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Dynamic Channel Allocation Schemes for Current and Next Generation Cellular Systems

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School of Electrical & Electronic Engineering

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SUMMARY

This Thesis is to propose and study various channel allocation schemes for the current TDMA and future TDD-CDMA cellular systems to enhance the system capacity. We first propose a channel partitioning idea to use different reuse factors to support multiple services in the TDMA cellular systems. The fixed channel partitioning, called FCP, is analyzed with Markov chain. Both the performances with stationary and mobile users are studied in this Thesis. To further increase the system capacity, a dynamic channel allocation scheme is combined with our proposed channel partitioning idea, called dynamic channel partitioning with interference information (DCP-WI). The main idea behind this DCP-WI scheme is to minimize the effect of assigned channels on the availability of channels for use to the interfering cells. We also propose a Flexible channel combination DCP-WI scheme, called FDCP to solve the channel combination requirements in FCP and DCP-WI schemes. In FDCP, any channels can be used for the incoming calls and no pre-channel combination is required. And from the results, it is found that the proposed channel partitioning idea can reduce the average reuse factor of the whole system to support multiple services. The improvement of CP scheme depends on the traffic load ratio between services. And it is irrespective of the mobile speed or GOS factor.

In this Thesis, we also study the performance of general TDD-CDMA cellular system. We analyze the capacity both in crossed time slot and same time slot. It is found that the number of MSs supported in each time slot degrades severely with the increasing of the BS's direct coverage. And the high downlink transmission power could cause severe inference to the surrounding uplink transmission. Thus, we propose to use

multihop TDD-CDMA cellular system to solve the crossed time slot problem. Both inner region and outer region capacity are studied. And we conclude that if a proper relay and inner-outer boundary is selected, multihop cellular system can give a very high improvement in capacity as compared with conventional one-hop TDD-CDMA system, even though two radio units are used for each communication link.

In practical TDD-CDMA cellular system, 15 time slots exist within one frame. Thus, time slot allocation scheme gives another freedom of using the available radio resources. At the end of this Thesis, we study the performances of different time slot allocation schemes. We also proposed two time slot allocation schemes for multihop TDD-CDMA system to compare the performance with conventional schemes. Our proposed maximum interference first (MIF) scheme can group the interference within the whole frame into sequence. Thus, a MS is allocated to the TS that can just meet its requirement. Our proposed MIF scheme can increase the total system capacity and the data rate for each MS at the same time.

Table of Contents

ACKNOWLEDGEMENT	I
SUMMARY	II
TABLE OF CONTENTS	IV
LIST OF ABBREVIATIONS	VII
LIST OF FIGURES.....	IX
LIST OF TABLES.....	XII
CHAPTER 1 : INTRODUCTION	1
1.1 BACKGROUND	1
1.1.1 History of Wireless Cellular Communications.....	1
1.1.2 Major Multiple Access Techniques	2
1.1.3 Duplexing Transmission Methods.....	3
1.1.4 Modern Wireless Cellular Network Standards	4
1.2 MOTIVATIONS AND OBJECTIVES	6
1.2.1 Channel Partitioning for Stationary and Mobile Users.....	8
1.2.2 Capacity Analysis of Multihop TDD-CDMA Cellular System	10
1.2.3 Time Slot Allocation Scheme for Multihop Cellular System	12
1.3 ORGANIZATION OF THE THESIS	13
CHAPTER 2 : LITERATURE REVIEW	15
2.1 FUNDAMENTAL KNOWLEDGE IN WIRELESS CELLULAR COMMUNICATION SYSTEMS	15
2.1.1 Frequency Reuse for FDMA/TDMA Cellular System	15
2.1.2 Power Control in CDMA Systems.....	16
2.1.3 Soft Handover in CDMA Systems	18
2.1.4 Capacity Analysis in CDMA Cellular Systems.....	19
2.1.5 Inter-cell Interference in TDD-CDMA Systems	20
2.2 OVERVIEW OF CHANNEL ALLOCATION SCHEMES	22
2.2.1 Fixed Channel Allocation Schemes in TDMA Cellular Systems	22
2.2.2 Dynamic Channel Allocation Schemes in TDMA Cellular Systems.....	26
2.2.3 General Comparison of Channel Allocation Schemes in TDMA Cellular Systems	33
2.2.4 Multiple Service Supporting.....	34
2.2.5 Channel Allocation Schemes in TDD-CDMA System	35

2.3 OVERVIEW OF MULTIHOP CELLULAR SYSTEMS.....	39
2.3.1 <i>Why Multihop</i>	39
2.3.2 <i>Overview of Multihop Cellular Architectures</i>	41
2.3.3 <i>Comparison of Different Multihop Cellular Architectures</i>	46
CHAPTER 3 : FIXED CHANNEL ALLOCATION WITH CHANNEL PARTITIONING.....	48
3.1 INTRODUCTION	48
3.2 FCP WITH STATIONARY USERS	49
3.2.1 <i>Analysis Model</i>	49
3.2.2 <i>Performance Study of FCP with Stationary Users</i>	50
3.2.3 <i>Performance Study of FCP with Switching</i>	53
3.2.4 <i>Simulation Results and Discussion</i>	55
3.3 FCP WITH MOBILITY	59
3.3.1 <i>Analysis Model</i>	59
3.3.2 <i>Performance Analysis of FCP with Mobility (Analytical Model1)</i>	60
3.3.3 <i>A Simplified Analytical Model of FCP with Mobility (Analytical Model2)</i>	64
3.3.4 <i>Analytical and Simulation Results</i>	67
3.4 CONCLUSIONS.....	71
CHAPTER 4 : DYNAMIC CHANNEL ALLOCATION WITH CHANNEL PARTITIONING..	73
4.1 INTRODUCTION	73
4.2 DCP-WI SCHEME	74
4.2.1 <i>System model</i>	74
4.2.2 <i>Interference Information Table (IIT) for DCP-WI</i>	75
4.2.3 <i>DCP-WI Channel Allocation Scheme</i>	77
4.2.4 <i>Numerical Results of DCP-WI</i>	81
4.3 FDCP SCHEME	86
4.3.1 <i>System Model</i>	86
4.3.2 <i>Interference Information Table (IIT) for FDCP</i>	86
4.3.3 <i>FDCP Channel Allocation Scheme</i>	88
4.3.4 <i>Simulation Results</i>	90
4.4 CONCLUSIONS.....	97
CHAPTER 5 : UPLINK CAPACITY ANALYSIS FOR MULTIHOP TDD-CDMA CELLULAR SYSTEM.....	99
5.1 INTRODUCTION	99
5.2 ONE-HOP TDD-CDMA CELLULAR NETWORK	101
5.2.1 <i>System Model</i>	101
5.2.2 <i>One-hop TDD-CDMA Uplink Capacity Analysis</i>	102

5.2.3 Simulation and Analysis Results for One-hop TDD-CDMA System	111
5.3 UPLINK CAPACITY IMPROVEMENT FOR MULTIHOP TDD-CDMA SYSTEM.....	115
5.3.1 System Model	115
5.3.2 Capacity Analysis of Multihop Cellular System.....	116
5.3.3 Simulation and Analysis Results for Multihop TDD-CDMA System.....	120
5.4 CONCLUSIONS.....	123
CHAPTER 6 : TIME SLOT ALLOCATION SCHEME FOR MULTIHOP TDD-CDMA	
CELLULAR SYSTEM	126
6.1 INTRODUCTION	126
6.2 SYSTEM MODEL.....	127
6.2.1 Cell Structure	127
6.2.2 Frame Structure	127
6.2.3 Unbalanced Traffic Pattern	128
6.2.4 Multihop Signaling.....	128
6.3 CHANNEL ALLOCATION SCHEMES FOR MULTIHOP CELLULAR STRUCTURE	129
6.3.1 Fixed Switching Point (FSP).....	129
6.3.2 Dynamic Switching Point (DSP).....	131
6.3.3 Dynamic Switching Point with Multihop (DSPM)	132
6.3.4 Maximum Interference First (MIF).....	134
6.4 SIMULATION RESULTS AND DISCUSSION	138
6.5 CONCLUSIONS.....	146
6.6 LIMITATIONS AND ASSUMPTIONS	146
CHAPTER 7 : CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK	147
7.1 CONCLUSIONS.....	147
7.2 RECOMMENDATIONS FOR FUTURE WORK.....	150
7.2.1 Multiple MSs Supporting by Each TS	150
7.2.2 General RS Selection	151
7.2.3 Other Issues	151
REFERENCES	153
APPENDIX	161
A. DETAILED SOLUTION OF TWO-DIMENSIONAL MARKOV CHAIN	161
AUTHOR'S PUBLICATIONS.....	163

List of Abbreviations

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
AMPS	Advanced Mobile Phone Service
ASP	Adaptive Switching Point
B3G	Beyond third Generation
BER	Bit Error Rate
BS	Base Station
CA	Channel Allocation
CP	Channel Partitioning
CDD	Code Division Duplexing
CDMA	Code Division Multiple Access
CT	Cordless Telephone
CTS	Crossed Time Slot
DCA	Dynamic Channel Allocation
DCA-WI	Dynamic Channel Allocation with Interference Information
DGP-WI	Dynamic Channel Partitioning with Interference Information
DECT	Digital European Cordless Telecommunication
DSP	Dynamic Switching Point
DSPM	Dynamic Switching Point with Multihop
E_b/I_0	Bit Energy to Interference Ratio
EDGE	Enhanced Data rates for GSM Evolution
FA	First Available
FCA	Fixed Channel Allocation
FCP	Fixed Channel Partitioning
FDCP	Flexible Channel Combination Dynamic channel Partitioning
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FSP	Fixed Switching Point
GOS	Grade of Service

GPRS	General Pachet Radio Service
GSM	Global System for Mobile Communication
iCAR	Integrated Cellular and Ad-hoc Relaying
IIT	Interference Information Table
IMT-2000	International Mobile Telecommunications 2000
LP-DDCA	Local Packing Dynamic Distributed Channel Assignment
MCN	Multihop Cellular Network
MD	Moving Direction
MIF	Maximum Interference First
MS	Mobile Station
MSQ	Mean Square
ODMA	Opportunity Driven Multiple Access
QoS	Quality of Service
RF	Radio Frequency
RP	Reuse Partitioning
RS	Relay Station
SF	Spreading Factor
SIR	Signal to Interference Ratio
SP	Switching Point
SSP	Same Switching Point
STS	Same Time Slot
TD-SCDMA	Time Division-Synchronous Code Division Multiple Access
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TS	Time Slot
UCAN	Unified Cellular and Ad-hoc Networks
UMTS	Universal Mobile Telecommunications Service
VCN	Virtual Cellular Network
WiDen	Wideband Integrated Dispatch Enhanced Network
WCDMA	Wideband Code Division Multiple Access

List of Figures

FIGURE 1.1: ILLUSTRATION OF FDMA, TDMA AND CDMA	2
FIGURE 1.2: CROSS TIME SLOT SCENARIOS IN TDD CDMA SYSTEM	11
FIGURE 2.1: POWER CONTROL IN CDMA SYSTEMS	17
FIGURE 2.2: FOUR TYPES OF INTERFERENCE IN TDD-CDMA SYSTEM	21
FIGURE 2.3: ILLUSTRATION OF BORROWING ALGORITHM BASED ON A REUSE FACTOR OF 7	23
FIGURE 2.4: REUSE PARTITIONING ARCHITECTURE	25
FIGURE 2.5: MOVING DIRECTION: A NETWORK-BASED DISTRIBUTED DCA SCHEME	29
FIGURE 2.6: EXAMPLE OF FCA AND DCA WITH A REUSE FACTOR OF 7	33
FIGURE 2.7 ZONE DIVISION SCHEME	37
FIGURE 2.8: DIRECT AND MULTIHOP LINK	40
FIGURE 2.9: MULTIHOP ARCHITECTURE: ICAR	43
FIGURE 2.10: ODMA MODEL	44
FIGURE 2.11: MULTIHOP VCN MODEL	45
FIGURE 3.1: FLOW-CHART OF FCP SCHEME	51
FIGURE 3.2: MARKOV CHAIN OF FCP WITH OVERFLOW FOR STATIONARY USERS	51
FIGURE 3.3: MARKOV CHAIN OF FCP WITH OVERFLOW AND SWITCHING FOR STATIONARY USERS	54
FIGURE 3.4: COMPARISON OF FCP AND FCA $P_1:P_2=1:2$ (NS: NO SWITCHING, WS: WITH SWITCHING)	56
FIGURE 3.5: COMPARISON OF FCP AND FCA $P_1:P_2=8:1$	57
FIGURE 3.6: IMPROVEMENT OF FCP OVER FCA UNDER DIFFERENT TRAFFIC LOAD RATIO	58
FIGURE 3.7: CELLULAR STRUCTURE FOR MOBILITY WITH WRAP-AROUND TECHNIQUE	59
FIGURE 3.8: AN EXAMPLE OF TRANSITION RATE OF FCP WITH MOBILE USERS WHEN $C_1=2$ AND $C_2=3$	61
FIGURE 3.9: MARKOV CHAIN OF THE ANALYTICAL MODEL2 FOR MOBILE USERS	65
FIGURE 3.10: AVERAGE CALL BLOCKING AND DROPPING PROBABILITIES WITH TRAFFIC LOAD RATIO $P_1:P_2=2:1$ ($A_1:A_2=1:1$) FOR FCA AND FCP WITH $C(21:18)$	68
FIGURE 3.11: GOS RESULTS WITH TRAFFIC LOAD RATIO $P_1:P_2=2:1$ ($A_1:A_2=1:1$) FOR FCA AND FCP WITH $C(21:18)$	69
FIGURE 3.12: GOS=1% IMPROVEMENT VS. DIFFERENT TRAFFIC LOAD RATIOS UNDER DIFFERENT SPEEDS	70
FIGURE 3.13: GOS=1% IMPROVEMENT VS. DIFFERENT TRAFFIC LOAD RATIOS UNDER DIFFERENT GOS FACTORS	71
FIGURE 4.1: SYSTEM MODEL FOR 49 CELLS WITH TWO REUSE FACTORS	74
FIGURE 4.2: FLOW-CHART OF DCP-WI SCHEME	80
FIGURE 4.3: COMPARISON OF DCP-WI OVER FCA AND DCA-WI FOR $P_1:P_2=1:2$ IN UNIFORM TRAFFIC DISTRIBUTION. ($C(x,y)$: x IS THE NUMBER OF CHANNEL FOR S_1 AND y IS THE NUMBER OF CHANNEL FOR S_2)	82

FIGURE 4.4: COMPARISON OF DCP-WI OVER FCA AND DCA-WI FOR $P_1:P_2=8:1$ IN UNIFORM TRAFFIC DISTRIBUTION. ($C(x,y)$: x IS THE NUMBER OF CHANNEL FOR S_1 AND y IS THE NUMBER OF CHANNEL FOR S_2).....	82
FIGURE 4.5: IMPROVEMENT OF DCP-WI, FCP (WITH AND WITHOUT SWITCHING) OVER FCA UNDER DIFFERENT TRAFFIC LOAD RATIOS IN UNIFORM TRAFFIC DISTRIBUTION. ($C(x,y)$: x IS THE NUMBER OF CHANNEL FOR S_1 AND y IS THE NUMBER OF CHANNEL FOR S_2).....	83
FIGURE 4.6: COMPARISON OF DCP-WI OVER FCA AND DCA-WI FOR $P_1:P_2=1:2$ IN NON-UNIFORM TRAFFIC DISTRIBUTION. ($C(x,y)$: x IS THE NUMBER OF CHANNEL FOR S_1 AND y IS THE NUMBER OF CHANNEL FOR S_2).....	84
FIGURE 4.7: COMPARISON OF DCP-WI OVER FCA AND DCA-WI FOR $P_1:P_2=8:1$ IN NON-UNIFORM TRAFFIC DISTRIBUTION. ($C(x,y)$: x IS THE NUMBER OF CHANNEL FOR S_1 AND y IS THE NUMBER OF CHANNEL FOR S_2).....	85
FIGURE 4.8: SIMULATION RESULTS WITH $\Gamma_1:\Gamma_2 = 1:1$ ($P_1:P_2=2:1$)	90
FIGURE 4.9: IMPROVEMENT OF FDCP AND DCP-WI (OPTIMUM CHANNEL COMBINATION) OVER FCA ...	91
FIGURE 4.10: BLOCKING PROBABILITY RESULTS WITH TRAFFIC LOAD RATIO $P_1:P_2=2:1$ ($A_1:A_2=1:1$)	92
FIGURE 4.11: DROPPING PROBABILITY RESULTS WITH TRAFFIC LOAD RATIO $P_1:P_2=2:1$ ($A_1:A_2=1:1$).....	93
FIGURE 4.12: GOS RESULTS WITH TRAFFIC LOAD RATIO $P_1:P_2=2:1$ ($A_1:A_2=1:1$).....	94
FIGURE 4.13: THE GOS IMPROVEMENT OF FDCP AND FCP (OPTIMUM CHANNEL COMBINATION) OVER FCA.....	95
FIGURE 4.14: GOS IMPROVEMENT OF FCP (OPTIMUM CHANNEL COMBINATION) AND FDCP OVER FCA UNDER DIFFERENT AVERAGE SPEEDS (KM/H).....	96
FIGURE 5.1: INTERFERENCE FROM SURROUNDING UPLINK MS	104
FIGURE 5.2: NUMBER OF USERS VS. THE FARTHEST DISTANCE MOBILE USERS (USER x IS THE FARTHEST USER. MAXIMALLY, THIS TS COULD SUPPORT N USERS)	109
FIGURE 5.3: AVERAGE NUMBER OF USERS UNDER DIFFERENT E_b/I_0 REQUIREMENTS WITH ALL BSs UPLINK	112
FIGURE 5.4: AVERAGE NUMBER OF USERS UNDER DIFFERENT E_b/I_0 REQUIREMENTS WITH 3 UPLINK INTERFERENCE BSs AND 3 DOWNLINK INTERFERENCE BSs	113
FIGURE 5.5: AVERAGE NUMBER OF USERS COULD SUPPORTED GIVEN THE LARGEST BS COVERAGE DISTANCE, R , FOR SF=16 AND $E_b/I_0=5$ dB	114
FIGURE 5.6: RELAYING SYSTEM MODEL	116
FIGURE 5.7: AVERAGE NUMBER OF USERS UNDER DIFFERENT BS DIRECT COVERAGE AREA FOR OUTER REGION WITH SF=16.....	121
FIGURE 5.8: IMPROVEMENT OF MULTIHOP CELLULAR SYSTEM OVER ONE-HOP SYSTEM WHEN SF=16...	122
FIGURE 5.9: SYSTEM CAPACITY UNDER DIFFERENT E_b/I_0 REQUIREMENT WHEN SF=16	123
FIGURE 6.1: FSP SCHEME	129
FIGURE 6.2: DSP SCHEME	131
FIGURE 6.3: DSPM SCHEME.....	133

FIGURE 6.4: MULTIHOP MODEL IN THE CENTER CELL 133

FIGURE 6.5: MIF SCHEME..... 135

FIGURE 6.6: FLOW-CHART OF MIF SCHEME 136

FIGURE 6.7: DATA RATE DISTRIBUTION OF EACH MS IN THE UPLINK IN THE CENTER CELL 142

FIGURE 6.8: DATA RATE DISTRIBUTION OF EACH MS IN THE DOWNLINK IN THE CENTER CELL..... 144

FIGURE 6.9: DATA RATE DISTRIBUTION OF EACH MS IN UPLINK STS IN THE CENTER CELL..... 145

FIGURE 6.10: DATA RATE DISTRIBUTION OF EACH MS IN UPLINK CTS IN THE CENTER CELL 145

List of Tables

TABLE 2-1: COMPARISON OF SOME SELECTED MULTIHOP CELLULAR ARCHITECTURES47

TABLE 4-1: IIT OF CELL 25 FOR S_1 OF DCP-WI 76

TABLE 4-2: IIT OF CELL 25 FOR S_2 OF DCP-WI 76

TABLE 4-3: INTERFERENCE INFORMATION TABLE OF CELL 25 OF FDCP 87

TABLE 6-1: SIMULATION PARAMETERS 139

TABLE 6-2: SYSTEM THROUGHPUT FOR BALANCED TRAFFIC AMONG CELLS 139

TABLE 6-3: SYSTEM THROUGHPUT FOR UNBALANCED TRAFFIC AMONG CELLS (CENTER MORE UPLINKS).
..... 140

TABLE 6-4: SYSTEM THROUGHPUT FOR UNBALANCED TRAFFIC AMONG CELLS (SURROUNDING MORE
UPLINKS)..... 140

Chapter 1: Introduction

1.1 Background

1.1.1 History of Wireless Cellular Communications

The first usage of wireless radio can be traced back in 1897 when Marconi successfully demonstrated the ability of the wireless radio to carry message across the Bristol Channel [1]. Ever since then, people developed all kinds of wireless communication technologies and applications to have a good usage of radio frequencies. Among all the wireless communication systems, wireless cellular communication systems play the most important role in our daily life. Thus far, they become the most popular, wide-spread, stable and economical systems within the wireless communication family. The idea of wireless cellular communication was proposed in 1960s by Bell Lab [2]. One of the most important reasons for developing the cellular communication is the inefficient spectrum utilization when cellular structure is not deployed. It was recent 30 years that wireless cellular system had really been commercialized. The commercialization in the wireless cellular operation decreases the costs for users, improves the quality of the service for the whole system, accelerates the revolution for new techniques and thus attracts more subscribers to enjoy all kinds of services. At the end of year 2005, more than 31% of the people on this world own a mobile phone [3]. With the development of more advanced technologies, it can be foreseen that future wireless cellular systems with higher speed multimedia services supported would influence our daily life more significantly.

1.1.2 Major Multiple Access Techniques

Multiple access techniques are used to allow many mobile users to share the limited radio frequencies simultaneously. There are three major access techniques that are commonly used in the wireless communication systems: Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). The illustrations for FDMA, TDMA and CDMA are shown in Figure 1.1.

In FDMA, a given Radio Frequency (RF) is divided into a number of much smaller frequency bands called sub-frequencies. Each sub-frequency is a channel that communicates between mobile station (MS) and base station (BS). Channel allocation (CA) schemes must be used so that the same frequency is not permitted to be shared by two MSs that can interfere with each other. Similar to FDMA, different time slots and spreading codes are used in TDMA and CDMA respectively to separate different communication channels. The radio frequency left for wireless cellular communication becomes more and more scarce. It has been found [4, 5] that CDMA is likely to become a suitable multiple access method for future generation cellular systems by providing higher system capacity in a given radio spectrum.

Figure 1.1: Illustration of FDMA, TDMA and CDMA

1.1.3 Duplexing Transmission Methods

Modern cellular communication systems provide 'bi-directional' communication between connection ends. It is either in half-duplex or in full-duplex communication mode. Unlike Half-duplex transmission mode, which allows only one direction transmission at a time, full-duplex permits both callers to speak simultaneously. Most of the modern telephone networks are full-duplex. There are three duplexing transmission methods: frequency division duplexing (FDD), time division duplexing (TDD) and lately proposed code division duplexing (CDD) [7].

The most commonly used duplexing method is FDD. FDD uses different frequencies to provide channels to callers between communication end. FDD has the fundamental advantage that it makes the radio planning among network easier since different BSs (which share the same frequency band) do not have to coordinate with each others about the transmission direction. BSs use different frequency-bands for uplink and downlink transmissions. Thus, there is no possibility that the over-powered downlink transmission interfere the uplink transmission in the own and surrounding cells. FDD is more efficient in the case that both uplink and downlink transmission require symmetric service, e.g., voice call.

TDD uses the same frequency for both uplink and downlink transmissions. If certain direction transmission needs more radio resources, adaptive arrangement of the time slot can be realized in TDD method. TDD is more efficient in the case of asymmetric service between uplink and downlink, e.g., high-speed unbalanced multiple services between uplink and downlink. Specially, in CDMA cellular system, TDD mode can also take the advantage of the reciprocal nature of the physical channel. Thus, TDD-CDMA cellular system can easily give raise to several adaptive communications

techniques, including transmission diversity, closed loop power control and downlink adaptive antennas, resulting in enhanced system throughput and simplified receiver structures [8].

CDD is a duplexing method that was proposed in recent year. Different codes within the same frequency-band can be used for uplink and downlink transmissions. CDD method can effectively eliminate the interference that is encountered in the FDD or TDD method if a proper smart code is chosen. It is expected [7] that CDD will be the main duplexing method for future generation cellular systems.

1.1.4 Modern Wireless Cellular Network Standards

The first-generation (1G) cellular systems, analog cellular systems, were firstly introduced in 1979 [9]. They are originally excogitated to provide the voice communication between different receptors. Almost all the 1G cellular systems use FDD FDMA and analog frequency modulation (FM). A typical example of 1G cellular system is Advanced Mobile Phone Service (AMPS) in North America. It was first developed by AT&T Bell Laboratories and was the most popular 1G system deployed throughout the world. The 1G cellular systems make them a great success because they practically use the seamless cellular technology. But the limited capacity per carrier frequency cannot match the rapid increasing number of subscribers. And the poor security mechanism allows people to steal a phone's serial code to make an illegal phone call. The 1G cellular systems were later replaced by the second-generation digital systems.

The second-generation cellular systems (2G) began in the late 1980s [9]. Global System for Mobile Communications (GSM) is one of the most popular 2G cellular systems that had been deployed widely in Europe, Asia, Australia, etc. By the year

2005, GSM service is used by over 1.6 billion people across more than 210 countries and territories [10]. GSM employs TDMA method and digital modulation technique to provide services. The key advantages which make GSM a big success are the high digital voice quality and the ability to send the low cost text messages. Besides, the open standard allows GSM subscribers to roam between different network operators without terminating their communication services.

Compared with 1G cellular system, a common feature to all 2G cellular systems is that they are all digital. And these digital cellular systems provide the implementation of a wide variety of data and speech services such as facsimile, paging, and low-data-rate network access. Besides, remarkable channel allocation schemes can be implemented in 2G system [11], which results in more efficient usage of radio spectrum. With the development of the more advanced technologies, higher speed data rate is also achieved to satisfy various applications.

The requirement for higher speed data rate has never been satisfied. Before the real scope and the application for the next generation cellular system is clear, some other transitional generations, such as 2.5G and 2.75G systems, are deployed as transitional systems. Some typical standards include General Packet Radio Service (GPRS), Enhanced Data rates for GSM Evolution (EDGE), CDMA2000 1xRTT, Wideband Integrated Dispatch Enhanced Network (WiDen). Third generation (3G) cellular communication systems, which are designed to allow the transmission of very large quantities of data, are also becoming increasingly popular. Some typical 3G system standards include Wideband CDMA (WCDMA), CDMA2000 1xEV, Time Division-Synchronous CDMA (TD-SCDMA). The major objectives for 3G systems and their key differences from the current 2G cellular systems are [12]:

Chapter1: Introduction

- Use a common global frequency band for both terrestrial and satellite components.
- Use a small pocket terminal with worldwide roaming.
- Maximize the commonality and optimization of radio interfaces for multiple operating environments, such as vehicular, pedestrian, office, and fixed wireless access systems.
- Provide significantly high transmission speed capability encompassing circuit- and packet- switched as well as multimedia services
- Support for both symmetric and asymmetric data capacities in all operating environments.
- Provide compatibility of services within International Mobile Telecommunications 2000 (IMT-2000) and with fixed networks.
- Provide spectrum efficiency, quality, flexibility, and overall cost improvement as a result of the utilization of advanced technologies.

