Comparison of some time slot allocation schemes in TDD-CDMA multihop cellular networks

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Comparison of Some Time Slot Allocation Schemes in TDD-CDMA Multihop Cellular Networks

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Summary

Cellular networks are becoming more and more popular among people these days and at the same time digital multimedia technologies and Internet services are advancing. These progresses result in new demands in mobile communications that can support different services as well as high data rates. Thus, new technologies are deployed in cellular systems in order to increase their capacity and performance. One of the proposed solutions is to combine the idea of ad hoc networks and cellular networks to design a cellular system that can support multi-hop transmission. These systems are called Multi-hop Cellular Networks (MCN). This technique improves capacity and coverage of conventional single-hop cellular systems.

This Thesis focuses on implementing MCNs based on Code Division Multiple Access (CDMA) networks with Time Division Duplexing (TDD). Performance of various time slot allocation schemes in TDD-CDMA systems are studied and compared in single-hop and multi-hop scenarios. Our goal is to find the best-performing time slot allocation scheme in such systems.

First, we study performance of time slot allocation schemes in TDD-CDMA cellular systems and investigate the effect of employing multi-hop data relaying in such systems. Maximum capacity of these schemes will be compared. A multi-hop time slot allocation scheme, Maximum Interference First, is proposed in this study. This scheme reduces crossed-time slot interference and utilizes allocation of time slots by assigning new user

to time slots that receive high interference and support the user with maximum data rate. Thus, low-interfered time slots will be reserved for coming users with weak signal qualities. Simulation results show that this scheme outperforms others in terms of overall capacity in all traffic scenarios.

In second part of this study, performance of single-hop and multi-hop time slot allocation schemes are compared in supporting multimedia services with various QoS requirements. Call blocking and call dropping probability in each scheme is investigated. First, multihop time slot allocations schemes which support uplink data relaying are proposed and studied. Then, data relaying is deployed in both uplink and downlink transmissions and two other multihop time slot allocation schemes are proposed which support assignment of multiple uplink and downlink communication links to the same time slot. The proposed schemes enable maximum TS utilization in multihop cellular systems. Results show that deploying these schemes significantly improves system capacity for both low data rate and high data rate services.

In the last part, energy consumption in mobile devices is measured and compared for single-hop and multihop schemes. As the results show, for different traffic scenarios multihop schemes result in less power consumption and more energy saving in mobile devices. Even if we consider the energy consumed in devices by hardware and electronic parts, deploying multihop schemes still can save energy in mobile devices and increase their battery life.

List of Abbreviations

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
AMPS	Advanced Mobile Phone Service
ASP	Adaptive Switching Point
BS	Base Station
CDD	Code Division Duplexing
CDMA	Code Division Multiple Access
CTS	Crossed Time Slot
DL	Downlink
DSP	Dynamic Switching Point
E_b/I_0	Bit Energy to Interference Ratio
EDGE	Enhanced Data rates for GSM Evolution
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FSP	Fixed Switching Point
GOS	Grade of Service
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication
IMT-2000	International Mobile Telecommunications 2000
MCN	Multihop Cellular Network
MDSP	Multihop Dynamic Switching Point
mDTSA	multihop Dynamic Time Slot Allocation
mFTSA	multihop Fixed Time Slot Allocation
MIF	Maximum Interference First
ML-DTSA	Multiple-link Fixed Time Slot Allocation
ML-FTSA	Multiple-link Dynamic Time Slot Allocation
MS	Mobile Station

ODMA	Opportunity Driven Multiple Access
QoS	Quality of Service
RS	Relay Station
SA	Same Allocation
SIR	Signal to Interference Ratio
SP	Switching Point
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TS	Time Slot
UL	Uplink
UMTS	Universal Mobile Telecommunications Service
VCN	Virtual Cellular Network
WCDMA	Wideband Code Division Multiple Access

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Chapter 1

Introduction

1.1 Background

The first steps in wireless communication were taken back in 1897, when Guglielmo Marconi used radio communications to contact with ships. Since then this industry has faced enormous changes as a result of the advances in designing and miniaturizing electronic devices and the latest digital and RF techniques. Although in the beginning, pace of this evolution was not comparable to what we have experienced during the last decade, there has been remarkable improvements in mobile communication and faster growth in wireless systems is expected during the next decade.

The police radio system of the U.S. was one of the earliest mobile communication systems. This amplitude modulation-based (AM-based) system was developed for Detroit police vehicles in 1921. Later, in 1935, Edwin Armstrong introduced the concept of frequency modulation (FM) to wireless systems, which became the most adopted modulation technique since then [1]. As communication technologies improved during World War II, the number of users started to increase enormously. However, the technology at that time could not overcome the growing need of new users. The number of channels was limited and service providers could only serve a

few users in each market. For example by 1976, the Bell Mobile Phone service had only twelve channels and could support maximum of 543 users in New York City [2].

Introducing and developing the concept of cellular networks in 1960s and 1970s by AT&T Bell laboratories and other companies made it possible for telecommunication companies to think of providing mobile communication services for everyone. The idea of cellular networks was to divide the coverage area into several hexagonal cells. Each cell had its own base station and assigned channels. The frequency channels could be reused in cells which were far enough from each other. Thus, more channels were available to users in system. Advanced Mobile Phone Service (AMPS) in U.S. and the European Total Access Communication System (ETACS) were the first systems to deploy this idea. The first generation of cellular networks was adopting the analog technology and could only support voice services. They were based on frequency division multiple access (FDMA) where the frequency bandwidth is divided into a number of smaller frequency bands. Each small frequency band is called a channel and is used for communication between mobile station (MS) and base station (BS).

Second generation of cellular networks was introduced when US digital cellular (USDC) system (IS-136) and the global system for mobile communication (GSM) were developed in early 1990's. These systems could provide higher capacity and better channel quality with lower costs and could support wide area roaming. The second generation of cellular systems migrated from analog technology to digital and

changed their multiple access technique from FDMA to time division multiple access (TDMA) and code division multiple access (CDMA). In TDMA systems, users share the frequency by accessing the medium in specific time durations, called time slots (TS). CDMA systems such as 2G *cdmaOne* (IS-95), separate users by coding them with orthogonal codes.

2G cellular networks were designed to support circuit-switched voice communications and thus, were not able to provide data rates higher than order of 10 kilobits per second. The data rates were not enough to support Internet browsing or e-mail services. The only data service that 2G systems presented was short message service (SMS), which became one of the most famous features of GSM. In order to increase the data transmission rate, new standards were developed which were compatible with the existing systems. These new standards led to 2.5G and 2.75G technology which could support higher data rates as well as the web browsing language developed for wireless devices, Wireless Application Protocol (WAP). Some of the 2.5G systems were high speed circuit switched data (HSCSD) and general packet radio service (GPRS). The enhanced data rates for GSM (EDGE) was known as a 2.75G system.

Third Generation (3G) cellular networks are expected to increase the data transmission rate to multi-megabits per second in order to support real-time applications, interactive web browsing and voice over Internet protocol (VoIP). They also promise to provide high-quality seamless connection for mobile and stationary users. International Mobile Telephone 2000 (IMT-2000) is the plan which is set by International

Telecommunications Union (ITU) to unite all proposals and define a single ubiquitous standard for 3G communications systems [3, 4, 5]. Currently the activities of IMT-2000 organizations are divided into two major groups: 3GPP(3G partnership project) and 3GPP2. The former group focuses on Wideband CDMA (W-CDMA) standards which is compatible with GSM and IS-136 and the latter focuses on cdma2000 standards which are compatible with IS-95 [1]. W-CDMA is the most popular 3G system around the world and as reported by Global mobile Suppliers Association (GSA), 274 commercial operators have launched W-CDMA systems in 116 countries [6] by the year 2009. High Speed Packet Access (HSPA) systems are developed as the next step in migrating from 2G systems to mobile broadband. High Speed Downlink Packet Access (HSDPA) is the first evolution of WCDMA which provides advanced mobile multimedia services with higher capacity and user data rates. This system can support fast downloading and sharing services as well as various web-based services such as web surfing, streaming and large e-mail attachments which gives a sense of fixed broadband service to mobile users. HSDPA can deliver downlink data rates of 7.2 Mbps peak or higher. High Speed Uplink Packet Access (HSUPA) also improves uplink capacity, reduces latency and increases data throughput typically up to 2.1 Mbps. The main advantage of HSPA system is that implementation of this system on W-CDMA systems is possible through a software upgrade. The "Evolved HSPA" or "HSPA+" is theoretically able to support user data rates up to 42 Mbps in uplink using MIMO and advanced antenna technologies and data rates up to 28 Mbps for downlink on a 5MHz carrier.

On the path to mobile broadband, 3GPP is defining Long-Term Evolution (LTE) [7], which allows UMTS operators to use new and wider spectrum (up to 20 MHz) based on the success of HSPA systems. LTE is has higher performance in wider bandwidths, and thus is suitable for deployments in dense urban areas where demand for data services is higher. LTE is totally compatible with HSPA+ and performs similar to HSPA+ in 5 MHz. Thus, HSPA+ can provide a seamless user experience for users of VoIP services outside the LTE coverage area. LTE supports a flat IP-based architecture and promises high voice capacity through VoIP services and higher user data rate experience.

1.2 Motivation and Objective

Demands for high-speed and high-quality multimedia services as well as continuous growth of cellular subscribers has made it clear that the main challenge facing future cellular systems is to increase system capacity. One way of reaching this goal is to allocate more radio spectrum to cellular networks. But, as available bandwidth for wireless communication is limited, other approaches should be considered to increase system capacity by making efficient use of available resources. One way is to use advanced transmission schemes such as modulation and coding. The other way is to efficiently assign resources to users by developing efficient radio resource management schemes.

Unlike voice traffic, data traffics such as Internet web browsing or multimedia traffics are asymmetric. Asymmetric traffic often requires unequal amount of resources in

downlink and uplink. Time Division Duplex CDMA (TDD-CDMA) air interface technology, which is one of the most promising air interfaces to be used in next generation of cellular systems, can easily support asymmetric traffic. Using TDD-CDMA, system can adaptively adjust the resources allocated to uplink or downlink by assigning enough number of TSs to each link. The valuable capability of TDD in providing varying capacity for uplink and downlink connections has made TDD-CDMA networks a promising candidate for supporting unbalanced traffic generated by multimedia applications. To allocate the resources in the most effective manner, a proper time slot allocation scheme should be selected.

Although the air interface standards proposed to IMT-2000, such as W-CDMA, provide high capacity for cellular networks, they are still interference-limited and the interference generated by arriving users can degrade the quality of existing users' connections. To further increase performance of such systems, multi-hop data relaying technique was proposed by 3GPP. In multi-hop cellular networks, subscribers exchange data with base stations through intermediate relay nodes instead of directly communicating with each other. Multihop cellular networks are expected to have higher capacity [8] as well as the ability to provide better resource utilization [9].

Considering the limited amount of resources such as available bandwidth for wireless communication, designing an efficient resource allocation scheme for multihop TDD-CDMA networks is of great importance. The objective of this research is to benefit from merits of multi-hop data relaying in TDD-CDMA systems. We compare

performance of conventional single-hop time slot allocation schemes and our proposed multihop schemes in TDD-CDMA systems and attempt to find the best scheme for satisfying emerging requests of users.

1.3 Major Contributions

In this study, we focus on multihop data relaying in TDD-CDMA systems. We study performance of various time slot allocation schemes and compare them in single-hop and multi-hop scenarios. This Thesis focuses on three major issues of resource allocation in multihop cellular systems: the maximum system capacity that each scheme can provide, performance of time slot allocation schemes in supporting multimedia traffic and their impact on energy consumption of mobile devices.

1.3.1 Maximum Capacity of Resource Allocation Schemes

Performance of single-hop and multihop time slot allocation schemes for TDD-CDMA cellular networks is studied in this Thesis. In Chapter 3 we compare the maximum throughput (in terms of kbps) that one frame can support for various schemes. In every scheme, each TS is able to support one user with the maximum allowed data rate in order to achieve the maximum throughput. Two single-hop schemes are selected as benchmark schemes, Fixed Switching Point (FSP) and Dynamic Switching Point (DSP). FSP reserves the TSs for uplink and downlink and uses the same fixed frame arrangement for every cell in system. DSP does not use a

fixed arrangement for frame and dynamically changes the number of TSs which are allocated to uplink and downlink in each cell.

Since the main purpose is to find the maximum capacity of the selected schemes, the following algorithm is employed in multihop schemes. Whenever a MS is not supported with the maximum data rate in a single-hop uplink connection, multihop schemes establish a two-hop connection for MS through the nearest fixed relay station. Switching to multihop mode increases the chance of receiving higher data rate in uplink. For TDD-CDMA MCNs, we introduce a *multihop* dynamic switching point scheme (MDSP). This scheme defines a dynamic switching point for each cell and supports two-hop links when user cannot receive the maximum data rate. We propose another slot allocation scheme for TDD-CDMA MCNs, namely Maximum Interference First (MIF). In this scheme, there is no switching point to separate uplink and downlink TSs and TS selection algorithm is allowed to select any free TS. This scheme tries to maximize system throughput in three ways. TS selection algorithm 1) tries to avoid selecting a crossed-time slot for uplink, 2) selects high-interfered TSs first and saves the low-interfered TSs for new users and 3) establishes multihop connections for MSs that cannot receive the maximum data rate. Results of comparison between benchmark single-hop schemes and the proposed multihop schemes show that MDSP and MIF significantly improve uplink data rate as well as system capacity.

1.3.2 Multihop Resource Allocation Schemes and Multimedia Services

One of the featuring characteristics of multimedia traffic is asymmetry. Unlike conventional voice traffic which is balanced between two links of communication, data traffic such as the traffic generated by web browsing applications requires much less uplink data (that is mostly the data used for commands) compared to the data that is transferred in downlink. Usually, the traffic generated by these applications is biased towards uplink or downlink, which means that variable amount of capacity should be allocated to uplink and downlink each time. Time Division Duplexing (TDD) mode of WCDMA is capable of assigning capacity to uplink and downlink based on users' demand by changing the number of allocated resources in each frame. Thus, it is more appropriate for asymmetric traffic compared to Frequency Division Duplexing (FDD) mode [10]. Some studies have been conducted on capabilities of TDD-CDMA networks in supporting multimedia traffic. [11] shows that in TDD-CDMA networks, by allocating different number of time slots to uplink and downlink the blocking rate reduces in multimedia environments. In [12], the effect of combining different traffic types is studied in CDMA systems. The study shows that high-bit-rate services have great impact on outage probability and can significantly degrade performance of low-bit-rate users.

Investigating the system performance in presence of different types of traffic generated by various applications is of a great importance. In addition to comparing maximum capacity of single-hop and multihop schemes in Chapter 3, their ability in supporting voice and multimedia services in various traffic scenarios is studied in

Chapters 4 and 5. To perform a better comparison between single-hop and multihop schemes, simulation environment is further enhanced in order to meet the requirements of the real world implementation. Supporting multiple users in one time slot is one of the abilities of CDMA networks which will be added to the simulation as well as different types of voice and data traffic requests with various quality requirements.

In order to support more than one user in each TS, some mechanisms are needed to be deployed in multihop time slot selection algorithms. TDD-CDMA systems use the same frequency for all communication links, but relay stations are not able to send and receive on the same frequency at the same time. Thus, to avoid self-interference at relay stations, multihop schemes should use different TSs for sending and receiving data at relay stations. Based on this idea, two multihop schemes are proposed in Chapter 4 which can support only uplink multihop transmission. Fixed and dynamic time slot allocation modes of this scheme, namely Multihop Fixed Time slot Allocation (MFTSA) and Multihop Dynamic Time Slot Allocation (MDTSA), are studied in Chapter 4. Simulation results show that these multihop schemes can significantly increase the number of accepted calls compared to single-hop schemes. The number of supported high data rate service requests is noticeably greater in MFTSA and MDTSA regardless of traffic scenario. However, precise analyses of results show that in our multihop schemes, probability of dropping ongoing calls in downlink is higher than uplink connections. Although data relaying provides the requested uplink data rate for multimedia services and high BS transmission power

supports the requested downlink data rate, many of them cannot maintain the connection in downlink and eventually, ongoing calls are dropped.

Since on-going calls are dropped due to insufficient signal quality in downlink, data relaying is deployed for both uplink and downlink transmissions in multihop schemes in Chapter 5. Also, a different approach is used to deal with self-interference problem of multihop schemes in this chapter. This approach does not limit TS selection to choose from predefined number of TSs and any free TS can be used to allocate any type of link. Unlike all previous time slot allocation schemes, a TS can be simultaneously assigned to uplink and downlink of two different transceivers in a cell. The behavior of these two multihop schemes, Multiple Link Fixed Time Slot Allocation (MLFTSA) and Multiple Link Dynamic Time Slot Allocation (MLDTSA), is investigated in Chapter 5. Results show that these schemes can increase the number of accepted calls and significantly reduce call dropping probability regardless of traffic scenario.

1.3.3 Energy Consumption in Multihop Cellular Networks

After investigating the effect of multihop data relaying on capacity and data rate, we compare the single-hop and multihop schemes in terms of energy consumption in system. Some previous studies have been done on power consumption of multihop cellular networks. Since propagation loss is proportional to distance between transmitter and receiver raised to the power of path-loss exponent, shorter transmission links require less transmission power to maintain the connection. Thus, a multihop link consumes less transmission power compared to a direct single-hop link.

In [13], authors propose a virtual cellular network (VCN) and investigate the effect of multihop relaying on transmission power. In their system they assume channels with path loss, shadowing loss and Rayleigh fading. Simulation results of the paper show that average transmission power decreases as the number of maximum hops increases in multihop links. However, as stated in [14] only measuring the transmission power would not be enough to conclude that multihop relaying saves energy. To get more accurate results on the amount of consumed energy in a system, we should also consider the energy consumed by transmitter and receiver electronics and digital processing. As the number of hops increase for each link, the total consumed energy in a multihop link may become greater than a direct single-hop link. [15] gives an analysis on transmission power of multi-hop cellular networks based on the model suggested in [14]. They show that two-hop links consume less power compared to direct single-hop links and the amount of saved power increases as path loss becomes greater. In their model they limit the number of hops to 2 and do not assume shadowing and fading in channels. An analysis on consumed energy per bit in multihop cellular systems is presented in [16]. Their results show that multi-hopping has greater impact on reducing the average consumed energy per bit in systems with power control. However, this paper also only assumes path loss for modeling the environment. In Chapter 5 we use the model suggested in [14] and define a model considering path loss and shadow fading to measure the consumed energy in our schemes. Unlike previous studies that only consider the effect of environment modeling parameters, we investigate a comprehensive system including inter-cell and intra-cell interferences as well as different types of service requests. We compare the

results of single-hop and multihop schemes for different traffic scenarios and also study the impact of hardware energy consumption on total consumed energy per link.

1.4 Organization of the Thesis

The rest of the Thesis is organized as follows.

Literature review is presented in Chapter 2. It gives an overview on the basic concepts that the study is based on. A brief introduction to the W-CDMA and the W-CDMA TDD mode is presented. Moreover, multihop cellular networks are described and their advantages and disadvantages are mentioned. This chapter also reviews the previous works and proposed time slot allocation schemes for single-hop and multihop cellular networks.

In Chapter 3, we measure maximum capacity of time slot allocation schemes. We propose two multihop time slot allocation schemes in order to measure the maximum capacity of multihop cellular networks and compare the results with single-hop schemes in various traffic scenarios.

In Chapter 4, we investigate and compare performance of time slot allocation schemes for supporting voice and multimedia services in conventional and mulihop cellular networks. We improve the simulation environment and study behavior of the schemes in practical conditions similar to the environment of implemented systems.

In Chapter 5, multihop data relaying is extended to downlink transmission and more flexible multihop time slot allocation schemes are proposed by avoiding reserving TSs for particular links and reducing the number of switching points as much as possible. Similar sets of results are obtained for these schemes as in Chapter 4.

In Chapter 6, we propose a model to measure and compare energy consumption of TDD-CDMA single-hop and multihop time slot allocation schemes in a comprehensive system with various services and traffic scenarios. Finally, Chapter 7 concludes the thesis and gives some recommendations for future research work.

