Journal of the Nigerian Association of Mathematical Physics
***Volume* 11 (November 2007), 605 - 614**
© J. of NAMP

Capacity and coverage of power controlled CDMA cellular systems

[1*]Joseph Isabona, [1]Bede Asuquo and [2]Moses Ekpenyong
[1*,1]Department of Physics,
[2]Department of Mathematics, Statistics and Computer Science,
University of Uyo, Uyo, Nigeria
[1]*e-mail: josephisa_09@yahoo.com
[2]e-mail: ekpenyong_moses@yahoo.com

Abstract

Coverage and capacity are among the ambitious challenges to be met by the third generation (3G) systems for successful deployment of its services to both residential and commercial subscribers. This paper reports on the performance study of CDMA systems in relation to an optimum step-regulated SNR-based transmitted power. We derive the system model and present a computer simulation to optimize the transmitted power for each user and maintain the required $\frac{\lambda_b}{N_0}$ (signal-to-noise ratio) for satisfactory call quality by achieving a minimal $\frac{\lambda_b}{N_0}$ for every user with an acceptable channel performance. We observe from the simulation that SNR based power control with updating step-size of 0.8dB provides acceptable system availability and stability.

***Keywords**:* CDMA, QoS, transmit power control, optimization, signal-to-noise ratio.

1.0 Introduction

Code Division Multiple Access (CDMA) is the Multi access technology of 3G wireless networks that has wide range of services. CDMA has been recognized as a viable alternative to both Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA). CDMA schemes have many advantages such as universal one-cell frequency reuse, Narrowband interference rejection, inherent multiple diversity, soft hand off capacity and soft capacity limit. But these advantages can be hindered by the increasing interference caused by other users, since all signals in the CDMA system are sharing the same transmission bandwidth. Blocking occurs when the tolerance limit to interference is exceeded. Hence, in CDMA, the level of interference is a limiting factor.

One critical problem with CDMA is the near-far problem. This problem occurs in the absence of power control. If all mobiles are transmitting at the same power level, the mobile closest to the base station will overpower all others. Yet, another reason for power control is the

---

[2]Corresponding author

battery lifetime, if the mobile station continuously transmits at a higher power. Thus, to maintain an acceptable SNR, the battery lifetime could be reduced using power control. Each mobile station can then transmit at the minimum power needed to maintain the required SNR ratio, thus conserving its battery life.

Generally, power control is referred to as the mechanism or technique required to adjust, correct and manage the transmission power from the base station (BS) and mobile station (MS) in an efficient manner such that the interference problem is minimized and sufficient quality of service (QoS) simultaneously achieved. Several power control techniques have been studied. These include: the Eigen value problem for non-negative matrices [1], iterative power control algorithms [2], [3], optimization based approach [4] and useful framework for the uplink [5]. In this paper, we contribute to this important research area by using an optimum step regulated SNR-based power control approach to simulate the system model and satisfactorily maintain the QoS.

2.0 SNR-based power control

CDMA systems have to support multi media services like voice, data and fax. Issues in providing multimedia services on wireless networks include multi-access, bandwidth rationing and power control. Different services have different QoS requirements and power constraints. In order to achieve the required QoS, these services could alter their power constraints since users are interfered with each other. Therefore achieving each user's QoS requirement is coupled with their transmit power. This is formulated as a constrained optimization problem. Thus the users are spread into distance based on their SNR requirement and their transmitted power, which are calculated by the base station to achieve better performance of the entire CDMA cell.

2.1 SNR-based power control services variety requirements

QoS requirement and power needed for each user are different due to different types of services provided by CDMAs such as digital picture, e-mail, fax, voice, GPRS, etc. So fixed requirement for each user is no longer efficient. A perfect management scheme for providing these resources based on their need is a must. The following are the services requirements for SNR-based power control:

(*i*) ***Interface:*** Each user operates with high power in the system and hence there is interference inside the system. Most times it produces problems such as near-far effect, dropping users, and increase in noise.