Preliminary works on the fourth generation (4G) have already started [13-15]. Typically, a new generation of cellular system means a new air-interface with higher data rates in the least. And some see change in the way data transport is handled end-to-end. From the past experience, a generation is defined by the result of technology changes over a 10-15 year time frame. The period for 2.5G, 2.75G and 3G deployment is predicted to be from 2000 to 2009. Thus, 4G would refer to whatever is deployed in the 2010-2015 period.

1.2 Motivations and Objectives

The rapid increasing number of mobile subscribers and their demands for high-speed multiple services stand in clear contrast to the rather limited spectrum radio

Chapter1: Introduction

frequencies that have been allocated with international agreements. Thus, efficient spectrum resource management is of paramount importance. One way to settle this problem is to reduce the cell size and reuse the same radio resource more frequently [16]. But on one hand, this increases the number of BSs, which costs more for communication operators. At the same time, the small size of cell coverage increases the possibility of handoff, which causes the system to be unstable. Another way to increase the system capacity is to implement more advanced technology, e.g., introducing wideband CDMA system. A more attractive way is to use an efficient channel allocation algorithm to accept more users into the system. In the wireless transmission systems, co-channel interference caused by frequency reuse is the most restraining factor on the overall system capacity. The main idea behind channel allocation algorithms is to make use of radio propagation path loss [17] characteristics to minimize the carrier-to-interference ratio and hence to increase the radio spectrum reuse efficiency.

The objective of this Thesis is to propose and study various channel allocation schemes for TDMA and CDMA cellular system to enhance their performances.

The contributions of this Thesis are as follows:

1. Proposing a channel partitioning (CP) idea and mathematically analyzing the performance of CP with fixed channel allocation (FCA) for stationary and mobile users in a TDMA cellular system.
2. Proposing two CP with dynamic channel allocation (DCA) schemes, i.e., dynamic channel partitioning with interference information (DCP-WI) scheme and flexible channel combination of DCP-WI (FDCP) scheme, to optimize the performance of the TDMA cellular system.

3. Studying the performance of one-hop TDD-CDMA cellular system with same time slot (STS) and crossed time slot (CTS) scenarios and then proposing and studying a multihop cellular structure to solve the CTS's problem.
4. Proposing two time slot allocation scheme, namely Dynamic Switching Point with Multihop (DSPM) and Maximum Interference First (MIF), for multihop TDD-CDMA cellular system.

1.2.1 Channel Partitioning for Stationary and Mobile Users

With the development of the more advanced technologies, wireless communication systems perform more than voice-provider systems. The trend of wireless communication system is to merge the telephone and computer networks together to provide various types of traffic, such as voice, data and video. These services are distributed over the network and require different quality of service (QoS). Thus an efficient resource allocation algorithm is needed to support these multiple traffic optimally. There are two main factors in dealing with the QoS problem, one is the time sensitive problem and the other one is signal-to-interference ratio (SIR) problem. For example, the required bit error rate (BER) for speech service is 10^{-3} , while the required BER for circuit-switched or packet data service is 10^{-6} . It means that for data service, we need a higher SIR. And a relative smaller SIR may be enough for the speech service. On the other hand, speech service is time-sensitive. If a connection is established, it must be sent with no or less delay. But for the data service, a longer delay is tolerable. A feasible channel allocation scheme must consider all these factors.

To support multiple services, if they have different SIRs and hence have different reuse factors, the conventional way in TDMA cellular systems is to allocate channels

Chapter 1: Introduction

based on the largest reuse factor to all the services in the system. This may result in wasting the limited spectrum because some services may enjoy more than enough QoS with this largest reuse factor.

Based on the fact that different services may require different signal-to-interference ratios and thus different reuse factors, we proposed a channel allocation scheme called channel partitioning (CP) [18, 19] to support different services using different reuse factors. In this proposed CP scheme, the channels in each cell are divided into two or more sets of channels and each set of the channels supports certain service, depending on the required reuse factor of the service. We study the blocking and dropping probability in the multi-service cellular systems with stationary and mobile users. We apply this channel partitioning with fixed channel allocation scheme called Fixed Channel Partitioning (FCP). First, we study the performance of FCP with stationary users by using a two-dimensional Markov chain model. Then, a three-dimensional Markov chain is developed to analyze the impact of the mobile user. A simpler model, which can estimate the numerical results from a closed-form solution, is then presented to make the analysis easier. This result also gives the upper bound performance of CP scheme.

In order to cater for the traffic variation between services and between cells, a dynamic channel partitioning with flexible channel combination scheme, called FDCP, is proposed to support multiple services. This FDCP tries to minimize the effect of assigned channels on the availability of channels for use in the interfering cells. The analysis and the simulation results show that for equal arrival rate of two services, the proposed FCP and FDCP scheme can provide about 32% and 54% improvement respectively in terms of grade of service (GOS) as compared with

conventional FCA scheme using a single reuse factor to support two services for the mobile users.

1.2.2 Capacity Analysis of Multihop TDD-CDMA Cellular System

In the next generation cellular systems, which are established to support more high-speed multiple data services, it is expected that the ratio of downlink-to-uplink traffic will change from current slightly larger than one to more than four [8]. Besides, different types of services may require different uplink to downlink traffic ratios. The exact unbalanced uplink-to-downlink traffic ratio for each BS cannot be predicted and will continue to change with the time prolonging. Therefore, conventional FDD mode air interface, which has the same radio resources for uplink and downlink, loses its advantage in 3G or beyond 3G (B3G) to support future multiple services.

TDD-CDMA cellular system uses both time and code dimension separations to provide 'channels' to each service requirement. Each frame of WCDMA system consists of 15 time slots (TS) within 10ms. With flexible allocation of TS to uplink and downlink directions, TDD-CDMA can adapt the time-variable unbalanced traffic in 3G or B3G systems. Besides, a new cellular network structures namely multihop cellular system [20], which can further increase the system capacity and/or coverage area by incorporating ad-hoc characteristics into cellular system, is better of using TDD mode transmission. This is because the uplink and downlink traffic ratio in multihop cellular system is different from time to time and unpredictable. Thus, TDD-CDMA attracts more attentions in the recent research work.

Besides the conventional STS interference in WCDMA FDD system, which is the interference from MSs to BSs in uplink transmission and BSs to MSs in downlink transmission, new kind of interference namely cross-time-slot (CTS) interference is

introduced in TDD-CDMA system due to the unbalanced time slot allocation among different BSs. CTS interference is either from MSs to MSs in the uplink transmission or BSs to BSs interference in the downlink. As shown in Figure 1.2, BS0 is in uplink and BS1 is in downlink from TS2 to TS14. The downlink transmission power of BS1 could cause interference for uplink transmission with the same time slot at BS0 and the uplink power of MS1 also cause interference to MS2. Normally, the fully loaded transmission power of BS will be much larger (in about 10dB) than that of MS. It has been shown [21] that CTS interference could severely degrade the system performance.

Figure 1.2: Cross time slot scenarios in TDD CDMA system

In this Thesis, we study the performance of a multihop TDD-CDMA cellular system [22]. We begin the mathematical analysis from a conventional one-hop TDD-CDMA cellular system with different BS's coverage distance. The capacity studies for both STS and CTS are included. From the analytical results, we find that the system capacity can be improved if BS only covers the center small area of the cell. Besides, the high downlink transmission power of the surrounding BSs can degrade the

capacity severely. Thus, we propose a simple technique used in multihop cellular model to overcome the high inter-cell interference from downlink power of surrounding BSs. In this model, a cell's area is divided into two regions: inner-region and outer-region. The users in the inner- and outer- region of the cell communicate with BS and relay station (RS), respectively. Based on this simple model, the uplink system capacity in both regions is studied with the assumption that the inter-cell and intra-cell interference follow the Gaussian distribution. In addition, we conduct a comparison equation to establish a fair comparison between a conventional one-hop TDD-CDMA and multihop TDD-CDMA cellular system in terms of system throughput. From the analysis and simulation results, we conclude that multihop cellular system can improve the TDD-CDMA system capacity significantly.

1.2.3 Time Slot Allocation Scheme for Multihop Cellular System

Finally, we propose simple time slot allocation schemes in multihop cellular system to optimize the throughput per frame. Our primary goal here is to achieve the maximum capacity for the multihop cellular system with unbalanced traffic supported among cells. The results are compared with a one-hop cellular system using fixed and dynamic time slot allocation.

As mentioned above, multihop cellular system is a new emerging but promising cellular structure. Compared with one-hop cellular systems, the multiple interfaces and the routing problem introduced in multihop system become new tasks. Novel architectures and the related channel allocation schemes should be also carefully studied to cater for the requirement of future generation cellular system.

1.3 Organization of the Thesis

In Chapter 2, we first give some concepts in the area of wireless communication. This will help us understand the basic principles that are used for analyzing the cellular system. After that, the overview of the research work in area of channel allocation and multihop cellular system is outlined. The limitations and the advantages of these research works are mentioned and compared.

In Chapter 3, we begin our research work from the proposed scheme called: fixed channel partitioning (FCP) for TDMA system. Two scenarios, MS with mobility and MS without mobility is mathematically analyzed with Markov chain. To simplify the analysis, we also propose simplified models so that the results can be expressed with closed-form solutions. The improvement over conventional FCA scheme is also shown and the limitation of the scheme is mentioned.

In order to further improve the system capacity of the TDMA system, another dynamic channel portioning with interference information scheme called DCP-WI is proposed in Chapter 4. Both FCP and DCP-WI scheme have a common problem of channel combination. In the left following part of the Chapter 4, we focus on solving this problem by proposing another scheme of flexible channel combination DCP-WI (FDCP).

In Chapter 5, the uplink system capacity for one-hop TDD-CDMA system is first analyzed. Both STS and CTS capacity are obtained. From the observation of this analysis, we proposed to use multihop technique to solve the CTS problem in TDD-CDMA system. A comparison technique between one-hop and multihop TDD-CDMA system is also proposed to achieve a fair result.

Chapter1: Introduction

In Chapter 6, we propose a time allocation scheme, called maximum interference first (MIF), to obtain the maximum throughput (in kbps) for the multihop TDD-CDMA cellular system. This scheme selects the first TS with the maximum interference that MS can tolerate. It will give other MSs that are not in the good situation an opportunity to be accepted by the system with good transmission speed.

In the end, we summarize the achievement and make some conclusions based on this Thesis. Discussion and the some possible future works are also outlined in Chapter 7.

Chapter 2: Literature Review

In wireless cellular communication systems, there are some basic but important concepts that will affect the system capacity a lot. Besides, the channel allocation schemes can increase the usage efficiency for a given radio spectrum. The study of these concepts and the channel allocation schemes can help us understand the relationship of communication elements. As a result, more insightful ideas can be proposed based on the observations. In this chapter, we begin to review some basic knowledge of wireless communication, which are being used in this Thesis. Then, the overview of channel allocation techniques for TDMA- and CDMA-based cellular systems is given. Finally, the concept and idea of multihop cellular system is presented.

2.1 Fundamental Knowledge in Wireless Cellular Communication Systems

2.1.1 Frequency Reuse for FDMA/TDMA Cellular System

The basic idea of cellular system is frequency reuse that is mainly applied for FDMA- or TDMA-based cellular systems. In a given area, several cells could use the same set of frequencies without severe interference with each other. These cells are called co-channel cells. The interference from the same channel between these cells is called co-channel interference. Thermal noise could be overcome by increasing the power of the transmitter, but the co-channel interference could not be combated by simply increasing the power of the transmitters because this may cause all the transmitters to increase their transmitted power. To reduce this co-channel interference, the co-

channel cells should be separated by a certain minimum distance in order to provide sufficient isolation due to the propagation of the signal [23]. We define Q as the co-channel reuse ratio that is given by

$$Q = \frac{D}{R} = \sqrt{3N} \quad (2.1)$$

where D is the minimum reuse distance between two nearest co-channel cell, R is the radius of the cell and N is the cluster size. As we can see from the function, a large Q provides better service in terms of signal quality (due to the larger separation distance); while a small Q can improve the system capacity (due to repeating using the same channel more frequently). A trade-off must be made on Q to achieve a good performance.

2.1.2 Power Control in CDMA Systems

The fast power control technique is one of the most important aspects in CDMA systems. It is used in CDMA systems to avoid a single over-powered MS to block the whole cell's communication. As illustrated in Figure 2.1, MS1 and MS2 use the same frequency and same time slot. If the transmission power, P_{MS1} and P_{MS2} , of MS1 and MS 2, respectively, are same with no power control, the received power at BS from MS1 is much larger than it is of MS2 because MS1 is much closer to BS. Thus, MS1 can block MS2's communication in the same cell. This is also called *near-far effect*. The goal of uplink power control is to justify the power of each MS such that the received power at BS for each MS is almost same. And the objective of the downlink power control is to transmit enough power for the users in the bad receiving scenario.

Figure 2.1: Power control in CDMA systems

There are two types of power control employed in CDMA systems: open-loop power control and closed-loop power control. Open-loop power control attempts to estimate the path loss from the stable beacon signal. In FDD duplexing method using different frequencies for uplink and downlink, open-loop power control scheme may not be accurate enough because the channel status is uncorrelated between uplink and downlink. But this technique is still useful to roughly transmit the initially power of MS or to determine the appropriate transmission power when closed-loop power control commands are missing. In TDD duplexing method, open loop power control is a very important and accurate technique to estimate the channel status because both uplink and downlink use the same frequency. The change of the received signal strength from one link can determine the change of the transmission environment of the other link. Thus, fast fading can be partially overcome in TDD duplexing method [24] using power control. In addition, the accurate information in TDD method also provides a good estimation for Rake receivers [25].

In FDD CDMA system, fast closed-loop power control scheme is the primary way to adjust the transmission power. In Figure 2.1, after the initialization of the transmission power from MS1 and MS2 using open-loop power control, BS judges the SIR from each MS. If the received SIR of one MS, e.g., MS1, is more than enough, BS informs

MS1 to decrease its transmission power through a downlink control channel. MS1, as a result, will decrease its transmission power according to the power control command from BS. The closed-loop power control cycle is effectively executed as fast as 1500 times per second for each MS in WCDMA system, even faster than the speed of fast Rayleigh fading for low to moderate mobile speeds. Thus, it can balance the received signal for each of the uplink transmission. In the downlink direction, the motivation of closed-loop power control is not because of near-far problem since the signals within one cell originate from one BS. The power control in this case is to provide additional power to the users near the boundary, which suffer more interference from the surrounding cells.

2.1.3 Soft Handover in CDMA Systems

Despite the hard handovers same as in FDMA or TDMA, CDMA employs another handover technique of soft handover. In hard handover, a MS stops its communication with the crossing-out BS and establishes the communication with the crossing-in BS again. And this may cause the communication to be interrupted. While in the soft handover, a MS can communicate with two different BSs at the same time because two adjacent cells can use the same frequency. Only different codes are used to differentiate the communication channels. The MS does not stop its communication with original BS during soft handoff. As a result, the users in CDMA system enjoy better QoS. Another reason to use soft handover technique is similar to power control scheme to avoid near-far effect. If soft handover technique is not used, the near-far effect could happen when a MS travels deeply from one cell to another cell without being power-controlled by the new arrival cell. Fast hard handoff could avoid this near-far effect during handoff. However, the interrupted communication during the

hard handoff period causes certain delay which could result in near-far effect to the new cell.

2.1.4 Capacity Analysis in CDMA Cellular Systems

CDMA system is first developed for the military purpose [26]. But it is also found that CDMA can improve the system capacity significantly, especially for the cellular system [4, 5]. Since the radio frequency given to the cellular system is limited, the improvement in a given spectrum means a lot for both researchers and cellular network operators. In literature, some papers [4, 5, 27-31] obtain the capacity for CDMA with analysis. In [4], the performance analysis of a CDMA system is obtained based on perfect power control scheme. With the perfect power control scheme, the bit energy-to-interference density ratio is expressed with

$$E_b / I_0 = \frac{SF}{(N_s - 1) + I / P_r} \quad (2.2)$$

where SF , N_s , I and P_r are the spreading factor, number of users supported, total received interference and received power at BS, respectively. In [4], the uplink interference from the surrounding cells is assumed to be Gaussian distribution and the received power at each BS from the MSs is assumed to be same. Thus, given a pre-defined E_b/I_0 requirement, the outage probability when N_s users are in the system is given. The paper also mentions that the downlink interference from surrounding BSs cannot be analyzed. Thus, Monte Carlo simulation is used to obtain the results. The paper concludes that the interference suppression feature of CDMA results in an increase in system capacity over the conventional analog and other digital non-CDMA terrestrial cellular systems. Besides, the sectorization and the voice-activity monitoring techniques can also be implemented into CDMA system to further increase the system performance.

The paper [5] is to analyze the performance of power control schemes in CDMA systems. By analyzing two different cases, i.e., with and without power control in the CDMA, the paper shows that the radio capacity can be improved by using a proper power control scheme. This is because the power control scheme provides a necessary power delivery to the close-in mobile unit and reduces the total power for the mobiles at the boundary of the cell. The study also includes some natural attributes of CDMA, which include voice activity cycles, soft handoff, no guard time, less fading, no need or easy frequency management and coexistence. A detailed example is given to show that CDMA can provide higher capacity as compared with FDMA and TDMA systems.

The analysis for other techniques that is commonly used in CDMA system can be found in other papers [27-32]. These studies include soft handoff, power control schemes, admission control, mobility, etc. Some of these techniques are unique for CDMA from FDMA or TDMA systems. Thus, carefully studies can perfect CDMA to cater for the high-demand on the spectrum consuming before a new advanced access technique inheriting it.

2.1.5 Inter-cell Interference in TDD-CDMA Systems

There are basically four types of inter-cell interference in TDD-CDMA systems: BS-to-MS, MS-to-BS, BS-to-BS and MS-to-MS. As shown in Figure 2.2, the downlink power of BS3 gives MS2 a BS-to-MS interference; the uplink power of MS4 gives BS1 a MS-to-BS interference; the downlink power of BS2 gives BS1 a BS-to-BS interference; and the uplink power of MS1 gives MS3 a MS-to-MS interference. The first two types of interference, referring to STS interference, i.e., BS-to-MS and MS-to-BS interference, also exist in the FDD-CDMA systems and it is not considered in

this section. The other two types of interference, referring to CTS interference, are unique in TDD-CDMA systems. In literature, some papers [21, 24] study the effect these four types of interference to the system performance.

Figure 2.2: Four types of interference in TDD-CDMA system

In [24], Holma models different types of interference by setting different frame synchronization error, a . The case $a = 0.01$ is considered as fully synchronized frame. In this case, all cells are in the same transmission direction, i.e., all cells are in the uplink transmission or all cells are in the downlink transmission. This case corresponds to the first two types of interference. Similarly, $a = 0.99$ is assumed that TSs are employing asymmetrical transmission, i.e., one BS is receiving while the adjacent BS is transmitting, or the MSs in one BS are receiving while the adjacent cells' MSs are transmitting. This case represents the later two types of interference. Holma gives very important conclusions that for the downlink, the performance is not sensitive to the asymmetrical transmission. In each downlink TS, almost the same performance is achieved no matter whether $a = 0.01$ or $a = 0.99$. But for the uplink, the capacity degrades almost linearly as a increases.

2.2 Overview of Channel Allocation Schemes

In order to efficiently use the limited radio spectrum, channel allocation algorithm must be used to minimize the interference and increase the capacity of the system. Channel allocation algorithms [11] are classified as fixed channel allocation (FCA), dynamic channel allocation (DCA) and hybrid channel allocation (HCA). In this section, we review different FCA and DCA strategies in detail including performance comparison among them. We will present the channel allocation schemes used in TDMA and CDMA cellular systems.

2.2.1 Fixed Channel Allocation Schemes in TDMA Cellular Systems

In FCA [33], the entire area is divided into clusters with each cluster of N cells which depends on the required SIR. A certain number of channels (known as nominal channels) are assigned permanently to each cell. The channels assigned to cells are based on the co-channel interference constraints [11]. Any call attempting to connect to the system can only be allocated to an unused channel of its current positioning cell. If all the channels in that cell are busy, this call is blocked. FCA is an easy and basic allocation algorithm that is widely used in the cellular system we use today. FCA deals with the case that the networks operators have some information of the traffic distribution for each cell. However, the temporal and special fluctuation of the traffic load makes the prediction of the traffic load difficult. Thus, some cell may be expected with lower blocking probability and other with very high blocking probability. This results in poor channel utilization and unsatisfied QoS.

With FCA, two important techniques can be used to solve the unstable traffic problem and improve the performance. They are channel borrowing and reuse partitioning.

2.2.1.1 Channel Borrowing

In channel borrowing schemes [34, 35], a cell which empties its nominal channels can borrow a channel from the surrounding cells to accept a new call as long as this borrowing channel validate the co-channel reuse constraints. In the simple borrowing algorithm, a nominal set is assigned to each cell, as in the FCA scheme. After all the nominal channels are used, an available channel from a neighboring cell is borrowed. To be available for borrowing, the channel must not interfere with existing calls in other cells. Although channel borrowing can reduce the call blocking of the borrowing cell, it prevents the donor cell and the co-channel cells of donor cell from using the borrowed channel. In Figure 2.3, if a nominal channel, j , of cell A is lent to cell B , this channel cannot be used in all neighboring co-channel cells, i.e., cells C and D , of cell A . We assume that the reuse factor is 7 in Figure 2.3.

Figure 2.3: Illustration of borrowing algorithm based on a reuse factor of 7

As shown in [34], the simple borrowing algorithm gives lower blocking probability than FCA under light and moderate traffic, but FCA performs better in heavy traffic conditions. This is due to the fact that in light and moderate traffic conditions, borrowing of channels provides a means to adapt to the fluctuations of offered load and the number of donor cells is small. However, in heavy load, this borrowing may cause locking of many more surrounding cells, resulting in decreasing the system

capacity. In the simple borrowing algorithm, borrowed channels remain in the borrowing cell until the calls finish. This may also cause the high blocking probability in the donor cell.

To settle this problem, some other channel borrowing schemes are also proposed. The borrowing of a channel is based on some principles, e.g., channel sequence number or borrowed direction, so that the borrowing causes least interference to the whole system. Among these schemes, an algorithm called ordered channel assignment scheme with rearrangement (ODCA) introduced in [35] gives a good example. In ODCA, when a call requests a service, BS checks to see if there are any nominal channels available. If there are channels available, the user will be assigned one channel in an ordered sequence. The order of the channel is predefined in the system and the lowest numbered free channel is always first selected. If this is not the case, the BS will borrow a free highest numbered channel from a neighboring cell. During the period of borrowing, if a nominal channel in the own cell is free, the user is switched to use the nominal channel and frees the borrowing channel to the neighboring cell. Thus, ODCA scheme frees the borrowing channels as soon as possible. In this way, ODCA releases the channels of the blocking cell and results in high spectrum usage efficiency.

2.2.1.2 Reuse Partitioning

Reuse partitioning (RP) [36] is an effective concept to achieve high spectrum efficiency in cellular systems. RP scheme defines different con-centric regions in a cell as shown in Figure 2.4. Different regions use different sets of channels with different reuse factors. The underlying principle behind RP is to reduce SIR for those

units that already have more than adequate transmission quality while offering greater protection to those units that require it [11].

A practical example is shown in Figure 2.4. A cell in this case is divided into three concentric regions with difference radii of R_1 , R_2 and R_3 respectively.

Since the inner region with radius R_1 is closer to BS located at the center of the cell, the power received from this region is higher than the outer regions. The inner region can tolerate higher interference than the outer regions. Therefore, inner region could allocate a channel with lower reuse factor to users. From [37], each radius and the reuse factor must satisfy the following formula

$$\frac{N_1}{R_1^2} = \frac{N_2}{R_2^2} = \dots \frac{N_i}{R_i^2} \quad (2.3)$$

where $N_1, N_2, \dots, N_i$ are the reuse factors of the i_{th} region. And $R_1, R_2, \dots, R_i$ are the radii of the i_{th} region from the base station. RP gives the possibility that the reuse distance of the co-channel cell of the inner region is shorter. In this way, the overall reuse distance is decreased and channels could be reused more frequently to provide larger system capacity. Reuse partitioning can also be used in the FCA and DCA schemes [38, 39].

Figure 2.4: Reuse partitioning architecture

2.2.2 Dynamic Channel Allocation Schemes in TDMA Cellular Systems

Due to the time-varying and special variations of traffic load in cellular systems, FCA scheme, together with the improvement techniques, cannot use the available channels efficiently. To improve the system capacity, DCA schemes have been studied for many years. Unlike FCA scheme, the channels in DCA scheme are not permanently allocated into the cells. Instead, all the available channels are kept in a central channel pool. If a new call arrives in a cell, this cell picks up an available channel from the pool and assigns the channel to the new user. After a call is completed, its used channel is returned to the pool for other calls. Generally, any channel can be selected in any cell to be used as long as the selection of the channel does not violate the co-channel interference constraints. For example, if a channel j is used in cell A , this channel j cannot be used in the surrounding cells. Otherwise, strong interference is generated for each user to the surrounding cells. DCA has been used in the Digital European cordless telecommunication (DECT) system and cordless telephones known as CT2 [40]. The main idea of all DCA schemes is to evaluate the cost for all available channels and select the one that cause the least influence to the whole system. The cost selection functions define different dynamic channel allocation schemes .

Thus far, various of DCA schemes have been proposed for cellular systems. Based on the controller manner, they can be divided into centralized and distributed DCA schemes. In centralized DCA schemes, a channel from the central channel pool is assigned to a call for temporary use. And the cost function of a specific DCA scheme is calculated from the whole system point of view. Several research works have shown that centralized DCA schemes can produce near-optimum channel allocation

Chapter2: Literature Review

solution [47-49]. But at the same time, centralized DCA schemes also increase the burden of the network because of the frequent-exchanged centralization overhead.

Distributed DCA schemes, on the other hand, attract more attention due to their simplicity of implementing the algorithm based on the information of the cell itself and/or its near surrounding cells. The proposed distributed DCA schemes are either based on the local information about the channel availability (network-based) [44, 50] [51-53] or based on the interference information received in each channel (measurement-based) [19, 39, 46, 49, 54-58]. Network-based DCA schemes use the predicted information about the SIR from the surrounding cells to calculate the cost. Thus, they must have a relative regular cell shape and satisfy the SIR requirement at the worst place of the region. This produces a lot of exchanged information between surrounding cells. And this exchanging information may bring the network to have a big burden under heavy traffic loads. Measurement-based DCA schemes perform better in terms of information overhead because they just need local SIR information for each channel. And the capacity is also improved due to the fact that each user adjusts its transmission power to meet the minimum required SIR. But measurement-based DCA schemes are more likely to be interfered with respect to ongoing calls in the surrounding cell. This may cause the interruption of the existing services, deadlock of the power control and the instability of the system performance.