Chapter 2

Literature Review

2.1 Introduction

In this chapter we present a review on some basic knowledge in CDMA cellular networks. This chapter covers the issues related to our studies in this Thesis. First, some fundamental information is given on principles of wireless CDMA systems. Then, we present a review on previous works which have been done in the area of this study in literature. Going through this chapter gives readers an insight into our work.

2.2 Wideband CDMA systems

2.2.1 Background

In 1990s, research works were started on W-CDMA systems in Europe. Several air interfaces were proposed for Universal Mobile Telecommunications Service (UMTS) 3G standard at the time. Five concept groups were formed in European Telecommunications Standards Institute (ETSI) based on these proposals in 1997. These five groups were: W-CDMA, W-TDMA, TDMA/CDMA, OFDMA and ODMA. In 1998, ETSI decided to select W-CDMA as the standard for the UTRA (UMTS Terrestrial Radio Access) air interface and in the following year, 3GPP was formed to continue the technical work and proceed the detailed standardization [17].

Since then, W-CDMA has been widely deployed in Europe and Asia including Japan and Korea.

Unlike the second generation systems, which were designed to provide voice services in macro-cells, 3G systems are expected to be able to provide high data rate, support asymmetric traffic generated by web browsing and multimedia applications and handle several services with different quality requirements. To satisfy the 3G requirements, several features have been added to W-CDMA standard.

2.2.2 Features of W-CDMA

In W-CDMA information bits are multiplied by quasi-random bits which are called chips. These bits are obtained from CDMA spreading codes. The chip rate in W-CDMA is 3.84 Mcps, thus by multiplying user's bits, the data will be spread over a wide bandwidth of approximately 5 MHz. This is why W-CDMA is called a Wideband Direct Sequence Code Division Multiple Access (DS-SS) system. Figure 1 shows the bandwidth allocation in W-CDMA. As shown in the figure, several 5 MHz carriers can be used to increase the capacity.

W-CDMA provides high user data rates of up to 2 Mbps and also can support variable user data rates. However, during each frame of 10ms the user data rate will remain constant. Figure 1 shows that users' data rates change from frame i to frame j . User's data rate in each frame is defined by the number of codes that are allocated to the user.

Unlike other CDMA systems such as IS-95, W-CDMA operates with asynchronous base stations and this feature obviates the need for global timing systems like GPS. Moreover, advanced receiver techniques such as multi-user detection, smart adaptive antennas and Rake receivers can be deployed in W-CDMA systems to increase capacity. Moreover, this system is backward compatible with GSM networks and GSM infrastructures can be used to increase coverage of W-CDMA.

W-CDMA supports two duplexing modes: Frequency Division Duplex (FDD) and Time Division Duplexing (TDD). In the FDD mode, one 5 MHz bandwidth is used for uplink and another 5 MHz bandwidth is assigned to downlink. In the TDD mode only one bandwidth of 5 MHz is shared between uplink and downlink. More information on W-CDMA and basic principles of CDMA operation can be found in [18-21].

Figure 1: Allocation of bandwidth in W-CDMA in time-frequency-code space

2.2.3 Power Control

CDMA systems are interference-limited. Therefore, controlling the transmission power of transceivers, MSs and BSs, will have a great impact on capacity of system. In WCDMA, all MSs use the same frequency band and they are identified from each other at the base station by their spreading codes. Signals of MSs that are near BS will be received with higher power, while signals of MSs that are near cell boundaries suffer from path loss and reach the BS with lower powers. Strong signals can easily affect performance of BS in detecting weaker signals. As a result, a single over-powered MS is able to block a huge part of cell. This is called near-far problem.

To overcome this problem three power control techniques are implemented in W-CDMA systems. Open-loop power control is used to estimate the initial power of MS at the beginning of connection. In open-loop power control, MS roughly estimates the uplink power based on the path loss information that receives from pilot downlink signals. This method is not accurate enough because fast fading may not be correlated between uplink and downlink, especially in FDD mode where uplink and downlink band are separated. Thus, a closed-loop power control is used in W-CDMA systems. In closed-loop power control, BS frequently measures the received Signal-to-Interference Ratio (SIR) and compares it with the target SIR. Whenever SIR falls below target SIR, BS commands MS to increase transmission power and similarly, when SIR exceeds the target SIR, BS command MS to reduce its power. BS repeats this action with frequency of 1.5 kHz (1500 times per second) which is faster than any changes in path loss and Rayleigh fading. Although the near-far problem does not

apply for downlink, closed-loop power control is used in downlink to provide enough power for MSs which are far from BS and face inter-cell interference from adjacent cells. There is also one other power control technique used in W-CDMA systems; the outer-loop power control. Outer-loop power control happens between BS and Radio Network Controller (RNC). This mechanism is used to dynamically change the target SIR at BS. Should there be any changes to the connection conditions of a MS, i.e., the speed of MS or the multipath profile of connection, the required SIR has to be changed in order to have consistent quality at MS. RNC decides on modifying the target SIR based on the information that it receives from BS.

2.2.4 UTRA TDD mode

W-CDMA works in two FDD and TDD modes. In FDD, uplink and downlink use different frequency bands for transmission. In TDD the same frequency band is used for both uplink and downlink, but the transmission direction changes in time. It means that the same frequency band is used for uplink and downlink in different portions of time, called time slots (TS).

TDD systems can use unpaired bands, while FDD has to be implemented on paired bands. Also, asymmetric traffic is allocated more easily in TDD compared to FDD, since capacity can be moved from uplink to downlink by simply changing the number of TSs assigned to each link. In addition, as both uplink and downlink use the same frequency, fast fading would be the same for both links and the information can be used for estimating the fast fading in opposite direction.

One problem of TDD-CDMA systems is that using a single frequency band results in interference between uplink and downlink, while this does not happen in FDD where the frequency bands are separated enough to avoid interference. The other problem in TDD is that transceivers are not able to instantly switch the transmission direction. To provide some time for switching between uplink and downlink, guard gaps should be implemented between time slots. Large gaps may cause delay and affect voice communications.

2.3 Multihop Cellular Networks

In multi-hop cellular networks (MCNs), user data is exchanged between the mobile station and the base station by being relayed through some intermediate nodes or relay stations (RS) whenever a direct connection is not possible or has low quality. Various proposals have been suggested for MCNs with different characteristics. Some systems propose using the existing MS devices of subscribers as relays while others suggest deploying fixed RSs in the cell. The other difference among proposed designs is in the air interfaces which are used for the links. The communication between RSs and BS usually takes place using the cellular interface, but the communication between MS and RS may be through other interfaces such as the Industrial, Scientific and Medical (ISM) radio bands which is different from RS-BS links, or the same cellular air interface can be used for both MS-RS and RS-BS links. Figure 2 shows the scenario used in MCNs. The main idea in such systems is to break the paths between MSs and BS into shorter links.

Why relaying the data is beneficial to system?

Multi-hop can result in several advantages for cellular networks. These advantages include enhancing the coverage area for high quality services, reducing transmission power and increasing capacity under certain circumstances [22]. Since the propagation attenuation of a radio signal is proportional to the link distance, by breaking a long-distance path into several shorter links, signal attenuation becomes much lower at each link. In addition, heavily shadowed users can bypass obstacles by employing multi-hop relaying in order to improve their channel conditions and avoid residing in dead spots. Users also benefit from reduced power consumption, since lower transmission power is required for maintaining a connection in shorter distances.

Figure 2: Multi-hop architecture used in MCNs

2.3.1 3GPP - Opportunity Driven Multiple Access

Multi-hop relaying was first studied in the field of ad hoc wireless networks and was used to establish a network without any infrastructure. Later, the relaying concept

began to become an interesting architecture to be applied in the field of cellular networks. The Third Generation Partnership Project (3GPP) proposed the Opportunity Driven Multiple Access (ODMA) [23] mechanism which is a multi-hop relaying protocol as a modification of a Patent by Salbu Pty. Ltd. [24]. ODMA is a relaying communication protocol which was proposed for UMTS TDD mode.

In order to determine the feasibility of implementing ODMA, W-CDMA and WB TDMA/CDMA systems were studied to see whether they can support data relaying. The results of the ETSI studies showed that by applying slight changes to the design of mobile stations, multihop relaying can be deployed in both W-CDMA and WB TDMA/CDMA systems. Since then, ODMA was known as an enhancement to these technologies and it was added to the standardization documents of W-CDMA and WB TDMA/CDMA. ODMA was removed from the standard after a while due to some shortcomings, however, multihop cellular networks are still a very attractive subject of research for future mobile communication systems.

ODMA Scenario

Based on the description for ODMA in [25], ODMA is an intelligent protocol that can be employed in W-CDMA systems. The goal of ODMA is to increase the quality of communication for MSs by providing multiple communication paths between them. In ODMA, nodes have the intelligence to find available communication paths, evaluate them and select the least cost option. This protocol breaks the low-quality radio paths into several shorter links by relaying MS's data through other nodes. Data relaying

provides higher data rate or lower transmission power for MSs. Moreover, it gives more opportunities to MSs to receive better services and avoid dead spots. It is mentioned in [25] that relaying has the potential to improve coverage and increase capacity by lowering transmission powers and associated inter-cell interference.

2.3.2 Advantages and Disadvantages of ODMA

Here, we describe some of the features of ODMA as mentioned in [25].

Radio Resource Re-use

Whenever a connection link is established in the cell, radio resources such as codes should be assigned to these links. In conventional systems each radio resource can be used only once in each cell, while in ODMA radio resources can be reused in a cell. This is because of the fact that shorter communication distance requires less transmission power. Thus, the interference caused by that resource will be localized and this results in increased radio resource reuse.

Figure 3: Radio Resource Reuse in ODMA

As shown in the

Figure 3, when information is relayed through relay stations, one radio resource can be reused in the same route or in other routes built by relayers in the same cell as long as the circles do not overlap and the interference is avoided. Reusing radio resources in a cell will certainly increase the capacity.

Potential for Capacity Gain

Conventional single-hop cellular systems are usually designed in a way that coverage areas of BSs overlap each other. In this way, coverage will increase and dead spots will be covered. On the negative side, the resulting overlap causes inter-cell interference and thus, capacity will be reduced. By using ODMA, we can avoid the overlap of the base stations' coverage areas. This is possible because the users placed in the uncovered areas can receive signal through the relayers which reside inside the coverage areas. This approach can be useful in country boundaries. This concept is illustrated in Figure 4.

Figure 4: A) Overlapping coverage areas B) ODMA used to cover the user when coverage areas do not overlap

Aside from these advantages, multi-hop relaying has some drawbacks. A multi-hop connection consumes more radio resources for establishing several links instead of using one channel to directly connect to the base station. Routing also has to be considered in such networks to find the route with least cost which may result in delay or signal overhead. However, it seems that the effect of these drawbacks can be minimized by employing efficient routing and resource allocation algorithms.

2.3.3 ODMA Infrastructure Configurations

There are two different configurations for introducing ODMA into the core network structure. One method is to use integrated TDD/ODMA NodeB that can support ODMA function. The other method is to employ Last Hop Gateway ODMA relay nodes [23].

In the former method, implementation of ODMA uses a TDD system and adds ODMA functions to the infrastructure. The point of this implementation is that system information such as synchronization and paging messages are readily available from the standard TDD system. One of the aims of ODMA is to extend the range of high rate data coverage to match that offered by TDD and FDD for speech coverage. Increased high data rate coverage can be achieved by the help of terminals which support both TDD and ODMA transmission and work as relayers in low bit rate coverage areas. A simplistic view of this concept is shown in Figure 5.

Figure 5: ODMA with integrated TDD/ODMA NodeB

In systems where FDD infrastructure may be widely deployed but limited TDD infrastructure is available, Last Hop gateway ODMA relay nodes should be deployed. Last Hop Gateway ODMA Relay Nodes provide the ability to extend high data rate communications within 3G systems by enabling cooperation between ODMA functions and standard FDD infrastructure. Only nominal changes to the RNC are required in this method. A simplistic view of this concept is illustrated in Figure 6.

As shown in Figure 6, Gateway ODMA Relay Nodes are used at the boundary of FDD system coverage. This gateway is used to give service to ODMA-enabled terminals that reside outside the coverage area of FDD system. Data of ODMA terminals is relayed through this gateway and sent to the BS.

Figure 6: ODMA with last hop gateway

2.4 Time Slot Allocation Schemes

2.4.1 Time Slot Allocation Schemes for Single-hop Cellular Systems

In TDD-CDMA air interface, access time is divided into frames of 10ms and each frame consists of 15 Time Slots (TSs). One or more than one user can be assigned to one TS. Any TS can be used for uplink or downlink transmission. Using different spreading codes, users will be identified from each other. Here, we present the time slot allocations schemes which are proposed for single-hop TDD-CDMA systems in literature.

Same Time Slot Allocation (SA)

Selecting a proper time slot allocation algorithm is one of the major issues in designing an efficient TDD-CDMA network. A number of these algorithms have been proposed. One basic scheme is to apply a predefined fixed time slot arrangement for

uplink and downlink TSs to every cell of system. In this way, one TS will be used for either Uplink direction or Downlink direction in the whole system [11]. Figure 7 shows an example of a frame in SA. For example in Figure 7, TS1 is used for downlink in every cell, while TS15 is used for uplink in every cell.

Figure 7: Example of TDD frame in SA

To arrange the TSs in a frame, a switching point should be defined to separate the TSs that are dedicated to uplink and downlink. In SA the location of the switching point is the same in all cells. For the voice traffic that is balanced in uplink and downlink the switching point can be simply placed in the middle of the frame. Thus, equal number of TSs would be dedicated to uplink and downlink connections. But for the multimedia traffic, which is unbalanced and usually has more traffic in downlink, the previous arrangement may not be the optimal solution. In [11] authors show that the network operator has to find the optimal number of U-slots and D-slots for different traffics and define the frame arrangement based on the traffic requirements in order to increase utilization of resources. This paper considers different types of traffic in the system. One class of traffic requires the same bandwidth for both links (e.g. voice communication) and the other class of traffic needs much more bandwidth for downlink (e.g. Internet access). The efficiency of TDD-CDMA systems under multimedia environment is demonstrated by Markov analysis and computer simulation. SA suggests dedicating different number of TSs to uplink and downlink in

TDD frame concerning the unbalanced traffic of multimedia services, which is an improvement to the conventional schemes that utilize equal bandwidth for uplink and downlink. However, this scheme defines a fixed switching point for the whole system. Thus, every cell uses the same TSs for uplink and downlink.

Time Slot Scoring (TScoring)

This is another algorithm based on same fixed switching point in every cell. The number of uplink and downlink TSs of frames is defined during the system start-up. This switching point cannot be shifted afterwards and remains the same for whole system. This strategy which is presented in [26] is a distributed algorithm. The main idea here is to find the best time slot among dedicated TSs by scoring each time slot based on the interference and the number of available Resource Units (RU). Each code in one time slot is defined an RU.

Before starting the scoring procedure, the interference in each time slot is measured. The time slots which can satisfy the Quality of Service (QoS) requirements of the specified traffic and have at least one free RU, earn +4 points. Other TSs that fail, get -1 point and they are omitted from the list of available TSs. Then, +4 extra points is given to a TS that has enough free RUs. +2 extra points is given to TSs that can support 50% of required RUs. And one extra point is given to TSs with at least one available RU. Finally, the TS with the highest score will be selected. TSs are randomly selected when they have equal scores.

Adaptive Switching Point (ASP)

To provide flexible resource allocation provided in TDD-CDMA, time slot allocation schemes with dynamic switching point should be used. Although SA strategy is very simple, in case of asymmetric traffic, when more data is requested on downlink compared to uplink or vice versa, a dynamic scheme can assign resources to more users. The simplest dynamic TS allocation scheme is adaptive switching point (ASP) proposed in [27]. In ASP, a switching point is defined which is used to separate uplink and downlink TSs in one frame. When all reserved TSs are occupied on one side of switching point, the switching point can be shifted to allocate more users. Thus, different cells will have different switching points and TS arrangements.

The algorithm is better explained in an example. We assume that TS0 to TS7 are defined for uplink and TS8 to TS15 are for downlink. Upon arrival of a new call, uplink TSs are compared based on the TScoring algorithm. When none of the uplink TSs can support the new user, TS8 will be tested to support the new user. If TS8 was able to support uplink of the new user, switching point will shift one TS to assign TS8 to uplink transmission. Then, all the downlink connections in TS8 have to be reassigned to other downlink TSs from TS9 to TS15. In case of successful reassignment, new user will be assigned to TS8 for uplink. After uplink TS assignment, the algorithm will look for a proper downlink TS among TS9 to TS15 for this new-coming user.

ASP scheme is able to accept more users by dynamically changing the uplink and downlink capacity. Free TSs can be utilized by shifting the switching point in each cell according to the cell's traffic. Thus, the optimal position for the switching point can be obtained in each cell individually. ASP can increase the capacity in each cell but on the negative side, this method causes *crossed-time slot (CTS)* interference in system.

There are two types of inter-cell and intra-cell interferences. Intra-cell interference is caused by users using the same TS in same cell that the connection is requested, while inter-cell interference is caused by the users using the same TS in surrounding cells. *Crossed-time slot (CTS)* interference mentioned by [28] is inter-cell interference that happens when a TS is used for uplink in one cell and for downlink in an adjacent cell. Figure 8 shows this situation.

Figure 8: Crossed-time slot interference

During CTS, these interferences occur:

- *Base Station-to-Base Station Interference*

This happens when one BS is transmitting in cell 1 and the other BS, BS in cell 2, is receiving in the same TS. BS-to-BS interference depends heavily on the path loss between two base stations and, therefore, can be controlled by network planning. As it can be seen in Figure 8, signal transmitted from BS1 is interfering with the received signal at BS2.

- *Mobile-to-Mobile Interference*

As shown in Figure 8, when MS2 is transmitting and MS1 is receiving, received signal at MS1 will be interfered by the signal transmitted from MS2. This kind of interference cannot be avoided by network planning because the position of the MSs cannot be controlled.

MS-to-MS interference usually may not cause a serious problem, since the power of uplink signal is weaker than the power of downlink signal coming from the BS. However, in cases that two MSs are close to each other, for example when they are both near cell boundary, the signal received from an MS may be much stronger than the signal received from BS. Thus, MS cannot decode its signal.

Zone Division Dynamic Allocation Scheme

Applying dynamic time slot allocation causes CTS interference in the system and degrades system performance. To overcome this problem, other dynamic time slot allocation schemes have been proposed. One solution is to divide the cell area into two

regions of inner-area and outer-area [29, 30]. Let N denote the number of slots in TDD frame. N_u is the number of time slots that can only be assigned to uplink, N_d is the number of TSs that can be assigned to downlink and N_c will be the number of time slots that can be used for uplink in one cell and downlink in another cell. N is equal to $N_u + N_d + N_c$. The resources of crossed-slots, N_c , are only assigned to users in inner-area [29, 30]. Thus, only users in inner-area of different cells will create CTS interference to each other. Spatial separation of the time slots which are in opposite directions helps in reducing the interference they cause to each other.

In [31] this idea is modified to achieve better results. In this approach, the cell area is further divided into several service zones. Main purpose of this scheme is to maximize the spatial separation so that the minimum inter-cell interference can be achieved. In this paper the service is divided into inner and outer areas and six zones using directional antennas. Figure 9 illustrates the service area.

Figure 9: Zone division of TDD-WCDMA cell

The simulated system consists of two adjacent cells. Each cell defines its own switching point in the frame in order to obtain the maximum capacity based on its

traffic. Since it is assumed that Cell A has symmetric traffic and Cell B has asymmetric traffic, position of switching points will be different in each cell. Different positions of switching points result in crossed-time slots in two neighboring cells. When time slot allocation algorithm reaches the crossed-slot section of the frame, the crossed-time slots are assigned to mobiles based on predefined zone priorities which are derived from numerical results. The crossed-time slots will be first assigned to the users in zone 5 of cell A and B. Then, zone 6 will become active for both cells followed by zones 2(4) and 4(2) and in the next step zones 1(3) and 3(1). Following this sequence provides the maximum capacity by minimizing the crossed-time slot interference.

