King Saud University
College of Engineering
Electronics Engineering Department

INVESTIGATION OF COVERAGE VERSUS CAPACITY OF CELLULAR CDMA SYSTEMS

BY
Khalid Muqbel Al-Ossimi

Submitted in fulfillment of the requirements for the Master’s degree in the Department of Electronics Engineering at the College of Engineering, King Saud University.

RIYADH
Shaban 1425
September 2004

ACKNOWLEDGEMENT

Knowledge is cumulative. It is not based on each person's reinventing everything that is known, rather on accumulating what has been learned in the past, synthesizing new ideas from old formulas and principles, and creating completely new insights. I hope elements of all three can be found in these pages.

Most deeply acknowledgement is for my advisor, Prof. Adel A. Ali for his unlimited guidance, assistance, encouragement and patience until finishing this work.

I want to acknowledge the contribution of all those whose work has added to my understanding of various topics in this thesis.

ABSTRACT

An increase in cell coverage and number of users in-cell are important for code division multiple access (CDMA) cellular network design and deployment, which will be utilized for third generation systems and beyond.

Literature has provided results since the early work of Viterbi and the work continued in analyzing CDMA system for cell coverage and its capacity.

It should be mentioned that all the work is concentrated on Binary modulation. The benefit of using error-correcting code was not accounted.

The extended analysis and results presented earlier, investigated the benefits of using M-ary modulation (higher alphabet signaling) over the mobile channel.

This thesis aims to investigate the theoretical analysis of the benefits of using the Forward Error Correcting Code (FECC) and/or higher alphabet signaling, Trellis Code Modulation (TCM), simple space-time transmit diversity (STTD) and higher alphabet signaling with STTD on the coverage and capacity of the cell in cellular CDMA system by employing single user detection. In-cell interference limits the coverage of the cell. Thus, for a given upper limit to transmit power, the outage probability is calculated using the Gaussian approximation (central limit theorem approximation) for powers received at the base station. The number of active users in the cell is considered as a random variable with Poisson distribution. Also, the channel bandwidth and transmitted power signal are unchanged on all investigations done here.

Our main results show that, when the system employs the BCH, the coverage will be improved. By changing higher code rate there is an improvement in coverage up to a certain limit of code rate. If the code rate exceeds further, there is degradation in service.

Also, by employing higher alphabet signaling with coding, the result shows that, the system can select a proper alphabet signaling depending on the number of active users in the cell in order to obtain higher coverage.

When TCM is employed, the number of states increases causing an increase in cell coverage and its capacity, but only up to a certain value of number of states. When the number of states exceeds further, the cell coverage and its capacity will not increase. Also when the system employs TCM with higher alphabet signaling, the system can select the proper alphabet signaling depending on the number of active users in the cell in order to obtain higher coverage.

Finally, there is a high improvement when the system employs the STTD in comparison to the system not employing STTD. Also it is observed that, when the number of antenna transmitters increases, while fixing the number of antenna receivers, causes an increase in coverage and capacity of the cell and vice versa. Moreover, there is an improvement in coverage and capacity by employing higher alphabet signaling with STTD,

TABLE OF CONTENTS

LIST OF FIGURES

NOMENCLATURE

Additive White Gaussian Noise (AWGN)

Binary Phase Shift-Keying (BPSK)

Bose-Chaudhari-Hocquenghem (BCH)

Code Division Multiple Access (CDMA)

Forward Error Correcting Code (FECC)

Frequency Division Multiple Access (FDMA)

Phase Shift Keying (PSK)

Quadrature Amplitude Modulation (QAM)

Space-Time Block Code (STTB)

Space-Time Transmit Diversity (STTD)

Space-Time Trellis Code (STTC)

Time Division Multiple Access (TDMA)

Trellis Code Modulation (TCM)

1.0 INTRODUCTION

1.1 Introduction

Mobile communications was (and continues to be) the fastest growing sector of all communication and information services of the last decade. Digital mobile subscribers have grown 80-fold from a mere 17 million in 1995 to over 1369 million by the end of 2003 (source : EMC-database.com). This was mainly due to the introduction of 2G digital system; (especially GSM) and rapid technological developments in the field. Third generation (3G) standards promise to push mobile growth even higher and introduce new and better services, especially in mobile data applications.

The most difficult challenge facing mobile communication is the severe spectrum shortage. Novel methods were introduced to help alleviate this limitation, improve the spectrum utilization efficiency and increase system capacity. Examples of such methods include cellular radio and multiple access techniques.

Code Division Multiple Access (CDMA) networks has recently seen a rapid growth all over the world. The reason of this lies in its technological advantages over Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA), the basis for any air interface design is how to share the common transmission medium between users, that is Multiple Access scheme.

In FDMA system, the total system bandwidth is divided into frequency channels that are allocated to the user, blocking in FDMA system occurs when all frequency channels have been assigned to others.

In TDMA system each frequency channel is divided into time slots and each user is allocated a time slot, blocking in TDMA system occurs when all time slots are assigned to others. In CDMA system, all users share a common spectral frequency bandwidth allocation over the time that all users are active. Blocking in CDMA systems occurs when the interference level, due primarily to other users activity, reaches a predetermined level above the background noise level of mainly thermal origin.

In cellular CDMA systems with non-orthogonal users and single user detection, it is well known that the coverage of a cell has an inverse relationship with the user capacity of the cell. An increase in the number of active users in the cell causes the total interference seen at the receiver to increase. This causes an increase in the required received power for each user, due to the fact that each user has to maintain a certain signal to interference ratio at the receiver for satisfactory performance. For a maximum allowable transmit power, an increase in the required received power will result in a decrease in the maximum distance a mobile can be from the base station, thereby reducing coverage [1].

So that, if the signal-to-interference ratio of a given user is lower than the desired value for certain period of time, it has an outage, so there is a noticeable degradation in call quality. If the outage lasts long enough, then the call is dropped. If the system accepts new calls, the impact of those at the fringe of the cell would face a deteriorating service. Therefore, both coverage and capacity of a cell needs to be planned in such a way that all calls are sufficiently supplied.

The cell coverage and capacity in FDMA and TDMA systems are purely determined by radio frequency (RF) aspects.

From the above discussion, the cell coverage in CDMA system is extremely sensitive to the active users that are supplied in the cell.

Here, it is considered that a cell in a CDMA network is with a Base Transceiver Station (BTS) supporting a number of calls. The probability that the customers get an acceptable link quality is a function of the distance d to the base station (BS) and the current interference characteristics is however not only depending on d but is also a function of the distribution of active user currently supported in the cell. Here, the active users considered as a Poisson Random Variable employing single user detection.

Unlike [1] which assumes the number of active users is deterministic. Also in this thesis, the outage probability is calculated by using central limit approximation [2]. This thesis is an extension of the work presented in [1], [2] and [3]. Our aim is to study the benefits of employing FECC, higher alphabet signaling of modulation, Trellis code modulation, and space time transmit diversity (STTD) on coverage and capacity of the cell in cellular CDMA system.

In all modulation and coding analysis, presented in this thesis, it is assumed that the channel bandwidth and transmitter power are un-changed due to the system employing modulation and/or coding.

1.2 Previous Work

This thesis is intended to investigate the benefits of using FECC, higher alphabet signaling of modulation, Trellis code modulation and STTD on Coverage-Capacity tradeoff of cellular CDMA system by employing single-user detection.

As the analysis of the capacity and coverage of a cellular CDMA system are crucial issues for network dimensioning, numerous works on this topic already exists. A first approach to the evaluation of the reverse link capacity of a CDMA cellular voice system by analyzing the capacity of a cell by modeling it as $M/M/\infty$ queue was performed in [2], where equally loaded cells are assumed. An extension on that paper is presented in [4], which also includes a good overview on further traffic models. Another study that also assumes a non-uniform loading of cells is given in [5]. In [6], an equation for outage probability is developed that is conditioned on the number of currently supported customers and their location. In [7-9] analysis of CDMA cell coverage have mainly focused on the extension of cell coverage that results from soft and hard handoff.

A method for estimation of reverse-link CDMA cell coverage based on an instantaneous outage criterion was presented in [1]. Cell-coverage estimation based on duration outage criterion for CDMA cellular systems was presented in [10].

In [3], the benefits of modulation on coverage and capacity of cellular CDMA system employing single-user detection is studied. This thesis aims to study the benefits of modulation, coding, Trellis code modulation and STTD on coverage and capacity of cellular CDMA system by employing single-user detection. Here, results from [2], [1] and [3] are used as starting points.

1.3 Outline of the thesis

Chapter 2 gives a brief description on the probability of error for uncoded MQAM, MPSK, and Linear Block Codes based on error correction [11]. It also describes the concepts of Trellis Code modulation [12]. Finally, it describes the simple Space Time Transmit Diversity [13].

Chapter 3 gives a summary of the analysis and results which are presented in [2] and [1]. This helps in further reading and understanding this thesis.

The objective of Chapter 4 is to show the benefits of using the FECC, higher alphabet signaling, TCM, simple STTD and/or merging some of them on coverage and capacity of the cell in cellular CDMA system. This chapter also reproduces the derivation of outage equations when the system employs FECC and/or higher alphabet signaling in line with [1 - 3].

CHAPTER TWO

2.0 MODULATION, CODING AND DIVERSITY

This section gives a brief description of the probability of error for uncoded MQAM, MPSK, and Linear Block Codes based on error correction [11]. It also describes the concepts of Trellis Code modulation [12]. Finally, it describes the simple Space Time Transmit Diversity [13].

2.1 Probability of error for various modulations.

This section describes the probability of error of the various modulation methods, when the channel corrupts the transmitted signal by the Additive White Gaussian Noise (AWGN).

2.1.1 Probability of symbol error for M-ary PSK

In digital phase modulation the M signal waveforms are represented as [11].

$$S_m(t) = g(t)\ Cos\left[2\pi fct + \frac{2\pi}{M}(m-1)\right] \tag{2.1}$$

Where $g(t)$ is the signal pulse shape and $m=1,2....,m,$ are the M possible phases of the carrier that conveys the transmitted information. Digital phase modulation is usually called phase-shift keying (PSK). The symbol error probability of M-ary PSK is approximated as [11].

$$P_S = 2Q(\sqrt{2\gamma_S}\sin\frac{\pi}{M}) = 2Q(\sqrt{2k\gamma_b}\sin\frac{\pi}{M}) \tag{2.2}$$

Where $\gamma_s = k\gamma_b$ is the SNR per symbol, and $k = \log_2 M$ bits per M-ary symbol.

2.1.2 Probability of symbol error for M-ary QAM

The Quadrature Amplitude Modulation (QAM) signal waveforms can be expressed as [11].

$$Sm(t) = Amc\, g(t)\cos(2\lambda f_c t) - Ams\, g(t)\, Sin(2\lambda f_c t), \quad o \le t \le T \qquad (2.3)$$

Where Amc and Ams are the information bearing signal amplitude of the quadrature carriers and $g(t)$ is the signal pulse. The symbol error probability Ps upper bounded for M-ary QAM is [11].

$$P_b \le \frac{4}{k} Q\left(\sqrt{\frac{3k\gamma_{bav}}{M-1}}\right) \qquad (2.4)$$

For any $k \ge 1,$ where γ_{bav} is the average SNR per bit and $k = \log_2 M$

2.2 Linear Block Code and its error probability based on error correction

A block code consists of a set of fixed-length vectors called code words. The length of code word is the number of elements in the vector and is denoted by n. There are 2^n possible code words, in a binary block code of length n. From these 2^n code words, it may select $M = 2^k$ code words $(k < n)$ to form a code. Thus, a block of k information bits is mapped into a code work of length n. Selected from the set of $M = 2^k$ code words. It refers to the resulting block code as (n, k) code, and the ratio $k/n = R_c$ is defined to be the rate of the code.

Bose-Choudhari-Hocquenghem (BCH) codes; One of the most important and powerful classes of linear block codes are BCH codes, which are cyclic codes with a wide variety of parameters. The most common binary BCH codes, known as primitive BCH codes, are characterized for any positive integers $m = (equal\ to\ or\ greater\ than\ 3)$ and $t\left[less\ than\ (2^m - 1)/2\right]$ by the following parameters:

Block length	:	$n = 2^m - 1$
Number of message bit	:	$k \ge n - mt$
Minimum distance	:	$d_{\min} \ge 2t + 1$

Each BCH code a t-error correcting code in that it can detect and correct up to t random errors per code word. Hence, this class of binary codes provides the communication systems designer with a large selection of block length and code rates. An extensive list of generator polynomials for BCH codes can be found in [14].

Probability of error based on error correction

This section describes the probability of error for hard-decision decoding of linear binary block codes based on error correction only. The optimum decoder for a binary symmetric channel will decode correctly if (but not necessarily only if) the number of errors in a code word is less than half the minimum distance $d_{\min}$ of the code. That is, any number of errors up to [11].

$$t = \left\lfloor \frac{1}{2}\left(d_{\min} - 1\right) \right\rfloor \tag{2.5}$$

Are always correctable. Since the binary symmetric channel is memory less, the bit error occurs independently. Hence, the probability of m errors in a block of n bits is [11].

$$p(m,n) = \binom{n}{m} p^{m}(1-p)^{n-m} \tag{2.6}$$

And, therefore, the probability of a code word error is upper-bounded by the expression [11]

$$P_M \leq \sum_{m=t+1}^{n} P(m,n) \tag{2.7}$$

2.3 Trellis Coded Modulation (TCM)

Trellis coded modulation, or TCM, was invented as a method to improve the reliability of a digital transmission system without bandwidth expansion or reduction of data rate. Normal channel codes such as block and convolution codes improve the performances of the communication system by expanding the bandwidth. The Euclidean distance between the transmitted coded waveforms would be increased by the use of coding, but at the price of increasing the bandwidth. Trellis-coded modulation is a coded modulation scheme that can increase the noise immunity and simultaneously do not increase the bandwidth.

2.3.1 The Concept of TCM

An example will introduce the concept of TCM. Consider a digital communication scheme to transmit data from a source emitting two information bits every T seconds. Several solutions are possible.

(a) Use un-coded 4-Phase Shift Keying (4PSK) modulation, with one signal transmitted every T seconds. In this situation, every signal carries two information bits.

(b) Use a convolutional code at rate 2/3 and 4PSK modulation. Since now every signal waveform carries 4/3 information bits, it must have duration of 2T/3 seconds to match the information rate of the source. This results that, with respect to the un-coded scheme, the bandwidth increase by a factor of 3/2.

(c) Use a convolutional code with rate 2/3, and 8-Phase Shift Keying (8PSK) modulation to avoid reducing the signal duration. Each signal still carries 2 information bits, and hence no bandwidth expansion is incurred because coded 8PSK and un-coded 4PSK occupy the same bandwidth.

With solution (c), it can use coding with no bandwidth expansion. One should expect that the use of a higher-order signal constellation would involve a power penalty with respect to 4PSK. The fact is, the coding gain achieved by the rate 2/3 convolution codes could offset this penalty, the net results is some coding gain at no price in bandwidth.

2.3.2 Set Partitioning

The new concept of the TCM that led to the noticeable gains was to use the signal-set partition to provide redundancy for coding, and to design coding and signal mapping functions jointly so as to maximize the “free distance” (minimum Euclidean distance) between coded signal sequences. This allowed the construction of modulation codes whose free distance is significantly exceeding the minimum distance of the uncoded modulation signals, at the same information rate, bandwidth, and signal power. Set partitioning has been described as "the key that cracked the problem of constructing efficient coded modulation techniques for band-limited channels".

The concept of set partitioning is of central significance for TCM schemes. Figure 2.2 shows this concept for a 16 QAM signal constellation. Set partitioning divides the signal set successively into smaller sets with maximally increasing smallest intra-set distances. The finally obtained small signal constellations, labeled D0, D1, … , and D7 in the case of Figure 2.2, will be referred to as the "subsets". Every constellation point is used once, and if the subsets are used with equal probability, the constellation points all appear with equal probability.

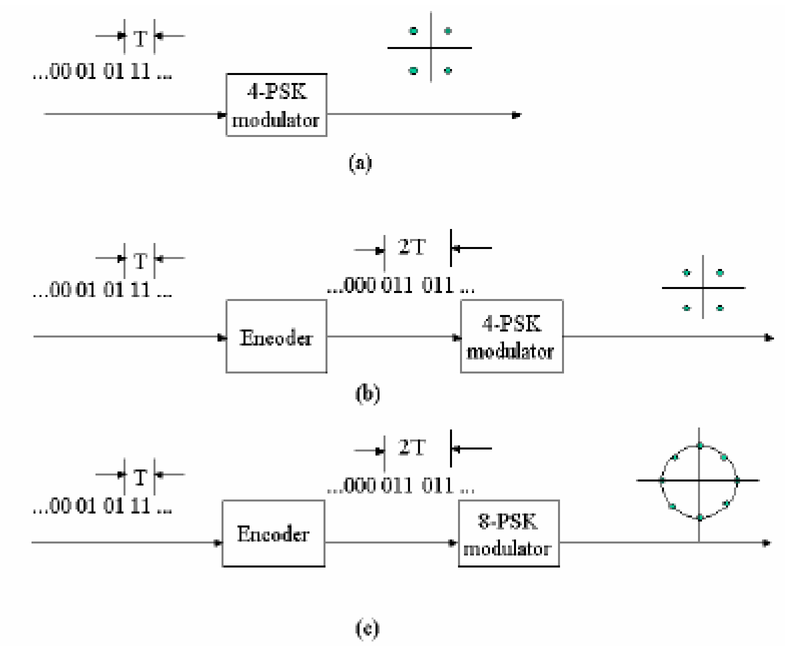

FIGURE 2.1 : THREE DIGITAL COMMUNICATION SCHEMES TRANSMITTING 2 BITS EVERY T SECONDS.

