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The Graduate School
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DYNAMIC TIME DIVISION DUPLEX AND TIME SLOT ALLOCATION
STRATEGY FOR MULTIMEDIA TRAFFIC IN WIRELESS APPLICATIONS

A Thesis in
Electrical Engineering
by
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ABSTRACT

This thesis deals with dynamic time division duplex (D-TDD) operation and time slot allocation (TSA) strategy for dynamic traffic pattern in fixed wireless applications.

The nature of emerging multimedia traffic is that it consists of several classes, which require different quality-of-service (QoS), and the bandwidth between uplink and downlink is quite asymmetric and dynamic. Frequency division duplex (FDD) operation and static time division duplex (S-TDD) operation may result in poor frequency utilization for this type of traffic, since the transmission bandwidth of these operations is fixed. Meanwhile, dynamic time division duplex (D-TDD) operation can support such asymmetric and dynamic traffic robustly, by adapting its transmission bandwidth according to traffic pattern. Thus, significant statistical multiplexing gain can be obtained in D-TDD operation. However, D-TDD is vulnerable in terms of strong interfering signals coming from base stations in co-channel cells, while the reference cell is busy with uplink receptions. Since the strong interference presence is due to the unique feature of D-TDD, the statistical multiplexing gain, which is also obtained via the unique feature, may not be obtained.

In this thesis, we develop an analytic model of signal-to-interference ratio (SIR) distribution in D-TDD systems. Using the analytic model, we show that the probability density function (PDF) of SIR distribution in D-TDD system has two peaks, while that in conventional S-TDD systems has one peak. From the investigation of PDF, we show how the strong co-channel interference severely degrades the performance of SIR outage
probability in D-TDD systems, when omni-directional antennas are employed at base station (BS) sites and subscriber (SC) sites. Also, we estimate the spatial resolution in terms of antenna beamwidth to obtain the target outage probability, when a spatial filter is employed at BSs. Numerical results show that 3.4-degree beamwidth is required to obtain an outage probability of 1% at the threshold SIR value of 17 dB.

To suppress the effect of strong co-channel interference in D-TDD systems, we develop a time slot allocation strategy (TSA), exploiting spatially distributed SCs’ location over the cell coverage, combined with cost effective sector antenna layouts. We propose two TSA algorithms: the MaxMin \{SIR\} and the Max \{SIR\} algorithms. The MaxMin \{SIR\} is an exhaustive search algorithm, which searches the best pair set of time slots and SCs among all possible combination sets. The performance of this algorithm is used as an benchmark. Meanwhile, MaxMin \{SIR\} searches the pair in a specific order, which reduces the computational complexity, substantially. Our simulation results show that both algorithms perform well for a fairly large range of dynamic traffic pattern and the difference in performance between the two algorithms is not noticeable. Also, we compare the performance of TSA to that of adaptive array antennas. Our simulation shows that the performance of D-TDD system employing TSA, combined with 15 sector antennas, is comparable that employing adaptive array antennas with 26 sensing elements.

Finally, we compare the spectral efficiency of TDD systems for various frame-loading conditions. In the analysis, we consider two types of modulation schemes: fixed modulation and adaptive modulation. Fixed modulation is suitable for the delay-sensitive traffic, while adaptive modulation is proper for the delay-tolerant traffic, since the
transmission rate in delay-tolerant traffic can be reduced and the data bits can be buffered, until the channel quality is improved. In fixed modulation system, it is observed that the spectral efficiency of D-TDD systems can be improved significantly by employing TSA strategy. For instance, as much as 9 times higher spectral efficiency is obtained by employing TSA strategy, when the traffic is highly dynamic and the frame is fully loaded. Meanwhile, in adaptive modulation system, the spectral efficiency of D-TDD systems does not improve significantly by employing TSA strategy. This is due to the fact that the objective of the proposed system is to maximize the minimum value of SIR, not to improve the SIR values over all uplink time slots. Our numerical results show that the merit of statistical multiplexing can be obtained for a fairly large range of frame loading, by employing the proposed TSA strategy, compared to S-TDD systems.
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<th>Acronym</th>
<th>Description</th>
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<tr>
<td>AAA</td>
<td>Adaptive Array Antenna</td>
</tr>
<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
</tr>
<tr>
<td>BCA</td>
<td>Borrowing Channel Assignment</td>
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<tr>
<td>BER</td>
<td>Bit Error Rate</td>
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<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
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<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>DCA</td>
<td>Dynamic Channel Allocation</td>
</tr>
<tr>
<td>DECT</td>
<td>Digitally Enhanced Cordless Telecommunications</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processor</td>
</tr>
<tr>
<td>D-TDD</td>
<td>Dynamic Time Division Duplex</td>
</tr>
<tr>
<td>FBCA</td>
<td>Forcible-Borrowing Channel Assignment</td>
</tr>
<tr>
<td>FCA</td>
<td>Fixed Channel Assignment</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
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<tr>
<td>LMP</td>
<td>Local Mean Power</td>
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<tr>
<td>MMSE</td>
<td>Minimum Mean Square Error</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>NCA</td>
<td>Non-fixed Channel Assignment</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>PSTN</td>
<td>Public Switched Telephone Network</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality-of-Service</td>
</tr>
<tr>
<td>RHS</td>
<td>Right Hand Side</td>
</tr>
<tr>
<td>RNC</td>
<td>Radio Network Controller</td>
</tr>
<tr>
<td>SDMA</td>
<td>Space Division Multiple Access</td>
</tr>
<tr>
<td>SIMO</td>
<td>Single Input Multi Output</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal-to-interference plus noise ratio</td>
</tr>
<tr>
<td>SIR</td>
<td>Signal-to-interference ratio</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
</tr>
<tr>
<td>S-TDD</td>
<td>Static Time Division Duplex</td>
</tr>
<tr>
<td>TD-CDMA</td>
<td>Time Division Code Division Multiple Access</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TSA</td>
<td>Time Slot Allocation</td>
</tr>
<tr>
<td>UCA</td>
<td>Uniform Circular Array</td>
</tr>
<tr>
<td>ULA</td>
<td>Uniform Linear Array</td>
</tr>
<tr>
<td>WLL</td>
<td>Wireless Local Loop</td>
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Chapter 1

Introduction

1.1 Motivation

The popularity of Internet service in wired networks has flamed the demands on broadband access. Since 90’s, Internet has shown a significant success in terms of number of users, and effects on our daily lives. Recently, various types of Internet services, some of which require high data rates such as video-on-demand (VoD), video conferencing, large file transfer etc., are being offered via wired networks, while integrated packet voice and some primitive forms of data services, e.g., e-mail, are being offered via wireless networks. As the advent of the third generation mobile communications, the universal efforts are concentrated on supporting integrated high quality voice and data service [1,2]. Moreover, as the need for broadband multimedia communications involving digital audio and video grows, the demand on broadband access from subscribers is expected to be boosted up in wired networks and its counterpart, wireless networks, as well.

One of distinguished features of broadband applications is that the traffic consists of different classes. This integrated traffic is different from the conventional voice telephony, in terms of quality-of-service (QoS) requirements for its constituent classes of traffic. The classes constituting the integrated broadband traffic can be roughly
categorized in two groups: delay sensitive and delay tolerant data traffic. The characteristics of delay sensitive traffic is static in its bandwidth between uplink and downlink transmission, on the average sense, and the delay constraint at the reception of information usually requires a strict resource allocation strategy to guarantee the QoS requirements. Meanwhile, the characteristics of delay-tolerant traffic are bursty and asymmetric in its uplink and downlink transmission bandwidth, and usually require low bit error rate (BER) values. When wireless networks deliver the integrated traffic, spectral efficiency may be poor if the bandwidth allocation between uplink and downlink transmission is fixed.

Recently, dynamic time division duplex (D-TDD) has gained much attention as an efficient duplex scheme for delivering bursty multimedia traffic. Time division duplex (TDD) can be divided into two operations: S-TDD and D-TDD. In S-TDD operation, the transmission bandwidth of uplink (or downlink) is fixed all the time, while it varies according to the traffic pattern in D-TDD operation. Besides its benefits of TDD air interface, such as single carrier shared by uplink and downlink transmission, D-TDD provides statistical multiplexing gain by adapting its switching point between uplink and downlink transmission to the traffic pattern. This is a major attractive feature in D-TDD operation. Thus, D-TDD enables efficient and flexible asymmetric services, which improve the spectral efficiency of the network.
1.1.1 Statistic multiplexing gain over dynamic traffic pattern

To visualize the benefit of D-TDD for dynamic traffic pattern, let us consider a single cell wireless system, where a number of subscribers are present over the cell coverage. For a single cell environment, the spectral efficiency is simply given as:

$$\eta = \sum_{i=1}^{n} \delta_i \log_2 (1 + \gamma_i), \quad (1.1)$$

where $\delta_i$ is a fraction of bandwidth assigned to $i$-th channel; $n$ is the number of active channels; $\gamma_i$ is signal-to-interference plus noise ratio (SINR) of the $i$-th channel. For time division multiple access (TDMA) systems, a channel is given as a form of time slot, and only one subscriber is served at a time slot. Since there is no co-channel interference in a single cell environment, SINR reduces to signal-to-noise ratio (SNR), and the distribution of SNR is the same over all time slots. Thus, in a single cell environment, $\gamma_i$ simply reduces to $\gamma$.

To model the dynamic traffic pattern in D-TDD operation, let us define the number of active uplink time slots in a D-TDD frame as follows:

$$n_{D-TDD} = L + N', \quad (1.2)$$

In Eq. (1.2), $L$ is the number of uplink time slots, which is fixed and always served in a frame. $L$ models the bandwidth of static traffic. $N'$ is the number of additionally requested uplink time slots from subscribers and models the bandwidth of bursty traffic. For analysis, let us model $N'$ as a uniform integer random variable, expressed as $U[0, N]$, where $N$ represents a range of variation of this bursty traffic. The D-TDD frame is
assumed to be fully loaded, i.e., a time slot in a frame is assigned either to uplink or to downlink transmissions.

