Optimal Allocation of Power to AMCS for Maximum Throughput in WCDMA

By

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For the degree of
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Abstract

In WCDMA systems, the quality of the received signal depends on distance from the desired and interfering sources, path loss and lognormal shadowing. In order to increase the capacity of the system, adaptive modulation and coding (AMCS) is used. With AMCS, we can change the modulation and coding scheme to match the received signal quality. The drawback of using AMCS with the normal power allocation scheme is that in some cases the highest data rate is not obtained. High Speed Downlink Packet Access (HSDPA) is the key part of 3G mobile communications systems. During data transmission in HSDPA, Base stations always transmit at maximum power; several users share fixed number of codes in a frame and AMCS is refreshed on frame by frame-basis. When using AMCS in HSDPA, the object of achieving maximum throughput transforms to find the optimal power allocation method to codes.

In this thesis we explore the effect of power optimization allocation problem to AMCS (or codes) on throughput. With the optimal power allocation scheme, the combination of AMCS is flexible because power is totally assigned to different AMCS. The advantage of using this method is to optimize the throughput so that the highest data rate is achieved for all possible C/I values. As a result of using optimal power allocation, the maximum throughput of multi-codes can be as high as 10.7Mbps. With the estimated error of C/I as 1 dB, the average maximum throughput loss is 10.82%.

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List of Abbreviations

AMCS	Adaptive Modulation and Coding Scheme
ARIB	Association of Radio Industries and Businesses
AWGN	Additive White Gaussian Noise
BS	Base Station
CDF	Cumulative Distribution Function
CWTS	China Wireless Telecommunications Standards
C/I	Carrier to Interference Ratio
CPICH	Pilot Channel
DCH	Dedicated Channel
DEMUX	Demultiplexer
DPCCH-HS	Dedicated Physical Control Channel
ETSI SMG	European Telecommunications Standards Institute-Special Mobile Group
FCS	Fast Cell Selection
FDD	Frequency Division Duplex
FER	Frame Error Rate
H-ARQ	Hybrid Automatic Repeat Request
HSDPA	High Speed Downlink Packet Access
HS-DSCH	High Speed Downlink Shared Channel
IMT-200	International Mobile Telecommunication-2000
ITU-R	International Telecommunication Union
IR	Increment Redundant
LOS	Line of Sight
mph	In figure 2.2-6, meter per hour
MCS	Modulation and Coding Scheme
MIMO	Multiple Input and Multiple Output
MS	Mobile Station

MUX	Multiplexer
Node B	A logic node responsible for radio transmission/reception in one or more cells to/from the UE.
NLOS	None Line of Sight
OVSF	Orthogonal Variable Spreading Factor
pdf	Probability Density Function
PICH	Paging Channel
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
R_s	Symbol rate
Rx	Receiver
SF	Spreading Factor
SNR	Signal Noise Ratio
TD-CDMA	Time Division Code Division Multiple Access
TDD	Time Division Duplex
TTA	Telecommunications Technology Association of South Korean
Tx	Transmitter
UMTS	Universal Mobile Telecommunications Systems
USCH	Uplink Shared Channel
UTRA	UMTS Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
VSF	Variable Spreading Factor
WCDMA	Wideband Code Division Multiple Access
3GPP	the Third Generation Partnership Project
UE	User Equipment

List of Symbols

bps	bits per second
C	Carrier
dB	decibel
dB _i	decibel Isotropic
E_b/I_{oc}	The ratio of energy per bit to the total interference power spectral density
E_b/N_o	The ratio of the energy per bit to the noise power spectral density
E_c/N_t	The ratio of average energy per chip to the effective noise power spectral Density
I	Interference
I_{or}/I_{oc}	The ratio of total power spectral density to the total interference power spectral density.
$I_{or}/(I_{oc} + N_o)$	The ratio of the total transmitting power spectral density to the sum of the interference power spectral density and the noise power spectral density
L	Pathloss
mb/s	megabits per second
ms	millisecond
mW	milli Watt
m	Meter
Mcps	Megachips per second
q	In figure 2.2-6, modulation scheme PSK or QAM
cr	In figure 2.2-6, code rate
mr	In figure 2.2-6, maximum number of repeats
nc	In figure 2.2-6, number of code
W	Watt
W1...WM	1 to M Walsh Codes

Chapter 1

Introduction

1.1 General

Today, market expectations for third-generation (3G) mobile communications indicate an increasing need for a wide range services from voice to different data rate services. New radio networks should provide each service with the required quality and optimum use of resources. In this scenario, it is very important to assign signal resources in a way to fulfill the dream of “any thing-any time-any where” to exchange “any kind” of information [1], [2], [3].

Depending on the application, in a radio environment, different attenuation, fading and interference characteristics are encountered. In some cases, applications must function in different environment. Multiple services imply that multiple data rates offered by the 3G systems will be available to users [4], [5], [6]. Some application mainly in the downlink direction such as download web pages, requires high data rates. Therefore, high data rate transmission and efficient packet access become necessary to satisfy these service requirements [7], [8].

In January 1998, the European standardization body for third generation mobile radio systems, the ETSI SMG (European Telecommunications Standards Institute-Special

Mobile Group), agreed to use Universal Mobile Telecommunications Systems (UMTS) as a radio access scheme for 3G systems [4]. ETSI SMG submitted the UTRA (UMTS Terrestrial Radio Access) concept [9] to ITU-R (International Telecommunication Union) for IMT-2000 (International Mobile Telecommunication-2000). The Japanese standardization body ARIB (Association of Radio Industries and Businesses) proposed WCDMA (Wideband Code Division Multiple Access) for IMT-2000. The Japanese and the European WCDMA for FDD (frequency division duplex) were very similar. In December 1998, the Third Generation Partnership Project (3GPP, [Http://www.3gpp.org/](http://www.3gpp.org/)) was formed. The objective of 3GPP was to merge the already well-harmonized UTRA proposals by the regional standardization bodies (Europe-ETSI, US-T1, Japan –ARIB, Korea-TTA, China-CWTS). UTRA consists of two modes: a frequency division duplex (FDD) mode, where the uplink and the downlink are transmitted on different frequencies, and the time division duplex (TDD) mode, where the uplink and the downlink are transmitted on the same frequency at different time. In the concept of UTRA, WCDMA is for UTRA FDD where TD-CDMA is for UTRA TDD. The FDD mode supports wide area coverage mainly for low or intermediate speed symmetrical services, whereas TDD mode is used in small areas mainly for high-speed asymmetric services.

Now WCDMA is being developed as the main technology for wideband personal radio communications of Internet, multimedia, video and other capacity demanding applications. It is a code division multiple access technology that support multi-rate streams in a 5 MHz radio channel.

1.2 Simple System Description

WCDMA is based on a 3.84 Mcps chip rate with 5 MHz channel bandwidth. The frame length is 10 ms; each frame is divided into 15 slots; each of which is 0.000667 ms long. Each frame is part of super frame, which is 720 ms long. Duplex schemes are FDD or TDD modes or the combination of FDD and TDD modes. Synchronous CDMA is used in downlink whereas asynchronous is used in uplink but synchronous operation is possible in uplink. PSK and QAM are used as modulation schemes in both links. Channel coding adopts convolutional codes and turbo codes. Long code or short code is used for scrambling the data. These codes are mobile station specific in the uplink and base station specific in the downlink. An orthogonal variable spreading code (OVSF) tree is used on both uplink and downlink for data spreading. The spreading factor of codes can vary from 4 to 256 in uplink and 4 to 512 in downlink. Multi-rate transmission can be implemented by variable spreading or by multi-code transmission [2], [10], [11].

1.3 System Capacity

1.3.1 Main technologies

In WCDMA capacity is measured by the throughput, which is the information bits per second [2], [8]. The main technologies for high-speed packet access currently considered in both FDD and TDD modes are:

- **Adaptive Modulation and Coding (AMCS)** The modulation size and code rate can be chosen according to an estimate value of the carrier-to-interference (C/I). If C/I is good, then high-order modulation (16QAM and 64 QAM) can be used to increase the bit rate.
- **Time Domain Packet Scheduling** Based on C/I values, scheduling enables transmission at a higher bit rate by performing resource (frame or slot) allocation.

In my research, only **AMCS** is used to maximize throughput in the WCDMA system.

1.3.2 A Problem in Applying AMCS

Wireless channels vary over time due to fading and changing interference conditions. To compensate for the variations of wireless channel, besides the technique of fast power control, adaptive modulation and coding (AMCS) [1] can also be used to support the reliable transmission while maintaining high capacity of the WCDMA system.

AMCS exploits the channel variations to maximize the data rate that can be transmitted over such channels by adapting the modulation and coding scheme. A high data rate is achieved with high modulation-order and high coding rate under good radio conditions, which depends on the position of the user in the cell.

In WCDMA, the user data could be sent on a single coded channel or several coded channels. In single coded channel, the throughput per frame is the information bit rate transmitted. In several coded channels, the total throughput per frame is the sum of all data rates transmitted on all codes. The problem of applying AMCS in several codes is that the throughput is not maximized in some cases when the power is allocated to codes equally without an optimal scheme. Therefore, in order to maximize the throughput when applying AMCS, the power allocated to each code must be optimized based on the channel condition of that code.

1.4 Thesis Objective

In this thesis, the throughput of one code and several codes applying AMCS will be investigated. The simulation follows the steps mentioned in [2], but simulation condition and implement methods are different from [2].

This thesis consists of three important parts: **the C/I samples, AMCS, and throughput hull.**

1. In the first part we conduct a comprehensive simulation study to estimate the C/I distribution of multi-cell packet radio channel for both downlink and uplink. The distribution of C/I will determine what kind of AMCS will be chosen and how high of data rate can be obtained. The simulation results will be analyzed and compared with the Gaussian approximation.

2. In the second part we simulate traffic and use the optimal AMCS for each data stream based on the simulation results of Frame Error Rate (FER) of different AMCS in [2]. The C/I values are mapped to the throughput hull of one code.
3. In the third part we optimize the power allocation to maximize the throughput of several codes. The results of throughput with and without optimal power allocation scheme will be compared and discussed. At last, the throughput of several codes will be approximated by a number of polynomials. The approximated data will serve as the maximum data rate for the scheduler.

1.5 Thesis Organization

The remainder of this thesis is organized as follows:

Chapter 2 will review previous simulations done in the area of Signal to Noise (E_b/I_{oc} , I_{or}/I_{oc} or C/I) distribution in cells, the frame error rate of AMCS in the wireless channel and maximum throughput achieved in multiple codes.

Chapter 3 will describe the C/I distribution in downlink and uplink. In this part, besides the cell layout, three propagation modes (path loss model, slow fading model and interference model) will be included. Simulation results will be shown and discussed.

Chapter 4 will introduce modulation and coding schemes of AMCS and signal processing in the system. The first part of this section will cover modulation and modulation size, constellation of 4PSK, 8PSK, 16QAM, 64QAM, convolution code and turbo code rate, adaptive modulation and coding (AMCS) and so forth. The second

section will describe the signal processing in the system as well as the concept and equation of spreading factor and processing gain.

Chapter 5 will study the behavior of the maximum throughput of one code and multi-codes. In order to study the throughput of different AMCS schemes in WCDMA channels, the following will be described in several sections:

- The channel performance
- Throughput computation algorithms
- Throughput hull
- Power allocation schemes
- Polynomial approximation
- Simulation and simulation result analysis

Chapter 6 will conclude by reviewing the material presented, especially the data and the results. Last, recommendations for further related research work would be given.

Chapter 2

Review of the Relative Research

2.1 Introduction

Before 1998, Europe, Japan, North America, China, and Korea had already shown interest in the third generation mobile communication. Later on, the 3GPP and 3GPP2 projects were formed, where companies such as Motorola, Ericsson, Nokia, Lucent Technologies, Panasonic, SONY Corporation and CSELT performed a lot of research on the high speed packet access.

2.2 Schemes of High Speed Packet Access

In these two years, many specifications and reports for implementation of the 3GPP system have been released, and these documents elaborate further. A scheme known as High Speed Downlink Packet Access (HSDPA) has been proposed and its technical specification was released in 2000. This scheme considers techniques that can be applied to provide high speed downlink packet access by means of high speed downlink shared channel (HS-DSCH). Among these techniques, adaptive modulation and coding scheme (AMCS) in conjunction with time domain scheduling can be used to increase the data

rate. Within the HSDPA concept, the modulation and coding are adapted to channel and user requirements. In the communication procedure, all the base stations always transmit at maximum power (17 W in our research) but only one base station is transmitting the desired signal at one observation time. 20% of transmission power is allocated to overhead channels (such as pilot (CPICH), paging (PICH), synchronization (SCH), etc.) and dedicated control channels. The remaining 80% of power is allocated to the data channel, which may be using one code or multi-codes. The user equipment (UE) estimates the carrier-to-interference ratio (C/I) and the channel condition (channel FER), then transmits these information to its serving Node B using the DPCCH-HS channel (Dedicated Physical Control Channel associated with HS-DSCH). According to this information from the active user, proper AMCS is chosen and thus the scheduler knows the maximum data rate that each mobile station can achieve. Node B is continuously selecting the user to be served and its data rate based on a scheduling algorithm (e.g Maximum C/I or Round Robin). C/I based scheduler provides maximum throughput at the expense of fairness since all frames can be allocated to a single user with good channel conditions. The Round Robin scheduler provides a fair sharing of resources at the cost of a lower system capacity. Both of scheduling schemes and AMCS can further improve the total system capacity in downlink.

In uplink, high speed data transmission is realized by AMCS and time domain scheduling scheme. The data can be transmitted either on DCH (Dedicated Channel) or the USCH (Uplink Shared Channel). Although several mobile stations can transmit at the same time on DCH, interference is higher when several mobile stations are active at the

same time. If data is carried in USCH, only one mobile station is allowed to transmit at one observation time thus there is no interference from other mobile stations in the same sector, and the active mobile station can transmit at full power for the duration of its transmission. Our research focuses on the data transmission in USCH, thus in uplink we assume that one user is active at one frame time. During the communication in uplink, the base station calculates the current C/I, estimates channel quality, and send this information to the mobile station. Based on these conditions, proper AMCS is chosen so that scheduler knows the maximum transmission data rate.

2.3 Current Research and Results

From the above information, we can see that the AMCS and scheduling are used both in the uplink and downlink to increase data rate. In order to choose an optimal AMCS for the channel, the carrier-to-interference ratio need to be estimated. Once the C/I is measured, channel quality of each AMCS will determine which AMCS is used to obtain the maximum transmission data rate in the channel. Some companies have already performed studies on the C/I distribution, performance of various AMCS (FER of each AMCS in channel) and the maximum throughput based on C/I and channel frame error rate for each AMCS with equal power allocation. Their simulation results are discussed in different 3GPP meetings.

To measure the distribution of carrier-to-interference ratio in a multi-cell packet radio channel, we must decide the cell layout, cell size, signal propagation model, fading model, base station and mobile station transmission power, antenna high, antenna gain,

frequency and so forth. To study the throughput of channels in the WCDMA system, chip rate, spreading factor, frame length, modulation and coding scheme are the essential elements to be considered. These factors are all included in the system level and link level assumptions in various proposals of 3GPP.