T=2Tb, where Tb is the time duration of one information bit. From [15].

(a) Un-coded transmission with 4PSK.

(b) 4PSK with a rate 2/3 convolutional encoder and bandwidth expansion.

(c) 8PSK with a rate 2/3 convolutional encoder and no bandwidth expansion.

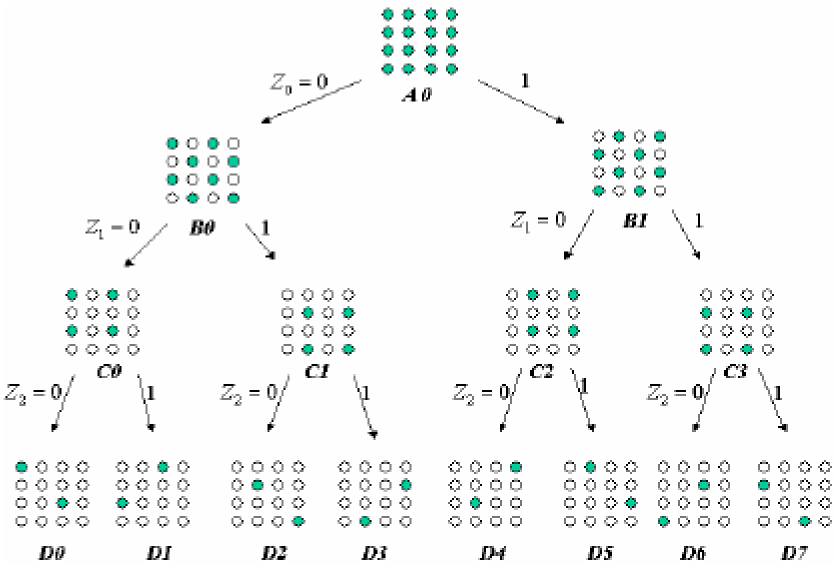

FIGURE 2.2 SUCCESSIVE PARTITION OF THE 16QAM CONSTELLATION ACCORDING TO THE UNGERBOECK RULES. FROM [15].

The subset square minimum intra-set distance doubles after each split, i.e. each subset partition contributes 3dB-coding gain. On this point of view, there should be as many subset splits as possible. However, the complexity also grows with the number of splits.

The degree to which the signal is partitioned depends on the characteristics of the code. In general, the encoding process is performed as illustrated in figure 2.3. A block of m information bits is separated into to groups of length k1 and k2, respectively. The k1 bits are encoded into n bits, while the k2 bits are left uncoded. Then, the n bits from the encoder are used to select on of the possible subsets in the partitioned signal set, while the k2 bits are used to select one of 2^k2 signal points in each subset, when k2=0, all m information bits are encoded. Another important point needs be remembered is that, to get the best TCM schemes, set partitioning should be done according three "Ungerboeck rules".

1. Members of the same largest partition are assigned to parallel transitions.
2. Members of the next larger partition are assigned to "adjacent" transitions, i.e. transitions stemming from, or merging into the same node.

3. All the signals are used equally often.

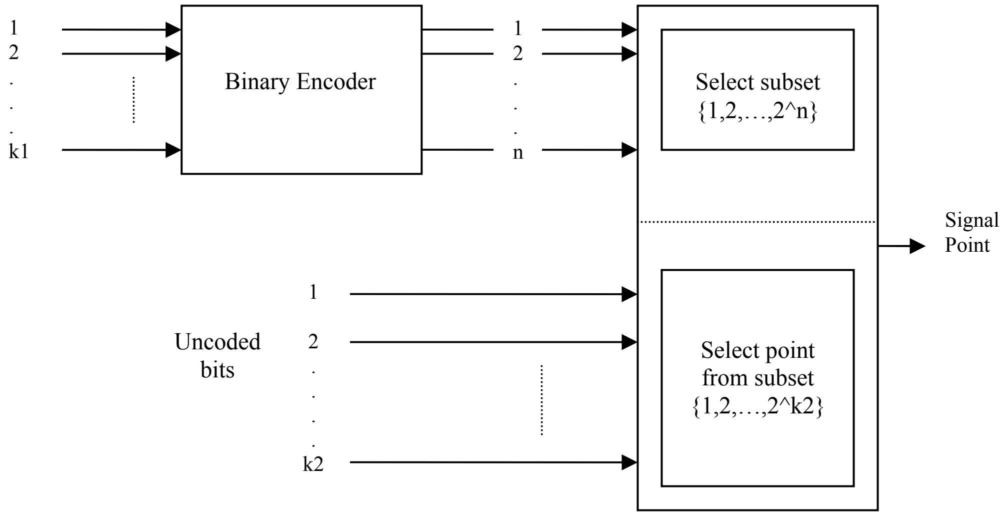

FIGURE 2.3 : GENERAL STRUCTURE OF COMBINED ENCODER/MODULATOR.

Table 1 contains the coding gains obtained with trellis-coded QAM signals [11]. It observed that for rate 2/3 trellis codes yields a gain of 6 dB with 128 trellis stages for m=3 and m=4.

Table 1 Coding gains for trellis-coded QAM modulation [11]

Number of State	k_1	Code Rate $\frac{k_1}{k_1+1}$	$m = 3$ Gain (dB) of 16-QAM vs Uncoded 8-QAM	$m = 4$ Gain (dB) of 32-QAM vs Uncoded 16-QAM	$m = 5$ Gain (dB) of 64-QAM vs Uncoded 32-QAM	$m = \infty$ Asymptotic Coding Gain	N_{fed}
4	1	1/2	3.01	3.01	2.80	3.01	4
8	2	2/3	3.98	3.98	3.77	3.98	16
16	2	2/3	4.77	4.77	4.56	4.77	56
32	2	2/3	4.77	4.77	4.56	4.77	16
64	2	2/3	5.44	5.44	5.23	5.44	56
128	2	2/3	6.02	6.02	5.81	6.02	44
256	2	2/3	6.02	6.02	5.81	6.02	44

2.4 Space Time Transmit Diversity (STTD)

Multipath fading in multiple antenna wireless systems was mostly dealt with by other diversity techniques, such as temporal diversity, frequency diversity and receive antenna diversity, with receive antenna diversity being the most widely applied technique. However, it is hard to efficiently use receive antenna diversity at the remote units because of the need for them to remain relatively simple, inexpensive and small. Therefore, for commercial reasons, multiple antennas are preferred at the base stations, and transmit diversity schemes are growing increasingly popular as they promise high data rate transmission over wireless fading channels in both the uplink and downlink while putting the diversity burden on the base station.

Alamouti's Scheme:

In 1998, Alamouti [13] proposed a simple transmit diversity scheme (see Figure 2.4), which improves the signal quality at the receiver on one side of the link by simple processing across two transmit antennas at the opposite end.

2.4.1 Two Antenna Transmit Diversity Scheme

At a given symbol period, two signals are simultaneously transmitted from the two antennas, namely c_1 from the first antenna, Tx 1, and c_2 from the second antenna, Tx 2. In the next symbol period, signal $\left(-c_2^*\right)$ is transmitted from Tx 1 and signal c_1^* is transmitted from Tx 2, where * denotes complex conjugation.

Assuming that fading is constant across two consecutive symbols, it can be write

$$h_1(t) = h_1(t = T) = h_1 = \alpha_1 \exp j\phi_1 \quad (2.8)$$

$$h_2(t) = h_2(t = T) = h_2 = \alpha_{12} \exp j\phi_2 \quad (2.9)$$

Where T is the symbol period. The received signals are

$$r_1 = r(t) = h_1 c_1 + h_2 c_2 + \eta_1 \quad (2.10)$$

$$r_2 = r(t = T) = -h_1 c_2^* + h_2 c_1^* + \eta_2 \quad (2.11)$$

Where r_1 and r_2 are the received signals at time t and $t + T$.

The combiner combines the received signals as follows:

$$\tilde{c}_1 = h_1^* r_1 + h_2 r_2^* = \left(\alpha_1^2 + \alpha_2^2\right) c_1 + h_1^* \eta_1 + h_2 \eta_2^* \tag{2.12}$$

$$\tilde{c}_2 = h_2^* r_1^* - h_1 r_2^* = \left(\alpha_1^2 + \alpha_2^2\right) c_2 - h_1 \eta_2^* - h_2^* \eta_1 \tag{2.13}$$

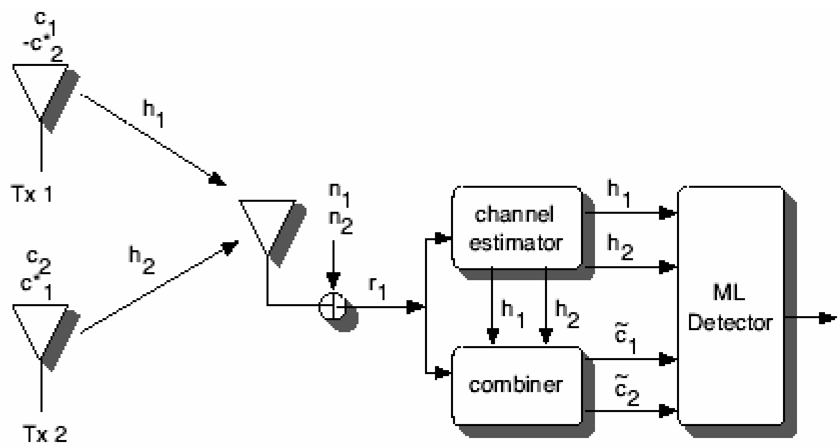

FIGURE 2.4 : ALAMOUTI'S TWO ANTENNA TRANSMIT DIVERSITY SCHEME

2.4.2 Maximum Ratio Combining

In the case of maximum ratio combining (see Figure 2.5), the resulting received signals are

$$r_1 = h_1 c_0 + \eta_1 \tag{2.14}$$

$$r_2 = -h_2 c_0 + \eta_2 \tag{2.15}$$

And the combined signal is

$$c_0 = h_1^* r_1 + h_2^* r_2 \tag{2.16}$$

$$\approx \left(\alpha_1^2 + \alpha_2^2\right) c_0 + h_1^* \eta_1 + h_2^* \eta_2 \tag{2.17}$$

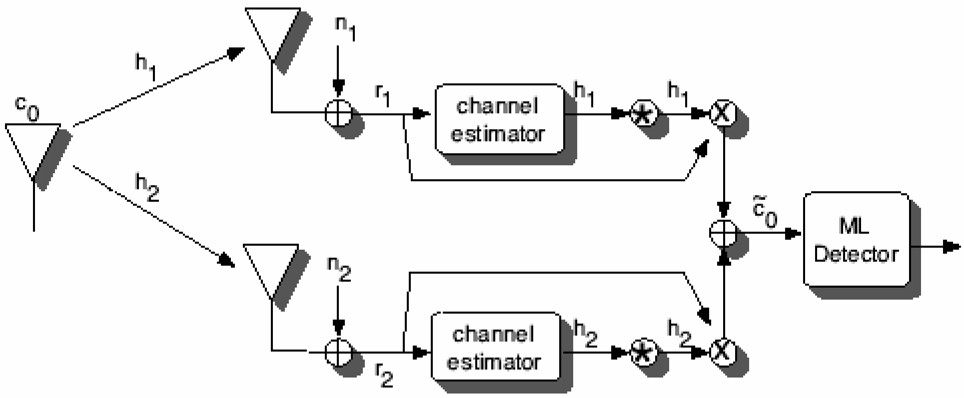

FIGURE 2.5 : MAXIMUM RATIO COMBINING WITH 1 TX AND 2 RX

2.4.3 Summary of Alamouti's scheme

Alamouti further extended this scheme to the case of 2 transmit antennas and m receives antennas, and showed that the scheme provided a diversity order of 2m. Characteristics of this scheme include:

- No feedback from receiver to transmitter is required.
- No bandwidth expansion (as redundancy is applied in space across multiple antennas, not in time or frequency).
- Low complexity decoders.
- Identical performance as MRC if the total radiated power is doubled from that used in MRC, else if transmit power is kept constant, this scheme suffers a 3dB penalty in performance.
- Added reliability as scheme includes a soft failure mode, where the transmitted signal may still be received with lower quality even if diversity gain was lost.
- No need for a complete redesign of existing systems to incorporate this diversity scheme.

Simulations in Alamouti's paper [13] also demonstrated a significant improvement in the error performance of un-coded coherent BPSK for maximum ratio combining and the new transmit diversity scheme in Rayleigh fading (under the assumption of independent fading gains).

CHAPTER THREE

3.0 ERLANG CAPACITY OF POWER CONTROLLED CELLULAR CDMA SYSTEM

The objective of this section is to summarize the analysis and results presented in [1] and [2]. This will help in further understanding this thesis. To facilitate the analysis, the effects of soft handoff and sectorization are not included.

3.1 Erlang Capacity of Power Controlled CDMA System

For the CDMA reverse link (or uplink), which is the limiting direction, blocking is defined to occur when the total collection of users both within the given cell and in other cells introduce an amount of interference density I_0 so great that it exceeds the background noise level N_0 by an amount $1/\eta$, taken to be 10 dB.

If there were always

1) a constant number of users N_u in every cell,

2) each (perfectly power controlled) user were transmitting continually, and

3) Required the same E_b / I_0 (under all propagation conditions).

Then, the number of users N_u would be determined by equating

N_u (Signal power/user) + other cell interference + thermal noise = total interference.

Taking

W = Spread-spectrum bandwidth

R = Data rate

E_b = Bit energy

N_0 = Thermal (or background) noise density

I_0 = Maximum total acceptable interference density

f = Ratio of other cell interference to own cell interference

Then the condition for nonblocking is

$$N_u E_B R(1+f) + N_0 W \le I_0 W \tag{3.1}$$

Whence it follow that

$$N_u \le \frac{W/R}{E_b/I_0} \cdot \frac{1-\eta}{1+f} \tag{3.2}$$

Where

$$\eta = N_0 / I_0 = 0.1 \quad \text{(Nominally)} \tag{3.3}$$

In fact, however, none of the three assumptions above holds since

a) the number of active calls is a Poisson random variable with mean λ/μ (there is no hard limit on servers);

b) each user is gated on with probability ρ and off with $1-\rho$;

c) Each user's required energy-to-interference E_b/I_0 ratio is varied according to propagation conditions to achieve the desired frame error rate (about 1 percent).

For simplicity, it will be assumed to continue that all cells are equally loaded. With assumptions a), b), and c) replacing 1), 2), and 3), the condition for non-blocking, replacing (3.1) becomes

$$\sum_{i=1}^{k} \nu_i E_b R + \sum_{j}^{othe-rcell} \sum_{i=1}^{k} \nu_{i(j)} E_{i_{i(j)}} R + N_0 W \le I_0 W \tag{3.4}$$

with k, the number of users/cell, being a Poisson random variable with mean λ/μ; and ν being the binary random variable taking values 0 and 1, which represents voice activity, with

$$P(\nu = 1) = \rho. \tag{3.5}$$

Dividing by $I_0 R$ and defining

$$\varepsilon = E_b / I_0 \tag{3.6}$$

The non-blocking condition (3.4) becomes

$$Z \stackrel{\Delta}{=} \sum_{i=1}^{k} \nu_i \varepsilon_i + \sum_{j}^{other-cells} \sum_{i=1}^{k} \nu_i^{(j)} \varepsilon_i^{(j)} \leq (W/R)(1-\eta) \qquad (3.7)$$

Hence, the blocking probability for CDMA becomes

$$P_{blocking} = \Pr[Z > (W/R)(1-\eta)]. \qquad (3.8)$$

Setting this equal to a given value (nominally 1 percent) establishes the Erlang capacity of CDMA cellular system. Again, it noted that this soft blocking phenomenon which can be occasionally relaxed by allowing I_0 / N_0, and consequently $1-\eta$ to increase.

Naturally, when condition (3.8) is exceeded, call quality will suffer. Thus, this probability is kept sufficiently low so that it can be ensure high availability of good quality service. Conventional multiple access systems also are limited to providing good quality service only on the order of 90-99 percent of the time because of the variability of interference from just one or a few other users, in contrast with the CDMA case where quality depends on the average over the entire user population.

To evaluate this blocking probability, it must be determine the distribution function of the random variable Z which in turn depends on the random variables ν, k, and ε representing voice activity, number of users in a cell, and E_b / I_0 of any user, respectively.

The distribution of ν is given by (3.5). Since k is Poisson, its distribution is given by

$$P_k = \Pr(k \; acive \; users / cell) = \frac{(\lambda/\mu)^k}{k!} e^{-\lambda/\mu}. \qquad (3.9)$$

Where λ and μ are the arrival and service rates, and λ/μ is the offered average traffic measured in Erlangs.

On the other hand, ε, the E_b / I_0 ratio of a single user, depends on the power control mechanism which attempts to equalize the performance of all users. It has been demonstrated that inaccuracy in power control loops is approximated log-normal distributed with a standard deviation between 1 and 2 dB [17].

However, since under some propagation conditions (e.g. excessive multipath) higher than normal E_b / I_0 will be required to achieve the desired low error rates, the overall distribution, also log-normal distributed, will have a large standard derivation. An example drawn from fields trials with all cells fully loaded, in which E_b / I_0 is varied in order to maintain frame error rate below 1 percent is shown by the histogram of Fig. 3.1. Fig.3.1 is typical of data from a large number of field tests conducted in widely varying terrain in a large number of cities and in several countries. As demonstrated by the dotted curve, the density, with the mean and standard deviation of the normal exponent equal to 7 and 2.4 dB, respectively. Hence, it shall be use the log-normal approximation because this gives us more flexibility in obtaining a general analytical result.

$$\varepsilon = 10^{x/10} \tag{3.10}$$

Where x is a Gaussian variable with mean $m \approx 7$ dB and standard deviation $\sigma = 2.5$ dB.