Meanwhile, the uplink transmission bandwidth of S-TDD is fixed, regardless of availability in downlink transmissions. This means that, for the same traffic pattern in D-TDD operation, the number of uplink time slots requested from subscribers, which exceeds uplink transmission bandwidth fixed in S-TDD operation, can not be accommodated in S-TDD operation, no matter how many time slots are available in downlink transmission. For the same reason, there are idle time slots in S-TDD frame, when the number of uplink time slots requested is less than the uplink transmission bandwidth. Thus, S-TDD frame may not be always fully loaded. This results in less efficient spectral utilization. For comparison, we define the maximum number of active uplink times in a S-TDD frame to be the same as the average number of active uplink time slots in D-TDD frames, i.e.,

$$\text{Max}[n_{S-TDD}] = E[n_{D-TDD}] = L + \frac{N}{2}$$  \tag{1.3}$$

where $n_{S-TDD}$ is the number of active uplink time slots in S-TDD frame; $\text{Max}[\cdot]$ selects the largest value of its arguments; $E[\cdot]$ represents expectation value of random variable. It should be noticed that the S-TDD frame may not be fully loaded.

Now, the spectral efficiency of TDMA/TDD system is expressed as:

$$\eta_{S-TDD} = E[n_{S-TDD}] \log_2 (1 + \gamma),$$

$$\eta_{D-TDD} = E[n_{D-TDD}] \log_2 (1 + \gamma).$$  \tag{1.4}$$
Let us define the multiplexing gain ($\Xi$) of D-TDD operation obtained over S-TDD operation for a single cell system as:

$$\Xi = \frac{\eta_{D-TDD}}{\eta_{S-TDD}} \quad (1.5)$$

From the traffic model, Eq. (1.5) reduces to,

$$\Xi = \frac{L + \frac{N}{2}}{L + \frac{1}{2(N+1)} \left( \left\lfloor \frac{N}{2} \right\rfloor \left( \left\lfloor \frac{N}{2} \right\rfloor - 1 \right) \right)} \quad (1.6)$$

shows the multiplexing gain obtained in D-TDD operation over S-TDD operation for various traffic patterns. To investigate the effect of dynamic traffic pattern on statistical multiplexing gain asymptotically, let us change the range of bursty traffic variation ($N'$) in the uplink transmission bandwidth, while the static traffic bandwidth ($L$) is kept the same. The horizontal axis in the figure represents the ratio of bursty traffic bandwidth ($E[N']$) to the uplink transmission bandwidth ($L + E[N']$), in the average sense. For instance, the origin in the figure represents static traffic pattern, i.e., $N = 0$, while the right-most point represents the entirely dynamic traffic pattern, i.e., all the time slots in a D-TDD frame can be assigned either to uplink or to downlink transmissions. As shown in the figure, the spectral efficiency of D-TDD mode becomes four times higher than that of S-TDD mode, as the traffic pattern approaches to become entirely bursty.
This simple illustration shows that substantial gain can be obtained in a single cell environment by statistical multiplexing of uplink and downlink transmission bandwidth, when bursty traffic is present in the network.

*Figure 1–1: Statistical multiplexing gain versus traffic pattern.*
1.1.2 Effect of co-channel interference in D-TDD systems

Compared to benign wired environments, harsh wireless environments place many challenges in providing broadband wireless access. The major challenges in wireless communication system design stem from physical impairments through transmission channel, and finite frequency spectrum resource that must be shared by multi-users. Physical impairments, such as multipath fading, and delay spread, etc., pull the achievable system capacity far away from its theoretic limit, while the spectral efficiency in wired networks is getting close to its upper bound.

Especially, the limited radio frequency resource, which must be shared by multi-users, requires sophisticated cellular architecture to utilize the available bandwidth efficiently, over the entire cellular network. In commercial wireless communication systems, frequency reuse concept is widely employed. In such multi-cellular networks, the available spectrum is broken into several channel sets, and the same channel set is reused in a distance such that the interference level does not degrade the performance of the cellular system, significantly. Since the co-channel interference level is much higher than the thermal noise generated from electronic circuits, the performance of wireless cellular networks is limited by co-channel interference.

The statistical multiplexing gain obtained by employing D-TDD may not be justified in multi-cellular networks, due to strong co-channel interference present at extra time slots. It has been noted that strong co-channel interference is introduced in TDD system if the frame is not synchronized [3]. Even when the frame is synchronized, strong
co-channel interference, still exists due to the inherent feature of dynamic partitioning between uplink and downlink transmission in D-TDD operation [4,5].

The strong co-channel interference degrades the signal-to-interference ratio (SIR) outage probability performance of a D-TDD system, severely. This is mainly due to the difference in antenna heights between a base station (BS) site and a subscriber (SC) site. In S-TDD operation, where all the interfering signals come from the same source, either a SC or a BS at co-channel cell, the statistical characteristic of co-channel interference is homogeneous. However, as shown in chapter 3, the dynamic partitioning between uplink and downlink transmission in D-TDD operation makes it possible that some of the interfering signals come from co-channel cells in opposite duty cycle, as in the reference cell. Thus, the characteristic of co-channel interference in D-TDD operation is heterogeneous, i.e., the statistical parameters of interfering signals are different. It is observed that the strong interfering signals coming from the co-channel cells in downlink cycle, while the reference cell is in uplink duty cycle, degrade the SIR outage performance of TDD systems, severely [3,4,5]. This heterogeneous co-channel interference in D-TDD operation places a new problem set to improve the SIR outage probability. To suppress the strong co-channel interference in D-TDD operation, Li et al. employed adaptive array antennas at the BS sites [4,5].

1.2 Objective

In this thesis, we focus on the performance of D-TDD operation for dynamic traffic pattern in fixed wireless cellular networks.
First, we investigate how the presence of bursty traffic affects the performance of TDD operations in terms of SIR outage probability. We develop an analytic model of SIR outage probability. Employing the analytic model, we investigate how the dynamic range of bursty traffic affects the SIR outage performance.

Second, we devise cost-effective transmission scheduling algorithms, combined with simple spatial filter, sectored antenna, to improve the SIR outage performance of D-TDD systems. The optimization of the best signal reception using spatial filter can be performed by suppressing the antenna gain in the direction of incoming co-channel interference. In S-TDD systems, where the characteristics of spatially distributed incoming interfering signals are statistically the same, the selection of mainlobe direction, which is looking toward the desired SC, does not improve the signal quality, substantially. However, in D-TDD system, interference level can be significantly different whether it comes from a BS or a SC in a co-channel cell. Thus, for given geographical location of co-channel interference, the SIR level may be improved substantially by choosing the direction of the effective aperture of spatial filter looking toward the desired SC. Since the SCs are spatially distributed over the cell coverage area, an intelligent transmission scheduler assigns the transmission order of the spatially distributed SCs, such that the SIR outage probability is improved. Thus, an intelligent transmission scheduler, combined with simple spatial filter, can improve the performance of D-TDD operation. The attractive feature of the scheduling strategy is that the spatial filter employed in the scheduler does not necessarily have the ability of adaptive beamforming, as long as it provides the spatial resolving capability. Consequently, cost
of the cellular deployment can be reduced substantially by employing low-cost sector antennas, compared to a system employing highly expensive adaptive array antennas. Since the transmission scheduling process is to assign spatially distributed SCs to time slots, we refer to this scheduling strategy as time slot allocation (TSA) strategy.

Finally, we evaluate the performance of TDD systems in terms of spectral efficiency. We compare the spectral efficiency of D-TDD system and that of S-TDD system for various frame-loading conditions. Since the co-channel interference degrades the spectral efficiency of D-TDD operation, we also investigate the improvement of D-TDD mode, when the proposed TSA strategy is employed.

Throughout the thesis, we consider fixed cellular systems, employing TDD operations. We assume that frames are perfectly synchronized, thereby, there is no strong co-channel interference introduced, due to frame asynchronism.

1.3 Thesis Overview

This thesis consists of six chapters, including this introduction. In chapter 2, we discuss the background information needed for the research. This includes the basic concepts behind spatial filtering such as antenna sectoring and adaptive array beamforming schemes; resource allocation schemes; adaptive transmissions; and general aspects of wireless local loops.

In chapter 3, we characterize the statistical behavior of co-channel interference in D-TDD fixed wireless systems. We develop an analytical model of SIR. First, we show that the probability distribution of SIR in D-TDD operation is bimodal, due to dynamic
partitioning between uplink and downlink transmissions, i.e., the probability density function (PDF) curve has two peaks. This statistical behavior is totally different than in S-TDD operation, where homogeneous distribution makes PDF curve unimodal. Using the analytic model, we investigate how the dynamic pattern affects the performance of SIR outage probability, when omni-directional antennas are employed at BS and SC sites. We verify our model using computer simulation. It is illustrated that catastrophic effects due to dynamic boundary in D-TDD frames cause serious degradation in the uplink performance. Also, we show the performance of D-TDD operation in fixed wireless cellular networks is limited by uplink, rather than by the downlink performance, due to presence of strong co-channel interference during extra uplink time slots.

In chapter 4, we propose a novel intelligent co-channel interference management scheme for D-TDD operation. This scheme is called TSA strategy. We propose two types of TSA algorithms. An exhaustive search algorithm, which searches the best pair set among all possible combination sets, is referred to as MaxMin \{SIR\} algorithm. Due to a sharp increase in computational complexity, as the dynamic range of traffic is increased, we use the performance of this algorithm as a benchmark for comparisons. As an efficient and simple algorithm, we propose Max \{SIR\} algorithm. The complexity of this algorithm does not increase, significantly. Our simulation results show that both algorithms perform well for fairly large range of dynamic traffic pattern and the difference in performance between the two algorithms is not noticeable.

In chapter 5, we assess the spectral efficiency of TDD modes for dynamic traffic. For various frame-loading conditions, we investigate the effect of dynamic range of
bursty traffic on the spectral efficiency of TDD systems. Especially, we will show how much improvements can be obtained in D-TDD system for bursty traffic, when the proposed TSA algorithm is employed. We consider two types of transmission schemes. Fixed modulation scheme, which sustains the modulation level throughout the communications, is considered to take into account of the scenario that the network delivers all delay-sensitive traffics. Meanwhile, adaptive modulation scheme, which adapts its modulation level to the channel quality, is considered to take into account the scenario that the network delivers all delay-tolerant data traffics.