Time Slot-Opposing Scheme

TS-opposing scheme [32] is another solution to crossed-time slot interference. When a mobile station exceeds the maximum permitted power in a TS, TS A in cell i , a report is sent to its base station. Then, the BS of cell i measures the interference caused by surrounding cells in all TSs. If another TS, TS B, in a surrounding cell, C_j , was found that would cause less interference to the TS A in cell i , **and** the low-interference TS, TS B in cell j , and the high-interference TS, TS A in cell j , were in opposite transmission directions, system will exchange these two TSs in cell C_j . This approach tries to reduce the interference received at each time slot when crossed-time slots are also supported in time slot allocation. Reducing the interference in CDMA systems increases the capacity.

The results of this study show that by developing an algorithm that reduces interference in TDD-CDMA systems, we would be able to reduce the impact of opposite TSs on capacity reduction. Hence, we can conclude that disadvantages of different rates of asymmetry traffic within neighboring cells of the system can be eliminated if we employ a proper TS allocation scheme.

2.4.2 Time Slot Allocation Schemes for Multi-hop Cellular Systems

Delay Sensitive Slot Assignment (DSSA)

DSSA [33] is proposed for TDD-CDMA multihop cellular systems. The DSSA scheme does not estimate the position of switching point. The algorithm attempts to efficiently select the slots after the position of switching point is determined. This makes the approach compatible with any algorithm that uses switching points. It starts by finding a channel that a) the current node is not using for receiving data and b) the next hop is not using for transmitting or receiving data. In this study, channel is defined as a pair of (TS, code). These channels are added to the list of possible candidates.

Slot selection then continues based on computing the *slot waiting time*. Slot waiting time is the time a mobile terminal has to wait before it reaches the assigned slot and starts transmitting. The objective of this algorithm is to ensure that the time slot assigned to the next node is just ready by the time that packet reaches the next node, so that the slot waiting time of the packet would be as small as possible. This will guarantee fast delivery of data from the source node to the BS. For example, a 5-hop

route from node a to the BS which passes through nodes (a,b,c,d,e) will deliver the packets faster when slots (1, 2, 3, 4, 5) are assigned to the nodes compared to slots (1, 2, 3, 4, 2). The last node, which is assigned to slot 2 in the latter case, has to wait for the next frame since slot 2 has already passed in the current frame. But in the former case, the last node can use slot 5 of the current frame and start transmitting immediately. Thus, waiting time of last node will be more in the latter case compared to the former case. This idea is further extended in [34].

Integrated Radio Resource Allocation for Multi-hop Cellular Networks

[35] proposes an integration of routing and radio resource allocation for multi-hop cellular networks, namely Integrated Radio Resource Allocation (IRRA). By integrating routing and resource scheduling algorithms, the saved resources from multihop relaying can be used to improve the condition of users with insufficient resources. Deploying multi-hop enables users to establish links with higher data rates and better qualities. User can either communicate directly with the base station or use intermediate nodes to relay its data to the base station. Fixed relay stations (RS) are assumed inside each cell and FDD is used to avoid self-interference at the relay stations when they send and receive data at the same time. MS to BS and MS to RS links use the same frequency band while RS to BS links use a different frequency band. Thus, four separated frequency bands will be used in such systems to support frequency duplex and avoid self-interference at RSs.

The routing is based on the consumed system capacity of each route when unit amount of traffic is delivered on that. It can be measured by dividing the consumed capacity of a route by the data rate on that route. The definition for consumed capacity or consumed resources is different in various systems. For example, in TDMA systems it can be determined by the number of used time slots, while in FDMA systems it is determined by frequency. Assuming limited system capacity, selecting the least capacity-consuming routes can maximize system throughput. After selecting the route, resources such as data rate will be assigned to users based on the available BS capacity. To estimate the consumed capacity of each link at BS, BS should know whether the link is single-hop or multihop. In single-hop link, the user is directly connected to the BS and the load of user can be easily calculated at the BS. In a multihop link, the load of a link at BS should be calculated considering the load of user and all involved intermediate nodes at BS. In the final step of the algorithm, relay stations are checked to make sure they are not overloaded. The load-balancing procedure is executed on an overloaded RS based on the priorities given to the users. In this prioritization method, users that benefit more from the relaying compared to direct communication would be less likely to go through the relief process. There are two approaches for decreasing the load in RS. One option is to change the relay station of users and relay their data through RSs which are not overloaded. The second option is to reduce data rate of users in order to decrease RS load. In CDMA systems, which are interference-limited, the first approach may not be effective enough, since the high data rate connection and its associated interference remains in system. The second

approach would be more appropriate for reducing consumed capacity in CDMA systems.

IRRA finds the sub-optimal solutions. The optimal radio resource allocation problem in MCNs, with the objective of throughput maximization, is formulated mathematically and proven to be NP-hard in this paper.

Chapter 3

Capacity of Time Slot Allocation Schemes in TDD-CDMA Networks

3.1 Introduction

Some studies have been done on resource allocation in MCNs and various time slot allocation schemes have been proposed for TDD-CDMA systems. The simplest scheme is to define a fixed switching point between uplink and downlink time slots (TS) in frame [11]. In fixed switching point (FSP) scheme, the position of SP will be the same for every cell in system. The drawback of this scheme is that it cannot fully utilize all free TSs of the frame when asymmetric traffic is generated. Thus, Adaptive Switching Point (ASP) scheme [27] was proposed which uses dynamic switching points. ASP assigns the new-coming user to free TSs by shifting the SP whenever all dedicated TSs are fully occupied. As a result of dynamic shifting, the position of SP in each cell would be different from other cells. Although this scheme utilizes the free TSs more flexibly, ASP results in crossed-time slot (CTS) interference in system [17]. The CTS interference is generated whenever one TS is used for uplink in one cell, while the same TS is used for downlink in a neighboring cell. Holma [17] has mentioned that the CTS interference caused by surrounding cells' downlink power can generate unacceptable interference to uplink transmission of MSs in one cell.

Consequently, MSs using crossed-time slots cannot transmit with the maximum data rate in uplink. To overcome the problem of CTS interference, one proposed solution is to divide the cell area into two regions of inner-region and outer-region [29-31]. The CTSs will only be assigned to the users in the inner-region. The main idea in such schemes is to reduce the inter-cell interference by maximizing the spatial separation. There are several other schemes that do not concern the problem of switching point placement, such that any TS within a frame can be assigned to uplink or downlink. One example is TS-opposing scheme [32]. This paper proposes a dynamic time slot allocation scheme. TS-opposing scheme, unlike FSP scheme that predefines the transmission direction of each TS, dynamically changes the direction of transmission for TSs. The transmission direction changes whenever transmission power of a MS exceeds the maximum allowable power in a TS due to interference.

So far, few papers have studied resource allocation schemes for MCNs. The studies of resource allocation for W-CDMA MCNs have been presented in [35, 36], whereas the studies of resource allocation for TDD-CDMA MCNs have been presented in [33,34,37]. Authors of [36] introduce a distributed multihop scheme. Each MS is equipped with a channel priority table. The priority of each channel is computed by dividing the number of times the channel has been allocated to the number of the times the channel has been tested. The paper studies the FDD mode where channels are separated by frequency and have different carrier frequencies. An integration of load-based routing algorithm and a mode-aware resource scheduler is proposed in [35]. The load-based routing algorithm selects the route which provides a certain data

rate with the least amount of system load. This routing algorithm is then integrated with a resource scheduling algorithm that unlike conventional schedulers used in single-hop schemes, is able to calculate user's load at BS and RS separately. Thus, it can be used in MCNs. This paper also introduces a load-balancing scheme to avoid overloading in RSs, but it does not study any channel allocation scheme in FDD mode or time slot allocation scheme in TDD mode for MCNs.

Resource allocation has a great impact on system capacity in TDD-CDMA MCNs. In [37] a formulation of slot allocation matrix is presented that enables the sequential time slot allocation required by relaying schemes. This allows authors to combine their proposed congestion-based routing and dynamic channel allocation. However, this paper does not specify a method for selecting uplink and downlink TSs. Delay sensitive slot allocation (DSSA) [33, 34] is another scheme proposed for TDD-CDMA MCNs. This scheme attempts to assign TSs to MSs in a multihop link to minimize the waiting time for each MS before reaching its designated TS and compares performance of this scheme with a single-hop scheme in terms of end-to-end delay. However, the papers mentioned above do not investigate the maximum system capacity when different types of symmetric and asymmetric traffic are generated in system.

In this chapter we study performance of the single-hop and multihop time slot allocation schemes for TDD-CDMA cellular networks. The objective is to compare the maximum supported throughput (in terms of kbps) of single-hop and multihop

schemes in various traffic scenarios. First, we introduce a *multihop* dynamic switching point scheme (MDSP) for TDD-CDMA MCNs. This scheme defines a dynamic switching point for each cell and supports multihop links when needed. Then, we propose another slot allocation scheme for TDD-CDMA MCNs, namely Maximum Interference First (MIF). In this scheme, we remove the switching points so that there will be no separation between the uplink and downlink TSs in each frame. MIF attempts to increase the throughput by assigning MSs to the TS which receives the highest interference and at the same supports the maximum data rate. Following this greedy algorithm, MIF saves the low-interfered TSs for new users. Thus, more high-quality channels would be accessible to new users, while existing users receive the maximum available data rates. We compare performance of these multihop schemes, MDSP and MIF, with benchmark single-hop schemes, FSP and DSP.

The rest of this chapter is organized as follows. In Section 3.2, we present system modeling and mathematical description. Section 3.3 describes the time slot allocation schemes selected for this study. In this section the benchmark conventional single-hop and our proposed multihop schemes are described. Subsequently, based on the selected schemes the simulation results are presented in Section 3.4 followed by discussions. Finally, Section 3.5 concludes the chapter.

3.2 System Modeling

In this Section, we define a model to study performance of different time slot allocation schemes.

3.2.1 System specifications

A. Cell Structure

A nineteen-cell model with two-tier configuration is assumed to be the service area as shown in Figure 10-A. MSs are uniformly distributed within the service area. The MSs are assumed to be immobile. Downlink transmission in all nineteen cells uses one-hop transmission in all four TS allocation schemes because most of downlink transmissions can be supported with high data rates. In uplink transmission, MSs are allowed to use multihop transmissions in TDD MCN using MDSP and MIF schemes. The TDD-CDMA MCN has six fixed RSs placed in the positions shown in Figure 10-B. In Figure 10, R is the cell radius whereas R_{relay} is the distance between the BS and the RSs.

Figure 10: A) 19-cell two-tier configuration B) Arrangement of fixed relay stations

B. Frame Structure

The standard frame structure of TDD-CDMA is used in this study. Time duration of each frame is 10ms and each frame consists of 15 TSs. The spreading factor (SF) of

each MS in a TS can be changed from 1 to 16, providing data rates from 256kbps to 16kbps. Only one MS can be assigned to each TS.

C. Multihop Signaling

It is assumed that the BS in each cell is able to send and receive the multihop control signals within the whole cell. Hence, in case a MS is in multihop transmission mode, the BS is able to select a proper RS which has the shortest distance from that 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. This multihop communication link between MS and BS will require one connection between MS and RS, MS-to-RS link, and another connection between RS and BS, RS-to-BS link. Since we focus on TS allocation for multihop networks, the details of the signaling mechanism is not considered here.

3.2.2 Traffic Model

The traffic in TDD-CDMA systems is expected to be asymmetric. In simulations, we model the asymmetry of traffic by requesting unequal number of TSs for uplink and downlink. We define the ratio between requested uplink and downlink TSs with U:D. For example, if $U:D = 1:4$ in a given cell, it means that the users in that cell require 1 TS for uplink and 4 TSs for downlink transmissions. In addition, we assume traffic requests with various U:D ratios in each cell in order to make an unbalanced traffic scenario in our model. For simplicity, we assume that uplink transmission always requires 1 TS, i.e. $U = 1$, while the downlink transmission can require 1 or more TSs, i.e. $D \geq 1$, since normally the multimedia traffic is biased towards downlink.

3.2.3. Signal Measurement

In our simulation, the propagation model consists of path loss and log-normal shadowing with zero-mean log-normally distributed random variable, X_σ , and a standard deviation σ of 4 dB.

To compute the received signal power, P_{rec} , at the receiver we can use (1):

$$P_{rec} = kd^{-l} P_t X_\sigma \quad (1)$$

where P_t is transmission power, d is the distance between transmitter and receiver, l is the path-loss exponent which is equal to 3.52 [38] in our study, which is suitable for cellular radio transmission in shadowed urban areas, and k is the path loss constant. To assign a TS to Transmitter x , we should calculate the received bit energy-to-noise density ratio (E_b/N_0) at the Receiver y for Transmitter x ;

$$\left(\frac{E_b}{N_0} \right)_{y,x} = \frac{P_{y,x}}{\left(I_{inter_cell} + \eta \right) \frac{r}{W}} \quad (2)$$

where $P_{y,x}$ is the received power at Receiver y from Transmitter x ; I_{inter_cell} is sum of received power of signals coming from transmitters in other cells causing inter-cell interference. I_{inter_cell} can be calculated based on propagation loss of signals, using (1), between transmitters in other cells and receiver in designated cell. η is the background noise and W denotes the chip rate of 3.84 Mcps and r is the data rate of connection. (2) can be used to measure the E_b/N_0 of received signals at BS, RS or MS in order to establish uplink, relay or downlink connections, respectively.

3.3 Description of Time Slot Allocation Schemes

In this Section, we describe four time slot allocation schemes for TDD-CDMA systems deploying single-hop and multihop scenarios. These schemes are FSP, DSP, MDSP and MIF. Two types of traffic are defined; symmetric and asymmetric. The former is described with $U:D = 1:1$ and the latter is defined as $U:D = 1:4$.

In multihop schemes, MDSP and MIF, when a MS cannot support the maximum data rate even with the maximum transmit power; the MS will forward its data to BS via RS using a multihop link. Multihop communication is not considered for downlink because the direct single-hop connection in downlink can provide the maximum data rate in most of the TSs. Hence, the multihop connection does not significantly improve the data rate in downlink.

3.3.1 Single-hop Schemes

A. Fixed Switching Point (FSP) scheme

In FSP, every cell in system has the same switching point (SP) between uplink and downlink TSs. The SP is placed between TS7 and TS8 as shown in Figure 11. In the case that only symmetric traffic requests, $U:D = 1:1$, are generated in system, 7 MSs can be assigned to the cell using 7 TSs for uplink and 7 TSs for downlink. When asymmetric traffic requests are generated, i.e., $U:D = 1:4$, each cell can accommodate only 2 users using 2 uplink TSs and 8 downlink TSs due to the asymmetry between required uplink and downlink TSs. Apparently, for asymmetric traffic, the TSs are not

fully utilized as shown for cell j in Figure 11. Therefore, the maximum capacity of FSP scheme for asymmetric traffic is expected to be low.

	Switching Point														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Symmetric traffic 1:1 (cell i)	U1	U2	U3	U4	U5	U6	U7		D7	D6	D5	D4	D3	D2	D1
Asymmetric traffic 1:4 (cell j)	U1	U2						D2	D2	D2	D2	D1	D1	D1	D1

Figure 11: Example of time slot allocation in FSP Scheme. U1 refers to the uplink transmission for MS1. Similarly, D1 refers to the downlink transmission for MS1.

Allocation of a MS to TS consists of three steps: TS allocation, power adjustment and data rate re-selection. The TS allocation in FSP is based on first-come-first-served. In FSP, a new MS is allocated to the leftmost free TS in frame for uplink transmission and the rightmost D free TSs are allocated to downlink transmission. The new MS/BS tries to transmit with the maximum data rate of 256 kbps with certain power level for uplink/downlink in the selected TSs. If the maximum data rate was not supported even with the maximum transmit power, a lower data rate, such as 128 kbps, with certain transmit power will be chosen. Then, the power adjustment and data rate re-selection will be executed for all MSs/BSs that use the *selected* TSs for uplink or downlink transmissions in all 19 cells. During power adjustment process, those MSs/BSs using the same *selected* TSs need to increase their transmit powers to overcome the extra interference caused by the new MS/BS in order to maintain the connection. Accordingly in data re-selection process, some of those MSs/BSs may need to lower their data rates if the transmission power exceeds the maximum transmission power of MS. This cyclic action of power adjustment and data rate reselection continues in all 19 cells including the cell of new user. This procedure ends when transmission powers

of all MSs/BSs, which transmit in the selected TSs, are adjusted to support their data rates.

It should be noted that the supported data rate in each TS depends on the interference status of that TS. Thus, each TS may have a different data rate for the same MS. For example, one MS may use TS1 with data rate of 256kbps for uplink and TS15 with data rate of 128kbps for downlink because TS1 receives less interference than TS15. Similarly, for asymmetric traffic of $U:D=1:4$, one MS may use TS1 with data rate of 256kbps for uplink; whereas, this MS may set different data rates for the 4 TSs used in downlink such as 256kbps for TS15, 128kbps for TS14, 128kbps for TS13 and 64kbps for TS12.

Uplink will always get the TS first. Then, the remaining free TSs will be allocated to downlink. It is possible to face the case where the number of remaining free TSs for downlink is less than the requested number. If the total number of free TSs is 1, the new call will be blocked by system.

B. Dynamic Switching Point (DSP) scheme

Similar to FSP, TS allocation in DSP is also based on FCFS rule except that each cell defines its own switching point. For uplink transmission, the leftmost free TS is selected. For downlink transmission, the rightmost D free TSs are selected. Similarly, uplink will always get the TS first. Then, the remaining free TSs will be allocated to downlink. It is possible to have the case where the number of remaining free TSs for

downlink is less than D . If the number of total free TSs is 1, this new call will be blocked by system.

As shown for cell i in Figure 12, 7 MSs with symmetric traffic requests can be assigned to the cell which is the same as FSP because of balanced uplink to downlink ratio of 1:1 in symmetric traffic. For cell j with asymmetric traffic, $U:D = 1:4$, each MS requires 1 TS for uplink and 4 TSs for downlink. As shown in Figure 12, cell j can allocate one more MS compared to FSP because of the dynamic switching point in DSP. Thus, all $3 \times (1+4) = 15$ TSs can be used in DSP scheme.

Figure 12: Example of time slot allocation in DSP Scheme

As mentioned before, this scheme suffers from the crossed-time slot interference because it allows a TS to be used for uplink in one cell and for downlink in an adjacent cell. Thus, although this scheme can support more users, maximum data rate will not be supported in crossed-time slots. In order to enhance uplink data rate for a user, we introduce multihop TS allocation schemes.

3.3.2 Multihop Schemes

C. Multihop Dynamic Switching Point (MDSP) scheme

Similar to DSP, in this scheme a switching point is defined that can dynamically change according to the cell traffic. Thus, the position of switching point may be different in each cell. The difference between DSP and MDSP schemes is that in MDSP whenever a single-hop connection with the maximum data rate, 256 kbps, is not available, a two-hop connection will be established.

In MDSP scheme, the TS allocation procedure is based on FCFS rule as in DSP. TS allocation is executed for the uplink transmission first and the leftmost free TS is selected. If the maximum uplink transmission data rate of 256kbps was not supported in the TS even with maximum transmission power, a RS will be selected to relay the data to BS. RSs are placed in the positions shown in Figure 10 with a distance of R_{relay} from BS. BS selects the nearest RS to the MS 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 set up the connection from MS to RS. For example, as shown in Figure 13, since MS1 cannot transmit with the maximum data rate in the leftmost TS, TS1, even with the maximum uplink transmission power, MS1 attempts to use TS1 for RS-to-BS link and uses the next leftmost TS, TS2, for MS-to-RS link. Commonly, the communication link of MS-to-RS or RS-to-BS can transmit at the maximum data rate because of shorter distances between receiver and transmitter. However, if this is not possible, a lower transmission data rate will be set for transmission 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 equal in order to be consistent. After TS allocation, power

adjustment as well as data rate re-selection will be preceded as described for FSP scheme. After uplink TS allocation, the TS allocation procedure selects the rightmost D free TSs for downlink transmission with no multi-hop transmission. As illustrated in Figure 13, multihop links require two time slots for uplink. One TS is assigned to MS-to-RS link and the other is assigned to RS-to-BS link.

Figure 13: Example of time slot allocation in MDSP scheme. A multihop link requires 2 TSs for UL.

Uplink will always get 1 or 2 TSs first. Then, the remaining free TSs will be allocated to downlink. If the number of total free TSs is 1, the new call will be blocked by the system. If the number of free TSs is 2, it is not enough to support a multihop connection, because a multihop link requires 2 TSs for uplink and at least 1 TS for downlink. In this case, one TS will be allocated to uplink transmission (without multihop transmission) and the other to downlink transmission. The other procedures, power adjustment and data rate re-selection, in MDSP are similar to the above schemes.