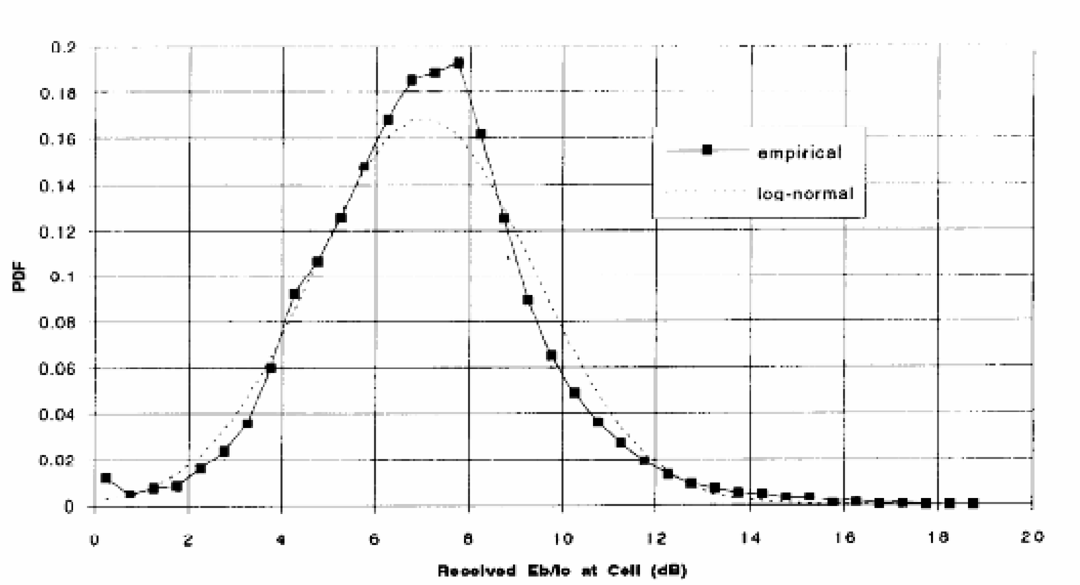

FIGURE 3.1 : EMPIRICAL E_b / I_0 PROBABILITY DENSITY AND LOG-NORMAL APPROXIMATION (MEAN=7DB AND SEGMA=2.5DB)[2].

Note then that the first and second moments of ε are given by

$$E(\varepsilon) = E(e^{\beta x}) = \exp[(\beta\sigma)^2/2]\exp(\beta m) \quad (3.11)$$

$$E(\varepsilon^2) = E(e^{2\beta x}) = \exp[2(\beta\sigma)^2]\exp(2\beta m) \quad (3.12)$$

Where $\beta = (\ln 10)/10$.

Although all moments exist, the moment generating function of ε does not converge; hence the ordinary Chernoff bound for the blocking probability (3.8) cannot be obtained. The result for a single cell (no interference from other cells) is

$$P_{blocking} < \underset{\substack{\delta>0 \\ \tau>0}}{Min} \exp\{\rho(\lambda/\mu)[E(e_T^{\delta\varepsilon'}) - 1] - \delta A\} + \rho(\lambda/\mu)Q(\tau/\sigma) \quad (3.13)$$

Where

$$A \overset{\Delta}{=} \frac{(W/R)(1-\eta)}{\exp(\beta m)} = \frac{(W/R)(1-\eta)}{E_b/I_{0\,median}} \quad (3.14)$$

$$E(e^{\delta\varepsilon'_\tau}) = \int_{-\infty}^{\tau/\sigma} \exp[\delta e^{\beta\sigma\zeta}]e^{-\zeta^2/2}d\zeta/\sqrt{2\pi} \quad (3.15)$$

$$Q(\tau/\sigma) = \int_{\tau/\sigma}^{\infty} e^{-\zeta^2/2}d\zeta/\sqrt{2\pi} \quad (3.16)$$

this bound is obtained through numerical integration of (3.15), and is plotted, for the single cell case, as the upper curve of Fig. 3.2.

A much simpler approach is to assume a central limit theorem approximation for Z and to compute its mean and variance. Then

$$P_{blocking} \approx Q\left[\frac{A - E(Z')}{\sqrt{Var\, Z'}}\right] \quad (3.17)$$

Where $Z' = Z/\exp(\beta m) = Z/(E_b/I_0)_{median}$.

Now since Z is the sum of k random variable, where k is itself a random variables, letting $\varepsilon' = \varepsilon / \exp(\beta m)$,

$$E(Z') = E(k)E(\nu\varepsilon') \\ = (\lambda / \mu)\exp\left[(\beta\sigma)^2 / 2\right] \quad (3.18)$$

$$Var(Z') = E(k)\,Var(\nu\varepsilon') + Var(k)\left[E(\nu\varepsilon')\right]^2 \quad (3.19)$$

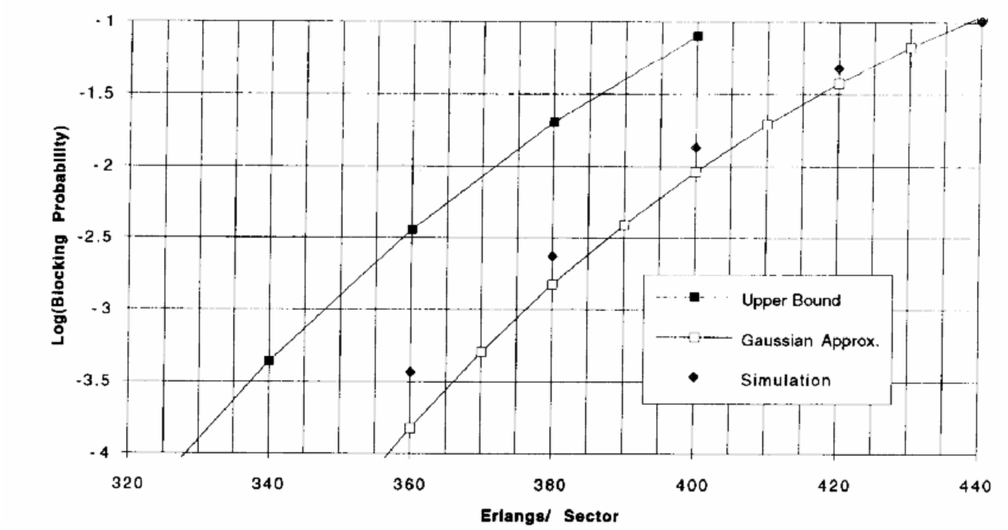

FIGURE 3.2 : BLOCKING PROBABILITIES FOR A SINGLE CELL INTERFERENCE (CDMA PARAMETER W/R=1280; VOICE ACTAIVITY IS 0.4; I_0 / N_0=10DB; MEDIAN E_b / I_0=7DB; SIGMA=2.5DB [2].

3.2 Coverage-Capacity Tradeoff in Cellular CDMA System

3.2.1 Introduction

An accurate prediction of cell coverage as a function of user capacity is essential in code-division multiple access (CDMA) network design and deployment, and is therefore of great interest. Cell coverage is defined as the maximum distance that a given user, of interest, can be from the base station and still have a reliable received signal strength at the base station.

In cellular CDMA systems with non-orthogonal users and single-user detection. it is well known that the coverage of a cell has an inverse relationship with the user capacity of the cell. An increase in the number of active users in the cell causes the total interference seen at the receiver to increase. This causes an increase in the required received power for each user, due to the fact that each user has to maintain a certain signal-to-interference ratio at the receiver for satisfactory performance. For a maximum allowable transmit power, an increase in the required received power will result in a decrease in the maximum distance a mobile can be from the base station, thereby reducing coverage. It will be assumed that coverage is limited by the maximum transmit power at the mobile.

3.2.2 Outage Equation

It will be begun by introducing the relevant variables and the notation required for our analysis.

For any power or signal-to-interference ratio variable X expressed in decibels, $\hat{X}$ denotes $10^{10/X}$.

- k denotes the number of users in the cell, i.e., those being controlled by the cell's base station (BS).
- $\hat{S}_j$ is the power received at the BS from the jth user in watts. (The received power in decibel-watts is, by the above notation, given by $S_j = 10 \log \hat{S}_j$.)
- $\hat{\varepsilon}_j$ is the signal-to-interference ratio (SIR or E_b / I_0) for the j th user.
- v_j is the voice activity factor of jth user. The variables v_j are modeled as independent Bernoulli random variables that take the value 1 with probability ρ and the value 0 with probability $1-\rho$.
- R denotes the information bit rate in bits per second.
- W denotes the system bandwidth in hertz.
- N_0 is background noise power spectral density.
- I is the other-cell interference density.

The signal-to-interference ratio (SIR) for the jth user at the BS may be expressed in terms of the received powers of the various users as [7].

$$\hat{\varepsilon}_j = \frac{\dfrac{\hat{S}_j}{R}}{\displaystyle\sum_{i:i\neq j} \frac{v_i \hat{S}_i}{W} + N_0 + I} \tag{3.20}$$

The SIR requirements for the various users in the cell vary with time due to changes in the multipath fading environment and imperfections in power control. In particular, let $\hat{\varepsilon}_j^{target}$ denote the target SIR that is a function of the target frame error rate (FER) and the multipath conditions, and let $\delta_j^{\hat{\varepsilon}}$ denote the error in the power control algorithm. Then, the required SIR for the jth user is given by

$$\hat{\varepsilon}_j^* = \hat{\varepsilon}_j^{target} \ \delta_j^{\hat{\varepsilon}} \tag{3.21}$$

That is, $\hat{\varepsilon}_j^*$ is the SIR that the power control algorithm is demanding from the mobile at that particular point in time, even though the target SIR may be slightly different. Field trials reported in [2] have shown that the SIR requirements $\hat{\varepsilon}_j^*$ are well modeled by lognormal random variables. Furthermore, it can be assumed that the fading processes that cause the fluctuations in SIR requirements for the various users are independent. By the above discussion, it can be model $\hat{\varepsilon}_j^*$ at any given time by independent and identically distributed (i.i.d.) lognormal random variables.

In order to meet the SIR requirements $\hat{\varepsilon}_j^*$, the required received powers $\hat{S}_j^*$ must satisfy the power control equations

$$\hat{\varepsilon}_j^* = \frac{\dfrac{\hat{S}_j^*}{R}}{\displaystyle\sum_{i:i\neq j} \frac{v_i \hat{S}_i^*}{W} + N_0 + I} \tag{3.22}$$

If the SIR of a given user is lower than the desired value for a certain period of time, we have an outage, i.e., a noticeable degradation in call quality. If the outage lasts long enough, then the call is dropped.

Our approach, therefore, is to simply look at the probability of instantaneous outage, that is, the event that the SIR falls below the required value at any time. The justification for this is two-fold.

First, this corresponds to a worst case outage probability measure. If it contain the probability of instantaneous outage to a small value, say p_m, then the probability of outage will necessarily be smaller than p_m. The reason is that any event corresponding to outage will always contain an instantaneous outage event. The precise relationship between outage and instantaneous outage depends on the nature of the fading experienced by the mobile. In the worst case, when the fading is perfectly correlated for duration equal to the minimum duration for outage, the events will have the same probability. Thus containing the probability of instantaneous outage to p_m guarantees that the worst case outage probability is also contained to p_m.

Second, it is clear that, due to the time correlation in the fading, whenever the SIR $\hat{\varepsilon}$ is below some threshold $\hat{\varepsilon}^*$, even instantaneously, it will necessarily be below any other threshold $\hat{\varepsilon}' > \hat{\varepsilon}^*$ for a duration that is greater than or equal to the duration of being below $\hat{\varepsilon}^*$. Therefore, it can be address the minimum duration outage issue by analyzing instantaneous outage using an SIR threshold that is lower than the actual threshold. That is, given a fading environment, and given that the SIR should not fall below a threshold equal to $\hat{\varepsilon}'$ for a period exceeding τ, there exists a $\hat{\varepsilon}' > \hat{\varepsilon}^*$ such that the probability of instantaneous outage corresponding to $\hat{\varepsilon}^*$ equals the probability of minimum duration outage corresponding to $\hat{\varepsilon}'$ and τ.

Therefore, it can be use a simpler analysis in order to determine coverage. In doing so, it not only avoid the complexity of the calculations involving minimum duration outage but, more importantly, it can avoid the intractability of these calculations. The intractability is due to the fact that, for our coverage analysis, it needs to take into account all possible fading scenarios that a mobile user may face in a given cellular environment. In practice, the desired $\hat{\varepsilon}^*$ can be found empirically for different cellular environments, such as rural, urban, dense urban, highway, etc.

Based on the above discussion, by focusing on the instantaneous outage event for user j, i.e., the event $\hat{\varepsilon}' < \hat{\varepsilon}^*$. There are two ways in which this event can happen: i) the power control equations of (3.22) do not have a feasible solution (That is, no matter how large the received powers are, the SIR requirements of the users cannot be satisfied.) (call this event A_{out}) and ii) the power control equations have a feasible solution, but the maximum transmit power $S_{\max}$ at the mobile is exceeded (call this event B_{out}). Thus the probability of outage is given by

$$P_{out} = P(A_{out}) + [1 - P(A_{out})]P(B_{out} \left| A_{out}^{c} \right.) \qquad (3.23)$$

Where $A^{c}{}_{out}$ is the complement of event A_{out}, i.e., $A^{c}{}_{out}$ is the event that the power control equations have a feasible solution. It will be use the outage equation to characterize the capacity-coverage tradeoff. To begin the analysis, by focusing on the feasibility of the power control equations of (3.22).

It can be shown that the equation (3.22) have a feasible solution (i.e., $\hat{S}_j^* \in (0,\infty), \forall j$) if and only if

$$\sum_{i=1}^{k} \frac{R\,\hat{\varepsilon}_i^*\,\nu_i}{W + R\,\hat{\varepsilon}_i^*\,\nu_i} < 1 \qquad (3.24)$$

Under this condition, it can be shown that the required received power for user j is given by

$$\hat{S}_j^*(k) = \frac{\dfrac{(N_0 + I)WR\,\hat{\varepsilon}_j^*}{W + R\,\hat{\varepsilon}_j^*\,\nu_j}}{1 - \sum_{i=1}^{k} \dfrac{R\,\hat{\varepsilon}_i^*\,\nu_i}{W + R\,\hat{\varepsilon}_i^*\,\nu_i}} \qquad (3.2.25)$$

It will be focused on the coverage seen by user 1 when the number of users in the cell is k. Let d be the distance of user 1 from BS. Then, the transmit power (in decibel-watts) of user 1 is given in terms of its received power S_1 at the BS by

$$S_{trans} = S_1 + PL(d) + Z_1 \qquad (3.26)$$

Where $PL(d)$ is the path loss at distance d from the BS (including antenna gains) and Z_1 is a random variable representing shadow fading. The path loss is usually well modeled as (see, e.g., Hata's model [16])

$$PL(d) = K_1 + K_2 \log(d) \qquad (3.27)$$

The shadow fading variable Z_1 is well modeled as a zero-mean Gaussian random variable with variance σ_Z^2 [16].

The probability of event B_{out} for user 1 is the probability that S_{trans} exceeds $S_{\max}$, the maximum power available at the mobile. Thus by (3.23), the probability of outage at a distance d from the BS is given by

$$P_{out} = P(A_{out}) + [1 - P(A_{out})]P(S_1^* + PL(d) + Z_1 > S_{\max} \big| A_{out}^c) \qquad (3.28)$$

The largest outage probability is seen at the edge of the cell. It can define the coverage of the cell R_{cell} to be the distance from the BS at which P_{out} equals the maximum allowable outage probability ρ_m. Thus R_{cell} is obtained as a solution to

$$\rho_m = P(A_{out}) + [1 - P(A_{out})]P(S_1^* + PL(R_{cell}) + Z_1 > S_{\max} \big| A_{out}^c) \qquad (3.29)$$

In (3.29), there are two quantities that depend on the number of users k in the system: $P(out)$ and S_1.

Conditioned on A_{out}^c, the power control equations have a feasible solution and this solution for user 1 is given by [see (3.25)]

$$\hat{S}_1^*(k) = \frac{\dfrac{(N_0 + I)WR\ \hat{\varepsilon}_1^*}{W + R\ \hat{\varepsilon}_j^*\ \nu_j}}{1 - \sum_{i=1}^{k} \dfrac{R\ \hat{\varepsilon}_i^*\ \nu_i}{W + R\ \hat{\varepsilon}_i^*\ \nu_i}} \qquad (3.30)$$

From (3.22), the required SIR for the user 1 at the BS may be expressed in terms of the received powers of the other users as

$$\hat{\varepsilon}_1^* = \frac{\dfrac{\hat{S}_1^*}{R}}{\sum_{i:i \neq j} \dfrac{\nu_i \hat{S}_i^*}{W} + N_0 + I} \qquad (3.31)$$

Since the required SIR $\hat{\varepsilon}_1^*$ is lognormal, $\varepsilon_1^* = 10 \log \hat{\varepsilon}_1^*$ is Gaussian. (Typical values for the mean and standard deviation of ε_1^* are $m_\varepsilon = 7$ dB and $\sigma_\varepsilon = 2.5$ dB [2].) If let $m_{\hat{\varepsilon}}$ and $\delta_{\hat{\varepsilon}}$ denote the mean and second moment of $\hat{\varepsilon}_1^*$, then it can easily show that

$$m_{\hat{\varepsilon}} = \exp\left(\frac{(\beta\sigma_{\varepsilon})^2}{2}\right)\exp(\beta m_{\varepsilon}) \tag{3.32}$$

and

$$\delta_{\hat{\varepsilon}} = \exp\left(2(\beta\sigma_{\varepsilon})^2\right)\exp(2\beta m_{\varepsilon}) \tag{3.33}$$

Where $\beta = \ln(10)/10$.

