-C);

 % Revenue
paytot(j)=pay1(j)+pay2(j)+pay3(j)+pay4(j)+pay5(j)+pay6(j)+pay7(j)+...
    pay8(j)+pay9(j);
unettotal(j)=unet1(j)+unet2(j)+unet3(j)+unet4(j)+unet5(j)+unet6(j)+...
    unet7(j)+unet8(j)+unet9(j);
disp(paytot)
```

```
 j=j+1;

end
[unetmax,i1]=max(unettotal);
C1=Cmin+(i1-1)*10^3;


   pay11=L*C1*(R/M)*((1-exp((-0.5*G*p1(i1,10)*h1)/((p2(i1,10)*h2)+...
        (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
        (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M);

   pay21=L*C1*(R/M)*((1-exp((-0.5*G*p2(i1,10)*h2)/((p1(i1,10)*h1)+...
        (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
        (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M);

   pay31=L*C1*(R/M)*((1-exp((-0.5*G*p3(i1,10)*h3)/((p2(i1,10)*h2)+...
        (p1(i1,10)*h1)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
        (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M);

   pay41=L*C1*(R/M)*((1-exp((-0.5*G*p4(i1,10)*h4)/((p2(i1,10)*h2)+...
        (p3(i1,10)*h3)+(p1(i1,10)*h1)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
        (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M);

   pay51=L*C1*(R/M)*((1-exp((-0.5*G*p5(i1,10)*h5)/((p2(i1,10)*h2)+...
        (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p1(i1,10)*h1)+(p6(i1,10)*h6)+...
        (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M);

   pay61=L*C1*(R/M)*((1-exp((-0.5*G*p6(i1,10)*h6)/((p2(i1,10)*h2)+...
        (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p1(i1,10)*h1)+...
        (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M);

   pay71=L*C1*(R/M)*((1-exp((-0.5*G*p7(i1,10)*h7)/((p2(i1,10)*h2)+...
        (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
        (p1(i1,10)*h1)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M);

   pay81=L*C1*(R/M)*((1-exp((-0.5*G*p8(i1,10)*h8)/((p2(i1,10)*h2)+...
        (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
        (p7(i1,10)*h7)+(p1(i1,10)*h1)+(p9(i1,10)*h9)+N)))^M);

   pay91=L*C1*(R/M)*((1-exp((-0.5*G*p9(i1,10)*h9)/((p2(i1,10)*h2)+...
        (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
        (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p1(i1,10)*h1)+N)))^M);


   unet11=(L*(R/M)*((1-exp((-0.5*G*p1(i1,10)*h1)/((p2(i1,10)*h2)+...
        (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
        (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M))...
        *((1/(p1(i1,10)))-C1);

   unet21=(L*(R/M)*((1-exp((-0.5*G*p2(i1,10)*h2)/((p1(i1,10)*h1)+...
        (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
        (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M))...
        *((1/(p2(i1,10)))-C1);

   unet31=(L*(R/M)*((1-exp((-0.5*G*p3(i1,10)*h3)/((p2(i1,10)*h2)+...
        (p1(i1,10)*h1)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
        (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M))...
        *((1/(p3(i1,10)))-C1);

   unet41=(L*(R/M)*((1-exp((-0.5*G*p4(i1,10)*h4)/((p2(i1,10)*h2)+...
        (p3(i1,10)*h3)+(p1(i1,10)*h1)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
        (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M))...
        *((1/(p4(i1,10)))-C1);
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unet51=(L*(R/M)*((1-exp((-0.5*G*p5(i1,10)*h5)/((p2(i1,10)*h2)+...
     (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p1(i1,10)*h1)+(p6(i1,10)*h6)+...
     (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M))...
     *((1/(p5(i1,10)))-C1);

unet61=(L*(R/M)*((1-exp((-0.5*G*p6(i1,10)*h6)/((p2(i1,10)*h2)+...
     (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p1(i1,10)*h1)+...
     (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M))...
     *((1/(p6(i1,10)))-C1);