Finally, we summarize our research results and suggest future research directions in chapter 6.
Chapter 2

Background

2.1 Introduction

The purpose of this chapter is to provide a common framework for understanding of topics related to the main scope of this thesis.

Section 2.2 provides an introduction to the fundamental concepts involving duplex schemes. As commonly used duplex schemes, time division duplex (TDD) and frequency division duplex (FDD) schemes are studied and compared.

Section 2.3 is devoted to the introduction of spatial filtering scheme as a means to increase the spectral efficiency of cellular systems. First, sector antenna systems are introduced, then, smart antenna systems are reviewed. As a beamforming strategy for adaptive array antenna, minimum mean square error (MMSE) criterion is explained.

Section 2.4 provides a brief introduction to dynamic channel allocation (DCA) strategy.

In section 2.5, adaptive transmission techniques are reviewed.

Section 2.6 describes general feature of wireless local loop, which is the cellular model considered in this thesis.
2.2 Duplex Schemes

Two kinds of duplex schemes have been widely deployed in cellular networks. In frequency division duplex (FDD), traffic is carried in separate carrier frequencies, while it is carried in orthogonal time slots in time division duplex (TDD). A simple illustration is shown in Figure 2–1.

FDD has been widely deployed in conventional wireless systems such as GSM, IS-136 and IS-95. It delivers uplink and downlink traffic simultaneously via a largely separated pair of carrier frequencies, thus, FDD is a full duplex scheme. In cellular systems, interference between uplink and downlink can be avoided in FDD operations, even though base stations are not synchronized. In FDD systems, the uplink and downlink channel bandwidth is fixed. Thus, the spectrum of FDD systems is utilized more efficiently for static symmetric (or, asymmetric) traffic, e.g., voice traffic.

Meanwhile, TDD shares a single carrier frequency for uplink and downlink transmissions. TDD operation can be further divided into two modes: static TDD (S-TDD) and dynamic TDD (D-TDD). In S-TDD operation, a fraction of frame time for uplink reception (or downlink transmission) is fixed. The digital European cordless telephone (DECT) is an example of commercial TDMA/TDD system [6]. On the other hand, the portions of uplink and downlink transmissions are assigned dynamically in D-TDD systems.

TDD operation offers many benefits in cellular systems. First, compared to FDD systems, in TDD systems, channel coordination is easier, and RF hardware is potentially less complicated and thus lowers the cost. Second, the uplink and downlink can be
considered reciprocal, provided that the channel characteristics have not changed considerably over a frame interval. This channel reciprocity holds for fixed cellular systems where the channel fading is considered as quasi-static, i.e., the fading state is not changed over one frame. The channel reciprocity introduces a reduction of complexity for the transceiver design. For instance, the beam weighting coefficients achieved from uplink can be used for downlink transmission, which reduces the complexity of the adaptive array antenna systems. In addition, the channel information from uplink transmission can be used to pre-distort downlink transmission such that the multipath fading and/or multipath delay spread is overcome at the receiver. This pre-distortion relieves the burden of channel estimation for a SC (or mobile) terminal. Most of all, D-TDD systems utilize spectrum efficiently by adapting the bandwidth of uplink and downlink transmissions to the traffic pattern. Thus, for dynamic asymmetric traffic, large statistical multiplexing can be obtained in D-TDD systems [7, 8]. Even for voice traffic, of which transmission bandwidth in either-direction is balanced on the average sense, improvements in utilization can also be brought by recognizing the periodic nature of speech and having a reservation mechanism for time slots. In [9], high multiplexing gain has been reported in D-TDD system, by exploiting the nature of periodic activity and the negative correlation in uplink and downlink traffic in voice telephony. Thus, D-TDD is robust to asymmetric and time-varying multimedia traffic by adapting its boundary to dynamic traffic load level [1, 10].
However, there are several drawbacks in TDD operation, compared to FDD operation. It has been established that the throughput of TDD systems is decreased, as the cell coverage is increased. This is mainly due to the increase in the guard time. Thus, D-TDD operation is appropriate for a small cell with low mobility and highly asymmetric uplink and downlink traffic, where broadband is required. For high-speed mobile networks, the limitation on the cell coverage causes severe trouble regarding hand-over problem. Also, TDD requires synchronization. Since uplink and downlink transmissions share the same frequency, transmission of one direction can be interfered by the other one in TDD systems [3, 4]. Indeed, TDD systems are seriously limited by a steady incoming

Figure 2–1: Conceptual illustration of duplex schemes. (a) TDMA/TDD (b) FDMA/FDD systems.
interfering signals from co-channel base stations (BS) in their downlink cycle when a reference BS is in its uplink cycle, receiving signal from subscribers (SC). This stems from the fact that the propagation from a base station to a base station (BS-to-BS) suffers less attenuation than that from a subscriber to a base station (SC-to-BS), because the antenna height at a BS site is much higher than that at a SC location. This happens when the frames are not synchronized in S-TDD systems [3], while the performance of D-TDD system is seriously degraded, even if the system is synchronized [4].

2.3 Spatial Filter

It is known that the performance of a cellular system is very much interference limited rather than thermal noise limited. To reduce the deleterious effects of co-channel interference, spatial filtering is a widely applied scheme in commercial wireless communication systems. Especially, as we will see in chapter 3, strong co-channel interference is present in D-TDD systems. In this section, we briefly study spatial filtering schemes to suppress co-channel interference.

2.3.1 Sector Antenna

Sector antenna is the most widely used spatial filter in commercial mobile cellular systems. It can suppress the amount of co-channel interference introduced, by reducing the mainlobe beamwidth and/or the sidelobe gain. In sector antenna systems, the cell
coverage is subdivided into sectors and covered using directional antennas looking out from the same BS location.

There are several advantages using sector antennas. Operationally, each sector is treated as a different cell; thus, the range is greater than in the omni directional case. Sector antennas increase the possible reuse of a frequency channel in such cellular systems by reducing potential interference across the original cell, and they are widely used for this purpose. Each sector is operated as a RF switch, i.e., the antenna is always either on or off. This simple operation reduces the system cost significantly.

However, to meet the required communication quality of emerging broadband traffic, the sector antenna layout may require many sectors. Since frequent hand-over is required in a mobile system with large number of sectors, the overall system performance will be poor. Also, [11] has shown that the performance of sector antenna systems is inferior to that of adaptive array antenna systems, no matter how many number of sectors are provided.

2.3.2 Smart Antenna

The antenna array processing for single input multi output (SIMO) system, that takes advantage of spatial resolution, is referred to as smart antenna processing.
2.3.2.1 Types of Smart Antennas

Smart antennas are categorized as either switched beam or adaptive array antenna systems. The distinction between the two categories of smart antennas is that the switched beam systems have a finite number of fixed, predefined patterns or combining strategies as illustrated in Figure 2–2, while adaptive array systems have an infinite number of patterns that are adjusted in real time. In switched beam antennas, a grid of beams chooses the beam that gives the best SNR. The advantage of switched beams is that, it can be easily deployed and tracked at beam switching rate. However, this system has a low-gain between beams, limited interference suppression ability and may falsely lock to shadowing. Meanwhile, adaptive array antennas synthesize a beam pattern such that antenna pattern is optimized with respect to output SINR (See Figure 2–3). As a consequence, this system provides an optimum SINR gain.
Typically, the received signal from spatially distributed antenna elements is multiplied by a weight, and a complex adjustment of amplitude and phase. These signals are combined to yield the array output. An adaptive algorithm controls the weights according to predefined objectives. For a switched beam system, this may be primarily maximum gain; for an adaptive array antenna system, other factors may receive equal consideration. These dynamic calculations enable the system to change its radiation pattern for optimized signal reception.

*Figure 2–2: Switched Beam System Coverage Patterns.*
Especially, adaptive array antenna systems have been said to increase the coverage of the cell by launching more power in the direction of the desired SC; and to increase the system capacity using spatial selectivity, and thus, increase the received SNR with optimum combing [12, 13]. Until recently, cost barriers have prevented their use in commercial systems. However, the advent of powerful low-cost DSP chips, general-purpose processors, as well as innovative software-based signal-processing techniques (algorithms) have made intelligent antennas practical for cellular communications systems.

*Figure 2–3: Illustration of Beamforming: (a) Switched Array systems (b) Adaptive array antenna systems. Co-channel interference is denoted as CI in the figure.*
Adaptive array antenna systems have been known as efficient means for combating multipath fading of the desired signal and to suppress co-channel interference [14, 15, 16]. Spatial resolution can be increased using a number of sensing antenna elements in the uplink direction. The important advantage is the possibility of receiving weak signals from the outskirts of the cell thereby increasing the range covered by the base station. Basically, these antenna systems take advantage of diversity gain, using spatial signal processing. In other words, antenna arrays can resolve the desired signal by increasing the spatial resolution of signal reception, suppressing the effect of interfering signals.

By employing array antennas, novel system architectures have been proposed. Naguib et al. have stated that one can integrate spatial division multiple access (SDMA) with any existing multiple access standard, and gain significant channel capacity with limited increase in system complexity [39]. In a SDMA system, the adaptive array antenna can form multiple narrow beams to serve different users. SCs in different angular positions can be served in the same frequency band and in the same time slot, the data intended for each SC are separately processed in such a way to give a SC-specific antenna pattern. Also, when array antennas are deployed both at BS sites and SC sites, it has been shown that enormous spectral efficiency can be obtained, provided that rich scattering environment between the transmitter and the receiver ensures statistically independent paths between the antenna elements. Especially, Foschini et al. showed that the spectral efficiency of such a system is increased linearly, as the number of antenna
elements is increased [17, 18]. Meanwhile, Tarokh et al. have devised coding scheme to obtain maximum diversity gain and coding gain for such system [19, 20].

2.3.2.2 MMSE Beamforming

The main feature of the adaptive array antenna is the signal processing to generate a beam pattern, adaptively. There are several criteria in beamforming strategy. Among them, MMSE criterion has intensively studied [14]. In this sub-section, the optimum beamforming using MMSE criterion to achieve maximum SINR is studied. In this thesis, we apply MMSE criterion to synthesize beampattern of adaptive array antennas.