Using the i.i.d. approximation for, it can obtain equations for all of the moments of by taking expectations of appropriate powers. A moment analysis using four moments reveals that is very well approximated by a lognormal random variable 3 for (see Table III). Thus only the mean and second moment of need to be Calculated. These are given by

$$m_{\hat{S}}(k) = \frac{(N_0 + I)Wm_{\hat{\varepsilon}}}{\frac{W}{R} - \rho(k-1)m_{\hat{\varepsilon}}} \tag{3.34}$$

and

$$\delta_{\hat{S}}(k) = \frac{\left\{\left[(N_0 + I)W + \rho(k-1)m_{\hat{S}}\right]^2 - (k-1)\rho^2 m_{\hat{S}}{}^2\right\}\delta_{\hat{\varepsilon}}}{\left(\frac{W}{R}\right)^2 - \rho(k-1)\delta_{\hat{\varepsilon}}} \tag{3.35}$$

Under the lognormal approximation for $\hat{S}_1^*$, $\hat{S}_1^*$ is Gaussian. The mean and variance of $\hat{S}_1^*$ can easily be calculated in terms of $m_{\hat{S}}$ and $\delta_{\hat{S}}$ as given below

$$m_S(k) = 20\log_{10} m_{\hat{S}}(k) - 5\log_{10}\delta_{\hat{S}}(k) \tag{3.36}$$

and

$$\sigma_S^2(k) = \frac{1}{\beta}\left(10\log_{10}\delta_{\hat{S}}(k) - 20\log_{10} m_{\hat{S}}(k)\right) \tag{3.37}$$

Now, in order to evaluate the probability on the left-hand side (LHS) of (3.29), it is need to determine the joint statistics of $\hat{S}_1^*$ and Z_1. The means and variances of these random variables have been specified, so all that remains to be determined is the correlation between them.

It can be argued that the correlation between $\hat{S}_1^*$ and Z_1 is close to zero, since the fluctuations in the required received power $\hat{S}_1^*$ are mainly due to multipath fading and imperfections in power control, whereas the fluctuations in Z_1 are due to shadow fading. It can compute the conditional probability $P(B_{out}|A_{out}^c)$ in (3.29) as

$$P(S_1^* + PL(R_{cell}) + Z_1 > S_{\max}|A_{out}^c) = Q\left(\frac{S_{\max} - (K_1 + K_2 \log R_{cell}) - m_S(k)}{\sqrt{\sigma_S^2(k) + \sigma_Z^2}}\right) \qquad (3.38)$$

Where it can be used the path loss model of (3.2.8), and where $Q(\cdot)$ is the complementary cdf of a zero-mean, unit-variance Gaussian random variable. Substituting (3.2.19) in (3.2.10), it can be getting the following explicit equation relating the coverage R_{cell} and the number of users k :

$$\log R_{cell} = \frac{1}{K_2}\left[S_{\max} - K_1 - m_S(k) - \sqrt{\sigma_S^2(k) + \sigma_z^2}\,Q^{-1}\left(\frac{p_m - P_A(k)}{1 - P_A(k)}\right)\right] \qquad (3.39)$$

Where $P_A(k)$ is $P(A_{out})$ written explicitly as a function of k .

CHAPTER FOUR

4.0 ANALYTICAL RESULTS

4.1 Introduction

The objective of this thesis is to study the benefits of using the FECC, higher alphabet signaling, TCM and STTD on coverage and capacity of the cell in cellular CDMA system. Here, the active user is considered as *Poisson Random Variable* employing *single user detection*.

Also, it is considered that the channel bandwidth and transmitted power signal are limited. When coding is applied to the bandwidth-limited channel, a performance gain is desired without expanding the signal bandwidth, by maintaining the power signal constant for both uncoded as well as coded system. It is also considered that a cell in a CDMA network is with a Base Transceiver Station (BTS) supporting a number of active users.

The coverage of the cell has an inverse relationship with the user capacity of the cell. An increase in the number of active users in the cell causes the total interference seen at the receiver to increase. This causes an increase in the required received power for each user, due to the fact that the system will try to find a proper code rate and modulation to maintain a certain signal-to-interference ratio at the receiver for satisfactory performance. Therefore, both coverage and capacity of a cell need to be planned in such a way that all calls are sufficiently supplied, i.e. adaptive modulation and coding according to the desired quality of service.

To ease the further reading of this thesis, it will, in the following sections, summarize and reproduce the derivation of outage equations by employed FECC and/or higher alphabet signaling, in line with [1-3].

4.2 Parameters Definitions and Values

It will be begun by introducing the Parameters values and definitions used in our analytical result are as follows:

k	Number of user in the cell	
R	Information bit rate in bits per second	14.4Kbps
W	System bandwidth in hertz	1.25M bps
N_0	Thermal noise power spectral density	-169 Bm/Hz
I	Other cell interference density	$2N_0$
I_0	Maximum total acceptable interference density	
K_1	Path loss constant	17.3 dB
K_2	Path loss exponent	33.8dB
$S_{\max}$	Maximum mobile transmit power	23 dBm
ρ	Average voice activity factor	0.45
p_m	Maximum outage probability	0.05
m_ε	Mean of SIR required for BPSK modulation	7 dB
$P_{blocking}$	Blocking probability	
σ_ε	Standard deviation of SIR required	2.5dB
σ_z	Shadow fading standard deviation	8 dB
$m_S(k)$	Mean of S_k	
$\sigma_k^2(k)$	Variance of S_k	
$\delta_{\hat{S}}(k)$	Second moment of S_k	
R_{cell}	Cell coverage in meter	
n	Number of bits per symbol	

f Ratio of inter-cell interference (other cell interference) at base station for given cell to intera-cell interference (own cell interference)

η_v	Ratio of thermal noise to maximum total acceptable interference
η	Ratio of inter-cell interference to thermal noise

λ Arrival rate

μ Service rate

β $\ln(10)/10$

4.3 Outage Probability Equation using M-ary Modulation and FECC

The signal-to-interference ratio (SIR) for the jth user at the BS may be expressed in terms of the received powers of the various users as [18].

$$\varepsilon_j = \frac{\frac{S_j}{R}}{\sum_{i:i\neq j} \frac{\nu_i S_i}{W} + N_0 + I} \tag{4.1}$$

Here, ν_i is the voice activity factor of the jth call. The variables ν_i are modeled as independent Bernoulli random variables that takes the value 1 with probability ρ. R denotes the information bit rate in bits per second and W is the system bandwidth in Hz. The total interference in the denominator is added by the background noise power spectral density N_0 and the other cell interference density I.

The random variables $S, S_1, S_2, \ldots S_{k-1}$ are modeled as i.i.d. log-normal distributed random variables.

In this thesis, it is considered that the channel bandwidth and transmitted power signal are unchanged. When coding is applied to the bandwidth-limited channel, a performance gain is desired without expanding the signal bandwidth.

For example, if the system employs uncoded BPSK modulation with symbol rate R_s at a certain error probability, for this error rate, the SNR per bit is γ_b. We may try to reduce the SNR per bit by use of coding. But this must be done without expanding the bandwidth. If the system chooses a code rate R_c, the symbol rate R_s will be replaced by R_s/R_c. This will yield the same information rate as uncoded BPSK.

From above discussion, it can be rewritten (4.1) as (4.2) see change.

$$\varepsilon_j = \frac{\frac{R_c S_j}{R}}{\sum_{i:i\neq j} \frac{v_i S_i}{W} + N_0 + I} \tag{4.2}$$

When coding and M-ary modulation are applied to the bandwidth-limited channel, a performance is desired without expanding the signal bandwidth.

For example, if the system employing uncoded BPSK modulation with symbol rate R_s at a certain error probability, for this error rate, the SNR per bit is γ_b. We may try to reduce the SNR per bit by using both modulation and coding. But this must be done without expanding the bandwidth. If the bandwidth chooses a code rate R_C and higher M-ary modulation with a $n=\log_2 M$ bits per M-ary symbol the symbol rate R_s will be replaced by R_s/nR_c. This yields the same information rate as uncoded BPSK.

From above discussion, it can be rewritten (4.1) as

$$\varepsilon_j = \frac{\frac{nR_c S_j}{R}}{\sum_{i:i\neq j} \frac{v_i S_i}{W} + N_0 + I} \tag{4.3}$$

[3] has presented the application of M-ary modulation in cellular CDMA system.

If the SIR of a given user is lower than the desired value for a certain period of time, it will be there is an outage, i.e., a noticeable degradation in call quality. If the outage lasts long enough, then the call is dropped.

Based on the analysis in [1], and by summarizing the results of instantaneous outage event for the user j.

There are two ways in which this event can occur:

I) Interference limited case: the power control equations of (4.1) do not have a feasible solution (That is, no matter how large the received powers are, the SIR requirements of the users cannot be satisfied.) (call this event A_{out}) and

II) Power limited case: the power control equations (4.1) have a feasible solution, but the maximum transmit power $S_{\max}$ at the mobile is exceeded (call this event B_{out}).

Thus the probability of outage is given by:

$$P_{out} = P(A_{out}) + [1 - P(A_{out})]P(B_{out} \mid A_{out}^{c}) \qquad (4.4)$$

Where $A^{c}{}_{out}$ is the complement of event A_{out}, i.e., $A^{c}{}_{out}$ is the event that the power control equations have a feasible solution.

It can be seen that in [1] the probability that the power control equation of (4.1) a feasible solution (event A_{out} of (4.4)) is given by

$$P(A_{out}) = p\left[\sum_{i=1}^{k} \frac{\varepsilon_i v_i}{\frac{nW}{R} + \varepsilon_i v_i} \geq 1\right] \qquad (4.5)$$

When using coding bandwidth-limited channel system, the equation (4.5) can be rewritten (4.6) as

$$P(A_{out}) = p\left[\sum_{i=1}^{k} \frac{\varepsilon_i v_i}{\frac{nW}{R} + \varepsilon_i v_i} \geq 1\right] \qquad (4.6)$$

When using coding and modulation bandwidth-limited channel system, the equation can be rewritten (4.7) as

$$P(A_{out}) = p\left[\sum_{i=1}^{k}\frac{\varepsilon_i v_i}{\frac{nW}{R}+\varepsilon_i v_i} \geq 1\right] \qquad (4.7)$$

[3] has presented the application of M-ary modulation in cellular CDMA system.

Under the log-normal assumption on required SIR's, the probability of event A_{out} is always non-zero as long as η , and $P(A_{out})$ increases with increasing k. Thus even if there were no constraint on the maximum mobile transmit power, the probability that the SIR requirements are not met P_{out} increases toward 1 with increasing k. For a given set of parameter values, $P(A_{out})$ can be computed for various values of k using Monte Carlo techniques [1], repeated numerical convolution of the probability density function [1], or by assuming a central limit theorem approximation for sum of the k random variables in (4.5), where k is itself a random variable, it can be have [2]

$$P_{blocking} \approx Q\left[\frac{A - E(Z')}{\sqrt{Var\, Z'}}\right] \qquad (4.8)$$

Where A in (4.8) is

$$A \stackrel{\Delta}{=} \frac{(W/R)(1-\eta)}{\exp(\beta m)} = \frac{(W/R)(1-\eta)}{E_b / I_{0\ median}} \qquad (4.9)$$

When coding is applied to the bandwidth-limited channel, the equation (4.9) can be rewritten (4.10) as,

$$A \stackrel{\Delta}{=} \frac{(nW/R)(1-\eta)}{\exp(\beta m)} = \frac{(nW/R)(1-\eta)}{E_b / I_{0\ median}} \qquad (4.10)$$

and when coding and modulation are applied to the bandwidth-limited channel, the equation (4.9) can be rewritten (4.11) as,

$$A \overset{\Delta}{=} \frac{(nW/R)(1-\eta)}{\exp(\beta m)} = \frac{(nW/R)(1-\eta)}{E_b/I_{0\,median}} \tag{4.11}$$

and

$$Z \overset{\Delta}{=} \sum_{i=1}^{k} \nu_i \varepsilon_i + \sum_{j}^{other-cells} \sum_{i=1}^{k} \nu_i^{(j)} \varepsilon_i^{(j)} \tag{4.12}$$

Now since Z is the sum of k random variable, where k is itself random variables, it can be have from [16], letting $\varepsilon' = Z' = \varepsilon / \exp(\beta m) = Z / \exp(\beta m)$,

$$E(Z') = (\lambda/\mu)\ \rho\ (1+f)\ \exp\left[(\beta\sigma)^2/2\right] \tag{4.13}$$

$$Var(Z') = (\lambda/\mu)\ \rho\ (1+f)\ \exp\left[2(\beta\sigma)^2\right] \tag{4.14}$$

and

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp(-t^2/2)\ dt \tag{4.15}$$

Where λ and μ are the arrival and service rates, and λ/μ is the offered average traffic measured in Erlangs.

4.4 Coverage versus Number of Users when the System Employs Coding and Modulation.

Following the analysis in [1], let d be the distance of user 1 from BS. Then, the transmit power (in decibel-watts) of user 1 is given in terms of its received power S_1 at the BS by

$$S_{trans} = S_1 + PL(d) + Z_1 \tag{4.16}$$

Where $PL(d)$ is the path loss at distance d from the BS (including antenna gains) and Z_1 is a random variable representing shadow fading. The path loss is usually well modeled as (see, e.g., Hata's model [16])

$$PL(d) = K_1 + K_2 \log(d) \tag{4.17}$$

The shadow fading variable Z_1 is well modeled as a zero-mean Gaussian random variable with variance σ_Z^2 [2].

The probability of event B_{out} for user 1 is the probability that S_{trans} exceeds $S_{\max}$, the maximum power available at the mobile. Thus by (4.3), the probability of outage at a distance d from the BS is given by

$$P_{out} = P(A_{out}) + [1 - P(A_{out})]P(S_1^* + PL(d) + Z_1 > S_{\max} \middle| A_{out}^c) \qquad (4.18)$$

The largest outage probability is seen at the edge of the cell. It can be define the coverage of the cell R_{cell} to be the distance from the BS at which P_{out} equals the maximum allowable outage probability ρ_m. Thus R_{cell} is obtained as a solution to

$$\rho_m = P(A_{out}) + [1 - P(A_{out})]P(S_1^* + PL(R_{cell}) + Z_1 > S_{\max} \middle| A_{out}^c) \qquad (4.19)$$

In (4.19), there are two quantities that depend on the number of users k in the system: $P(out)$ and S_1.

Conditioned on A_{out}^c, the power control equations have a feasible solution and this solution for user 1 is given by

$$\hat{S}_1^*(k) = \frac{\dfrac{(N_0 + I)WR\ \varepsilon_1^*}{W + R\ \hat{\varepsilon}_j^*\ \nu_j}}{1 - \sum_{i=1}^{k} \dfrac{R\ \hat{\varepsilon}_i^*\ \nu_i}{W + R\ \hat{\varepsilon}_i^*\ \nu_i}} \qquad (4.20)$$

From (4.1), the required SIR for the user 1 at the BS may be expressed in terms of the received powers of the other users as

$$\hat{\varepsilon}_1^* = \frac{\dfrac{\hat{S}_1^*}{R}}{\sum_{i:i \neq j} \dfrac{\nu_i \hat{S}_i^*}{W} + N_0 + I} \qquad (4.21)$$

Since the required SIR β is lognormal, $\varepsilon_1^* = 10 \log \hat{\varepsilon}_1^*$ is Gaussian. (Typical values for the mean and standard deviation of ε_1^* are $m_\varepsilon = 7$ dB and $\sigma_\varepsilon = 2.5$ dB [2].) If let $m_{\hat{\varepsilon}}$ and $\delta_{\hat{\varepsilon}}$ denote the mean and second moment of $\hat{\varepsilon}_1^*$, then it can easily show that

$$m_{\hat{\varepsilon}} = \exp\left(\frac{(\beta\sigma_{\varepsilon})^2}{2}\right)\exp(\beta m_{\varepsilon}) \tag{4.22}$$

and

$$\delta_{\hat{\varepsilon}} = \exp\left(2(\beta\sigma_{\varepsilon})^2\right)\exp(2\beta m_{\varepsilon}) \tag{4.23}$$

Where $\beta = \ln(10)/10$.