(*ii*) ***Increase in Capacity:*** Only a limited number of users can use a CDMA cell. By introducing SNR base power control scheme in the CDMA system, equalizes the subscribed signal power to the same level at the base station by adjusting the power by the amount required to achieve the required signal threshold in one step. This algorithm should find exactly the transmitted power each subscriber should transmit in order to satisfy the required SNR level by the receiver. This gives room for more users to enter system by reducing the overall interference as well as the noise in the system.

3.0 Model parameters

The capacity and coverage of a CDMA cell depends on factors such as power control, interference power and propagation model predictions. In this paper we consider a perfect power control.

Let K and K_P be the minimum and maximum active number of users allowed in a power-controlled DMA system. Each user has QoS and power constraint. The data rate (R) and the total bandwidth (W) of the available signal are fixed.

Each user specifies a minimum QoS tolerance for system stability and service availability. Usually this is either in terms of BER or FER. Here it is assumed that BER/FER requirement could be mapped from energy per bit to noise power density level ($\frac{\lambda_b}{N_0}$) requirement [6]. A user specifies a maximum power limit he/she can afford and the minimum data transfer rate he/she requires. By assuming perfect power control, the SNR exactly needed to have an acceptable error rate can be summarized as follows:

$$\frac{\lambda_b}{N_0} = \frac{W}{R} . \frac{S.L(d,S)}{N} . \frac{K_p - K}{K_p - 1} \tag{3.1}$$

where:

λ_b = bit error rate (BER)
N_0 = frame error rate (FER)
$\frac{W}{R}$ = processing (spreading) gain
$N = F_N K_B T_0$ = thermal noise of the receiver (F_N = receiver noise figure)
S = the receiver power at the base station from an active user
$\frac{K_p - K}{K_p - 1}$ = multiple access interface factor

4.0 The propagation model

The signal propagation model in the mobile channel (when fast fading is ignored) is generally modeled as a product of three components: the first component is one which is inversely proportional to the distance representing path-loss, the second is a variable with lognormal distribution representing shadow losses [7], and the third represents the directional antenna. The shadowing represents the slow variations in the signal strength even for mobile users. On the other hand, fast fading, which is largely due to multipart propagation, could be assumed to have no effect on the average signal power level [8]. Hence for a user at a distance *d* from a base station, the total propagation loss is a function of *d*, δ and *g* and is given by

$$L(d,\delta) = d^{-n} 10^{(\frac{\delta}{10})} .g \tag{4.1}$$

where δ is the standard deviation of lognormal shadowing process and n is the propagation path-loss. In order for a base station to be most favourable to mobiles, the $L(d,\delta)$ with respect to the base station must be smaller than $L(d,\delta)$ with respect to other base stations [9]. Our model uses an ideal directional antenna pattern. Therefore

$$L(d,\delta) = d^{-n} 10^{(\frac{\delta}{10})} \tag{4.2}$$

From (3.1) and (4.2) we can build relations among the received power, number of users and the coverage area.

4.1 Power-controlled CDMA cellular system capacity

In digital communication systems, the measure that indicates the link quality is expressed by the bit-energy-to-noise density ratio $\frac{\lambda_b}{N_0}$. This term can be related to the conventional SNR by recognizing the energy per bit duration, such that

$$\lambda_b = ST \tag{4.3}$$

where *S* is the average signal power and *T* is the time duration of the bit. We can further analyze (4.3) by substituting the bit data rate R_b, which is the inverse of the bit duration *T*:

$$\lambda_b = \frac{S}{R_b} \tag{4.4}$$

The noise-power-spetra-density N_0, is the total interference power *I* divided by the transmission bandwidth *W*, i.e.

$$N_0 = \frac{I}{W} \tag{4.5}$$

Given this, the bit-energy-to-noise density can be rewritten as:

$$\frac{\lambda_b}{N_0} = \left(\frac{S}{I}\right)\cdot\left(\frac{W}{R_b}\right) \tag{4.6}$$

Where the ratio $\frac{W}{R_b}$ is known as the processing gain of the system.

In the following, we examine the capacity for a simplified case of the uplink as this is the main focus of our investigation and generally considered as the limiting link.