*Figure 2–4* shows a block diagram of an *m* antenna element adaptive array. Let the weight vector $\mathbf{w}$ be given by:

$$w = [w_1, w_2, \cdots, w_m]^T$$  \hspace{1cm} (2.1)  

where the superscript $T$ denotes transpose, and the received signal vector $\mathbf{x}$ is given by

$$\mathbf{x} = [x_1, x_2, \cdots, x_m]^T$$  \hspace{1cm} (2.2)  

The received signal consists of the desired signal, thermal noise, interference, and therefore, can be expressed as
\[ x = x_d + x_n + \sum_{j=1}^{L} x_j \]  \hspace{1cm} (2.3)

where \( x_d, x_n, \) and \( x_j \) are the received desired signal, noise, and the \( j \)-th interfering signal vectors, respectively, and \( L \) is the number of interferers. Let \( s_d(k) \) and \( s_j(k) \) be the desired and the \( j \)-th interfering signals at the \( k \)-th symbol interval, with

\[ E[s_j^2(k)] = 1, \quad E[s_d^2(k)] = 1 \quad \text{for} \ 1 \leq j \leq L. \]  \hspace{1cm} (2.4)

Furthermore, let us assume that the desired received signal, noise and interfering signal are independent of each other.

Then, \( x \) is expressed as

\[ x = u_d s_d(k) + x_n + \sum_{j=1}^{L} u_j s_j(k) \]  \hspace{1cm} (2.5)

where \( u_d \) and \( u_j \) are the desired and the \( j \)-th interfering signal propagation vectors, respectively.

After the beamweight is computed, the complex baseband signal received by the \( i \)-th element in the \( k \)-th symbol interval \( x_i(k) \), is multiplied by a complex weight \( w_i(k) \). The weighted signals are then summed to form the array output \( s_o(k) \),

\[ s_o(k) = w^T \cdot x \]  \hspace{1cm} (2.6)
The output signal is subtracted from a reference signal \( r(k) \) to form an error signal, 
\[
\epsilon(k) = s_o(k) - r(k).
\]

The optimum beamweights \( w \) can be computed so to minimize the mean-squared error,
\[
\min J = E(\|\epsilon(k)\|^2)
\]  
(2.7)

From Eq. (2.4), (2.6), and by applying the principle of orthogonality to Eq. (2.7), the solution for the antenna weights that minimize the mean-square error (and maximize the output SINR) is given by [40]:
\[
w = R_{xx}^{-1}u_d^*
\]  
(2.8)

where the superscript * denotes complex conjugate and the superscript \(-1\) denotes the inverse of the matrix. Note that, scaling of the weights by a constant does not change the output SINR. The received signal correlation matrix is given by:
\[
R_{xx} = E\left[ \left( x_d + x_n + \sum_{j=1}^{L} x_j \right)^\dagger \left( x_d + x_n + \sum_{j=1}^{L} x_j \right)^T \right]
\]  
(2.9)

where the expectation is taken with respect to signals \( s_d(k) \) and \( s_j(k) \). Assuming the desired signal, noise and interfering signals are uncorrelated, the expectation is evaluated to yield
\[ R_{xx} = \mathbf{u}_j^* \mathbf{u}_j^T + \sigma^2 \mathbf{I} + \sum_{j=1}^{L} \mathbf{u}_j^* \mathbf{u}_j^T \]  \hspace{1cm} (2.10)

where \( \sigma^2 \) is the noise power and \( \mathbf{I} \) is the identity matrix. The transmission power is assumed to be unity for simplicity. However, the transmission power can be optimized to improve the SINR and control the transmission power in order not to interfere with co-channel signal. For instance, Rashid-Farrokhi et al. have proposed joint optimization algorithms of power control algorithm and antenna beamforming [21].
2.4 Dynamic Channel Allocations

In spectrum-starved wireless networks, the allocation of available resource (channel band) is of importance. Fixed channel assignment (FCA) is widely employed in commercial cellular networks. Using FCA techniques means to allocate a fixed fraction of all available channels to an individual cell of a cellular environment. The same set of channels is only used in cells that are separated by a minimum distance. The frequency reuse distance ensures that co-channel interference does not degrade the system

*Figure 2-4: Block diagram of a MMSE beamformer.*
performance greatly. In a cellular system using FCA, cells always occupy pre-assigned channels whether there is a frame to transmit or not. Hence, FCA is not desirable from a system’s utilization standpoint.

In contrast, there have been several algorithms for reducing the frequency reuse factor, e.g., dynamic channel assignment (DCA), hybrid channel assignment, borrowing channel assignment (BCA), forcible-borrowing channel assignment (FBCA), and dynamic packet assignment (DPA) [22, 23, 24]. Unlike the FCA strategy, these non-fixed channel assignment (NCA) algorithms allocate the channel to the cell dynamically based on available resource status, so as to suppress co-channel interference. Especially, DCA techniques enable a cellular system to adapt flexibly to different load situations, thereby increasing the total traffic that can be carried per cell [25]. In addition, the efforts for frequency planning can be reduced or eliminated.

A classification of different DCA approaches was made in [26]. A DCA algorithm can be developed from one of the following three criteria, or combination of them: Traffic adaptability, interference adaptability, and minimum frequency reuse. The criterion of traffic adaptability is to maximize the number of simultaneously active SCs in every cell, resulting in maximum packing. The algorithm based on this aspect requires knowledge about the traffic in every cell. Thus, in a mobile system, the traffic tracking may also be required. The criterion of interference adaptability focuses on the adaptability to interference variations, which is particularly important for interference-limited wireless systems. This requires the DCA to have information on the instantaneous interference. The last criterion is to minimize the channel reuse distance. An ideal DCA
algorithm tries to optimize each of the three criteria. Since the ideal DCA algorithm would require information beyond the scope of a single cell, DCA algorithm should ideally be operated at a central site.

DCA schemes are usually realized either centralized or decentralized [27]. A centralized DCA algorithm collects the required information for channel assignment decisions from the associated BSs and SCs. This type of DCA algorithm is located at higher hierarchical levels of the wireless network architecture. For instance, in TDMA networks, a centralized DCA algorithm can be located at the radio network controller (RNC), which connects several co-channel BSs. The basic disadvantage is that a great amount of signaling is necessary to supply the information about load, interference, and channel status. Meanwhile, when a decentralized DCA algorithm is employed, the channel assignment decision is made locally [28, 29, 30]. Hence, the complexity is considerably reduced.

Interference-Based DCA is one of decentralized DCA schemes. In this scheme, channels are assigned based on the interference power measured, which yields a high degree of flexibility. If the SINR drops below a certain threshold, a new channel is acquired. This requires steady and reliable measurements of the interference power and power control to minimize interference. Due to its simplicity, this type of DCA is widely used. A notable example is the DCA algorithm of the DECT standard [41]. Furthermore, since code division multiple access (CDMA) is an interference-limited multiple access method, interference-based DCA algorithms play an important role in such systems [24, 31]. In [32], a carrier-to-interference (C/I) based DCA algorithm is compared with an
FCA algorithm assuming non-uniform traffic, where FDD operation is assumed. However, as mentioned in section 2.2, D-TDD offers a more flexible adaptation to different uplink and downlink traffic bandwidth. Since many data-oriented services such as, e.g., Web-browsing, are likely to require significantly more capacity on the downlink than on the uplink [1], a D-TDD system seems to be appropriate for such services. Little research has been done to design DCA algorithms for a TDMA/TDD cellular system. As we will show in chapter 3, there may exist strong co-channel interference over extra uplink time slot region in D-TDD system. This strong interference is present if two adjacent cells apply different rates of asymmetry, i.e., the ratio of uplink and downlink time slots, between neighboring cells is different. Since it would be a significant limitation to apply the same rate of asymmetry throughout the entire network, it is interesting to investigate a DCA algorithm which allows for cell-independent asymmetry and at the same time avoids significant capacity losses in a D-TDD system. Since the strong co-channel interference is present only over an extra time slot interval, we are particularly interested in a DCA algorithm, of which objective is to assign a time slot over this interval, such that the effect of strong co-channel interference is minimized.

In this thesis, we will devise DCA algorithms for fully loaded TDMA/TDD system. In such fully loaded system, all channels (time slots) are occupied, thus, the interference adaptation will be considered as the most important criterion.
2.5 Adaptive Transmission

Adaptive transmission is one of the efficient schemes to increase the average spectral efficiency of wireless data communications systems. Adaptive transmission takes advantage of the time-varying nature of wireless channels. Considerable research has been done on adaptive techniques, which are in the form of adapting transmission power level, symbol rate, coding rate/scheme, constellation size, or any combinations of these parameters [33, 34, 35, 36, 37].

Figure 2-5 shows a block diagram of an adaptive transmission system. As shown in the figure, receiver estimates channel state, and the estimated channel state information (CSI) is fed back to the transmitter. Then, the transmitter determines its power and modulation level and coding rate to meet the required BER, based on the CSI. Since there is feedback delay in the feedback channel, the CSI may be different from actual channel state at the time of transmission. However, the channel state varies slowly and shadowing is the major contribution in fixed wireless applications. Yun et al. have analyzed the effect of estimation error on the throughput of adaptive modulation, combined ARQ scheme for lognormal shadowed fixed wireless systems [38]. They showed that substantial gain can be obtained by employing adaptive modulation, even in the presence of CSI estimation errors. Thus, adaptive modulation is expected to be an efficient scheme to increase the spectral efficiency of fixed wireless system.

However, since adaptive transmission adapts the transmission rate to the channel state, the incoming data bits may be delayed in transmission when the channel state is poor. Thus, the adaptive transmission may require buffering at the transmitter. The
buffering may not cause significant degradation of system performance for the data traffic, which is bursty and delay-tolerant. However, the buffering may degrade the quality of voice communications severely, which usually does not require high data rates, but is sensitive to the delay. Consequently, adaptive transmission is suitable for delay-tolerant traffic.