Using the i.i.d. approximation, it can obtain equations for all of the moments by taking expectations of appropriate powers in (4.21). Thus only the mean and second moment needs to be calculated. These are given by

$$m_{\hat{S}}(k) = \frac{(N_0 + I)Wm_{\hat{\varepsilon}}}{\frac{W}{R} - \rho(k-1)m_{\hat{\varepsilon}}} \tag{4.24}$$

and

$$\delta_{\hat{S}}(k) = \frac{\left\{\left[(N_0 + I)W + \rho(k-1)m_{\hat{S}}\right]^2 - (k-1)\rho^2 m_{\hat{S}}{}^2\right\}\delta_{\hat{\varepsilon}}}{\left(\frac{W}{R}\right)^2 - \rho(k-1)\delta_{\hat{\varepsilon}}} \tag{4.25}$$

And when coding is applied to the bandwidth-limited channel system, equations (4.24) and (4.25) can be rewritten as,

$$m_{\hat{S}}(k) = \frac{(N_0 + I)Wm_{\hat{\varepsilon}}}{\frac{R_c W}{R} - \rho(k-1)m_{\hat{\varepsilon}}} \tag{4.26}$$

And also for second moment

$$\delta_{\hat{S}}(k) = \frac{\left\{\left[(N_0 + I)W + \rho(k-1)m_{\hat{S}}\right]^2 - (k-1)\rho^2 m_{\hat{S}}{}^2\right\}\delta_{\hat{\varepsilon}}}{\left(\frac{R_c W}{R}\right)^2 - \rho(k-1)\delta_{\hat{\varepsilon}}} \tag{4.27}$$

Also when coding and higher alphabet signaling are applied to the bandwidth-limited channel, equations (4.24) and (4.25) can be rewritten as

$$m_{\hat{S}}(k) = \frac{(N_0 + I)Wm_{\hat{\varepsilon}}}{\frac{nR_c W}{R} - \rho(k-1)m_{\hat{\varepsilon}}} \tag{4.28}$$

And also for second moment

$$\delta_{\hat{S}}(k) = \frac{\left\{\left[(N_0 + I)W + \rho(k-1)m_{\hat{S}}\right]^2 - (k-1)\rho^2 m_{\hat{S}}{}^2\right\}\delta_{\hat{\varepsilon}}}{\left(\frac{nR_c W}{R}\right)^2 - \rho(k-1)\delta_{\hat{\varepsilon}}} \tag{4.29}$$

Under the lognormal approximation for $\hat{S}_1^*$, $\hat{S}_1^*$ is Gaussian. The mean and variance of $\hat{S}_1^*$ can easily be calculated in terms of $m_{\hat{S}}$ and $\delta_{\hat{S}}$ as given below

$$m_S(k) = 20\log_{10} m_{\hat{S}}(k) - 5\log_{10}\delta_{\hat{S}}(k) \quad (4.30)$$

and

$$\sigma_S^2(k) = \frac{1}{\beta}\left(10\log_{10}\delta_{\hat{S}}(k) - 20\log_{10} m_{\hat{S}}(k)\right) \quad (4.31)$$

Now, in order to evaluate the probability on the left-hand side (LHS) of (4.19), it is needed to determine the joint statistics of $\hat{S}_1^*$ and Z_1. The means and variances of these random variables have been specified, so all that remains to be determined is the correlation between them.

It can be argued that the correlation between $\hat{S}_1^*$ and Z_1 is close to zero, since the fluctuations in the required received power $\hat{S}_1^*$ are mainly due to multipath fading and imperfections in power control, whereas the fluctuations in Z_1 are due to shadow fading. It can hence compute the conditional probability $P(B_{out}\left|A_{out}^c\right.)$ in (4.19) as

$$P(S_1^* + PL(R_{cell}) + Z_1 > S_{\max}\left|A_{out}^c\right.) = Q\left(\frac{S_{\max} - (K_1 + K_2\log R_{cell}) - m_S(k)}{\sqrt{\sigma_S^2(k) + \sigma_Z^2}}\right) \quad (4.32)$$

Where it can be used the path loss model of (4.17), and where $Q(\cdot)$ is the complementary cdf of a zero-mean, unit-variance Gaussian random variable. Substituting (4.32) in (4.19), gives the following explicit equation relating the coverage R_{cell} and the number of users k:

$$\log R_{cell} = \frac{1}{K_2}\left[S_{\max} - K_1 - m_S(k) - \sqrt{\sigma_S^2(k) + \sigma_z^2}\; Q^{-1}\left(\frac{p_m - P_A(k)}{1 - P_A(k)}\right)\right] \quad (4.33)$$

Where $P_A(k)$ is $P(A_{out})$ written explicitly as a function of k. All the terms in (4.33) are expressed in decibels (dB).

In case of Rayliegh channel, it will be use the approach of [20] by assuming P(Aout) <<P(Bout) over the range of k and it is focus on bounding the probability of event Bout, so the following explicit equation relating the coverage and capacity:

$$\log R_{cell} = \frac{1}{K_2}\left[S_{\max} - K_1 - m_S(k) - \sqrt{\sigma_S^2(k) + \sigma_z^2}\; Q^{-1}(p_m)\right] \quad (4.34)$$

4.5 Analytical Results

4.5.1 Introduction

By employing single user detection for limited transmit power, in-cell interference limits cell-coverage. It is considered that, the channel bandwidth and transmitted power signal are unchanged, when FECC and/or higher alphabet signaling M-ary modulation employed to the system.

The number of active calls (users) is a Poisson random variable and the voice activity factor being the binary random variable, the ratio of other cell interference to-own cell interference is 0.55 [2].

In this thesis, in order to calculate the outage probability, the central limit theorem approximation [2] is used. Note that, all parameters value used in these analytical results are mentioned in section 4.2.

4.5.2 Coverage-Capacity Tradeoff, Effected by Varying Some Parameters.

The purpose of this section is to study the effect due to varying other-cell interference ratio, the mean of signal-to-interference ratio and path loss exponent.

4.5.2.1 Coverage-Capacity Tradeoff, by Variation in Other-cell interference

Other-cell interference signals are often generated within the cellular system. They are difficult to control, in practice, due to random propagation effects.

Figure 4.1 illustrates that the cell coverage and its capacity will be affected by variations in other-cell interference. So, with an increase of other-cell interference density *I*, the cell coverage will decrease. Therefore, the coverage of the cell has an inverse relationship with other cell interference.

Note that, the maximum number of users in-cell is unaffected by other-cell interference. As expected, the cell-coverage is considerably more sensitive to variations in other-cell interference *I* when the number of users on other adjacent cells are large.

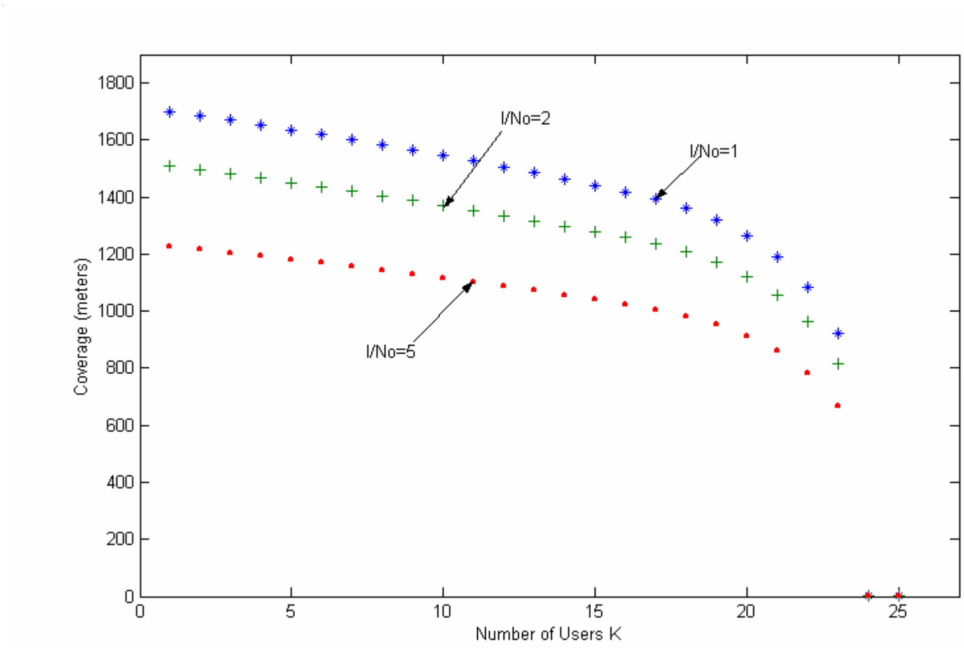

FIGURE 4.1 : COVERAGE-CAPACITY TRADEOFF, SENSIVITY TO VARIATION ON THE OTHER-CELL INTERFERENCE.

4.5.2.2 Coverage-Capacity Tradeoff, by Variation in Mean of Signal-to-Interference ratio

Figure 4.2 illustrates that, the cell coverage and its capacity tradeoff will be affected by variations in mean of SIR (Signal-to-Interference Ratio) required.

It is observed that, an increase in the mean of SIR required will cause the cell coverage to decrease.

The probability of outage will increase when the mean of SIR required is increased as shown in Figure 4.2. As such, when the mean of SIR is 8, the maximum number of users is 17, but when the mean of SIR is 6 the maximum number of users is 31. Therefore, the coverage of the cell has an inverse relationship with the mean of signal-to-interference ratio.

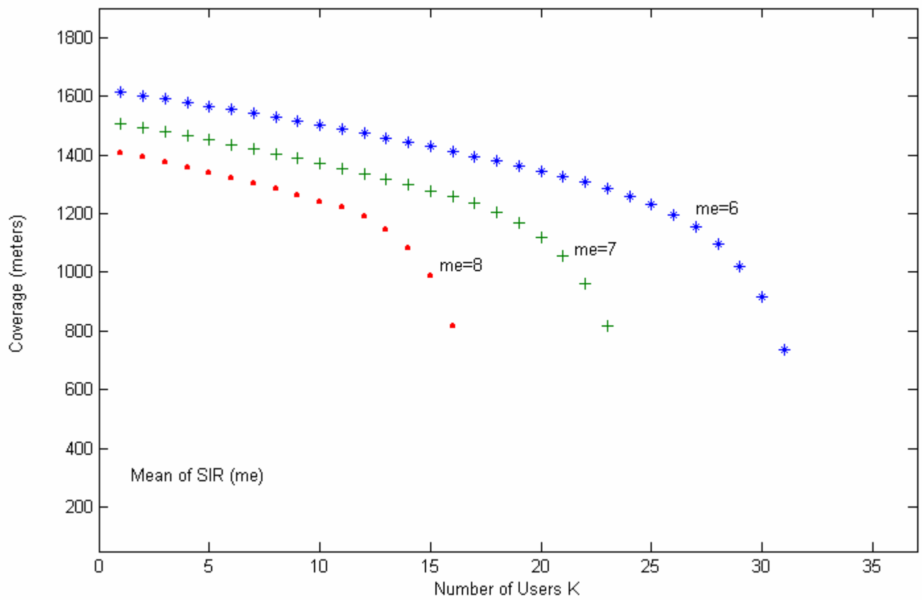

FIGURE 4.2 : COVERAGE-CAPACITY TRADEOFF, SENSITIVITY TO VARIATION IN MEAN OF SIGNAL-TO-INTERFERENCE RATIO.

4.5.2.3 Coverage-Capacity Tradeoff, by Variation in Path Loss Exponent

Figure 4.3 illustrates the coverage-capacity tradeoff curves by variation of path loss exponent. It can be observed that by increasing the path loss exponent value, the cell coverage decreases.

Note that, the maximum number of users will not be affected by variations in Path Loss Exponent, as shown in Figure 4.3.

4.5.3 Coverage-Capacity Tradeoff, by Employing uncoded Higher Alphabet Signaling Modulation

The purpose of this section is to argue the cell coverage and its capacity when the system employs uncoded MPSK and MQAM modulations. The investigation of coverage and capacity of cellular CDMA system by using high alphabet signaling is presented in [3].

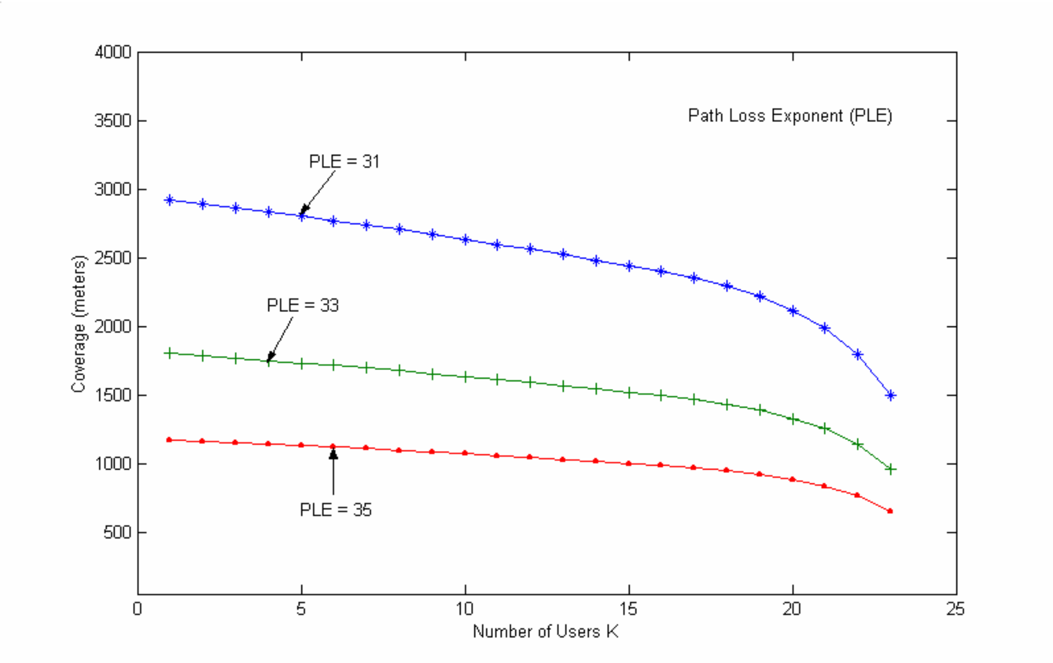

FIGURE 4.3 : IMPACT OF THE PATH LOSS EXPONENT ON THE COVERAGE AND CAPACITY OF THE CELL.

4.5.3.1 Coverage-Capacity Tradeoff, by Employing uncoded MPSK Modulation

Figure 4.4 and figure 4.5, show that the coverage-capacity tradeoff curves are affected by varying higher alphabet signaling of PSK modulation when the probabilities of bit error are 10^{-3} and 10^{-5} respectively.

It can be observed from figure 4.4, the 4PSK has more coverage and capacity than 8PSK and BPSK. So, the probability of outage is high for BPSK. This causes a drop in calls when the number of users reaches 15 with minimum coverage and therefore 8PSK will have a drop in calls when the number of users reaches 23.

Figure 4.5 shows that, when the probability of bit error is 10^{-5}, the overall coverage and capacity will be decreased when compared to $10^{-3,}$ as shown in figure 4.4. The 4PSK still gives better performance than the other two MPSK in terms of coverage and capacity.

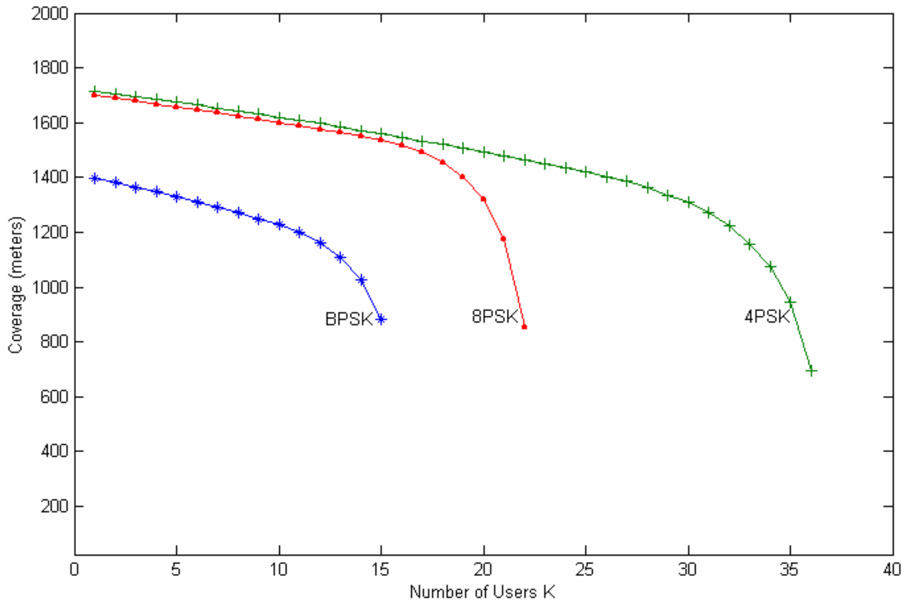

FIGURE 4.4 : COVERAGE-CAPACITY TRADEOFF CURVES, IN TERMS OF VARIATION IN ALPHABET SIGNALING OF PSK MODULATION. THE MEANS OF SIR FOR BPSK, 4PSK AND 8PSK ARE 8.0861, 8.0861 AND 10.0034 RESPECTIVELY, WHEN THE BER IS 10^{-3}.

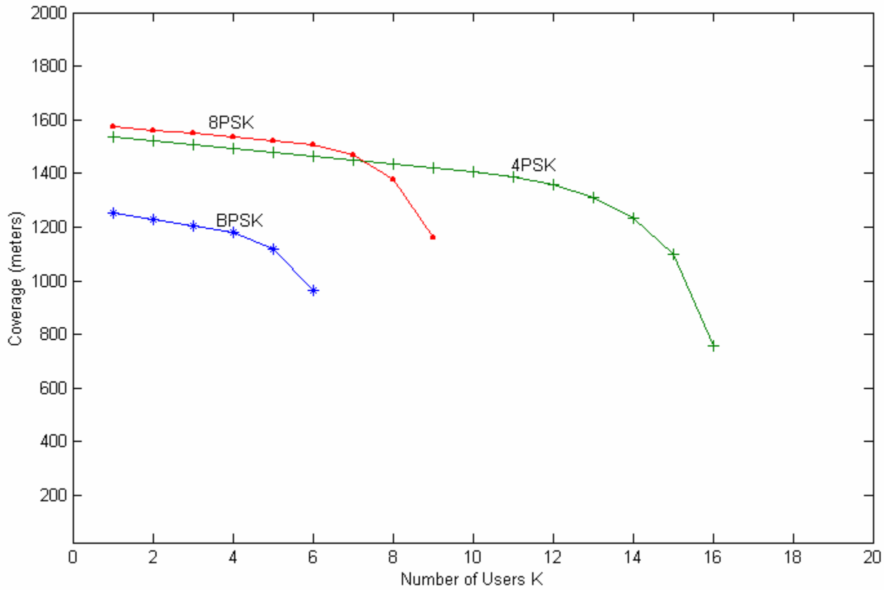

FIGURE 4.5 : COVERAGE-CAPACITY TRADEOFF, IN TERMS OF VARIATION IN ALPHABET SIGNALING OF PSK MODULATION. THE MEANS OF SIR FOR BPSK, 4PSK AND 8PSK ARE 9.6159, 9.6159AND 11.0467 DB RESPECTIVELY WHEN BER IS 10^{-5}.