Figure 13 shows that establishing multihop connections increase the amount of consumed resources in both symmetric and asymmetric traffic. Thus, we propose MIF

scheme to avoid replacing a single-hop link with a multihop connection as much as possible.

D. Maximum Interference First (MIF)

In MIF we do not define any switching point as shown in Figure 14. MIF can search among all free TSs in frame to select a TS for uplink or downlink. This scheme increases system throughput in three ways. 1) TS selection algorithm tries to avoid selecting a crossed-time slot for uplink. It gives higher priorities to TSs which are used for uplink in larger number of adjacent cells, 2) Among TSs with the same priority, MIF selects high-interfered TSs first and saves the low-interfered TSs for new users and 3) MIF establishes multihop connections for MSs that cannot receive the maximum data rate. MIF scheme follows these steps to select a TS for uplink:

1. BS first checks the status of all free TSs and assigns a priority to each free TS. The priority number is equal to the number of adjacent cells that use this TS for uplink. A free TS, which has been used more often for uplink transmission in all surrounding cells, will receive a higher priority. In this way, MIF selects TSs that receive less CTS interference and also avoids generating CTS interference in system. If we find more than one free TS with the same priority, higher priority will be given to the one with higher uplink interference level received at BS.
2. Then, BS allocates the new MS to a free TS with the highest priority. If that TS could not accept the new MS with the maximum data rate (256 kbps), TS

with the next highest priority will be selected. This TS selection procedure ends when a free TS is found to support the *maximum/desired* data rate.

3. If none of the free TSs could support this MS with the *maximum* data rate, the closest RS to the MS will be selected by BS to relay the MS data to BS. The selection priority of TSs for RS-to-BS link is similarly based on TS priority. BS follows the procedure in Step 2 to select a TS that can provide the *maximum* data rate (256 kbps) for the selected RS in RS-to-BS link.
4. If the BS could not find a free TS to provide a data rate of 256 kbps for that RS, it will lower the data rate for one step, e.g., to 128 kbps, 64 kbps, 32 kbps or 16 kbps. The selection priority of TSs for RS-to-BS link is still based on TS priority. BS follows the procedure in Step 2 to select a TS that can provide the *desired* data rate for the selected RS. The data rate continues to be lowered until a TS is found to support the RS with a *certain* data rate. Otherwise, the MS is blocked.
5. Once a TS is found for the RS to establish the RS-to-BS link, RS assigns a priority to each free TS based on the procedure in Step1. Once the priority of free TSs is set, the RS follows the procedures in Steps 2 and 3 to select a TS with a proper data rate for the MS to establish the MS-to-RS link.
6. Whenever the transmission data rate of RS-to-BS link is different from that of MS-to-RS link, the lower data rate is selected for both links. It should be noted that the two TSs for RS-to-BS link and MS-to-RS link can be separated as shown in Figure 14.

7. Subsequently, power adjustment as well as data rate re-selection will be executed in every cell. After uplink TS allocation, the rightmost D free TSs are selected for downlink connection with no multihop transmission. For MIF, the TSs selected for downlink transmission are not necessarily consecutive as shown in Figure 14.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Symmetric traffic 1:1 (cell i)	U1		U2		U1								D2	U2	D1
Asymmetric traffic 1:4 (cell j)	U1										D1	D1	U1	D1	D1

Figure 14: Example of time slot allocation in MIF scheme. Any time slot can be assigned to uplink or downlink.

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

In multihop scenarios, since the distance between transmitter and receiver reduces, higher data rate can be achieved in both links. Consequently, MSs with longer connection links in FSP or DSP schemes can now transmit with higher data rate in MDSP and MIF schemes. Hence, QoS increases for MSs near cell's boundary.

3.4 Simulation Results and Discussions

We have studied performances of four TS allocation schemes, FSP, DSP, MDSP and MIF, by computer simulations. We have programmed the simulated TS allocation algorithms for both single-hop and multihop schemes using C++. We have used the *math.h* library and the *rand()* function to randomly select the cell which initiates the call. The simulated service area consists of 19 cells with two-tier configuration. MSs are uniformly distributed over the service area. Whenever a new call is generated in the system, it is randomly allocated to one of nineteen cells. This procedure continues till all nineteen cells in the system are no longer able to support any more MS. This is when all 19 cells have less than 2 free TSs and therefore, they cannot accept new users. Here, our goal is to investigate the maximum throughput of system with various TS allocation schemes. Thus, we try to assign one MS to each TS with the maximum *possible* data rate that can be supported according to the received interference. Notice that each time slot can support only one MS.

In all four schemes, whenever a new MS is added to any one of the cells, every existing MS/BS adjusts its transmission power to meet the required uplink/downlink E_b/N_0 with the maximum available data rate. If a RS is needed in MDSP or MIF scheme, the one with the shortest distance from MS is selected. BS monitors transmission status of each MS and decides on selecting a RS for multi-hop transmission. Transmission powers of MS, RS or BS ensure that the E_b/N_0 at the relevant receiver is, at least, equal to desired E_b/N_0 . The parameters used in the

simulation are summarized in Table 1. Few R_{relay} values were simulated and we found that $R_{\text{relay}} = 0.45R$ is able to achieve the best performance [39].

Table 1: Parameters of the simulation

Number of cells	19
Cell Radius (R)	500 m, 1 km, 2 km
R_{relay}	$0.45 R$
E_b/N_0	5 dB
Max. MS/RS Power	20 dBm
Max. BS/ Power	43 dBm
Pathloss Exponent (l)	3.25
Pathloss Constant (k)	137 dB
Background Noise (η)	-103 dBm
Log-normal Shadowing	Mean: 0dB Standard Deviation: 4 dB

Here, we present results and discussions of the simulations for three different traffic scenarios including symmetric traffic, asymmetric traffic and the mixed traffic. In symmetric traffic scenario (U:D=1:1), each user requires 1 uplink TS and 1 downlink TS in every cell. In asymmetric traffic scenario (U:D=1:4), each user requires 1 uplink TS and 4 downlink TSs in every cell. In the mixed traffic scenario, each user may require 1 uplink TS and 1 downlink TS or 1 uplink TS and 4 downlink TSs with equal probability in every cell.

3.4.1 Results on Mean Data Rate per Time Slot

In this sub-section, we present the results to show the mean supported data rate in each TS for all four schemes. Mean supported data rate in each TS reflects the quality of connection between MS and BS.

A. Symmetric Traffic

Table 2 shows mean uplink and downlink MS data rate and the number of users supported in the center cell for symmetric traffic with different cell radii, R . It can be seen that FSP and DSP can provide the same mean UL data rate because these two schemes result in identical TS allocation in frame when only symmetric traffic requests are generated in the system. By comparing mean UL data rate of FSP/DSP with multihop TS allocation schemes, MDSP and MIF, we can observe that multihop schemes result in higher UL mean data rate regardless of R . The improvement is about 30% and 50% for $R=500\text{m}$ and 1 km , respectively. Since multihop links are shorter in distance, they are less affected by propagation loss and have higher received signal strength at the receiver, RS or BS, to support higher data rate. In MIF, MSs can use any TS for UL or DL whereas, in MDSP, a switching point is used to separate the UL and DL TSs. Therefore, MIF is more likely to be affected by CTS interference. In small cells, e.g., $R = 500\text{ m}$, MIF provides lower UL data rate compared to MDSP due to more severe impact of inter-cell interference and CTS interference in shorter distances. However, MIF can provide higher UL mean data rate compared to MDSP in large cells, $R \geq 1\text{ km}$, because the distances increase between cells. For $R \geq 2\text{ km}$, the results show that multihop schemes do not significantly improve UL data rate because for very large cells, multihop connections with more than two hops should be established. Otherwise, multihop relaying will not show a significant impact on improving the data rate.

As shown in Table 2, DL mean data rate is almost the same for all four schemes because all of them establish single-hop connections between MS and BS and use the same algorithm for selecting downlink TS. As mentioned earlier, in symmetric traffic, FSP and DSP result in the same TS arrangement and they both support the same number of users in each frame. However, multihop schemes require more resources (TSs) for establishing uplink connections. Thus, more TSs are occupied for each MS and fewer users are supported in each frame in multihop schemes.

Table 2: Results for symmetric traffic scenario

Traffic Scenario	Cell Radius	Schemes	Center cell UL mean supported data rate in TS (kbps)	Center cell DL mean supported data rate in TS (kbps)	No. of MSs supported per frame in center cell
100% U:D=1:1	500 m	FSP	176	193	7
		DSP	176	193	7
		MDSP	235	196	6.4
		MIF	213	199	6.7
	1.0 km	FSP	117	191	7
		DSP	117	191	7
		MDSP	204	195	5.5
		MIF	227	194	5.6
	2.0 km	FSP	41	177	7
		DSP	41	177	7
		MDSP	52	178	5.1
		MIF	57	189	5.1

B. Asymmetric Traffic

Table 3 shows the simulation results for asymmetric traffic scenario. As mentioned previously, FSP can support fewer MSs in asymmetric traffic due to fixed switching point as shown in Figure 11. Not being able to use all free TSs, FSP can support only 2 users in each frame while DSP can fully utilize TSs and it can support 3 users in each frame as shown in Figure 12. Similarly, MDSP and MIF can support 3 users per

frame. Since every cell generates the same type of traffic (U:D=1:4), no TS is used for opposite transmission directions among adjacent cells according to the channel selection algorithm in FSP and DSP. So, none of the schemes suffer from CTS interference and thus, the mean UL data rate is almost the same for both FSP and DSP schemes. As expected, we can see that multihop TS allocation schemes can provide higher data rate for MSs in this scenario. MIF performs worse than MDSP for small R , $R = 500\text{m}$, because in MIF MSs can use any TS for UL or DL and they are more likely to create crossed-time slot interference to other cells. The results for $R = 2\text{ km}$ are not shown in Table 3 because multihop TS allocation schemes, which only allow 2-hop connections, do not perform much better than single-hop TS allocation schemes in large cells. Hence, more hops should be considered for greater R .

Table 3: Results for asymmetric traffic

Traffic Scenario	Cell Radius	Schemes	Center cell UL mean supported data rate in TS (kbps)	Center cell DL mean supported data rate in TS (kbps)	No. of MSs supported per frame in center cell
100% U:D=1:4	500m	FSP	176	193	2
		DSP	174	192	3
		MDSP	214	193	3
		MIF	167	198	3
	1.0 km	FSP	117	191	2
		DSP	114	190	3
		MDSP	170	191	3
		MIF	174	196	3

C. Mixed Traffic

Results for mixed traffic scenario are presented in Table 4. It can be seen that FSP can support fewer MSs in each frame compared to other schemes due to its fixed switching point. From the mixed traffic scenario we can clearly notice the impact of CTS interference on MS data rate in DSP. In mixed traffic, each cell may generate different types of traffic (U:D=1:1 or U:D=1:4). In DSP, TSs can be used for opposite

transmission directions among adjacent cells because of the dynamic switching point. This TS arrangement causes CTS interference in system. Therefore, UL data rate decreases in DSP compared to FSP with fixed switching point. Moreover, it is understood from the table that multihop TS allocation schemes increase UL MS data rate compared to single-hop schemes regardless of cell size in mixed traffic scenario because they can effectively reduce the impact of CTS interference by transmitting the data in shorter distances. The improvement is between 15% and 50%. Similarly, MIF performs worse than MDSP for small R , $R = 500\text{m}$, due to higher CTS interference.

Table 4: Results for mixed traffic

Traffic Scenario	Cell Radius	Schemes	Center cell UL mean supported data rate in TS (kbps)	Center cell DL mean supported data rate in TS (kbps)	No. of MSs supported per frame in center cell
50% U:D=1:1 50% U:D=1:4	500m	FSP	191	199	3
		DSP	166	197	4.4
		MDSP	216	198	4.1
		MIF	190	200	4.2
	1.0 km	FSP	121	198	3
		DSP	109	194	4.4
		MDSP	184	197	3.8
		MIF	202	198	3.8

3.4.2 Results on Cell Capacity

In previous section, the results illustrated the QoS of a MS connection for a given TS allocation scheme. However, those results do not reflect the impact of multihop relaying on cell capacity. In this section, we show cell throughput of all four schemes in three different traffic scenarios; symmetric, mixed and asymmetrical traffic. The findings can be different from previous section. For example, in Table 3, we found

that the UL mean data rate is about the same for both FSP and DSP schemes; however, the cell throughput for FSP can be much lower than that for DSP.

Figure 15 shows the maximum uplink cell capacity of center cell for each TS allocation scheme in different traffic scenarios and cell radii. Comparing FSP and DSP in mixed traffic, even though the UL mean data rate for FSP is higher than that for DSP as shown in Table 4, the uplink cell capacity of DSP is much higher than that of FSP as shown in Figure 15. This is because DSP has no fixed switching point and thus, all free TSs can be fully used in order to support more users. It can be seen that multihop TS allocation schemes provide higher uplink cell capacity compared to single-hop TS allocation schemes. And the improvement of multihop schemes over single-hop schemes increases with R . With mixed traffic and $R = 500$ m, MDSP performs better than DSP for about 20%. With mixed traffic and $R = 1$ km, MDSP performs better than DSP for about 50%. This is because of the fact that in small cells, $R = 500$ m, MSs are not so far away from the BS and it is less probable for them to establish multihop links. More to the point, from the results we can infer that employing multihop TS allocations schemes improves uplink capacity regardless of the traffic scenario. In small cells, e.g., $R = 500$ m, since MIF does not define any switching point, CTS interference degrades UL capacity. As we increase the cell size, e.g., $R = 1$ km, the impact of CTS interference becomes weaker and MIF can outperform MDSP in terms of UL capacity. Nevertheless, as shown in Figure 17, MIF outperforms MDSP in terms of total cell capacity (including uplink and downlink capacity) even in small cells.

Figure 15: Uplink capacity in center cell for different traffic scenarios.

Figure 16 shows DL capacity of center cell for all four schemes in different traffic scenarios and cell radii. FSP has much lower DL capacity compared to other schemes for mixed and asymmetric traffic because of the unused TSs in FSP. Since DL TS allocation follows the same algorithm for all four schemes, there is no increase in DL mean data rate as shown in previous Tables. Thus, we do not expect any DL capacity improvement from multihop TS allocation schemes. On the contrary, the DL capacities of MDSP and MIF are lower than that of DSP for a maximum of 10% due to the extra resources used for establishing a relaying link in multihop TS allocation schemes. In MDSP and MIF, assigning more TSs to UL for multihop transmission reduces the number free TSs that can be allocated to DL.

Figure 16: Downlink capacity in center cell for different traffic scenarios.

Figure 17 shows the total (UL and DL) capacity of four schemes. Using this comparison, we can study the combined effect of changes in MS data rate and the number of supported users on maximum capacity of system. FSP has much lower total capacity compared to other schemes for mixed and asymmetric traffic because of the unused TSs in FSP. It can be seen that the proposed multihop TS allocation scheme, MIF, outperforms the other schemes, DSP and MDSP, in terms of total capacity regardless of R . The improvement is smaller for asymmetric traffic (U:D=1:4) because the asymmetric traffic requires more DL TSs and thus, there are less TSs that can be used for UL in multihop connections. Since MSs are not so far away from the BS in small cells, $R = 500\text{m}$, establishing a multihop link is less probable. In general, in small cells multihop TS allocation schemes perform slightly better than single-hop TS

allocation schemes; while in larger cells, multihop TS allocation schemes show greater effect on the total system capacity.

Figure 17: Total capacity in center cell for different traffic scenarios.

Figure 18 shows data rate distribution in uplink and downlink of different schemes for mixed traffic scenario with $R = 1\text{km}$.

a) Uplink data rate distribution

b) Downlink data rate distribution

Figure 18: Data rate distribution in center cell for a) Uplink b) Downlink with mixed traffic.

It can be seen that MDSP and MIF can provide 60% and 70% of users with data rate of 256kbps for uplink connection, respectively. FSP and DSP can only support about 30% of users with the maximum data rate, 256kbps, for uplink connection. It indicates that multihop relaying has a great impact on providing high uplink data rate for users. We can also see that about 10% of users in FSP and DSP cannot establish a connection (data rate = 0kbps) where this amount is relatively smaller for multihop TS allocation schemes. In terms of DL data rate distribution, results are almost the same for all four schemes because the same procedure is used for DL TS allocation in all four schemes.

3.5 Conclusions

In this chapter, we proposed dynamic time slot allocation schemes, MDSP and MIF, for TDD-CDMA multihop cellular systems. We conducted a study on comparing performance of the proposed schemes with other conventional single-hop schemes, FSP and DSP. Our simulations were based on a nineteen-cell model assuming path loss and log-normal shadowing. FSP provides the lowest TS utilization when asymmetric traffic requests are generated in system. DSP scheme, on the other hand, can improve the capacity because of the dynamic switching point. But, a severe capacity is lost due to high crossed-time slot interference in cells caused by surrounding cells. In MDSP scheme the high interference is suppressed with the multihop communication but, more resources are allocated to uplink communication. The mean uplink data rate can be improved significantly. In addition, MDSP can improve the uplink capacity in almost every case. The performance can be further

improved by using MIF which can provide higher overall capacity. In general, multihop TS allocation schemes can provide better QoS, in terms of mean data rate, as well as cell capacity. However, from our observation, two factors, which will affect the effectiveness of multihop TS allocation schemes, are asymmetric traffic and cell coverage. As downlink traffic increases in asymmetric traffic, performance of multihop TS allocation schemes degrades because fewer available time slots remain there for multihop transmission in uplink. If the cell radius, R , is too small, multihop communications become less effective because the distances would be short enough to provide good link quality without multihop transmission. In large cells, the distances in each hop would still be too large to provide adequate link quality. Thus, more hops would be required.

In this study, we assume that BS selects the nearest RS to the MS whenever a relay station is needed. To achieve that, one suggestion is to use GPS system to locate position of the MSs/RSs. Other issues, such as power control and routing, can be the future study of this topic.

Chapter 4

Performance of Time Slot Allocation Schemes in Supporting Multimedia Services

4.1 Introduction

In this chapter, we modify the simulation environment to simulate more realistic conditions. The objective of this study is to analyze behavior of single-hop and multihop time slot allocation schemes in networks that provide multimedia services and compare their performance in handling various service requests with different Quality of Service (QoS) requirements. Here, capacities of the schemes are measured in terms of probability of blocking or dropping users' calls. We assume that more than one user can be assigned to each time slot and different types of circuit-switched multimedia traffic requests are generated in system. Next generation of cellular networks are expected to manage asymmetric traffic generated by various applications. Two schemes are proposed in this chapter which can support more than one user in each TS and deploy multihop relaying only in uplink. To compare performance of the proposed multihop resource allocation schemes with conventional single-hop schemes, we have defined three traffic scenarios with two low data rate (voice) and high data rate (video) traffic classes.

The rest of this chapter covers the following topics. First, we describe how we have modeled the system, including the traffic model, call admission process and the description of selected single-hop schemes and our proposed multihop schemes. In the second section, we present the simulation results and discussions and the last section concludes this chapter.

4.2 System model

In this Section, we define the model we have used to study performance of different time slot allocation schemes in supporting multimedia services. We have simulated the cellular system and the TS allocation schemes using C++ programs. In the programs we have used three random generating libraries, `math.h`, `RANDGEN.h` and `RANDGEN1.h`, to generate required random values. The random values are used to determine 1) the random cell that initiates a call, 2) call duration and call initiation time in Poisson process and 3) the log-normally distributed value of shadow fading. Structure of the cells and the frames used in this model is similar to the structures used in simulations of chapter 3. TDD-CDMA time frames of 10 (ms) with 15 time slots are assumed. The system consists of 19 cells and six fixed relay stations (RS) are deployed in each cell. The fixed relay stations are placed with distance R_{relay} from BS as shown in Figure 10-B. For more details on the RSs, you can see section 3.2.1.