Alouini et al. have considered adaptive transmission for the integrated voice and data traffic. They have employed the adaptive modulation, which adapts the constellation size, for data traffic, while fixed modulation is employed for the voice traffic to sustain the constant bit rate requirement. In chapter 5, we will consider the adaptive transmission to evaluate the spectral efficiency of D-TDD systems.
Figure 2–5: Block diagram of adaptive transmission system.
2.6 Wireless Local Loop

Wireless local loop (WLL) is a system that connects SCs to the public switched telephone network (PSTN) using radio signals as a substitute for copper for all or part of the connections between the SC and the switch. This includes cordless access systems, proprietary fixed radio access, and fixed cellular systems. WLL systems are used in lieu of wired access for fixed residential and business customers. In WLL deployments, instead of providing service to mobile SCs, WLL services provide wireline-quality service to fixed SCs that are traditionally served by links wired to PSTN.

In mobile telephony, highly complicated signal processing schemes are required to combat severe physical impairments, mostly due to mobility. Thus, there are still many challenges to deliver a heterogeneous class of traffic, e.g., an integral of high-quality voice and broadband data traffic, via mobile networks. In contrast, WLL environment shows relatively favorable channel condition. However, since WLL system is considered as a substitute for a broadband-wired network, all classes of traffic should be served with guaranteed QoS. As a consequence, extremely efficient resource allocation strategies, which efficiently utilize the available spectrum, are required to accommodate the heterogeneous multimedia traffic. In this thesis, we will investigate efficient duplex schemes to deliver such broadband communications traffic in WLL environments.
Chapter 3

Characteristics of Co-channel Interference in TDD systems

3.1 Introduction

The unique feature of D-TDD operation, dynamic partitioning between the uplink and downlink transmission, provides many benefits. The major advantage of D-TDD operation, as discussed in chapter 1, is the statistical multiplexing gain obtained by exploiting the nature of burstiness and asymmetric bandwidth between uplink and downlink traffic.

However, the attractive feature of dynamic partitioning results in severely degraded SIR outage performance in cellular networks. It has been noted that TDD systems are seriously limited by co-channel interference from BS in downlink cycle when a reference base station is in its uplink cycle, receiving signal from users [3, 4]. This stems from the fact that the propagation from a base station to a base station (BS-to-BS) suffers less attenuation than that from a subscriber to a base station (SC-to-BS). Chuang has shown that BS-to-BS co-channel interference ($I_{BB}$) degrades the uplink performance severely in S-TDD systems, if information frames are not synchronized [3]. On the other hand, Li et al. have shown that $I_{BB}$ is introduced by the movable boundary in the dynamic-TDD frame, even when frames are synchronized [4].
In this chapter, we investigate the characteristics of co-channel interference, and evaluate SIR outage probability in D-TDD systems for dynamic traffic pattern, in fixed wireless applications. We develop an analytic model of SIR in D-TDD fixed wireless systems. Two antenna layouts are considered in developing the analytic model. First, we employ omni-directional antennas both at BS sites and SC sites. Then, we employ spatial filters at BS sites to suppress the co-channel interference, while omni-directional antennas are deployed at SC sites. The proposed model is verified with the results via Monte Carlo computer simulations.

The rest of this chapter is organized as follows: In section 3.2, we explain the cellular structure and structure of a D-TDD frame used in our analysis. In section 3.3, the path loss model is introduced. In section 3.4, we investigate the characteristics of co-channel interference in TDD systems, qualitatively. In section 3.5, we develop an analytic model of SIR outage probability for two antenna layouts: omni-directional antenna layout and spatial filters. In section 3.6, numerical results are shown. The results from analytical model are verified, using those via Monte Carlo computer simulations. Finally, we conclude with a brief summary of our work shown in this chapter in section 3.7.

### 3.2 Cellular Structure and D-TDD Frame Structure

We consider a hexagonal cellular structure. The reference cell of interest, aimed for analyses, is interfered by two tiers; six cells in the inner tier and twelve cells in the outer tier. The entire cellular system is continuously covered by the hexagonal structure with no overlap. It is assumed that the co-channel cells beyond the second tiers do not
contribute significantly to the aggregate co-channel interference. *Figure 3–1* illustrates the structure of cellular system considered herein.

A D-TDD frame is illustrated in *Figure 3–2*. The frame serves *L*-SCs, which are assumed to be distributed uniformly over the cell coverage. Each SC requests at least one time slot for the transmission of each direction, i.e., uplink and downlink transmission. The first and the last *L*-time slots are assigned to uplink receptions and downlink transmissions. During this time slot interval, all the co-channel cells are in the same cycle as in the reference cell. We denote this time slot interval as the fixed time slot region, $\Pi_{Fix}$. The rest of the time slots in the frame are assigned either to the uplink or to the downlink transmission (otherwise, they remain idle) according to the traffic load. In this chapter, we assume that the frame is perfectly loaded, i.e., all the time slots in the frame are assumed to be assigned to either an uplink or a downlink transmission. The mini time slot structure, shown in *Figure 3–2* (b), is used for call-setup establishment. The detailed description of the mini time slot will be provided in chapter 4.
Figure 3–1: Illustration of the cellular structure (a) Hexagonal Cellular Structure (b) Cluster of Cells. Frequency reuse of 7 is applied.
Figure 3–2: Illustration of a D-TDD Frame structure (a) Whole frame structure (b) Mini slot structure. For illustrative purpose, it is assumed that the number of extra uplink time slots is 6; the number of time slots in a frame is 48; and 12 SCs are served in a frame.
Now, the number of uplink time slots ($n_{up}$) is expressed as:

$$n_{up} = L + N', \quad (3.1)$$

where $N'$ is the number of extra uplink time slots. To model the dynamic traffic pattern, we assume that $N'$ is a uniform integer random variable, which is given as $U[0, N]$. $N$ is a fixed number, which represents the maximum number of extra uplink time slots allowed in each frame. Thus, a larger value of $N$ means more dynamic freedom in the traffic pattern. The time slot interval, from the $(L+1)$-th to the $(L + N')$-th time slot, is called the extra uplink time slot region, denoted as $\Pi_{Ext}$. During this interval, co-channel cells are in uplink or downlink cycle. Since our prime concern is placed on the outage probability performance of D-TDD/TDMA systems, the assumption of perfectly loaded frames provides the worst scenario for co-channel interference evaluation. Therefore, the outage performance reported in this chapter sets an upper bound on similar practical system performance.

### 3.3 Path Loss Model

In our analysis, only lognormal fading is considered to model the shadowing effects in a fixed wireless loop environment. The received signal power level in dB under lognormal fading can be modeled as follows [42]:

$$P_r = \mu + \varsigma, \quad (3.2)$$

where $\varsigma$ is a random variable representing the shadowing effects in propagation and it is a zero mean Gaussian random variable with standard deviation of $\sigma$ in dB, $N(0, \sigma^2)$. 
The parameter $\mu$ denotes local mean power (LMP), which is modeled as a function of the distance between transmitter and receiver $R$, the path loss exponent $n$, the transmitter power level $P_t$ in dBm, and the transmitter and receiver antenna gains, $G_t(\phi)$ and $G_r(\phi)$ in dBi, respectively:

$$\mu = P_t + G_t(\phi) + G_r(\phi) - 10n \log_{10} R.$$  \hspace{1cm} (3.3)

We consider an azimuth plane only, which is of interest in cellular systems. In cellular systems, antenna height at a BS site is much higher than that at a SC site, which results in different signal propagation environments. For instance, signal propagated between two BSs (BS-to-BS propagation) is less blocked by obstacles and attenuated than that propagated between BS and SC (BS-to-SC propagation), or between two SCs (SC-to-SC propagation).

From Eq. (3.2), the received signal power in dB from the desired SC is given by:

$$P_S = \mu_s + \xi_{SB},$$  \hspace{1cm} (3.4)

where $\xi_{SB}$ is a Gaussian random variable with $N(0,\sigma_{SB}^2)$, and $\sigma_{SB}$ is the standard deviation in dB, due to the propagation environment between SC and BS; local mean power, $\mu_s$, is given by:

$$\mu_s = P_t + G_t(\phi) + G_r(\phi) - 10n_{SB} \log_{10} R_d,$$  \hspace{1cm} (3.5)

where $R_d$ is the distance between the reference BS and a desired SC, $n_{SB}$ is the path loss exponent for the propagation between BS and SC.

Meanwhile, the aggregate co-channel interference in dB consists of a number of interfering signals from co-channel cells:
\[
P_i = 10 \log_{10} \left( \sum_{i=1}^{\alpha} p_i \right), \quad (3.6)
\]

where \(\alpha\) is the total number of co-channel interferers, which is related to the number of tiers; \(p_i\) is the interfering signal from the \(i\)-th co-channel cell. We assume that interfering signals from co-channel cells are statistically independent of one another.

In D-TDD systems, partitioning between uplink and downlink time slots is dynamic. All the co-channel cells over \(\Pi_{Fix}\) are in the same cycle, as in the reference cell. However, over \(\Pi_{Ext}\), the aggregate co-channel interference consists of two types of interfering signals, due to dynamic partitioning. Specifically, at the \(m\)-th extra uplink time slot in \(\Pi_{Ext}\), some co-channel cells are in the downlink cycle, while some are in the uplink cycle. Thus, the interfering signal level in dB from the \(i\)-th co-channel cell over \(\Pi_{Ext}\) can be written as:

\[
10 \log_{10} p_i = \begin{cases} 
\mu_{SB} + \xi_{SB} & \text{if originated from SC} \\
\mu_{BB} + \xi_{BB} & \text{if originated from BS}
\end{cases} \quad (3.7)
\]

where \(\xi_{SB}, \xi_{BB}\) are respectively Gaussian random variables with \(N(0, \sigma_{SB}^2), N(0, \sigma_{BB}^2)\); \(\mu_{SB}, \mu_{BB}\) are the LMP values, which are respectively given by:

\[
\mu_{SB} = P_i + G_r(\phi) + G_t(\phi) - 10n_{SB} \log_{10} D_i,
\]

\[
\mu_{BB} = P_i + G_r(\phi) + G_t(\phi) - 10n_{BB} \log_{10} D_i, \quad (3.8)
\]

where \(D_i\) is the distance between the BS in the reference cell and the \(i\)-th co-channel interferer; \(n_{SB}, n_{BB}\) are propagation exponents for SC-to-BS and BS-to-BS propagation environment, respectively. Due to the difference in antenna heights at the BS and SC, the propagation environment of co-channel interference from a BS in a co-channel cell
differs compared to that from a SC in a co-channel cell when the reference cell is in uplink reception. Considering the heterogeneous propagation environments, we use an $n_{SB}$ equal to 4 and a $\sigma_{SB}$ equal to 8 dB for the propagation between a BS and a SC, while an $n_{BB}$ equal to 3 and a $\sigma_{BB}$ equal to 6 dB are used for the propagation between BSs. Also, for the sake of simplicity, we use median values for $R_d$ and $D_i$, in developing analytic model. Although the actual values for the standard deviation of shadowing fading and the path loss exponents depend not only on the antenna height difference but also on the terrestrial configuration itself, we chose those values for the propagation parameters in our cellular model for analysis purpose. However, the parameters for SC-to-BS propagation are typical values in a suburban area cellular system.