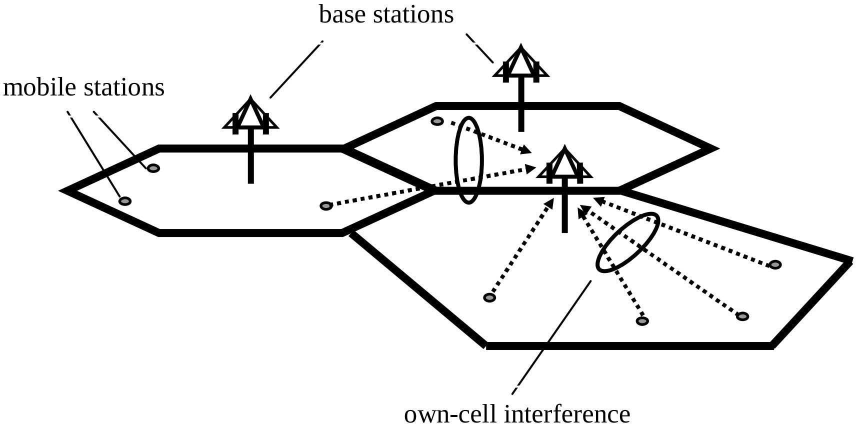


Figure 1: Uplink own cell and other-cell interference in CDMA

An example of the uplink scenario is depicted in Fig. 1., where the $\frac{\lambda_b}{N_0}$ for a specific user is measured at the BS. In order to evaluate the $\frac{\lambda_b}{N_0}$ value, we need to specify I_{total} in (4.5). It can be seen in Figure 1. that the total interference power on the uplink consists of the following contributions:

(*i*) Background (thermal) noise-power spectral density N_0,

(*ii*) External interference,

(*iii*) Own-cell (= intra-cell) interference I_{own}, i.e. the interference by other users in the same cell,

(*iv*) Other-cell (= inter-cell) interference I_{other}, i.e. the interference by other users in neighbouring cells at the base station receiver.

Whereas the first two sources of interference can be found in other wireless systems as well, the latter two are unique to CDMA. This is due to the fact that all users operate in the same radio frequency transmission band. The fundamental capacity equations for the uplink were first given in [10]. In order to simplify the calculation, no other-cell interference is at first taken into account. Further studies in [11] extend these models to include the computation of the other-cell interference.

We will follow the derivation in [12]. Let us consider a single cell loaded with K users that are in power control with the base station. The total interference power for user i is composed of the received signal power S_j from all other users in the cell

$$I_{total} = \sum_{j=1, j\neq i}^{k} \frac{vS_j}{W} + N_0 \tag{4.7}$$

where *v* is the voice activity factor. Voice activity detection of the speech encoder ensures that data is only transmitted at full rate when the user actively speaks. In silence periods, the data rate is much more reduced and thus less interference is created.

If we assume perfect power control, all users are received with exactly the same signal power *S*. We can now simplify (4.7) as

$$I_{total} = \frac{(K-1)vS}{W} + N_0 \qquad (4.8)$$

Inserting (4.8) into (4.6), the $\frac{\lambda_b}{N_0}$ on the uplink can be given for an arbitrary user as

$$\frac{\lambda_b}{N_0} = \frac{W}{R}\frac{S}{N_0 + (K-1)Sv} \qquad (4.9)$$

solving (4.9) for *K* yields the capacity in terms of the number of users in the system,

$$K = 1 + \frac{W}{R}\left(\frac{1}{\frac{\lambda_b}{N_0}}\right) - \frac{N_0 W}{vS} \qquad (4.10)$$

We should note that (4.9) only considers a single cell with a class of service and therefore only of limited use in UMTS capacity evaluation.