Before a proper link and system simulation assumptions are formed, the simulation results of various studies cannot be compared since different companies used different parameters. Thus, in order to evaluate the improvement of high speed packet access by different techniques, careful assumptions should be stated. In the proposal of HSDPA and reference [12] (provided by Nokia), a limited set of possible link and system level simulation assumptions are presented, which offers some harmonization of link and system simulation assumptions that we will use in our simulation. Moreover, in [12], the simulated cellular layout and information bit rate of one code and multiple codes are given. When using AMCS with power equally assigned to each channel, simulation results show that the information bit rate can reach 10.7Mbps with multi-code transmission when channels apply 64QAM modulation and $\frac{3}{4}$ code rate (MCS 7).

After making the proper simulation assumptions, we must build up an appropriate simulation model and find the computation algorithm to obtain C/I distribution. The simulation model mainly consists of path loss model, fading model and interference model. HSDPA and the radio transmission technologies specification of the UMTS [22] propose the same signal attenuation and lognormal shadowing models, which are used in

our simulation. CSELT company offers criteria for cell selection algorithm in [13]. Path loss, transmitting power, receiving power, interference from other Base stations in downlink and interference from other mobile stations in uplink are explained and expressed by dB in this document. In downlink, interference is equal to the signal powers received by a mobile station from surrounding base stations other than from the desired base station. In uplink, the interference is equal to the signal powers received by a base station from surrounding mobile stations except the desired mobile station. The C/I calculation algorithm (the ratio of receiving power of the desired signal to the total receiving powers of interfering signals) in our simulation is based on the algorithms that were suggested in [13].

Before transmitting data, the channel condition should be estimated to choose the appropriate modulation and coding scheme. The performance of a channel is determined by the Frame Error Rate, which is estimated based on the signal to noise ratio (SNR). A more accurate measure of the SNR is the energy per bit relative to the noise power spectral density, E_b/N_o . We also use E_c/N_t (ratio of average energy per chip to the effective noise power spectral density), I_{or}/I_{oc} (ratio of the total transmitting power spectral density to the interference power spectral density), $I_{or}/(I_{oc} + N_o)$ (ratio of the total transmitting power spectral density to the sum of the interference power spectral density and the noise power spectral density) and C/I (ratio of carrier to interference). A channel has different performance with different modulation and coding schemes. During a frame period, if the changing rate of a channel is much slower than the changing rate of

the signal, the channel is approximately static in a frame time. Under these conditions of static channel, Panasonic company studied channel performance with AMCS (adaptive modulation and coding scheme) (FER vs. E_b/N_o and FER vs. $I_{or}/(I_{oc} + N_o)$). In this simulation, eight AMCS were used in the HSDPA (listed in **Table 2.3-1**); CPICH is transmitted at 10% of maximum transmission power of Node B and HS-DSCH is transmitted at 40% of maximum transmission power of Node B. Simulation results of **Figure 2.3-1** and **Figure 2.3-2** from [14] show that when FER of different AMCS varies from 1 to 0.001, E_b/N_o varies from 0dB to 10 dB, whereas $I_{or}/(I_{oc} + N_o)$ changes from -11dB to 5.5 dB. Higher order AMCS need large $I_{or}/(I_{oc} + N_o)$ or E_b/N_o to obtain the same FER as the low order AMCS.

AMCS	Code rate	Modulation
MCS8	$\frac{3}{4}$	64 QAM
MCS 7	$\frac{1}{2}$	64 QAM
MCS 6	$\frac{3}{4}$	16 QAM
MCS 5	$\frac{1}{2}$	16 QAM
MCS 4	$\frac{3}{4}$	8 PSK
MCS 3	$\frac{1}{2}$	8 PSK
MCS 2	$\frac{3}{4}$	4 PSK
MCS 1	$\frac{1}{2}$	4 PSK

Table 2.3-1 Eight AMCS used in FER vs. E_b/N_o (or $I_{or}/(I_{oc}+N_o)$) by Panasonic [14]

Figure 2.3-1 Static (AWGN) Channel FER vs. $I_{or}/(I_{or}+N_o)$, Simulation result of Panasonic

Figure 2.3-2 Static (AWGN) Channel FER vs. E_b/N_o , Simulation result from Panasonic

SONY Corporation makes an effort to reduce the number of AMCS modes to simplify the scheme and reduce the implement complexity of Node B and UE [15], while link

level and system level simulation are conducted to analyze HS-DSCH performance when some of the AMCS modes were not used. The document shows that the removal of QPSK $R=1/4$ (code rate), 8PSK $R=3/4$, and 64QAM $R=3/4$ is possible with negligible system throughput loss since these modes do not contribute a significant increase in system throughput. The simulation also gives the E_c/N_t (ratio of average energy per chip to the effective noise power spectral density) CDF (cumulative distribution function) distribution in 19 cell, 3 sectored system when transmission power is 44dBm. The simulation result in **Figure 2.3-3** shows that the CDF of E_c/N_t varies from -25 dB to 4 dB [15]. This result provides a probable comparable distribution of C/I in our research.

Figure 2.3-3 E_c/N_t Distribution within a Service Area (from SONY Corporation)

Lucent technologies also made an effort with respect to the distribution of signal to noise ratio and channel performance. It suggests replacing the FER vs. E_b/N_o with FER vs. I_{or}/I_{oc} in [16]. Lucent performs the system simulation based on a hexagonal grid, 19 cell, 3 sectored system. In the simulation, the placement of the user determines the path loss and shadow fading from each base station. The path loss, shadowing and Rayleigh fading are combined to determine the I_{or}/I_{oc} at the terminals. In 20 AWGN (additive white Gaussian Noise) channels, if Rayleigh fading is 3.0 Km/h and Doppler fading (Jakes model) is considered; retransmission scheme use H-ARQ (IR) and Maximum C/I scheduling is applied, the cumulative distribution function of the I_{or}/I_{oc} is obtained in **Figure 2.3-4** from [17]. This figure shows that I_{or}/I_{oc} is mainly distributed from -10 dB to 15 dB. Once I_{or}/I_{oc} is determined, then AWGN (static) channel FER vs. I_{or}/I_{oc} curves for the eight modulation and coding schemes (listed in **Table 2.3-1**) are used to determine the FER for each data rate (FER vs. I_{or}/I_{oc} shown in [18]). This FER then determines the success of delivering of the packet. Base on those channel conditions in [18], the throughput results (with H-ARQ) are depicted in **Figure 2.3-5**. The figure shows that correspond throughput of I_{or}/I_{oc} is 1 Mbps to 8 Mbps. (Aggressive and not aggressive here are relative to H-ARQ scheme and depend on IR sub-block rates. H-ARQ is not discussed in this thesis thus we only care about the throughput obtained from these I_{or}/I_{oc} values.)

Figure 2.3-4 CDF of Ior/Ioc (from Lucent technologies)

Figure 2.3-5 Throughput of channel (from Lucent technologies)

The proposal of HSDPA [2] provides static channel performance of various AMCS schemes (**Figure 2.3-6**). This channel condition (FER vs. I_{or}/I_{oc} , frame length is 10ms) is used to simulate data traffic of each channel in our simulation. The following abbreviations are used in the figure:

Abbreviation	Definition
ce	channel estimation – 0 (ideal), 1 (non-ideal)
nc	number of codes
std	transmit diversity – 0 (off), 1 (on)
arq	Hybrid ARQ using Chase combining – 0(off), 1(on)
np	number of paths
fc	carrier frequency (2 GHz)
ibm	ray imbalance
ecior	power allocation (set to 80%)
speed	vehicle speed
q	modulation level (4PSK/8PSK/16QAM/64QAM)
cr	code rate
mr	maximum number of repeats
mph	meters per hour

Table 2.3-2 Abbreviation used in Figure 2.3-7 [2]

Figure 2.3-6 FER vs. Ior/Ioc for various MCS schemes in static channel

From **Figure 2.3-6**, we can see that in order to support data transmission in a static channel that applies 4-PSK as modulation and 0.25 as code rate, the minimum Ioc/Ior value is about -17dB . If applying 64QAM and 0.75 code rate in a channel, however, the minimum Ioc/Ior is over 1dB .

After obtaining the distribution of C/I and the channel performance with various AMCS, we can calculate the maximum data rate of any channel. In [2], [19], [20], [21], the throughput of each AMCS is defined as the product of one minus FER and information bit rate, which is used as throughput algorithm of one code in our simulation.

From the information collected above, we know that the study of the channel's performance of different AMCS is done in WCDMA. Our research of throughput is based on the simulation result provided by [2] under the assumption of static channel.

2.4 Simulation Outline

Our simulation program is aimed at obtaining maximum throughput of one code and multiple codes. We selected the channel performance to be the Frame Error Rate (FER). This performance is estimated based on the C/I, which is a highly variable parameter. The FER vs. C/I performance of various AMCS were concluded and presented in [2], thus the simulation result of FER vs. C/I will be sampled and used in our simulation. Based on the C/I simulation values and FER vs. C/I samples from [2], the characteristics of maximum throughput with the traditional resource allocation scheme in [2] and the proposed new resource allocation scheme will be investigated.

Chapter 3

C/I distribution in a Multi-Cell Packet Radio Channel

3.1 Introduction

In the WCDMA system, the signal quality depends on the factors such as environment, cell layout, signal propagation model, fading and interference. References [9,22, 23, 24, 25] give a very detailed description in these aspects. In this chapter, 19-cell layout, path loss model for urban and suburban areas, lognormal shadowing, interference for downlink and uplink and C/I compute algorithm will be described. The simulation assumptions, simulation results and analysis of the results will be shown and discussed.

3.2 Characteristic of the Cell and Cell Layout

A 3-G mobile radio system can be operated in different environments such as a large city or small city with low or high building construction, tropical, rural, desert and mountainous areas. We assume there is no LOS component in cells, thus the received signal mainly consists of reflections. The average power decreases with the distance raised to path loss exponent. The path loss exponent is between 3 and 5 and varies with

the different environments. The shadowing is caused by obstructions such as trees and produces large-scale fading in received signal. The lognormal distribution is used to model the variation of the shadowing. The standard deviation varies depending on the environments. 10dB can be used in urban and suburban areas. Smaller values are used in rural and mountainous areas. In the simulation, the standard deviation is set to 8dB [22], [23], [25].

Figure 3.2-1 Cell Layout: 19 cells, 3 sectors hexagonal grid
(the concept is from the system simulation assumption in [2])

The cell layout is assumed to be a homogenous hexagonal grid, and 3 sector cells with distance between base stations equal to 1400 meters. The base station antenna height must be above the average roof top height of 15 meters. As depicted in **Figure 3.2-1**, the 19 cell system deployment is applied in downlink simulation. In this system, the Base station in the center is the reference cell, which is interfered by the 18 cells of the surrounding 2 tiers of cells [2].

3.3 Path Loss Model

The propagation effects are divided into three distinct types of models. These are mean path loss, slow variation about the mean due to shadowing and scattering, and the rapid variation in the signal due to multi-path effects. In our research, slow movement is assumed; thus the mobility model-Jakes model for doppler fading is not considered here. Rayleigh fading (the rapid variation in the signal), caused by the channel impulse response, is included in the lognormal fading in WCDMA system. In [22], [23], [26], equations are given for mean path loss as a function of distance for each of the terrestrial environments. Hata model is an empirical formulation of the graphical path loss. The path loss is computed as a distance's function $d^{-\gamma}$. γ is the path loss exponent varying from 3 to 5.

$$L_{pathloss} = \gamma \cdot 10 \cdot \log(d_n)$$

Equation 3.3-1

Where:

d_n is the distance between base station and mobile station in kilometers

The model we used is applicable for the test scenarios in urban and suburban areas, which is based on COST 231-Hata model,

$$L_{pathloss} = 40 \times (1 - 0.004) \times \log(d_n) - 18 \times \log(ht) + 21 \times \log(f) + 80 \quad \text{Equation 3.3-2}$$

Where:

d_n is the distance between base station and mobile station in kilometers

f is the carrier frequency of 2000 MHz

ht is the base station antenna height, in meters

If $f = 2000$ MHz, $ht = 15$ meters, the formula becomes:

$$L_{pathloss} = 128.1 + 37.6 \times \log(d_n) \quad \text{Equation 3.3-3}$$

Where:

d_n is the distance between base station and mobile station in kilometers

$L_{pathloss}$ offers the mean value of the path loss. This model is valid for the NLOS case.

The propagation exponent is set to 4. The base station and mobile station antenna gains are not included here.

3.4 Lognormal Shadowing

The authors of [22], [26], [27] mention that the signal power in the direct propagation path decreases relatively slowly when the mobile station moves away from the base station. But as the receiver goes away, obstacles such as trees, building and moving trucks, which block the signal path, will cause occasional drops in received power. The

reduction in power occurs over many wavelengths of the carrier. Thus, this is called slow fading, or shadowing. Since the slow fading occurs randomly, it can be model by the lognormal distribution with mean power and standard deviation.

In [26], [27], the lognormal Pdf¹ is given by

$$f(x) = \frac{1}{x\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(\ln(x) - \text{mean})^2}{2\sigma^2}\right] \quad \text{Equation 3.4-1}$$

The lognormal distribution can be generated by the Gaussian random variable with mean and standard deviation σ . Gaussian random variable's unit is dB.

When signal propagates through the obstructions, each object attenuates the signal to some extent, thus the total path loss of the signal should be the sum of path loss and lognormal shadowing [27].

$$L_{\text{pathloss}} = x_{\sigma} + \gamma \cdot 10 \cdot \log(d_n) \quad \text{Equation 3.4-2}$$

Where:

d_n is the distance between base station and mobile station in kilometers.

x_{σ} is Gaussian random variable in dB.

γ is the path loss exponent.

The equation used in practice is:

$$L_{\text{pathloss}} = x_{\sigma} + 128.1 + 37.6 \times \log(d_n) \quad \text{Equation 3.4-3}$$

Where:

¹ Pdf Power density function.

d_n is the distance between base station and mobile station in kilometers.

x_σ is Gaussian random variable in dB. Standard deviation σ is 8 dB.

3.5 Interference in Downlink

When the signal transmits through the air, it is not only subjected to the attenuation and shadowing; it is also subjected to interference transmission signals from other surrounding Base stations. If the mobile station is near the reference base station that transmits the desired signal, the interferences from other base stations are small, if the mobile station is away from the reference (desired) base station, the interference from other base stations will become greater and the desired signal become weak. Since the interference experienced by the mobile station depends on its path loss and shadowing to all base stations, users receive different interference levels mainly depending on their location (the distance between the transmitter and receiver). In the 19 cell, 3 sector system, center base station is the reference Base station, and the other 18 base station work as interferers. The distance from the interfering base station to the mobile station can be computed as:

$$d_n = \sqrt{d_1^2 + D^2 + 2d_1D\cos\theta} \quad \text{Equation 3.5-1}$$

Where:

d_1 is the distance between reference base station and mobile station.

D is the distance between reference base station and interfering base station.

θ is the angle between D and d_1 .

d_n is the distance between the interfering base station and mobile station.

R is the cell radius.

In **Figure 3.5-1**, the desired signal power received by the mobile station depends on the shadowing and the distance d_1 , which is determined by the path loss attenuation. The interfering power depends on the shadowing and the distance d_n .

Figure 3.5-1 Interference from base station in another cell. Tx–Transmitter Rx –Receiver

3.6 C/I Computation Algorithm

When the transmitter antenna and receiver antenna gain are factored into the receiving power, the receiving power is equal to transmitting power minus path loss and plus transmitter and receiver antenna gains:

$$p_r = p_t - L_{pathloss} + transmittergain + receivergain \quad \text{Equation 3.6-1}$$

Where:

p_r is the receiving power.

p_t is the transmitting power.

$L_{pathloss}$ comes from **Equation 3.4-3**.