Since different propagation environments introduce different values in the path loss exponents and standard deviation values, the interference level from the $i$-th co-channel cell at the $m$-th extra time slot is different whether it is originated from a SC or a BS. This feature differs from that in S-TDD systems, where the source of co-channel interference is homogenous. Furthermore, different distance values $D_i$ will result in different LMP values, even if all the co-channel interference is initiated from SCs (or BSs). For instance, there are three values of $D_i$ in the cellular model considered herein (See Figure 3–1). Therefore, in D-TDD systems, the distribution of aggregate co-channel interference depends not only on the geographical configuration of co-channel interferer, it also depends on the source of co-channel interference, i.e., whether the co-channel interference is originated from a BS or a SC.
3.4 Statistical Behavior of Aggregate Co-channel Interference in TDD Systems

In this section, we investigate statistical behavior of aggregate co-channel interference in TDD systems, qualitatively. The observation of aggregate co-channel interference will give the insight for the statistical behavior of co-channel interference in TDD systems and the effect of dynamic partitioning on SIR outage probability.

In D-TDD systems, there are four possible configurations of co-channel interferers. (See Figure 3–3) For the convenience of illustration, we split a D-TDD frame into three time slot regions: fixed time slot region (the first and the last $L$-time slots), extra uplink time slot region (the uplink time slots after the first $L$-time slots), and extra downlink time slot region (the downlink time slots before the last $L$-time slots).

3.4.1 Fixed time slot region

Figure 3–3 (a) and Figure 3–3 (d) illustrate configurations of co-channel interferers during uplink and downlink transmission, respectively. During the fixed time slot region, all co-channel cells are in the same cycle as in reference cell. Thus, the interfering signals from co-channel cells are homogeneous. This means that the values for $\sigma$ and $n$ are the same for all interfering signals. When the frames are fully loaded, the number of co-channel interferers is the same for all time slots; thus, the distribution of aggregate co-channel interference is the same for all time slots in this time slot region.

Note that, the distribution of aggregate co-channel interference over this region in D-TDD systems is the same as that in S-TDD systems.
3.4.2 Extra uplink time slot region

Inherent nature of D-TDD, dynamic partitioning, results in two distinguished feature of co-channel interference over extra time slot region, compared two the co-channel interference in S-TDD systems: heterogeneous co-channel interference, and dependency of the distribution of co-channel interference.

Due to dynamic partitioning, there may be co-channel cells in downlink cycle, while the reference cell is in uplink cycle over the extra uplink time slot region. This circumstance is illustrated in Figure 3–3 (b).

As mentioned in the previous section, the signal propagation between two BSs is relatively less blocked than that between a BS and SC site. For the system shown in Figure 3–3 (b), the received interference level from CC1 at the reference cell (CC0) is much stronger than that from CC2. Thus, the aggregate co-channel interference of D-TDD system is much stronger than that of S-TDD systems, where all the co-channel cells are in uplink cycle as shown in Figure 3–3 (a).

The distribution of co-channel interference in D-TDD systems over this region is much affected by the number of co-channel cells in downlink transmission. Since the number of co-channel cells in downlink transmission varies at time slots, the distribution of co-channel interference is different at time slots over the extra uplink time slot region. For instance, it is probable that there are more co-channel cells in downlink transmission at the last extra uplink time slot than at the first extra uplink time slot. The distribution of co-channel interference heavily depends on the traffic pattern, i.e., the more dynamic the
traffic pattern is, and the co-channel interference is stronger over the extra uplink time slot region.

3.4.3 Extra downlink time slot region

Now, let us investigate the characteristics of co-channel interference present over the extra downlink time slot region. Over this time slot region, there may be co-channel cells in uplink, while the reference cell is in the downlink duty cycle, as illustrated in Figure 3–3 (c).

In contrast to the configuration shown in Figure 3–3 (b), the aggregate co-channel interference of the D-TDD system in Figure 3–3 (c) is much weaker than that of S-TDD systems, where all the co-channel cells are in downlink cycle as shown in Figure 3–3 (d). Also, the distribution of co-channel interference in D-TDD systems over this region varies at time slots. The aggregate co-channel interference at the first extra downlink time slot is much weaker than at the last extra downlink time slot, since there would be more co-channel cells in uplink cycle. The SIR performance in D-TDD systems over the extra downlink region is expected to be improved, compared to that in S-TDD systems.

Considering the investigation over the three time slot regions, we claim that the SIR performance of D-TDD systems is limited by uplink reception, due to strong interfering signals coming from co-channel in downlink cycle. In consequence, we focus on the evaluation of the system performance for uplink reception only throughout this thesis. (Do not type text in this document beyond here)
Figure 3–3: Configuration of co-channel interference in D-TDD systems over time slot regions (a) Fixed uplink time slot region (b) Extra uplink time slot region (c) Extra downlink time slot region. In the figures, CC0 denotes the reference cell, and CC1, CC2 represent co-channel cells.
Figure 3–3 (cont.)
3.5 Analytical Model of SIR

In this section, we develop an analytical model of SIR outage probability in D-TDD systems. Muammar and Gupta have derived the probability of co-channel interference in Rayleigh and lognormal fading, when an omni-directional antenna is used at the base station [43]. Petrus et al. have extended their analysis to take into account the spatial filter used at the BS [44]. In D-TDD systems, the characteristic of co-channel interference is different than the systems considered therein. In our analysis, we extend those analyses to the D-TDD systems.

3.5.1 Omni-directional antenna layouts

Usually, omni-directional or sector antennas are used at BS site to provide uniform service coverage. For an omni-directional antenna layout, the normalized antenna gain in LMP is 0 dBi for all values of azimuth angle. Thus, the desired signal power is reduced to:

\[ P_S = \mu_S + \varsigma_{SB} \]

(3.9)

where \( \mu_S = -10n_{SB} \log_{10} R_d \).

Then, the PDF of the desired signal power is a Gaussian random variable, expressed as:

\[ f_{P_S}(\gamma) = N(\mu_S, \sigma_{SB}^2) = \chi_{SB}^1(\gamma), \]

(3.10)
where $\mu_s$ and $\sigma_{sb}$ are respectively the mean and standard deviation values of the random variable $(P_S)$ in Eq. (3.9).

Since the co-channel interference over time slots are mutually exclusive, due to their time orthogonal nature in a system using TDMA, the PDF of aggregate co-channel interference can be expressed as:

$$f_{\gamma_i}(\gamma) = \sum_{N'=0}^{N'} f_{N'_{IPf}}(\gamma) \times \text{Prob}\{\text{No. of Ext. Time slots at the reference cell} = N'\} \quad (3.11)$$

where $f_{N'_{IPf}}$ is the conditional PDF of aggregate co-channel interference, provided that the number of extra uplink time slots is $N'$. As we will see later in Eq. (3.16), this conditional PDF is expressed as the sum of two PDFs’ over two regions, $\Pi_{Fix}$ and $\Pi_{Ext}$. When the frame is fully loaded, the distribution of co-channel interference over $\Pi_{Fix}$ ($f_{N'_{IPf}}$) in Eq. (3.16) is not a function of the time slot index. This is because the number of co-channel interferers is fixed and all sources of co-channel interference are homogeneous, thereby, the distribution of co-channel interference is the same over this time slot region. Meanwhile, the distribution of co-channel interference over $\Pi_{Fix}$ ($f_{N'_{IPf}}$) in Eq. (3.16) depends on the extra uplink time slot index $m$, due to the dynamic partitioning. For simplicity, we analyze the PDF of aggregate co-channel interference over these two regions, separately.

Over $\Pi_{Fix}$, all the co-channel cells are in the same cycle as in the reference cell. Thus, the co-channel interference is the same as in Eq. (3.7), whose LMP is expressed as in Eq. (3.8). $D_i$ is determined by the geographical location of the co-channel interferer.
(See Figure 3–1) Note that, \( p_i \) is characterized solely by the geographical location of a co-channel interferer, \( D_i \).

Aggregate co-channel interference in \( \Pi_{Fix} \) is given by:

\[
P_{Fix} = 10 \log_{10} \left( \sum_{i=1}^{\alpha} p_i \right),
\]

where \( \alpha \) is the number of co-channel interferers. Since the frame is assumed to be fully loaded, the number of co-channel interferers (\( \alpha \)) is fixed in the analysis. Also, we assume that the interfering signals from co-channel cells are statistically independent. It has been known that sum of independent lognormal RV’s can be well approximated by another lognormal random variable. In addition, the computation of the statistical parameters of the sum has been studied extensively [45, 46]. In our analysis, we use Schwartz & Yeh’s method [46] to obtain the parameters, i.e., the mean and standard deviation of the sum.

Now, \( f_{\beta_{Fix}} \) is expressed as:

\[
f_{\beta_{Fix}}(\gamma) = N(\mu_{\beta_{Fix}}, \sigma_{\beta_{Fix}}^2) = \chi_{SC}(\gamma),
\]

where \( \mu_{\beta_{Fix}} \) and \( \sigma_{\beta_{Fix}} \) are respectively the mean and standard deviation values of the random variable \( P_{\beta_{Fix}} \) expressed in Eq. (3.12). In this section, we use symbol \( \chi_{SC}^u(\gamma) \) to denote the PDF of the sum of \( u \)-co-channel interference originated from SC sites, while \( \chi_{BS}^v(\gamma) \) is used to denote PDF of the sum of \( v \)-co-channel interference from BS sites.