To include what happens with the neighboring cells, we introduce the quantity referred to as the effective frequency reuse factor, *F*, defined as

$$F = \frac{TotalInterferencePower}{Own - cellInterferencePower} = \frac{1}{1+N} \qquad (4.11)$$

where *N* is the noise power. Similar quantities have been defined in [13]. It is easy to show that SNR is related to *F* by the expression:

$$SNR = \frac{S}{I+N} = \frac{S}{N}(1-F) \qquad (4.12)$$

We may derive a more direct relationship between the number of active users and average interference. Consider that the interference power is some fraction of the interference and noise power:

$$I = \varepsilon P = \varepsilon(1+N) = (K-1)S = \varepsilon(K_p - 1)S$$

where ε = $\frac{\lambda_b}{N_0}$; $0 \le \varepsilon \le 1$, *S* is the power of each interfering signal (they are all assumed to be equal), *K* is the number of active users and K_p is defined as the maximum number of active users supported by an interference-limited system. As S→∞, the last term in (4.10) approaches

0 and a maximum of K is reached at $K_p = \frac{\frac{W}{R}}{\left(\frac{\lambda_b}{N_0}\right)_{eff} + 1}$, which is called the pole capacity of the system. Using these relationships, we can see that $F = \varepsilon = \frac{(K-1)}{(K_p - 1)}$. If we consider that $\lambda_b \approx \frac{S}{R}$ and $I_0 + N_0 \approx \frac{I}{W} + \frac{N}{W}$, a convenient relationship for $\frac{\lambda_b}{N_0}$ results:

$$\left(\frac{\lambda_b}{N_0}\right)_{eff} = \frac{\lambda_b}{I_0 + N_0} = \frac{W}{R}.\frac{S}{N}.\left(\frac{K_p - K}{K_p - 1}\right) \tag{4.13}$$

where $N = F_N K_p T_0.$

Here F_N is the receiver noise figure, K_B, the Boltzmann constant and T_0, the absolute temperature in Kelvin.

5.0 Simulation algorithm and program

We present below the simulation algorithm for two cases:

(*i*) varying transmit power with distance and

(*ii*) varying transmit power with users.

(*i*) Case 1 Algorithm – Varying transmit power with distance

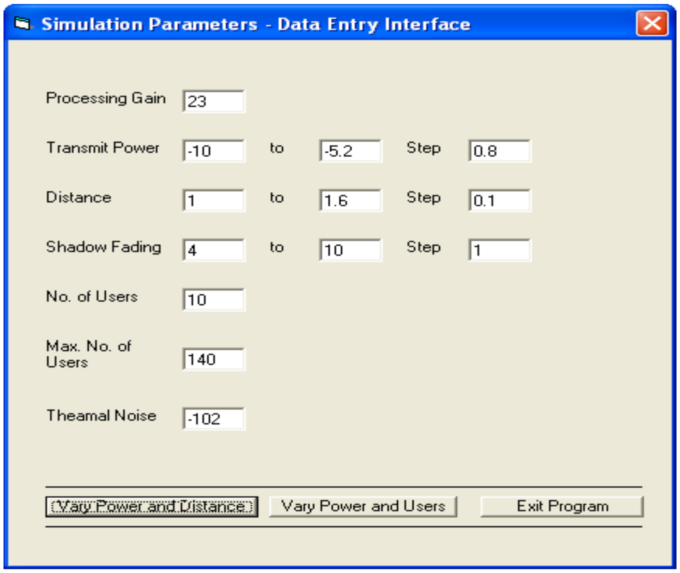
- (a) Open file for simulation output
- (b) Initialize distance and shadow fading
- (c) Vary transmit power
- (d) Compute Signal (i.e. $\frac{\lambda_b}{N_0}$)
- (e) Print signal and distance to output file
- (f) Vary distance and shadow fading
- (g) Signal end of simulation
- (h) End Simulation

(*ii*) Case 2 Algorithm – Varying transmit power and users

- (a) Open file for simulation output
- (b) Initialize number of users from the negative exponential CDF (i.e. $1\text{-}e^{-\gamma x}$)
- (c) Initialize distance and shadow fading.
- (d) Vary transmit power
- (e) Compute signal (i.e. $\frac{\lambda_b}{N_0}$)
- (f) Print signal and number of users to output file
- (g) Draw another user from $1\text{-}e^{-\gamma x}$
- (h) Vary shadow fading
- (i) Signal end of simulation
- (j) End Simulation

The algorithms were then coded into a computer program using Visual Basic 6.0, an Object Oriented Programming language suitable for scientific simulations/applications. We show below a sample Graphic User Interface (GUI) of the simulation environment.