4.5.3.2 Coverage-Capacity Tradeoff, by Employing uncoded MQAM.

The following two figures (fig. 4.6 & fig. 4.7) show that coverage-capacity tradeoff curves being affected by varying ALPHABET SIGNALING of QAM when the probabilities of bit error are 10^{-3} and 10^{-5} respectively.

It can be observed from figure 4.6, the 64QAM has the highest probability of outage and the maximum number of users is 13. Whereas, 32QAM gives lesser probability of outage than 64QAM and the maximum number of users is 21. The 16QAM gives yet lower probability of outage than the previous two and maximum number of users is 27. This concludes that the coverage and capacity for 16QAM is better than the coverage and capacity of 64QAM & 32QAM.

The 16QAM, can give good coverage for up to 26 users. But, if the number of users exceeds 26, it is observed that the 4QAM gives a better coverage and has a lower outage probability than 64QAM and 16QAM.

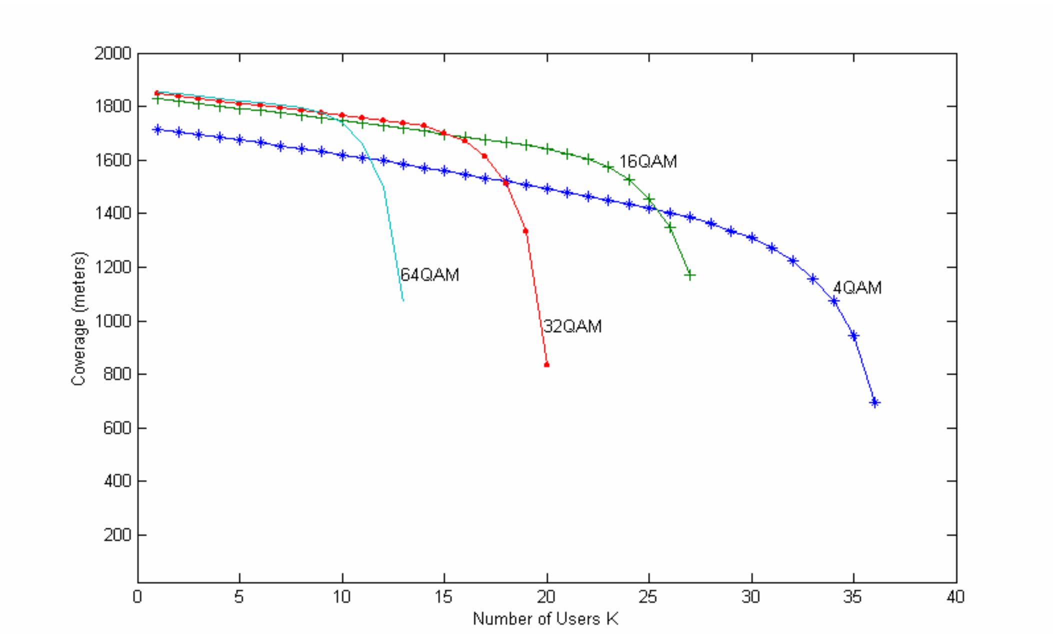

FIGURE 4.6 : COVERAGE-CAPACITY TRADEOFF, WITH REGARD TO VARIATION IN ALPHABET SIGNALING OF QAM. THE MEANS OF SIR FOR 4QAM, 16QAM, 32QAM AND 64QAM ARE 8.0861, 10.1767, 11.0033 AND 11.7280 DB RESPECTIVELY. AT BER 10^{-3}.

Figure 4.7 shows that, when the probability of bit error is 10^{-5}, the overall coverage and capacity will be decreased in comparison to 10^{-3}, as shown in figure 4.6. The 16QAM still gives better performance if the number of users is less than 26. If the number of users is more than 26, the 4QAM gives a much better performance.

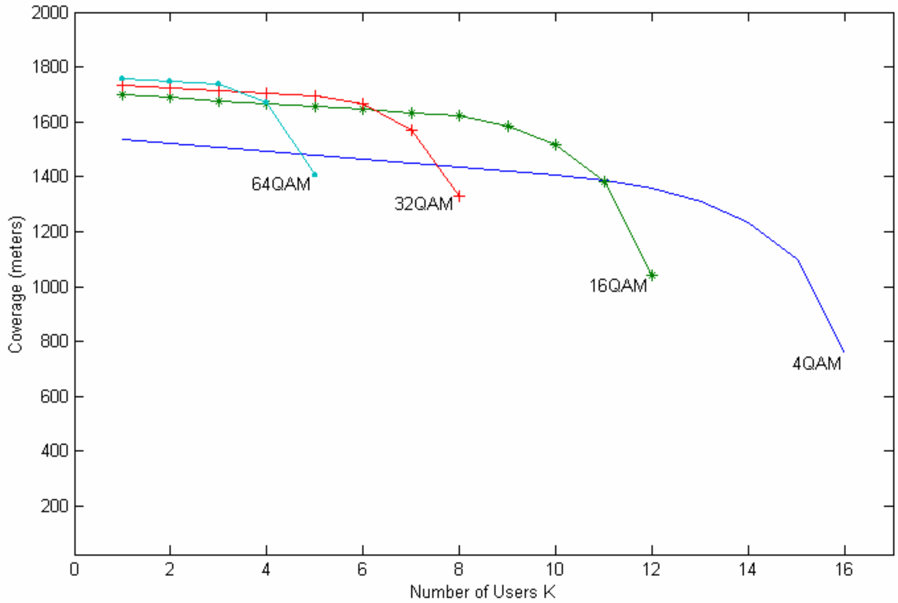

FIGURE 4.7 : COVERAGE-CAPACITY TRADEOFF, WITH REGARD TO VARIATION IN ALPHABET SIGNALING OF QAM. THE MEANS OF SIR FOR 4QAM, 16QAM, 32QAM AND 64QAM ARE 9.6159, 11.1836, 11.8516 AND 12.4562 DB RESPECTIVELY. AT BER 10^{-5}.

4.5.3.3 Comparison of Coverage-Capacity tradeoff curves between MQAM and MPSK

Figure 4.8 shows the overall performances of MPSK and MQAM. It is observed that, coverage wise the 16QAM has a better coverage than others, till the number of users reaches 25. If the number of users exceeds 25, the 4QAM has a better performance as depicted in figure 4.9.

It is observed from figure 4.9 that, the system can change the ALPHABET SIGNALING of QAM from 16QAM to 4QAM or from 4QAM to 16QAM, depending on the number of users as shown in figure 4.9. So, the system can apply adaptive modulation techniques on this state.

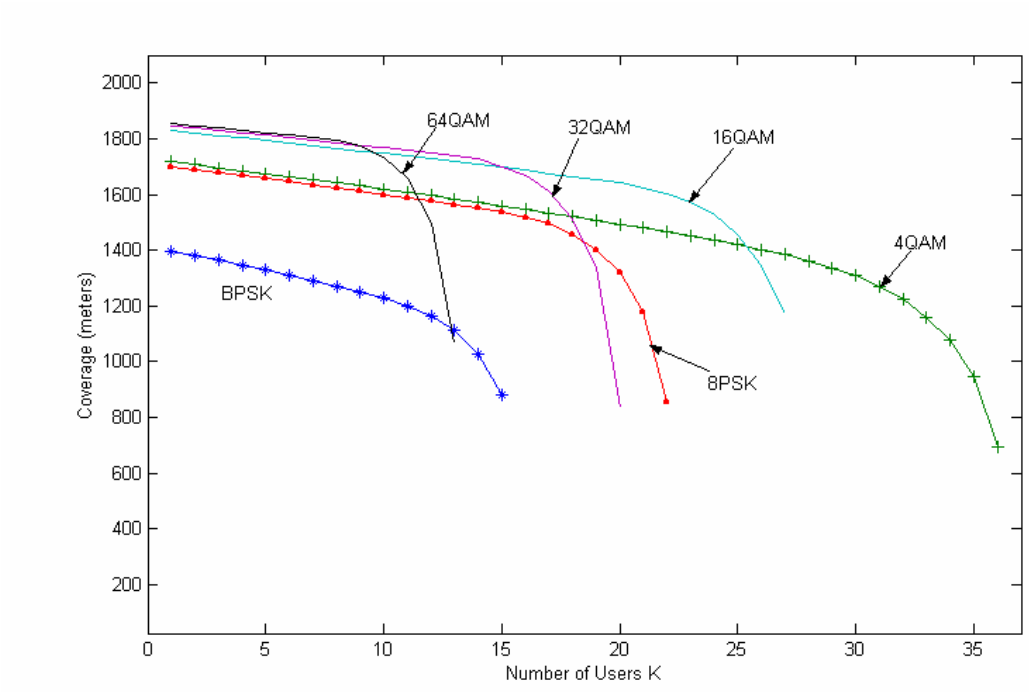

FIGURE 4.8 : COVERAGE-CAPACITY TRADEOFF CURVES, BENIFITTED BY VARIATION IN ALPHABET SIGNALING OF PSK & QAM MODULATIONS. THE MEANS OF SIR FOR BPSK, 4QAM, 8PSK, 16QAM, 32QAM AND 64QAM ARE 8.1117, 8.1117, 10.0198, 10.1925, 11.0163 AND 11.7390 DB RESPECTIVELY. AT BER 10^{-3}.

Table 1 relating to figure4.8.

M-ary	K	Cell Accessibility	Coverage
BPSK	< 15	Admitted	1400 ~ 800
	> 15	NA	-
4QAM	< 36		1700 ~ 800
	> 36		-
8PSK	< 23	Admitted	1700 ~ 900
	> 23	NA	-
16QAM	< 28	Admitted	1850 ~ 1200
	> 28	NA	-
32QAM	< 21	Admitted	1850 ~ 800
	> 21	NA	
64QAM	< 13	Admitted	1850 ~ 1000
	> 13	NA	

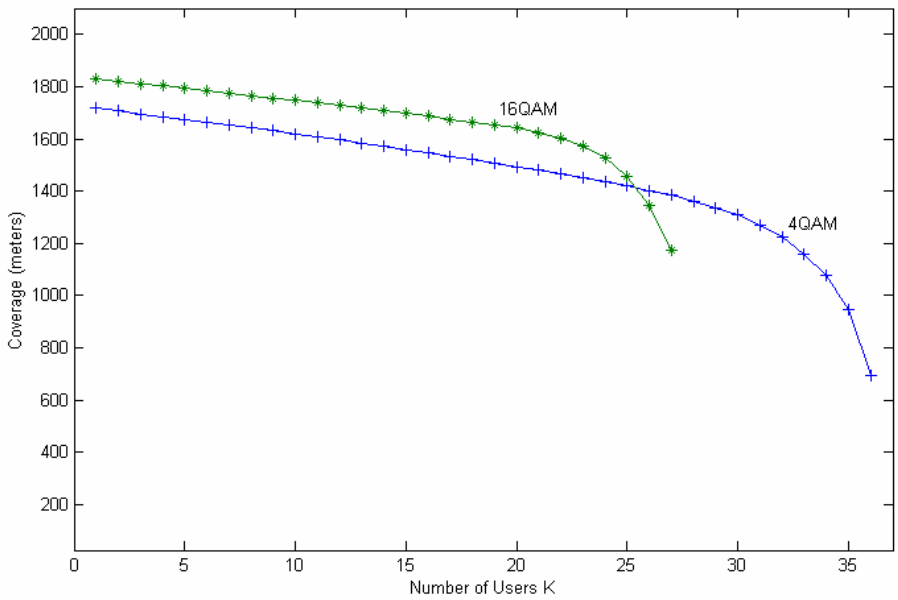

FIGURE 4.9 : COVERAGE-CAPACITY TRADEOFF CURVES, WHEN THE SYSTEM EMPLOYS 4QAM & 16QAM. THE MEANS OF SIR FOR 4QAM, 16QAM ARE 8.1117 10.1925 DB RESPECTIVELY AT BER 10^{-3}.

4.5.4 Coverage-Capacity Tradeoff, by Employing Linear Block Code

The following sub-sections studies the coverage and capacity of the cell benefited by using Linear Block Code (such as Bose-Chaudhari-Hocquenghem (BCH) code) on an AWGN channel.

4.5.4.1 Comparison of Coverage-Capacity tradeoff curves between Coded and uncoded System

Figure 4.10 shows that the cell coverage and its capacity tradeoff curves, being improved by applying the BCH coding, in terms of coverage and capacity, versus uncoded system.

Figure 4.10 illustrates the performance of encoded and uncoded system on the coverage and capacity. It is apparent from Figure 4.10 that, the used of BCH coding causes vast improvement in terms of coverage and coding than the uncoded system.

It can be observed that, the maximum number of users on uncoded curve is 13 and the coverage is between 1500 ~ 1000. Whereas, the maximum number of users on coded curve is 31 and the coverage is between 1700 ~ 700.

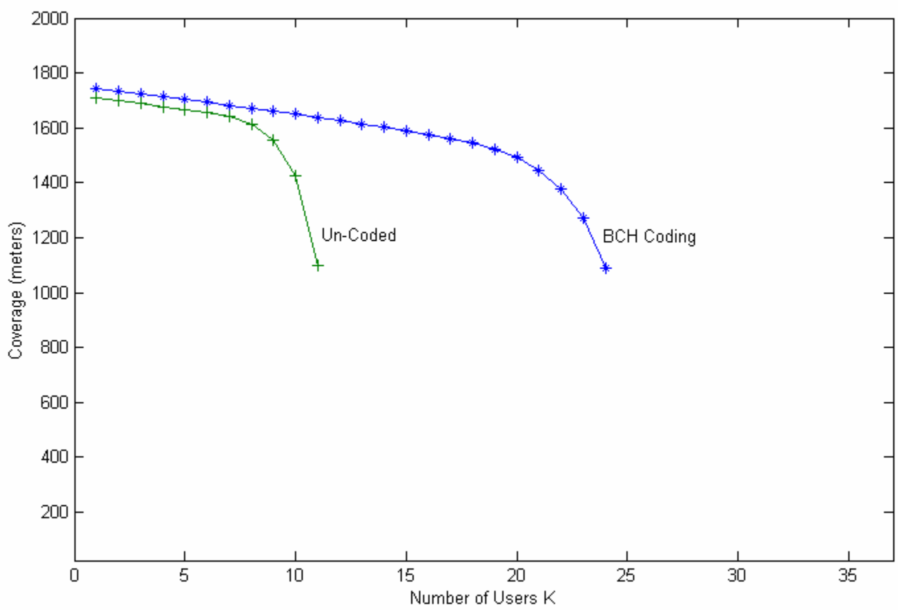

FIGURE 4.10 : COVERAGE-CAPACITY TRADEOFF CURVE, BY CONSIDERING UNCODED AND CODED SYSTEM

4.5.4.2 Coverage and Capacity Tradeoff, when the system employs different code rates

Figure 4.11 illustrates the coverage-capacity tradeoff curves when the system employs different code rates for 16QAM modulation (points 0.57, 0.73, 0.84, 0.9 and 0.945) at BER 10^{-3}. It is apparent that, the cell coverage exceeds when the code rate increases, but only up to a certain value of a code rate. When the code rate exceeds further, the cell coverage will not increase. From the capacity viewpoint, it is apparent that, the 0.57, 0.73 and 0.84 have same cell capacity (maximum number of users is 22). But, when the code rate exceeds further, this causes the outage probability to increase, which in turn causes the active number of users in the cell to decrease.

Figure 4.12 illustrates the coverage-capacity tradeoff curves when the system employs different code rates for 16QAM modulation (points 0.57, 0.73, 0.84, 0.9 and 0.945) at BER 10^{-5}. When the BER is 10^{-5}, both the coverage and capacity will be decreased; the behavior of coverage-capacity tradeoff curves is similar to the one seen in Figure 4.11, when the code rate exceeds.