Then, an instantaneous carrier-to-interference ratio is the receiving power of desired signal divided by the total receiving powers of interfering signals:

$$C/I = \frac{p_r \text{ of desired signal}}{\sum_n p_r \text{ of interfering signal}} \quad \text{Equation 3.6-2}$$

Where:

C is the received power of the carrier or desired signal.

I is the total received power of the interferers.

n means there are n interferers.

p_r is the received power in receiver.

The average carrier-to-interference ratio in a sample point, the mean value of C/I in a sample point, is the sum of the total instantaneous C/I in a sample point divided by the total simulation times in this sample point:

$$\left(\frac{C}{I}\right)_{average} = \frac{\sum_{i=1}^N (C/I)}{N} \quad \text{Equation 3.6-3}$$

Where:

C/I comes from **Equation 3.6-2**.

i is the simulation times, ranges from 1 to N .

N is the total simulation times for a sample point.

3.7 Simulation Conditions and Assumptions

The simulation assumptions are given in Table 3.7-1 from [2]. These assumptions are based on the scenarios adopted in 3GPP.

Parameter	Assumption
Cellular layout	Hexagonal, 3 sectors
Site to Site distance	2800 meters
Antenna high	15 meters
Propagation model	$L=128.1+37.6\log(R)$ R in kilometer
BS Tx Power	80% of total power 17 W
Slow fading (shadowing)	Lognormal shadowing
Standard deviation of shadowing	8 dB
Carrier frequency	2000 MHz
User Tx power	200 mW
BS antenna gain	14 dB
User antenna gain	0 dBi
Power control	Not simulate in this simulation
Signal correlation	No
Thermal noise N_0	Not considered here

Table 3.7-1 System simulation assumption

3.8 Simulation of Downlink

The distribution of the carrier-to-interference ratio can be obtained from the 19 hexagonal, 3 sectored system (Figure 3.2-1) in downlink In HSDPA, the base stations in the system always transmit a constant power of 17 watts. Data users are supposed to occupy a maximum 80% of total transmission power. At one observation time, only one

base station is transmitting desired signal. Other base stations are transmitting interfering signals. All transmitting signals are supposed to propagate through three distinct types of models: mean path loss, slow variation about the mean due to shadowing and scattering, and the interference from other transmitters.

Figure 3.8-1 Random sample points in the cell

C/I distribution can be sampled in two ways:

1. Assuming that users are uniformly distributed in the cell, the C/I values can be randomly tested in the uniform distributed points from the cells.
2. Fixing distance away from the desired (reference) base station every 100 meters, C/I values are tested at each point. In this case, C/I is tested in fixed points and these fixed points are not uniformly distributed in a line. In **Figure 3.8-2**, sample

points with the same distance away from base station have the same C/I distributions. Thus in the simulation, we can select points shown in this picture and fix the sample points every 100 meters. We start at a distance 10 meters from the base station.

Figure 3.8-1 and **Figure 3.8-2** give us sample points in the cells with these two methods separately.

Figure 3.8-2 Fixed sample points every 100 meters in the cell

3.9 Simulation Result of Downlink

Figure 3.9-1 C/I distribution with fixed distance every 100 meters in downlink

Figure 3.9-2 Histogram of C/I with random sample points in downlink

Figure 3.9-3 Histogram of C/I with fixed sample points in downlink

Figure 3.9-4 distribution of the C/I value—mean value of C/I every 100 meters

Figure 3.9-5 comparison of cumulative distribution of C/I in simulation and Gaussian approximation

Figure 3.9-6 distribution of the C/I value—mean value of C/I every 100 meters with only one BS as interferer

- In **Figure 3.9-1**, we start from 10 meters, test the C/I values in every 100 meters until 1610 meters, which is very near the edge of the cell 1616 meters. **Figure 3.9-1**, **Figure 3.9-4** show that C/I values decrease along with the user distance away from the base station, which is matched with the path loss model we mentioned before. The farther the distance, the smaller the C/I values are obtained.

- **Figure 3.9-1** conveys variation of C/I values in every 100 meters. In every sample point, due to the effect of the lognormal shadowing, C/I is a highly variable value in **Figure 3.9-1**. For example, C/I differs from 100 dB to 20 dB within 100 meters. In 810 meters, the scope of C/I is 30 dB to -10 dB. After 1100 meters, the C/I locates below 20dB. In the worst case, at 1610 meters, which is the edge of the cell, the C/I values are very low, about -20 ~ -40 dB.

- **Figure 3.9-4** shows the mean value of C/I in every simulated point. In this figure, the mean value of C/I drops very quickly within the distance of 210 meters away from the Base station, from 80 dB to 30 dB. At 700 meters, the mean of C/I is about 10 dB. At 1210 meters, the mean of C/I drops to 0 dB, and between 1210 meters and 1610 meters, the mean of C/I values could be negative.

- **Figure 3.9-2** and **Figure 3.9-3** display the probability of the distribution of C/I with random and fixed sample points respectively.

- **Figure 3.9-2** shows that most of C/I vary between 0 ~ 10 dB; whereas in **Figure 3.9-3**, most of C/I are between -5 ~ 8 dB. **Figure 3.9-3** shows that C/I has more probability in 80 dB than in 60dB, 70 dB and 100dB, which is matched with **Figure 3.9-1** in that C/I values are rarely occur in 60 dB, 70dB and 100 dB since the signal drops fast within 100 meters. Both histograms look like Gaussian distribution.
- As the sample points become large, the central limit theorem dictates that the distribution of the sum approximates a Gaussian, even if the individual terms are not Gaussian. **Equation 3.9-1** and **Equation 3.9-2** compute the C/I sample mean and the C/I sample variance. In **Equation 3.9-2**, in order to obtain an unbiased estimator of the variance, we use $n-1$ instead of n . The C/I distribution simulation result is compared with the Gaussian approximation with the same mean and variance in **Figure 3.9-5**. From this figure we know that the simulation result is close to the Gaussian distribution. If the difference of two curves is ignored, the distribution of C/I can use Gaussian distribution to approximate. Since most problems occur at the edge of the cell, the C/I values should be correctly estimated at this part. Therefore, the original sample values of C/I are more preferable than the Gaussian approximation in the research.

$$mean = \frac{1}{n} \sum_{i=1}^n (C/I)_i$$

Equation 3.9-1

$$\text{variance} = \frac{\sum_{i=1}^n ((C/I)_i - \text{mean})^2}{n - 1}$$

Equation 3.9-2

Where:

Mean is the C/I sample mean. Variance is the C/I sample variance. n is the total sample times. i is the individual sample times, $i=1, 2, 3, \dots$

- In **Figure 3.9-6** we test the mean of C/I value every 100 meters along the distance from 10 meters to 1610 meters away from the base station with only one base station as the interferer. The simulation result reveals that when only two base stations are transmitting the signal at the same time, if the interfering signals from other base stations in the 19 cells are ignored, then one of these two base stations will transmit the reference signal and the other base station will send the interfering signal. In the figure, the mean of C/I value reaches 0 dB at 1610 meters, which is very near the boundary of the cell. If we change test points, we will see that the means of C/I will reach 0 in the mid-points of intersection of two cell. This proves that the C/I samples are reasonable values since the average desired signal power is equal to the average interfering signal power when both distances away from each base station are the same if only two base stations are included. When comparing **Figure 3.9-6** with **Figure 3.9-4**, because mean values of C/I in **Figure 3.9-4** drop faster than those in **Figure 3.9-6**, it is easy to get a conclusion that C/I values fall down faster with distance when more interferers are added into the simulation.

From the simulation result of distribution of C/I , we can draw the following conclusions:

1. C/I decreases as distance from base station increases. This is compatible with the path loss model in that signal power attenuates with distance.
2. C/I varies greatly in fixed sample points due to the effect of lognormal fading.
3. When more interference sources are included, the C/I value decreases.
4. Although CDF of C/I looks like Gaussian, we will not use Gaussian distribution to approximate the simulation result because the approximation will overlook the big difference between the true C/I value and the approximation value at the edge of a cell.
5. From the figure of static channel performance with AMCS (the figure of FER vs. I_{or}/I_{oc} for various MCS in static channel in Chapter 2 (Figure 2.2-6)), we can see that most of I_{or}/I_{oc} used by AMCS are from -18 dB to 10 dB. The values of C/I are about equal to the values of I_{or}/I_{oc} . Therefore, based on this channel performance, sample results of C/I lower than -18 dB will not be used by AMCS in any channel. In **Figure 3.9-1**, perhaps AMCS are used very often between 510 meters and 1210 meters because most C/I values vary from -15 dB to 20 dB in these distances.
6. Since the throughput of a channel is bounded by the estimated C/I value and AMCS scheme in that channel, the larger the estimated C/I value in

the channel, the higher order AMCS (higher modulation and coding scheme) can be used in that channel, the higher data rate can be obtained in that channel. Thus, there is a higher chance to obtain maximum throughput between 510 meters and 1210 meters.

3.10 Histogram of C/I in Fixed Sample Points

Figure 3.10-1 histogram of C/I from 10~ 310 meters

Figure 3.10-2 histogram of C/I from 410~ 710 meters

Figure 3.10-3 histogram of C/I from 810~ 1110 meters

Figure 3.10-4 histogram of C/I from 1210~ 1510 meters

Figure 3.10-5 histogram of C/I from 1610 meters

Figure 3.10-1, Figure 3.10-2, Figure 3.10-3 Figure 3.10-4 and Figure 3.10-5 are histograms for every fixed point. From these figures we can see that C/I distribution in every fixed point is similar to Gaussian distribution. The C/I value with the highest probability changes from 80 dB to -5 dB between 10 meters and 1610 meters. The C/I varies significantly in a fixed point due to the lognormal shadowing and interference, implying that a wide range of AMCS can be chosen in a fixed point. Therefore, information can be transmitted by different data rates in a fixed point, which depends on the estimated C/I value of this point.

3.11 Signal Model For Uplink

In uplink, signal propagates through the same path loss attenuation and shadowing models in the radio environment as in downlink. However, the interference in the uplink is quite different from that in the downlink.

3.12 Cellular Scenario for Uplink

Figure 3.12-1 Cell layout in uplink

Like downlink cellular layout in [28], the cellular layout in uplink is still a hexagonal, 3 sector cellular layout. Although the center base station is the reference cell interfered with

by the surrounding 2 tiers of cells, the interferences are not from mobile stations in the total 18 surrounding cells but just from mobile stations in the 2 tiers of cells covered in the antenna direction of the reference sector. The scheduling technique assumes, that in time domain scheduling, only one user is active at one observation time. In that case 17 mobile stations in this region will be interferers.

3.13 Interference in Uplink

As mentioned above, in downlink the interference comes from a few sources while the interfering power is relatively high. In uplink, where the interference comes from many sources (almost one interferer per sector in the region), interfering power is not very high because the mobile station transmission power is set to 200 mw [2]. Since the interference experienced by the base station depends on its path loss and shadowing to all interfering mobile stations, the reference base station receives different interference levels depending on the interfering mobile station's location. The distance from interfering mobile station to reference base station in **Figure 3.13-1** can be computed as:

$$d_n = \sqrt{d_1^2 + D^2 + 2d_1D\cos\theta} \quad \text{Equation 3.13-1}$$

Where:

d_1 is the distance between interfering mobile station and the base station where the interfering mobile Station is located.

R is the cell radius.

D is the distance between reference base station and the base station where interfering mobile station is located.

θ is the angle between D and d_1 .

d_n is the distance between the reference Base station and interfering Mobile Station.

Figure 3.13-1 Interference form Mobile Station in a sector in another cell. Rx-receiver Tx-Transmitter

3.14 Simulation of Uplink

In simulation, the same C/I calculation algorithm used in downlink is employed to compute the C/I instantaneous values in uplink.

$$C/I = \frac{p_r \text{ of desired signal}}{\sum_n p_r \text{ of interfering signal}}$$

Equation 3.14-1

Where:

C is the received power of the carrier or desired signal.

I is the total received power of the interferers.

n means there are n interferers.

p_r is the received power in receiver.

The only difference is that here the received power is received by reference base station instead of the mobile station, and the interfering received powers are coming from the interfering mobile stations instead of base stations as is the case in the downlink.

3.15 Simulation Result

Figure 3.15-1 C/I distribution with fixed distance very 100 meters in uplink

- In Figure 3.15-1, we start from 10 meters, test the C/I values in very 100 meters until 1610 meters, which is very near the edge of the cell 1616 meters. **Figure**

3.15-1 and Figure 3.15-3 show that as in downlink, C/I values decrease along with the user distance away from the base station, which is matched with the path loss model mentioned previously. The farther the distance, the smaller the C/I values obtained.

- **Figure 3.15-1** conveys variation of C/I values in every 100 meters. In every sample point, due to the effect of the lognormal shadowing, C/I is a highly variable value. For example, C/I differs from 100 dB to 15 dB within 100 meters. In 810 meters, the scope of C/I is 30 dB to -17 dB. After 1100 meters, the C/I falls below 20dB. In the worst case, at 1610 meters, which is the edge of the cell, the C/I values are very low, about -20 ~ -40 dB.

Figure 3.15-2 Histogram of C/I with fixed sample points in uplink

- **Figure 3.15-2** displays the probability of the distribution of C/I with fixed sample points. **Figure 3.15-2** shows that most C/I values vary between $-4 \sim 8$ dB, a little bit higher than in downlink. It shows C/I has more probability in 80 dB than in 60dB, 70 dB and 100dB, which is matched with **Figure 3.15-1** in that C/I values are rarely occur in 60 dB, 70dB and 100 dB. This histogram looks like Gaussian distribution.

Figure 3.15-3 distribution of the C/I value—mean value of C/I every 100 meters

- **Figure 3.15-3** shows the mean value of C/I in very sample point. The mean of C/I drops very quickly within the distance of 210 meters away from the base station, from 80 dB to 29 dB, a little bit lower than that in downlink. At 710 meters, the

mean of C/I drops to 8 dB. At 1210 meters, the mean of C/I is about 0 dB. Between 1210 meters and 1610 meters, the means of C/I values could be negative.

Figure 3.15-4 comparison of cumulative distribution of C/I in simulation and Gaussian approximation

- As the sample points become large, the central limit theorem dictates that the distribution of the sum approximates a Gaussian, even if the individual terms are not Gaussian variables. **Equation 3.9-1** and **Equation 3.9-2** stated in downlink compute the C/I sample mean and the C/I sample variance in uplink. The C/I distribution simulation result is compared with the Gaussian approximation with the same mean and variance in **Figure 3.15-4**. The simulation result is close to the Gaussian distribution. If the difference of the two curves is ignored, the

distribution of C/I can use Gaussian distribution to approximate. Since most problems occur at the edge of the cell, the C/I values should be correctly estimated at this part. Therefore, the original sample values of C/I are more preferable than the Gaussian approximation in the research.

From the simulation result of distribution of C/I , we can draw the following conclusions:

1. C/I decreases as distance from base station increases. This is compatible with the path loss model in that signal power attenuates with the distance.
2. C/I varies greatly in a fixed sample point due to the effect of lognormal fading.
3. The more the interference include, the faster the C/I decreases.
4. Although CDF of C/I looks like Gaussian, we will not use Gaussian distribution to approximate the simulation result because the approximation will overlook the difference between the true C/I value and the approximation value at the edge of a cell.
5. From the figure of static channel performance with AMCS (the figure of FER vs. I_{or}/I_{oc} for various MCS in static channel in Chapter 2 (Figure 2.2-6)), we can see that most of I_{or}/I_{oc} used by AMCS are from -18 dB to 10 dB. The values of C/I are about equal to the values of I_{or}/I_{oc} . Therefore, based on this channel performance, sample results of C/I lower than -18 dB will not be used by AMCS in any channel. In **Figure 3.15-1**, perhaps

AMCS are used very often between 510 meters and 1210 meters because most C/I values vary from -15 dB to 20 dB in these distances.