The program is designed to be interactive and the results are simulated to a text file, which makes it comfortable for a user to copy and work with offline.



Processing Gain 23

Transmit Power -10 to -5.2 Step 0.8

Distance 1 to 1.6 Step 0.1

Shadow Fading 4 to 10 Step 1

No. of Users 10

Max. No. of Users 140

Theamal Noise -102

Figure 2: Sample GUI simulation data entry environment

6.0 Presentation and discussion of simulation results

In this section, we present and discuss the simulation results as follows:

(i) ***System performance with no fading compensation:*** The effect on system performance without power control is shown in Fig. 3. Here the SNR strength decreases exponentially as the distance of MUs increases. This is a trivial case of no fading boost. The result shows that mobiles cannot transmit with fixed power, because the cells would be dominated by the closest mobiles to the base station. Far-away mobiles could not get their signals heard in the base station, which calls for the need for appropriate power management schemes.

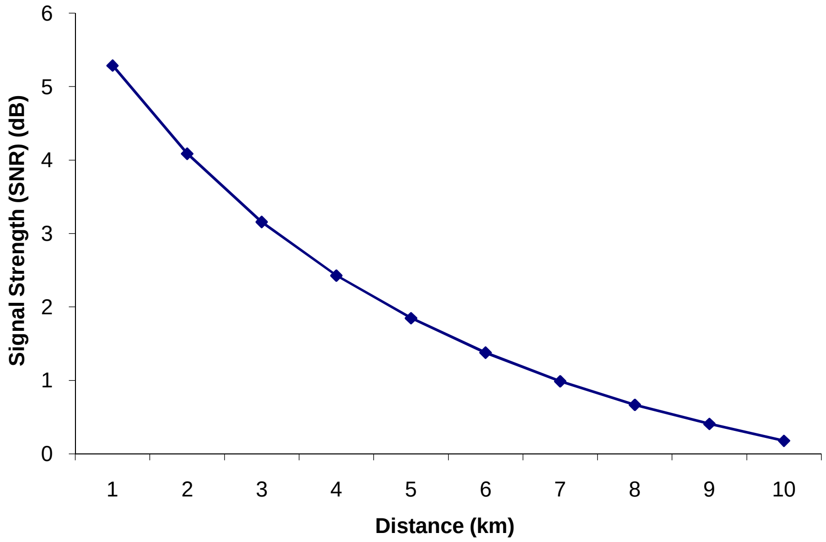


Figure3: Graph of SNR vs distance – with no fading compensation

(ii) ***Effect of Transmit Power on system availability and stability:*** Figure 4 shows SNR for different distance of subscriber locations. It was observed that the signal strength remained approximately constant regardless of the subscribers' distance or location from the base station receiver. Here we introduce a control into the system that helps the system meet and maintain the minimum signal required by subscribers. This could be made possible in real-life by providing cellular amplifiers that can makeup for signal variations, fluctuations and fading for long distance subscribers. We achieved this amplification through the compensation of all forms of multi-access interference properties, with a general term "near-far-effect", and step-size update as the distance increases.