2.2.2.1 Centralized DCA Schemes

The most simple centralized DCA scheme is *first available* (FA) [11, 59]. FA selects the first available channel within the reuse distance for a new call to be used. Since there is not cost function for this scheme, the total computational time is minimized. It is reported that FA can give about 20% improvement as compared with FCA scheme

for low and moderate traffic load. In [42], a *Bookkeeping* process is done for every available channels in the system. Then a channel that has the most number of blocked cells by the first and second tiers of the cell is selected for the new arrival call. This proposed scheme is much better than the randomly chosen and FA centralized DCA schemes. In [59], another proposed scheme *Selection with Maximum Usage on the Reuse Ring* (RING) also selects the channel which is in use in the most cells of co-channel set. If more than one channel has the same value, a special selection is performed [11]. Another centralized DCA scheme called *Mean Square* (MSQ) [59] selects the first available channel that minimizes the mean square of the distance among the cells with the same channel.

Compared to FCA schemes, centralized DCA schemes can flexible adapt to the traffic variation among cells at the expense of a high centralization overhead. Thus, channels can be efficiently used to increase the capacity for the whole networks. In order to further improve the performance of DCA schemes in high traffic load scenario, channel reassignment techniques are proposed. Channel reassignment technique is to reallocate an existing user to another channel, which is either released in the current cell or in the surrounding cell. The objective of this reassignment technique is to keep the reuse distance in the system remaining as short as possible. In this way, more traffic can be carried per channel from the system point of view.

2.2.2.2 Distributed DCA Schemes

Network-based DCA Schemes

Local Packing Dynamic Distributed Channel Assignment (LP-DDCA) is a simple distributed DCA scheme proposed in [51]. Each base station holds an augmented channel occupancy (ACO) matrix. ACO has the information about the allocated

channel status both with own cell and with neighboring cells. If any channel in ACO is empty for the own and the surrounding cells, that means this channel can be used by a new arrival call. LP-DDCA selects the first such channel to be used. The allocating or releasing of the channel in any cell triggers the updating process both in its own cell and the surrounding cells.

Moving direction (MD) [60, 61] was proposed for one-dimensional microcell systems. In one-dimensional microcell systems, forced call termination and channel changing occur frequently because of the fast speed of the mobile car and relative small size of the cell. The objective of MD scheme is to decrease the probability of call termination and channel changing. MD first tries to detect the moving direction for the mobile car. A channel is selected among the available channels that have been allocated to the mobile moving with the same direction in other co-channel cells. The MD channel allocation scheme can be explained with Figure 2.5.

Figure 2.5: Moving direction: a network-based distributed DCA scheme

As shown in Figure 2.5, there are four available channels, *a*, *b*, *c* and *d*, in the channel pool and *DR* is the minimum reuse distance in this system. The new arrival call in cell 1 that requires a channel from the system moves in the same direction with another mobile using channel *a* in cell 5. Since the distance between cell 1 and cell 5 is larger

Chapter2: Literature Review

than DR, MD scheme selects channel a to be used by the new arrival call. When the mobile with a new arrival call move to cell 2, the mobile using channel a in cell 5 is also likely to move out of cell 5 to cell 6. The reuse distance between these two mobiles using channel a is still larger than DR. Thus, both of these two mobiles can continue to use channel a after handoff. This scheme lowers the probability of changing channel and the probability of forced termination of the existing calls. The MD scheme can work well in the one-dimensional microcell systems. However, it is difficult to implement MD scheme into the two-dimensional systems.

In [62], a *dynamic channel allocation with interference information* (DCA-WI) scheme is proposed. In this scheme, each cell has an interference information table (IIT), which has enough information about the channel status of the own cell and the surrounding neighboring cells. A cost function, based on the number of locked channel in surrounding cells, is used to calculate the expense when a channel is allocated to the new MS. The channel that provides the least interference to the surrounding cells is allocated to the new arrival call.

In [63], a *Hopfield Neural Network* (HNN)-based scheme that only requires local information of the surrounding cells is proposed. HNN relies on minimizing an energy function, which is related to the channels assigned, interference, reuse pattern, etc., to model a channel assignment problem. It is reported in [64] that HNN-DCA model has the advantage of having regular algorithmic structure, which is well-suit to digital machine. However, HNN-based schemes also have the disadvantage of instability arising from non-convexity of the algorithm. And only with carefully design, can neural DCA schemes become practical applications [65].

Measurement-based DCA Schemes

In the network-based DCA schemes, the channel reusability depends on MSs in the worst location or at cell boundary in most of the cases. The exact positions of the MSs are not considered. These schemes omit the fact that MSs may not be at the worst location at all time. Thus, the channel reusability distances in these schemes are far more than enough. Measurement-based DCA schemes, on the other hand, allocate a channel to a new arrival call depending on the real-time interference condition. A typical example of measurement-based DCA scheme used in wireless communication system is DECT [40].

The simplest measurement-based DCA scheme is *Sequential Channel Search* (SCS) [55]. In SCS, the first available channel that can satisfy the minimum required SIR is selected by the system. SCS scheme supports more traffic as compared with FCA and other network-based schemes. But SCS also cause unexpected channel interruptions to the existing MSs. Thus, another scheme, called *Minimum Signal-to-Noise Interference Ratio* (MSIR) [55] is proposed. In MSIR, a channel is selected only when it experiences the least interference (an unused channel or lightly loaded channel) among all the available channels. It is reported that MSIR has lower interruption probability than SCS. But it increases the blocking probability at the same time. From the simulation, it is found that there is a tradeoff between avoiding the call blocking probability and avoiding call interruptions in the measurement-based DCA schemes.

Autonomous Reuse Partitioning (ARP) [39] is a measurement-based DCA scheme applying reuse partitioning technique. In ARP, channels are numbered and viewed in the same sequence in each cell. A new call searches for the available channel from the lower numbered channels and the first channel that satisfies the minimum SIR is

Chapter2: Literature Review

selected for the new arrival call. The reuse pattern within each cell is similar to FRP, in which the area of the cell is divided into several concentric areas. ARP is a relative simple decentralized dynamic channel allocation. The channels in the higher order are reused at shorter distance. Thus, significant traffic improvement can be achieved and higher interference could be tolerated at the same time.

Dynamic Channel Selection (DCS) is another fully distributed measurement-based DCA schemes proposed in [66]. DCS assumes that MSs have the information about the interference of each channel. Based on a particular interference probability cost function, which is related to the received signal power, channels availability, received interference, etc., DCS selects a channel which minimizes the interference probability.

Channel segregation (CS) is proposed in [67] as a self-organized DCA scheme. In CS, each cell has the information of selection probability for each channel. The selection probability is defined by the total number of successful and rejection use of this channel. When a new call arrives, the channel with the highest selection probability is first selected. Then, the received power level for that channel is evaluated to determine whether this channel is a free channel or not by defining an interference threshold. If this channel is free, it can be used by the new call. Otherwise, the channel with next highest selection probability is evaluated. After the evaluation of a channel (no matter whether it is free or not), channel updating process is followed. In [68], another scheme combining CS and interference sensing [54] is proposed to further increase the system performance. It is found in [67] that CS-related schemes are adaptive to the traffic changes of the system. It can reduce the blocking probability greatly comparing to FCA and other measurement-based DCA schemes. And the CS-related scheme can also decrease the number of intracell handoffs.

With an infinite effort of reallocating the channels among cells, measurement-based DCA in [58] declares to have the optimum channel efficiency among others. But, again, this can cause the cellular system unstable because of the continuous reallocating.

Figure 2.6: Example of FCA and DCA with a reuse factor of 7

2.2.3 General Comparison of Channel Allocation Schemes in TDMA Cellular Systems

The analysis [69] and simulation works [41, 59, 70] show that under low traffic load, DCA schemes provide a good system performance. This is because DCA scheme can flexibly arrange the channels among cells and this is not true in FCA scheme. However, FCA schemes outperform DCA schemes under high traffic load due to the random channel allocation nature of DCA scheme. Under a high traffic load, the best way of allocating channel i is shown in Figure 2.6 (a) to maximally pack the co-channel cells as close as possible. FCA can satisfy the minimum reuse distance requirement without wasting the radio frequency. DCA scheme may not allocate channel i with the minimum reuse distance among co-channel cell. As shown in

Figure 2.6 (b), the distance between co-channel cells is larger than the minimum one. Since the available channels in channel pool of DCA scheme under high traffic load is less than that under low traffic load, the choice to allocate a free channel to maintain the minimum reuse distance among other co-channel cells is small. Therefore, the flexible channel arrangement of DCA scheme is not efficient in heavy traffic load.

In terms of non-uniform traffic distribution among cells, which may be caused by hot-spot or time-variation of the traffic load, DCA schemes provide much better performance due to the fact that it can allocate the channels flexibly. On the other hand, FCA has fixed number of channels in each cell and cannot be adaptive to the traffic variation among cells.

In terms of algorithm complexity, FCA is a simple and quick way to allocate a channel to a new call. In FCA, BS only needs to know the channel status of its own cell to make a channel allocation determination. However, DCA needs either surrounding cells' information or detection of the interference level to make a determination by calculating a certain cost function. A new call may be delayed for a while before an available channel is ready for it.

2.2.4 Multiple Service Supporting

Various works have been done to support multiple services [71-73]. One way is to split the data into two or more parts and transmitted them independently through different channels [71, 72]. In [71], the system supports two types of services, namely broadband service and narrowband service. If a narrowband service requires a connection from the system, one channel will be allocated if there is a free channel in the system. If a broadband service requires a connection from the system, two or more channels will be allocated to the new service if they are available.

Another way to support different types of service is to use different kinds of network and each service is transmitted through certain network [73]. In [73], the total system uses hierarchical cellular structure consisting of two cell layers such as macrocell and microcell. Voice traffic is allocated to macrocells; while multimedia traffic is assigned to microcells. When there are not enough channels in each cell layer, the system performs the partial cell overflow and switching-back strategy. The reason of using this hierarchical cell structure is:

- First, not only does the hierarchical cellular system increase channel capacity, it also uses channels efficiently in accordance with traffic load. So, the cells with a small radius provide a more efficient system economically for high traffic densities.
- Next, it can efficiently provide services for subscribers according to characteristics of traffic such as mobility.

In these papers, they all assume that the reuse factor for all types of services is same.

2.2.5 Channel Allocation Schemes in TDD-CDMA System

From the study of [24], we can understand that the newly introduced CTS interference in the asymmetrical transmission in TDD-CDMA system can degrade uplink capacity severely. Some papers suggest that each cell should have the same switching point (SSP) [74], which is the changing point between uplink and downlink TS in one frame, to avoid problem of CTS. However, different cells may support different types of services and different traffic load. If a single switching point is fixed for the whole networks, the flexibility beauty of TDD-CDMA to support unbalanced traffic among cells is lost. Based on the characteristic of cellular, different channel allocation schemes [75-85] are proposed to increase the TDD-CDMA capacity. Holma [24]

Chapter2: Literature Review

suggests that dynamic channel allocation should be used in TDD-CDMA system to optimize the resource allocation and expects that dynamic channel allocation can reduce the interference between uplink and downlink as well.

The most simple one called *adaptive switching point* (ASP) is proposed in [75]. In ASP, all cells have the same switching point at the beginning of the allocation. However, if any cell cannot allocate a new MS but still have an empty time slot, the switching point for the current cell can be shifted to allocate this new MS. ASP scheme attempts to allocate more MSs without considering too much about the CTS interference. The simulation results in [75] show that ASP can provide some improvement in terms of number of satisfied users as compared with SSP.

Another novel scheme called *TS-opposing* scheme is proposed by Haas and McLaughlin [76]. With TS-opposing, a MS attempting to transmit power higher than the maximum power in a given TS reports this information to its base station (BS). If there is some other TS in the surrounding cells that can cause less interference to that given TS, the system will switch the users between high interference TS and low interference TS of the surrounding cells. The goal of TS-opposing scheme is to reduce the occurrence of the opposite direction high interference to the interested cell. The key result of *TS-opposing* scheme is that this DCA algorithm enables neighboring cells to adopt different ratios of asymmetry without significant capacity loss.

2.2.5.1 Interference Avoidance: Region Investigation

One way of solving CTS problem for uplink MSs is to avoid MSs that cannot tolerate high interference from allocating a CTS. In [77], a dynamic slot allocation scheme called *zone division* is proposed to avoid the interference between cells. A simple two-cell model is used in [77]. As shown in Figure 2.7, each cell is divided into six regions

by different distances between two cells and within each cell. Users which are located in the predefined higher priority region are first allocated to the CTS. For example, the users which are located in region 5 in both cells will first be allocated to the CTS. This is because MSs in these two regions generate the least interference to each other. And this is followed by the region 6, region 2/4 and region 1/3. The idea of this zone division is to maximizing the spatial separation between inter-cell interferers such that the interference level from the other cell will be kept to a minimum. The simulation results of [77] show that a substantial capacity gain with respect to the same switching point scheme is achieved in this zone division scheme.

Figure 2.7 Zone division scheme

A similar scheme called *inner-outer region* is proposed in [78] [86] and [80]. In this scheme, a two-cell model is also used. But each cell is divided into two regions: inner-region and outer-region. The CTS can only be allocated to those MSs that are within the inner-region. [78] reports that the size of inner-region area does not cause any effect to the finally results if proper time slot is selected. The paper provides the simulation results to show the inner-outer region idea. But, no clear reasons or analyses are made to prove the proposed idea because the authors believe that it is too complex to give a mathematical calculation.

In these allocation schemes, two-cell model is used. Thus, it is difficult to extend the idea to a practical multi-cell model.

2.2.5.2 Interference Avoidance: New Antenna Techniques

Another research direction to avoid the asymmetrical transmission interference is to adopt new antenna techniques in TDD-CDMA systems [81-84]. In [82, 83], authors combine sector antennas with time slot allocation methods to avoid the opposite direction interference. And in [84], Choi suggests to employ a pre-RAKE transmitter to improve downlink capacity in TDD-CDMA and apply spatial diversity to improve uplink capacity. The authors in [81] study the performance improvements by adopting antenna beamforming techniques to suppress the opposite direction interference. Two types of antenna beamformers, conventional beam-steering technique and *minimum-variance distortionless-response* (MVDR) beamformer, are investigated in this paper. Chen concludes that by adopting the MVDR beamformer in the uplink and the beam-steering in the downlink, the strong opposite direction interference can be effectively suppressed. Thus, asymmetric traffic services are allowed in every cell within the networks.

In [85], Wang and Huang propose a directional antenna assisted resource allocation scheme. In this scheme, a concept called *virtual cell*, which is defined as the same coverage area of a cell but is composed of three sectors from the three adjacent BSs, is used. The main propose of the slot assignment scheme is to set the same switching point in three sectors of each virtual cell, while neighboring virtual cells can have different settings on their switching points. As a result, the directional antenna receives no interference from the CTS transmission and the surrounding cells that may cause interference are in the same transmission direction. In this way, the

problem of CTS transmission in TDD-CDMA system can be avoided. The simulation results show this channel allocation scheme substantially reduce the strong interference in CTS and a high system capacity is achieved.

2.3 Overview of Multihop Cellular Systems

Multihop cellular networks have been proposed as extension to the conventional single-hop cellular network by combining the characteristics of ad hoc networks. Unlike the current centralized cellular networks where every communication has to go through the central base station, multihop cellular networks can provide the possibility of *peer-to-peer* (mobile to mobile) communication as well as *relayed* communication through other fixed and/or mobile terminals for future generation cellular systems. Due to the potential of the multihop relaying to enhance coverage area, data rate, system capacity and flexible adaptation, multihop cellular networks have been attracting considerable attention for 3G and beyond systems.

With the increasing amount of subscribers, limited bandwidth has become the bottleneck of wireless communication. Next, it is not practical to allow simultaneous transmission and reception in the same frequency band due to the large difference between transmission and reception signal power levels. Thus, TDD duplexing method transmission becomes a suitable access mode for the multihop cellular network. Besides, the multihop transmission means that it will cost more radio resources for just one end-to-end communication. And different selection algorithms of the relay station (RS) could give different performances to the overall system.

2.3.1 Why Multihop

First, we consider a simple example where mobile A wants to transmit data to mobile C as shown in Figure 2.8.

Figure 2.8: Direct and multihop link

If the minimum required received signal power for each mobile is P , for the direct link, we have

$$P_{direct} = P \times d_{AC}^u \quad (2.4)$$

For the relay link, the total transmitted power is

$$P_{relay} = P \times (d_{AB}^u + d_{BC}^u) \quad (2.5)$$

where u is the path loss exponent depending on the environment of the signal transmission. The nominal value of path loss exponent u is from 2 to 4. If transmission angle θ in Figure 2.8 is an obtuse angle, it is always satisfied that

$$P_{relay} < P_{direct} \quad (2.6)$$

(2.6) means that if we break the original direct link into two or more relaying links, the total transmission power can be reduced. In CDMA system, this reduced total transmitted power can result in decreasing the interference to the system and thus, increasing of the system capacity. On the other hand, if the maximum transmitted power remains same, a larger transmission region or a higher data speed can be

achieved from the relaying link. This permits BS to connect with a MS who is out of the coverage area of center BS.

2.3.2 Overview of Multihop Cellular Architectures

In multihop cellular systems, a MS has multiple interfaces such that it can work under different transmission modes. Since the ad-hoc characteristics of multihop system can lead to the problem of routing, the network must have certain mechanism to discover the system topology and find best route for a new MS. In literature, many multihop cellular architectures, e.g., Multihop Cellular Network (MCN) [20], Unified Cellular and Ad-hoc Networks (UCAN) [87], Integrated Cellular and Ad-hoc Relaying (iCAR) [88], Opportunity Driven Multiple Access (ODMA) [89], multihop Virtual Cellular Network (VCN) [90], etc., are proposed to cater for different requirement.

In [20], Lin and Hsu propose a MCN architecture to reduce the transmission power (so is the coverage area) of BS and MS. If the destination MS is within the same cell of source MS, other MSs can be used to relay packets to the destination. BS keeps the topology of the network by exchanging information with each MS and selects a shortest path between source and destination. If the destination is not within the same cell of the source MS, packets can be sent first to some BS, probably through multihop link, and then forwarded to the destination, probably also through multihop link. The goal of MCN architecture is to increase the spatial reuse of the channels. And this is realized by reducing the transmission power for both MS and BS. It is demonstrated that the half reduction of the transmission power of MS and BS provide the best tradeoff between a good spatial reuse and the number of hops for each source-destination link.

In UCAN [87] architecture, each MS integrates cellular CDMA interface and IEEE 802.11b interface that can work with ad-hoc mode. BS monitors the quality of the signal in the downlink channels. When the downlink channel is *bad*, BS will first transmit the data packets to the RS via cellular mode, which is another MS device; then RS will forward the packets to the MS via the 802.11b mode. Two proxy discovery protocols are proposed in [87], a greedy scheme and an on-demand scheme. The goal of the UCAN architecture is to improve the downlink system throughput. Finally, the paper discusses that on-demand proxy scheme can deliver the highest throughput at the expense of high uplink overhead. The greedy scheme provides some similar lower results with much lower uplink overhead.

In [88], Wu *et al.* propose an iCAR architecture. New equipments, *ad hoc relaying stations* (ARSs), which are located fixedly over the service area, are introduced in iCAR to relay packets between MS and BS. Like UCAN, each MS in iCAR is equipped with two interfaces, one to communicate with cellular system and another to communicate with ARS. Different from other multihop architectures, the main goal of iCAR is to balance the traffic load between cells. As shown in Figure 2.9, [88] proposes three relaying strategies, *primary relaying*, *secondary relaying* and *cascaded relaying*. Figure 2.9(a) illustrates the primary relaying strategy. If all the channels in cell A are occupied, MS first transmit its packets to ARS; then ARS will forward the packets to the surrounding cell that has some channel available. Figure 2.9 (b) demonstrates the secondary relaying strategy. If all the channels in cell A are occupied and MS A cannot find a ARS nearby, a MS B in cell A will give up its channel to MS A and uses ARS to forward its packets. Figure 2.9 (c) presents the cascaded relaying strategy. If all the channels in cell A and cell B are busy, MS C in cell B surrenders its

current channel to MS *B* in cell *A* and is relayed to cell *C* through a ARS. Then the same strategy as secondary relaying will be used. The results in [88] show that iCAR, with a limited number of ARSs placed at the center boundary of hexagonal cell, can balance the traffic among cells, reduce the call blocking probability and improve the system throughput.

Figure 2.9: Multihop architecture: iCAR

ODMA is the only architecture that has been put to the standardization procedure [89] within 3rd Generation Partnership Project (3GPP) standard. ODMA can be considered as an extension of the current Universal Mobile Telecommunications Service (UMTS) TDD transmission mode. The principal goal of ODMA is to increase the MS's data rate at the boundary of the cell. As shown in Figure 2.10, MSs that have to transmit

with low data rate in UMTS TDD mode can switch to the ODMA mode. Thus, high data rate can also be realized in the area near the cell boundary. Besides, MSs that cannot be covered in UMTS TDD mode can also transmit with low data rate via ODMA mode. Thus, with multihop transmission, ODMA can provide high data rate over a larger coverage area. And each MS only needs to equip with only one cellular transmission interface.

The frame of ODMA is similar to UMTS-TDD standard. However, in ODMA, some TSs are used for relaying purpose. Bursts are sent to broadcast the cost to send data from that MS. The neighboring table, which contains the cost of each neighbor, is established in each MS. And the data packets are sent based on different routing protocols from this cost table. The routing protocol, power control and other designing issues have been studied in literature [91-94].

Figure 2.10: ODMA model

In [90], Kudoh and Adachi propose a multihop Virtual Cellular Network (VCN) to decrease the transmission power of the wireless port while increasing frequency efficiency. As shown in Figure 2.11, each multihop VCN consists of a central port

and a lot of distributed wireless ports. The uplink signal of wireless port is forwarded to central port, perhaps in multihop route. The downlink signal from central port is multicasted directly to the wireless port. The relaying routing algorithm in multihop VCN is based on minimum total transmit power scheme introduced in [95]. And slow transmit power control is assumed in [90]. From the results in [90], the authors suggest that the maximum number of allowable hops should be limited in certain number, e.g., 5 hops in [90], to avoid unnecessary large time delay. [90] also proves that this maximum number of allowable hops is irrespective of the path loss exponent and the shadowing loss. The multihop VCN structure can reduce the transmission power of the wireless port significantly while remaining a reasonable time relay between source wireless ports to central port.

Figure 2.11: Multihop VCN model

Besides the above mentioned architectures, other multihop cellular architectures, based on different optimization goals, are also proposed in [79, 96-99] .

2.3.3 Comparison of Different Multihop Cellular Architectures

In this section, we compare some of these architectures based on their goals, interfaces and the types of relay station.

For the iCAR, MCN, UCAN and ODMA architectures, MSs must register to the BS so that they can be supported either by direct or by multihop link transmission. In other word, those MS that are out of the coverage of BS control channel cannot be supported in these architectures. BSs take the responsibility to find a proper routing for the requiring MS. A common goal of these architectures is to improve the capacity for the proposed system. But this may be achieved by different schemes or from different (single MS or system) points of view by different architectures.

For example, iCAR and MCN increase the capacity for the whole system. iCAR balancing the traffic load from *hot* cells to *cool* cells such that more MSs can be accepted by multihop system. MCN increases the spatial reuse efficiency to accept more users within the same cell. UCAN and ODMA are alike to increase the data rate for some single users. But the overall system capacity may not be increased due to the fact the more radio resources are used for a single MS. Multihop VCN decreases the transmission power of the wireless port.

Another important issue of multihop cellular systems is the interface type. Besides the original cellular interface, some other interfaces are also introduced. For example, iCAR also integrates WLAN interface to each MS such that MS can communicate with ARS. Similarly, UCAN introduces ad-hoc interface when MS tries to relay data packets to final destination MS. Differently, MCN, ODMA and Multihop VCN use single cellular interface to communicate both between RS and MS and between BS and RS/MS. A single interface keeps the transmission unit of mobile devices simple.

Chapter2: Literature Review

But the simultaneous transmission (sending and receiving) in one frequency cannot be realized for full-duplexing unless two or more radio frequency-bands are used. This problem can be solved by using TDD method of duplexing. On the contrary, multiple interfaces integrating into the same device permit MS to transmit and receive for both directions at the same time. Better QoS can be satisfied. But the complexity of the transmission unit makes the devices costly.

RS type is a very important factor in the designing of the multihop cellular systems. The fixed positions of RSs at the strategic locations, e.g., iCAR, make the designing more complicated. But after the establishing of the networks, the routing scheme becomes a simple task. Less overhead and control information are needed in the system like iCAR. However, if MS can be a RS, it makes the network to be deployed easily. In such a case, the routing strategies and power consumption schemes must be carefully studied to achieve fair and efficient services. The summary of the some multihop cellular schemes is presented in Table 2-1.

Table 2-1: Comparison of some selected multihop cellular architectures

Architecture	Main goal	Interfaces type	RS type
<i>iCAR</i>	Balance traffic load between cells	Cellular and WLAN	Fixed at strategic locations
<i>MCN</i>	Increase spatial reuse efficiency	Cellular	Mobile
<i>UCAN</i>	Improve the downlink data rate	Cellular and MANET	Mobile
<i>ODMA</i>	Increase the data rate at the boundary of cells	Cellular	Mobile
<i>Multihop VCN</i>	Decrease the transmission power of wireless port	MANET	Mobile

Chapter 3: Fixed Channel Allocation with Channel Partitioning

3.1 Introduction

The trend of the wireless communication systems is to provide various types of services such as voice, data message, video conference, etc. Due to the limited radio resources with international agreements, how to achieve the optimum system capacity becomes a paramount issue. In this chapter, we introduce a channel partitioning (CP) idea employing different reuse factors to support these multiple services requiring different SIRs in a TDMA cellular system. CP scheme divides the total system channels into two or more sets. Each set of the channels supports traffic with lower or higher reuse factor. From the system point of view, the overall reuse factor becomes smaller and the capacity of the system can be improved.

In this chapter, we first introduce and analyze this CP with FCA scheme, called fixed channel partitioning (FCP). Two types of services requiring different SIRs are to be supported for fundamental study. Thus, we use a large reuse factor to support the high SIR required service, i.e., data service. And we use a small reuse factor to support the low SIR required service, i.e., voice service. In FCP, we allocate fixed number of channels to large reuse factor requiring service as well as small reuse factor requiring service. FCP with stationary users is first analyzed with a two-dimensional Markov chain. *Switching* technique is also introduced to further improve the system capacity. After that, we also study the effect of mobility to the performance of FCP scheme. A three-dimensional Markov chain is developed to support two types of services. Then, a simpler approximated model is proposed from which FCP performance can be

expressed with close-form solution. The analysis and simulation results show that our proposed FCP scheme can improve the capacity of the TDMA cellular system by giving a suitable channel partitioning to each service. And the improvement of FCP over FCA is not constrained by the factors such as mobile speed or Grade of Service (GOS) factor. Finally, the limitations of the proposed model and the relative assumptions are discussed such that more general study can be established for future research work.