unet71=(L*(R/M)*((1-exp((-0.5*G*p7(i1,10)*h7)/((p2(i1,10)*h2)+...
     (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
     (p1(i1,10)*h1)+(p8(i1,10)*h8)+(p9(i1,10)*h9)+N)))^M))...
     *((1/(p7(i1,10)))-C1);

unet81=(L*(R/M)*((1-exp((-0.5*G*p8(i1,10)*h8)/((p2(i1,10)*h2)+...
     (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
     (p7(i1,10)*h7)+(p1(i1,10)*h1)+(p9(i1,10)*h9)+N)))^M))...
     *((1/(p8(i1,10)))-C1);

unet91=(L*(R/M)*((1-exp((-0.5*G*p9(i1,10)*h9)/((p2(i1,10)*h2)+...
     (p3(i1,10)*h3)+(p4(i1,10)*h4)+(p5(i1,10)*h5)+(p6(i1,10)*h6)+...
     (p7(i1,10)*h7)+(p8(i1,10)*h8)+(p1(i1,10)*h1)+N)))^M))...
     *((1/(p9(i1,10)))-C1);

[paymax,i2]=max(paytot);
C2=Cmin+(i2-1)*10^3;

pay12=L*C2*(R/M)*((1-exp((-0.5*G*p1(i2,10)*h1)/((p2(i2,10)*h2)+...
     (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
     (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M);

pay22=L*C2*(R/M)*((1-exp((-0.5*G*p2(i2,10)*h2)/((p1(i2,10)*h1)+...
     (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
     (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M);

pay32=L*C2*(R/M)*((1-exp((-0.5*G*p3(i2,10)*h3)/((p2(i2,10)*h2)+...
     (p1(i2,10)*h1)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
     (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M);

pay42=L*C2*(R/M)*((1-exp((-0.5*G*p4(i2,10)*h4)/((p2(i2,10)*h2)+...
     (p3(i2,10)*h3)+(p1(i2,10)*h1)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
     (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M);

pay52=L*C2*(R/M)*((1-exp((-0.5*G*p5(i2,10)*h5)/((p2(i2,10)*h2)+...
     (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p1(i2,10)*h1)+(p6(i2,10)*h6)+...
     (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M);

pay62=L*C2*(R/M)*((1-exp((-0.5*G*p6(i2,10)*h6)/((p2(i2,10)*h2)+...
     (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p1(i2,10)*h1)+...
     (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M);

pay72=L*C2*(R/M)*((1-exp((-0.5*G*p7(i2,10)*h7)/((p2(i2,10)*h2)+...
     (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
     (p1(i2,10)*h1)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M);

pay82=L*C2*(R/M)*((1-exp((-0.5*G*p8(i2,10)*h8)/((p2(i2,10)*h2)+...
     (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
     (p7(i2,10)*h7)+(p1(i2,10)*h1)+(p9(i2,10)*h9)+N)))^M);

pay92=L*C2*(R/M)*((1-exp((-0.5*G*p9(i2,10)*h9)/((p2(i2,10)*h2)+...
     (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
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    (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p1(i2,10)*h1)+N)))^M);

unet12=(L*(R/M)*((1-exp((-0.5*G*p1(i2,10)*h1)/((p2(i2,10)*h2)+...
    (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
    (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M))...
    *((1/(p1(i2,10)))-C2);

unet22=(L*(R/M)*((1-exp((-0.5*G*p2(i2,10)*h2)/((p1(i2,10)*h1)+...
    (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
    (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M))...
    *((1/(p2(i2,10)))-C2);

unet32=(L*(R/M)*((1-exp((-0.5*G*p3(i2,10)*h3)/((p2(i2,10)*h2)+...
    (p1(i2,10)*h1)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
    (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M))...
    *((1/(p3(i2,10)))-C2);