6. Since the throughput of a channel is bounded by the estimated C/I value and AMCS scheme in that channel, the larger the estimated C/I value in the channel, the higher order AMCS (higher modulation and coding scheme) can be used in that channel, the higher data rate can be obtained in that channel. Thus, there is a higher chance to obtain maximum throughput between 510 meters and 1210 meters.

3.16 C/I Histogram with Fixed Distance

Figure 3.16-1 histogram of C/I from 10~ 310 meters

Figure 3.16-2 histogram of C/I from 410~ 710 meters

Figure 3.16-3 histogram of C/I from 810~ 1110 meters

Figure 3.16-4 histogram of C/I from 1210~ 1510 meters

Figure 3.16-5 histogram of C/I from 1610 meters

Figure 3.16-1, Figure 3.16-2, Figure 3.16-3, Figure 3.16-4, and Figure 3.16-5 are histograms for every fixed point. From these figures we can see that C/I distribution in every fixed point is similar to Gaussian distribution. The C/I value with the highest probability changes from 79 dB to -5 dB between 10 meters and 1610 meters. The C/I varies significantly in a fixed point due to the lognormal shadowing and interference, implying that a wide range of AMCS can be chosen in a fixed point. Therefore, information can be transmitted by different data rates in a fixed point, which depends on the estimated C/I value of this point.

Chapter 4

AMCS and Signal Processing

4.1 Introduction

Modulation and coding are used to transmit data over the channel. In order to achieve reliable transmission, channel coding is used to recognize and eventually correct distorted code words. This coding realizes a simple and secures data transmission from the source to the sink [26].

Three attributes can be varied in proportion to the modulating signal: the **amplitude**, the **phase**, and **frequency**. The first scheme is called **Amplitude Modulation** that is modulating the amplitude of the carrier wave. The other two schemes are called **Angle Modulation**. Phase Shift Keying (PSK) modulates the phase of the carrier wave, and Frequency Shift Keying (FSK) modulates the frequency of the carrier wave [26].

M-ary Amplitude Shift Keying (M-ASK, M-PAM), M-ary Phase Shift Keying (M-PSK) and M-ary Frequency Shift Keying (M-FSK) modulation schemes are used to transmit multiple bits during a single symbol interval. These M-ary data modulation, converts incoming data symbols into complex valued symbols, the M-ary data modulator can convert m incoming data bits into one of M ($M = 2^m$) possible data symbols represented by the channel symbols [29].

Two coding schemes are being used in wireless systems: (1) Convolutional codes and (2) Turbo codes. Both of these two codes have a variety of coding rates.

4.2 Standard Constellations for M-ary Modulation

In this research, M-ary modulations of 4-PSK, 8-PSK, 16-QAM, 64-QAM are used as the modulation schemes in the channel [2],[29].

In the case of 4-PSK modulation, every **two** binary symbols from the channel interleaver output shall be mapped onto one of the possible modulation symbols according to **Figure 4.2-1** [2].

In the case of 8-PSK modulation, every **three** binary symbols from the channel interleaver output shall be mapped onto one of the possible modulation symbols according to **Figure 4.2-2.2** [2].

In the case of 16-QAM modulation, every **four** binary symbols from the channel interleaver output shall be mapped onto one of the possible modulation symbols according to **Figure 4.2-3** [2].

In the case of 64-QAM modulation, every **six** binary symbols from the channel interleaver output shall be mapped onto one of the possible modulation symbols according to **Figure 4.2-4** [2].

Figure 4.2-1 Signal Constellation for 4-PSK Modulation

Figure 4.2-2 Signal Constellation for 8-PSK Modulation

Figure 4.2-3 Signal Constellation for 16-QAM Modulation

Figure 4.2-4 Signal Constellation for 64-QAM Modulation

From the constellation diagram of Q-PSK, 8-PSK, 16-QAM and 64-QAM, it can be seen that signal power vector of Q-PSK, 8-PSK (distance between signal points and the center of the constellation) is $\sqrt{E_s}$, where E_s is the energy of a symbol. The smallest power vector of 16 QAM is $\sqrt{E_s/5}$. If the power vector of 64 QAM is the same as that of 16 QAM, the signal space will expand. More power will then be needed in 64 QAM. If the total power for the 16 QAM and 64 QAM is the same, the power allocated to each signal point in 64 QAM will be less than that of 16 QAM. The power vector will be shrunk and distance between adjacent signal points will be smaller in 64 QAM. This will result in a higher error rate than that of 16 QAM because the average probability of error depends on the distance between the signals in the signal space diagram. The bigger the distance is, the smaller probability an error will occur. Therefore, for fixed frame error rate (FER), higher order modulation schemes require more power or signal to noise ratio (SIN) than lower order modulations do (**Figure 4.2-5**). Here SIN can be C/I or E_b/N_o .

Figure 4.2-5 Frame error rate vs. SIN (signal to noise ratio) for different modulation schemes

4.3 Code Rate

In order to improve the capacity of a channel, some carefully designed redundant information can be added to the data being transmitted through the channel. The process of adding the redundant information is known as channel coding [11], [29]. Convolutional coding and turbo coding are two main forms of channel coding used in adaptive modulation and coding schemes AMCS.

Convolutional codes are serial codes. Their constraint length and code rate need to be selected. The constraint length should be as large as possible for good performance.

Turbo coding is parallel-concatenated recursive convolutional codes. The turbo code encoding structure is based on a combination of two or more encoders (**Figure 4.3-1**), generating two parity streams. These streams are then multiplexed and possibly punctured. The whole process results in a code that has powerful error correction properties [2],[11],[29].

Figure 4.3-1 Block diagram of a Turbo Encoder

In this research, we do not simulate the actual coding/decoding process, instead we consider encoder decoder as a black box with certain error correction capabilities.

The information data is encoded with an $\{n, k\}$ turbo or convolution encoder, where k is information bit length and n is the code word length.

Code rate R is defined as:

$$R = \frac{k}{n} \quad \text{Equation 4.3-1}$$

As in **Figure 4.3-2**, k bits information are encoded into n bits encoded data through some mapping functions with code rate $R=k/n$.

Figure 4.3-2 Code rate

4.4 AMCS

Besides the technique of fast power control, adaptive modulation and coding schemes (AMCS) [2] can also be used to increase the capacity of the wireless system.

The AMCS technique adapts the modulation and coding scheme to channel conditions in order to obtain the maximum throughput. When the channel condition is good and the user is near the base station, the C/I ratio is large. Hence, high order modulation with higher code rate can be assigned to the user. If the channel condition is poor and the user is far away from the base station, the C/I ratio is small. Therefore, lower order

modulation with lower code rate has to be assigned to the user. As a result, the higher data rate will be realized when the user is in a good location and the C/I is higher. In HSDPA standard only seven AMCS are being used. They are shown in **Table 4.4-1**.

AMCS	Code Rate	Modulation	Information bits/symbol
MCS 7	$\frac{3}{4}$	64 QAM	6
MCS 6	$\frac{3}{4}$	16 QAM	4
MCS 5	$\frac{1}{2}$	16 QAM	4
MCS 4	$\frac{3}{4}$	8 PSK	3
MCS 3	$\frac{3}{4}$	4 PSK	2
MCS 2	$\frac{1}{2}$	4 PSK	2
MCS 1	$\frac{1}{4}$	4 PSK	2

Table 4.4-1 Seven AMCS

4.5 Spreading Signal

In WCDMA, the signal processing normally goes through several steps. Besides coding, modulation, and spectrum spreading, rate matching and interleaving are also applied in the system.

As showed in **Figure 4.5-1** [2], the signal in physical layer must be processed before it is sent from the transmitter [25], [30]. First, the tail bits are inserted in certain known positions of the turbo encoder input data. The number of bits encoded by turbo code, compared to convolutional code, has these extra bits (tail bits). These bits are punctured at the known positions of the coded data in order to get the required data rate. Since the chip rate is fixed in data transmission, rate matching is used to match the coded bit rate to the limited set of possible bit rates of a channel through code puncturing and repetition. Coding and interleaving are used to improve the channel error performance. The turbo codes and convolutional codes are most effective against random errors, while

interleaving is used to randomize the burst errors. The interleaved data will then be modulated by different modulation schemes for transmission, which match the coding scheme in AMCS. Finally, the signals are spread by a set of Walsh codes and then combined together [2], [9], [27]. The number of the orthogonal codes (spreading factor) used here is set to 32. ($W1 \dots W32$).

Figure 4.5-1 Physical layer structure

Spreading transforms every data symbol into a number of chips. Thus the bandwidth of the spread signal is much greater than the bandwidth of the original information signal. Orthogonality between the different spreading factors can be achieved with a tree-structure as shown in **Figure 4.5-2** [2], [25], [27]. Two codes are orthogonal if their inner product is zero. The orthogonal code can be designed according to **Equation 4.5-1**. For instance, in **Figure 4.5-2**, the first element in the tree is 1. For each tree element, there are two possible sub-tree elements: left-element and right-element. The left-element is constructed by repeating the root of that element twice. Thus, the left-element of (1) is

(1,1). The right-element is constructed by concatenating the root of that element with the inverse of itself. Thus, the right-element of (1) would be (1, -1). At each level, when all the code words are constructed in this way, the constructed codes will be orthogonal.

Figure 4.5-2 The tree-structured codes (spreading factor)

The tree-structured codes are generated recursively according to [25]:

$$C_{2n} = \begin{pmatrix} C_{2n,1} \\ C_{2n,2} \\ \vdots \\ C_{2n,2n} \end{pmatrix} = \begin{pmatrix} \begin{pmatrix} C_{n,1} & C_{n,1} \\ C_{n,1} & -C_{n,1} \end{pmatrix} \\ \vdots \\ \begin{pmatrix} C_{n,n} & C_{n,n} \\ C_{n,n} & -C_{n,n} \end{pmatrix} \end{pmatrix} \quad \text{Equation 4.5-1}$$

4.6 Spreading Factor and Processing Gain

Spread spectrum is a means of transmission in which the signal occupies a bandwidth much wider than the bandwidth necessary to send the information. The spreading is accomplished by means of a code, which is independent of the data. There are three

methods for spreading: (1) Coding (adding parity bit to information bits), (2) Symbol repeating, and (3) Replace coded data symbol by chips [31].

Spreading factor is the numbers of the chips per symbol interval. The symbols are the encoded and modulated data. The spreading factor can also be considered as the length of code that replaces a data symbol. In **equation 4.6-1**, the spreading factor is expressed in many ways [24], [27]:

$$\text{Spreading Factor} = \frac{T_{symbol}}{T_{chip}} = \frac{\text{chip rate}}{\text{symbol rate}} \quad \text{Equation 4.6-1}$$

Where:

T_{symbol} is the period of a symbol.

T_{chip} is the period of a chip.

$$\text{Chip Rate} = \text{symbol rate} \times \text{spreading factor} \quad \text{Equation 4.6-2}$$

$$\text{Symbol Rate} = \frac{\text{Chip Rate}}{\text{Spreading factor}} \quad \text{Equation 4.6-3}$$

$$\begin{aligned} \text{Data Rate} &= \text{coded symbol rate} \times \text{modulation size} \times \text{code rate} \\ &= \frac{\text{chip rate} \times \text{modulation size} \times \text{code rate}}{\text{spreading factor}} \end{aligned} \quad \text{Equation 4.6-4}$$

Symbol rate is the ratio of chip rate and spreading factor (**Equation 4.6-3**). Data rate is equal to symbol rate times modulation size and code rate (**Equation 4.6-4**).

Unlike spreading factor, which is the number of chips per symbol, the processing gain, is equal to the ratio of chip rate and information bit rate. [31] From **Figure 4.5-1**, the processing gain can be expressed as:

$$\begin{aligned}
 \text{Processing Gain} &= \frac{\text{transmission bandwidth}}{\text{bandwidth of information bit}} \\
 &= \frac{\text{Chip Rate}}{\text{Data Rate}} = \frac{T_{bit}}{T_{chip}} \\
 &= \frac{\text{Spreading factor}}{\text{Modulation Size} \times \text{Code Rate}}
 \end{aligned}
 \tag{Equation 4.6-5}$$

Where:

T_{bit} is the duration of a bit.

T_{chip} is the duration of a chip.

Chapter 5

Throughput

5.1 Introduction

Throughput is a means to measure the system capacity. In order to study the throughput of different AMCS as they are applied to different WCDMA channels, it is necessary to study the channel performance as well as the throughput computation algorithms as they are applied to throughput hull and the power allocation schemes. The calculation and the results of the calculations will be analyzed in the following several sections.

5.2 Channel performance

Figure 5.2-1 FER vs. C/I

The quality of a wireless channel is characterized by the bit error rate (BER) or frame error rate (FER). Here the frame length is 10 ms. Both criteria are functions of the carrier-to-interference (C/I) ratio. The relationship between FER and C/I for each AMCS of one code is given in [2] under the condition of the static channel. **Figure 5.2-1** shows sample values of FER vs. I_{or}/I_{oc} from [2]. I_{or} is the total transmitted power spectral density, while I_{oc} is the sum of the interference power spectral density. In these sample values, C/I is about equal to I_{or}/I_{oc} .

In simulating C/I distribution, all intra-cell interferences are completely ignored based on the assumption of orthogonal codes. The thermal noise is also ignored. Only inter-cell interferences are modeled. Sometimes BER or FER is given as a function of the average E_b/N_o in dB (E_b is the energy a bit and N_o is the inter-cell interference power spectral density). The relation between C/I and E_b/N_o is mentioned in [9] as:

$$\frac{C}{I} = \frac{E_b}{N_o} \cdot \frac{\text{code rate} \cdot \log_2 M}{B \cdot SF \cdot T_c} \quad \text{Equation 5.2-1}$$

Where:

M is the size of the data symbol alphabet.

B is the user bandwidth, $B=R_c=\text{chip rate}=3.84 \text{ Mbps}$.

$SF = 32$, is the spreading factor.

$T_c=1/\text{chip rate}=1/R_c$, is the chip duration.

$\log_2 M$ is the number of bits per data symbol, equals to modulation size.

Form **equation 4.6-1~4.6-4**, C/I can be given as:

$$\begin{aligned}
\frac{C}{I} &= \frac{E_b}{N_o} \cdot \frac{\text{code rate} \cdot \text{modulation size}}{B \cdot SF \cdot 1/\text{chiprate}} \\
&= \frac{E_b}{N_o} \cdot \frac{\text{Data Rate } (R_b)}{R_c} \\
&= \frac{E_b/N_o}{\text{processing gain}} \\
&= \frac{E_b/T_b}{N_o \cdot R_c}
\end{aligned}$$

Equation 5.2-2

The relationship between C/I and E_b/N_o is deduced because some references and papers provide their channel performance simulation results as FER vs. E_b/N_o .

5.3 Throughput

The throughput is defined as the effective information bits per second. In [2], the throughput of each AMCS is calculated as:

$$\text{Throughput} = R_b \times (1 - \text{overhead}) \times \left[\frac{1 - FER}{N} \right]$$

Equation 5.3-1

Where:

R_b is the transmitted information bit rate from **Equation 4.6-4**.

The overhead is assumed to be fixed for all schemes.