4.2.1 Signal Measurement

In our simulation, the propagation model consists of path loss and log-normal shadowing with zero-mean Gaussian distributed random variable, X_σ , and standard deviation σ . As mentioned in previous chapter, to compute the received signal power, P_{rec} , at the receiver we can use (1):

$$P_{rec} = kd^{-l} P_t X_\sigma \quad (1)$$

where P_t is transmission power, d is the distance between transmitter and receiver, l is the path-loss exponent which is equal to 3.52 in our study and k is the path loss constant. To assign Transmitter x to a TS, the received bit energy-to-noise density ratio (E_b/N_0) of Transmitter x at Receiver y should be calculated in the given TS by

$$\left(\frac{E_b}{N_0} \right)_{y,x} = \frac{P_{y,x}}{\left(I_{Inter_cell} + I_{Intra_cell} + \eta \right) \frac{r}{W}} \quad (3)$$

where $P_{y,x}$ is the received power at Receiver y from Transmitter x ; I_{inter_cell} is sum of received interfering signals at Receiver y from other cells. I_{inter_cell} can be calculated by summing the received powers, P_{rec} , of interfering signals using (1). I_{intra_cell} is the interference caused by transmitters in the same cell at the Receiver y . This amount, similar to I_{iner_cell} , is the sum of received powers, P_{rec} , of intra-cell signals at Receiver y . η is the background noise and W denotes the chip rate of 3.84 Mcps and r is the data rate of connection.

Formula (3) is a general formula for calculating E_b/N_0 for a transmission link. In Single-hop schemes signals are transmitted by MSs and BSs whereas in multihop schemes, RSs also transmit signals in addition to MSs and BSs. Therefore, the

scenarios for inter-cell and intra-cell interferences are different in single-hop and multihop schemes. In single-hop schemes, the inter-cell interferences are coming from MSs and BSs in neighboring cells whereas in multihop schemes, the inter-cell interferences are coming from MSs, RSs and BSs in neighboring cells. The scenarios for intra-cell interferences of single-hop and multihop schemes are described in following cases:

- Single-hop schemes - uplink: The intra-cell interference at BS is caused by signals coming from other MSs in the same cell.
- Single-hop schemes - downlink: There is no intra-cell interference, i.e., $I_{intra_cell} = 0$, because signals transmitted from BS are synchronized and use orthogonal codes. Thus, it is assumed that the received signals do not interfere with each other at MS.
- Multihop schemes – uplink (MS-to-BS and RS-to-BS): Signals coming from other MSs or other RSs in the same cell result in intra-cell interference at BS.
- Multihop schemes – uplink (MS-to-RS): Signals coming from BS, other MSs or other RSs in the same cell result in intra-cell interference at RS.
- Multihop schemes - downlink (BS-to-MS and BS-to-RS): Signals coming from the BS are orthogonal and do not cause intra-cell interference at MS or RS; however, signals coming from other MSs or RSs in the same cell result in intra-cell interference at MS or RS.
- Multihop - downlink (RS-to-MS): Signals transmitted from BS, other MSs or other RSs in the same cell cause intra-cell interference at MS.

It should be noted that the above analysis on inter-cell and intra-cell interferences is very general and includes every possible case. Some of the mentioned cases may not apply to time slot algorithms of this chapter, however, they are useful for analyzing the algorithms which will be described in Chapter 5. For example, for the multihop schemes presented in this chapter we only consider data relaying in uplink. Thus, we will not have any BS-to-RS and RS-to-MS links. We will establish direct single-hop links in downlink and only BS-to-MS links should be analyzed. In Chapter 5 we will employ data relaying for both uplink and downlink and all three BS-to-MS, BS-to-RS and RS-to-MS links need to be analyzed. The sources of intra-cell interference are also very general in each case. For example, in the multihop schemes of this chapter we separate the TSs dedicated to uplink and downlink. Thus, during a MS-to-RS link we will not have any intra-cell interference coming from BS. However, in the schemes presented in Chapter 5 a MS-to-RS is allowed to be simultaneously assigned to a TS with a BS-to-MS link. This causes intra-cell interference from BS at RS.

4.2.2 Traffic Model

Next generation of cellular networks are expected to manage asymmetric traffic generated by various applications. To compare performance of our proposed resource allocation schemes, we have defined three traffic scenarios with two traffic classes. The characteristics of the traffic classes [40] are shown in Table 5. In Table 5, Duty Factor, α , shows the proportion between *on time* and *off time* of the service. *On time* in voice services can be interpreted as the speech duration and *Off time* can be interpreted as the silence duration. Call durations are exponentially distributed with a mean rate of

$1/\mu=120$ sec. The study is conducted for three traffic scenarios including pure Class A requests, pure Class B requests and mixed traffic with 50% Class A requests and 50% Class B requests.

Table 5: Requirement Details of Multimedia Services

Service	UL Data Rate	DL Data Rate	Target Eb/N0	Duty Factor (α)	Ave Holding Time
HQ-voice	32 kbps	16 kbps	5 dB	0.4	120 sec
LQ-video	64 kbps	32 kbps	7 dB	1.0	120 sec

4.2.3 Description of Single-hop Schemes

In this section and the next section we describe two single-hop time slot allocation schemes and the schemes that we have proposed for multihop cellular networks.

A. Fixed Time Slot Allocation (FTSA)

This scheme is used for TDD-CDMA SCNs. In this scheme we define a *fixed* switching point to divide 15 TSs of a frame into two groups. One group of TSs is used for uplink connections and the other group is used for downlink connections. In our model we set the switching point between TS7 and TS8. Hence, first 7 TSs will be reserved for uplink and next 8 TSs will be dedicated to downlink. The placement of switching point is fixed in a cell and the same switching point is used in every cell in the system.

When a new call initiates in a given cell, the algorithm begins searching for a TS between TS 1 and TS 7 to support the uplink connection. TS 1 will first go through the call admission process (described later). If the call admission process is successful for that MS in TS 1, TS 1 is selected for uplink connection. Otherwise, the algorithm

continues testing the next uplink TS until TS 7. If call admission process was not successful in any TS between TS 1 and TS 7, the new call will be **blocked**. After selecting the uplink TS, the TSs between TS 8 and TS 15 are tested for downlink connection. Downlink TS selection follows the same procedure, except that searching for downlink TS starts from the rightmost TS, TS 15, in frame and continues to TS 8. Similarly, if call admission process was not successful in any TS between TS 8 and TS 15, the new call will be **blocked**. A new call is accepted when TSs are successfully allocated to both uplink and downlink. As shown in Fig. 2, a TS can support multiple MSs as long as their data rate and SIR requirements are satisfied in the TS.

Figure 19: An example of time slot allocation using FTSA scheme. Note that each TS can support more than one user. In this example TS 1 supports 3 MSs.

B. Dynamic Time Slot Allocation (DTSA)

This scheme is also used for TDD-CDMA SCNs. The algorithm works in a similar way as previous scheme in selecting TSs for uplink and downlink. The only difference of this scheme is that no switching point is defined in the frame.

When a new call initiates in a given cell, the algorithm starts from TS 1 to look for an *empty* TS or an *uplink* TS (which already supports uplink transmission) to allocate the uplink connection. If TS x is an *empty* TS or an *uplink* TS, it will go through the call admission process. If call admission succeeds for that MS in TS x , TS x is selected for

uplink connection. Otherwise, the algorithm continues testing the next *empty* or *uplink* TS until it reaches TS 15. If call admission process does not succeed for any TS, the new call will be **blocked**. The same procedure is followed for downlink TS selection, except that searching for an *empty* or a *downlink* TS starts from TS 15. If call admission process does not succeed in any TS, the new call will be **blocked**. A new call is accepted when TSs are allocated to both uplink and downlink.

Removing the switching point enables the algorithm to fully utilize all free TSs of the frame and increases the chance of accepting a new-coming user. Figure 20 shows an example of time slot allocation using DTSA scheme. It can be seen that any TS can be used for uplink or downlink transmission. However, since each cell independently arranges the TSs of a frame for uplink and downlink, crossed-time slot interference [28] may appear between adjacent cells. CTS interference happens when a TS is used for uplink in one cell and for downlink in a neighboring cell.

Figure 20: An example of time slot allocation using DTSA scheme.

4.2.4 Description of Multihop Schemes

A. Multihop Fixed Time Slot Allocation (mFTSA)

To study multihop scenario, multihop Fixed Time Slot Allocation scheme (mFTSP) is proposed first. In this scheme, we deploy six fixed relay stations (RSs) with distance R_{relay} from BS in each cell. The positions of six RSs are shown in Figure 10. MSs with

distance shorter than R_{relay} from BS directly connect to BS, while other MSs establish a two-hop connection from MSs to BS using the nearest RS. Relaying is only implemented for uplink transmission in our study because downlink can normally provide adequate data rate. Maximum of two hops are allowed for relaying data from MS to BS in mFTSA.

To design a system that can support multihop relaying, we should consider the channels that are required at the RS for receiving and transmitting data. Since RSs receive data from MS and transmit the relayed data to BS, self-interference will occur if transmission and reception take place at the same time and on the same frequency. To avoid self-interference at RS, we separate uplink and downlink transmission using different TSs. As shown in Figure 21, 15 time slots of the frame are divided into three groups using two fixed switching points. The first group of time slots can only be assigned to MS-to-BS links in single-hop and MS-to-RS links in multihop. The second group of time slots can be assigned to RS-to-BS links in multihop scenario and the last group is only used for downlink single-hop connection from BS to MS. Here, we group the TSs to avoid self-interference at the RSs.

Figure 21: An example of time slot allocation in mFTSA scheme.

When a new single-hop call arrives, it selects a TS from the left-side of first time slot group for uplink transmission and a TS from the right-side of third time slot group for downlink transmission. If the required data rate for uplink or downlink was not supported in any TS, the new call will be blocked. When a new two-hop call arrives, it selects a TS from the left-side of first time slot group for MS-to-RS link transmission and a TS from the left-side of second time slot group for RS-to-BS link transmission. Then, it will select a TS from the right-side of third time slot group for downlink transmission. Failure in finding a time slot that can support the required uplink or downlink data rate in any one of the groups, results in blocking the new call.

B. Multihop Dynamic Time Slot Allocation (mDTSA)

In the next step, we introduce a multihop Dynamic Time Slot Allocation (mDTSA). In mDTSA, no switching point is employed. When a new single-hop call arrives, mDTSA follows the same procedure as mFTSA to select uplink and downlink TSs such that the MS selects a TS from the left-side of the frame for uplink transmission and a TS from the right-side of the frame for downlink transmission. If no time slot is found to support the required data rate for uplink or downlink, the new call is blocked. When a new two-hop call arrives, searching for a TS starts from the left-side of frame for MS-to-RS link transmission. Any TS that can provide the new user's required uplink data rate is assigned to MS-to-RS uplink transmission. For RS-to-BS link, searching for a TS starts from TS 8 as shown in Figure 22. If new user's uplink data rate was not supported in TS 8, the time slot next to TS 8 on left-side, TS 7, will be tested. If TS 7 could not support user's uplink data rate as well, a time slot next to TS

8 on right-side, TS 9, will be tested. Similarly, if user's uplink data rate was not supported in TS 9, the next left time slot, TS 6, will be tested. Thus, the sequence of searching for a time slot to allocate RS-to-BS link is: TSs 8, 7, 9, 6, 10, 5, 11, ... For downlink, searching for time slot starts from the right-side of frame. A TS that can provide the user's required downlink data rate is assigned to downlink transmission. The reason of using this approach for selecting time slots is to evenly use the time slots and attempt to minimize the CTS effect. If time slot selection for any of the links, MS-to-RS, RS-to-BS or BS-to-MS, fails to support the required data rate, the new call will be blocked.

Figure 22: An example of TS allocation in mDTSA scheme.

4.2.5 Call Admission Process

Call admission process is to check whether the selected TS can support the MS's requested data rate with the requested quality of service (QoS) requirements for a new call. In our call admission process, a TS will be allocated to a new call if the call admission criteria is met. One of the call admission conditions is that the received E_b/N_0 for a new call must achieve the required E_b/N_0 . To make the system more stable, in our study, the required E_b/N_0 is set to a threshold, $\delta=1$ dB, above target E_b/N_0 for different traffic classes. The received E_b/N_0 at a receiver is calculated using (3) for

different data rate requests. If the call admission criteria is not met, the call admission process is considered unsuccessful and the next proper time slot will be selected. The call admission criteria for single-hop and multihop schemes are described next. More detailed description of the call admission procedure can be found in Appendix A.

Call Admission Criteria for Single-hop Schemes

The call admission criteria of single-hop schemes for each link is described as follows:

- *Uplink connection:* TS a is selected for uplink if 1) the received E_b/N_0 of this uplink can meet the required E_b/N_0 , which is $\delta=1$ dB above the target E_b/N_0 , in TS a while the MS's transmission power $\leq P_{MS}$ (which is the MS maximum permissible transmission power) and (2) all other uplinks of the existing calls using TS a in the same cell can also meet their target E_b/N_0 while the transmission power of every MS $\leq P_{MS}$.
- *Downlink connection:* TS b is selected for downlink if 1) the received E_b/N_0 of this downlink can meet the required E_b/N_0 in TS b while the total BS transmission power $\leq P_{BS}$ (which is the BS maximum permissible transmission power) and 2) all other downlinks of the existing calls using TS b in the same cell can also meet their target E_b/N_0 while the total BS transmission power $\leq P_{BS}$.

A new call is accepted when call admission processes for both uplink and downlink are successful. The existing calls in other neighboring cells (which is 18 neighboring cells in our study) using the same selected TSs, TS a for uplink and/or TS b for

downlink, will be **dropped** if 1) they cannot meet target E_b/N_0 in uplink even with P_{MS} or 2) their downlink cannot meet target E_b/N_0 even with P_{BS} .

Call Admission Criteria for Multihop Schemes

The call admission criteria for each type of link in multihop schemes are described as follows.

A. 1-hop Call

- *Uplink MS-to-BS*: TS a is selected for uplink MS-to-BS if 1) the received E_b/N_0 of this MS-to-BS link can meet the required E_b/N_0 in TS a when MS's transmission power $\leq P_{MS}$ and 2) all other connection links, e.g., RS-to-BS, of the existing calls using TS a in the same cell can also meet their target E_b/N_0 when transmission powers of MSs $\leq P_{MS}$ and transmission powers of RSs $\leq P_{RS}$. Where P_{RS} is the maximum permissible RS transmission power for each connection link.

- *Downlink BS-to-MS*: TS b is selected for downlink BS-to-MS if 1) the received E_b/N_0 of this BS-to-MS link can meet the required E_b/N_0 in TS b with the total BS transmission power $\leq P_{BS}$ and 2) all other connection links, e.g., BS-to-RS, of the existing calls using TS b in the same cell can also meet their target E_b/N_0 without exceeding the maximum transmission powers of the corresponding transmitters, such as P_{MS} , P_{RS} and P_{BS} .

When a new 1-hop call is accepted, any existing 1-hop or 2-hop call in one of the other 18 neighboring cells using the same selected TSs, TS a and/or TS b for transmission, will be **dropped** if any of its transmission links fails to meet the target E_b/N_0 even with the maximum transmission power of the related transmitter, i.e., P_{MS} , P_{RS} or P_{BS} .

B. 2-hop Call

- *Uplink MS-to-RS link:* TS a is selected for uplink MS-to-RS if 1) the received E_b/N_0 of this MS-to-RS link can meet the required E_b/N_0 in TS a while the MS's transmission power $\leq P_{MS}$ and 2) all other connection links of the existing calls using TS a in the same cell can also meet their target E_b/N_0 without exceeding P_{MS} , P_{RS} and P_{BS} .
- *Uplink RS-to-BS link:* TS b is selected for uplink RS-to-BS if 1) the received E_b/N_0 of this RS-to-BS link can meet the required E_b/N_0 in TS b while RS's transmission power $\leq P_{RS}$ and 2) as above.
- *Downlink BS-to-RS link:* TS c is selected for downlink BS-to-RS if 1) the received E_b/N_0 of this BS-to-RS link can meet the required E_b/N_0 in TS c while the total BS transmission power $\leq P_{BS}$ and (2) as above.

- *Downlink RS-to-MS link:* TS d is selected for downlink RS-to-MS if 1) the received E_b/N_0 of this RS-to-MS link can meet the required E_b/N_0 in TS d while RS's transmission power $\leq P_{RS}$ and (2) as above.

If a new 2-hop call is accepted, any existing 1-hop or 2-hop call in one of the other 18 neighboring cells using the same selected TSs, TS a , b , c and d for transmission, will be **dropped** if any of their transmission links fail to meet the target E_b/N_0 even with P_{MS} , P_{RS} or P_{BS} .

As mentioned for signal measurement, the above description for call admission process is general and includes all possible links. The multihop downlinks (BS-to-RS and RS-to-MS links) may not be applicable to time slot allocation algorithms of this chapter. However, in order to avoid duplication in next chapter all cases are explained here.

4.3 Simulation results and discussions

A 2-tier cellular system consisting of 19 cells is assumed. Users are uniformly distributed over these 19 cells. When a new call is generated in the system based on Poisson process, it is randomly assigned to a cell. More than one user can be assigned to each TS as long as users' required data rates are supported. Simulation parameters are summarized in Table 6. The desired accuracy for our simulation results is set to be 10^{-6} . The simulation was repeated with 5 different seed values for random generator algorithm. For all simulation results, the 95% confidence intervals within $\pm 5\%$ of the average values are observed.

Table 6: Simulation Parameters

Number of cells	19
Cell radius, R	1km
R_{relay}	450m
Maximum MS Power	21 dBm
Maximum RS Power	21 dBm
Maximum BS Power	43 dBm
Pathloss Exponent (l)	3.25
Pathloss Constant (k)	137 dB
Background Noise (η)	-103 dBm
E_b/N_0 margin for accepting new user, δ	1 dB

In order to investigate both performance metrics of call blocking and call dropping probabilities together, we define the Grade of Service (GoS) parameter as the probability of the calls which are blocked or dropped. GoS is defined as following [41]:

$$\begin{aligned}
 \text{GoS} &= P \{ \text{Blocked or Dropped calls} \} \\
 &= P \{ \text{call is blocked} \} + P \{ \text{call is accepted} \} \\
 &\quad \times P \{ \text{call is dropped} \mid \text{call is accepted} \} \\
 &= P_b + (1 - P_b) \times P_{dropping}
 \end{aligned}$$

During the analysis, we will simply use P_d instead of $(1 - P_b) \times P_{dropping}$. In order to study the GoS value from different points of view, weighted factors can be added to the formula of GoS. These factors would show the importance of each probability from a special standpoint. For example, from user's point of view, a dropped call might be less desirable than a blocked call so, we would have: $w_1 < w_2$. The weighted GoS is given by:

$$\text{GoS} = w_1 \times P_b + w_2 \times P_d$$

$$w_1 + w_2 = 1$$

Here, we compare call blocking, P_b , and call dropping, P_d , probabilities of four schemes in three different traffic scenarios including pure voice traffic, pure video traffic and mixed traffic which includes 50% voice service and 50% video service. The results are collected from the seven center cells of system.

Figure 23 illustrates the results for pure voice traffic. Since the P_b of mDTSA is very low and is out of range of plotted traffic load, it did not appear in this figure. It can be seen that as traffic load per cell, ρ , increases, FTSA shows higher P_b compared to DTSA. Since traffic is asymmetric, more resources remain unused in FTSA because of the fixed switching point. On the contrary, DTSA is able to dynamically change the position of switching point in order to accommodate the asymmetric traffic. For low ρ , mFTSA has lower P_b compared to single-hop schemes, FSTA and DTSA, because mFTSA can provide sufficient link quality to meet the required data rate with shorter transmission range. However, for high ρ , mFTSA has higher P_b compared to single-hop schemes because multihop schemes occupy more resources (time slots) to support multihop links. As ρ increases, mFTSA may not have enough time slots to support new users even though the link quality is good. Since the number of reserved time slots in each group, MS-to-RS/MS-to-BS, RS-to-BS and BS-to-MS, is fixed in mFTSA, it is very likely to block calls for the reason that there is no more free time slot in one of the groups. Thus, a dynamic scheme for multihop transmission is needed. The P_b can be reduced substantially by using mDTSA in which time slots can be used in a more flexible way. This scheme can use all time slots to support transmissions in different links. The P_d is lower in multihop schemes.

Figure 23: Pure voice traffic scenario

As ρ increases, the difference between P_d in multihop and single-hop schemes becomes less significant, because multihop schemes occupy more resources (time slots) to support multihop links. As ρ increases, there may not be enough time slots to support more users.