Over the uplink time slots in \( \Pi_{Ext} \), the number of co-channel cells allocated for downlink transmission is a random variable. Thus, unlike \( P_{\beta_{Fix}} \), the aggregate co-channel interference over time slots in \( \Pi_{Ext} (P_{\beta_{Ext}}) \) is a function of \( k \) and \( m \), where \( k \) is the number
of co-channel cells over downlink cycle and $m$ is the time slot index in the reference cell
in $\Pi_{\text{Ext}}$.

At the $m$-th extra time slot, $f_{\gamma_{\text{Ext}}}$ is expressed by:

$$f_{\gamma_{\text{Ext}}} (\gamma, m) = \sum_{k=0}^{\alpha} W(k,m) \cdot \chi_{\text{Ext}} (\gamma, k) = W(m) \cdot \chi_{\text{Ext}} (\gamma).$$  \hspace{1cm} (3.14)$$

In Eq. (3.14), $W(k,m)$ is the probability that $k$ co-channel cells are in downlink cycle and
$(\alpha-k)$ co-channel cells are in uplink cycle at the $m$-th extra uplink time slot, i.e.,
$W(k,m) = c_m^k d_m^{\alpha-k}$, where $c_m = \text{Prob.} \{ \text{The number of uplink time slots at a co-channel cell} < m \} = \sum_{i=0}^{m-1} \frac{1}{N+1} = \frac{m}{N+1}$, and $d_m = 1 - c_m$. We assume the number of extra uplink time
slots is determined independently for different BSs. $W(m) = [W(0,m) \ W(1,m) \ W(2,m)$
$\ldots W(\alpha,m)]$ and $\chi_{\text{Ext}} (\gamma) = [ \chi_{\text{Ext}} (\gamma,0) \ \chi_{\text{Ext}} (\gamma,1) \ \ldots \ \chi_{\text{Ext}} (\gamma,\alpha) ]^T$. Also, $\chi_{\text{Ext}} (\gamma, k)$ is the
PDF of sum of co-channel interference that $k$ co-channel cells are in downlink and
$(\alpha-k)$ co-channel cells are in their uplink cycle, which is expressed as:

$$\chi_{\text{Ext}} (\gamma, k) = \sum_{i} \Psi \cdot [ \chi_{BB,i}^k (\gamma) + \chi_{SC,i}^{\alpha-k} (\gamma) ].$$  \hspace{1cm} (3.15)$$

As stated in section 3.3, the co-channel interference depends on the geographical location
of a co-channel interferer, i.e., the configuration of co-channel interferer. In Eq. (3.15),
subscript $i$ denotes the different configurations of co-channel interferers, given the values
for $k$ and $\alpha$. The constant $\Psi$ in Eq. (3.15) is introduced to meet: $\int_{\gamma} \chi_{\text{Ext}} (\gamma,k) d\gamma = 1$. Over
many user transmission trials, because configurations of co-channel interferers appear
uniformly, $\Psi$ is simply a reciprocal of the number of all these possible configurations.
Provided that the total number of extra uplink time slots at the reference cell is \( N' \), the PDF of co-channel interference is expressed by:

\[
f_{E_{P}}(\gamma) = \frac{L}{L+N'} f_{E_{P}}(\gamma) + \frac{1}{L+N'} \sum_{m=1}^{N'} f_{E_{P}}(\gamma, m). \tag{3.16}
\]

Now, the PDF of co-channel interference is expressed by:

\[
f_{E_{P}}(\gamma) = \sum_{N'=0}^{N} f_{E_{P}}(\gamma) \times \text{Prob}\{\text{No. of Ext. Time slots at the reference cell} = N'\} = \sum_{N'=0}^{N} f_{E_{P}}(\gamma) \times \frac{1}{N+1}. \tag{3.17}
\]

Substituting Eq. (3.16) and Eq. (3.13) into Eq. (3.17) results in:

\[
f_{E_{P}}(\gamma) = \sum_{N'=0}^{N} f_{E_{P}}(\gamma) \times \frac{1}{N+1} + \frac{1}{N+1} \sum_{N'=0}^{N} \sum_{m=1}^{N'} f_{E_{P}}(\gamma, m). \tag{3.18}
\]

Notice that, in Eq. (3.18), the term corresponding to \( N' = 0 \) is excluded from the summation in the second term, since it is zero. Thus,

\[
f_{E_{P}}(\gamma) = \frac{C(m) \times L \times \chi_{SC}(\gamma)}{N+1} + \frac{1}{N+1} \sum_{N'=0}^{N} \sum_{m=1}^{N'} f_{E_{P}}(\gamma, m), \tag{3.19}
\]

where \( C(m) = \sum_{i=1}^{N} \frac{1}{L+i} \).

The summation in the second term of Eq. (3.19) can be written as:

\[
\sum_{N'=1}^{N'} \sum_{m=1}^{N'} f_{E_{P}}(\gamma, m) = \left( \frac{1}{L+1} + \frac{1}{L+2} + \cdots + \frac{1}{L+N} \right) \times f_{E_{P}}(\gamma, 1)
\]

\[
+ \left( \frac{1}{L+2} + \frac{1}{L+3} + \cdots + \frac{1}{L+N} \right) \times f_{E_{P}}(\gamma, 2)
\]

\[
\vdots
\tag{3.20}
\]
Thus, by substituting Eq. (3.20) into Eq. (3.19), the PDF of co-channel interference is expressed in a matrix form as:

\[
E_{\text{IP}}(\gamma, 1) = \sum_{m=1}^{N} f_{p,m} \left( \gamma, m \right) \sum_{j=m}^{N} \frac{1}{L + j} = \sum_{m=1}^{N} C(m) \times f_{p,m} \left( \gamma, m \right)
\]

where \( C = [C(1) \; C(2) \; \cdots \; C(N)] \), and \( W = [W(1) \; W(2) \; \cdots \; W(N)]^T \).

Now, let us investigate SIR outage probability. The outage is declared when SIR is lower than a threshold value \( \tau \), i.e.,

\[
\text{Prob}\{\text{Outage}\} = \text{Prob}\{\text{SIR} < \tau\} = \int_{\tau}^{\infty} f_{\text{SIR}}(\gamma) \, d\gamma = 1 - \int_{0}^{\tau} f_{\text{SIR}}(\gamma) \, d\gamma , \quad (3.22)
\]

where \( f_{\text{SIR}} \) is the PDF of SIR. Since the desired signal and aggregate co-channel interference in dB are Gaussian random variables, the signal and aggregate co-channel interference are assumed to be statistically independent in our analysis, the PDF of SIR can be expressed as convolution of these two PDFs [47]:

\[
f_{\text{SIR}}(\gamma) = f_{p_s}(\gamma) \otimes f_{p_i}(-\gamma), \quad (3.23)
\]

where \( \otimes \) denotes convolution operator; \( f_{p_s} \) is PDF of the desired signal power and \( f_{p_i} \) is PDF of the aggregate co-channel interference.
3.5.2 Spatial filter

Spatial filtering is one of well-known scheme to suppress the deleterious effect of co-channel interference, thereby, increase the capacity of cellular networks. Petrus et al have considered two types of spatial filters to model the beam pattern of adaptive array antennas [44]. An ideal beamformer has employed to model the beam pattern of adaptive array antennas, when the array is underloaded, while a flat-top beamformer is employed to model the beam pattern when the array is overloaded. When the number of interferers is one less than the number of elements, the array is said to be underloaded, otherwise, the array is said to be overloaded. The beam patterns of spatial filter models are illustrated in Figure 3–4.

In our analysis, we assume that array is always underloaded. When the array is underloaded, it can form deep nulls in the direction of the interferers and hence is closely modeled by an ideal beamformer. Thus, we employ an ideal beamformer in the analysis. The gain of an ideal beamformer is defined as:

\[
G (\phi) = \begin{cases} 
G_{\text{Ideal}} & \phi \in \Theta_{\text{Ideal}}, \\
0 & \text{otherwise,}
\end{cases}
\]

(3.24)

where \(\Theta_{\text{Ideal}}\) is beamwidth of an ideal beamformer. Since it is assumed that the mainlobe of the antenna pattern is aligned with the direction of incoming desired signal, PDF of desired signal is independent of the beamwidth of the antenna array. However, PDF of co-channel interference is related to the array beamwidth.
Outage probability performance can be improved using a spatial filter by increasing spatial resolution. We employ an ideal beamformer at a BS site for uplink reception. For the sake of simplicity, we assume that omni-directional antennas are employed for downlink transmission. Thus, a BS employs an adaptive array antenna for uplink reception, while it switches to an omni-directional antenna for downlink transmission.

*Figure 3–4: Beam pattern of analytic beamformer. (a) Ideal beamformer (b) Flat-top beamformer. $\Theta_{\text{ideal}}$ denotes beamwidth of an ideal beamformer, and $\Theta_{\text{ML}}$ denotes beamwidth of mainlobe.*
Let us denote $\alpha_{UL}$ as the number of co-channel interferers within the beamwidth of an ideal beamformer $\Theta_{\text{ideal}}$. By observing the cellular structure, one can find that $\alpha_{UL} \in \{0, 1, 2\}$, when $\Theta_{\text{ideal}} < \pi/6$. We denote the event that $\alpha_{UL} = i$, where $i \in \{0, 1, 2\}$ as $E_i$.

The PDF of co-channel interference, conditioned on $E_i$, is given by:

$$f_{\gamma|E_i}(\gamma) = \frac{1}{N+1} \left[ C(0) \cdot L \cdot \gamma^{\alpha_{UL}} + C \cdot W \cdot \chi_{\text{Ext}}(\gamma) \right], \quad (3.25)$$

where $i \in \{0,1,2\}$.

Thus, PDF of co-channel interference is given by:

$$f_{\gamma}(\gamma) = \sum_{i} f_{\gamma|E_i}(\gamma) \cdot \text{Prob.}\{E_i\}, \quad (3.26)$$

where $\text{Prob.}\{E_i\} = 3 \cdot \Theta_{\text{ideal}}/\pi$ for $i \in \{1,2\}$ and $\text{Prob.}\{E_0\} = 1 - [\text{Prob.}\{E_0\} + \text{Prob.}\{E_2\}]$.

Now, the SIR outage probability, when an ideal beamformer is employed, is obtained from Eq. (3.23), by substituting Eq. (3.26) into Eq. (3.23).