N is the average number of transmission attempts for each frame.

If we exclude the effects of overheads and retransmission times, the equation becomes:

$$\text{Throughput} = R_b \times [1 - FER]$$

Equation 5.3-2

Where:

FER is the residual Frame Error Rate, which is obtained from **Figure 5.2-1** in [2].

R_b is the transmitted information bit rate from **Equation 4.6-4**.

5.4 Throughput Hull

Parameter	Assumption
Chip rate	3.84 Mcps
Bandwidth	5 MHz
Spreading factor	32
Spreading codes available	20
Frame duration	10 msec
Channel coding	Turbo code and Convolution code, code rate $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$
Modulation scheme	4PSK, 8PSK, 16QAM, 64QAM

Table 5.4-1 Link level assumption

The “throughput hull” is defined as the envelope of the maximum throughput of individual AMCS that can be achieved using the measured C/I. The channel capacity is calculated in a cell out of a 19- cell system, where each cell consists of 3 sectors. System level assumption is given in **Table 3.7-1**, and link level simulation assumption is given in **Table 5.4-1**. **Equation 5.3-2** and **Figure 5.2-1** were used for the throughput hull calculation. The procedure is as follows:

- 1) A table of target FER is established, where FER—residual frame error rate is from the **Figure 5.2-1**.
- 2) Take a channel measurement sample and estimate the current C/I. C/I samples are from the C/I distribution simulation results.

- 3) The intersection of a target FER and the measured C/I indicate an operation point as shown in **Figure 5.4-1**.

Figure 5.4-1 Simulation operation point

- 4) The throughput of different AMCS is calculated using **Equation 5.3-2**. For an operation point, there are seven calculation results of seven AMCS for choosing. The throughput of an operating point is the highest throughput of these seven AMCS.
- 5) Select another operation point, repeat 1) to 4) to get another throughput.
- 6) Repeat 1) to 5) thousands of times.
- 7) If we plot the throughput vs. (C/I) measure, we obtain a curve as shown in **Figure 5.4-2**.

In fact, the “throughput hull” curve is the envelope of the throughputs of individual AMCS when plotted against the (C/I).

Figure 5.4-2 Throughput Hull

5.5 Calculation Results of Throughput

Throughput hull obtained from the calculation is shown in **Figure 5.5-1** and **Figure 5.5-2**. From these two figures, we can see that AMCS are mainly useful when C/I values are above -17.8dB . When C/I is lower than -17.8dB , the FER is so high (close to 1) that the throughput can be considered zero. The relationship between FER and C/I of the seven AMCS has dictated the kind of data rate that can be attained. Different AMCS can achieve different maximum data rates with different C/I values. **Figure 5.5-1** shows the throughput of individual AMCS. In the envelope of the seven schemes shown in **Figure 5.5-2**, throughput hull gives the results of the maximum throughput obtained from

different AMCS. Both figures show the highest data rate that can be transmitted in one code is 540000 bps when using MSC7.

For every AMCS there are two minimum C/I requirements. One is called lower bound; whose corresponded FER equals to 0.9 in **Figure 5.2-1**. The other is called upper bound; whose corresponded FER is equal to or less than 10^{-5} . If the estimated C/I is lower than the lower bound for one MCS, the throughput of this MCS is zero. Thus a lower order MCS will be selected instead of this MCS because the estimated C/I is bigger than the lower bound of the lower order MCS. For example, in **Table 5.5-1**, the lower bound of MCS7 is 0.8 dB. If estimated C/I values are lower than 0.8 dB, the throughput of MCS7 is zero. Then MCS6 will be selected instead of MCS7.

The upper bound of an AMCS scheme can support maximum throughput associated with this AMCS. Different AMCS can achieve different maximum data rates with different C/I values, which is listed in **Table 5.5-1**. For instance, when estimated C/I reaches upper bound of MCS7 (3.1 dB), the highest data rate of MCS7 of one code (**540000 bps**) will be achieved. Maximum throughput (360000 bps) of MCS6 will be reached when the estimated C/I is bigger or equal to its upper bound -2.5 dB.

Figure 5.5-1 Throughput of one code of every AMCS

Figure 5.5-2 Throughput hull of one code applied seven AMCS

One code	Chip rate = 3.84 Mcps	Spreading factor = 32	One frame = 10 ms
AMCS	Maximum data rate when $C/I > C/I$ of $FER = 10^{-5}$	Minimum C/I requirement for $FER=0.9$ (Lower bound)	Minimum C/I requirement for $FER=10^{-5}$ (Up bound)
MCS1	60000 bps	-17.8 dB	-14 dB
MCS2	120000 bps	-13.8 dB	-10.1 dB
MCS3	180000 bps	-10.5 dB	-7.9 dB
MCS4	270000 bps	-7 dB	-2 dB
MCS5	240000 bps	-8.5 dB	-5.9 dB
MCS6	360000 bps	-4.5 dB	-2.5 dB
MCS7	540000 bps	0.8 dB	3.1 dB

Table 5.5-1 Maximum data rate of AMCS of one code and relative C/I values

5.6 Throughput of Multi-Codes

In a cell out of a 19 cell, 3 sectors system, if the chip rate and the spreading factor are fixed, then the transmission data rate of a code will be fixed if modulation and coding schemes are chosen according to the channel condition. From throughput calculation of one code, we know that if the chip rate is 3.84Mchip and spreading factor is 32, when using AMCS with estimated C/I, the maximum data rate that can be transmitted in a code is only 540000 bps. This bit rate is not fast enough for high-speed transmission. The limitation of data transmission in one code triggers the possible solutions for multi-rate transmission.

In WCDMA, high-speed transmission is attained by one of two possible schemes: (1) Variable spreading factor (VSF) or (2) Multi-codes. In the VSF scheme where a single code transmission is realized with different spreading factors of $SF = 4, 8 \dots 512$, the

spreading factor is reduced as the data rate increases. Therefore, in the VSF scheme, if spreading factor is large (more than 32), the data rate will be decreased. If spreading factor is small, where the signal's delay spread will be much longer than one symbol duration, this will result in inter symbol interference between symbols and cause distortion in signals.

Due to these shortcomings of the VSF scheme, we adopt the multi-code scheme as a solution to the multi-rate transmission. In the multi-code scheme, the spreading is fixed and the spreading factor is set to a fixed number, and additional parallel codes are allocated as the data rate increases [2], [25], [30], [32]. With all the transmissions modulating the same carrier, occupying the same bandwidth, and having the same spreading factor, multi-code provides easy integration of data streams into a common unified architecture. Here data streams can have the same or variable rates.

When applying multi-codes transmission with fixed spreading, several spreading codes of constant length (Spreading factor is 32) will be used within each frame. The spreading factor is set to 32 because this code length is fitted to increase the data rate and counter the ISI successfully. Similar to the proposal of HSDPA, we set the maximum number of codes to 20 in order to compare throughput of 20 codes in our calculation with that of the proposal. These 20 codes can be allocated to a single user for uplink or either single user or different users for downlink. In the proposal, the maximum throughput of 20 codes can be 10~11 Mbps.

5.7 C/I Requirement of Seven AMCS

To obtain the capacity of a channel, we first need to specify its error characteristic. **Figure 5.2-1** (FER versus C/I) shows that different AMCS schemes need different values of C/I to meet the FER (Frame Error Rate) requirements of the channel. In order to achieve the same FER, higher AMCS need larger C/I values than lower AMCS do. In our calculation, the channel requires 10^{-3} as minimum FER, and it can be observed from the **Figure 5.2-1** that seven C/I values of different AMCS satisfy this requirement. These seven C/I values (shown in **Table 5.7-1**) will serve as the target values for assigning the numbers of codes in different AMCS schemes.

AMCS	Code rate	Modulation	size	FER=0.001
MCS 7	$\frac{3}{4}$	64 QAM	m = 6	Snr1 = 2.7dB
MCS 6	$\frac{3}{4}$	16 QAM	m = 4	Snr2 = -3dB
MCS 5	$\frac{1}{2}$	16 QAM	m = 4	Snr3 = -6.5dB
MCS 4	$\frac{3}{4}$	8 PSK	m = 3	Snr4 = -4.5dB
MCS 3	$\frac{3}{4}$	4 PSK	m = 2	Snr5 = -8.5dB
MCS 2	$\frac{1}{2}$	4 PSK	m = 2	Snr6 = -12dB
MCS 1	$\frac{1}{4}$	4 PSK	m = 2	Snr7 = -15dB

Table 5.7-1 C/I target value for AMCS of one code

5.8 Power Allocation and Maximum Throughput

As explained previously, each AMCS requires a minimum C/I value {snr1, snr2, snr3, snr4, snr5, snr6, snr7} (**Table 5.7-1**). Based on these minimum C/I values, we consider using a power allocation scheme to obtain the maximum throughput of all codes in the

multi-rate transmission. There are two methods to implement power allocation: one solution is without optimal power allocation. Estimated C/I is equally assigned to the available number of codes (Maximum 20). The other method is with optimal power allocation scheme. Whether or not this method will be a solution is yet unknown. However, an effort is made to assign the estimated C/I optimally to the available number of AMCS (or codes) to get maximum throughput.

To study the behavior of maximum throughput with these two methods, we must determine: (1) with an estimated C/I, how many codes can this C/I support for the same or different AMCS? and (2) what is the highest data rate? These issues will be detailed in the following sections.

5.8.1 Maximum Throughput without Optimal Power

Allocation

The simplest way to use multi-code is to allocate the same power to all codes. In the multi-code transmission, a high-rate data stream is encoded and modulated as a single stream, which is then split into several low-rate streams. The multiple data streams are spread by different codes with the same chip rate. All spread streams are then simply added together (**Figure 5.8-1**) [25]. In this figure, R_b is the information bit for each AMCS, R_s is the Symbol rate for each AMCS, n_i is the numbers of codes in the i^{th} AMCS, R_{bit} is the total bit rate of the i^{th} AMCS, R_{symbol} is the total symbol rate of the i^{th} AMCS.

Figure 5.8-1 Multi-code transmission without optimal power allocation

Since the power is equally assigned to each channel, the number of channels the estimated C/I could support with one AMCS scheme is the quotient of estimated C/I divided by the target SNR (minimum requirement for AMCS shown in **Table 5.7-1**) of that AMCS scheme (**Equation 5.8-1**). The total throughput for an AMCS scheme is the product of the throughput of that AMCS in one channel (code) times the number of channels using that AMCS scheme (**Equation 5.8-2**). For every estimated C/I value, the maximum throughput is chosen from the highest total throughput of all seven AMCS (**Equation 5.8-3**).

Equation of the number of codes for an AMCS is:

$$n_{MCSI} = \left\lceil \frac{\text{estimated } C/I}{SNR_i} \right\rceil \quad \text{Equation 5.8-1}$$

Where:

i stands for the number of AMCS scheme, 1, 2, 3...7.

n_{MCSi} is the number of codes (channels) of the i^{th} AMCS scheme. Maximum value of n_{MCSi} is 20.

Estimated C/I comes from the simulation result of C/I distribution.

SNR_i is the target C/I, minimum C/I requirement for the i^{th} AMCS. (**Table 5.7-1**)

[] means the integer part of the quotient.

Equation for total throughput of an AMCS is:

$$\begin{aligned} Thr_i &= n_{MCSi} \times \text{throughput of one code of MCS } i \\ &= n_{MCSi} \times R_b \times (1 - FER) \\ &= n_{MCSi} \times \frac{\text{chip_rate} \times \text{modulation size} \times \text{code rate} \times (1 - FER)}{\text{spreading factor}} \end{aligned}$$

Equation 5.8-2

Where:

Thr_i is the total throughput of the i^{th} AMCS scheme.

Throughput of one code of i^{th} AMCS is given in **Equation 5.3-2**.

n_{MCSi} is the number of codes (channels) of the i^{th} AMCS scheme from **Equation 5.8-1**.

FER is the residual Frame Error Rate, which is obtained from **Figure 5.2-1**.

R_b is the transmitted information bit rate from **Equation 4.6-4**.

Chip_rate is fixed to 3.84 Mchips.

Spreading factor is 32.

Modulation size and code rate are corresponding values of the i^{th} AMCS listed in **Table 5.7-1**.

Equation for maximum throughput is:

$$Maxthr = maximum(Thr_1, Thr_2, \dots, Thr_i, Thr_7) \quad \text{Equation 5.8-3}$$

Where:

Maxthr is the maximum throughput of seven AMCS.

Thr_i is the total throughput of the i^{th} AMCS scheme from **Equation 5.8-2**.

5.8.2 Throughput Calculation Without Optimal Power Allocation

In a cell of a 19 cell, 3 sector system, based on the simulation result of C/I distribution and the channel performance in [2], the maximum throughput of multi-codes for seven AMCS without optimal power allocation is calculated. The procedure is as follows:

- 1) A target FER is established at 10^{-3} , where FER—residual frame error rate is from the **Figure 5.2-1**. The corresponding SNR table is setup for each AMCS. (SNR values listed in **Table 5.7-1**). SNR_i provides the minimum C/I requirement for the i^{th} AMCS.

- 2) Take a channel measurement sample and estimate the current C/I , which is the total C/I value for the data transmission. C/I samples are from the C/I distribution simulation results.
- 3) Decide the number of channels for each AMCS that the estimated C/I can support. (**Equation 5.8-1**).
- 4) Calculate throughput for each AMCS according to **Equation 5.8-2** with the available number of channels for each AMCS scheme.
- 5) From calculation results of throughputs for seven AMCS, select the maximum throughput.
- 6) For all estimated C/I values, repeat steps 2) to 5). Throughput hull will consist of the maximum throughputs of all estimated C/I .

The flowchart of the maximum throughput for an estimated C/I without power optimal allocation is shown in **Figure 5.8-2**. The maximum throughput calculation result is shown in **Figure 5.8-3**.

Figure 5.8-2 Flowchart of Maximum throughput without power optimal allocation

Figure 5.8-3 Throughput hull without optimal power allocation scheme

Since there are only seven AMCS schemes, the throughput hull obtained from the calculation shown in **Figure 5.8-3** resembles the stair function. If there are many AMCS schemes, the throughput hull will not be a stair function, but a continuous curve.

To achieve maximum throughput in multi-codes without power optimal allocation is simple and easy to implement if throughput performance is not very sensitive to the small change in power. If throughput is sensitive to the small variation of power, however, the throughput of equal power allocation scheme is not optimized.

In **Figure 5.8-3**, since C/I value allocated in each code is the same; the data rate in every code (channel) is the same. The fact that C/I value is equally assigned to the codes

implies the C/I value would be wasted if the C/I value were more than the total sum of allocated C/I values to AMCS.

Normally real throughput is equal to or less than maximum throughput. Throughput is near system capacity if the estimated C/I is close to the real C/I value, whereas throughput is less than the maximum when the estimated C/I is larger than the real C/I value. Throughput is also less if the equal power allocation scheme cannot totally utilize the actual C/I value. Both of these two situations will result in throughput loss. There is an issue with respect to how many bit rates are lost in maximum with the equal power allocation scheme, which is why the optimal power allocation is used to obtain the maximum throughput: to avoid the big throughput loss caused by power equal allocation.