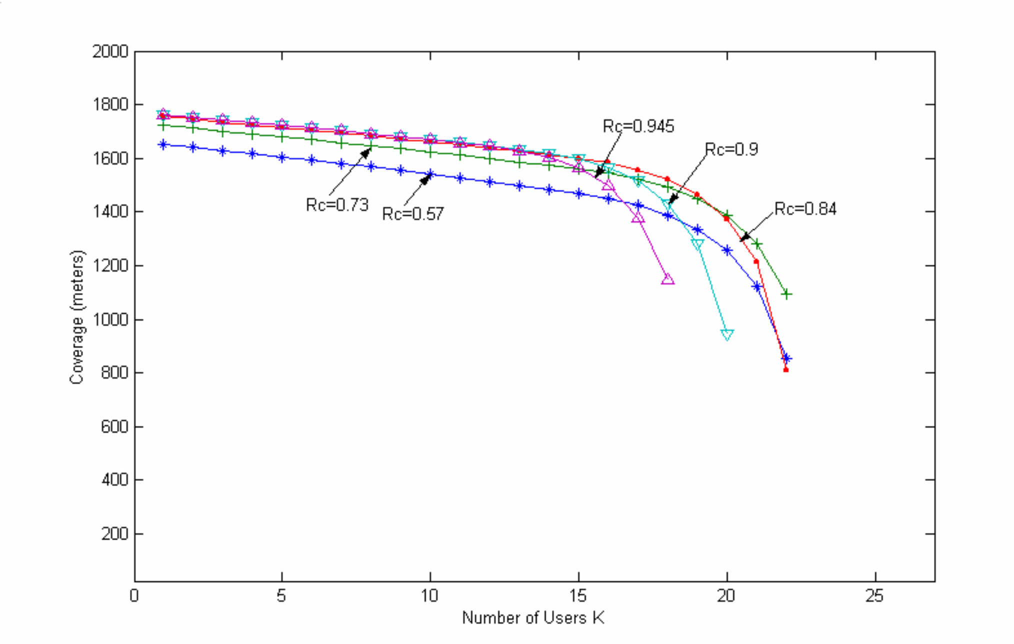

FIGURE 4.11 : COVERAGE-CAPACITY TRADEOFF CURVES IN TERMS OF DIFFERENT CODE RATES FOR 16QAM MODULATION. THE MEAN OF SIR FOR CODE RATE 0.57, 0.73, 0.8387, 0.9 AND 0.945 ARE 9.3951, 9.8676, 10.1702, 10.4335 AND 10.6219 RESPECTIVELY AT BER 10^{-3}

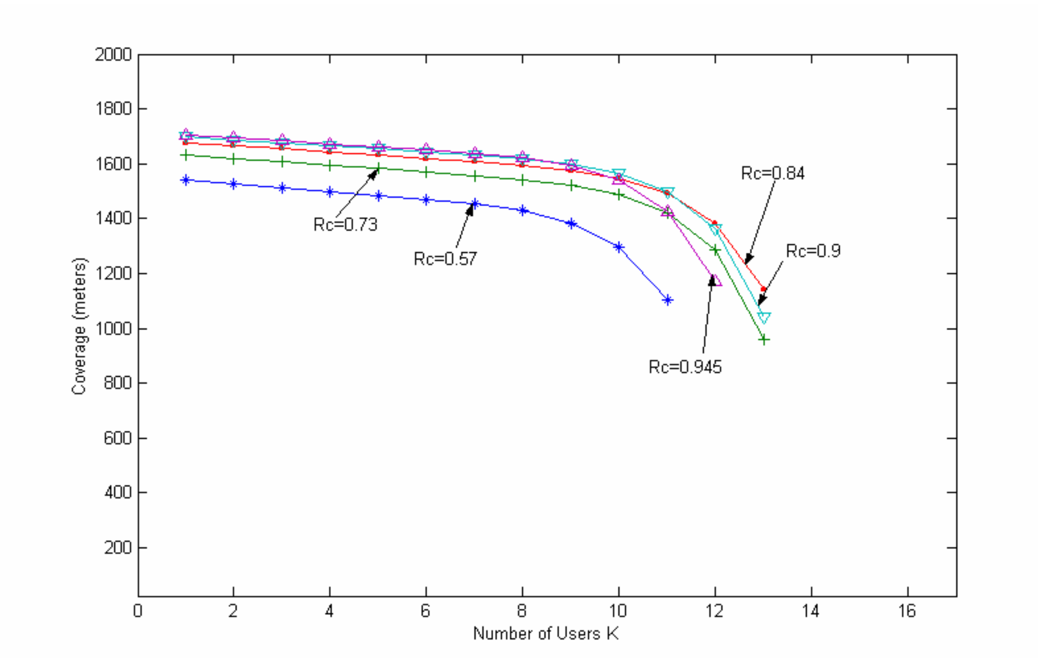

FIGURE 4.12 : COVERAGE-CAPACITY TRADEOFF CURVES, IN TERMS OF DIFFERENT CODE RATES FOR 16QAM MODULATION. THE MEAN OF SIR FOR CODE RATE 0.57, 0.73, 0.8387, 0.9 AND 0.945 ARE 10.4138, 10.6631, 10.8457, 10.9863 AND 11.1226 RESPECTIVELY AT BER 10^{-5}

4.5.4.3 Comparison of Coverage-Capacity Tradeoff when the system employs encoded Higher Alphabet Signaling QAM Modulation.

This section studies the cell coverage and its capacity by applying different encoded higher alphabet signaling QAM modulation.

Figure 4.13 illustrates that, the 64QAM gives higher coverage when the number of users is les than 9. While the number of users exceeds 10 up to 20; the 64QAM has an outage within this period; and it is apparent from figure 4.13, the 16QAM has higher coverage in this period once the number of users exceeds 20 up to 29. the 16QAM will have an outage during this period and the 4QAM has higher coverage.

From the above discussions, it is concluded that the system can select the proper M-ary modulation to obtain a higher coverage. Figure 4.14 uses 0.75 as code rate and gives the same behavior but more coverage and capacity.

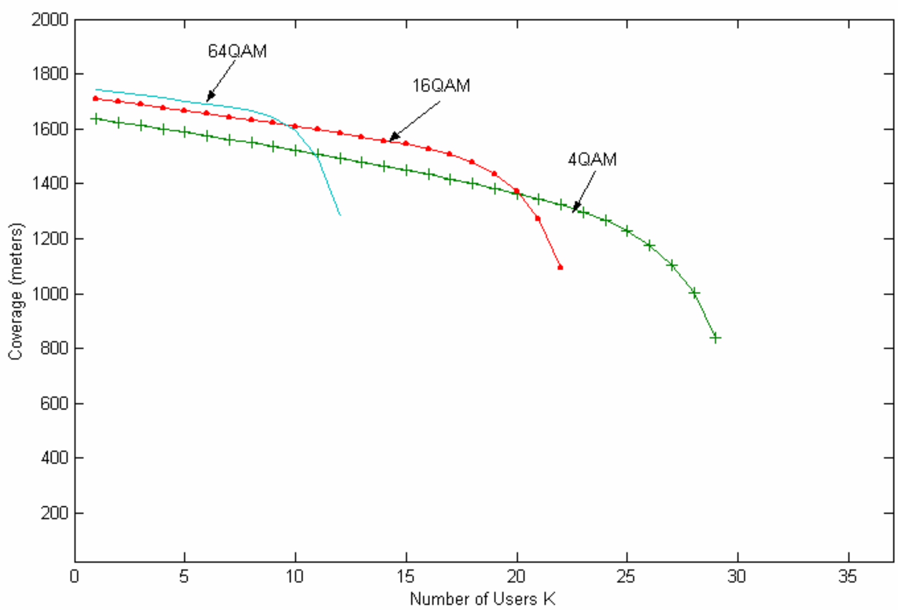

FIGURE 4.13 : COVERAGE-CAPACITY TRADEOFF, WHEN THE SYSTEM EMPLOYS ENCODED HIGH ALPHABET SIGNALING OF QAM MODULATION AT CODE RATE 0.7

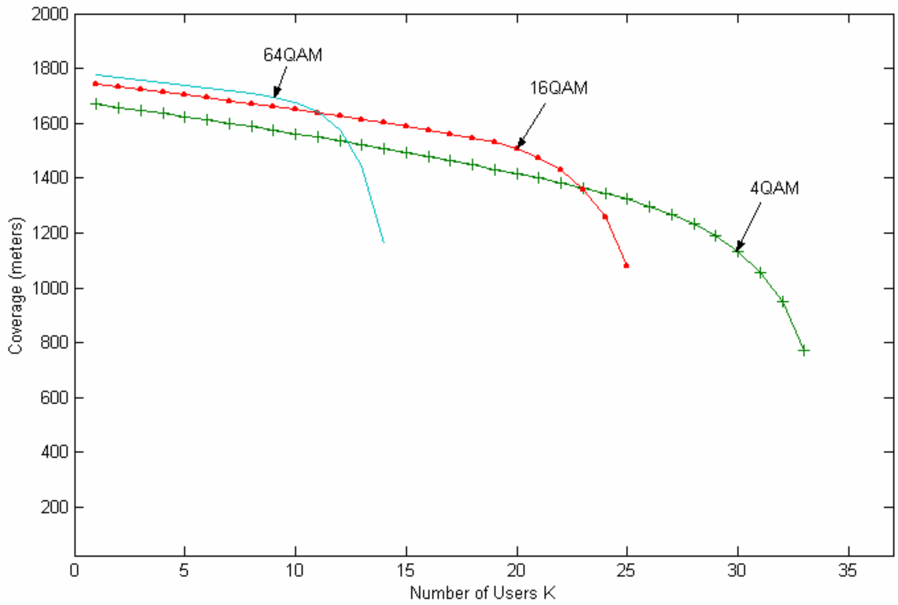

FIGURE 4.14 : COVERAGE-CAPACITY TRADEOFF, WHEN THE SYSTEM EMPLOYS ENCODED HIGH ALPHABET SIGNALING OF QAM MODULATION AT CODE RATE 0.75

4.5.5 Coverage-Capacity Tradeoff, by using Trellis Code Modulation Technique

This section will argue the cell coverage and its capacity of the cell in cellular CDMA system when the system employs the Trellis code modulation, by considering the channel bandwidth and transmitted signal power are unchanged.

Trellis code modulation involves the combination of convolution coding with spectrally efficient M-ary modulation and it improves the system performance without increasing the transmitted energy per bit, reducing the message transmission rate and increasing the bandwidth.

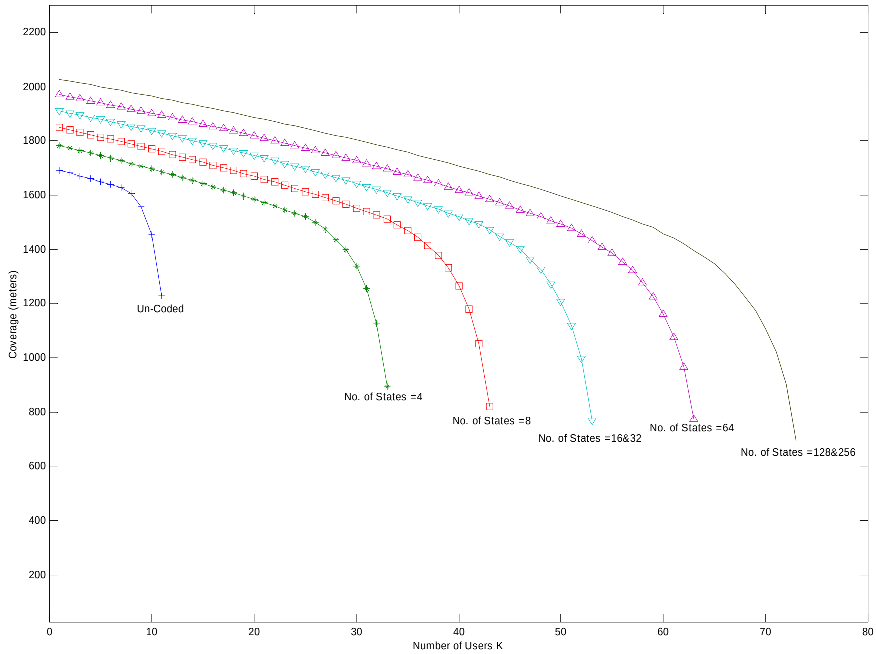

FIGURE 4.15 : COVERAGE-CAPACITY TRADEOFF, WITH REGARD TO VARIATION IN NUMBER OF STATES FOR 16QAM MODULATION. THE MEAN OF SIR FOR UN-CODED AND NUMBER OF STATES ARE 4, 8, (16&32), 64 AND (128&256) ARE 11.3346, 9.3132, 8.7837, 8.3042, 7.8514 AND 7.433 RESPECTIVELY AT BER 10^{-5}.

4.5.5.1 Coverage-Capacity Tradeoff, when the System Applied Different Number of States

Figure 4.15 and figure 4.16 depict the cell coverage and its capacity when the system employing TCM by variation of number of states for 16QAM and 32QAM respectively when BER is 10^{-5}. It can be observed that, an increase in the number of states causes the coverage of the cell and number of users to increase and an improvement also takes place by using Trellis code modulation when compared to un-coded system. It is apparent that, the cell coverage and its capacity exceeds when the number of states increases, but only up to a certain value of number of states. When the number of states exceeds further, the cell coverage and its capacity will not increase.

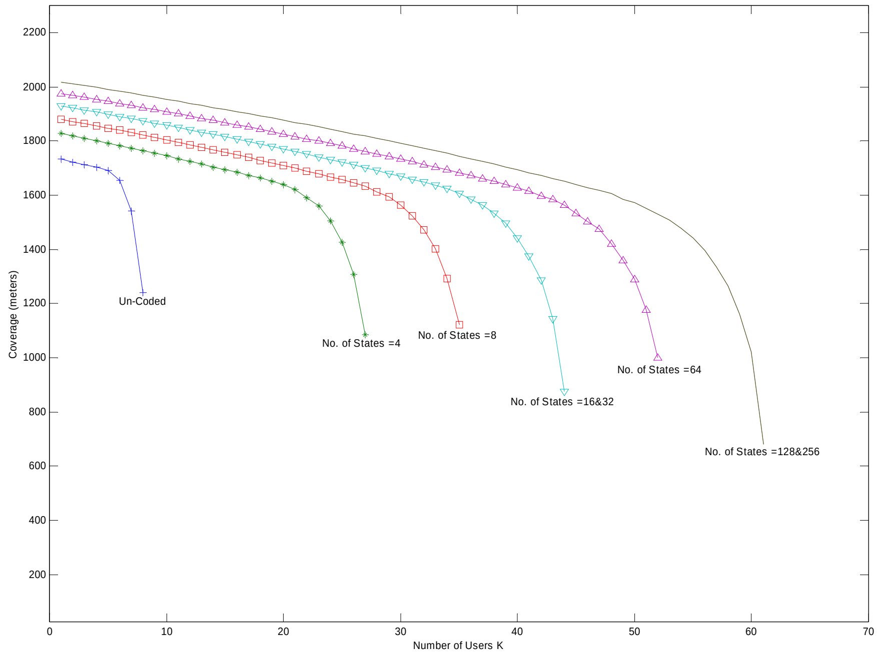

FIGURE 4.16 : COVERAGE-CAPACITY TRADEOFF, SENSITIVITY TO VARIATION IN NUMBER OF STATES FOR 32QAM. THE MEAN OF SIR FOR UN-CODED AND NUMBER OF STATES ARE 4, 8, (16&32), 64 AND (128&256) ARE 11.9532, 10.2101, 9.7844, 9.4080, 9.0611 AND 8.748 RESPECTIVELY AT BER 10^{-5}.

4.5.5.2 Coverage-Capacity Tradeoff, by using MQAM and Trellis Code Modulation

Figure 4.17, 4.18 and 4.19 illustrate the cell coverage and its capacity tradeoff curves when the system employs TCM with 4QAM, 16QAM and 64QAM when the probability of bit error is 10^{-3}, 10^{-4} and 10^{-5} respectively.

It is observed that 4QAM has the lower coverage than 16QAM and 64QAM. But the 64QAM has higher outage probability than 4QAM and 16QAM. Also, it is observed the 16QAM has a good performance than others.

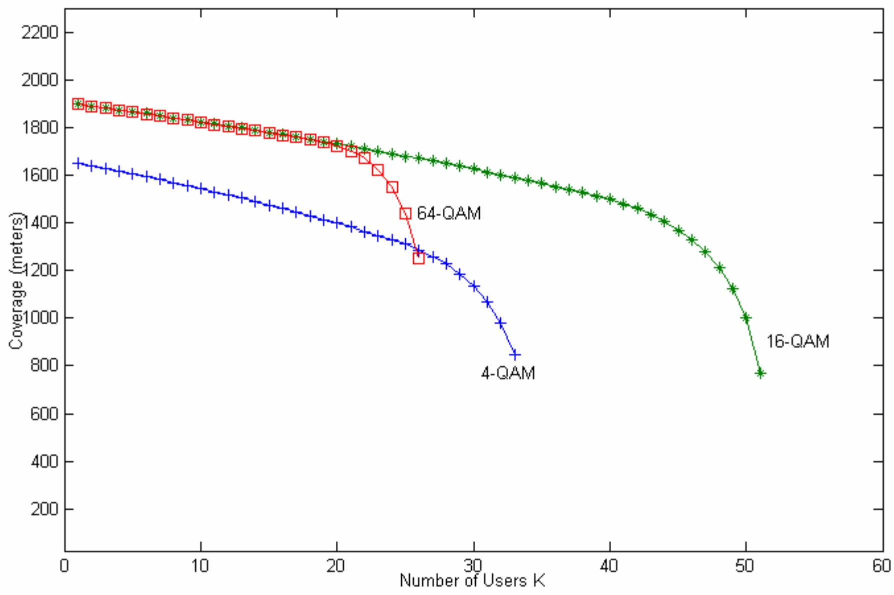

FIGURE 4.17 : COVERAGE-CAPACITY TRADDOFF, BY USING TCM FOR HIGHER ALPHABET MQAM MODULATION. THE MEAN OF SIR FOR 4QAM, 16QAM AND 64QAM ARE 5.6786, 8.3985 AND 10.6295 RESPECTIVELY AT BER 10^{-3}