3.2 FCP with Stationary Users

3.2.1 Analysis Model

In our model, for simplicity, we assume to support two types of services: service type1 (S_1) and type2 (S_2). We assume that the reuse factor, N_1 , of S_1 is smaller than the reuse factor, N_2 , of S_2 . The supporting of more services may depend on the reuse factors they require. The fraction of arrival rate for S_1 and S_2 is assumed to be γ_1 and γ_2 , respectively. Calls are assumed to be uniformly distributed over the service area and arrive at the system according to a Poisson process with a per cell arrival rate of $\lambda = \lambda_1 + \lambda_2$, where λ_1 and λ_2 is per cell arrival rate for S_1 and S_2 calls, respectively. Therefore, we have

$$\lambda_i = \gamma_i \times \lambda \quad i=1 \text{ or } 2 \quad (3.1)$$

An arriving call that cannot be assigned a channel is blocked and departs the system. Call durations are exponentially distributed for S_1 and S_2 calls with a mean of $1/\mu_1$ and $1/\mu_2$, respectively. The offered traffic load (in Erlangs) for S_1 and S_2 of a cell is defined as ρ_1 and ρ_2 respectively. Therefore, we have

$$\rho_i = \lambda_i / \mu_i \quad i=1 \text{ or } 2 \quad (3.2)$$

And the total traffic load of the system is given by

$$\rho = \rho_1 + \rho_2 = \lambda_1 / \mu_1 + \lambda_2 / \mu_2 \quad (3.3)$$

In FCP, the total system channels are partitioned into two groups and each group of channels support service with lower (S_1) and higher (S_2) reuse factor. Let C_1 and C_2 be the number of channels supporting S_1 and S_2 calls respectively in each cell (as traffic1 or traffic2 channels) and $C_{fcp}=C_1+C_2$ be the total number of channels per cell. If the total number of system channels is m , it must satisfy

$$N_1 C_1 + N_2 C_2 \leq m \quad (3.4)$$

Since FCP uses two reuse factors instead of the highest reuse factor for channel allocation as used in a conventional FCA, the average reuse factor of FCP is smaller. Thus, C_{fcp} is larger than the number, C_{fca} , of channel per cell in FCA, i.e., $C_{fca} = m / N_2$.

3.2.2 Performance Study of FCP with Stationary Users

Because the reuse factor for S_1 is smaller than the reuse factor for S_2 , S_1 can use traffic2 channel without violating the co-channel interference constraints. Thus, in our proposed FCP, we allow the so-called *overflow* technique. When a new S_1 call arrives at the system, it is first assigned to an unused traffic1 channel. If all traffic1 channels are busy, the overflow technique will be used. That is the new call will be assigned an unused traffic2 channel. If there is still no such unused traffic2 channel found, this new S_1 call is blocked. A new S_2 calls can only use traffic2 channels. If no traffic2 channel is found, the new S_2 call is blocked. The reverse overflow, i.e., S_2 calls to use traffic1 channels, is not allowed due to co-channel interference constraints. The flow-chart of FCP scheme can be shown in Figure 3.1.

Chapter3: Fixed Channel Partitioning

Figure 3.1: Flow-chart of FCP scheme

Figure 3.2: Markov chain of FCP with overflow for stationary users

A two-dimensional Markov chain as shown in Figure 3.2 can represent this two-traffic FCP system for the same average call duration for S_1 and S_2 , i.e., $\mu_1=\mu_2=\mu$.

Chapter3: Fixed Channel Partitioning

Each node represents a state (x, y) , where x, y are the numbers of traffic1 and traffic2 channels already used respectively. Since there are C_1 and C_2 channels allocated to as traffic1 and traffic2 channels respectively, the set of allowable states is $Q_1 = \{(x, y) | 0 \leq x \leq C_1, 0 \leq y \leq C_2\}$.

An assignment of a S_1 call to traffic1 channel corresponds to a transition from the current node to the node to its right with an arrival rate of λ_1 . If all traffic channels are busy, a S_1 call can be assigned to a traffic2 channel as shown in Figure 3.2 by an rightmost upward transition with an arrival rate λ_1 , i.e., from nodes $(C_1, C_x : x \in [0, C_2 - 1])$ to $(C_1, C_{x+1} : x \in [0, C_2 - 1])$. An arriving S_2 call can only be assigned to a traffic2 channel by an upward transition with rate λ_2 from any node (x, y) with $0 \leq x \leq C_1, 0 \leq y \leq C_2 - 1$. And because of this overflow technique, the arrival rate for an upward transition from nodes $(C_1, C_x : x \in [0, C_2 - 1])$ to $(C_1, C_{x+1} : x \in [0, C_2 - 1])$ is therefore $\lambda_1 + \lambda_2$, as shown in Figure 3.2. This is because when no traffic1 channel is found for S_1 , it will look for a free traffic2 channel. This is illustrated in Figure 3.2 that from nodes $(C_1, C_x : x \in [0, C_2 - 1])$ to $(C_1, C_{x+1} : x \in [0, C_2 - 1])$ is $\lambda_1 + \lambda_2$.

The releasing of traffic1 or traffic2 channel is represented in the figure by a transition from the current node to the leftward or downward node with a transition rate of $\mu_1 = \mu_2 = \mu$.

If $\mu_1 \neq \mu_2$, Figure 3.2 cannot be used directly to model the FCP because the downward rightmost transition rate is no longer $n\mu_2$, where n is an integer, but in terms of μ_1 and μ_2 . Thus, in order to use the previous Markov chain, the scaling method must be used and given by

$$\overline{\mu_2} = \mu_1 \quad (3.5)$$

and

$$\overline{\lambda_2} = \left(\frac{\mu_1}{\mu_2} \right) \lambda_2 \quad (3.6)$$

Then, in Figure 3.2 we replace λ_2 by $\overline{\lambda_2}$ and use the same Markov chain to represent the system when $\mu_1 \neq \mu_2$.

The Markov chain in Figure 3.2 can be solved numerically [100] to obtain the steady-state probabilities for each node $\pi(x,y)$. And the details of the solution are shown in Appendix A. From Figure 3.2, it can be seen that the call blocking probability for S_1 is all the states that there is neither free traffic1 channel nor free traffic2 channel and is given by

$$P_1 = \pi(C_1, C_2) \quad (3.7)$$

For the blocking probability of S_2 , it is all the states that there is no free traffic2 channel and is given by.

$$P_2 = \sum_{x_1=0}^{C_1} \pi(x_1, C_2) \quad (3.8)$$

Therefore, the average call blocking probability, $P_{B,ave}$, for FCP is given by

$$P_{B,ave} = \gamma_1 P_1 + \gamma_2 P_2 \quad (3.9)$$

3.2.3 Performance Study of FCP with Switching

In the previous channel allocation procedure, we have such situation that some C_1 channels are free and all the C_2 are busy (with some C_2 channels might be borrowed by S_1). If a new S_2 call comes into the system, that S_2 call is blocked because there is no free C_2 channel available even though there are some free C_1 channels. Switching technique is then proposed to solve this problem. Switching technique can ensure that S_1 calls use its own C_1 channel whenever they are available. Thus, it can reduce the blocking for the S_2 calls.

Chapter3: Fixed Channel Partitioning

With switching, when a S_1 call using C_1 channel completes its service and releases a C_1 channel, an on-going S_1 call using C_2 channel, if any, will release its currently used C_2 channel and switch to that just released C_1 channel.

Such FCP with switching can be represented by a standard two-dimensional Markov chain as shown in Figure 3.3. At this time, the states, a and b , represent the numbers of S_1 and S_2 calls existing in the system. And the allowable states are given by $Q_2 = \{(a,b) | 0 \leq a \leq C, b = \min\{C-a, C_2\}\}$, where C is the total number of available channels per cell in FCP system.

The procedure of assigning or releasing of a channel to a call is same with the previous Markov chain. Except that the overflow and switching are represented by the right part of the Markov chain in Figure 3.3 for all states $a \geq C_1 + 1$. For example, a state, $(C_1+1, 2)$, means that all the C_1 channels are busy and three C_2 channels are used with one channel borrowed by S_1 call.

Figure 3.3: Markov chain of FCP with overflow and switching for stationary users

Chapter3: Fixed Channel Partitioning

This standard two-dimensional Markov chain can be solved numerically by a closed product form solution [100] and the blocking probability for each state is given by

$$P(a,b) = \frac{\frac{\rho_1^a}{a!} \frac{\rho_2^b}{b!}}{\sum_{(x,y) \in Q_2} \frac{\rho_1^x}{x!} \frac{\rho_2^y}{y!}} \quad (3.10)$$

So, the blocking probability, P_1 , of S_1 call is the states that all C_1 and C_2 channels are busy and is given by

$$P_1 = \sum_{\{(a,b) | C-C_2 \leq a \leq C, b=C-a\}} P(a,b) \quad (3.11)$$

and the blocking probability, P_2 , of S_2 call is the states that all C_2 channels are busy and is given by

$$P_2 = \sum_{\{(a,b) | 0 \leq a \leq C, b=\min\{C-a, C_2\}\}} P(a,b) \quad (3.12)$$

And the average call blocking probability, $P_{B,ave}$, for FCP with switching is still given by (3.9)

3.2.4 Simulation Results and Discussion

A single cell model is used in the simulation. We assume that a very large population of mobiles is in the system so that call origination rate is independent of the number of calls in the progress. The mean value of the average call duration time for S_1 and S_2 is 100 and 50s respectively. The value of N_1 and N_2 is assumed to be 4 and 7 for S_1 and S_2 respectively. The values of N_1 and N_2 depend on the service requirements of their SNR. For a path loss factor of 3.5, reuse factor of 4 and 7 can provide about 9.15dB and 14dB of SIR. The S_1 can be considered as a traditional voice call that requires low reuse factor and longer call duration. The S_2 can be considered as a data service. A total of 210 channels are available in the system. So the number of channel per cell for FCA is 30. Different channel combination $C(C_1:C_2)$ is simulated in order to achieve the best results.

Figure 3.4: Comparison of FCP and FCA $\rho_1:\rho_2=1:2$ (ns: no switching, ws: with switching)

Figure 3.4 shows the results of $P_{B,ave}$ values for two traffic with traffic load ratio $\rho_1:\rho_2=1:2$. For FCA system, each cell has 30 channels based on the larger reuse factor of 7 to support both service types. The $P_{B,ave}$ for FCA system is obtained by Erlang B formula. For FCP system, a few combinations of channel allocation, $C(C_1, C_2)$, to each traffic channel is considered. Under the traffic load ratio of 1:2, the channel combination, $C(7:26)$, provides the best performance compared with others at the $P_{B,ave}=1\%$. The improvement of FCP without switching for $C(7:26)$ over FCA is 9%. This is because some of the S_1 users use the reuse factor of 4 for channel allocation and thus, the average reuse factor of the FCP system is lower than the FCA system. We can also see that the FCP with switching can get higher improvement over FCP without switching. With switching, the improvement reaches 12% compared with

FCA. The simulation results also prove the validation of the scaling method used in (3.5) and (3.6)

Figure 3.5: Comparison of FCP and FCA $\rho_1:\rho_2=8:1$

Figure 3.5 shows the results under the traffic load ratio of 8:1. As we can see from the figure, with increasing S_1 traffic load ratio, the improvement of FCP as compared with FCA is also increased significantly. This is because that more S_1 users in the system use channel of reuse factor of 4. So the overall reuse factor of the system becomes much smaller and the system capacity is improved. The improvement of FCP without switching over FCA is about 59%. And the improvement of FCP with switching can even reach 64%. Since the probability that the switching can happen is not very high (referring to Sect. 3.2.3), the improvement of FCP with switching to FCP without switching is only about 5%.

Figure 3.6: Improvement of FCP over FCA under different traffic load ratio

Figure 3.6 shows the improvement of FCP (with and without switching) over FCA with the best $C(C_1, C_2)$ at different traffic ratios between S_1 and S_2 . As we can see from Figure 3.6, for the low traffic load fraction for S_1 , i.e., $\rho_1:\rho_2=1:4$, the improvement of FCP over FCA is little. This can be expected. For example of an extreme case with no S_1 users, both FCP and FCA will have the same performance because the channel allocation for all users will use a reuse factor of 7. That means FCP and FCA are converged to become the same algorithm. As the traffic load for S_1 increases, i.e., $\rho_1:\rho_2=8:1$, the improvement of FCP over FCA is increased to about 60%. This is because more S_1 users are in the system and they can use the reuse factor of 4. Thus, the overall reuse factor is much lower. In conclusion, Figure 3.6 shows clearly that with the increasing of the traffic load for S_1 , the improvement of FCP over FCA can be increased substantially. And the FCP with switching can always get about 5% higher improvements as compared with FCP without switching. This is because

the switching must satisfy the following conditions to work: (1) Some C_1 channels are free and (2) all C_2 channels are busy (with some C_2 channels might be borrowed by S_2 calls). (3) A new S_2 call comes into the system. The probability that all three conditions are satisfied is not very high. Thus, the improvement of FCP with switching over FCP without switching may not be too much. However, this switching technique is still valuable when the system is in a high traffic load. So the FCP with switching is more effective.

3.3 FCP with Mobility

3.3.1 Analysis Model

To analyze the effect of the mobility to the FCP scheme, we assume a service area of 49 hexagonal cells, as shown in Figure 3.7, to represent the practical system. To avoid boundary effect, ‘wrap-around’ technique is used. That is the left-most cells are connected with right most cells. It is also true for the upper cells and bottom cells of this 49-cell scenario. Other model parameters are same with that of FCP without mobility analysis model.

Figure 3.7: Cellular structure for mobility with wrap-around technique

Chapter3: Fixed Channel Partitioning

The mobility model as in [101], where MS moves in a straight line without changing its speed and direction, is used in our system model. We define the residence time as the time that an MS stays in the current cell. And from [101], we can get that the residence time is exponentially distributed with a mean of $1/\mu_h$. μ_h is the handoff rate per user and is given by

$$\mu_h \approx \frac{E[V]L}{\pi A} \quad (3.13)$$

where $E[V]$ is the average mobile user speed, L is the length of the perimeter of the cell and A is the area of the cell. In the hexagonal cell, L and S are given by $6R$ and $3R^2\sqrt{3}/2$, respectively. Because S_1 and S_2 have the same traveling area, so we can get $\mu_{h1}=\mu_{h2}=\mu_h$.

In practical system, we may reserve some channels for the handoff calls to be used because the dropping of an on-going call will be more annoying than blocking a new-coming call. For simplicity, we assume that there are no reserved channels for S_1 and S_2 handoff calls in our model. So the handoff call is deemed to be a new incoming call and will be dropped if there is no free channel.

In this paper, we use GOS as defined in [102] to evaluate the system performance. GOS is given by

$$\text{GOS}=(1-\alpha)P_{B,ave} + \alpha P_{D,ave} \quad (3.14)$$

where $\alpha \in [0,1]$ is the GOS factor to indicate the relative importance of $P_{B,ave}$ and $P_{D,ave}$ in a particular system, where $P_{D,ave}$ is the average call dropping probability.

3.3.2 Performance Analysis of FCP with Mobility (Analytical Model1)

In this section, we present the theoretical analysis of FCP with mobility. If mobility exists in the system, handoff problem should be considered. When a new or handoff

Chapter3: Fixed Channel Partitioning

S_1 call arrives, it is first assigned to an unused traffic1 channel. If all traffic1 channels are busy, i.e., $x = C_1$, then the overflow technique will be used. That means the new or handoff S_1 calls will use unused traffic2 channels. If there is still no such unused traffic2 channel found, this S_1 call is blocked. The new or handoff S_2 calls can only use traffic2 channels. If there is no traffic2 channel found, the S_2 call is blocked.

Figure 3.8: An example of transition rate of FCP with mobile users when $C_1=2$ and $C_2=3$

A three-dimensional Markov chain can model the above FCP with mobile user scheme. An example of using channel $C_1=2$ and $C_2=3$ is shown in Figure 3.8. And the transition state, Q_3 , is given by

$$Q_3 = \{(x, y, z) | 0 \leq x \leq C_1, 0 \leq y \leq C_2, 0 \leq z \leq C_2, y + z \leq C_2\} \quad (3.15)$$

Chapter3: Fixed Channel Partitioning

where x means the number of S_1 calls using traffic1 channels (x type calls); y means the number of S_1 calls using traffic2 channels (y type calls); z means the number of S_2 calls using traffic2 channels (z type calls). If we assume that λ_{hx} , λ_{hy} , λ_{hz} are the handoff arrival rate for x , y , z type calls, respectively, then they are given by

$$\lambda_{hx} = E[X]\mu_h, \lambda_{hy} = E[Y]\mu_h \text{ and } \lambda_{hz} = E[Z]\mu_h \quad (3.16)$$

where $E[X]$, $E[Y]$ and $E[Z]$ are the average numbers of x , y , z type calls respectively.

They are given by

$$E[J] = \sum_{(x,y,z) \in Q} jP(x,y,z) \quad j = x, y, z \quad (3.17)$$

where $P(x,y,z)$ is the probability for each state (x, y, z) .

The handoff arrival rate for each service can be obtained from the iteration procedure. We first give an initial value of handoff arrival rate as, $\beta\lambda_i$ (where $i = 1$ or 2 & β is a positive constant), for each type (x , y , or z) of calls. From Markov chain, we can numerically obtain the state probability [100], i.e., $P(x,y,z)$. After this, we use (3.16) and (3.17) to estimate $\lambda_{hx,est}$, $\lambda_{hy,est}$ and $\lambda_{hz,est}$. Then, we use the new estimated values, $\lambda_{hx,est}$, $\lambda_{hy,est}$ and $\lambda_{hz,est}$, as the new handoff rates to obtain new estimation of $P(x, y, z)$. The iteration procedure will continue until the difference between the estimated value and the resulting value is lower than a predefined desired accuracy, ϵ . From the analytical results, we find this iterative method will always produce convergent handoff rates. What is more, the initial estimated value β does not affect the convergent speed and results in the same handoff arrival rates.

In Figure 3.8, the transition rate that a new or handoff S_1 call is assigned to C_1 or C_2 channel is $\lambda_1 + \lambda_{hx} + \lambda_{hy}$. Note that when all the traffic1 channels are busy, i.e., $x = C_1$, the new or handoff S_1 calls will use traffic2 channels. So, there is a transition rate of $\lambda_1 + \lambda_{hx} + \lambda_{hy}$ from (C_1, y, z) to $(C_1, y+1, z)$ ($(C_1, y, z) \in S$ and $(C_1, y+1, z) \in S$). We

Chapter3: Fixed Channel Partitioning

notice that this is not true when there is still some free traffic1 channels, i.e., $x \leq C_1$, because traffic1 channels have higher priority for S_1 to be used. The transition rate that a new or handoff S_2 call is assigned to a C_2 channel is $\lambda_2 + \lambda_{h2}$. And when a call finishes its service, the released transition rate of a S_1 and S_2 call is $\mu_1 + \mu_h$ and $\mu_2 + \mu_h$, respectively.

The above three-dimensional Markov chain can be solved to get the numeric results [100]. And the blocking probability for S_1 is the states that all the traffic1 and traffic2 channels are busy and is given by

$$P_{b1} = \sum_{y=0}^{C_2} \sum_{z=C_2-y}^{C_2} P(C_1, y, z) \quad (3.18)$$

And the blocking probability for S_2 is the states that all the C_2 channels are busy and is given by

$$P_{b2} = \sum_{x=0}^{C_1} \sum_{y=0}^{C_2} \sum_{z=C_2-y}^{C_2} P(x, y, z) \quad (3.19)$$

So, the average blocking probability of the system is given by

$$P_{B,ave} = \gamma_1 P_{b1} + \gamma_2 P_{b2} \quad (3.20)$$

The call dropping probability, P_d , is the probability that a non-blocked called is dropped because of handoff failure. Thus, the average probability that a non-blocked called is dropped at the first handoff is given by

$$P_d(1) = \gamma_1 P_{h1} P_{b1} + \gamma_2 P_{h2} P_{b2} \quad (3.21)$$

where P_{h1} and P_{h2} is the probability that the handoff occurs before a call completing for S_1 and S_2 . They are given by

$$P_{hi} = \frac{\mu_h}{\mu_h + \mu_i} \quad i=1 \text{ or } 2 \quad (3.22)$$

Consequently, the average probability that a non-blocked call is dropped at the m_{th} ($m \geq 1$) handoff is given by

$$P_d(m) = \gamma_1 P_{h1} P_{b1} (P_{h1} (1 - P_{b1}))^{m-1} + \gamma_2 P_{h2} P_{b2} (P_{h2} (1 - P_{b2}))^{m-1} \quad (3.23)$$

Thus, the average dropping probability is given by

$$P_{D,ave} = \sum_{m=1}^{\infty} P_d(m) = \frac{\gamma_1 P_{h1} P_{b1}}{1 - P_{h1} (1 - P_{b1})} + \frac{\gamma_2 P_{h2} P_{b2}}{1 - P_{h2} (1 - P_{b2})} \quad (3.24)$$

3.3.3 A Simplified Analytical Model of FCP with Mobility (Analytical Model2)

From the analysis of FCP with mobility, we could see that the steady-state probabilities, i.e., $P(x, y, z)$, for the two services model is obtained by numerically solving the three-dimensional Markov chain. Since the computation time of λ_{hx} , λ_{hy} and λ_{hz} from the iteration could take a very long time as the number of state increases, this method is not an ideal way of producing the steady-state probability $P(x, y, z)$. In this section, an analytical model2 is introduced for analyzing the performance of the FCP with mobility. This analytical model2 allows the state probabilities to be expressed with a close-form solution and can be represented by a two-dimensional Markov chain as shown in Figure 3.9.

Chapter3: Fixed Channel Partitioning

Figure 3.9: Markov chain of the analytical model2 for mobile users

In Figure 3.9, a represents S_1 calls in the system using traffic1 or traffic2 channels; b represents S_2 calls in the system using traffic2 channels. As shown in the figure, the maximum number of channels that can be used by S_1 is $C_1 + C_2 = C$, whereas the maximum number of channels for S_2 calls is C_2 . The parameter λ_{h1} and λ_{h2} are S_1 and S_2 handoff call arrival rates and they are given by $\lambda_{h1} = E[N_a] \mu_h$ and $\lambda_{h2} = E[N_b] \mu_h$, respectively, where N_a and N_b are the number of S_1 and S_2 users in the system. The values of λ_{h1} and λ_{h2} are obtained by using the iterative procedure similar to that introduced in the previous section.

This method is not same as analytical model1 of FCP with mobility system. Because when a S_1 call using traffic1 channel releases its channel, this analytical model2 will switch an existing S_1 call using traffic2 channel to the just release traffic1 channel automatically. However, the analytical model1 does not perform this call switching when a S_1 call using traffic1 channel releases its channel. But in order to meet the above switching in the analytical model2, the following conditions must be satisfied:

Chapter3: Fixed Channel Partitioning

1) All the traffic1 channels are occupied; 2) Some S_1 call is using traffic2 channel and 3) one S_1 call leaves the system. Hence, such a switching probability in the analytical model2 is relatively low (and this will be proved in section 3.3.4). Thus, this analytical model2 can suitably estimate the numeric results of FCP with mobility obtained from the analytical model1. We can derive that the blocking probability for the analytical model2 is a little lower than the analytical model1 due to switching.

The Markov chain as shown in Figure 3.9 is a standard two-dimensional Markov chain that has close-form solution. And the probability for each state (a,b) is given by

$$P(a,b) = \frac{\frac{\rho_1^a}{a!} \frac{\rho_2^b}{b!}}{\sum_{(x,y) \in Q_4} \frac{\rho_1^x}{x!} \frac{\rho_2^y}{y!}} \quad (3.25)$$

where Q_4 is all the allowable states and is given by

$Q_4 = \{(a,b) | 0 \leq a \leq C, b \leq \min\{C-a, C_2\}\}$. And ρ_1 and ρ_2 are the traffic loads for S_1 and S_2 . They are given by $\rho_1 = \frac{\lambda_1 + \lambda_{h1}}{\mu_1 + \mu_h}$ and $\rho_2 = \frac{\lambda_2 + \lambda_{h2}}{\mu_2 + \mu_h}$. The close-form solution

could make the computation time much shorter.

Similar to (3.18) and (3.19), we can get that the new call blocking probability for S_1 is given by

$$P_{b1} = \sum_{i=C_1}^C P(i, C-i) \quad (3.26)$$

and the new S_2 call blocking probability is given by

$$P_{b2} = \sum_{i=C_1}^C P(i, C-i) + \sum_{j=0}^{C_1-1} P(j, C_2) \quad (3.27)$$

And the average new call blocking probability is still given by (3.20) and the average call dropping probability is given by (3.24). Particularly, for the stationary user, we could set $\lambda_{h1} = \lambda_{h2} = 0$ and $\mu_h = 0$ and this Markov chain becomes Figure 3.3.

3.3.4 Analytical and Simulation Results

A total of $m = 210$ channels are available in the system. So, the number of channel per cell for FCA is 30. To achieve the best results, different channel combinations, i.e., $C(C_1, C_2)$, are simulated in FCP scheme. We use a simple mobility model in [101] where all the mobiles move in the straight line without changing their speed and direction. For simplicity, there is no reserved channel in FCP and FCA schemes. Connection call blocking probability, handoff call dropping probability and GOS are considered in our analysis and simulation results. The desired accuracy, ϵ , is set to be 10^{-6} in our analysis. We assume the GOS factor $\alpha = 0.5$. For all the simulation results, the 95% confidence intervals within $\pm 5\%$ of the average values are observed.

Figure 3.10: Average call blocking and dropping probabilities with traffic load ratio $\rho_1:\rho_2=2:1$ ($\lambda_1:\lambda_2=1:1$) for FCA and FCP with $C(21:18)$

Figure 3.10 shows the results of $P_{B,ave}$ and $P_{D,ave}$ values for two services with the call arrival rate ratio of $\gamma_1:\gamma_2 = 1:1$ (corresponding to the traffic load ratio of $\rho_1:\rho_2=2:1$). For the FCA system, each cell has 30 channels based on a reuse factor of 7 to support both service types. The $P_{B,ave}$ for FCA system is obtained by using Erlang B formula. For FCP system, a few combinations of channel allocation, $C(C_1, C_2)$, to each traffic channel have been considered and the best combination is shown in the figure. Under the arrival rate ratio of $\gamma_1:\gamma_2 = 1:1$, the channel combination, $C(21:18)$, gives the best performance compared with other channel combination at the GOS of 1%. In Figure 3.10, it can be seen that the FCP with $C(21:18)$ for mobile users can provide about 32% capacity improvement as compared with FCA for 1% blocking probability and 33% capacity improvement for 1% dropping probability. This is because some of the

Chapter3: Fixed Channel Partitioning

S_1 users use the reuse factor of 4 for channel allocation and thus, the average reuse factor of the FCP system is lower than the FCA system. Therefore, the system improvement can be achieved.