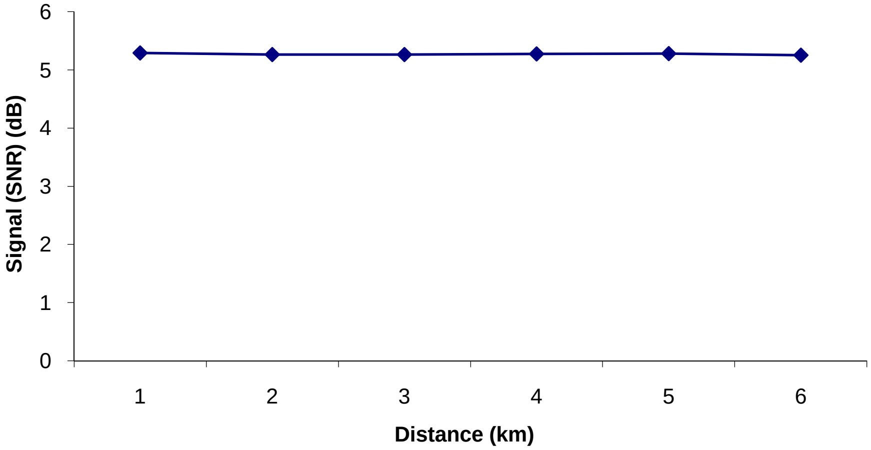


Figure4: Graph of SNR vs distance – with cellular amplification

(iii) ***Effect of Transmit Power on system availability and capacity:*** Figure 5 (a) shows the performance of the system evaluated as a function of number of users versus SNR. The users are drawn randomly from the negative exponential cumulative density function (CDF). This density function ($1\text{-}e^{-\gamma x}$) is a memoriless function, which depicts the real-life scenario, i.e. the number of users at time t_1 is not dependent upon number of users at time t_0. The result is a scatter plot. But cumulatively, we observe that the signal strength increases with increase in users. This confirms that more signal strength is required for more users in the system. A model equation that determines the simulation trend was fitted and found to be $Y = 32.215e^{0.0307x}$, where Y is the trend signal variable and x in this case, the number of users.

Figure 5(b) is a normalization of 5(a) where the numbers of users are increasingly ordered. The result is almost a straight line. To predict the performance in real-life, we again fit an exponential trend line and the trend equation is derived as $Y = 17.363e^{0.3117x}$. We also observe an increase in signal strength, which allows the system to accommodate more users, thus increasing the network capacity. The fluctuation signal is reduced through this normalization and hence, less interference is introduced into the system.

7.0 Conclusion and outlook

This paper has presented a classical approach that aids the establishment of an optimum power control step-size to combat interference limited CDMA systems and solve the near-far problem. The simulation results show that SNR based power control with updating step size of 0.8dB provides an acceptable system availability and stability. After extensive simulation, we observed that the step-size value must be carefully chosen as too small or too large a value affects the system's stability and service availability.