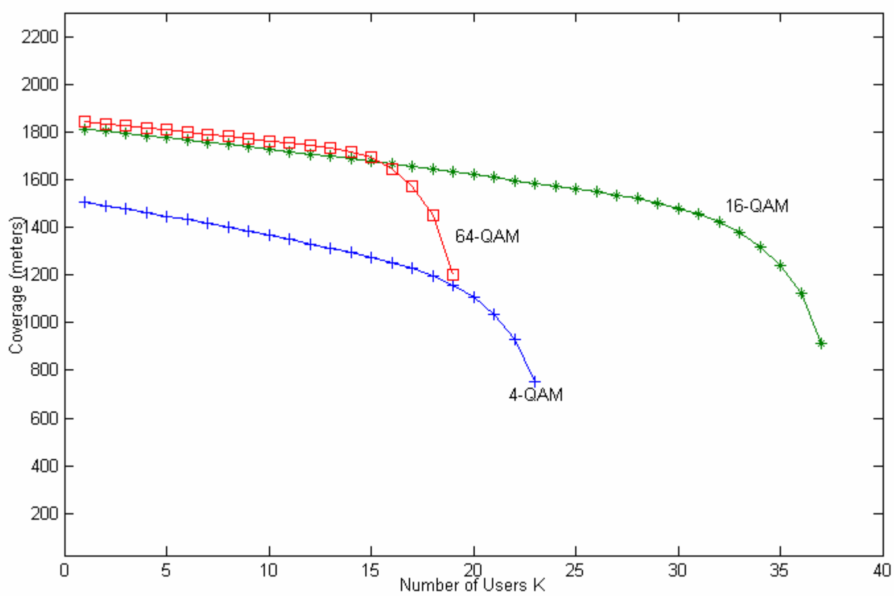

FIGURE 4.18 : COVERAGE-CAPACITY TRADEOFF, SENSITIVITY TO VARIATION IN ALPHABET SIGNALING OF MQAM-TCM. THE MEAN OF SIR FOR 4QAM, 16QAM AND 64QAM ARE 7.0386, 9.0850 AND 11.0446 RESPECTIVELY AT BER 10^{-4}

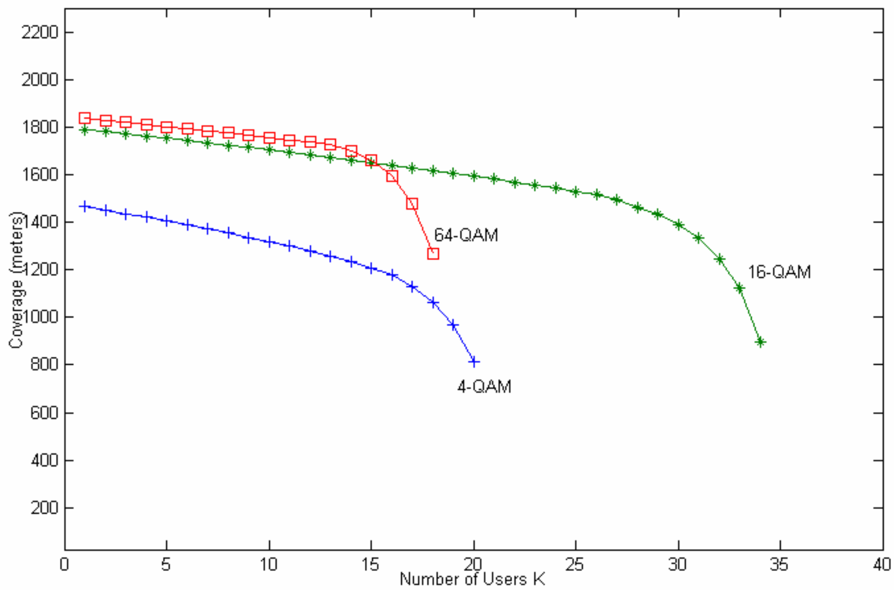

FIGURE 4.19 : COVERAGE-CAPACITY TRADEOFF, SENSITIVITY TO VARIATION IN ALPHABET SIGNALING OF QAM-TCM. THE MEAN OF SIR FOR 4QAM, 16QAM AND 64QAM ARE 7.4166, 9.2558 AND 11.0989 RESPECTIVELY AT BER 10^{-5}

4.5.6 Coverage-Capacity Tradeoff, by using Space-Time Transmit Diversity Techniques over Rayleigh Fading Channel.

Here, it is argued the benefits of employing the space-time transmit diversity as a simple and with varying the alphabet signaling of QAM modulation.

4.5.6.1 Simple Space-Time Transmit Diversity for un-coded BPSK

Here, it is argued that the simple space-time transmit diversity without employing higher alphabet signaling and so it is assumed that the total transmit power from the two antennas is the same as the transmit power from the single transmit antenna. It is also assumed that no power control is employed here. BER performance of STTD with MMRC and new schemes under Rayleigh fading channel is presented in [13] for un-coded coherent BPSK. System parameters used in this sub-section are shown in table 2.

Table 2 System Parameters of sub-section 4.5.6.1.

Bit Error Probability	10^{-5}
Modulation type	BPSK, uncoded
Mean of SIR for (1TX, 1Rx)	16.43 dB
Mean of SIR for (1Tx, 2Rx)	13.22 dB
Mean of SIR for (1Tx, 4Rx)	10 dB
Mean of SIR for (2Tx, 1Rx)	13.8 dB
Mean of SIR for (2Tx, 2Rx)	11.13 dB
Fading channel type	Rayleigh

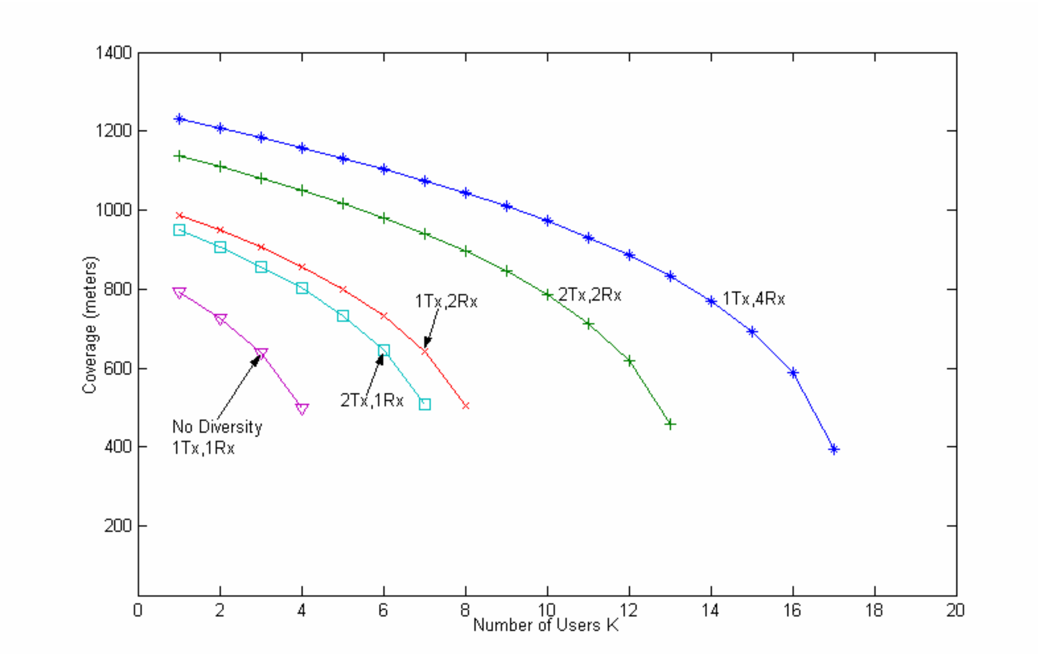

FIGURE 4.20 : COVERAGE-CAPACITY TRADOFF, BY EMPLOYING SIMPLE SPACE-TIME TRANSMIT DIVERSITY UNDER RAYLEIGH FADING CHANNEL FOR BPSK MODULATION

Figure 4.20 illustrates the improvement in the cell coverage and its capacity of cellular CDMA system by using space-time transmit diversity technique under Rayleigh fading channel without power control for un-coded BPSK modulation. It is observed that the antenna diversity has high effect on the cell coverage of the cell and its capacity as shown in figure 4.20, the system has higher coverage and capacity by using one transmitter and four receivers. And it is observed that there is a high improvement when the system employs the STTD in comparison to the system not employing STTD. Also it is observed that, when the number of antenna transmitters increases, while fixing the number of antenna receivers, causes an increase in coverage and capacity of the cell and vice versa.

4.5.6.2 Space-Time Transmit Diversity with Higher Alphabet Signaling QAM

In this sub-section, it is considered that, two transmits and one receiver antenna are used. It is assumed that, the total transmit power from the two antennas is the same as the transmit power from the single transmit antenna. It is considered no power control is used.

Here, the cell coverage and its capacity of CDMA cellular system will be examined over Rayleigh fading channel for higher alphabet signaling of QAM with or without STTD. BER performance of MQAM with or without STTD under Rayleigh fading channel is presented in [19]. Table 3 shows the system parameters that are used here

Table 3 System Parameters of sub-section 4.5.6.2.

Number of transmit antenna	2Tx
Number of receiver antenna	1Rx
Mean of SIR for BPSK, STTD	13.8 dB
Mean of SIR for BPSK, without STTD	11.46 dB
Mean of SIR for 16QAM, STTD	12.3 dB
Mean of SIR for 16QAM, without STTD	14.3 dB
Mean of SIR for 64QAM, STTD	13.42 dB
Mean of SIR for 64QAM, without STTD	15 dB
Probability of bit error	10^{-3}
Fading channel type	Rayleigh

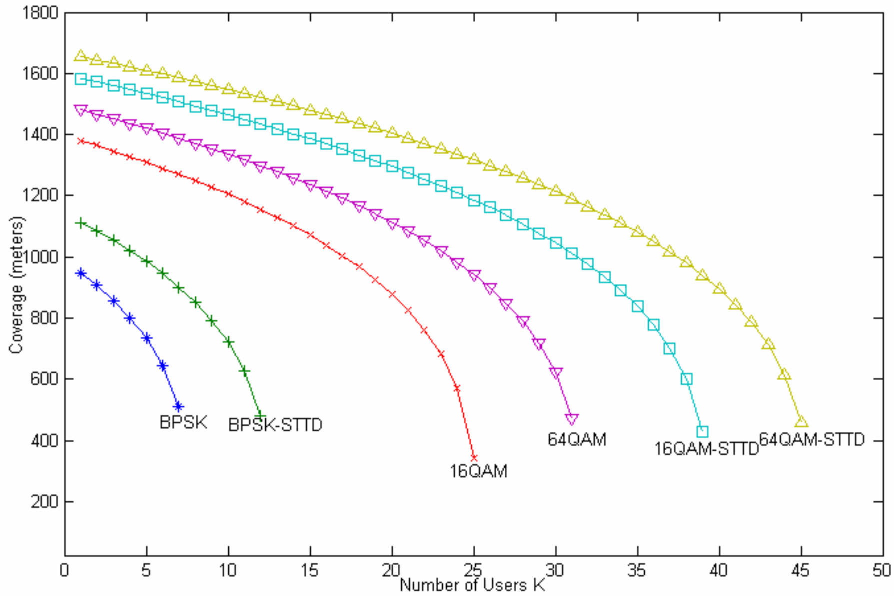

FIGURE 4.21 : COVERAGE-CAPACITY TRADEOFF, BY EMPLOYING THE STTD TECHNIQUES WITH VARYATION IN ALPHABET SIGNALING OF QAM MODULATION UNDER RAYLEIGH FADING CHANNEL

Figure 4.21 illustrates the cell coverage and its capacity of cellular CDMA system by employing the STTD techniques under Rayleigh fading channel without power control. When the system employed 64QAM with STTD, it gives an improvement in cell coverage and its capacity than 64QAM without STTD. It is also observed that when the system employed 16QAM with STTD, it gives an improvement in coverage and capacity than 16QAM without STTD. It is clear from figure 4.21, the 64QAM with STTD causes a more increase in the cell coverage and its capacity than 16QAM with STTD system.

4.6 Conclusion

An increase in cell coverage and its capacity are important for (CDMA) cellular network design and deployment.

All the theoretical analysis done here is concentrated on investigating the benefits of system employing the Forward Error Correcting Code (FECC) and/or higher alphabet signaling, Trellis Code Modulation (TCM), simple space-time transmit diversity (STTD) and higher alphabet signaling for QAM with STTD on the coverage and capacity of the cell in cellular CDMA system.

Our main results show that, when the system employs the BCH, the coverage will be improved. By changing higher code rate there is an improvement in coverage up to a certain limit of code rate. If the code rate exceeds further, there is degradation in service.

Also, by employing higher alphabet signaling with coding, the result shows that, the system can select a proper alphabet signaling depending on the number of active users in the cell in order to obtain higher coverage.

When TCM is employed, the number of states increases causing an increase in cell coverage and its capacity, but only up to a certain value of number of states. When the number of states exceeds further, the cell coverage and its capacity will not increase. Also when the system employs TCM with higher alphabet signaling, the system can select the proper alphabet signaling depending on the number of active users in the cell in order to obtain higher coverage.

Finally, there is a high improvement when the system employs the STTD in comparison to the system not employing STTD. Also it is observed that, when the number of antenna transmitters increases, while fixing the number of antenna receivers, causes an increase in coverage and capacity of the cell and vice versa. Moreover, there is an improvement in coverage and capacity by employing higher alphabet signaling with STTD,

Due to the study of the Coverage Cellular CDMA system, it is observed that the coverage of a cell depends on several factors such as,

- In-cell interference
- Other-cell interference
- Media channel characteristics
- Quality of service
- The distribution of the customer, within the cell
- The dynamics of control procedure
- Limitation of transmit power at the mobile

Therefore, both coverage and capacity of a cell needs to be planned in such a way that all calls are sufficiently supplied.

It observed that, when FECC, higher alphabet signaling, TCM, simple STTD and/or merging some of them are applied to the system, an improvement in cell coverage and its capacity is achieved. This improvement may not be achieved by higher transmit power or additional bandwidth. A user has to maintain a certain signal to interference ratio at the receiver for satisfactory performance. Therefore, the system can select the proper way by changing the alphabet signaling and/or code rate to enhance the performance of the system when there is degradation in call quality or by employing other techniques such as STTD, space-time Trellis code, space-time block code, etc.

The extended analysis and results presented earlier [3], investigated the benefits of using M-ary modulation (higher alphabet signaling) can be compared to the system that employs FECC with modulation, TCM and STTD.

REFERENCES

[1] Venugopal V. Veeravalli and Andrew Sendonaris, "The Coverage-Capacity Tradeoff in Cellular CDMA System," IEEE Transaction on Vehicular Technology, vol. 48, No. 5, September 1999, pp. 1443-1449.

[2] A. M. Viterbi and A. J. Viterbi, "Erlang capacity of a power controlled CDMA system," IEEE J. Select. Areas Commun., vol. 11, pp. 892–899, Aug. 1993.

[3] Adel A. Ali," MQAM Modulation for Maximum Coverage-Capacity in Cellular CDMA Systems", Wireless 2001, Calgary, Canada 9-11 July 2001.

[4] J. Evans and D. Everitt, "Analysis of reverse link traffic capacity for cellular mobile communication networks employing code division multiple access," in Proc. Australian Telecommunication Networks and Applications Conference, (Melbourne), pp. 775–780, Dec. 1994.

[5] Landolsi, .A.;Veeravalli, V.V.; Jain, N.; "New results on the reverse link capacity of CDMA cellular networks," Vehicular Technology Conference, 1996. 'Mobile Technology for the Human Race'., IEEE 46th, Volume: 3 , 28 April-1 May 1996 Pages:1462 - 1466 vol.3

[6] *Sendonaris, A.; Veeravalli, V.;* "The capacity-coverage tradeoff in CDMA systems with soft handoff," Signals, Systems & Computers, 1997. Conference Record of the Thirty-First Asilomar Conference on , Volume: 1 , 2-5 Nov. 1997 Pages:625 - 629 vol.1

[7] A. J. Viterbi *et al.*, "Soft handoff extends CDMA cell coverage and increases reverse link capacity," *IEEE J. Select. Areas Commun.*, vol. 12, pp. 1281–1288, Oct. 1994.

[8] Y. W. Chang and E. Geraniotis, “Accurate computations of cell coverage areas for CDMA hard and soft handoffs,” in *Proc. 1996 IEEE VehicularTechnology Conf.*, Atlanta, GA, May 1996, pp. 411–415.

[9] M. Chopra, K. Rohani, and J. D. Reed, “Analysis of CDMA range extensions due to soft handoff,” in *Proc. 1995 IEEE Vehicular Technology Conf.*, Chicago, IL, July 1995, pp. 917–921.

[10] Hai Jiang and Curt H. Davis, “Cell-Coverage Estimation Based on Duration Outage Criterion for CDMA Cellular Systems,” IEEE Transaction on Vehicular Technology, vol. 52, No. 4, July 2003.

[11] J.G. Proakis, Digital Communications, 4th ed. New York: McGraw-Hill, 2001.

[12] Ungerboeck, G. “Channel Coding with Multilevel/Phase Signals,” IEEE Transaction Inform. Theory, vol. IT-28, pp. 55-67, January 1982.

[13] S.M. Alamouti, "Simple transmit diversity technique for wireless communications," IEEE Journal on Select Areas in Communications, vol. 16, pp. 1451{1458, 1998.

[14] Peterson and Weldon, 1972

[15] Sergio Benedetto, Ezio Biglieri, “Principles of Digital Transmission with Wireless Applications” Kluwer Academic / Plenum Publisher, July 1999.

[16] T. S. Rappaport, Wireless Communications: Principles and Practice. Upper Saddle River, NJ: Prentice-Hall, 1996.

[17] A.J. Viterbi, A.M. Viterbi, and E. Zehavi, “Performance of power-controlled wideband terrestrial digital communications, “to appear in IEEE Trans. Commun., 1993.

[18] A. J. Viterbi, CDMA: Principles of Spread Spectrum Communication. Reading, MA: Addison-Wesley, 1995.

[19] Rong He and Junsong Xie, "BER Performance of MQAM and MPSK in Nakagami Fading Channel with STTD," The 14th IEEE 2003 International Symposium on Personal, Indoor and Mobile Radio Communication Proceedings.

[20] Veeravalli, V.V.; Sendonaris, A.; Jain, N.;"CDMA Coverage, Capacity AND Pole Capacity," Vehicular Technology Conference, 1997 IEEE 47th , Volume: 3 , 4-7 May 1997 Pages:1450 - 1454 vol.3.