5.8.3 Maximum Throughput with Optimal Power

Allocation

A complex way to use multi-code is to allocate different powers to codes. In the multi-code transmission, a high-rate data stream is encoded and modulated as a single stream, and then is split into several low-rate streams to feed into each code. These low rate streams may have the same or various data rate, depending on the AMCS scheme. The channels (codes) using the same AMCS have the same data rate; where those using different AMCS have different data rates. Thus, allocating power to AMCS schemes is the same as allocating power to the codes. The multiple data streams are spread by

different codes with the same chip rate. Then all spread streams are added for transmission. The processing is described in **Figure 5.8-4**. In this figure, $Rs_{of\ mcs\ j}$ is the symbol rate of the j^{th} AMCS, $R_{b\ of\ mcs\ i}$ is bit rate of the i^{th} AMCS, R_{smbol} is the total symbol rate of different AMCS, R_{bit} is the total bit rate of different AMCS.

Figure 5.8-4 Multi-code transmission with power optimal allocation

Since estimated C/I is unequally assigned to each channel, the number of channels using one of the AMCS schemes is the quotient of C/I allocated to this AMCS divided by the target SNR (minimum requirement for AMCS shown in **Table 5.7-1**) of the AMCS scheme (**Equation 5.8-4**). Estimated C/I is equal to or bigger than the sum of the C/I allocated to each AMCS. C/I allocated to each AMCS is equal to the number of channels

for each AMCS times SNR (SNR from **Table 5.7-1**) for each AMCS (**Equation 5.8-5**). The total throughput for an AMCS scheme is the product of the throughput of that AMCS in one channel (code) times the number of channels of the AMCS scheme (**Equation 5.8-6**). The total number of channels (Maximum 20) that an estimated C/I could support is the sum of the numbers of channels using each AMCS scheme (**Equation 5.8-7**). Total throughput that an estimated C/I could support is the sum of the total throughput of each AMCS (**Equation 5.8-8**). The maximum throughput is the highest throughput of all these total throughputs that an estimated C/I could support (**Equation 5.8-9**).

Since the maximum throughput is attained in this method by dynamically assigning the estimated C/I to different AMCS to achieve the highest data rate, when allocating estimated C/I to different AMCS, it is unknown how many C/I will be assigned to an AMCS scheme and how many channels will use an AMCS scheme before maximum throughput is calculated. Therefore, every possible C/I assigning combination (the sum of C/I allocations is equal to or less than estimated C/I) of codes for all AMCS is tested, and the combination providing the maximum throughput is selected.

Equation of the number of codes for an AMCS is:

$$n_{MCSi} = \left\lceil \frac{C/I \text{ allocated to MCS}_i}{SNR_i} \right\rceil \quad \text{Equation 5.8-4}$$

Where:

i stands for the number of AMCS scheme, 1, 2, 3...7.

n_{MCSi} is the number of codes (channels) of the i^{th} AMCS scheme. Maximum value of n_{MCSi} is 20.

C/I allocated to MCSi is unknown, which comes from the calculation result in program.

SNR_i is the target C/I-minimum C/I requirement for the i^{th} AMCS. (Table 5.7-1)

[] means get integer from the quotient.

Equation for C/I allocating to each AMCS is:

$$estimated\ C/I \geq \sum_{i=1}^7 n_{MCSi} \times SNR_i \quad \text{Equation 5.8-5}$$

Where:

i stands for the number of AMCS scheme, 1, 2, 3...7.

n_{MCSi} is the number of codes (channels) of the i^{th} AMCS scheme. Maximum value of n_{MCSi} is 20.

Estimated C/I comes from the simulation result of C/I distribution.

SNR_i is the target C/I, minimum C/I requirement for the i^{th} AMCS. (Table 5.7-1)

Equation for total throughput of an AMCS is:

$$\begin{aligned}
Thr_i &= n_{MCSi} \times \text{throughput of one code of MCS } i \\
&= n_{MCSi} \times R_b \times (1 - FER) \\
&= n_{MCSi} \times \frac{\text{chip_rate} \times \text{modulation size} \times \text{code rate} \times (1 - FER)}{\text{spreading factor}}
\end{aligned}$$

Equation 5.8-6

Where:

Thr_i is the total throughput of the i^{th} AMCS scheme.

Throughput of one code of the i^{th} AMCS is given in **Equation 5.3-2**.

n_{MCSi} is the number of codes (channels) of the i^{th} AMCS scheme from **Equation 5.8-4**.

FER is the residual Frame Error Rate, which is obtained from **Figure 5.2-1**.

R_b is the transmitted information bit rate from **Equation 4.6-4**.

Chip_rate is fixed to 3.84 Mchips.

Spreading factor is 32.

Modulation size and code rate are corresponding values of the i^{th} AMCS listed in **Table 5.7-1**.

Equation of total number of channels is:

$$N = \sum_{i=1}^7 n_{MCSi}$$

Equation 5.8-7

Where:

N is the total number of all the channels, N is less than or equal to 20.

n_{MCSi} is the number of codes (channels) of the i^{th} AMCS scheme from **Equation 5.8-4**.

Equation of total throughput that estimated C/I could support is:

$$total\ thr_k = \sum_{i=1}^{i \leq 7} Thr_i \quad \text{Equation 5.8-8}$$

Where:

$total\ thr_k$ is the total throughput that estimated C/I could support. k varies from 1 to the maximum number of possible C/I combination.

Thr_i is the total throughput of the i^{th} AMCS scheme, which comes from **Equation 5.8-6**.

Equation for maximum throughput is:

$$Maxthr = maximum(total\ thr_1, total\ thr_2, \dots, total\ thr_k) \quad \text{Equation 5.8-9}$$

Where:

Maxthr is the maximum throughput of seven AMCS.

$total\ thr_k$ is the total throughput that estimated C/I could support (from **Equation 5.8-8**). k varies from 1 to the maximum number of possible C/I combination.

To achieve maximum throughput with the power allocation scheme, the **optimal method** is key. The idea behind the optimal problem is to find the highest point on an objective function [33]. Normally for the optimization problems, there is more than one

solution available. The optimization process of requiring maximum throughput is to choose the best solution from all the available C/I allocation combinations.

In this research, constrained optimization is applied to obtain the solution of the optimal power allocation. Various constraints must be satisfied besides finding the maximum throughput. Otherwise, the answer obtained without these conditions will not be useful.

With this calculation, the goal is to find how many codes of each AMCS and how much power should be assigned to each AMCS. The objective function is the maximum of total throughput of all the channels. To achieve this goal, there are two constraints to be considered. First, the total number of codes is less than or equal to 20. Second, the sum of the C/I assigned to each code equals to or less than the estimated C/I.

5.8.4 Throughput Calculation with Optimal Power Allocation

In a cell out of a 19 cell, 3-sector system, based on the simulation result of C/I distribution and the channel performance done in [2], maximum throughput of multi-codes is calculated for seven AMCS with optimal power allocation. The procedure is as follows:

- 1) Establish a target FER of 10^{-3} , where FER—residual frame error rate is from the **Figure 5.2-1**. Set up the corresponding SNR table for each AMCS. (SNR values listed in **Table 5.7-1**). SNR_i provides the minimum C/I requirement for the

i^{th} AMCS. Then calculate throughput of one code for seven AMCS according to **Equation 5.3-2** and make a table of calculated result (thr1, thr2 ..., thr7).

- 2) Take a channel measurement sample and estimate the current C/I, which is the total C/I value for the data transmission. C/I samples are from the C/I distribution simulation results.
- 3) Set different numbers of channels for each AMCS ($n_1, n_2, \dots, n_7$), $n_1, n_2, \dots, n_7$ are all range from 1 to 20, but sum of $n_1, n_2, \dots, n_7$ is equal to or less than 20 (**Equation 5.8-7**). For every combination of $n_1, n_2, \dots, n_7$, we will calculate the total throughput of channels with seven AMCS.
- 4) Set two conditions: A) The sum of C/I allocated to each AMCS is equal to or less than estimated C/I. C/I allocated to each AMCS equal to number of channels for each AMCS times SNR for each AMCS. (**Equation 5.8-5**). B) Total number of codes is less than or equal to 20.
- 5) Calculate throughput for each AMCS according to **Equation 5.8-6** with the available number of channels for each AMCS scheme.
- 6) Calculate total throughputs of channels with seven AMCS according to **Equation 5.8-8**.
- 7) From calculation results of total throughputs of seven AMCS, select the maximum throughput (**Equation 5.8-9**).
- 8) For all estimated C/I values, repeat steps from 2) to 7). Throughput hull will consist of the maximum throughputs of all estimated C/I.

Figure 5.8-5 dictates that the throughput with optimal power allocation is a smooth curve, which increases with increasing C/I values. Since the C/I values assigned to different AMCS are different, the data rates of AMCS are general different. The fact that the power is not equally allocated to AMCS indicates the power is completely utilized. Power is not wasted; therefore throughput is maximized at all times. In a word, the fact that the power is not equally allocated to AMCS helps to avoid the problem of big throughput loss of the equal power allocation scheme.

Figure 5.8-5. Throughput hull with optimal power allocation scheme

Figure 5.8-6 Throughput comparing -with and without optimal power allocation

With or without optimal power allocation, the maximum data rate of twenty codes can reach 10.7Mbps (**Figure 5.8-6**) when C/I is equal to or is larger than 15dB. This is almost twenty times the maximum throughput of one code. However, the cost is that larger C/I is needed to support multi-codes transmission. When comparing throughput hull of the optimal power allocation scheme with that of the equal power allocation scheme, it can be seen that there is not much difference between two curves, if the C/I is small. If the C/I is large, then optimal power allocation can further improve throughput. This also means that the power allocation scheme is more effective in higher order AMCS such as MCS4~MCS7.

The numerical results of **Figure 5.8-6** illustrate that there is no throughput loss caused by equal power allocating when the power is small, while the throughput loss is large when the power is large. Calculations show that there is little difference between two curves when the C/I is below 1dB. There is more or less throughput loss from 1 dB to 10dB without optimal power allocation. The throughputs are quite different when the C/I varies between 10 dB and 14 dB. For instance, at 14dB, throughput without optimal method is 7.2Mbps whereas throughput with optimal method is 8.4Mbps.

The difference of 1.2Mbps with the two methods indicates that the method with optimal power allocation is better and more flexible than the method without. However, optimal power allocation results in a more complicated method. The calculation time of throughput with optimal power allocation is much longer, and the throughput calculation with optimal power allocation is much more difficult to implement.

5.8.5 Throughput of Different FER

From the last section, it is known that with the multi-code transmission, assigning different numbers of codes to each user can obtain different data rates, while assigning the same numbers of codes but using different AMCS can result in different rates as well. However, the amount of power that may enable reliable transmitting different speed information depends on FER in the channel.

Figure 5.8-7 Throughput hull of different FER with optimal power allocation

Figure 5.8-7 shows maximum throughput with optimal power allocation under different channel condition (FER is 10^{-1} , 10^{-2} , 10^{-3} , 10^{-4} , 10^{-5}). From this figure, it can be seen that FER values affect the throughput, though minimally, because different channel conditions need different C/I to make reliable data transmissions. These throughput hulls exhibit minor differences. In the **Equation 5.8-6**, the retransmission factor N is ignored, since this equation is used under the condition that FER is not very high. Thus there is no need for package retransmission. When FER is small, it cannot affect the throughput very much (**Equation 5.8-6**), which is why throughputs of different FER are very close.

Figure 5.8-7 shows that when FER is 10^{-1} , a higher data rate can be achieved using the same C/I compared to the other throughputs with a better FER. This means that if it is

possible for safe data transmission, data could be transmitted in channels with a slightly poor FER to save power. However, the problem is that when the C/I value is larger, channels with poor FER can not support higher speeds of data due to poor channel conditions.

FER of 10^{-4} and 10^{-5} indicate very good channel performances, although channels with these performance levels require more power to transmit the same data rate as poorer condition channels. Since the FER requirement is higher in the channel, the demand of C/I values should be higher than that of lower FER requirements. If FER of 10^{-2} or 10^{-3} has already satisfied the transmission requirements, there is no need to pursue higher channel performance since higher channel performance will consume more power.

The throughputs of FER 10^{-2} and 10^{-3} are very similar as they are almost overlap together in the figure. When FER is 10^{-2} or 10^{-3} , the channel condition is good enough to transmit high-speed data and it will not waste power as much as FER of 10^{-4} and 10^{-5} . Therefore, throughput results of these two conditions can be used as the maximum data rate in scheduling. In this research, the throughput of 10^{-3} is chosen as the maximum throughput in the time domain scheduling.

	MCS1	MCS2	MCS3	MCS4	MCS5	MCS6	MCS7
CODE	C/I dB	C/I dB	C/I dB	C/I dB	C/I dB	C/I dB	C/I dB
1	-15.0000	-12.0000	-8.5000	-4.5000	-6.5000	-3.0000	2.7000
2	-11.9897	-8.9897	-5.4897	-1.4897	-3.4897	0.0103	5.7103
3	-10.2288	-7.2288	-3.7288	0.2712	-1.7288	1.7712	7.4712
4	-8.9794	-5.9794	-2.4794	1.5206	-0.4794	3.0206	8.7206
5	-8.0103	-5.0103	-1.5103	2.4897	0.4897	3.9897	9.6897
6	-7.2185	-4.2185	-0.7185	3.2815	1.2815	4.7815	10.4815
7	-6.5490	-3.5490	-0.0490	3.9510	1.9510	5.4510	11.1510
8	-5.9691	-2.9691	0.5309	4.5309	2.5309	6.0309	11.7309
9	-5.4576	-2.4576	1.0424	5.0424	3.0424	6.5424	12.2424
10	-5.0000	-2.0000	1.5000	5.5000	3.5000	7.0000	12.7000
11	-4.5861	-1.5861	1.9139	5.9139	3.9139	7.4139	13.1139
12	-4.2082	-1.2082	2.2918	6.2918	4.2918	7.7918	13.4918
13	-3.8606	-0.8606	2.6394	6.6394	4.6394	8.1394	13.8394
14	-3.5387	-0.5387	2.9613	6.9613	4.9613	8.4613	14.1613
15	-3.2391	-0.2391	3.2609	7.2609	5.2609	8.7609	14.4609
16	-2.9588	0.0412	3.5412	7.5412	5.5412	9.0412	14.7412
17	-2.6955	0.3045	3.8045	7.8045	5.8045	9.3045	15.0045
18	-2.4473	0.5527	4.0527	8.0527	6.0527	9.5527	15.2527
19	-2.2125	0.7875	4.2875	8.2875	6.2875	9.7875	15.4875
20	-1.9897	1.0103	4.5103	8.5103	6.5103	10.0103	15.7103

Table 5.8-1 C/I requirements for 1~20 codes for each AMCS when FER= 10^{-3}

	MCS1	MCS2	MCS3	MCS4	MCS5	MCS6	MCS7	THROUGHPUT
C/I dB	N	N	N	N	N	N	N	bps
-16	0	0	0	0	0	0	0	0
-15	1	0	0	0	0	0	0	59940
-14	1	0	0	0	0	0	0	59940
-13	1	0	0	0	0	0	0	59940
-12	0	1	0	0	0	0	0	118800
-11	2	0	0	0	0	0	0	119880
-10	3	0	0	0	0	0	0	179820
-9	3	0	0	0	0	0	0	179820
-8	5	0	0	0	0	0	0	299700
-7	6	0	0	0	0	0	0	359640
-6	7	0	0	0	0	0	0	419580
-5	10	0	0	0	0	0	0	599400
-4	12	0	0	0	0	0	0	719280
-3	15	0	0	0	0	0	0	899100
-2	0	10	0	0	0	0	0	1188000
-1	15	5	0	0	0	0	0	1493100
0	9	11	0	0	0	0	0	1846260
1	1	19	0	0	0	0	0	2317140
2	0	16	4	0	0	0	0	2620080
3	0	11	9	0	0	0	0	2925180
4	1	3	16	0	0	0	0	3293460
5	0	0	16	0	4	0	0	3836160
6	0	0	7	0	13	0	0	4375620
7	0	0	1	0	17	2	0	4975020
8	0	0	0	1	13	6	0	5542020
9	0	0	0	1	7	12	0	6261300
10	0	0	0	1	0	19	0	7100460
11	0	0	0	0	1	17	2	7432560
12	0	0	0	0	0	16	4	7912080
13	0	0	0	0	0	13	7	8451540
14	0	0	0	0	0	9	11	9170820
15	0	0	0	0	1	3	16	9950040
16	0	0	0	0	0	0	20	10789200
17	0	0	0	0	0	0	20	10789200

Table 5.8-2 C/I allocation and throughput for FER= 10^{-3} .