Simulation results for video traffic scenario are shown in Figure 24. The P_b in single-hop schemes is quite high. Since single-hop schemes have longer transmission ranges, links have lower quality and are not able to support high data rate communications. As shown in the figure, for single-hop schemes, at least 30% of video service requests are not able to meet QoS requirements. As expected, employing multihop technique significantly reduces P_b of high-speed video traffic due to shorter transmission range. mDTSA scheme has the lowest P_b compared to other three schemes in supporting this

traffic. mFTSA and mDTSA have higher P_d because these schemes can accept more calls and thus, there is a higher probability to drop calls. However, as shown in Table 7, mFTSA and mDTSA provide higher cell capacity for a given grade of service (GoS).

Figure 24: Pure video traffic scenario

Figure 25 compares the performance of four schemes in mixed traffic scenario. Similar to Figure 24, mFTSA and mDTSA have lower P_b and higher P_d compared to FTSA and DTSA. However, as shown in Table 7, mFTSA and mDTSA have higher cell capacity in supporting mixed traffic for a given GoS. Again, mDTSA can further improve the performance since dynamic usage of time slots in mDTSA enables this

scheme to accommodate asymmetric traffic more efficiently and to utilize all free time slots in each frame.

Figure 25: Mixed traffic scenario.

Table 7 shows cell capacity in different traffic scenarios when meeting the GoS of 1%. For pure voice traffic, cell capacity in multihop schemes is much greater than single-hop schemes. Results also imply that by introducing video traffic in system, single-hop schemes are not able to meet the GoS of 1% any more due to high call blocking probability of high data rate video services as shown in Figure 24 and Figure 25.

Table 7: Cell capacity (Erlangs) of different traffic scenarios at GoS of 1%.

Grade of Service (GoS)	Scheme	100% voice 0% video	75% voice 25% video	50% voice 50% video	25% voice 75% video	0% voice 100% video
0.25* P_b + 0.75* P_d	FTSA	1.4	0	0	0	0
	DTSA	1.4	0	0	0	0
	mFTSA	5	1.4	1.2	1.4	1.6
	mDTSA	5.2	1.5	1.2	1.5	1.6
0.5* P_b + 0.5* P_d	FTSA	1.6	0	0	0	0
	DTSA	1.6	0	0	0	0
	mFTSA	5.4	1.6	1.6	1.6	1.6
	mDTSA	5.6	1.7	1.6	1.6	1.7
0.75* P_b + 0.25* P_d	FTSA	2.6	0	0	0	0
	DTSA	2.6	0	0	0	0
	mFTSA	6.3	2.4	2.4	1.9	1.8
	mDTSA	6.7	2.5	2.4	2	1.9

Even though the capacity in mDTSA is not significantly higher than mFTSA, it is still preferable to be used. This is because in mFTSA the number of time slots in each group is fixed and thus, performance may highly depend on the system parameters such as number of time slots in each group, traffic type, and channel conditions. However, mDTSA is flexibly using the time slot independent of any of these factors. So, it can dynamically adapt to the changes in these parameters.

Distribution of P_b and P_d for video and voice traffic in mixed traffic scenario is plotted in Figure 26. As shown in the figure, the majority of blocked calls in FTSA and DTSA in mixed traffic scenario are video calls. Since mFTSA and mDTSA schemes can provide shorter communication links with higher link quality to support higher data rate, these schemes can accommodate more video calls. By increasing the number of accepted voice and video calls in mFTSA and mDTSA, inter-cell and intra-cell interferences increase which result in higher dropping probability for voice and video calls.

Figure 26: Call blocking & dropping probability distribution of mixed traffic at 8 Erlangs/cell.

4.4 Conclusions

In this section we compared performance of multihop and conventional single-hop time slot allocation schemes in supporting different types of multimedia traffic. We proposed two time slot allocation schemes for TDD-CDMA MCNs. mFTSA separates the TSs reserved for uplink, downlink and relaying link using two fixed switching points, while mDTSA searches the whole frame by following a specific routine to find free time slots for each link. Simulations were conducted for three different traffic scenarios. Results show that our proposed multihop schemes can satisfy QoS requirements of high-speed multimedia services and therefore, blocking probability of generated calls significantly reduces regardless of the traffic scenario. Moreover, it is implied from the results that mDTSA outperforms all other three time slot allocation schemes in supporting asymmetric multimedia traffic.

Chapter 5

Performance of Multiple-link Time Slot Allocation Schemes

5.1 Introduction

Two multihop time slot allocation schemes, namely multihop fixed time slot allocation (MFTSA) and multihop dynamic time slot allocation (MDTSA), were proposed in chapter 4 that could support more than one MS in each TS. In MFTSA two *fixed* switching points are used to reserve the TSs for three types of transmission links. The first group of TSs is reserved for MS uplink transmissions; MS-to-BS and MS-to-RS. The second group of TSs is reserved for RS uplink transmission, RS-to-BS, and the last group of TSs is reserved for direct BS downlink transmission, BS-to-MS. In MDTSA schemes the switching points were removed, however, only one type of link could be assigned to each TS. Dedicating the TSs to specific links reduces the flexibility in selecting TSs. Besides, the proposed schemes in Chapter 4 did not support multihop transmission in downlink. In fact, not deploying multihop transmission in downlink, results in high call dropping probability in these schemes (shown in Section 5.4).

In this chapter we investigate performance of two other multihop schemes in supporting different multimedia services and traffic requests. In the first scheme we

reduce the number of switching points to one switching point which separates uplink and downlink TSs and redefine the time slot selection algorithm. This algorithm is able to intelligently select different time slots for uplink and downlink of a specific RS in order to avoid self interference. In this scheme we employ data relaying for both uplink and downlink. Using this scheme, uplink TSs can support any MS-to-RS, RS-to-BS or MS-to-BS link only if the TS is not assigned to both uplink and downlink of a transceiver. Similarly, any BS-to-MS, BS-to-RS or RS-to-MS link can be assigned to downlink TSs under the same condition. To further increase the flexibility and adaptability of the resource allocation algorithm, in the second multihop scheme we remove the switching point. So, any TS is able to accept any of the six link types, unless the rule of sending and receiving at the same time in one transceiver is broken [42]. This algorithm results in allocating *crossed-links* to one TS. For example, one MS-to-BS link, which is an uplink, and one RS-to-MS, which is a downlink, can be assigned to one TS in a frame. This feature distinguishes this scheme from all previous similar works in literature that separate uplink and downlink TSs.

5.2 System Model

The system environment configuration used in this chapter such as frame structure, cell structure and arrangement of the cells are the same as Chapter 4. The system consists of 19 cells that are arranged in two tiers and each cell has six fixed relay stations. The descriptions presented in previous chapter for signal measurement (referring to Section 4.2.1) and call admission process (referring to Section 4.2.5) are also applicable to the schemes of this chapter. In general, the same simulation

environment is used to study performance of the schemes presented in chapter 4 and 5. The only difference is in the traffic model. Three classes of traffic requests are assumed here in various traffic scenarios. Details of the traffic requests are presented in Table 8 [40,43].

Table 8: Details of traffic classes

Service	UL Data Rate	DL Data Rate	Target E_b/N_0	Duty Factor (α)	Ave Holding Time
Class A (High Quality Voice)	16 kbps	32 kbps	5.0 dB	0.4	120 sec
Class B (Facsimile)	32 kbps	64 kbps	7.0 dB	1.0	120sec
Class C (Low Quality Video)	64 kbps	128 kbps	7.0 dB	1.0	120sec

5.3 Description of Time Slot Allocation Schemes

5.3.1 Single-hop Time Slot Allocation Schemes

The selected single-hop conventional time slot allocation schemes for this study are fixed time slot allocation scheme (FTSA) and dynamic time slot allocation scheme (DTSA). These two schemes are explained in details in Section 4.2.3. We use these two schemes as benchmark to evaluate performance of our proposed multihop schemes.

5.3.2 Multihop Time Slot Allocation Schemes

In this section we propose two multihop time slot allocation schemes used for TDD-CDMA MCNs. The first scheme is based on fixed switching point while the second one does not have any switching point.

In our model, multihop schemes employ two-hop relaying for MSs with distance greater than R_{relay} from BS by relaying their data through the nearest relay station (RS). To design a system that can support multihop relaying, we should consider that two diverse channels are required at RS for receiving and transmitting data. Since RSs receive data from MS and transmit the relayed data to BS, self-interference will occur if transmission and reception take place at the same time and on the same frequency. Since TDD-CDMA systems use the same frequency bandwidth for both uplink and downlink, one solution to separate uplink and downlink transmission of a transceiver is using different TSs.

A. Multi-link Fixed Time Slot Allocation (ML-FTSA)

In order to increase TS utilization, we propose multi-link fixed time slot allocation (ML-FTSA) scheme which has only one switching point and supports downlink multihop transmission. The switching point is fixed between TS 7 and TS 8 in every cell, as shown in Figure 28, to divide a frame into two groups. One group of TSs is reserved to support all types of uplink connections; MS-to-BS, MS-to-RS and RS-to-BS, and the other group of TSs is reserved for all types of downlink connections; BS-to-MS, BS-to-RS and RS-to-MS. Hence, any uplink (downlink) transmission from MS or RS (BS or RS) can be assigned to one of the first 7 TSs (last 8 TSs). This results in more selection options for each link. However, one problem in our ML-FTSA is the self-interference at RS in a given TS. Since one TS is allowed to support any one of the three uplink connections or any one of the three downlink connections, uplink and downlink of a given RS might be assigned to one TS. To solve the self-interference

problem at RS, a RS is not allowed to transmit and receive data in a given TS simultaneously. Thus, the TS selection algorithm should select a TS which is not assigned to links that cause confliction. Figure 27 shows the possible links that conflict with the connection links. For example, in Figure 27-a, when RS_i establishes a RS-to-BS link, RS_i should not select a TS which is already assigned to a conflicting link such as MS-to- RS_i . In other words, RS_i should not select a TS in which RS_i is currently receiving data from other MSs. Table 9 shows the conflicting links for each connection link in ML-FTSA. Note that even though a RS_i -to-BS connection link is not supported in a TS which already supports a MS-to- RS_i conflicting link, all other links such as MS-to-BS link can be accepted in this TS (Refer to Figure 27). It should be also noted that there are no conflicting links for MS-to-BS or BS-to-MS connection links. Since the frame in ML-FTSA is divided into two groups to support uplink and downlink separately, self-interference never occurs at the BS.

Figure 27: The figure shows the links which conflict with a) UL RS-to-BS, b) UL MS-to-RS, c) DL BS-to-RS and d) DL RS-to-MS in one TS using ML-FTSA

Table 9: Conflicting and accepted links in ML-FTSA in one TS. RS_i represents a specific relay station

Schemes	Link	Connection Link	Conflict Links
ML-FTSA	Uplink	MS-to-BS	-
		RS_i -to-BS (Refer to Figure 27a)	MS-to- RS_i
		MS-to- RS_i (Refer to Figure 27b)	RS_i -to-BS
	Downlink	BS-to-MS	-
		BS-to- RS_i (Refer to Figure 27c)	RS_i -to-MS
		RS_i -to-MS (Refer to Figure 27d)	BS-to- RS_i

The procedure of selecting a TS for ML-FTSA is described as follows:

- For a new 1-hop call, a 1-hop MS, MS_a , will first establish an uplink MS-to-BS connection link to BS. Then, it will search for an uplink TS to support the uplink MS-to-BS connection starting from TS 1. TS 1 will first go through the call admission process. If the call admission process succeeds for MS_a in TS 1, TS 1 is selected for uplink MS-to-BS connection. Otherwise, the algorithm continues to test the next TS until TS 7 is reached. If call admission process does not succeed in any TS between TS 1 and TS 7, the new call will be **blocked**. After selecting uplink TS, the algorithm searches for a TS between TS 8 and TS 15 for downlink BS-to-MS connection. The search for downlink TS starts from TS 15 and goes on until TS 8 is tested. Similarly, if call admission process does not succeed in any TS between TS 8 and TS 15, the new call will be **blocked**. A 1-hop call is accepted if TS allocations for both uplink and downlink are successful.
- For a new two-hop call, a two-hop MS, MS_b , will first look for the nearest RS, RS_i , for multihop transmission.

- Then, it will establish the uplink MS-to- RS_i connection. Starting from TS 1, MS_b will search for a *conflict-free* TS, TS y , which does not have a conflicting link related to RS_i . It means that MS_b should make sure that RS_i is not transmitting any messages to the BS using TS y . Then, the selected *conflict-free* TS, TS y , will go through the call admission process. If the call admission process succeeds for MS_b in TS y , TS y is selected for uplink MS-to- RS connection. Otherwise, the algorithm continues to test the next TS, TS $y+1$, until TS 7 is reached. If call admission process does not succeed for any TS between TS 1 and TS 7, the new call will be **blocked**.
- After selecting a TS for uplink MS-to- RS connection, the uplink RS -to-BS connection will be established. Starting from TS 1, RS_i searches for a *conflict-free* TS, TS z , which is not already assigned to a conflicting link used by RS_i . It means that the algorithm has to make sure RS_i is not receiving any messages from other 2-hop MSs. Then, the selected *conflict-free* TS, TS z , will go through the call admission process. If the call admission process succeeds for RS_i in TS z , TS z is selected for uplink RS -to-BS connection. Otherwise, the algorithm continues to test the next TS, TS $z+1$, until TS 7 is reached. If call admission process does not succeed in any TS between TS 1 and TS 7, the new call will be **blocked**.
- After establishing a successful uplink connection for MS_b , the downlink connections, BS-to- RS and RS -to- MS links, will be

established through RS_i for MS_b . Similar to the uplink connection establishment described above, starting from TS 15, it will search for a *conflict-free* TS for each link based on Table 9. Then, the *conflict-free* TS will go through the call admission process. If call admission process fails in all available TSs between TS 8 and TS 15 for any one of the two links, BS-to-RS link or RS-to-MS link, the new call will be **blocked**.

A 2-hop call is accepted if TS allocations for uplinks, MS-to-RS and RS-to-BS links, and downlinks, BS-to-RS and RS-to-MS links, are successful. An example of time slot allocation for ML-FTSA is shown in Figure 28. It can be seen that each TS can support two links, direct link and relay link. For example, in TS 2, it can support the direct link, MS-to-BS, and the relay link, MS-to-RS (or RS-to-BS). As shown in Figure 28, each TS can support more than one link.

Figure 28: An example of time slot allocation using ML-FTSA scheme. The separated colored areas in each TS indicate the codes utilized by a given user. The Figure shows that one TS can be allocated to several users. A switching point separates UL and DL time slots.

B. Multi-link Dynamic Time Slot Allocation Scheme (ML-DTSA)

Here, we propose a Multi-link Dynamic Time Slot Allocation scheme (ML-DTSA) to further increase TS selection options for each link by removing the switching point.

Thus, different from ML-FTSA, no TS is reserved for uplink or downlink in ML-DTSA. Besides, ML-DTSA accepts uplink transmissions (MS-to-BS, MS-to-RS and RS-to-BS) and downlink transmissions (BS-to-MS, BS-to-RS and RS-to-MS) simultaneously in one TS in a given cell as long as the TS has enough free codes to support the requested MSs' data rates. This feature makes ML-DTSA quite different from all previous schemes in literature in which uplink and downlink transmissions are not allowed to be accepted in the same TS in one cell. As a result of this strategy, we can fully utilize the available resources to accept more users.

In ML-FTSA, since uplink and downlink transmissions are separated into two groups, they will not cause self-interference at BS in any TS. However, in ML-DTSA, uplink and downlink connections of BS are accepted in any TS. Thus, we need to consider the self-interference problem at BS as well as RS, so that we make sure BS is not transmitting and receiving messages in one TS. Figure 29 shows the possible conflicting links for a given connection link. For example, in Figure 29-a, the conflicting links for MS-to-BS connection link are BS-to-RS and BS-to-MS because BS is not allowed to transmit and receive at the same time in one TS. For RS-to-BS connection link at RS_i in Figure 29-b, the selected TS should not have the conflicting links, BS-to-RS and MS-to-RS, at RS_i and BS-to-MS at BS. Table 10 shows the possible conflicting links for each connection link in ML-DTSA. As we mentioned, ML-DTSA supports multiple links and allows uplink and downlink connections in one TS. Referring to Figure 29-a for the case of MS-to-BS connection link, one TS can support 3 links: uplink MS-to-BS, uplink RS-to-BS and downlink RS-to-MS.

Figure 29: The figure shows the links which conflict with a) UL MS-to-BS, b) UL RS-to-BS, c) UL MS-to-RS, d) DL BS-to-MS, e) DL BS-to-RS and f) DL RS-to-MS in one TS using ML-DTSA.

Table 10: Conflicting and accepted links in ML-DTSA in one TS. RS_i represents a specific relay station and RS represents all relay stations.

Schemes	Link	Connection Link	Conflict Links
ML-DTSA	Uplink	MS-to-BS (Refer to Figure 29a)	BS-to-MS BS-to-RS
		RS_i -to-BS (Refer to Figure 29b)	BS-to-MS BS-to-RS MS-to- RS_i
		MS-to- RS_i (Refer to Figure 29c)	RS_i -to-MS RS_i -to-BS
	Downlink	BS-to-MS (Refer to Figure 29d)	RS-to-BS MS-to-BS
		BS-to- RS_i (Refer to Figure 29e)	RS-to-BS RS_i -to-MS MS-to-BS
		RS_i -to-MS (Refer to Figure 29f)	BS-to- RS_i MS-to- RS_i

TS selection for ML-DTSA is described as follows:

- For a new 1-hop call, a 1-hop MS, MS_a , first establishes an uplink MS-to-BS connection link at the BS. It will search for a *conflict-free* TS starting from TS 1. The *conflict-free* TS in this case is a TS that does not contain the conflicting links, BS-to-RS and BS-to-MS, at the BS (Refer to Table 10). Similar to ML-FTSA, the selected *conflict-free* TS, TS x , will go through the call admission process. If the call admission process succeeds, TS x will be selected for uplink MS-to-BS connection. Otherwise, the algorithm continues to test the next TS, TS $x+1$, until TS 15. If call admission process does not succeed in any TS, the new call will be **blocked**. After selecting uplink TS, the algorithm searches for a *conflict-free* TS to support the downlink BS-to-MS connection. The search for such TS starts from TS 15 in frame and goes on until TS 1. Referring to Table 10, the conflicting links for BS-to-MS connection are RS-to-BS and MS-to-BS at the BS. Similarly, if call admission process does not succeed in any TS, the new call will be **blocked**. A 1-hop call is accepted if TS allocations for both uplink and downlink are successful.
- For a new two-hop call, a two-hop MS, MS_b , will first look for the nearest RS, RS_i , for multihop transmission.
 - Then, it will establish the uplink MS-to-RS connection. Starting from TS 1, MS_b will search for a *conflict-free* TS, TS y , which is not already assigned to conflicting links, RS-to-MS and RS-to-BS, at RS_i (Refer to Table 10). If the selected *conflict-free* TS, TS y , passes the call admission process, TS y will be selected for uplink MS-to-RS

connection. Otherwise, the algorithm continues to search for the next TS until TS 15. If call admission process does not succeed in any available TS, the new call will be **blocked**.

- After selecting a TS for uplink MS-to-RS connection, the uplink RS-to-BS connection will be established. Starting from TS 1, RS_i will search for a *conflict-free* TS, TS z , which is not already assigned to the conflicting links, MS-to-RS and BS-to-RS at RS_i , and BS-to-MS at the BS (Refer to Table 10). If the selected *conflict-free* TS, TS z , passes the call admission process, TS z will be selected for uplink RS-to-BS connection. Otherwise, the algorithm continues to test the next TS until TS 15. If call admission process does not succeed in any available TS, the new call will be **blocked**.
- After successful allocation of uplink connection for MS_b , the downlink connections, BS-to-RS and RS-to-MS links, will be established for MS_b . Similar to the uplink connection establishment described above, starting from TS 15, it will search for a *conflict-free* TS for each link based on Table 10. After selecting a *conflict-free* TS, MS_b will go through the call admission process. If call admission process fails in all available TSs for any one of the two links, BS-to-RS or RS-to-MS links, the new call will be **blocked**.

A 2-hop call is accepted if TS allocations for uplinks, MS-to-RS and RS-to-BS links, and downlinks, BS-to-RS and RS-to-MS links, are successful. An example of time slot

allocation for ML-DTSA is shown in Figure 30. It can be seen that a TS can accept both uplink and downlink transmissions.