unet42=(L*(R/M)*((1-exp((-0.5*G*p4(i2,10)*h4)/((p2(i2,10)*h2)+...
    (p3(i2,10)*h3)+(p1(i2,10)*h1)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
    (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M))...
    *((1/(p4(i2,10)))-C2);

unet52=(L*(R/M)*((1-exp((-0.5*G*p5(i2,10)*h5)/((p2(i2,10)*h2)+...
    (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p1(i2,10)*h1)+(p6(i2,10)*h6)+...
    (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M))...
    *((1/(p5(i2,10)))-C2);

unet62=(L*(R/M)*((1-exp((-0.5*G*p6(i2,10)*h6)/((p2(i2,10)*h2)+...
    (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p1(i2,10)*h1)+...
    (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M))...
    *((1/(p6(i2,10)))-C2);

unet72=(L*(R/M)*((1-exp((-0.5*G*p7(i2,10)*h7)/((p2(i2,10)*h2)+...
    (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
    (p1(i2,10)*h1)+(p8(i2,10)*h8)+(p9(i2,10)*h9)+N)))^M))...
    *((1/(p7(i2,10)))-C2);

unet82=(L*(R/M)*((1-exp((-0.5*G*p8(i2,10)*h8)/((p2(i2,10)*h2)+...
    (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
    (p7(i2,10)*h7)+(p1(i2,10)*h1)+(p9(i2,10)*h9)+N)))^M))...
    *((1/(p8(i2,10)))-C2);

unet92=(L*(R/M)*((1-exp((-0.5*G*p9(i2,10)*h9)/((p2(i2,10)*h2)+...
    (p3(i2,10)*h3)+(p4(i2,10)*h4)+(p5(i2,10)*h5)+(p6(i2,10)*h6)+...
    (p7(i2,10)*h7)+(p8(i2,10)*h8)+(p1(i2,10)*h1)+N)))^M))...
    *((1/(p9(i2,10)))-C2);

ueq1=[unet11,unet21,unet31,unet41,unet51,unet61,unet71,unet81,unet91];
ueq2=[unet12,unet22,unet32,unet42,unet52,unet62,unet72,unet82,unet92];
payeq1=[pay11,pay21,pay31,pay41,pay51,pay61,pay71,pay81,pay91];
payeq2=[pay12,pay22,pay32,pay42,pay52,pay62,pay72,pay82,pay92];
powereq1=[p1(i1,10),p2(i1,10),p3(i1,10),p4(i1,10),p5(i1,10),...
    p6(i1,10),p7(i1,10),p8(i1,10),p9(i1,10)];
powereq2=[p1(i2,10),p2(i2,10),p3(i2,10),p4(i2,10),p5(i2,10),...
    p6(i2,10),p7(i2,10),p8(i2,10),p9(i2,10)];
plot(payeq1,ueq1,'r*:',payeq2,ueq2,'rd:')
figure;
plot(d,ueq1);
figure;
plot(d,ueq2);
figure;
plot(d,payeq1);
figure;
```

```
    plot(d,payeq2);
    figure;
    plot(d,powereq1);
    figure;
    plot(d,powereq2);

e=Cmin:10^3:Cmax;
figure;
plot(e,paytot)
figure;
plot(e,pay1,e,pay2,e,pay3,e,pay4,e,pay5,e,pay6,e,pay7,e,pay8,e,pay9)
figure;
plot(e,t1,e,t2,e,t3,e,t4,e,t5,e,t6,e,t7,e,t8,e,t9)
figure;
plot(e,unet1,e,unet2,e,unet3,e,unet4,e,unet5,e,unet6,e,unet7,...
    e,unet8,e,unet9)
figure;
plot(e,unettotal)
figure;
plot(e,p1(:,10),e,p2(:,10),e,p3(:,10),e,p4(:,10),e,p5(:,10),...
    e,p6(:,10),e,p7(:,10),e,p8(:,10),e,p9(:,10))
```