N is the number of codes assigned to each AMCS

5.9 Analysis of C/I Allocation and Throughput

Hull of 20 codes

5.9.1 Mathematical Characteristic of Throughput Hull

Data rates grow with the increasing C/I value. This mathematical characteristic guarantees that the throughput hull must be a monotonically increasing curve. A data rate that is a monotonically increasing function of the C/I means that, for maximizing throughput, the C/I should be portioned to neighboring AMCS in order. Calculations prove that the C/I value is divided among 3 or 4 neighbors of AMCS to produce the highest data rate, as shown in **Table 5.8-2**.

The detail of C/I allocation to codes is showed in the appendix, which displays code assigning and throughput variation when C/I changes every 0.1 dB.

5.9.2 Estimated error in C/I

The effect of channel estimation error is very important to the performance of the optimal power allocation scheme. **Figure 5.9-1** shows the throughput loss versus C/I of 20 codes in the static channel. Ideally, the channel measurement error is 0dB. In the non-ideal case, the estimated error is 1dB. Compared to the ideal case, the throughput loss is largely due to the measurement error. When C/I becomes greater, the absolute throughput loss will increase while the relative throughput loss will decrease.

The throughput error caused by the C/I estimated error is calculated as [34]:

$$\text{Error-} = \text{Throughput of } C/I - \text{Throughput of } (C/I - e \text{ dB}) \quad \text{Equation 5.9-1}$$

$$\text{Error+} = \text{Throughput of } (C/I + e \text{ dB}) - \text{Throughput of } C/I \quad \text{Equation 5.9-2}$$

Where:

e dB is the estimated error in C/I .

Error- is the throughput error, which occurs when C/I estimated error is $-e$ dB.

Error+ is the throughput error, which occurs when C/I estimated error is $+e$ dB.

From **equation 5.9-1** and **equation 5.9-2** we get the maximum error in throughput, which is the maximum value from Error- and Error+.

$$\text{maxerror} = \max\{ |Error -|, |Error +| \} \quad \text{Equation 5.9-3}$$

Table 5.9-1 shows maximum error of throughput with the C/I estimated error within ± 1 dB when FER is 0.001. When C/I becomes larger, the maximum throughput loss will increase.

$$\text{Average maxerror} = \frac{\text{sum of maxerror}}{\text{number of error}} \quad \text{Equation 5.9-4}$$

$$\text{Average throughput} = \frac{\text{sum of throughput}}{\text{observed throughput number}} \quad \text{Equation 5.9-5}$$

$$\text{Relative maxerror} = \frac{\text{Average maxerror}}{\text{Average throughput}} \quad \text{Equation 5.9-6}$$

Average maxerror is defined as the sum of all the maximum error divided by the number of the error (**equation 5.9-4**). Average throughput is the ratio of the sum of throughput and observed throughput number (**equation 5.9-5**). The relative maxerror is obtained from the ratio of the average maxerror and average throughput (**equation 5.9-6**).

In **Figure 5.9-1**, if C/I estimated error is 1dB in the channel, the maximum loss of throughput will be 0.83916 Mbps, the average maximum loss of throughput is 0.38114 Mbps, and the relative average loss of throughput is 10.82%.

Figure 5.9-1 Throughput loss of C/I 1 dB estimated error

Figure 5.9-1 shows that when the estimated C/I value is lower than the actual C/I value, the actual C/I can result in larger throughput than the estimated C/I. However, the cost is

the loss in performance, since large C/I selecting higher order AMCS leads to poor FER.

When the estimated C/I value is higher than the actual C/I value, actual C/I cannot support higher order AMCS and throughput loss will be resulted.

	MCS1	MCS2	MCS3	MCS4	MCS5	MCS6	MCS7	throughput	maxerror
C/I dB	N	N	N	N	N	N	N	bps	bps
-16	0	0	0	0	0	0	0	0	
-15	1	0	0	0	0	0	0	59940	59940
-14	1	0	0	0	0	0	0	59940	0
-13	1	0	0	0	0	0	0	59940	58860
-12	0	1	0	0	0	0	0	118800	58860
-11	2	0	0	0	0	0	0	119880	59940
-10	3	0	0	0	0	0	0	179820	59940
-9	3	0	0	0	0	0	0	179820	119880
-8	5	0	0	0	0	0	0	299700	119880
-7	6	0	0	0	0	0	0	359640	59940
-6	7	0	0	0	0	0	0	419580	179820
-5	10	0	0	0	0	0	0	599400	179820
-4	12	0	0	0	0	0	0	719280	179820
-3	15	0	0	0	0	0	0	899100	288900
-2	0	10	0	0	0	0	0	1188000	305100
-1	15	5	0	0	0	0	0	1493100	353160
0	9	11	0	0	0	0	0	1846260	470880
1	1	19	0	0	0	0	0	2317140	470880
2	0	16	4	0	0	0	0	2620080	305100
3	0	11	9	0	0	0	0	2925180	368280
4	1	3	16	0	0	0	0	3293460	542700
5	0	0	16	0	4	0	0	3836160	542700
6	0	0	7	0	13	0	0	4375620	599400
7	0	0	1	0	17	2	0	4975020	599400
8	0	0	0	1	13	6	0	5542020	719280
9	0	0	0	1	7	12	0	6261300	839160
10	0	0	0	1	0	19	0	7100460	839160
11	0	0	0	0	1	17	2	7432560	479520
12	0	0	0	0	0	16	4	7912080	539460
13	0	0	0	0	0	13	7	8451540	719280
14	0	0	0	0	0	9	11	9170820	779220
15	0	0	0	0	1	3	16	9950040	839160
16	0	0	0	0	0	0	20	10789200	839160
17	0	0	0	0	0	0	20	10789200	0

Table 5.9-1 Maximum error of throughput with C/I estimated error within ± 1 dB when FER= 10^{-3}

N-numbers of channels in each AMCS

5.9.3 The Sensitivity Degree of Throughput Hull with Estimated Error in C/I

The simulation results show the channel measurement accuracy has a large impact on the throughput hull. The degree of sensitivity is used to evaluate the effect of the channel measured accuracy have on the magnitude of the throughput loss. The degree of sensitivity of the throughput is given in **equation 5.9-7**.

$$\text{degree of sensitivity} = \frac{\text{maxerror of throuhput of a C/I}}{\text{throughput of the C/I}} \quad \text{Equation 5.9-7}$$

Where:

Maxerror of throughput of a C/I comes from **equation 5.9-3**.

Figure 5.9-2 gives the result of the degree of sensitivity of maximum throughput loss in the calculation. When C/I value is small (lower than -12dB), the throughput is very sensitive to the channel estimation; the degree of sensitivity is almost 1 in some C/I values. When C/I values become larger, the degree of sensitivity decreases. The degree of sensitivity changes from 0.7 to 0 while the C/I changes from -11dB to 16dB. Most of the time the degree of sensitivity varies between 0.1 and 0.4. At 16dB, degree of sensitivity becomes 0. This means that for C/I values which are greater than or equal to 16dB the throughput will remain constant at 10.7 Mbps.

Figure 5.9-2 Degree of sensitivity of maximum throughput loss

5.10 Polynomial Approximation

Polynomials can be used for interpolation and extrapolation because they are simple functions that have a number of useful properties [35]. With respect to curve fitting, the most important property of polynomials is summarized in the Weierstrass approximation theorem, which dictates that if $y(x)$ is any continuous function defined over a finite interval $[a, b]$, then for each $\varepsilon > 0$, there exists a polynomial $f(x)$ such that [35]:

$$|f(x) - y(x)| < \varepsilon, \quad a \leq x \leq b$$

Equation 5.10-1

ε can be chosen arbitrarily small, this means that polynomials can be used to approximate continuous functions to an arbitrary degree of accuracy over any finite interval.

A polynomial of degree n is expressed as [35]:

$$f(x) = \sum_{k=1}^{n+1} a_k x^{k-1} \quad \text{Equation 5.10-2}$$

Table 5.10-1 shows that throughput of simulation can use five different polynomials to approximate. From -16 dB to -10 dB, the throughput increases slowly. A 6-degree polynomial can be used to approach the curve. The coefficients are seen in the table. 5, 6, 9, 6 are degrees of polynomials, which correspond to the different period of C/I [7dB, 12dB], [12 dB, 18 dB], [18 dB, 27 dB], [27 dB, 33 dB] respectively. These five polynomials are very close to the simulation results. In the observed points, the difference between the data rate of simulation results and polynomial results is zero. **Figure 5.10-1** shows that the approximated points and throughput are matched very well, indicating that in the time domain scheduling simulation, these five polynomials can be used to generate the maximum data rate if C/I value is given.

Figure 5.10-1 Polynomial approach throughput hull

	C/I dB x	data rate	polynomial	difference	coefficients	degree
	x	y	f	y-f	p	n
1	-16	0	0	0	810	
2	-15	59940	59940	0	64157	
3	-14	59940	59940	0	2105460	
4	-13	59940	59940	0	36641138	6
5	-12	118800	118800	0	356610060	
6	-11	119880	119880	0	1840240500	
7	-10	179820	179820	0	3933766100	
7	-10	179820	179820	0	-1499	
8	-9	179820	179820	0	-49950	
9	-8	299700	299700	0	-641858	5
10	-7	359640	359640	0	-3936060	
11	-6	419580	419580	0	-11254734	
12	-5	599400	599400	0	-10969020	
12	-5	599400	599400	0	-491	
13	-4	719280	719280	0	-5146	
14	-3	899100	899100	0	-14329	
15	-2	1188000	1188000	0	3769	6
16	-1	1493100	1493100	0	73680	
17	0	1846260	1846260	0	413397	
18	1	2317140	2317140	0	1846260	
18	1	2317140	2317140	0	-19	
19	2	2620080	2620080	0	964	
20	3	2925180	2925180	0	-20453	
21	4	3293460	3293460	0	243118	
22	5	3836160	3836160	0	-1773309	9
23	6	4375620	4375620	0	8170433	
24	7	4975020	4975020	0	-23553183	
25	8	5542020	5542020	0	40503005	
26	9	6261300	6261300	0	-36872375	
27	10	7100460	7100460	0	15618960	
27	10	7100460	7100460	0	1121	
28	11	7432560	7432560	0	-87764	
29	12	7912080	7912080	0	2848568	
30	13	8451540	8451540	0	-49038142	6
31	14	9170820	9170820	0	472269580	
32	15	9950040	9950040	0	-2412390400	
33	16	10789200	10789200	0	5112363600	

Table 5.10-1 Polynomial coefficients, degree and approach throughput value

Chapter 6

Conclusions and Recommendations

6.1 Conclusion

This thesis began with an introduction to the background and relative research in packet access of 3GPP. In the ensuing chapter the relative theory and models used in our research were described, the simulations and analysis of the results were arranged at the end of chapter 3 and chapter 5.

Through simulation, the C/I distribution is attained. The simulation results of FER vs. C/I in [2] are used to obtain the minimum requirement of C/I for each AMCS for a given FER. Based on the simulation results of C/I samples and FER relation with C/I, the throughput of one code and throughput of multi-codes were obtained. By comparing the throughput hull with and without the optimal power allocation, the advantage of optimal power allocation is seen. From the simulation result, the characteristic of throughput was analyzed and throughput loss due to the C/I estimated error was evaluated. Last, the throughput was approximated by the polynomials to serve as the maximum data rate for time domain scheduling.

Simulation results of C/I distribution indicate that C/I decrease with the increasing of distance, while varying significantly in the fixed sample point and attenuates faster if more interferences are included. These results match the path loss model, lognormal

shadowing model, and interference model respectively. Since channel performance (FER) of different AMCS depends on the C/I estimated value, the large variation of C/I in a sample point implies that several AMCS could be used in channels in a fixed position. This can result in different data rates. In a 19 cell system, when chip rate and spreading factor are fixed, based on the simulation results of C/I distribution and the channel performance (FER vs. C/I of different AMCS), the throughput hull of one code looks like a stair function when only seven AMCS are available in throughput calculation. The maximum throughput of one code is only 0.54 Mbps, which is not enough for high-speed transmission. Multi code is one of solutions to realize multi-rate data transmission. With or without an optimal power allocation scheme, the maximum data rate of twenty codes can reach 10.7Mbps when C/I is equal to or larger than 15dB. This is almost twenty times of maximum throughput of one code. However, the cost is a larger C/I is necessary to support the multi-code transmission. When comparing the throughput hull of the optimal power allocation scheme with that of equal power allocation scheme, there is little difference between two curves if the C/I is small. If the C/I is large, optimal power allocation scheme can further improve throughput. This implies that optimal power allocation is very useful in high order AMCS (MCS4~MCS7). With power optimal allocation scheme, throughput is a monotonically increasing function of C/I. Thus, in order to maximize the throughput, C/I is portioned to neighboring 3 to 4 AMCS in order. The results also show that when channel estimation error is 1dB, the average maximum throughput loss is 10.82%. The throughput is very sensitive to the channel estimation error when C/I less than -12dB. When C/I is big

enough, for example larger than 16dB, the throughput will reach the highest and the degree of sensitivity will decrease to 0. Five different degrees of polynomials can totally approximate the throughput curve of twenty codes. The difference between real throughput and polynomial at approximated values is zero.

6.2 Contribution

In this thesis, an optimal power allocation scheme was developed for WCDMA systems. The main objective of the proposed scheme is to provide a method for achieving a maximum throughput, while minimizing any waste of power and throughput loss. The simulation results provide insight for throughput improvements from the use of the optimal power allocation scheme. Since the throughput will increase with the augmenting of the C/I, the maximum throughput will be obtained by selecting the combination of the seven AMCS that affords the highest data rate. This optimal method protects against throughput loss caused by equal power allocation and is therefore superior to the equal power allocation scheme. However, implementation of this method is more complicated.

6.3 Recommendations for Future Research

Throughput study in our research does not capture and more study can be made in the following topics:

- Multi-rate transmission by changing the spread factor to achieve different data rates.