Figure 3.11: GOS results with traffic load ratio $\rho_1:\rho_2=2:1$ ($\lambda_1:\lambda_2=1:1$) for FCA and FCP with $C(21:18)$

Figure 3.11 shows the GOS results for two services with the call arrival rate ratio of $\gamma_1:\gamma_2 = 1:1$ (corresponding to the traffic load ratio of $\rho_1:\rho_2=2:1$) and $\alpha = 0.5$. The GOS results of both FCA and FCP are obtained by (3.14). The improvement of FCP over FCA is about 32% at GOS = 1%. In Figure 3.10 and Figure 3.11, we can see that the analytical results are very close to the simulation results, which validates the correctness of the analytical model. In these two figures, we can also see that although the analytical results using approximate (analytical) model2 is slightly lower than the exact (analytical) model1, the discrepancy between them is acceptable. This

observation agrees with our expectation as stated in section 3.3.3. But by using the approximate (analytical) model2, the computational time is much shorter than exact (analytical) model1.

Figure 3.12: GOS=1% improvement VS. different traffic load ratios under different speeds

Figure 3.13: GOS=1% improvement VS. different traffic load ratios under different GOS factors

Figure 3.12 shows the influence of speed of the mobile to the improvement of FCP over FCA with different traffic load ratios between two services. It can be seen that the improvement increases as the traffic of S_1 increases. Besides, we could see that although the speed of the mobile changes, the improvement of FCP over FCA does not change much. The same conclusion can be drawn with different GOS factors as shown in Figure 3.13. The above two results indicate the speed or the GOS factor does not decrease the effectiveness of our FCP scheme. And this conclusion is very important for our channel assignment scheme.

3.4 Conclusions

We propose a channel partitioning scheme to support multiple services requiring different reuse factors. Both cases, FCP with stationary and mobile users, are presented in this chapter. We also study the impact of different traffic ratios, mobile

Chapter3: Fixed Channel Partitioning

speeds and GOS factors. The simulation and analytical results show that with the increasing of the traffic ratio of lower SIR service, FCP can gain more throughputs as compared with a conventional FCA scheme using a single reuse factor. This is true for both cases. What is more, the mobile speed and the GOS factor do not decrease the effectiveness of our proposed FCP scheme with mobility case. Our proposed scheme could work for the reuse factor based systems such as GSM, GPRS, EDGE or cellular OFDM.

Chapter 4: Dynamic Channel Allocation with Channel Partitioning

4.1 Introduction

In cellular mobile systems, the traffic load distribution among different cells may be different. As discussed in Chapter 2, conventional FCA is not adaptive enough to cater for the short-term temporal and spatial variations of traffic load among cells. Basically, FCP scheme in Chapter 3 inherits same properties with that of fixed channel allocation scheme. Thus, traffic variation may also degrade the capacity of FCP scheme. This is even worse when the traffic load ratio between two services changes frequently. DCA on the other hand provides a more flexible way to use the limited radio resource. A network-based DCA scheme called dynamic channel allocation with interference information (DCA-WI) was proposed and studied in [62]. In DCA-WI, each cell uses an interference information table (IIT), which contains sufficient information about the status of channels in each interfering cell, to allocate channels to users. DCA-WI tries to manage the channel allocation between cells in a proper way so that each allocation of the channel causes least interference to the neighboring cells.

In this chapter, we first apply the CP algorithm to DCA-WI scheme called dynamic channel partitioning with interference information (DCP-WI) to study whether our proposed channel partitioning scheme can work well with DCA scheme. From the simulation results, we find that DCP-WI also has the problem of channel combination problem. This is because the optimum channel allocation to each service depends on

Chapter4: Dynamic Channel Allocation with Channel Partitioning

the traffic load of that service. In order to solve this problem both in FCP and DCP-WI schemes, we introduce a flexible channel combination DCP-WI scheme namely FDCP. FDCP scheme release the necessity of allocating a fixed number of channels to each service before the operation of the network. Thus, it is a fully flexible channel allocation scheme to support multiple services.

4.2 DCP-WI Scheme

4.2.1 System model

Same as Chapter 3, the minimum required reuse factor for S_1 and S_2 is 4 and 7 respectively. For S_1 , the first two tiers of the cells, except some cells with the same separation as the minimum reuse distance, are the interfering cells. As shown in Figure 4.1, twelve cells surrounded by the solid line, i.e., cell 12, 17, 18, ..., 38, are the interfering cells of cell 25. For S_2 , all the 18 cells in the first two tiers are the interfering cells of cell 25.

Figure 4.1: System model for 49 cells with two reuse factors

Chapter4: Dynamic Channel Allocation with Channel Partitioning

4.2.2 Interference Information Table (IIT) for DCP-WI

In DCP-WI, each cell has two IITs (for S_1 and S_2 calls respectively) that contain sufficient information of channel status of its own and interference cells. A certain numbers of channels, C_1 and C_2 , are allocated for S_1 and S_2 calls respectively, depending on the traffic load. For example, as shown in Table 4-1 and Table 4-2, there are 28 channels allocated as C_1 channels and 182 channels are allocated as C_2 channels, assuming $m=210$.

In Table 4-1 and Table 4-2, the first column indicates the own cell (O CELL) and all its interference cells (I CELL). As shown in Figure 4.1 for cell 25, if we assume the reuse factor of N_1 and N_2 are 4 and 7 respectively, there are 12 and 18 interference cells in Table 4-1 and Table 4-2 respectively. The other columns stand for the channels status corresponding for each channel of a particular cell. A letter U in Table 4-1 and Table 4-2 in [I CELL or O CELL, channel j] box indicates that this channel is a used channel. For example, in Table 4-2, the cell 25 uses channels 32 and 209 and the cell 39 uses channel 31. A letter U' in Table 4-2 indicates that this channel is a channel borrowed by S_1 call such that overflow is employed in DCP-WI. For example, in Table 4-2, channel 29 is borrowed by a S_1 call in cell 25. A letter L in [I CELL, channel j] box indicates that this channel is used and locked by an I CELL's interference cell, say cell X , which is not the interference cell of O CELL. This means that channel j is a LOCKED CHANNEL in I CELL and it is not allocated to use in that I CELL. For example, in Table 4-1, channel 2 is locked in cell 12 because one of cell 12's interference cell, say cell 5 (referring to Figure 4.1), which is not an I CELL of cell 25, is using channel 2. Thus, cell 12 cannot use channel 2 due to co-channel interference constraints, but cell 25 can still use channel 2. The letter L is addible if

Chapter4: Dynamic Channel Allocation with Channel Partitioning

this channel is locked by more than one I CELL. An empty box in [O CELL, channel j] box indicates that this channel is either a FREE CHANNEL (if there is no U or U' in this column) or a LOCKED CHANNEL (if at least one U or U' is in this column). For example, in Table 4-2, channel 30 is a FREE CHANNEL in cell 25 and channel 33 is a LOCKED CHANNEL, which is locked by cell 19. A LOCKED CHANNEL here means that one or more I CELL(s) of O CELL currently use(s) this channel.

Table 4-1: IIT of cell 25 for S_1 of DCP-WI

Cell No,	Channel Number for S_1							
	1	2	3	4	5	...	27	28
25	U							
12		L		L	L		3L	
17		L			L			L
18		L			L			
19		U	L	L	L			L
⋮								
39			U					

Table 4-2: IIT of cell 25 for S_2 of DCP-WI

Cell No,	Channel Number for S_2							
	29	30	31	32	33	...	209	210
25	U'			U			U	
⋮								
⋮								
19			2L		U'		L	
⋮								
38					L			
39			U					

Chapter 4: Dynamic Channel Allocation with Channel Partitioning

4.2.3 DCP-WI Channel Allocation Scheme

4.2.3.1 Channel Assignment and Reassignment

The channel allocation of DCP-WI tries to minimize the effect of the assignment on channel availability in all the interfering cells of O CELL. The idea is to allocate a channel that has been locked by the maximum number of I CELLS. For example, if a new S_1 call arrives in cell 25, referring to Table 4-1, channel 5 is preferred to be used because assigning channel 5 to this new call will affect 8 I CELLS and these 8 I CELLS cannot use channel 5. If other channel is assigned, more I CELLS will be affected. For example, the assigning of channel 28 will affect 10 I CELLS, which cannot use channel 28. Information about whether a channel j is locked or not in I CELL of O CELL is provided in the O CELL's IIT. A channel j is locked if there is at least an L in channel j 's column. A channel j with the smallest value of the cost functions, $\min\{C(j) \text{ or } C'(j,i)\}$, as in (4.1) and (4.2), is allocated to the new arrival call in O CELL to use. If that new call cannot get a channel, it is blocked.

The cost functions, $C(j)$ or $C'(j,i)$, for channel assignment and reassignment can be used for both S_1 and S_2 calls. The $C(j)$ for channel assignment is for all free channels in O CELL and is given as

$$C(j) = N(A) - L(A, j) \quad (4.1)$$

where $N(A)$ is the number of interference cells of O CELL, say cell A . In our assumption, $N(A)$ is 12 for S_1 calls using C_1 channels, while $N(A)$ is 18 for calls (S_1 or S_2) using C_2 channels. $L(A, j)$ is the number of locked cells of O CELL (cell A) for channel j , e.g., $L(25,4)$ is 2 as shown in Table 4-1. We can see from the function that $N(A)$ is pre-defined constant in the system. If we get the maximum value of $L(A, j)$ for a channel j , then we can achieve the minimum value of $C(j)$. To give an extreme case

Chapter4: Dynamic Channel Allocation with Channel Partitioning

for an example, when channel j in all I CELLS of O CELL are locked, i.e., $L(A, j) = N(A)$, then O CELL can use this channel j freely without causing any disturbance to its interference cells. Because all these I CELLS are locked and cannot use this channel j .

A single channel reassignment is considered here to further improve the system capacity. The $C'(j, i)$ for channel reassignment is for all locked channels with a single locked cell. A channel, channel j , is a locked channel with a single locked cell in O CELL if there is only one U or U' in an I CELL in channel j 's column. For example, referring to Table 4-2, channels 31 and 33 are locked channel with a single locked cell in cell 25. When allocating a locked channel j to a new call in O CELL, we may reassign the call using that channel j in I CELL to other channel i in I CELL in order to free channel j in O CELL. The cost function for the single channel reassignment is given by

$$C'(j, i) = [N(A) - L(A, j)] + [L(B, j) - L(B, i)] \quad (4.2)$$

where $L(B, j)$ is the number of locked cells of the I CELL, cell B, of O CELL for channel j . $L(B, i)$ is the number of locked cells of the I CELL, cell B, of O CELL for channel i . The locked cell number of $L(B, j)$ and $L(B, i)$ are obtained from cell B's IIT. The purpose of (4.2) is to minimize the impact on the interference cells of switching the on-gong call using channel j to channel i .

The costs for all free channels and locked channels with a single locked cell are obtained using $C(j)$ and $C'(j, i)$ respectively. A channel with the lowest cost will be allocated to the new arrival call.

Chapter4: Dynamic Channel Allocation with Channel Partitioning

4.2.3.2 The Priority of Channel for Assignment

From the cost functions with (4.1) and (4.2), we choose the channel with smallest cost value to be assigned to the new service call. When there is more than one channel with the same smallest cost function value, the selection order of the channel is based on the following rules with the first one having highest priority:

- 1) A channel with a larger number of locked cells has higher priority. For example, in Table 4-1, channel 5 with four locked cells, has higher priority than channel 27, with only one locked cell.
- 2) A free channel has higher priority, e.g., in Table 4-1, channel 27 has higher priority than channel 3.
- 3) If several channels have same number of locked cells, a lower-numbered channel has higher priority, e.g., in Table 4-1, channel 4 has higher priority than channel 28.

If several single reassignment channels have the same number of locked cells, a lower-numbered channel has higher priority, e.g., in Table 4-2, channel 31 has higher priority than channel 33.

4.2.3.3 Cell Updating

After assigning or releasing of a channel, the IITs should be updated to the changing status of the channel. When a BS attempts to allocate channel j to its O CELL, the updating procedure follows four steps:

- 1) A letter U (U' if the channel is borrowed by a S_1 call) should be inserted in the [O CELL, channel j] box in O CELL's IIT.
- 2) O CELL informs all its I CELLS that a letter U or U' should be inserted to the box of [O CELL, channel j] in I CELLS' IIT.

Chapter4: Dynamic Channel Allocation with Channel Partitioning

- 3) All the I CELLS inform all of their interference cells, say cell X , which is not the interference cell of O CELL, that a letter L should be added to the box of [I CELL, channel j] in cell X 's IIT.
- 4) Then, each cell X sends the latest number of locked cells of channel j to all its interference cells.

The updating procedure for releasing channel is done in the similar way as above except that the 'inserting' a letter U or U' should be replaced by 'removing'. The 'adding' of a letter L should be replaced by 'subtracting'. The flow-chart of DCP-WI scheme is shown in Figure 4.2.

Figure 4.2: Flow-chart of DCP-WI scheme

4.2.3.4 Other Assignment Technique-Rearrangement

Other assignment techniques such as overflow, switching and rearrangement are applied to DCP-WI in order to enhance the performance. Overflow and switching

Chapter4: Dynamic Channel Allocation with Channel Partitioning

have been introduced in section 3.2. In this section, we will introduce the technique of rearrangement.

In DCP-WI, an on-going call process may be rearranged to a released channel to minimize the effect on the interference cells during its service. Many algorithms have been proposed in this area [44, 53]. In DCP-WI scheme, the rearrangement of the channel is also based on the IIT's information. If a channel j is released in O CELL, an on-going call in O CELL using a channel i with the least number of locked cells will switch to that channel j provided that the number of locked cells in channel j is higher than that in channel i . If more than one channel has the same least number of locked cells, the highest numbered channel will perform the rearrangement.

Always, the rearrangement will work combined with switching algorithm. The difference between switching and rearrangement is that switching should be performed between two types of channels for S_1 calls only while rearrangement is performed between same traffic channels for both services. When a traffic1 channel is released, switching will first be performed. Then, the rearrangement will be followed. In our proposed DCP-WI algorithm, we consider *overflow*, *switching* and *rearrangement* at the same time.

4.2.4 Numerical Results of DCP-WI

Figure 4.3 and Figure 4.4 show the simulation results of DCP-WI over FCA and DCA-WI in uniform traffic distribution scenario. Under low S_1 traffic load ratio, e.g., $\rho_1:\rho_2 = 1:2$, DCP-WI provides about 38% and 8% improvement over FCA and DCA-WI respectively. But under high S_1 traffic load ratio, i.e., $\rho_1:\rho_2 = 8:1$, DCP-WI gives about 73% and 36% improvement over FCA and DCA-WI.

Chapter4: Dynamic Channel Allocation with Channel Partitioning

Figure 4.3: Comparison of DCP-WI over FCA and DCA-WI for $p_1:p_2=1:2$ in uniform traffic distribution. ($C(x,y)$: x is the number of channel for S_1 and y is the number of channel for S_2)

Figure 4.4: Comparison of DCP-WI over FCA and DCA-WI for $p_1:p_2=8:1$ in uniform traffic distribution. ($C(x,y)$: x is the number of channel for S_1 and y is the number of channel for S_2)

Chapter4: Dynamic Channel Allocation with Channel Partitioning

Figure 4.5: Improvement of DCP-WI, FCP (with and without switching) over FCA under different traffic load ratios in uniform traffic distribution. ($C(x,y)$: x is the number of channel for S_1 and y is the number of channel for S_2)

Figure 4.5 shows the improvement of FCP, DCP-WI over FCA under different traffic load ratio between S_1 and S_2 calls. As we can see from the figure, with the increasing of the S_1 traffic load ratio, the improvements of FCP and DCP-WI over FCA increase. This is because with the increasing of S_1 traffic load, more channels are allocated to support S_1 calls for reuse factor of 4 due to more S_1 users. So, the overall reuse factor of the channel usage becomes smaller and the system capacity is improved. In the present communication system, the traffic load for voice service (requiring small reuse factor) is higher than that for data service. So this proposed algorithm can work properly in the multiple services situation when $\rho_1 > \rho_2$. From Figure 4.5, we can see that even for equal arrival rate between S_1 and S_2 services, i.e., $\gamma_1:\gamma_2 = 0.5:0.5$ (corresponding to $\rho_1:\rho_2 = 2:1$), which is the test configuration for UMTS [103], FCP

Chapter4: Dynamic Channel Allocation with Channel Partitioning

and DCP-WI can provide about 33% and 60% improvement over FCA scheme respectively. Compared with FCP scheme, DCP-WI scheme always outperforms FCP. This shows that dynamic channel allocation scheme can further cater for the traffic variations between cells.

Figure 4.6: comparison of DCP-WI over FCA and DCA-WI for $\rho_1:\rho_2=1:2$ in non-uniform traffic distribution. ($C(x,y)$: x is the number of channel for S_1 and y is the number of channel for S_2)

Figure 4.7: comparison of DCP-WI over FCA and DCA-WI for $\rho_1:\rho_2=8:1$ in non-uniform traffic distribution. ($C(x,y)$: x is the number of channel for S_1 and y is the number of channel for S_2)

The performance of DCP-WI algorithm in the non-uniform traffic distribution scenario is studied. The non-uniform distribution model in [50] is used in the simulation. Figure 4.6 and Figure 4.7 show the simulation results of DCP-WI over DCA-WI and FCA algorithm under the traffic load ratio of 1:2 and 8:1 respectively. From the figures we can find that the conclusion of DCP-WI algorithm over DCA-WI algorithm is same as we get in the fixed cellular system model. That is with the increasing S_1 traffic load ratio, the improvement of DCP-WI over DCA-WI is also increasing. The improvements with the best channel combination of DCP-WI over DCA-WI under these two traffic scenarios are 9% and 33%. But as compared with FCA algorithm, DCP-WI can always provide better improvement. The improvement

Chapter4: Dynamic Channel Allocation with Channel Partitioning

is 98% and 143% in these two traffic scenarios. In conclusion, DCP-WI is able to cater for the non-uniform distribution environment.

4.3 FDCP Scheme

In DCP-WI, a portion of channels will be assigned permanently to certain type of service. The disadvantage of the current schemes is that the best channel combination (which can provide the best system performance) depends on traffic load ratio among services. In other words, different traffic load ratios require different best channel combination. But it is not adaptive enough because the network traffic load ratio may change from time to time. However, the optimum channel combination depends on the traffic load ratio among services. In this section, we introduce a new dynamic channel partitioning with flexible channel combination scheme called flexible dynamic channel partitioning (FDCP). In this scheme, all the channels are open to any incoming call as long as the allocation satisfies the co-channel interference constraints based on the reuse factor requirement. This means that we do not need the pre-allocation of channels for each service as required in section 4.2. FDCP attempts to derive a TDMA-based dynamic channel allocation scheme that is flexible enough to share radio resources among different services.

4.3.1 System Model

We use the same system model as it is of DCP-WI scheme and the mobility model is same with that of FCP with mobility.

4.3.2 Interference Information Table (IIT) for FDCP

Similar to DCP-WI scheme, the allocating and releasing of the channels in FDCP are based on the IIT. However, each cell has just one IIT that contains enough information about the channel status of its own and all the surrounding interfering

Chapter4: Dynamic Channel Allocation with Channel Partitioning

cells. One example IIT for cell 25 is shown in Table 4-3. The first column in the table lists the *Own Cell*, its interfering cells with the small reuse factor interfering cells (*SRF Int. Cell*) for S_1 , and large reuse factor interfering cells (*LRF Int. Cell*) for S_2 . The total number of system channels, as shown in the first row, is 210. All the other boxes refer to the channel status corresponding to a particular channel of a cell.

Table 4-3: Interference Information Table of Cell 25 of FDCP

Cell No.		Channel					Number			
		1	2	3	4	...	207	208	209	210
Own Cell	25	U1		U2		...				
SRF Int. Cell	12				L					L
	17	L		L			L	L		
	...					...				
	33			L	L			L		U1
	38	L								
LRF Int. Cell	11	U1		L			U2		L	
	...					...				
	39	2L			L		L		L	

$U1$ or $U2$ in the first row of the boxes indicates that this channel is occupied by S_1 or S_2 call respectively in the *Own Cell*. For example, in Table 4-3, channel 1 is occupied by S_1 call and channel 3 is occupied by S_2 call in cell 25. $U1$ or $U2$ in the other rows of the boxes indicates that this channel, say channel i , is occupied by S_1 or S_2 call respectively in the interfering cell, cell H . We call channel i a *locked* channel and cell H a *locking* cell if channel i **cannot be used** in *Own Cell*. For example, in Table 4-3, cell 11 is currently using channel 207 for a S_2 call. Then, cell 11 is a *locking* cell for cell 25 and channel 207 is a *locked* channel in cell 25. A letter L in the interfering cell row, say cell K and channel j , indicates that channel j is locked in cell K because one of the interfering cells of cell K is using channel j . Then, channel j is a *locked* channel for cell K and cell K is called the *locked* cell for *Own Cell*. For example, in Table 4-3, channel 1 is a locked channel in cell 17 because one of the interfering cells of cell 17, say cell 10 (referring to Figure 4.1), is currently using channel 1. Thus, channel 1

Chapter4: Dynamic Channel Allocation with Channel Partitioning

cannot be used in cell 17 and cell 17 is called a *locked* cell in cell 25. The symbol L is additive if more than one interfering cell uses the channel.

The allocating or releasing of a channel will cause the updating of the IIT. When the base station allocates channel j to a S_1 (S_2) call:

- It first updates its own IIT by inserting a U_1 (U_2) in the [*Own Cell, channel j*] box.
- It informs all the *SRF Int. Cells* (*LRF Int. Cells*) that a U_1 (U_2) should be inserted in [*Own Cell, channel j*] box in their IIT.
- Each *SRF Int. Cell* (*LRF Int. Cell*) informs its interfering cells (hereafter referred to as *Other Int. Cell*), which are not the interfering cells of *Own Cell*, that an L should be added in the [*SRF Int. Cell* (*LRF Int. Cell*), *channel j*] box of the *Other Int. Cell*'s IIT.

The releasing of a channel will follow the same procedure except that the inserting U_1 , U_2 and adding L should be replaced by deleting U_1 , U_2 and subtracting L in the corresponding box.

4.3.3 FDCP Channel Allocation Scheme

4.3.3.1 Channel Assignment and Reassignment

The channel assignment and reassignment procedure of FDCP is similar to DCP-WI scheme. The differences are:

- The channel allocation scheme for FDCP is based on one IIT.
- For S_1 and S_2 calls, we look for the number of locked cell in *SRF Int. Cell* and *LRF Int. Cell*, respectively.

Chapter4: Dynamic Channel Allocation with Channel Partitioning

We use the same cost function as (4.1) and (4.2) to execute the channel assignment and reassignment.

After obtaining the cost values for all free channels and locked channels with a single locking cell, a channel with the lowest cost will be allocated to the new arrival call.

4.3.3.2 The Priority for Channel Assignment for FDCP

The priority of channel assignment for FDCP scheme is same with that of DCP-WI scheme.

4.3.3.3 Channel Rearrangement for FDCP

After a call completes and releases its channel, the channel rearrangement process is followed. An on-going call switches to the just released channel to keep its cost to a minimum. When a S_1 releases its channel, the scanning process will be first done in the lower column of channel i (cells 11 to 39 in Table 4-3).

- If U_1 exists in the lower column of channel i , an on-going S_1 call with the smallest number of locked cells in the upper column (cells 12 to 38 in Table I) will switch to channel i provided that the number of locked cells in channel i is larger.
- If U_1 does not exist in the lower column of channel i , an on-going S_1 or S_2 call with the smallest number of locked cells in the whole column (cells 12 to 39) will be switched to channel i provided that the number of locked cells in channel i is larger.

When a S_2 call releases a channel i , a S_1 or S_2 call using a channel with a smallest number of locked cells in the whole column (cells 12 to 39) will be switched to channel i if the number of locked cells in channel i is larger.

4.3.4 Simulation Results

We first study the performance of FDCP scheme with stationary users. Other schemes compared with are FCA, DCA-WI and DCP-WI. DCA-WI is a network-based dynamic channel allocation scheme that is introduced in [62]. The average connection blocking probability, P_b , is to be evaluated here.

Figure 4.8: Simulation results with $\gamma_1:\gamma_2 = 1:1$ ($\rho_1:\rho_2=2:1$)

Figure 4.8 shows the simulation results with the arrival rate ratio of $\gamma_1:\gamma_2 = 0.5:0.5$ (corresponding to $\rho_1:\rho_2 = 2:1$) for FCA, DCA-WI, DCP-WI and FDCP. The *conventional* FCA and DCA-WI use the largest reuse factor of 7 to support both S_1 and S_2 calls. The optimum channel combination of DCP-WI for this traffic ratio is (110:100) for ($S_1 : S_2$). It can be seen that the FDCP scheme provides the best performance among the other schemes. FDCP can provide about a 55% improvement as compared with FCA at $P_b = 1\%$ because the average reuse factor of FDCP is

Chapter4: Dynamic Channel Allocation with Channel Partitioning

smaller than 7. Thus, system capacity is improved. FDCP also gives 24 % and 5 % better improvements as compared with DCA-WI and DCP-WI respectively. Although the average call arrival rates for both services are set to be about 1:1 in the simulation, there is still some traffic variation between cells. Therefore, the pre-allocation of channel in DCP-WI scheme cannot flexibly cater for this variation. But FDCP can always provide the optimum performance.

Figure 4.9: Improvement of FDCP and DCP-WI (optimum channel combination) over FCA

Figure 4.9 shows the improvement of DCP-WI and FDCP over FCA at $P_b = 1\%$ under different arrival rate ratios between S_1 and S_2 . It can be seen that as the traffic of S_1 increases, the improvement of DCP-WI and FDCP over FCA increases. Because more users use the reuse factor of 4 for channel allocation, the average reuse factor is smaller. In general, FDCP outperforms DCP-WI for all traffic ratios by about 5%. In addition, DCP-WI requires different channel combinations for different traffic

Chapter4: Dynamic Channel Allocation with Channel Partitioning

environments in order to provide the best system capacity. Therefore, FDCP is a fully dynamic channel allocation scheme that can cater for any traffic load ratio between services without pre-allocation of channels. The improvement of DCA-WI, not shown in Figure 4.9, has always about a 27% improvement over FCA for different traffic load ratios.

Figure 4.10: Blocking probability results with traffic load ratio $\rho_1:\rho_2=2:1$ ($\lambda_1:\lambda_2=1:1$)

We continue to evaluate the FDCP scheme with mobile users. FCA and FCP are the schemes to compare with. Figure 4.10 shows the results of $P_{B,ave}$ values for two services with the call arrival rate ratio of $\gamma_1:\gamma_2 = 1:1$ (corresponding to the traffic load ratio of $\rho_1:\rho_2=2:1$). For FCA system, each cell has 30 channels based on a reuse factor of 7 to support both services. The $P_{B,ave}$ for FCA system is obtained from Erlang B formula. For FCP system, a few combinations of channel allocation, $C(C_1,$

Chapter4: Dynamic Channel Allocation with Channel Partitioning

C_2), to each traffic channel was simulated (not shown here). The best combination of FCP is shown in Figure 4.10. Under the arrival rate ratio of $\gamma_1:\gamma_2 = 1:1$, the channel combination, $C(21:18)$, gives the best performance compared with other combinations at the $P_{B,ave} = 1\%$. The FCP with $C(21:18)$ for mobile users can provide about 32% improvement as compared with FCA and FDCP can provide about 58% as compared with FCA at $P_{B,ave} = 1\%$. This is because some of the S_1 users use the reuse factor of 4 for channel allocation and thus the average reuse factor of the FCP or FDCP system is lower than the FCA system. Thus, the system improvement is achieved.