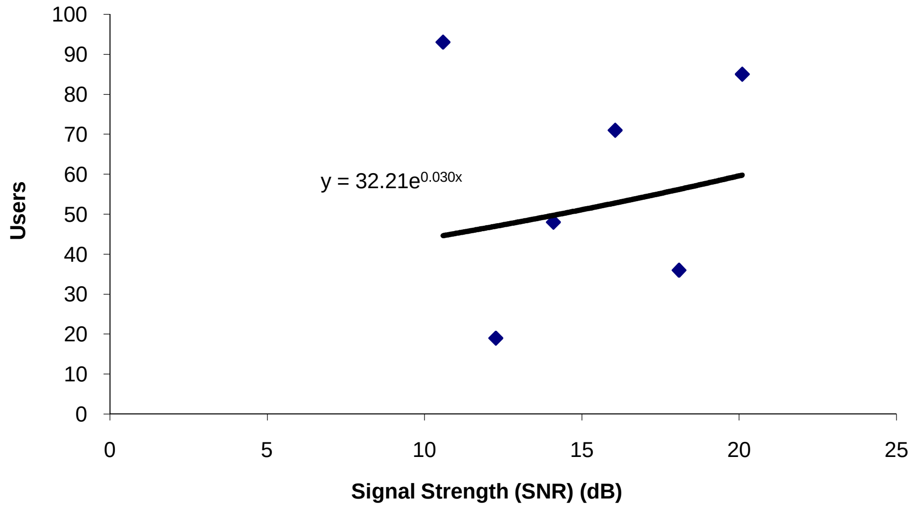


Figure 5(a): Graph of users (unordered) vs SNR

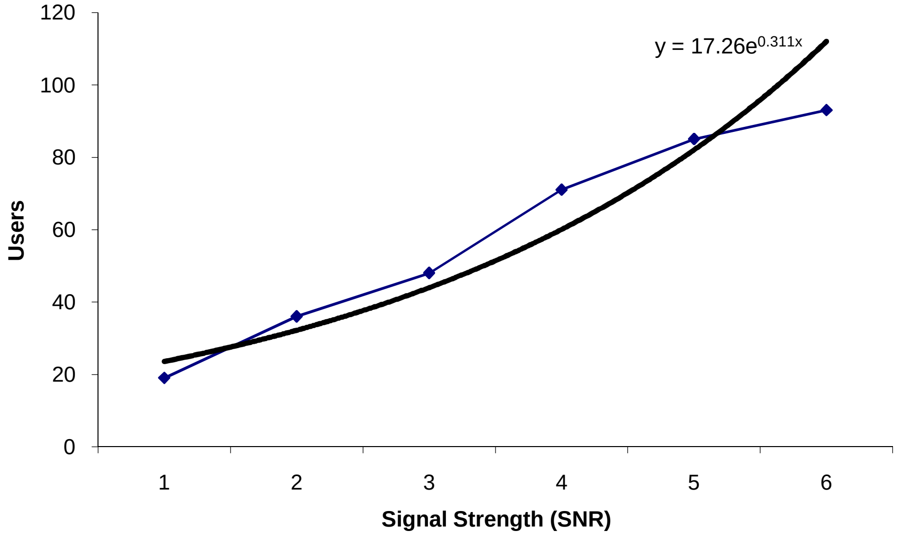


Figure 5(b). Graph of users (increasingly ordered) vs SNR

Our approach so far considers an additive white Gaussian noise (AWGN) channel with no time dependent behaviour. In reality however, correlations in the fading channel causes the propagated fluctuation of signal at a greater degree. Further research is required to include a model that considers fading in a more practical manner by modifying the looping driving variable.

The results in this paper present the inner loop (uses SNR as a performance measure) and do not include outer loop processing. Another extension possibility is to incorporate a dynamic algorithm to determine the threshold level.

References

[1] Lau, F. C. M. (1999). Intelligent Closed-Loop Power Control Algorithm in CDMA Mobile Radio System. Electronics Letters, 35 (10,13): 785-786.

[2] Hanly, S. V. (1995). An Algorithm for Combined Cell-site Selection and Power control to Maximize Cellular spread Spectrum Capacity. IEEE Journal on Selected Areas in Communication. 13(7): 1332-1340.

[3] Qiang, W. (1999). Optimum Transmitter Power control in Cellular Systems with Heterogeneous SIR Thresholds. IEEE Transactions on Vehicular Tech. 49(4): 571-575.

[4] Zander, J. (1992). Performance of optimum Transmitter Power control in Cellular Radio Systems. IEEE Transactions on vehicular tech. 41(1): 57-62.

[5] Yates, R. D. (1995). A Framework for Uplink Power control in Radio System. IEEE Journal on Selected Areas in Communication. 7: 1341-1347.

[6] Fleming, P. J. & B. Simon (1997). Closed-form Expressions for other Cell Interference in Cellular CDMA. UCD/CCM116, University of Colorado, Denver Co.

[7] Hata, M. (1980). Empirical Formula for Propagation loss in Mobile Radio Services. IEEE Transactions on Vehicular Tech. 29(3): 317-325.

[8] Hanly, S. V. (1996). Capacity and Power control in Spread Spectrum Macro-diversity Radio Networks. Automatrica. 35(12): 1987-2012.

[9] Rosberg, Z. & Zander, J. (1998). Toward a Framework for Power control in Cellular Systems. Wireless networks. 4(3): 215-222.

[10] Viterbi, A. J. (1995). CDMA – Principles of Spread Spectrum Communications. Reading, MA: Addison-Wesley.

[11] Viterbi, A. J. & Zehazi, E. (1994). Other-cell Interference in Cellular Power controlled CDMA. IEEE Transactions on Communications. 42(2/3/4): 1501-1504).

[12] Garg, V. K. (2000). Is-95 CDMA and CDMA 2000. Upper Saddle River, NJ: Prentice Hall.

[13] Leibnitz, K. P. (1998). Analysis of the Dynamics of CDMA Reverse link Power control. In Proceedings of IEEE GLOBECOM, Sydney, Australia.