- The effect of improving Hybrid ARQ on throughput
- How fast cell selection (FCS) affects throughput at the edge of the cell
- Multiple input Multiple output (MIMO) technology
- How multi-path fading and mobility (Doppler fading) affect the throughput
- Channel correlations and cell correlation effects

Appendix: Channel Allocation in AMCS

	MCS1	MCS2	MCS3	MCS4	MCS5	MCS6	MCS7	Throughput
C/I dB	N	N	N	N	N	N	N	bps
-16	1	0	0	0	0	0	0	59940
-15	1	0	0	0	0	0	0	59940
-14	1	0	0	0	0	0	0	59940
-13	1	0	0	0	0	0	0	59940
-12.9	1	0	0	0	0	0	0	59940
-12.8	1	0	0	0	0	0	0	59940
-12.7	1	0	0	0	0	0	0	59940
-12.6	1	0	0	0	0	0	0	59940
-12.5	1	0	0	0	0	0	0	59940
-12.4	1	0	0	0	0	0	0	59940
-12.3	1	0	0	0	0	0	0	59940
-12.2	1	0	0	0	0	0	0	59940
-12.1	1	0	0	0	0	0	0	59940
-12	1	0	0	0	0	0	0	59940
-11.9	2	0	0	0	0	0	0	119880
-11.8	2	0	0	0	0	0	0	119880
-11.7	2	0	0	0	0	0	0	119880
-11.6	2	0	0	0	0	0	0	119880
-11.5	2	0	0	0	0	0	0	119880
-11.4	2	0	0	0	0	0	0	119880
-11.3	2	0	0	0	0	0	0	119880
-11.2	2	0	0	0	0	0	0	119880
-11.1	2	0	0	0	0	0	0	119880
-11	2	0	0	0	0	0	0	119880
-10.9	2	0	0	0	0	0	0	119880
-10.8	2	0	0	0	0	0	0	119880
-10.7	2	0	0	0	0	0	0	119880
-10.6	2	0	0	0	0	0	0	119880
-10.5	2	0	0	0	0	0	0	119880
-10.4	2	0	0	0	0	0	0	119880
-10.3	2	0	0	0	0	0	0	119880
-10.2	3	0	0	0	0	0	0	179820
-10.1	3	0	0	0	0	0	0	179820
-10	3	0	0	0	0	0	0	179820

-9.9	3	0	0	0	0	0	0	179820
-9.8	3	0	0	0	0	0	0	179820
-9.7	3	0	0	0	0	0	0	179820
-9.6	3	0	0	0	0	0	0	179820
-9.5	3	0	0	0	0	0	0	179820
-9.4	3	0	0	0	0	0	0	179820
-9.3	3	0	0	0	0	0	0	179820
-9.2	3	0	0	0	0	0	0	179820
-9.1	3	0	0	0	0	0	0	179820
-9	3	0	0	0	0	0	0	179820
-8.9	4	0	0	0	0	0	0	239760
-8.8	4	0	0	0	0	0	0	239760
-8.7	4	0	0	0	0	0	0	239760
-8.6	4	0	0	0	0	0	0	239760
-8.5	4	0	0	0	0	0	0	239760
-8.4	4	0	0	0	0	0	0	239760
-8.3	4	0	0	0	0	0	0	239760
-8.2	4	0	0	0	0	0	0	239760
-8.1	4	0	0	0	0	0	0	239760
-8	5	0	0	0	0	0	0	299700
-7.9	5	0	0	0	0	0	0	299700
-7.8	5	0	0	0	0	0	0	299700
-7.7	5	0	0	0	0	0	0	299700
-7.6	5	0	0	0	0	0	0	299700
-7.5	5	0	0	0	0	0	0	299700
-7.4	5	0	0	0	0	0	0	299700
-7.3	5	0	0	0	0	0	0	299700
-7.2	6	0	0	0	0	0	0	359640
-7.1	6	0	0	0	0	0	0	359640
-7	6	0	0	0	0	0	0	359640
-6.9	6	0	0	0	0	0	0	359640
-6.8	6	0	0	0	0	0	0	359640
-6.7	6	0	0	0	0	0	0	359640
-6.6	6	0	0	0	0	0	0	359640
-6.5	7	0	0	0	0	0	0	419580
-6.4	7	0	0	0	0	0	0	419580
-6.3	7	0	0	0	0	0	0	419580
-6.2	7	0	0	0	0	0	0	419580
-6.1	7	0	0	0	0	0	0	419580
-6	7	0	0	0	0	0	0	419580

-5.9	8	0	0	0	0	0	0	479520
-5.8	8	0	0	0	0	0	0	479520
-5.7	8	0	0	0	0	0	0	479520
-5.6	8	0	0	0	0	0	0	479520
-5.5	8	0	0	0	0	0	0	479520
-5.4	9	0	0	0	0	0	0	539460
-5.3	9	0	0	0	0	0	0	539460
-5.2	9	0	0	0	0	0	0	539460
-5.1	9	0	0	0	0	0	0	539460
-5	10	0	0	0	0	0	0	599400
-4.9	10	0	0	0	0	0	0	599400
-4.8	10	0	0	0	0	0	0	599400
-4.7	10	0	0	0	0	0	0	599400
-4.6	10	0	0	0	0	0	0	599400
-4.5	11	0	0	0	0	0	0	659340
-4.4	11	0	0	0	0	0	0	659340
-4.3	11	0	0	0	0	0	0	659340
-4.2	12	0	0	0	0	0	0	719280
-4.1	12	0	0	0	0	0	0	719280
-4	12	0	0	0	0	0	0	719280
-3.9	12	0	0	0	0	0	0	719280
-3.8	13	0	0	0	0	0	0	779220
-3.7	13	0	0	0	0	0	0	779220
-3.6	13	0	0	0	0	0	0	779220
-3.5	14	0	0	0	0	0	0	839160
-3.4	14	0	0	0	0	0	0	839160
-3.3	14	0	0	0	0	0	0	839160
-3.2	15	0	0	0	0	0	0	899100
-3.1	15	0	0	0	0	0	0	899100
-3	15	0	0	0	0	0	0	899100
-2.9	16	0	0	0	0	0	0	959040
-2.8	16	0	0	0	0	0	0	959040
-2.7	13	2	0	0	0	0	0	1016820
-2.6	17	0	0	0	0	0	0	1018980
-2.5	17	0	0	0	0	0	0	1018980
-2.4	18	0	0	0	0	0	0	1078920
-2.3	18	0	0	0	0	0	0	1078920
-2.2	19	0	0	0	0	0	0	1138860
-2.1	19	0	0	0	0	0	0	1138860
-2	19	0	0	0	0	0	0	1138860

-1.9	20	0	0	0	0	0	0	1198800
-1.8	20	0	0	0	0	0	0	1198800
-1.7	19	1	0	0	0	0	0	1257660
-1.6	19	1	0	0	0	0	0	1257660
-1.5	18	2	0	0	0	0	0	1316520
-1.4	18	2	0	0	0	0	0	1316520
-1.3	17	3	0	0	0	0	0	1375380
-1.2	16	4	0	0	0	0	0	1434240
-1.1	16	4	0	0	0	0	0	1434240
-1	15	5	0	0	0	0	0	1493100
-0.9	15	5	0	0	0	0	0	1493100
-0.8	14	6	0	0	0	0	0	1551960
-0.7	14	6	0	0	0	0	0	1551960
-0.6	13	7	0	0	0	0	0	1610820
-0.5	12	8	0	0	0	0	0	1669680
-0.4	12	8	0	0	0	0	0	1669680
-0.3	11	9	0	0	0	0	0	1728540
-0.2	10	10	0	0	0	0	0	1787400
-0.1	10	10	0	0	0	0	0	1787400
0	9	11	0	0	0	0	0	1846260
0.1	8	12	0	0	0	0	0	1905120
0.2	7	13	0	0	0	0	0	1963980
0.3	7	13	0	0	0	0	0	1963980
0.4	6	14	0	0	0	0	0	2022840
0.5	5	15	0	0	0	0	0	2081700
0.6	4	16	0	0	0	0	0	2140560
0.7	3	17	0	0	0	0	0	2199420
0.8	2	18	0	0	0	0	0	2258280
0.9	2	18	0	0	0	0	0	2258280
1	1	19	0	0	0	0	0	2317140
1.1	0	20	0	0	0	0	0	2376000
1.2	1	18	1	0	0	0	0	2378160
1.3	0	19	1	0	0	0	0	2437020
1.4	0	19	1	0	0	0	0	2437020
1.5	1	17	2	0	0	0	0	2439180
1.6	0	18	2	0	0	0	0	2498040
1.7	1	16	3	0	0	0	0	2500200
1.8	0	17	3	0	0	0	0	2559060
1.9	1	15	4	0	0	0	0	2561220
2	0	16	4	0	0	0	0	2620080

2.1	1	14	5	0	0	0	0	2622240
2.2	0	15	5	0	0	0	0	2681100
2.3	0	15	5	0	0	0	0	2681100
2.4	0	14	6	0	0	0	0	2742120
2.5	1	12	7	0	0	0	0	2744280
2.6	0	13	7	0	0	0	0	2803140
2.7	1	11	8	0	0	0	0	2805300
2.8	0	12	8	0	0	0	0	2864160
2.9	1	10	9	0	0	0	0	2866320
3	0	11	9	0	0	0	0	2925180
3.1	1	9	10	0	0	0	0	2927340
3.2	0	10	10	0	0	0	0	2986200
3.3	0	9	11	0	0	0	0	3047220
3.4	1	7	12	0	0	0	0	3049380
3.5	0	8	12	0	0	0	0	3108240
3.6	0	7	13	0	0	0	0	3169260
3.7	1	5	14	0	0	0	0	3171420
3.8	0	6	14	0	0	0	0	3230280
3.9	0	5	15	0	0	0	0	3291300
4	1	3	16	0	0	0	0	3293460
4.1	1	2	17	0	0	0	0	3354480
4.2	0	3	17	0	0	0	0	3413340
4.3	0	2	18	0	0	0	0	3474360
4.4	0	1	19	0	0	0	0	3535380
4.5	1	0	18	0	1	0	0	3536460
4.6	0	0	20	0	0	0	0	3596400
4.7	0	0	19	0	1	0	0	3656340
4.8	0	0	18	0	2	0	0	3716280
4.9	0	0	17	0	3	0	0	3776220
5	0	0	16	0	4	0	0	3836160
5.1	0	0	16	0	4	0	0	3836160
5.2	0	0	15	0	5	0	0	3896100
5.3	0	0	14	0	6	0	0	3956040
5.4	0	0	13	0	7	0	0	4015980
5.5	0	0	12	0	8	0	0	4075920
5.6	0	0	11	0	9	0	0	4135860
5.7	0	0	10	0	10	0	0	4195800
5.8	0	0	9	0	11	0	0	4255740
5.9	0	0	8	0	12	0	0	4315680
6	0	0	7	0	13	0	0	4375620

6.1	0	0	5	0	15	0	0	4495500
6.2	0	0	4	0	16	0	0	4555440
6.3	0	0	3	0	17	0	0	4615380
6.4	0	0	2	0	18	0	0	4675320
6.5	0	0	1	0	19	0	0	4735260
6.6	0	0	0	0	20	0	0	4795200
6.7	0	0	1	0	18	1	0	4855140
6.8	0	0	0	0	19	1	0	4915080
6.9	0	0	0	1	18	1	0	4942620
7	0	0	1	0	17	2	0	4975020
7.1	0	0	0	0	18	2	0	5034960
7.2	0	0	1	0	16	3	0	5094900
7.3	0	0	0	0	17	3	0	5154840
7.4	0	0	0	1	16	3	0	5182380
7.5	0	0	0	0	16	4	0	5274720
7.6	0	0	0	1	15	4	0	5302260
7.7	0	0	0	0	15	5	0	5394600
7.8	0	0	0	1	14	5	0	5422140
7.9	0	0	0	0	14	6	0	5514480
8	0	0	0	1	13	6	0	5542020
8.1	0	0	0	0	13	7	0	5634360
8.2	0	0	0	1	12	7	0	5661900
8.3	0	0	0	0	12	8	0	5754240
8.4	0	0	1	0	10	9	0	5814180
8.5	0	0	0	0	11	9	0	5874120
8.6	0	0	1	0	9	10	0	5934060
8.7	0	0	0	1	9	10	0	6021540
8.8	0	0	0	0	9	11	0	6113880
8.9	0	0	1	0	7	12	0	6173820
9	0	0	0	1	7	12	0	6261300
9.1	0	0	0	0	7	13	0	6353640
9.2	0	0	1	0	5	14	0	6413580
9.3	0	0	0	1	5	14	0	6501060
9.4	0	0	0	0	5	15	0	6593400
9.5	0	0	1	0	3	16	0	6653340
9.6	0	0	1	0	2	17	0	6773220
9.7	0	0	0	1	2	17	0	6860700
9.8	0	0	0	0	2	18	0	6953040
9.9	0	0	0	0	1	19	0	7072920
10	0	0	0	1	0	19	0	7100460

10.1	0	0	0	0	0	20	0	7192800
10.2	0	0	0	0	0	20	0	7192800
10.3	0	0	0	0	0	20	0	7192800
10.4	0	0	0	0	0	20	0	7192800
10.5	0	0	0	0	1	18	1	7252740
10.6	0	0	0	0	0	19	1	7372620
10.7	0	0	0	0	0	19	1	7372620
10.8	0	0	0	0	0	19	1	7372620
10.9	0	0	0	0	0	19	1	7372620
11	0	0	0	0	1	17	2	7432560
11.1	0	0	0	0	0	18	2	7552440
11.2	0	0	0	0	0	18	2	7552440
11.3	0	0	0	0	0	18	2	7552440
11.4	0	0	0	0	0	18	2	7552440
11.5	0	0	0	0	0	17	3	7732260
11.6	0	0	0	0	0	17	3	7732260
11.7	0	0	0	0	0	17	3	7732260
11.8	0	0	0	0	0	17	3	7732260
11.9	0	0	0	0	0	16	4	7912080
12	0	0	0	0	0	16	4	7912080
12.1	0	0	0	0	0	16	4	7912080
12.2	0	0	0	0	1	14	5	7972020
12.3	0	0	0	0	0	15	5	8091900
12.4	0	0	0	0	0	15	5	8091900
12.5	0	0	0	0	0	15	5	8091900
12.6	0	0	0	0	0	14	6	8271720
12.7	0	0	0	0	0	14	6	8271720
12.8	0	0	0	0	0	14	6	8271720
12.9	0	0	0	1	0	12	7	8359200
13	0	0	0	0	0	13	7	8451540
13.1	0	0	0	0	0	13	7	8451540
13.2	0	0	0	1	0	11	8	8539020
13.3	0	0	0	0	0	12	8	8631360
13.4	0	0	0	0	0	12	8	8631360
13.5	0	0	0	0	0	11	9	8811180
13.6	0	0	0	0	0	11	9	8811180
13.7	0	0	0	0	1	9	10	8871120
13.8	0	0	0	0	0	10	10	8991000
13.9	0	0	0	0	0	10	10	8991000
14	0	0	0	0	0	9	11	9170820

14.1	0	0	0	0	0	9	11	9170820
14.2	0	0	0	1	0	7	12	9258300
14.3	0	0	0	0	0	8	12	9350640
14.4	0	0	0	0	1	6	13	9410580
14.5	0	0	0	0	0	7	13	9530460
14.6	0	0	0	0	1	5	14	9590400
14.7	0	0	0	0	0	6	14	9710280
14.8	0	0	0	0	1	4	15	9770220
14.9	0	0	0	0	0	5	15	9890100
15	0	0	0	0	1	3	16	9950040
15.1	0	0	0	0	0	4	16	10069920
15.2	0	0	0	1	0	2	17	10157400
15.3	0	0	0	0	0	3	17	10249740
15.4	0	0	0	0	0	2	18	10429560
15.5	0	0	0	0	0	2	18	10429560
15.6	0	0	0	0	0	1	19	10609380
15.7	0	0	0	0	0	1	19	10609380
15.8	0	0	0	0	0	0	20	10789200
15.9	0	0	0	0	0	0	20	10789200
16	0	0	0	0	0	0	20	10789200
17	0	0	0	0	0	0	20	10789200

N-number of channels assigned in each AMCS

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