**Figure 4.11: Dropping probability results with traffic load ratio $\rho_1:\rho_2=2:1$
($\lambda_1:\lambda_2=1:1$)**

Figure 4.11 and Figure 4.12 show the handoff dropping probability and GOS results under the call arrival rate ratio of $\gamma_1:\gamma_2 = 1:1$ and GOS factor of 0.5. Similar conclusion can be made from blocking probability. FDCP provides the lowest $P_{D,ave}$. In Figure

Chapter4: Dynamic Channel Allocation with Channel Partitioning

4.12, FCP provides about 32% improvement at $GOS = 1\%$ as compared with FCA scheme. This is further improved to be 54% by FDCP scheme.

In Figure 4.10, Figure 4.11 and Figure 4.12, we also find that FDCP provides further improvement as compared with FCP. This is because in FCP, the channel combination is optimized for a particular traffic ratio. In other words, different traffic ratio between two services requires different best channel combinations. However, FDCP is a distributed dynamic channel allocation scheme and it can flexibly re-justify and optimize the channel combination between traffic ratios and between cells.

Figure 4.12: GOS results with traffic load ratio $\rho_1:\rho_2=2:1$ ($\lambda_1:\lambda_2=1:1$)

Figure 4.13: The GOS improvement of FDCP and FCP (optimum channel combination) over FCA

Figure 4.13 shows the improvement of FCP (analytical models1 and model2) with the best $C(C_1, C_2)$ and FDCP over FCA at different traffic ratio between S_1 and S_2 with the average user speed of 50 Km/h and GOS factor of 0.5. For the low call arrival rate fraction for S_1 , i.e., $\gamma_1:\gamma_2 = 1:8$ (corresponding to $\rho_1:\rho_2 = 1:4$), only slight improvement of FCP over FCA is achieved. As we increase the traffic load for S_1 , i.e., $\gamma_1:\gamma_2 = 4:1$ (corresponding to $\rho_1:\rho_2 = 8:1$), the improvement of FCP over FCA is increased to about 62%. This is because more S_1 users are in the system and they can use the reuse factor of 4 for channel allocation. Thus, the overall reuse factor becomes lower and the system capacity is improved. Also from the figure, we can see that the analytical model2 of FCP always has about 3% higher as compared with analytical model1. But taking the computation time into consideration, the analytical model2 is good enough to estimate the performance of FCP with mobility. We can also say that the results in

Chapter4: Dynamic Channel Allocation with Channel Partitioning

analytical model2 are the upper bound for the system performance. The large improvement of FDCP over FCA under various arrival rate ratios is not only due to the effect of the proposed CP mechanism, but also due to the efficiency of the dynamic channel allocation scheme. In Figure 4.13, we can also observe that with the increase of S_1 traffic load, the improvement of FDCP over FCP decreases. This is because under high S_1 traffic load, there are more channels allocated to each cell for FCP. Thus, the channel trunking is more efficient for FCP. Generally speaking, Figure 4.13 shows clearly that with the increase of the traffic load for S_1 , the improvement of FCP and FDCP over FCA can be increased substantially.

Figure 4.14: GOS improvement of FCP (optimum channel combination) and FDCP over FCA under different average speeds (Km/h)

Figure 4.14 shows the impact of user speed with different traffic ratio. It can be seen that with different average user speeds, FCP provides almost the same improvement as compared with FCA. It can be explained that the user speed has the similar effect

Chapter4: Dynamic Channel Allocation with Channel Partitioning

both on FCA and FCP such that the throughput of both schemes decreases with the user speed (which is not shown here). For FDCP scheme, apparently, different user speeds could achieve different improvements. It shows that higher user speed provides higher improvement over FCA. But when we consider the actual throughput for FDCP (which is not shown here), we find that FDCP has about the same performance under different user speeds. This is because FDCP can flexibly arrange the channels among cells, especially between adjacent cells, for mobile users. When the handoff user finds a suitable channel in a new cell to be used, it will release a used channel in the old cell. Thus, the mobile user speed does not affect the system capacity by much. The reason why the improvement of FDCP over FCA increases with user speed is that the actual throughput of FCA decreases with the increasing of the user speed.

4.4 Conclusions

Our proposed CP scheme can work well with dynamic channel allocation scheme to support multiple services. As compared with FCP scheme, DCP-WI and FDCP scheme can provide further improvement due to the fact that they can adaptively arrange the channels among adjacent cell. More importantly, FDCP can cater for the traffic load variation between cells and between services without pre-allocation of channels to the system or pre-defined channel combination. FDCP is a fully distributed dynamic channel allocation scheme to support multiple services requiring different reuse factors. Thus, FDCP uses the radio resources efficiently.

An undesired side effect of FDCP is the extra overhead between base stations (BSs) due to the channel information updating. For example, for a reuse factor of 7, a total of 162 updating messages are sent for a new admission call or an on-going

Chapter4: Dynamic Channel Allocation with Channel Partitioning

rearrangement call. For a reuse factor of 4, 60 updating messages are sent. But since the exchange of information could pass through the wireline between BSs and the updating of information is very simple, it will not degrade the system performance by much.

Another limitation is that in this study, we assume that both services, voice and data, are equally important. This means that QoS is not considered. In order to provide certain level of QoS, two simple suggestions might help deal with this issue. If we consider that voice service is more time-sensitive and should have a higher priority in acceptance, the following two admission control algorithms can be applied before channel assignment is performed.

- We could reserve certain amount of channels, e.g., 10% of the total channels, depending on the system requirement, for voice calls only. If 90% of the total channels are occupied and a new data service call arrives at the system, then it will be rejected or queued by the system. But, the voice service calls are allowed to use all free channels in the system provided that the co-channel interference requirements are satisfied.
- Anytime a new call arrives at the system, it will have a certain acceptance probability, P_a . For example, we can set P_a for voice and data calls to be 0.8 and 0.2 respectively. Or we can employ such a policy only when the system reaches a certain congestion point, say 90% of the total channels.

Chapter 5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

5.1 Introduction

In IMT-2000, CDMA is approved to be the main access method because of its higher system capacity in a given radio spectrum. One of the most important aspects of CDMA cellular system is the power control scheme. The power control scheme in CDMA cellular system can avoid the situation that a single overpowering MS blocks the communication of the whole cell in the same TS. In such a case, a MS with the farthest distance from BS normally limits the capacity of the CDMA system. If a BS is under a very severe interference from surrounding cells (either from downlink BSs power or from uplink MSs power), the MS at the boundary of the cell has to either reduce its transmission rate or be blocked by BS in the uplink transmission direction. This is the major problem for the conventional direct (one-hop) communication in CDMA cellular system.

Multihop cellular system [20], on the other hand, combines ad hoc characteristics into cellular system. If a MS is under a bad communication mode, e.g., BS is under a high intercell interference, MS is very far from BS or MS is in a large fading area, the high-rate data service of MS can be delivered to BS via a RS. RS takes the responsibility of demodulating the mobile signal, decoding the original message, re-coding the message and re-modulating the signal to send to BS. Note that a RS cannot receive the signal from the MS and send it again to the BS using the same frequency at the same time. If the conventional FDD mode is used for multihop cellular system, an additional pair of radio frequency spectrums [104] must be used to support the

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

relay communication. However, TDD mode with multiple TSs can easily arrange the TSs between receiving and transmitting links. It means that the RS can relay the message to BS using the same frequency with different TSs. As a result, TDD-CDMA is a suitable wireless communication system for the multihop cellular system.

In this chapter, we study uplink capacity of TDD-CDMA multihop cellular system. We begin the uplink capacity analysis from the one-hop TDD-CDMA cellular system. The inter-cell interference is assumed to be Gaussian distributed. Based on different BS coverage distance, the probability that a certain number of MSs supported in each time slot is first obtained. Then, the average number of MSs supported in each TS is found. From the results of one-hop system, we find that system capacity can be improved if BS only covers the center small area of the cell. Besides, the high downlink transmission power of the surrounding BSs can degrade the capacity severely. This observation encourages us to extend the TDD-CDMA from normal one-hop to multihop system. The multihop TDD-CDMA system can improve the system capacity in CTS to overcome the high interference from the surrounding cells. In multihop TDD-CDMA cellular system, the area of each cell is divided into two regions: inner region and outer region. All MSs located in the inner region directly communicate with BS; while the MSs in the outer region communicate with BS with the help of a RS, which is located inside the inner region. Based on this model, the analysis for both region of the cell is followed. For the inner region, the number of users under different BS coverage distance can be obtained. Then, we can obtain the average number of MSs that the system can support in one inner-TS. For the outer region, we assume that the intracell interference from the same cell follows the Gaussian distribution; while the interference from other cells comes from the

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

maximum BS downlink power. Thus, the outage probability for n MSs in one outer-TS can be provided. Then, the average number of users that the system can support in the outer region can be found. Since multihop system uses more than one radio resource for one transmission link (MS-to-RS and RS-to-BS), we introduce a new technique to make a fair comparison between one- and multihop TDD-CDMA systems. Finally, we discuss the general rule for the best placement of RS position and inner-outer boundary. All the analytical results are verified by simulation.

5.2 One-hop TDD-CDMA Cellular Network

5.2.1 System Model

In this section, a system model with seven hexagonal cells with cell radius of R_{BS} as shown in Figure 1.2 is considered. To study the performance of uplink transmission, we assume that the center cell is in uplink transmission and other surrounding cells can either be in uplink or downlink transmission direction. Moreover, all MSs in the center cell are using the same service type with the same SF. In this chapter, the path loss model is given by $PL(r) = \kappa \cdot r^{-\mu}$ where r is the distance from transmitter to receiver; μ is the path loss exponent; and κ is a corresponding path loss constant. The perfect power control is assumed in this chapter, i.e., the received power at the BS for each MS in the same time slot is assumed to be same. For simplicity, no mobility is assumed for the MSs and handover control is not considered in this chapter. The slot allocation of a new MS will attempt to join the time slot that is currently using. If any MS cannot be allocated to the current time slot, a new time slot will be used. It also means that we will make each time slot fully loaded. The adding of one MS to a time slot is assumed to be independent of each other. The thermal noise is ignored in this

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

chapter with the assumption that it is much lower than inter-cell interference if the surrounding cells are also fully loaded.

5.2.2 One-hop TDD-CDMA Uplink Capacity Analysis

CDMA system is selected as standard 3G access method in UMTS because of its large improvement in capacity [5]. One of the most important aspects of CDMA cellular system is that each MS is power-controlled by BS. This also means that the received power for any user in the same time slot will be same at the BS. Power control scheme ensures that each MS, no matter what the distance from BS is, will have same opportunity of getting equal good service from BS if these MSs are using the same time slot. The E_b/I_0 ratio of each user in one time slot with perfect power control scheme in a desired BS is given by

$$E_b / I_0 = \frac{SF \times P_{\text{received}}}{P_{\text{received}} \times (n-1) + I_{\text{intercell}}} \quad (5.1)$$

where P_{received} is the received power of a particular user at BS; n is the number of MS currently supported in one time slot and $I_{\text{intercell}}$ is the inter-cell interference coming from surrounding cells. In this TDD-CDMA system, since any time slot can be used by either uplink or downlink direction in each surrounding cell, thus $I_{\text{intercell}}$ is given by

$$I_{\text{intercell}} = I_{\text{inter-up}} + I_{\text{inter-down}} \quad (5.2)$$

where $I_{\text{inter-down}}$ and $I_{\text{inter-up}}$ are the inter-cell interference coming from the surrounding BSs' downlink transmission and MSs' uplink transmission in the surrounding cells, respectively.

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

Given a pre-defined E_b/I_0 requirement and the number, n , of MSs existing in the current time slot, we could get the interference threshold, i.e., the maximum interference that can be tolerated in a time slot, by rewriting (5.1) as

$$I_{\text{threshold}} = \frac{SF \times P_{\text{received}}}{E_b / I_0} - P_{\text{received}} \times (n-1) \quad (5.3)$$

If the received interference at the desired BS is larger than $I_{\text{threshold}}$ (which should be larger than 0), it means these n MSs cannot be accepted in this time slot altogether. In addition, we assume that if a MS's E_b/I_0 is larger than the minimum E_b/I_0 requirement, it can achieve a good QoS from the system. Otherwise, this MS will be blocked. It means that a new MS will be blocked by the system if the received inter-cell interference is higher than $I_{\text{threshold}}$.

Then, by rewriting (5.1), we can also obtain

$$n = \left\lfloor \frac{SF}{E_b / I_0} - \frac{I_{\text{intercell}}}{P_{\text{received}}} + 1 \right\rfloor \quad (5.4)$$

where $\lfloor x \rfloor$ is the largest integer no larger than x . From (5.4), we observe that if $I_{\text{intercell}}$ is much smaller than P_{received} , i.e., $\frac{I_{\text{intercell}}}{P_{\text{received}}} \approx 0$, we can achieve the maximum number, n_{max} , of users that could be supported in one time slot, i.e.,

$$n_{\text{max}} = \left\lfloor \frac{SF}{E_b / I_0} + 1 \right\rfloor \quad (5.5)$$

This maximum number of MSs exists when all MSs are very close to center BS so that the influence of inter-cell interference from surrounding BSs is negligible as compared with P_{received} and can be omitted. In this case, no intercell interference is considered.

Chapter 5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

Next, we analyze the effect of the interference to the system capacity in the following three cases: (1) all the interference is coming from MSs' uplink power in surrounding cells; (2) all the interference is coming from surrounding BSs' downlink power; and (3) the interference comes from any number of uplink/downlink inter-cell interference combination.

5.2.2.1 Inter-cell Interference Coming from MSs' Uplink Power in the Surrounding Cells

We assume that MSs are uniformly distributed over the whole area of seven cells. For simplicity, P_{received} is assumed to be same in all cells. Same number of MSs is assumed in all seven cells. Because of the randomness of the MS's position and the limited number of MSs each time slot could be supported, the locations of the MSs supported in one time slot may not cover the whole cell of R_{BS} , which is the radius of the cell. In this instance, the system performance in terms of outage probability when BS covers a certain area can be obtained.

Figure 5.1: Interference from surrounding uplink MS

Chapter 5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

Since all six surrounding cells are in the uplink transmission, $I_{\text{intercell}} = I_{\text{inter-up}} \cdot P_{\text{received}}$

is the received power for each MS at the BS, $P_{\text{received}} \left(\frac{r_0}{r_d}\right)^\mu$ is the received power at

center BS for a MS. We assume that a MS can be uniformly allocated to each position of cell and farthest MS is at the distance of $R_c \leq R_{\text{BS}}$ in all seven cells, the intercell interference for one MS from the surrounding cell to the center BS is

$\int_{-\pi}^{\pi} \int_0^{R_c} P_{\text{received}} \left(\frac{r_0}{r_d}\right)^\mu \times \frac{r_0}{\pi R_c^2} dr_0 d\theta$. Totally, there are 6 surrounding cells. If each cell can

be allocated with n MSs, the mean, $E_{n,R_c}[I_{\text{intercell}}]$, of the random variable (RV),

$I_{\text{intercell}}$, can be expressed as

$$E_{n,R_c}[I_{\text{intercell}}] = 6n \int_{-\pi}^{\pi} \int_0^{R_c} P_{\text{received}} \left(\frac{r_0}{r_d}\right)^\mu \times \frac{r_0}{\pi R_c^2} dr_0 d\theta \quad (5.6)$$

where r_d is the distance from MS in a surrounding cell to the center BS as shown in Figure 5.1 and is given by

$$r_d = \sqrt{r_0^2 + D_{\text{BS to BS}}^2 + 2D_{\text{BS to BS}}r_0 \cos \theta} \quad (5.7)$$

where $D_{\text{BS to BS}}$ is the distance from surrounding BS to the center BS, i.e.,

$D_{\text{BS to BS}} = \sqrt{3}R_{\text{BS}}$. r_0 is the distance of MS in the surrounding cell to its BS of interested.

Similarly, the variance, $\text{Var}(I_{\text{intercell}})$, of $I_{\text{intercell}}$ is given by

$$\text{Var}_{n,R_c}[I_{\text{intercell}}] = 6n \left(\int_{-\pi}^{\pi} \int_0^{R_c} \left(\left(\frac{r_0}{r_d}\right)^\mu P_{\text{received}} - E_{1,R_c}[I_{\text{intercell}}] \right)^2 \times \frac{r_0}{\pi R_c^2} dr_0 d\theta \right) \quad (5.8)$$

where $E_{1,R_c}(I_{\text{intercell}})$ is the mean of one MS in each surrounding cell, given the coverage distance of R_c .

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

Assuming that $I_{\text{intercell}}$ is a Gaussian distributed RV, the probability that the interference, $I_{\text{intercell}}$, is higher than the threshold, $I_{\text{threshold}}$, when n users are in one time slot in all seven cells, is given by

$$P_{n,R_c}(I_{\text{intercell}} \geq I_{\text{threshold}}) = Q\left(\frac{I_{\text{threshold}} - E_{n,R_c}[I_{\text{intercell}}]}{\sqrt{\text{Var}_{n,R_c}[I_{\text{intercell}}]}}\right) \quad (5.9)$$

where $Q(\cdot)$ is Q-function which is given by $Q(x) = \int_x^{\infty} e^{-y^2/2} / \sqrt{2\pi} dy$

Considering, (5.3) (5.6) and (5.8), they all have the common factor of P_{received} in (5.9) so that P_{received} can be cancelled with each other. Thus, (5.9) gives the outage probability based on a certain coverage distance, R_c , of all seven cells given n MSs in one time slot.

The farthest MS can be in any position of the cell. And at the certain distance of R_c , the probability that one MS is within distance of R_c is $(\frac{\pi R_c^2}{\pi R_{\text{BS}}^2})$. Since one MS can be anywhere within the cell, the probability that all n MSs are within distance of R_c is given by $(\frac{\pi R_c^2}{\pi R_{\text{BS}}^2})^n$. Integrating R_c over the whole cell area from distance 0 to R_{BS} , the system failure probability, i.e., $P_n(I_{\text{intercell}} \geq I_{\text{threshold}})$, that the interference is larger than threshold in the center cell given n MSs in one time slot over whole cell coverage is given by

$$\begin{aligned} P_n(I_{\text{intercell}} \geq I_{\text{threshold}}) &= \int_0^{R_{\text{BS}}} P_{n,R_c}(I_{\text{intercell}} \geq I_{\text{threshold}}) d\left(\left(\frac{\pi R_c^2}{\pi R_{\text{BS}}^2}\right)^n\right) \\ &= \int_0^{R_{\text{BS}}} P_{n,R_c}(I_{\text{intercell}} \geq I_{\text{threshold}}) \times \frac{2n \times R_c^{2n-1}}{R_{\text{BS}}^{2n}} dR_c \end{aligned} \quad (5.10)$$

$P_n(I_{\text{intercell}} \geq I_{\text{threshold}})$ means the probability that the center BS cannot support n MSs in one time slot for a normal one-hop cellular system. From (5.10), we can also get the

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

system failure probability, $P_{n,R}(I_{\text{intercell}} \geq I_{\text{threshold}})$, when BS covers a certain coverage distance $R \leq R_{\text{BS}}$.

$$\begin{aligned} P_{n,R}(I_{\text{intercell}} \geq I_{\text{threshold}}) &= \int_0^R P_{n,R_c}(I_{\text{intercell}} \geq I_{\text{threshold}}) d\left(\left(\frac{\pi R_c^2}{\pi R_{\text{BS}}^2}\right)^n\right) \\ &= \int_0^R P_{n,R_c}(I_{\text{intercell}} \geq I_{\text{threshold}}) \times \frac{2n \times R_c^{2n-1}}{R_{\text{BS}}^{2n}} dR_c \end{aligned} \quad (5.11)$$

Another definition, the probability, Q_n , that only n users are in one TS in each BS is introduced. In other words, each time has Q_n to accept n users. From (5.10), the probability that the system can support at **least** n users in one time slot is given by $1 - P_n(I_{\text{intercell}} \geq I_{\text{threshold}})$. Thus, we have $1 - P_n(I_{\text{intercell}} \geq I_{\text{threshold}})$ probability to allocate n or more than n , i.e., $n, n+1, \dots, n_{\text{max}}$, MSs to a TS. Thus, it has the following equation

$$1 - P_n(I_{\text{intercell}} \geq I_{\text{threshold}}) = \sum_{i=n}^{n_{\text{max}}} Q_i \quad (5.12)$$

(5.12) could also be rewritten in another way as

$$Q_n = \begin{cases} P_{n+1}(I_{\text{intercell}} > I_{\text{threshold}}) & n = 0 \\ P_{n+1}(I_{\text{intercell}} > I_{\text{threshold}}) - P_n(I_{\text{intercell}} > I_{\text{threshold}}) & 1 \leq n \leq n_{\text{max}} - 1 \\ 1 - P_n(I_{\text{intercell}} > I_{\text{threshold}}) & n = n_{\text{max}} \end{cases} \quad (5.13)$$

and $\sum_{n=0}^{n_{\text{max}}} Q_n = 1$

From (5.13), the average number, $N_{\text{ave_1hop}}$, of MSs in each time slot in the center BS if all BSs cover the whole area, R_{BS} , of the cell, is given by

$$N_{\text{ave_1hop}} = \sum_{n=1}^{n_{\text{max}}} n \times Q_n \quad (5.14)$$

We can easily change the boundary of the integral in (5.11) to get the result for other BS direct coverage area, i.e., $R < R_{\text{BS}}$.

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

5.2.2.2 Intercell Interference Coming from Surrounding BSs Downlink Power

In this section, the downlink transmission power of the surrounding BSs is fixed to the maximum BS downlink power, P_{BS} . This assumption is dealing with the case that the downlink traffic is in the full load, e.g., MSs are downloading large files from the surrounding BSs. In the next generation system, we expect downlink radio resources to be used more frequently to support high-speed multimedia data services. Since we assume that all the surrounding BSs will transmit with P_{BS} , the intercell interference, $I_{intercell}$, at the center BS is given by

$$I_{intercell} = \frac{6 \times P_{BS}}{PL(\sqrt{3}R_{BS})} \quad (5.15)$$

With the assumption of perfect power-controlled scheme, MS with the farthest distance, R_c , from BS needs to transmit with the maximum MS power, P_{MS} . If this user cannot satisfy its required E_b/I_0 even though with P_{MS} in a timeslot, no more MSs will be accepted by that time slot. Thus, to accept the maximum number of user in one time slot, the received power at the BS could be obtained by

$$P_{received} = P_{MS} / PL(R_c) = \frac{P_{MS}}{\kappa \times R_c^\mu} \quad (5.16)$$

From (5.16), we could see that the received power of a MS not only depends on the maximum transmitted power of MS, but also relates to the farthest distance, r_{max} , that BS covers in the current time slot.

Figure 5.2: Number of users VS. the farthest distance mobile users (User x is the farthest user. Maximally, this TS could support n users)

Note that $I_{\text{intercell}}$ from the surrounding BSs is fixed. Based on (5.1) and (5.16), the number of users that each time slot could be supported becomes fixed if the farthest distance of a user is already known. Figure 5.2 shows the relationship between the farthest distance of MS and the number of users that could be supported in one time slot. d_n in the figure means that when farthest distance of a user is within the distance of d_n , it can support at least n users. d_n is given by rewriting (5.1) and (5.16) with the replacement of R_c by d_n

$$d_i = \sqrt[n]{\frac{P_{\text{MS}} \left(\frac{SF}{E_b / I_0} + 1 - n \right)}{\kappa \times I_{\text{intercell}}}} \quad n \in [n_{\text{max}}, n_{\text{min}}] \quad (5.17)$$

where n_{min} is the minimum number of MS could be supported in one time slot obtaining from (5.4). Referring to Figure 5.2, the probability, Q_n , of accepting n users only in each TS is obtained when all n users are within the distance of d_n and at least one of the $n+1$ users are between the distance $d=d_n$ to $d=d_{n+1}$. It means that not all users are within the distance of d_{n+1} . Otherwise, the system can support $n+1$ users

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

rather than n users if they are all within the distance of $d=d_{n+1}$. The probability that all n MSs is within the distance of d_n is given by $(\frac{\pi d_n^2}{\pi R_{BS}^2})^n = (\frac{d_n}{R_{BS}})^{2n}$. Similarly, the probability that all $n+1$ MSs is within the distance of d_{n+1} is given by $(\frac{\pi d_{n+1}^2}{\pi R_{BS}^2})^{n+1} = (\frac{d_{n+1}}{R_{BS}})^{2(n+1)}$. Considering the boundary condition, Q_n is given by

$$Q_n = \begin{cases} (\frac{d_n}{R_{BS}})^{2n} - (\frac{d_{n+1}}{R_{BS}})^{2(n+1)} & n \in [n_{\max}, n_{\min}] \\ 0 & \text{otherwise} \end{cases} \quad (5.18)$$

The average number, $N_{\text{ave_1hop}}$, of users when center BS covers whole area is still given by (5.14). The $N_{\text{ave_1hop}}$ for other coverage distance, $R < R_{BS}$, can be expressed by replacing R_{BS} in (5.18) to R .

5.2.2.3 Inter-cell Interference Coming from Any Number of Uplink/downlink in the Surrounding Cells

From the analysis in previous two sections, we are able to obtain the average TDD-CDMA system capacity for a general case with any number of uplink/downlink interference in the surrounding cells. Now, let N_{up} be the number of surrounding cells in uplink transmission and thus, the number, N_{down} , of surrounding cells in downlink transmission is $N_{\text{down}}=6-N_{\text{up}}$.

The inter-cell interference consists of two parts: fixed downlink BSs power and random uplink MSs' power. Thus, given the farthest MS's distance, R_c , both in the center cell and the surrounding cells with uplink transmission, the mean of $I_{\text{intercell}}$ when n users are in one slot is given by

$$E_{n, R_c}[I_{\text{intercell}}] = \frac{N_{\text{down}} P_{BS}}{PL(\sqrt{3}R_{BS})} + N_{\text{up}} n P_{\text{received}} \times \int_{-\pi}^{\pi} \int_0^{R_c} (\frac{r_0}{r_d})^{\mu} \times \frac{r_0}{\pi R_c^2} dr_0 d\theta \quad (5.19)$$

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

The fixed interference of BS downlink power causes no effect for the variation. Thus, the variance of $I_{\text{intercell}}$ is given by

$$\text{Var}_{n,R_c}[I_{\text{intercell}}] = N_{\text{up}} n \times \int_{-\pi}^{\pi} \int_0^{R_c} \left(\left(\frac{r_0}{r_d} \right)^{\mu} P_{\text{received}} - (E_{1,R_c}[I_{\text{intercell}}] - \frac{N_{\text{down}} P_{\text{BS}}}{PL(\sqrt{3} R_{\text{BS}})})^2 \times \frac{r_0}{\pi R_c^2} \right) dr_0 d\theta \quad (5.20)$$

$P_{n,R_c}(I_{\text{intercell}} \geq I_{\text{threshold}})$ gives the same expression as in (5.9). But P_{received} cannot be deleted directly in the expression (5.9). For the coverage distance of R_c , the received power of each MS in center BS is given by (5.16). Q_n and $N_{\text{ave_1hop}}$ can be obtained from (5.13) and (5.14) respectively.