Figure 30: An example of time slot allocation using ML-DTSA scheme. The separated colored areas in each TS indicate the codes utilized by a given user. The Figure shows that one TS can be allocated to several users. No switching point is defined in this scheme.

5.4 Simulation Results and Discussions

To compare performance of conventional single-hop schemes with the proposed multihop schemes, we have simulated FTSA, DTSA, ML-FTSA and ML-DTSA algorithms using a C++ program. The simulated area consists of 19 cells which are organized in two tiers. New calls are generated using the Poisson Process and are randomly assigned to one of the 19 hexagonal cells. The call duration is exponentially distributed. Results are collected from the central seven cells. Performance of each scheme is measured in terms of call blocking probability, P_b , and call dropping probability, P_d . Table 11 shows the simulation parameters. In our simulations, we compare performance of the schemes in supporting three classes of traffic requests in different scenarios.

Table 11: Simulation Parameters

Number of cells	19
Cell Radius, R	1 km
R_{relay}	$0.45R$
Max. MS/RS Power, P_{MS}/P_{RS}	20 dBm
Max. BS/ Power, P_{BS}	43 dBm
Pathloss Exponent, l	3.25
Pathloss Constant, k	137 dB
Background Noise, η	-103 dBm
Log-normal Shadowing	Mean: 0dB σ : 4 dB, 8 dB

The desired accuracy for our simulation results is set to be 10^{-6} . The simulation was repeated with 5 different seed values for random generator algorithm. For all simulation results, the 95% confidence intervals within $\pm 5\%$ of the average values are observed. The confidence intervals calculated for ML-FTSA and ML-DTSA schemes in three traffic scenarios and two different traffic loads are presented in Table 12.

Table 12: Calculated confidence intervals for ML-FTSA and ML-DTSA schemes

TS Allocation Scheme	Traffic Load (Erlang)	Blocking / Dropping Probability	Traffic Scenario		
			Class A	Class B	Mixed
ML-FTSA	2	P_b	0.00059 ± 0.000191	0.01408 ± 0.001896	0.007478 ± 0.000387
		P_d	0.000547 ± 0.000114	0.035307 ± 0.004121	0.012932 ± 0.001022
	4	P_b	0.00072 ± 0.00015	0.050717 ± 0.003284	0.008486 ± 0.000706
		P_d	0.001905 ± 0.000136	0.062438 ± 0.002724	0.029262 ± 0.002318
ML-DTSA	2	P_b	0.000534 ± 0.000332	0.013158 ± 0.000463	0.006426 ± 0.000823
		P_d	0.000409 ± 0.000109	0.028243 ± 0.002164	0.00776 ± 0.000828
	4	P_b	0.000662 ± 0.000316	0.013988 ± 0.000773	0.007381 ± 0.000454
		P_d	0.000784 ± 0.000387	0.053843 ± 0.007757	0.01569 ± 0.005708

In previous chapter, two time slot allocation schemes were proposed for TDD-CDMA MCNs. However, they do not support multihop transmission in downlink. As shown

in Table 13, the results showed that using multihop relaying only in uplink, as in Chapter 4, can significantly decrease P_b . However, P_d was still high. The reason was that due to high P_{BS} , most of downlink connections could pass the call admission process to set a call during the call set-up phase. However, many of them were dropped due to high inter-cell and intra-cell interference during the call connection. Thus, we proposed multihop schemes, ML-FTSA and ML-DTSA, to employ multihop relaying for both uplink and downlink connections and increase the number of supported calls. As shown in Table 13, our proposed multihop schemes can substantially reduce the P_d .

Table 13: Blocking and dropping probabilities for different time slot allocation schemes. Cell radius=1 km and $\sigma = 4$ dB.

Scheme	P_b	P_d	P_d of uplink	P_d of downlink
FTSA	0.111	0.035	0.018	0.017
DTSA	0.111	0.029	0.017	0.012
MFTSA	0.0004	0.046	0.006	0.040
ML-FTSA	0.005	0.011	0.008	0.003
ML-DTSA	0.005	0.007	0.003	0.004

Figure 31 shows P_b and P_d of the four schemes for pure Class A traffic with $R = 1$ km and $\delta=4$ dB. The P_b for all four schemes does not change much with traffic load, ρ , in terms of Erlang/Cell because the numbers of dropped calls increase as ρ increases. Therefore, more resources are available for new calls as ρ increases. As a result, the number of blocked calls remains more or less constant.

Figure 31: Comparison of time slot allocation schemes in class A traffic scenario. Cell radius = 1 km and $\sigma = 4$ dB.

The results show that multihop schemes perform significantly better than single-hop schemes in both P_b and P_d . As we expected, breaking a long connection path into two shorter links in multihop schemes reduces the transmission power and thus, it allows more accepted calls to communicate with BS with transmission power $< P_{MS}$. Since the links are shorter in multihop transmission, they can provide a better signal quality to avoid call dropping during call connection. The P_b for both multihop schemes is about the same because the traffic loads are moderate for multihop schemes for the ranges of ρ shown in Figure 31. A new call is blocked mainly due to insufficient resources or TSs. If the traffic load is not high, new calls can be easily accepted. Thus, ML-FTSA

has enough resources to support new calls and has about the same P_b as in ML-DTSA. In low traffic loads that MSs are not blocked due to lack of resources, they are mainly blocked because they cannot meet their desired E_b/N_0 requirements even with the maximum allowable transmission power. Multihop schemes establish shorter links that require less transmission power and therefore, MSs can meet the target E_b/N_0 . MSs that are far from the BS receive weak signals and are mostly blocked. This is the reason that a certain percentage of calls are blocked and the P_b remains constant for different traffic loads. For low traffic load, $\rho < 1.5$ Erlangs, ML-FTSA has lower P_d than ML-DTSA. An on-going call is dropped mainly due to an increase in inter-cell interference from a new accepted call. For low traffic load, both ML-FTSA and ML-DTSA have enough resources to support calls. ML-FSTA will not create cross-time slot (CTS) interference because of the fixed switching point with the same position in every cell. So, the on-going calls will not be easily dropped due to high inter-cell interference from a new accepted call. On the contrary, ML-DTSA will create CTS interference among cells due to its flexible use of TS and thus, an ongoing call can be easily dropped due to high inter-cell interference of neighboring cells caused by a new accepted call. However, for high traffic load, $\rho > 1.5$ Erlangs, ML-DTSA outperforms ML-FTSA. Since Class A traffic is asymmetric, more downlink resources are required. For higher ρ , ML-FTSA does not have enough resources to support downlink traffic, and thus more on-going calls are dropped. But, ML-DTSA can allocate more resources to downlink thanks to its flexibility in using TSs.

Figure 32 compares the simulation results for Class B traffic scenario. Similar to the previous results, the P_b does not change with ρ by much, except that P_b for ML-FTSA

increases sharply for high traffic load, $\rho > 2$ Erlangs. As mentioned in Figure 31, the P_b for both ML-FTSA and ML-DTSA is about the same for Class A traffic. In Figure 32, the P_b for ML-FTSA is higher than ML-DTSA for $\rho > 2$ Erlangs. As we know, Class B traffic requires higher downlink data rate compared to Class A traffic. For $\rho > 2$ Erlangs, Class B generates higher downlink traffic and thus, more downlink resources are required compared to Figure 31. Since the number of TSs for downlink in ML-FTSA is fixed, the number of blocked calls increases significantly when the traffic is high, $\rho > 2$. Again, the results show that multihop schemes have lower P_b and P_d compared to single-hop schemes.

Figure 32: Comparison of time slot allocation schemes in Class B traffic scenario. Cell radius = 1km and $\sigma=4$ dB.

In addition, this figure shows that the P_d of ML-DTSA is lower than that of ML-FTSA. Since Class B traffic is asymmetric and requires higher downlink data rate compared to uplink, more downlink TSs are needed to support incoming calls. However, in ML-FTSA, the number of uplink and downlink TSs are fixed. Thus, the number of available resources are limited for downlink and more calls will be dropped. On the contrary, due to flexible TS allocation in ML-DTSA, more TSs can be assigned to downlink traffic and more calls are supported.

Simulation results for Class C traffic scenario are presented in Figure 33. As the results show, multihop schemes, ML-FTSA and ML-DTSA, improve performance of system in supporting high data rate services.

Figure 33: Comparison of time slot allocation schemes in Class C traffic scenario. Cell radius = 1km and $\sigma=4$ dB.

Although the call dropping probability does not reduce, the probability of blocking a high data rate call reduces significantly when these two multihop schemes are employed in system. The reason is that data relaying provides high quality channels for MSs that are far from BS and increases the coverage area for high bit rate services.

Simulation results for the traffic scenario in which both Class A and Class B traffic requests are generated with the equal probability, are shown in Figure 34.

Figure 34: Comparison of time slot allocation schemes in mixed traffic scenario. Cell radius = 1km and $\sigma=4$ dB.

It can be seen from the results that as expected, multi-hop schemes result in higher capacity compared to conventional single-hop schemes and show better performance in supporting asymmetric and unbalanced traffic. Also, in this traffic scenario,

MLDTSA performs slightly better than MLFTSA scheme in terms of call dropping and call blocking probabilities.

Table 14 and Table 15 show the system capacity at GoS of 1% for all four schemes in mixed traffic scenario. Here, we assume that P_b and P_d are of equal importance. The GoS is given by:

$$\text{GoS} = 0.5 \times P_b + 0.5 \times P_d \quad (4)$$

Table 14 shows the results for $\sigma = 4$ dB with different R . As shown in this table, mutihop schemes provide significantly higher capacity compared to single-hop schemes in smaller cells ($R = 500\text{m}$). For $R = 1\text{km}$, ML-DTSA scheme still performs better than ML-FTSA while single-hop schemes cannot even meet the GoS of 1%. Since signals travel long distances in large cells for single-hop schemes, it is difficult to maintain the signal quality at target E_b/N_0 and therefore, P_b and P_d are high. With even larger cells ($R = 2$ km), none of the schemes can reach the required GoS. We believe that in such large cells more than one relay station or two hops are needed for MSs located far from BS in order to have GoS of 1%. Nevertheless, it should be noted that more resources will be assigned to links with more hops.

Table 14: Scheme capacity (Erlang/cell) at GoS = 1% for different cell sizes. $\sigma=4$ dB.

Scheme	500m	1km	2km
FTSA	0.9	0	0
DTSA	1.1	0	0
MLFTSA	4.2	2.0	0
MLDTSA	6.2	3.4	0

Table 15 shows the impact of σ on system performance. Although higher σ ($\sigma = 8\text{dB}$) results in lower capacity in all time slot allocation schemes, ML-DTSA scheme still outperforms other schemes in small cells. In this condition none of the schemes are able to meet the specified GoS in medium and large cells.

Table 15: Scheme capacity (Erlang/cell) at GoS = 1% for different cell sizes. $\sigma=8$ dB.

Scheme	500m	1km	2km
FTSA	0.1	0	0
DTSA	0.2	0	0
MLFTSA	0.6	0	0
MLDTSA	0.8	0	0

5.5 Conclusions

In this chapter we compared performance of two conventional single-hop schemes, FTSA and DTSA, with our proposed schemes, ML-FTSA and ML-DTSA, for multihop cellular networks. In our proposed multihop schemes we allow each time slot to support several links of various types as long a transceiver does not send and receive data at the same time. In addition, the main feature of ML-DTSA is that it allows allocating one time slot to both uplink and downlink connections. Thus, we can have simultaneous uplink and downlink transmissions within a cell.

We have studied and compared the performance of these schemes using three traffic scenarios; low-data rate traffic, high-data rate traffic and mixed traffic. The results show that in every traffic scenario multihop schemes significantly reduce call dropping and call blocking probabilities and hence, increase system capacity. The results also indicate that our proposed ML-DTSA scheme can further improve

performance of system in supporting asymmetric and unbalanced service requests in multihop cellular networks.

Chapter 6

Energy Consumption in Multihop Cellular Networks

6.1 Introduction

In multihop cellular networks, a direct path between mobile station and base station is divided into several shorter links. Shorter links are able to provide better channel quality and as a result, establishing multihop paths improves the service quality in two ways. First, signal attenuation due to path loss becomes smaller as the distance between transmitter and receiver decreases. Secondly, transmission power reduces in shorter links and therefore, less interference is generated in cell. Reducing the interference in CDMA systems has great impact on increasing the capacity of system which results in supporting more users. Kudoh and Adachi in [13] show that total transmission power is lower in multihop systems compared to conventional systems. They also show that as the propagation loss exponent or the shadowing loss standard deviation increases, reduction in total transmission power is more significant. Results of their studies indicate that total transmit power of multihop systems normalized by that of single-hop systems decreases as the number of hops increase in a multihop link. However, for links with more than maximum 5 hops, this value remains almost the same regardless of environment parameters such as path loss exponent and shadowing loss standard deviation. Thus, the maximum number of allowable hops can

be set to 5 in order to avoid large delays. An analysis on consumed energy per bit in multihop cellular systems is presented in [16]. Their results show that multihop data relaying has great impact on reducing the average consumed energy for data transmission per call and the impact is more significant in systems that employ power control. Moreover, impact of path loss model is studied in the paper which indicates that multihop relaying is more effective in environments with higher path loss. They also show that reduction in energy consumption of cellular systems depends on the type of hardware which is used in the system and the amount of energy they consume.

But, why would MSs volunteer to relay data of other MSs? Generally, cooperation between different units happens when all units use their resources to reach a common goal. In cellular systems each MS struggles for achieving the best service individually. Thus, their selfish behavior does not allow them to sacrifice their resources for other users. Relaying data of other users is energy-consuming and reduces the battery life of relay station. Some mechanisms should be employed to create forwarding incentive among RSs in multihop cellular systems. Several rewarding schemes bases on the consumed energy and bandwidth of RSs have been proposed [44,45]. In order to apply the rewarding schemes we should be able to measure the amount of consumed energy in such systems.

In this chapter, a model is defined to measure and compare energy consumption of single-hop and multihop time slot allocation schemes for TDD-CDMA cellular networks. We study the impact of multihop data relaying on reducing energy

consumption and increasing battery life of mobile devices. Unlike previous studies [13, 15, 16] which only focus on propagation model and parameters such as path loss and shadowing fading, here we study a comprehensive system in practical conditions considering the inter-cell and intra-cell interferences as well as various service data rates. This model measures the energy used for data transmission in environments with path loss and shadow fading in addition to the energy consumed by hardware.

6.2 System Specifications

6.2.1 Effect of Multihop Links on Reducing Transmission Power

In this section we show that why establishing multihop links result in lower transmission power of each node (MS or RS) in that link. To study the worst case, we assume that maximum of two hops are allowed in each multihop link. As shown previously in Figure 10, six fixed relay stations are deployed in each cell in our system. Transmission power, P_t , of a transmitter is proportional to its distance from receiver. Thus, for a transmitter, MS1, as shown in Figure 35, the transmission power for MS-to-BS link in single-hop scenario is given by

$$P_t = P_{rec} d^l \quad (5)$$

where P_t is transmission power of transmitter (MS), P_{rec} is the received power at receiver (BS) and l is the path loss exponent.

Figure 35: Two-hop data relaying in cellular network

In two-hop scenario, the lowest total transmission power per route is obtained when BS, RS and MS are in one line, since distance between MS and RS and the distance between RS and BS are the shortest compared to other cases. When all three nodes are in one line, assuming that MS1 has distance d from BS, the total transmission power is given by

$$P_{\min} = P_{\text{rec}} \left((d - R_{\text{relay}})^l + R_{\text{relay}}^l \right) \quad (6)$$

where R_{relay} is the distance between RS and BS.

The largest total transmission power in two-hop scenario is obtained when RS is at the intersection point of coverage area for MS and the coverage area of BS with radius= R_{relay} [15] because in this situation MS-RS and RS-BS links have the longest distances. This case is illustrated in Figure 35 for MS2. Hence, the largest power is given by

$$P_{\max} = P_{\text{rec}} (R_{\text{relay}}^l + R_{\text{MS}}^l) \quad (7)$$

By applying parameter values of our simulated systems, we calculate P_t , P_{max} and P_{min} .

We assume that MS1 and MS2 are located at the cell boundary and have the longest distance from BS, $d=R=1$ km, $R_{relay}=0.45 * R=0.45$ km and $l=3.25$.

$$P_t = P_{rec}$$

$$P_{max} = 0.321 * P_{rec}$$

$$P_{min} = 0.217 * P_{rec}$$

As the calculations show, transmission power is reduced by using two-hop data relaying in the worst case scenario compared to single-hop direct transmission. More details on this study are presented in [15].

6.2.2 Energy Consumption Model

To compare performance of different TDD-CDMA time slot allocation schemes in terms of energy consumption, we define a model and employ this model in our previous simulation environment to study the single-hop and multihop schemes in two traffic scenarios. In order to measure the amount of energy which is consumed in each MS or RS during a call in our simulation, we use the following equation:

$$E = (P_T + P_H) * T \quad (1)$$

where P_T is the transmission power of transmitter which changes from frame to frame during a call to provide the desired SIR at the receiver, P_H is the constant power which is used by electronic devices in hardware for signal processing and data transmission and T is the transmission time. In TDD-CDMA systems, data is not transmitted

continuously. Transmitters are allowed to transmit during certain time slots. Hence, the transmission time, T , is given by

$$T = \frac{\Delta t}{t_{frame}} * t_{slot} \quad (2)$$

where Δt is call duration, $t_{frame}=10$ (ms) is frame duration in TDD-CDMA systems and $t_{slot}=10 \text{ ms} / 15 = 6.7 * 10^{-4} \text{ s}$ is duration of a time slot.

6.2.3 Time Slot Allocation Schemes

The energy consumption model is applied to two single-hop time slot allocation schemes, FTSA and DTSA, and two multihop schemes, ML-FTSA and ML-DTSA. For single-hop schemes we measure the average amount of energy which is consumed in a MS for a completed call in uplink. A completed call is a call which is accepted in the cell i.e., it is assigned to TSs that can support the call, and is not dropped during the entire requested call duration. For multihop schemes, the average amount of energy which is consumed in MSs in 1-hop and 2-hop links is measured for completed calls in uplink. Using this measurement, we can see how much energy is saved in mobile devices when multihop schemes are deployed in cellular systems. We also measure the average total energy which is consumed per each 1-hop or 2-hop uplink for completed calls in multihop scenario. The four schemes, FTSA, DTSA, ML-FTSA and ML-DTSA, are described in details in Chapter 5.

6.2.4 Traffic Model

We investigate energy consumption of our proposed schemes in low data rate and high data rate traffic scenarios. Specifications of the two traffic classes are shown in Table 16.

In the first scenario we assume that only Class A traffic requests are generated in system and in the second scenario we only assume Class B traffic requests.

Table 16: Traffic classes

Service	UL Data Rate	DL Data Rate	Target E_b/N_0	Duty Factor (α)	Ave Holding Time
Class A	16 kbps	32 kbps	5.0 dB	0.4	120 sec
Class B	32 kbps	64 kbps	7.0 dB	1.0	120sec

6.3 Simulation Results and Discussions

The same system model which is described in Chapter 5 is used for this study. We assume a two-tier system with 19 cells. Six fixed relay stations are placed in each cell as shown in Figure 10 to relay the MS's data to BS whenever MS's distance from BS is more than R_{relay} . The maximum permissible transmission power of MS is 20 dBm. Each RS is able to support several MSs in one TS using different spreading codes. For each RS-to-MS or RS-to-BS link, the maximum transmission power of RS is also 20 dBm. The total transmission power of BS for all BS-to-RS or BS-to-MS links should not exceed 43 dBm in one TS. The cell radius, R , is 1 km and the results are gathered from central seven cells. Path loss exponent, ℓ , is 3.25 and the shadow fading standard deviation, σ , is 4 dB.

Two issues are investigated in the simulation results. The first issue is effect of multihop data relaying on energy consumption in mobile stations. We want to see if multihop schemes can save more energy for different types of traffic. The second issue is impact of hardware power consumption on the results for single-hop and multihop schemes. We want to see if hardware power consumption has a considerable impact on battery life of devices in system. Also, since more hardware is involved in multihop links compared to a single-hop link, we study that how this can affect the overall power consumption in system.