5.2.3 Simulation and Analysis Results for One-hop TDD-CDMA System

In this paper, the uplink capacity of the center BS is considered. The simulation environment and parameters are from [105]. The whole cell coverage, R_{BS} , is 200 meters. SF is fixed to be 16. The maximum transmission power for MS and BS is set to be 21dBm and 30dBm respectively. Path loss exponent, μ , is set to be 3.52 and path loss constant, k , is set to be 137 dB. In the simulation, MSs are admitted to the system based on first-come-first-serve principle. A new user will join the current time slot only when all users in the time slot, including the new user, could satisfy their E_b/I_0 requirements. Otherwise, this new user will attempt to join a new free time slot. The average number of users in the simulation is based on the results of many time slots.

Figure 5.3: Average number of users under different E_b/I_0 requirements with all BSs uplink

Figure 5.3 shows the average number of user, N_{ave_1hop} , that could be supported in one time slot under different E_b/I_0 requirements when six surrounding cells are in uplink transmission. Figure 5.3 shows clearly that when the SF is large, more users could be supported in one time slot. Figure 5.3 also shows that N_{ave_1hop} increases with the decreasing of E_b/I_0 requirement. This is expected because a MS can tolerate more inter-cell interference for a larger E_b/I_0 .

Figure 5.4 shows N_{ave_1hop} when 3 uplink and 3 downlink transmissions are in the surrounding cells. As we can see that the results are slightly lower as compared with Figure 5.3. In fact, if all the surrounding cells are in downlink transmission, N_{ave_1hop} is about 2 for SF=16 and $E_b/I_0=5\text{dB}$ (which is not shown here). This is because the

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

influence of the interference from downlink transmission power is relatively larger than that of uplink random interference due to the higher transmission power of BS.

Figure 5.4: Average number of users under different E_b/I_0 requirements with 3 uplink interference BSs and 3 downlink interference BSs

Figure 5.5: Average number of users could supported given the largest BS coverage distance, R , for $SF=16$ and $E_b/I_0=5\text{dB}$

Figure 5.5 shows $N_{\text{ave_1hop}}$ given a certain BS coverage distance, R , in all seven cells for $SF = 16$. From the figure, it can be seen clearly $N_{\text{ave_1hop}}$ is affected by R . When BS's coverage is small, i.e., $R \leq 0.2$, 6 MSs could be supported in one time slot in all three situations. When the distance extends to 0.5, on average, 5 MSs could be supported. The value of $N_{\text{ave_1hop}}$ drops to 4.2 and 2.5 for all surrounding cells in uplink and downlink transmission respectively when BS covers the whole cell's area. It can be seen that the capacity drops as the BSs cover larger area. This observation encourages us to extend the TDD-CDMA system from normal one-hop to multi-hop system. With multihop, BS could cover a smaller central area for single-hop and use RS to build connection for MSs far from the central direct coverage area.

5.3 Uplink Capacity Improvement for Multihop TDD-CDMA System

From Figure 5.5, we find that if the direct coverage distance, R , of cell is small, the high system capacity can be obtained. This observation encourages us to use another access scheme so that BS will only cover a certain distance of the cell. Multihop cellular system is such a system that could provide this function. Since the inter-cell interference with all surrounding BS in downlink transmission can severely degrade the system capacity in TDD-CDMA system, we analyze the uplink capacity for multihop TDD-CDMA system with downlink interference from the surrounding cells.

5.3.1 System Model

We assume that there are a lot of MSs located in the cellular system. These MSs are either in “silent” mode, which do not require service from BS, or in “active” mode, which require connection from BS. The area of the center BS is divided into inner and outer region as shown in Figure 5.6. If an “active” MS is within the distance of R_{inout} from BS, it belongs to the inner region and can communicate directly with BS with one-hop. Inner-region MSs only use *inner-region TS*. An outer-region MS first communicates with a RS, which is a “silent” MS inside the inner region of the cell. Since there are a lot of MSs in the system, we assume that we are able to choose a RS with a straight line from MS to BS at the distance of R_{relay} as shown in Figure 5.6. Each RS is permitted to relay only one outer-region MS. The transmission from MS to RS uses the *outer-region TS*. The RS takes the responsibility of demodulating and decoding the received signal and recoding and retransmitting the re-modulated signal to BS through the inner-region TS.

Figure 5.6: Relaying System Model

5.3.2 Capacity Analysis of Multihop Cellular System

5.3.2.1 Capacity Analysis for Outer Region

In section 5.2.2.2, the analysis for the inner region (with certain coverage distance) has already been introduced. Thus, we can get the average number, $N_{\text{ave_inner}}$, of user in the inner region as

$$N_{\text{ave_inner}} = \sum_{i=0}^{r_{\max}} Q_i \times i \quad (5.21)$$

where Q_i is given by (5.18) by replacing R_{BS} with R_{inout} . Next, we will analyze the capacity in the outer region of the cell. In the outer region of the cell, we cannot directly use the perfect power-controlled scheme as used in normal one-hop cellular system. This is because each RS is permitted to relay just one MS. For simplicity, in this paper, we introduce another transmission power scheme called Same Received Power Level (SRPL). In SRPL, we assume that all RSs receive exactly the same power, $P_{\text{rec_relay}}$, from their MSs regardless of their locations. Thus, the transmission power of the MS depends on the distance from MS to its RS. We also assume that

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

only if a MS is at the boundary of the cell, i.e., $r_m=R_{BS}$, will it transmit with the maximum MS uplink power, P_{MS} . Thus, the received power, P_{rec_relay} at RS for each MS is fixed and is given by

$$P_{rec_relay} = \frac{P_{MS}}{PL(R_{BS} - R_{relay})} \quad (5.22)$$

where R_{relay} is the distance of RS from BS. Thus, the transmitted power for any MS with distance of r_m in the outer region is given by

$$P_{tran_ms} = P_{rec_relay} \times PL(r_m - R_{relay}) \quad (5.23)$$

If n MSs are in one outer-region TS, there is $n-1$ independent interference for the RS.

The mean or the first moment of intra-cell interference, i.e., $I_{intracell}$, is given by

$$E[I_{intracell}] = (n-1) \int_{-\pi}^{+\pi} \int_{R_{inout}}^{R_{BS}} \frac{(r - R_{relay})^\mu}{(d_x(r, \theta))^\mu} P_{rec_relay} \times \frac{r}{\pi(R_{BS}^2 - R_{inout}^2)} dr d\theta \quad (5.24)$$

where R_{inout} is the distance of inner-outer region boundary and $d_x(r, \theta)$ is the distance from the interference MS to the RS, which is given by

$$d_x(r, \theta) = \sqrt{r^2 + R_{relay}^2 - 2rR_{relay} \cos \theta} \quad (5.25)$$

Similarly, the variance of the $I_{intracell}$ is given by

$$Var[I_{intracell}] = (n-1) \int_{-\pi}^{+\pi} \int_{R_{inout}}^{R_{BS}} \left(\frac{(r - R_{relay})^\mu}{(d_x(r, \theta))^\mu} P_{rec_relay} - E[I_{intracell}]/(n-1) \right)^2 \times \frac{r}{\pi(R_{BS}^2 - R_{inout}^2)} dr d\theta \quad (5.26)$$

The inter-cell interference comes from the surrounding BSs' downlink transmission power. Thus, the first moment of the inter-cell interference, $I_{intercell}$, is given by

$$E[I_{intercell}] = \int_0^{2\pi} \sum_{i=1}^6 \frac{P_{BS}}{PL(\sqrt{D_{BS to BS}^2 + R_{relay}^2 - 2D_{BS to BS} R_{relay} \cos(\theta + \frac{i \times \pi}{3})})} \times \frac{1}{2\pi} d\theta \quad (5.27)$$

Similarly, the variance of the $I_{intercell}$ is given by

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

$$\text{VAR}[I_{\text{intercell}}] = \int_0^{2\pi} \left(\sum_{i=1}^6 \frac{P_{\text{BS}}}{PL(\sqrt{D_{\text{BtoBS}}^2 + R_{\text{relay}}^2} - 2D_{\text{BtoBS}}R_{\text{relay}}\cos(\theta + \frac{i \times \pi}{3}))} - E(I_{\text{intercell}}) \right)^2 \times \frac{1}{2\pi} d\theta \quad (5.28)$$

Since we assume that $I_{\text{intercell}}$ and $I_{\text{intra-cell}}$ follow Gaussian distribution and are independent RVs, we can get the probability, $P_n(I \geq I_{\text{threshold}})$, that the inter- and intra- interference is higher than a pre-defined value when n MSs are within one TS, which is given by

$$P_n(I \geq I_{\text{threshold}}) = Q\left(\frac{I_{\text{threshold}} - (E[I_{\text{intra-cell}}] + E[I_{\text{intercell}}])}{\sqrt{\text{Var}[I_{\text{intra-cell}}] + \text{Var}[I_{\text{intercell}}]}}\right) \quad (5.29)$$

where the $I_{\text{threshold}}$ is the maximum interference that one MS can tolerant and is given by

$$I_{\text{threshold}} = \frac{SF \times P_{\text{received}}}{E_b / I_0} \quad (5.30)$$

(5.29) means that when n users are allocated to one outer-region TS, each user has $1 - P_n(I \geq I_{\text{threshold}})$ probability to be accepted by the system. With the assumption that all MSs in one TS is independent of each other, the probability, $P_{\text{allaccept}}(n)$, that all n users can be accepted by the system is given by

$$P_{\text{allaccept}}(n) = (1 - P_n(I \geq I_{\text{threshold}}))^n \quad (5.31)$$

Finally the probability, $Q_{n,\text{outer}}$, that only n users are within one outer-region TS is given by

$$Q_{n,\text{outer}} = P_{\text{allaccept}}(n) - P_{\text{allaccept}}(n+1) \quad (5.32)$$

Similar to (5.14), the average number, $N_{\text{ave_outer}}$, of MSs that each outer-region TS can be supported is given by

$$n_{\text{ave_outer}} = \sum_{i=1}^{\infty} Q_{i,\text{outer}} \times i \quad (5.33)$$

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

5.3.2.2 Fair Comparison with One-hop TDD-CDMA System

Multihop cellular system requires more than one radio resource as compared to the one-hop cellular system for one communication link (MS to RS and RS to BS). Thus, a general comparison rule should be developed to make a fair comparison. First, we assume that a total of L TSs are in the system. Let M_1 be the number of MSs that can be supported in the conventional one-hop cellular system. And in each TS of one-hop system, it can support $N_{\text{ave_1hop}}$ users. Then, L is given by

$$L = \frac{M_1}{N_{\text{ave_1hop}}} \quad (5.34)$$

For multihop cellular system, we divide the TS slot into two types: inner-region TS and outer-region TS. Let M_2 be the number of MSs that can be supported with L TSs. The average number of MS, $n_{\text{ave_inner}}$, in the inner-region TS and the average number of MS, $n_{\text{ave_outer}}$, in the outer-region TS are introduced in the previous sections. Then, L is given by

$$L = \frac{M_2 a}{n_{\text{ave_inner}}} + \frac{M_2 (1-a)}{n_{\text{ave_outer}}} + \frac{M_2 (1-a)}{n_{\text{ave_inner}}} = \frac{M_2}{n_{\text{ave_inner}}} + \frac{M_2 (1-a)}{n_{\text{ave_outer}}} \quad (5.35)$$

where a is the percentage of inner-region area over all BS area and is given by

$$a = \frac{2\pi R_{\text{relay}}^2}{3\sqrt{3}R_{\text{BS}}^2}.$$

Thus, average number of MSs, $N_{\text{ave_2hop}}$, per TS that can be supported in multihop cellular system is given by

$$N_{\text{ave_2hop}} = \frac{M_2}{L} = \frac{1}{\frac{1}{n_{\text{ave_inner}}} + \frac{(1-a)}{n_{\text{ave_outer}}}} \quad (5.36)$$

From (5.34) and (5.35), the improvement of multihop system over one-hop system is given by

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

$$P_{\text{imp}} = \frac{M_2 - M_1}{M_1} = \frac{\frac{1}{N_{\text{ave_1hop}}}}{\frac{1}{n_{\text{ave_inner}}} + \frac{1-a}{n_{\text{ave_outer}}}} - 1 \quad (5.37)$$

From (5.37), the improvement is based on the number of users that could be supported in one TS, i.e., $N_{\text{ave_1hop}}$, $n_{\text{ave_inner}}$ and $n_{\text{ave_outer}}$. Besides, the distance of the R_{inout} and R_{relay} also affect the improvement significantly. And the best choice of the position of the RS and the inner-outer boundary will be discussed in the next section.

5.3.3 Simulation and Analysis Results for Multihop TDD-CDMA System

Figure 5.7 shows the capacity in one outer-region TS under different inner-outer boundaries, R_{inout} , and RS positions, R_{relay} . The optimum combinations of $(R_{\text{inout}}, R_{\text{relay}})$ are presented in Figure 5.7. It can be shown that more system capacity can be achieved as R_{inout} increases. This is because, with our SRPL power control scheme, the intra-cell interference mainly comes from the interfering MSs closed to the interested MSs in the same straight line from interested MS to RS. For a large R_{inout} (or small outer-region), the probability that interfering MSs are close to MS of interested is very low. As a result, more MSs can be accepted in one outer-region TS. From Figure 5.7, we can also see that R_{relay} should be less than R_{inout} , not in-line with R_{inout} boundary, to provide the best capacity.

Figure 5.7: Average number of users under different BS direct coverage area for outer region with SF=16

Compared Figure 5.5 with Figure 5.7, we can see that the inner region achieves more capacity for small R_{inout} . However, the outer region needs large R_{inout} in order to accept more MSs. At the same time, R_{relay} also affects the capacity for the outer region. Thus, R_{relay} and R_{inout} should be carefully studied to conclude a general case.

Figure 5.8 shows the improvement of our proposed relay scheme over conventional one-hop TDD-CDMA system with different $(R_{\text{inout}}, R_{\text{relay}})$ combinations using Eq.(5.37). As we can see from the figure, two-hop cellular systems can significantly improve the system capacity. For $E_b/I_0=5\text{dB}$, the optimum R_{inout} and R_{relay} is $0.6R_{\text{BS}}$ and $0.5R_{\text{BS}}$, respectively. The improvement of the two-hop TDD-CDMA system over

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

conventional TDD-CDMA system is about 80%. Based on the results of this chapter, a general rule for multihop system is

- The inner region area should be large enough but remain a high inner-region capacity.
- The relaying station should be located near the inner-outer boundary but the capacity should be higher than it is at the boundary.

Figure 5.8: Improvement of multihop cellular system over one-hop system when SF=16

The inner-outer boundary and RS position combination of $0.6R_{BS}$ and $0.5R_{BS}$, respectively, satisfy this general rule. Thus, the highest system capacity is achieved. The average number of MS that each TS can be supported is given in Figure 5.9. We can also observe that the final system capacity is much less than the results of the

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

outer area. The reason is that whenever there is a MS in the outer region, there must be one inner RS to relay its service to occupy an inner TS. Thus, one TS used in the outer-region for MSs means more TSs in the inner-region for RS are generated. This can be explained by (5.36).

Figure 5.9: System capacity under different E_b/I_0 Requirement when SF=16

5.4 Conclusions

In this chapter, the uplink capacity study of a multihop TDD-CDMA cellular system is presented. We first analyze the system failure, $P_n(I_{\text{intercell}} \geq I_{\text{threshold}})$, when n users in the system, the probability, Q_n , that only n users is in each time slot and the average number, $N_{\text{ave_1hop}}$, of users that each time slot could support in three different intercell interference cases for one-hop TDD-CDMA system. From our analysis and simulation results for one-hop system, we find that the BS's direct coverage area in

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

TDD-CDMA is actually an important factor to the system capacity. If the coverage distance is small, high capacity can be obtained. Besides, the inter-cell interference from the surrounding downlink BS power causes severe influence to the system capacity in the CTS. This problem can be settled with the multihop cellular system. These issues motivate us to analyze the uplink capacity both in inner- and outer-region of the cell in the CTS situation. From the results, we observe that the inner-region area should be set large enough but remain a relatively high inner-region capacity; while the RS should be located inside the inner-region but near the inner-outer boundary. If a proper relay and inner-outer boundary is selected, multihop cellular system can give a very high improvement in capacity as compared with conventional one-hop TDD-CDMA system.

Some assumptions are made in this study. In practical system, the validity of these assumptions depends on the exact system implementation, including applications, terrain status, etc. These assumptions are made for the ease of analysis. Some assumptions can be changed in some other system model to make it more practical. In the analysis of one-hop system, 1) we assume that same number of MSs are in the center and surrounding cells with uplink transmission [4, 21, 106]; 2) perfect power control is scheme is also used for the uplink transmission [4, 104, 106]; 3) all uplink cells have the same farthest MS user within the area of the cell; 4) cells with downlink transmission will transmit with their maximum downlink transmission power. Besides these assumptions, in multihop model, we introduce a power control scheme, Same Received Power Level (SRPL), for the outer MSs. In this power control scheme, we assume that only if a MS is at the boundary of the cell, will it transmit with the maximum MS uplink power. Other MSs' transmission powers depend on the distance

Chapter5: Uplink Capacity Analysis for Multihop TDD-CDMA Cellular System

from MS to RS such that the received power at each RS is same. And the transmission power of each MS can be obtain from (5.23).

Chapter 6: Time Slot Allocation Scheme for Multihop TDD-CDMA Cellular System

6.1 Introduction

In Chapter 5, we have analyzed the performance of the TDD-CDMA cellular system. And we propose to implement multihop structure into cellular system to increase the system capacity of TDD-CDMA cellular system. The results obtained in Chapter 5 are based on the average value of unlimited number of TSs without any channel allocation scheme applied. However, in practical TDD-CDMA system, each frame consists of 15 TSs for TDD-CDMA. And any MS can be allocated to any TS in either uplink or downlink transmission. The time slot allocation scheme within these 15 TSs gives the system another freedom of adapting system environment. Consequently, as compared with general first-come-first-serve (FCFS) channel allocation method, capacity improvement can be obtained by various time slot allocation techniques such as interference avoidance, interference suppression or some other techniques introduced Chapter 2.

We study the maximum throughput of several channel allocation schemes for a TDD-CDMA cellular system with/without multihop. The channel allocation schemes are fixed switching point (FSP), dynamic switching point (DSP), our proposed dynamic switching point with multihop (DSPM) and maximum interference first (MIF). FSP and DSP are the most simple channel allocation scheme [74] [75] for TDD-CDMA cellular system. They provide lower bound of the system performance for general comparison. DSPM implements multihop structure using FCFS general allocation scheme. For MIF scheme, the basic idea is to allocate MSs into TSs that can just

satisfy their E_b/I_0 requirements with the maximum data rate. The objective of this chapter is to discover the maximum throughput (in kbps) that one frame can support for our model studied here.

6.2 System Model

6.2.1 Cell Structure

A seven-cell model is assumed to be the service area. MSs are uniformly distributed within the service area. The downlink transmission of seven cells uses one-hop transmission in all four TSs allocation schemes because most of the downlink transmission can be satisfied with a good data rate (shown in the simulation section later). In uplink transmission, the MSs in both the center cell and the surrounding cells allow to use multihop transmissions in DSPM and MIF schemes. For DSPM and MIF schemes, there are six fixed RSs placed in the position as planned in each cell as shown in Figure 6.4. The exact positions are simulated to achieve the best performance.

6.2.2 Frame Structure

The standard frame structure of UMTS is used in this study. Each frame consists of 15 TSs within 10ms [105, 107]. The SF of each MS can be changed from 1 to 16, corresponding to the data rate from 256kbps to 16kbps. In each TS, only one MS is allowed to be allocated with the maximum data rate (or smallest SF) in order to obtain the maximum throughput for each TS. If this maximum data rate cannot be supported in the current TS, a larger SF from 2, 4, ..., to 16 will be used. This will result in the lower transmission data rate of each MS to 128, 64, ..., 16kbps. If 16kbps data rate

cannot be supported, we assume that MS is in a very bad position and it cannot transmit any data (0kbps).

6.2.3 Unbalanced Traffic Pattern

Since the traffic in TDD-CDMA systems is expected to be unbalanced, the uplink-to-downlink TS ratio requirement, U:D, is different in each cell. For example, if U:D = 1:4 in a given cell, it means that the users in that cell require 1 TS and 4 TSs for uplink and downlink transmissions, respectively, with data rate as maximum as possible in each TS. In addition, we assume that U:D can be different between center cell and surrounding cells in order to make a unbalanced traffic scenario in our model. For simplicity, we assume the uplink transmission always requires 1 TS, i.e., $U = 1$, while the downlink transmission can require 1 or more TSs, i.e., $D \geq 1$ because normally the uplink data rate is lower than the downlink data rate.

6.2.4 Multihop Signaling

It is assumed that the BS in each cell is able to send/receive the *multihop* control signals within the whole cell. Hence, in case a MS is in the multihop transmission mode, BS is able to choose a proper RS which has the shortest distance from the MS. Once the RS is selected, the BS will send the necessary information to both RS and MS in order to establish a multihop communication link between MS and BS: MS-to-RS-to-BS. Since this chapter focus on the TS allocation for multihop, the details of the signaling mechanism is not considered here.

6.3 Channel Allocation Schemes for Multihop Cellular Structure

In this Section, we describe four time slot allocation schemes, FSP, DSP, DSPM and MIF, for TDD-CDMA systems without/with multihop capability. In this description, the $U:D = 1:1$ and $U:D = 1:4$ are used for the center cell and surrounding cells, respectively. For $U:D = 1:1$, it means that each MS requires 1 TS for uplink and 1 TS for downlink in the center cell with data rate as maximum as possible.

In multihop schemes, DSPM and MIF, if a MS does not satisfy its maximum data rate in the uplink, the uplink data can be forwarded to BS via RS. However, multihop communication is not considered for the downlink because the direct one-hop communication in the downlink can favor the maximum data rate in most of the TS as shown in the simulation section. Hence, the multihop communication does not improve the data rate in the downlink by much.

							SP									
TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	TS9	TS10	TS11	TS12	TS13	TS14	TS15	Center Cell Surrounding Cells	
U1	U2	U3	U4	U5	U6	U7		D7	D6	D5	D4	D3	D2	D1		
U7	U8						D8	D8	D8	D8	D7	D7	D7	D7		

Figure 6.1: FSP scheme

6.3.1 Fixed Switching Point (FSP)

In FSP, the center and the surrounding cells have the same switching point (SP) between uplink and downlink TSs. The SP is placed between TS 7 and TS 8 as shown in Figure 6.1. The center cell can be allocated with 7 MSs with 7 uplink TSs and 7 downlink TSs because of the balanced $U:D$ of 1:1. Each of the surrounding cells can be allocated with 2 users using 2 uplink TSs and 8 downlink TSs due to unbalanced $U:D$ of 1:4. Apparently, the surrounding cells cannot fully use all the available TSs in the scenario as shown in Figure 6.1. The maximum capacity of FSP scheme can be

Chapter 6: Time Slot Allocation Schemes

expected to be low. For the center cell, the average data rate of each TS is expected to be high because 5 of 7 MSs, i.e., U3 to U7, do not receive intercell interference from the surrounding cells.

The allocation of a MS to a TS consists of three steps: TS allocation, power adjustment and data rate re-selection. The TS allocation in FSP is based on FCFS. A new MS is allocated to the frame from the leftmost free TS for uplink transmission and the rightmost D free TS for downlink transmission. The new MS/BS tries to transmit with the maximum data rate first with certain power level. If the maximum data rate cannot be satisfied even with the maximum transmit power, a lower data rate with certain transmit power is tried. Then, the power adjustment and data rate re-selection will be executed for all MSs/BSs using the selected TSs for uplink and downlink transmissions in all cells (center and surrounding cells) so that they can satisfy their E_b/I_0 requirements. During this process, all MSs/BSs will adjust their powers to satisfy the E_b/I_0 requirements to maintain their current transmission data rates. If the maximum power of the MSs/BSs cannot satisfy the E_b/I_0 requirements, the MSs/BSs have to lower their transmission data rate and the power adjustment and data re-selection process will be executed again. Noted that the data rate used in each TS depends on the interference status of that TS. Thus, each TS may have different data rate for the same MS. For example, one MS in the center cell may use TS1 with data rate of 256kbps for uplink and TS15 with data rate of 128kbps for downlink because TS1 receives little interference whereas TS15 receives a high interference. Similarly, one MS in a surrounding cell, which needs 1 TS and 4 TSs for uplink and downlink, respectively, may use TS1 with data rate of 256kbps for uplink; whereas,

Chapter 6: Time Slot Allocation Schemes

this MS may use different data rates for the 4 TSs in downlink such as TS15 with 256kbps, TS14 with 128kbps, TS13 with 128kbps and TS12 with 64kbps.

The uplink will always get the TS first. Then, the remaining free TSs will be allocated to the downlink. It is possible that the number of remaining free TSs for downlink is less than D. If the number of free TSs is 1, the new call will be blocked by the system.

Figure 6.2: DSP scheme

6.3.2 Dynamic Switching Point (DSP)

Similar to FSP, the TS allocation in DSP is also based on FCFS rule except that each cell has its different SP. For uplink transmission, one TS is selected from the leftmost free TS. For downlink transmission, the rightmost D free TSs are selected. Similarly, the uplink will always get the TS first. Then, the remaining free TSs will be allocated to the downlink. It is possible that the number of remaining free TSs for downlink is less than D. If the number of free TSs is 1, this new call will be blocked by the system.

The new MS/BS tries to transmit with the maximum data rate first with certain power level. If the maximum data rate cannot be satisfied even with the maximum transmit power, a lower data rate with certain transmit power is tried. The other procedures, power adjustment and data rate re-selection, in DSP are similar to that of FSP scheme. As shown in Figure 6.2, the center cell can be allocated with 7 MSs that is same with FSP because of balanced U:D of 1:1 in the center cell. For surrounding cells, the U:D is 1:4. It means that each MS requires 1 TS for uplink and 4 TSs for downlink. As

shown in Figure 6.2 each surrounding cell can allocate one more MS as compared to FSP because of the dynamic SP in DSP. Thus, all $3 \times (1+4) = 15$ TSs can be fully used in DSP scheme in the surrounding cells.

Holma [24] mentioned that the CTS interference from surrounding downlink power can generate unacceptable interference to the uplink MSs in the center cell. Consequently, the uplink MSs in the CTS of the center cell cannot transmit with the maximum data rate. As expected, the MSs using TS4 to TS7 in the center cell cannot transmit with the maximum data rate in most of the time, which will be shown later. Thus, in order to enhance the uplink data rate for a user, we introduce multihop TS allocation schemes to solve this CTS problem.

6.3.3 Dynamic Switching Point with Multihop (DSPM)

In DSPM scheme, the TS allocation procedure will be preceded as in DSP based on FCFS rule in each cell. The TS allocation will be executed for the uplink transmission first and selects a leftmost free TS. If the uplink transmission data rate cannot reach the maximum data rate of 256kbps, a RS will be used to relay the data to the BS. RSs are placed in the position as shown in Figure 6.4 with a distance of R_{relay} . The RS with the shortest distance to a MS is selected by the BS for data relaying. For multihop transmission, the leftmost free TS will be used to establish the communication link from RS to BS. Then, the next leftmost free TS will be used to realize the communication from MS to RS. For example, as shown in Figure 6.4 since a MS, U1, cannot transmit with the maximum data rate in the leftmost TS, TS1, even with the maximum uplink transmit power in the center cell, U1 tries to use TS1 for RS-to-BS link and use the next leftmost TS, TS2, for MS-to-RS link. Normally, the communication link of MS-to-RS or RS-to-BS can transmit at the maximum data rate

Chapter 6: Time Slot Allocation Schemes

due to shorter distance. However, if this is not the case, a lower transmission data rate will be attempted to transmit in both links: MS-to-RS and RS-to-BS. Note that the transmission data rate in both MS-to-RS and RS-to-BS links for the same MS must be the same in order to be consistent. After TS allocation, power adjustment as well as data rate re-selection will be preceded in the center and the surrounding cells. After uplink TS allocation, the TS allocation selects the rightmost D free TSs for the downlink transmission with no multihop transmission.

The uplink will always get 1 or 2 TSs first. Then, the remaining free TSs will be allocated to the downlink. If the number of free TSs is 1, the new call will be blocked by the system. Different from FSP and DSP, if the number of free TSs is 2, it is not enough to support a multihop user because a multihop user requires 2 TSs for uplink and at least 1 TS for downlink. Thus, it will allocate 1 TS for uplink transmission (without multihop transmission) and the other TS for downlink transmission.

TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	TS9	TS10	TS11	TS12	TS13	TS14	TS15	
U1	U1	U2											D2	D1	Center Cell
U3	U4	U4					D4	D4	D4	D4	D3	D3	D3	D3	Surrounding Cells

Figure 6.3: DSPM scheme

Figure 6.4: Multihop model in the center cell

6.3.4 Maximum Interference First (MIF)

From the simulation section, it can be found that CTS has relatively low probability (77%) to support maximum data rate and DSP schemes. Thus, another TS is needed to relay the data from MS to BS via a RS in DSPM scheme when a MS cannot satisfy its maximum uplink transmission data rate. However, this lowers the number of MSs that can be supported in one frame. To solve this problem, we propose another multihop TS allocation scheme, MIF, to the multihop cellular system to increase the number of MSs that can be supported in each frame.

In MIF, the BS checks the TS status of the surrounding cells before it assigns the TS to a new MS for uplink transmission. If a TS has been used often for uplink transmission in the surrounding cells, it has higher priority to be allocated to a new MS. The MIF algorithm is described as follows. A BS first measures the uplink interference for all free TSs. Then the BS tries to allocate a new MS to a TS with maximum uplink interference among all the free TSs with the maximum uplink data rate of 256kbps. If that maximum *interfered* TS cannot accept this MS with the maximum data rate, a next-maximum *interfered* TS will be tried. This process continues until all free TSs cannot accept this MS with the maximum data rate. If no TS can support the new MS with maximum data rate, a RS will be selected by the BS to relay the data to the BS. The selection priority of TSs for multihop transmission is still based on the-maximum-*interfered*-TS first principle. First, the BS measures the uplink interference for all free TSs and tries to find a TS to support the maximum data rate (256 kbps) for the selected RS: RS-to-BS link. If no TS can support the selected RS with the maximum data rate, the BS tries to find a TS to support the next possible maximum data rate such as 128, 64, ... 16kbps. After that, the RS measures the uplink

Chapter 6: Time Slot Allocation Schemes

interference for all free TSs and tries to find a TS to support the maximum data rate (256 kbps) for the new MS: MS-to-RS link. If no TS can support the new MS with the maximum data rate, the RS tries to find a TS to support the next possible maximum data rate such as 128, 64, ... 16kbps. If the transmission data rate of RS-to-BS link is different from that of MS-to-RS link, a lower data rate will be selected for both link. Noted that the two TSs for RS-to-BS link and MS-to-RS link can be separated as shown in Figure 6.5 in the center cell. Then, power adjustment as well as date rate re-selection will be preceded in center and surrounding cells. After uplink the TS allocation, the TS allocation selects the rightmost D free TSs for the downlink transmission with no multihop transmission. For MIF, the TSs selected for downlink transmission are not necessary to consecutive as shown in Figure 6.5 in the surrounding cells. The flow-chart of MIF scheme is shown in Figure 6.6.

Similar to DSPM, the uplink will always get 1 or 2 TSs first. Then, the remaining free TSs will be allocated to the downlink. If the number of free TSs is 1, the new call will be blocked by the system. If the number of free TSs is 2, it will allocate 1 TS for uplink transmission (without multihop transmission) and the other TS for downlink transmission.

TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	TS9	TS10	TS11	TS12	TS13	TS14	TS15	Center Cell Surrounding Cells
U1		U2		U1								D2	U2	D1	
U3										D3	D3	U3	D3	D3	

Figure 6.5: MIF scheme

Chapter 6: Time Slot Allocation Schemes

Figure 6.6: Flow-chart of MIF scheme

Chapter 6: Time Slot Allocation Schemes

Our proposed MIF scheme can provide the following advantages:

1. In our model, the uplink interference level received at the BS in one TS reflects the physical location of the MSs in the surrounding cells using the same TS. The low uplink interference received at the BS implies that the MSs in the surrounding cells using the same TS are near to their BSs. This is because the MSs near to their BSs in the surrounding cells will transmit with low power to satisfy their maximum data rate and resulting in the low uplink interference to the other BSs. Thus, MSs in the bad position in a cell should use this low *interfered* TS and transmit with high power without significantly affecting those MSs in the good position in the surrounding cells. Thus, the maximum-*interfered*-TS-first principle in MIF scheme allows a far MS in a given cell to use the low *interfered* TS and transmit with high power without affecting the surrounding cells. Hence, it can adaptively allocate the TSs to the MSs in the cells according to the interference variation among surrounding cells.
2. In MIF, a good MS (close to the BS) that can tolerate high interference has a higher priority to be allocated to the TS with high interference. These good MSs can transmit with lower transmit power so that they will not seriously affect the MSs in the surrounding cells. In addition, this allows other bad MSs in the same cell that cannot tolerate high interference to be allocated to the TSs with lower interference. In this way, the probability of using relay is lower and more MSs can be accepted within one frame.
3. Sometimes, the maximum-*interfered*-TS-first principle may not be effective enough in the situation that the interference from the surrounding cells is very

high to support the maximum data rate. In this case, multihop transmission can be applied to increase the data rate. In addition, multihop transmission can further decrease the inter-interference to the surrounding cells. Thus, the data rate can be improved.

Since this paper is to study the maximum throughput of the single-hop/multihop systems for different TS allocation schemes, each TS can only accept one link, i.e., single-hop mode for MS-to-BS link or multihop mode in MS-to-RS link and RS-to-BS link. We have simulated the different distances of R_{relay} to achieve the best performance in multihop schemes. Since the distance between MS and RS and the distance between RS and BS becomes shorter, a higher data rate can be achieved in both links. Consequently, MSs with longer distance in the previous FSP or DSP scheme can now transmit with a higher data rate in DSPM and MIF schemes. Hence, this increases the QoS for the MSs near the cell's boundary.

6.4 Simulation Results and Discussion

Our simulation is running on *C* simulator. Different uplink and downlink (U:D) TS ratio requirements are simulated. MSs are uniformly distributed over the service area. A MS is randomly allocated to a cell until all seven cells are no longer to support any MS. In all four schemes, whenever a new MS is added to any of the cells (surrounding or center cell), the power of each MS/BS is adjusted to meet the uplink/downlink E_b/I_0 requirement with the maximum data rate. If MS/BS cannot meet the uplink/downlink E_b/I_0 requirement even with the maximum transmit power, the corresponding data rate is reduced with lower transmission power. If RS is needed for DSPM and MIF schemes, the one with the shortest distance from MS of interested is selected. BS monitors the transmission status of each MS and makes the decision to select a RS for

Chapter 6: Time Slot Allocation Schemes

multihop transmission. The transmission power from MS, RS or BS ensures that the E_b/I_0 at the relevant receiver is, at least, equal to requirement. The parameters used in the simulation are listed in Table 6-1. A few R_{relay} values are simulated and $R_{\text{relay}} = 0.45R$ is used to achieve the best performance.

Table 6-1: Simulation parameters

Cell Radius	200m
E_b/I_0	5dB
Max. MS Power	20dBm
Max. BS Power	30dBm
Pathloss Exponent μ	3.52
Pathloss Constant κ	137dB

Table 6-2: System throughput for balanced traffic among cells

	Schemes	Total capacity	Center cell capacity	Center UL capacity	Center DL capacity	Surrounding UL capacity	Surrounding DL capacity	Center UL mean data rate	Center DL mean data rate	Center users supported
U:D=1:1 in each cell	FSP	23947	3290	1633	1657	10346	10311	233	237	7
	DSP	23947	3290	1633	1657	10346	10311	233	237	7
	DSPM	24096	3395	1749	1646	10399	10302	252	237	6.96
	MIF	24180	3448	1792	1657	10421	10311	256	237	7
U:D=1:2 in each cell	FSP	25651	3532	1166	2366	7390	14729	233	237	5
	DSP	25651	3532	1166	2366	7390	14729	233	237	5
	DSPM	25568	3549	1245	2303	7418	14601	251	238	4.98
	MIF	25761	3619	1256	2363	7411	14731	251	237	5
U:D=1:4 in each cell	FSP	25642	3538	700	2839	4433	17671	233	237	3
	DSP	25642	3538	700	2839	4433	17671	233	237	3
	DSPM	25609	3552	751	2802	4457	17600	251	237	3
	MIF	25686	3579	744	2835	4434	17673	248	237	3

Table 6-2 shows the simulation results of different schemes with balanced traffic among cells with $E_b/I_0=5\text{dB}$ for three different U:D cases. Compared to FSP and DSP, DSPM and MIF can increase the data rate per MS in the center cell significantly and at the same time they can improve the uplink capacity in the center cell. But they do not improve much for the downlink data rate per MS or downlink capacity in the center cell. This is because, as expected, the downlink transmission normally does not require multihop transmission due to enough BS transmission power. Table 6-2 shows

Chapter 6: Time Slot Allocation Schemes

that the uplink and downlink capacity in the surrounding cells are about the same for all four schemes.

In U:D=1:1 scenario, MIF and DSPM have 10% and 7% improvement, respectively, over FSP/DSP in the uplink capacity in the center cell. The great improvement is due to that fact that FSP and DSP schemes use only 14 TSs (7 for uplink and 7 for downlink transmission) for balanced transmission between uplink and downlink. However, MIF and DSPM schemes can possibly use one more TS for data relaying to further improve the throughput. In U:D=1:2 and U:D=1:4 scenarios, all 15 TSs can be used in FSP and DSP schemes as well. Thus, less improvement, about 8%, is achieved from DSPM and MIF.

Table 6-3: System throughput for unbalanced traffic among cells (center more uplinks).

	Schemes	Total capacity	Center cell capacity	Center UL capacity	Center DL capacity	Surrounding UL capacity	Surrounding DL capacity	Center UL mean data rate	Center DL mean data rate	Center users supported
U:D=1:1 center U:D=1:4 others	FSP	18178	3402	1746	1656	2955	11820	249	237	7
	DSP	25436	3219	1562	1657	4434	17783	224	237	7
	DSPM	25438	3276	1671	1606	4462	17700	245	237	6.8
	MIF	25607	3362	1716	1645	4454	17792	246	236	6.97

Table 6-4: System throughput for unbalanced traffic among cells (surrounding more uplinks).

	Schemes	Total capacity	Center cell capacity	Center UL capacity	Center DL capacity	Surrounding UL capacity	Surrounding DL capacity	Center UL mean data rate	Center DL mean data rate	Center users supported
U:D=1:4 center U:D=1:1 others	FSP	23228	2378	466	1912	10538	10312	233	239	2
	DSP	24028	3566	700	2865	10149	10313	234	240	3
	DSPM	24104	3572	756	2817	10234	10297	252	239	3
	MIF	24137	3623	768	2855	10180	10334	256	240	3

Table 6-3 shows the simulation results for different unbalanced traffic among cells with $E_b/I_0=5\text{dB}$. The surrounding cells require higher downlink traffic and thus, more

Chapter 6: Time Slot Allocation Schemes

TSs for the uplink transmission in the center cell are in the CTS situation. As shown in Table 6-3, FSP provides the highest uplink capacity in the center cell. This is because FSP has the same switching point, which is placed between TS 7 and TS 8, in all seven cells. Thus, it has eight TSs for the downlink transmission. Because of $U:D = 1:4$ in the surrounding cells, it supports 2 MSs to use 10 TSs in which TS1 and TS2 are for uplink and TS8 to TS15 are for downlink as shown in Figure 6.1. This makes 5 TSs, from TS3 to TS7, for uplink transmission in the center cell not receive any CTS interference as shown in Figure 6.1. As a result, these TSs without any inter-cell interference can always reach the maximum data rate of 256kbps. Thus, FSP has a very high average uplink capacity in the center cell and its uplink data rate per MS is 249kbps. However, FSP has a very low capacity in the surrounding cells because it is not fully utilized all the TSs. Thus, FSP is not a good TS allocation scheme from the overall performance point of view. DSP has lower uplink capacity and uplink data rate per MS in the center cell due to the CTS interference in the center cell as shown in Figure 6.2. The CTS interference can be improved by DSPM and MIF. The improvement of the uplink data rate per MS for DSPM and MIF over DSP is about 10%. The improvement of the uplink capacity for DSPM and MIF over DSP is about 10% and 7%, respectively.

Finally, Table 6-4 shows the simulation results of different schemes with $U:D=1:4$ in the center cell and $U:D=1:1$ in the surrounding cells. The center cell requires more TSs for downlink transmission and less uplink transmission in the center cell. Similarly, both DSPM and MIF provide higher uplink data rate per MS and uplink capacity in the center cell. In addition, MIF outperforms DSPM in both uplink and downlink capacities in the center cell by about 1.6%. The improvement is less

compared to Table 6-3 because the number of uplink TSs to be selected in Table 4 is less.

From Table 6-2 to Table 6-4, it can be seen that DSPM can increase the data rate per user in the center cell. However, it may not be necessary to improve the capacity in the center cell. The enhanced multihop scheme, MIF, can further improve the capacity in the center cell. Next Figure 6.7 to Figure 6.10 show the uplink and downlink data rate distribution of the CTS and STS situations. The unbalanced traffic scenario among cells, i.e., U:D=1:1 in center cell and U:D=1:4 in surrounding cells, is presented. These results are used to study the effectiveness of different schemes in STS and CTS.

Figure 6.7: Data rate distribution of each MS in the uplink in the center cell

Figure 6.7 shows the MS uplink data rate distribution in the center cell. It can be seen that both DSPM and MIF has about 93% of the MSs transmitting with the maximum

Chapter 6: Time Slot Allocation Schemes

data rate of 256kbps. It means that both schemes can provide the maximum data rate for a given E_b/I_0 . But in DSP scheme, only about 80% of the MSs can transmit with the maximum data rate. In DSP, most of the MSs that can transmit with maximum data rate are in the STS situation. For CTS situation, a lower data rate is transmitted to meet the E_b/I_0 requirement. But from Figure 6.8, we can see that the inter-cell interference from the surrounding cells does not cause much influence to the downlink transmission of the center cell. This is because BS has higher transmission power as compared to MS. All four schemes have more than 78% of downlink transmission satisfying the maximum data rate of 256kbps. If we use multihop transmission to provide higher data rate in the downlink, the downlink data rate can be increased slightly. But, more TSs will be used to relay the data. As a result, less MSs can be supported in each frame and the overall downlink capacity will then be degraded. Thus, we do not recommend using multihop structure in the downlink transmission.

Figure 6.9 shows the MS uplink data rate distribution in the STS situation at the center cell. It can be shown that both DSPM and MIF schemes have the highest percentage of MS with maximum data rate because multihop scheme can work properly in STS. But these two schemes also require more TSs to build up a communication link. On the other hand, DSP scheme has high data rates, about 85% in STS. Thus, the proposed schemes may not provide a very good performance in STS situation. Figure 6.10 shows the MS uplink data rate distribution in the CTS situation at the center cell. FSP has no CTS as shown in Figure 6.1. DSP has about 77% of the MSs that can transmit with maximum data rate in CTS. Some MSs have to transmit with a lower data rates because of the high interference from the surrounding cells.

This problem is improved by DSPM and MIF by using multihop transmission. DSPM and MIF can provide about 90% of total MSs to enjoy maximum data rate of 256kbps.

Figure 6.8: Data rate distribution of each MS in the downlink in the center cell

Figure 6.9: Data rate distribution of each MS in uplink STS in the center cell

Figure 6.10: Data rate distribution of each MS in uplink CTS in the center cell

6.5 Conclusions

In this chapter, we propose dynamic time slot allocation schemes, DSPM and MIF, for multihop TDD-CDMA cellular systems. We study the performance comparison of the proposed schemes with other time slot allocation schemes without multihop, FSP and DSP, based on a seven-cell model. FSP provides the lowest overall capacity. DSP scheme, on the other hand, can provide an improvement of capacity due to dynamic switching point among cells. But, a severe capacity is lost in the CTS situation in the center cell due to the high interference from the surrounding cells. In DSPM scheme, the high interference is suppressed with the multihop communication to use two TSs for uplink communication. The uplink data rate per MS can be improved significantly. In addition, DSPM can improve the uplink capacity by 6% to 8% depending on the traffic scenarios. The performance can be further improved by using MIF which can provide higher overall capacity.

6.6 Limitations and Assumptions

In this study, we assume that the power of MS/RS/BS is adjusted so that E_b/I_0 requirement can be satisfied. The power control scheme is out of the scope in this study. In addition, the RS is selected by BS such that the distance from MS to RS becomes shortest. One suggestion is to use GPS system to locate the position of the MSs/RSs. The power control and the routing selection can be the future study of this topic.

Chapter 7: Conclusions and Recommendations for Future Work

7.1 Conclusions

This Thesis presents the investigation of various channel allocation schemes both for TDMA and TDD-CDMA cellular systems. In order to support multiple services requiring different E_b/I_0 , we first propose a channel partitioning idea to use different reuse factor to support different services in TDMA system. The fixed channel partitioning (FCP) scheme is first studied with stationary and mobile users. Markov chain is used to analyze the performance of FCP scheme. In practice, FCP can be applied in the environment that the traffic ratio between data and voice services in a system is relative stable and the channel utilization in each cell is almost same. In order to further increase the system capacity by adaptively arranging channels among adjacent cells, we propose a dynamic channel partitioning scheme with interference information (DCP-WI) scheme. The main idea behind DCP-WI scheme is to minimize the effect of assigned channels on the availability of channels for use in the interfering cells. DCP-WI scheme can deal with the case that the traffic among cells changes frequently or the traffic unbalance among cell is severe (*cool* cell mixed with *hot* cell). However, there is a common problem in FCP and DCP-WI schemes that the channel combination for different services changes with the variance of the arrival rate ratio between two services. Thus, it is difficult to determine which channel combination is the best one with the current system status. Based on the objective of solving problem of channel combination, we propose a flexible channel combination

Chapter 7: Conclusions and Future Work

DCP (FDCP) scheme. In this scheme, any nominal channel can be allocated to any user by any type of service and no channel pre-allocation is needed. FDCP is better to be applied in the environment that traffic ratio between services changes rapidly and the channels allocated for each service are very difficult to be predicted. Beside, FDCP can also be applied into the environment in which some cells are relative *cool* and some others are *hot*.

The simulation and analysis results show that our proposed CP scheme is an efficient idea to support multiple services requiring different reuse factors. As compared with conventional scheme using a single reuse factor, the CP idea can reduce the average reuse factor from the whole system point of view. The amount of improvement depends on the traffic load ratio between services. With the low call arrival rate fraction for service requiring small reuse factor, slight improvement of FCP over FCA is achieved. As we increase the traffic load for the small reuse factor requiring service, the improvement of FCP over FCA is increased. This is because more users requiring small reuse factor are in the system and they can use the lower reuse factor for channel allocation. Thus, the overall reuse factor becomes lower and the system capacity is improved. For the equal call arrival rate, FCP and FDCP schemes with mobile user can provide 32% and 54% improvement as compared with FCA at GOS = 1%. The results also show that our analytical model2, which can reduce computation time greatly, can produce very close results to the analytical values of analytical model1. Also from the results shown in the simulation, the improvements of our proposed schemes are very stable for different mobile user speeds or different GOS factors.

Chapter 7: Conclusions and Future Work

Then, we study the channel allocation for TDD-CDMA system. First, we study the performance of general TDD-CDMA systems. We analyze the capacity of TDD-CDMA system both in STS and CTS. From the analysis and simulation results, it is observed that the number of MSs that can be supported in each TS degrades severely with the increasing of the BS's coverage. Besides, the inter-cell interference from the surrounding downlink power causes severe influence to the system capacity in the CTS. This problem can be settled with the multihop cellular system. These issues motivate us to analyze the uplink capacity both in inner- and outer-region of the cell in the CTS. From the results, we observe that the inner-region area should be set large. However, BS must remain a relatively high inner-region capacity at the same time. The RS should be located inside the inner-region but near the inner-outer boundary. Noted that multihop structure uses two radio units (frequencies, time slots or codes) for each end-to-end link. Thus, we introduce a new technique to provide a fair comparison between one-hop and multihop systems. If a proper relay and inner-outer boundary is selected, multihop cellular system can give a very high improvement in capacity as compared with conventional one-hop TDD-CDMA system, even though two radio units are used for each end-to-end transmission.

Finally, we study the performance of several channel allocation schemes for a multihop TDD-CDMA cellular system. We propose channel allocation schemes for multihop system called DSPM and MIF schemes. In MIF scheme, a new MS first tries to be allocated to the TS with maximum interference among all the available TSs. If the maximum interference TS cannot accept this MS, a next-maximum interference TS will be tried. This process continues until all available TSs cannot accept this MS with the maximum data rate. Otherwise, multihop structure should be followed. Our

propose MIF scheme can group the interference within the whole frame into sequence. Since a MS is accepted to the TS that can just satisfy its requirement, it will give other MSs that are not in the good situation an opportunity to be accepted by the system with good transmission speed. MDSP and MIF can provide about 8% and 10% improvement respectively in terms of average data rate per user in the center cell.

7.2 Recommendations for Future Work

Multihop cellular system is a promising candidate for the future generation cellular system. And TDD-CDMA is a good access method to implement multihop cellular because we can adaptively arrange the radio resources including frequencies, time slots and codes to accept MSs. Besides, TDD-CDMA also provides unbalanced traffic allocation between uplink and downlink and this caters for the allocation property of multihop structure. Thus, multihop cellular TDD-CDMA is a good system that will attract more attention from researchers.

7.2.1 Multiple MSs Supporting by Each TS

In this Thesis, we already presented the performance analysis of TDD-CDMA. We get some basic knowledge of TDD-CDMA system. For example, the number of MSs supported in each TS degrades rapidly with the increasing of MS-to-BS distance. And the interference from the downlink full-loaded transmission power causes this problem to become even worse. Multihop cellular structure thus becomes a good solution. In Chapter 6, we already showed the maximum throughput with and without multihop structure. A simple but effective channel allocation scheme, MIF, is also proposed to increase the throughput for each frame. Our primary objective here is to get the maximum throughput of one frame and the maximum data rate for each MS.

Chapter 7: Conclusions and Future Work

Thus, in order to obtain the maximum throughput, we assume that each TS supports one MS. Hence, the maximum number of MSs each TS can be supported is 7 with our current assumptions.

In the practical system, one MS may not always enjoy the highest data rate. This is particularly true for the transmission direction of uplink. Thus, we should consider more realistic environment in which each TS can accept more than one MS with different data rate. It is expected that our currently proposed MIF scheme can also work properly with multiple MSs supported situation. And more simulation works should be done to prove our expectation.

7.2.2 General RS Selection

In Chapter 6, we assume that there are six fixed RSs placed in the situation as planned. And in Chapter 5, we assume that MS can find a RS in a straight line from MS to BS with the assumption that there are a lot of *silent* MSs within the network system. The possible future work also includes placing the RS with more general rules. For example, the RS can be randomly generated within the service area. Together with this general environment, more complex but effective routing algorithm must be proposed to cater for the randomness requirement.

7.2.3 Other Issues

In this Thesis, we propose use the two-hop structure for the multihop system. We do not study the cases for more than one hop for one communication link. In our future work for multihop TDD-CDMA cellular system, we should also consider more general 'hop' cases. In this way, we can determine the best multihop selection to

Chapter 7: Conclusions and Future Work

achieve a fair tradeoff between obtaining good system performance and remaining a relative low routing complexity.

In addition, power control scheme is a very important issue for the CDMA cellular system. Since CDMA system is an interference-limited system, a proper power control can reduce the overall transmission power of the system and as a results, increase the overall system capacity. The multihop cellular system cannot directly use the standard perfect power control scheme because there is more than one receiver in one transmission direction in a cell. Thus, we need further study to propose a more efficient power control scheme for multihop TDD-CDMA cellular system.

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Appendix

A. Detailed solution of two-dimensional Markov Chain

Figure A.1 Local balance of the FCP Markov Chain

The Markov chain in the Figure 3.2 can be solved numerically by the recursive formula to obtain the steady-state probability of (x, y) . As shown in the above figure, from the local balance concept we get

$$\begin{aligned} \pi(x, y)(\sigma_1\mu + \sigma_2\mu + \sigma_3\lambda_1 + \sigma_4\lambda_2) \\ = \sigma_1\pi(x-1, y)\lambda_1 + \sigma_2\pi(x, y-1)\lambda_2 \\ + \sigma_3\pi(x+1, y)\mu + \sigma_4\pi(x, y+1)\mu \end{aligned} \quad (\text{A.1})$$

where $\pi(x, y)$ is the probability for state (x, y) , and

$$\begin{cases} \sigma_1 = 0 & \text{when } x = 0 \\ \sigma_2 = 0 & \text{when } y = 0 \\ \sigma_3 = 0 & \text{when } x = C_1 \\ \sigma_4 = 0 & \text{when } y = C_2 \\ \sigma_i = 1 & \text{otherwise, } i = 1, 2, 3, 4 \end{cases} \quad (\text{A.2})$$

Thus, the steady-state probabilities, $\pi(x, y)$, can be obtained by solving the set of equations

$$\Pi Q = 0 \quad (\text{A.3})$$

and

$$\sum_{x=0}^{C_1} \sum_{y=0}^{C_2} \pi(x, y) = 1 \quad (\text{A.4})$$

In (A.3), $\Pi = [\pi(0,0), \pi(0,1), \dots, \pi(0, C_2), \pi(1,0), \pi(1,1), \dots, \pi(x, y), \dots, \pi(C_1, C_2)]$ and Q is a $(C_1 + 1)(C_2 + 1) \times (C_1 + 1)(C_2 + 1)$ matrix. Thus, from the system flow status, we can get that the blocking probability for S_1 and S_2 . For the solution of the FCP with switching Markov chain in Figure 3.3, it is K ($K=2$ in this figure) independent $M/M/1$ Markov queue system. From the solution of [1], page 184, it has close-form solution. And the finally results are shown in Equation (3.10).

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