Table 17 shows the results for four schemes when hardware power consumption is not considered, $P_H = 0$. For single-hop schemes, the values show the average amount of energy (in mJ) which has been consumed for a completed call in MSs. For multihop schemes, we present three values. The first value shows the average consumed energy in MSs in 1-hop or 2-hop uplinks, the second value shows the average consumed energy in each node (MS in a 1-hop link, MS or RS in a 2-hop link) and the third value shows the average total consumed energy per each completed call.

As shown in Table 17, the results for energy consumption per MS are almost the same for single-hop schemes because MSs are uniformly distributed in cell and the average distance of MSs from BS is the same in both schemes. In higher traffic loads, system faces larger interference. Transmitters increase their transmission power to overcome the interference and thus, more energy is consumed in mobile devices. This happens in single-hop schemes for both low data rate and high data rate traffic.

In low data rate traffic the consumed energy is significantly reduced in multihop schemes, ML-FTSA and ML-DTSA, both per MS and per link. This is because these schemes establish shorter links that require less transmission power. The same trend can be noticed in various traffic loads. Even though higher traffic load leads to higher interference and less resources in system, establishing shorter links in a multihop path enables transmitters to maintain the connection with lower transmission power and therefore, the amount of consumed energy will reduce per link as well as in each individual node. Thus, more energy can be saved in MSs for low data rate traffic when multihop schemes are deployed in system. As the results in Table 16 show, the average consumed energy per node is higher than the average consumed energy per MS in multihop schemes. This is due to the fact that RSs have the fixed distance of R_{relay} from BS, but MSs have variable distances from receiver (RS or BS) which is less than R_{relay} in most of the cases. Thus, RSs consume more energy compared to MSs in 1-hop or 2-hop links.

In high data rate traffic scenario, multihop schemes consume less energy for completed calls compared to single-hop schemes in both per MS and per link cases when traffic load is low ($\rho = 0.5$ Erlang/cell). In low traffic load call blocking probability in multihop schemes is considerably lower compared to single-hop schemes as it is shown in Figure 36. This means that there are more active calls which result in higher interference. However, we can see that multihop schemes can manage to avoid increasing cell interference by keeping the transmission powers low. When

interference is low, transmitters do not need to use high transmission powers and as a result, less energy is consumed in transmitters. The low call dropping probability of multihop schemes in Figure 36 also implies that less interference is generated when multihop links are established because ongoing calls are mostly dropped due to high interference. In higher traffic load, $\rho = 2$ Erlang/cell, multihop schemes significantly reduce the amount of consumed energy per MS. However, the average total consumed energy per link is almost the same for single-hop and multihop schemes. This is due to the fact that in high traffic loads multihop schemes accept more users as indicated by low call blocking probability in Figure 36 and much more 1-hop and 2-hop links are established. Thus, the level of interference rises significantly and transmitters are forced to transmit with higher transmission powers to overcome the substantial amount of interference. So, more energy is consumed in both MSs and RSs and the total consumed energy of a multihop link increases. Nevertheless, it should be noted that even in this case multihop schemes are performing better than single-hop schemes because more calls are receiving service with the same amount of consumed energy. Since the required SIR of Class B traffic is higher than Class A traffic, more energy should be used by transmitters in order to maintain an on-going Class B call. Thus, the energy consumption reduction of multihop schemes for Class B traffic is not as much as it is for Class A traffic.

Traffic type	Traffic load (Erlang/cell)	FTSA	DTSA	ML-FTSA			ML-DTSA		
				Per MS	Per node	Per link	Per MS	Per node	Per link
Class A	2	204	201	26	44	79	21	42	74
	6	229	221	40	72	129	24	63	113

Class B	0.5	322	320	72	146	259	67	158	281
	2	347	336	116	200	354	81	174	308

Table 17: Consumed Energy (mJ) of four schemes with PH = 0

On the other hand, it should be noticed that although employing multihop schemes saves energy in MSs, the energy which is consumed in RSs should not be neglected. In our simulations we assume that RSs are fixed and have unlimited power resources. Thus, multihop schemes are beneficial to the system as they save energy in MSs and increase their battery life. However, in multihop systems which do not use fixed relay stations and employ other MSs to relay the data of a MS, it would be vital to find a proper solution to reward the RSs and encourage them to consume their energy for data relaying. As the results in Table 17 show, the amount of consumed energy per node in each multihop link is approximately 20% of the energy that is needed for a completed voice call in a single-hop link. This percentage very much depends on the type of traffic and the data rate. For the high data rate traffic, about 50% of the energy which is used for a direct call would be consumed in a MS if the MS participates in a multihop link as a RS.

Figure 36: Comparison of time slot allocation schemes in high-data rate traffic scenario. Cell radius=1km and $\sigma=4$ dB.

In order to give a more precise analysis on the energy consumption of different schemes, we should consider the energy which is used in hardware and electronic devices of transmitters for signal processing and data transmission. In [45] the value $P_H = 80$ (mW) is suggested for transmitters in cellular networks. Figure 37 shows the energy consumption results for $P_H = 80$ (mW) in low data rate traffic and compares them with results for $P_H = 0$.

Figure 37: Energy consumption for low data rate traffic scenario with a) $P_H = 0$ and b) $P_H = 80$ mW.

$\rho = 2$ Erlang/cell.

As the results show, in both cases multihop schemes are able to reduce the amount of consumed energy per MS. About 87% less energy is consumed in MSs by using multihop schemes when $P_H = 0$ and about 25% reduction in energy consumption is obtained when $P_H = 80$ (mW). However, by adding P_H to our measurement multihop

schemes are no longer able to perform better than single-hop schemes in terms of power consumption per link. This is due to the fact that each 2-hop link contains two transmitters and each transmitter consumes a constant amount of energy for hardware operation. The amount of energy which is saved by using shorter links in multihop scenario is not enough to overcome the extra constant energy which is consumed in additional hardware in 2-hop links.

Figure 38 shows the energy consumption results for Class B traffic scenario. Similarly, the results show that in high data rate scenario multihop schemes can save energy in MSs by establishing shorter links. The figure shows that about 62% less energy is consumed in MSs for Class B traffic in multihop scenario when $P_H = 0$, while 22% energy consumption reduction is obtained when $P_H = 80$ (mW). Considering $P_H = 80$ (mW), for a completed call with mean duration $T = 120$ (sec) the average amount of consumed energy in hardware for each node would be $E_H = 80mW * \frac{120s}{10ms} * 0.667ms = 643.2 mJ$ which is a considerable amount compared to the consumed energy for data transmission. The amount of saved energy in MSs cannot compensate for the extra energy consumed by additional hardware devices in multihop paths. Thus, the amount of consumed energy per link in multihop schemes is much higher than a direct link in single-hop schemes. This study shows that energy consumption of hardware has a great impact on total energy consumption of system and should not be neglected.

Figure 38: Energy consumption for high data rate traffic scenario with a) $P_H = 0$ and b) $P_H = 80$ mW. $\rho = 2$ Erlang/cell.

6.4 Conclusion

In this chapter energy consumption of time slot allocation schemes was investigated.

Two single-hop schemes, FTSA and DTSA, were compared with two proposed

multihop schemes, ML-FTSA and ML-DTSA. The study was conducted in a comprehensive simulation environment which consists of 19 hexagonal cells configured in two tiers. The simulation considers all inter-cell and intra-cell interferences in TDD-CDMA systems. For signal propagation loss we assume path loss fading and log-normal shadow fading. Performance of the schemes was investigated in two different traffic scenarios; high data rate traffic scenario and low data rate traffic scenario. A model was defined to measure the consumed energy in mobile devices. The results were used to study the impact of data relaying on reducing energy consumption and increasing battery life of mobile devices. The results show that employing multihop data relaying reduces energy consumption by establishing shorter links that require lower transmission powers. In addition to the power used for transmitting signals, we should consider the energy consumed in hardware devices for signal processing and operation of electronic parts. The effect of hardware energy consumption was also investigated on performance of schemes. As the results show, also in this case energy consumption is reduced in mobile devices in systems that employ multihop schemes compared to systems with single-hop schemes. However, total energy consumption per link is higher in multihop schemes because of the additional hardware. This should be taken into consideration in designing multihop systems that use mobile stations as relay stations instead of deploying fixed relay stations.

Chapter 7

Conclusion and Recommendations

7.1 Conclusion

In this Thesis we studied performance of time slot allocation schemes in TDD-CDMA cellular systems and investigated the effect of employing multi-hop data relaying in such systems. Maximum capacity of these schemes was compared. To measure the maximum capacity, it was assumed that each TS can support only one user and the user was assigned to a TS with the highest available data rate. Results show that using data relaying strategy increases uplink data rate regardless of different combinations of symmetric and asymmetric traffic generated in system. A multi-hop time slot allocation scheme, Maximum Interference First, was proposed in this study. This scheme reduces crossed-time slot interference and utilizes allocation of time slots by assigning the user to the time slot with high interference and keeping the low-interfered TSs for new users. Simulation results show that this scheme outperforms others in terms of overall capacity in all traffic scenarios.

In the second part of this study, we compared performance of single-hop and multi-hop time slot allocation schemes in supporting multimedia services with various QoS requirements. The traffic model was changed to provide more realistic simulation environment and each TS was allowed to accept more than one user. Call blocking

and call dropping probabilities in each scheme are investigated. Putting call blocking probability of single-hop and proposed multihop schemes, MFTSA and MDTSA, side by side, we can see that relaying the data can reduce the probability of blocking a new-coming user. However, many of the accepted calls in these multihop schemes could not maintain the call in downlink due to high interference. Thus, data relaying was deployed both in uplink and downlink and two other multihop time slot allocation schemes were proposed in order to eliminate the limitations applied to time slot selection algorithm as much as possible. The proposed schemes, ML-FTSA and ML-DTSA, enable maximum TS utilization in multihop cellular systems. Results show that deploying these schemes significantly improves system capacity for both low data rate and high data rate services.

In the last part, energy consumption in mobile devices was measured and compared for single-hop and multihop schemes. As the results show, for different traffic scenarios multihop schemes result in less power consumption and more energy saving in mobile devices. Even if we consider the energy consumed in devices by hardware and electronic parts, deploying multihop schemes saves energy in mobile devices and increase their battery life.

7.2 Recommendations for Future Research

The proposed time slot allocation schemes in this Thesis for multihop cellular networks show that employing such schemes improve performance and capacity of cellular networks for supporting next generation of mobile services. To further study

feasibility of implementing multihop cellular networks with these capabilities, few recommendations are presented in this section.

1. Throughout the simulations in this study, mobile stations were assumed to be stationary in system. This is a simplified model for arrangement of mobile stations in each cell. More advanced models such as models that consider mobility of users, can be applied to investigate performance of the proposed schemes. Handoff issues should be considered for systems with mobile users. When users travel in a cell, they may get far from their relay station and thus, a handoff should take place for the MS to use the nearest fixed relay station for data relaying. Performance of the proposed schemes in handling such handoffs can be investigated in future studies.
2. The other issue concerning mobile users is that users do not have uniform distribution over a cell in a system with mobile users. Some areas might be heavily congested while other areas have few users. As a result, the RSs in areas with high traffic will become over-loaded. Load-balancing methods also need to be implemented in order to increase performance of multihop time slot allocation schemes in increasing system capacity and providing high quality services. Authors of [46] introduce Integrated Cellular and Ad Hoc Relaying System (iCAR) to address the congestion problem in cellular networks. The main idea in iCAR systems is to deploy ad hoc relay stations in hot spots with high traffic. The relay stations divert the traffic from a congested cell to other

cells. The ad hoc relay stations (ARS) are wireless communication devices with limited mobility which use an unlicensed band in the ISM band for communicating with MSs. Thus, by diverting MS's call to another cell, one channel in licensed band becomes free in the congested cell. More details on the load-balancing mechanism of iCAR systems are presented in [46-49]. iCAR is applicable to systems which use different bands (licensed and unlicensed bands) for communicating with relay stations, however, other solutions should be proposed for systems that use only one band (licensed band) for all communications.

3. This Thesis focuses on multihop cellular networks with fixed relay stations. However, the proposed multihop schemes are believed to be applicable to two-hop relaying networks with mobile relay stations. Investigating performance of the proposed schemes in cellular networks that use other MSs as relay stations can be another topic for future studies. Nevertheless, it should be noted that in case of non-fixed relay stations, a routing algorithm might be needed to find the least cost path to BS and simply selecting the nearest MS may not be the best option for user. Authors of [50] study some of the routing performance metrics in multi-hop cellular networks. Their routing algorithm covers three metrics: the number of dedicated relay nodes in the path, the residual energy of mobile nodes and the capabilities of the mobile nodes such as CPU power and memory.

4. For TDD-CDMA networks a proper routing algorithm can be based on finding a route that result in least interference in system. Lowering transmission powers of MS and RS in a route reduces the interference in each cell. The model defined in Chapter 6 and the associated studies on energy consumption and transmission power reduction of proposed multihop schemes can be useful in designing a routing algorithm for two-hop data relaying cellular networks. Such routing algorithm may look for the route with minimum energy consumption and transmission power as the least cost route. Many power-based routing algorithms for multi-hop cellular networks can be found in literature [22,37]. In [22], a power-efficient routing algorithm is proposed for ODMA systems which finds the minimum-power path by estimating the total required power and the number of relay stations. [37] also presents a congestion-based routing algorithm which minimizes the total transmit power in all circumstances and consequently, provides the highest system capacity.

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Appendix

Appendix A: Call Admission Procedure

In this Appendix, we describe the call admission process used in our study in detail. The call admission process has two phases; *initial power setting* and *power adjustment*.

A – Call Admission Process for Single-hop Schemes

The call admission process for uplink in single-hop schemes, FTSA and DTSA, is described as follows.

- *Initial Power Setting.* A particular time slot, TS a , is selected based on the policy of FTSA or DTSA. The total received interference power including both inter-cell and intra-cell interference at the BS is measured in order to calculate the MS transmission power. Transmission power is set to meet the required E_b/N_0 using (1). During the initial power setting, if the new call cannot meet the required E_b/N_0 in TS a even with the MS's maximum transmission power, P_{MS} , the call admission process is considered unsuccessful and the next suitable time slot, TS b , will be selected.
- *Power Adjustment.* After setting initial MS transmission power in TS a , power adjustment procedure begins in order to adjust the transmission powers of other existing transmitters (MSs and BSs) using the same TS.
 - Starting from the cell of new MS, powers of other transmitters (MSs) using the same selected time slot, TS a , are adjusted during this

process. Then, we adjust the transmission powers (of MSs and BSs) of other links using the same time slot, TS a , in the other neighboring cells (which is 18 of them in our study). After adjusting all transmitters in new MS's own cell and other adjacent cells, the new-coming MS will adjust its transmission power again to meet the required E_b/N_0 in TS a . This procedure is repeated until no further change is done to the transmission power of any transmitter in all 19 cells. Power adjustment procedure is explained as follows: Transmission power of a transmitter (MS/BS) is increased by 1 dB whenever the received E_b/N_0 at a receiver (BS/MS) is below target E_b/N_0 . Transmission power of a transmitter (MS/BS) is decreased by 1 dB whenever the received E_b/N_0 at a receiver (BS/MS) exceeds the required E_b/N_0 .

For downlink, call admission process is similar to uplink.

- *Initial Power Setting.* The total received interference power in the selected TS, TS b , at the new MS is measured in order to calculate the BS transmission power. Similarly, the BS transmission power is set to meet the required E_b/N_0 using (1). If the total BS transmission power exceeds the maximum permissible BS transmission power, P_{BS} , the call admission is failed and another time slot will be selected.
- *Power Adjustment.* The power adjustment procedure is same as used in uplink to adjust the transmission powers of other existing transmitters (MSs and BSs) using the same TS in new-coming MS's own cell and other adjacent cells.

B – Call Admission Process for Multihop-hop Schemes

The call admission process for uplink in multihop schemes, ML-FTSA and ML-DTSA, differs for 1-hop call and 2-hop call connections.

1-hop call connection

- Uplink MS-to-BS:* The initial power setting for uplink MS-to-BS is similar to the procedure for 1-hop connection. During the power adjustment, it also needs to adjust the transmission powers of RSs, which use the same selected TS for transmission, in new-coming MS's own cell and other 18 cells. After the power adjustment, TS a is assigned to uplink MS-to-BS if 1) the received E_b/N_0 of this MS-to-BS link can meet the required E_b/N_0 in TS a with its MS's transmission power $\leq P_{MS}$ and 2) all other connection links, e.g., RS-to-BS, of the existing calls using TS a in the same cell can also meet their target E_b/N_0 with their MSs' transmission powers $\leq P_{MS}$ or their RSs' transmission powers $\leq P_{RS}$. P_{RS} is the maximum permissible RS transmission power for each connection link. Otherwise, the call admission process is considered unsuccessful and the next suitable time slot will be selected.
- Downlink BS-to-MS:* The initial power setting for downlink BS-to-MS is similar to the procedure for 1-hop connection. During the power adjustment, it also needs to adjust the transmission powers of RSs, which use the same selected TS for transmission, in new-coming MS's own cell and other 18 cells. After the power adjustment, TS a is assigned to downlink BS-to-MS if 1) the received E_b/N_0 of this BS-to-MS link can meet the required E_b/N_0 in TS a with BS's transmission power $\leq P_{BS}$ and 2) all other connection links, e.g., RS-to-MS, of the existing calls using

TS a in the same cell can also meet their target E_b/N_0 with their MSs' transmission powers $\leq P_{MS}$ or their RSs' transmission powers $\leq P_{RS}$. Otherwise, the call admission process is considered unsuccessful and the next suitable time slot will be selected.

2-hop call connection

- *Uplink MS-to-RS*: For a 2-hop call connection, call admission process will be first executed for MS-to-RS link. The call admission process will go through initial power setting following the above procedure. Then, transmission powers of all transmitters (MSs, RSs and BSs) which use this TS in the same cell and all 18 neighboring cells will be adjusted following the power adjustment procedure. During the power adjustment procedure whenever the transmission power of a transmitter in neighboring cells exceeds the maximum allowable power, the line does not drop. We continue to keep the connection while the transmitter transmits with its maximum power. However, these calls are marked to be dropped. The marked calls are dropped only when both MS-to-RS and RS-to-BS links are established.

A time slot, TS x , is assigned to the MS-to-RS link for a new call if 1) the call can meet the required E_b/N_0 and 2) the other transmitters (MSs, RSs or BS) using TS x in the same cell can meet their target E_b/N_0 with their transmission powers $\leq P_{MS}$, P_{RS} or P_{BS} . Otherwise, the call admission process is considered unsuccessful and the next suitable time slot will be selected.

- Uplink RS-to-BS:* Establishment of RS-to-BS link follows the same procedure as described for MS-to-RS for initial power setting and power adjustment in the cell of new call and other 18 cells. Similarly, A time slot, TS y , is assigned to the RS-to-BS link for a new call if 1) the call can meet the required E_b/N_0 and 2) the other transmitters (MSs and RSs) using TS y in the same cell can meet their target E_b/N_0 with their transmission powers $\leq P_{MS}$ or P_{RS} . Otherwise, the call admission process is considered unsuccessful and the next suitable time slot will be selected.
- Downlink BS-to-RS:* To establish a 2-hop downlink, a TS is first selected for BS-to-RS link. Then, the initial power setting and power adjustment is done for the BS-to-RS link similar to the procedure in 1-hop downlink. Also as described in MS-to-RS link, whenever transmission power of transmitters in neighboring cells exceeds their maximum allowable power, they are marked to be dropped but they continue to transmit with their maximum power. The marked links are dropped when both BS-to-RS and RS-to-MS links are established.
- Downlink RS-to-MS:* After assigning a TS to BS-to-RS link, another TS, TS z , will be selected for RS-to-MS link. The initial power is set based on the inter-cell and intra-cell interferences received at MS and the power of all transmitters which use this TS (MSs, RSs and BSs) are adjusted in all 19 cells. TS z , is assigned to the RS-to-MS link for a new call if 1) the call can meet the required E_b/N_0 and 2) the other transmitters (MSs, RSs or BS) using TS x in the same cell can meet their target E_b/N_0 with their transmission powers $\leq P_{MS}$, P_{RS} or P_{BS} . Otherwise, the call

admission process is considered unsuccessful and the next suitable time slot will be selected.

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