### 3.6 Numerical Results

In our evaluations, we assume a hexagonal cellular system with a cell radius of 2 km, and a frequency reuse of 7 is considered. Each TDD frame is divided into 48 time slots and serves 12 SCs ($L = 12$). At least one slot is assigned for each user for uplink and downlink transmissions. Thus, the maximum number of time slots for the downlink can be 36. The frames are synchronized, and fully loaded. In our analysis, up to second tiers are considered, i.e., $\alpha = 18$. 
No specific modulation scheme, diversity reception, error control coding nor an equalization technique is considered, herein. Only SIR is investigated as a performance measure for the systems under investigation. Multipath fading is not considered, either. Since multi-carrier modulation has the potential to eliminate the ISI effect completely, orthogonal frequency division multiplexing (OFDM) can be used as a modulation scheme for the D-TDD system [48]. For simplicity, channel is assumed to be a single-ray, frequency-flat fading. The maximum transmission power over the azimuth plane from SCs and BSs are assumed to have the same levels. In practice, these are of different power levels. However, in the simulations, these differences are taken into account by the use of different propagation exponent factors.

3.6.1 Omni-directional antenna layouts

Figure 3–5 shows the PDF of aggregate co-channel interference, $f_{\gamma}(\gamma)$. In the figure, we compare the PDF of aggregate co-channel interference obtained by analytical model to that by Monte-Carlo computer simulation. In the computer simulation, 10000 frames are generated to evaluate. As shown in the figure, two curves agree well. There are two peaks in the PDF curve, i.e., the PDF is bimodal. The peak on the left, which causes severe outage probability degradation, is due to the strong co-channel interference present over $\Pi_{Ext}$, while the second peak is mainly due to the co-channel interference over $\Pi_{Fix}$. 
The SIR outage performance of D-TDD systems is shown in Figure 3–6. The effect of strong co-channel interference is dominant on the outage performance. Figure 3–7 shows the effect of $N$ on the SIR outage probability. A threshold SIR value of 17 dB is assumed. The value is sufficient for a fixed wireless local loop application. It is shown that the outage probability performance becomes poorer, as the number of extra uplink time slots ($N$) is increased. This is because the expected number of BS-to-BS co-channel

Figure 3–5: PDF of aggregate co-channel interference, for $N = 6$. 
interferers, which is the dominant source of co-channel interference is increased as $N$ is increased. In the figure, when $N = 0$, the outage probability represents that of S-TDD system. The outage probability of S-TDD system can be improved by increasing the frequency reuse number, at the cost of a poor spectral efficiency. As an alternative, the uplink outage performance of a S-TDD system can be improved by employing a high-gain antenna at SC sites, while that of a D-TDD remains severely degraded due to BS-to-BS co-channel interference [4]. The simulation results show that the performance of D-TDD system during uplink reception is seriously degraded, unless a certain countermeasure is employed to suppress the deleterious effects of the strong co-channel interference.
Figure 3–6: SIR outage curves, for $N = 6$. 
3.6.2 Spatial filter

*Figure 3–8* shows the effect of $\Theta_{\text{ideal}}$ on the outage probability, when $N = 6$. We use SIR threshold value ($\tau$) of 17 [dB]. The numerical results show that the outage probability performance is linearly improved as the beamwidth is reduced. The figure shows that beamwidth of 3.4 degrees are required to achieve outage probability of 1%. 

*Figure 3–7*: The effect of $N$ on the outage probability. An SIR threshold value of 17 dB is used.
This means that we need more than 106 sectors to obtain the required outage probability, which seems to be impossible to implement.

Another interest may be the number of antenna elements required to achieve the outage probability, when adaptive array antennas are employed at BS site. The array factor of uniform linear array (ULA) is given by [49]:

$$ A(\phi) = \left[ \sin \left( \frac{M \pi}{2} \sin \phi \right) / \sin \left( \frac{\pi}{2} \sin \phi \right) \right], \quad (3.27) $$

where $M$ is the number of antenna elements, and half lambda spacing is assumed between the elements. We choose $\Theta_{\text{ideal}}$ for ideal beamformer so that the power gain of ideal beamformer is the same as that of ULA over the main lobe:

$$ \Theta_{\text{ideal}} = \frac{\int_{-\Theta_N/2}^{\Theta_N/2} |A(\phi)|^2 d\phi}{\int_{-\Theta_N/2}^{\Theta_N/2} A(\phi)^2 d\phi}, \quad (3.28) $$

where $\Theta_N$ is main lobe beamwidth of ULA.

From the relation in Eq. (3.28) and Figure 3–8, we observe that 16 antenna elements can obtain the outage probability of 2%, while 30 antenna elements obtain the outage probability less than 1%, for the threshold SIR value of 17 dB. In [4], significant improvements on outage probability of D-TDD systems have been reported employing 8, 16, and 26 element uniform circular array (UCA) antennas in a square grid cellular system. Especially, they have shown via computer simulations that the adaptive array antenna with 26-antenna elements obtains the outage probability less than 1%. Although the assumption of flat antenna gain over antenna beamwidth in the analytic model overestimates the effect of co-channel interference, the numerical results employing our analytic model show close agreement with that via the computer simulations.
Summary and Conclusions

In this chapter, we evaluated outage probability in D-TDD/TDMA systems. We provided an analytic expression for outage probability. Numerical results using the proposed expression agree well with those obtained via Monte Carlo simulations. According to our investigation, the PDF of aggregate co-channel interference in

Figure 3–8: The Effect of beamwidth ($\Theta_{\text{ideal}}$) on the outage probability.

3.7 Summary and Conclusions

In this chapter, we evaluated outage probability in D-TDD/TDMA systems. We provided an analytic expression for outage probability. Numerical results using the proposed expression agree well with those obtained via Monte Carlo simulations. According to our investigation, the PDF of aggregate co-channel interference in
TDMA/D-TDD systems is *bimodal*, which is different compared to that in TDMA/S-TDD systems. Thus, a D-TDD system is vulnerable to strong co-channel interference, $I_{BB}$, due to dynamic partitioning of uplink and downlink time slots. It has been shown that the outage probability is seriously degraded when omni-directional antennas are used at BS sites and SC sites.

Meanwhile, we show that the outage probability is improved by deploying a spatial filter at BS sites. Since the dominant co-channel interferers can be resolved spatially, spatial filters such as sector antennas or adaptive array antennas at the BS site are expected to improve the outage performance substantially.
4.1 Introduction

In the chapter 3, we showed that the SIR outage performance of a D-TDD system is degraded severely by co-channel interference. Especially, it is observed that the strong BS-to-BS co-channel interference ($I_{BB}$) present over the extra uplink time slot region severely degrades the performance. Thus, a method of suppressing the effect of $I_{BB}$ will improve the outage probability of a D-TDD system.

In this chapter, we propose a novel interference avoidance method, time slot allocation (TSA) strategy, which consists of a simple spatial filter (sector antenna) and transmission scheduler. To reduce the SC-to-SC interference, we employ high gain antennas at SC sites, aligned in the direction of the desired BS. We consider two TSA algorithms: the $Max\{\text{SIR}\}$ and the $MaxMin\{\text{SIR}\}$ algorithms. The $MaxMin\{\text{SIR}\}$ algorithm searches for the best pair of SC and time slot for extra uplink time slots from all possible pairing combinations such that the minimum expected SIR value is maximized over the extra uplink time region. Since this algorithm performs the search procedure in an exhaustive manner, the computational complexity is increased steeply, as the number of extra uplink time slots is increased. Meanwhile, another algorithm, the...
Max \{SIR\}, searches the best SC for the time slot of interest, and the search algorithm is performed on the time slot basis, which reduces the complexity substantially.

An adaptive array antenna is a well-known spatial filter, as studied in chapter 2. In this chapter, we evaluate the SIR outage probability of a D-TDD system employing adaptive array antennas. In this system, adaptive array antennas are employed at BS sites for uplink reception, while omni-directional antennas are used for downlink transmission. The system performance is compared with that employing the proposed TSA algorithm.

The rest of this chapter is organized as follows. In section 4.2, we introduce a new co-channel interference management method in D-TDD systems. This strategy is referred to as interference avoidance, which employs time slot allocation strategy. We explain this strategy and compare it with conventional interference suppression method, spatial filtering. In section 4.3, we propose two time slot allocation strategies to improve SIR performance of D-TDD systems. First, the best pairing search algorithm (MaxMin \{SIR\}) is investigated as a performance benchmark. Then, a simple TSA strategy (Max \{SIR\}) is investigated. In section 4.4, we provide numerical results employing the proposed TSA strategies. The performance of the Max \{SIR\} algorithm is compared with that of an adaptive array antenna system, as well. In section 4.5, we conclude with a brief summary of our work and state our observation based on the results obtained.
4.2 Interference Management in D-TDD systems: Interference Suppression versus Interference Avoidance

In a D-TDD system, new entity, $I_{BB}$, degrades outage probability severely. To suppress the co-channel interference, we used spatial filters in chapter 3. As an interference management method, we refer to the spatial filtering scheme as interference suppression method. As shown in section 3.6.2, enormous number of sectors (or antenna elements) is required to provide SIR values of 17 dB at the target outage probability of 1%. This excessive number of sectors (or antenna elements) is required mainly to suppress the strong co-channel interference, $I_{BB}$, present only during the extra time slots. In contrast, a relatively small number of sectors (or antenna elements) may be required in S-TDD systems, since there is no $I_{BB}$. Thus, the cost of D-TDD system employing interference suppression method would be high, compared to that of S-TDD system.

Now, let us consider another possibility for improving the uplink SIR outage performance. One intelligent way of interference management is to schedule the SCs’ transmission order for all extra uplink time slots, by taking advantage of spatially distributed SCs’ locations. In other words, the scheduler arranges the transmission order such that the SIR values over the extra uplink time slot region are improved. To be specific, by employing a simple spatial filtering scheme, such as a sector antenna, a BS can estimate the aggregate co-channel interference caused by $I_{BB}$ for each sector. Also, spatially distributed SCs provide the degree of freedom for a BS to choose a sector, in reference to the SC position, which is the best, in the sense that minimum co-channel interference is introduced. Exploiting the orthogonal nature of TDMA frames, a BS can schedule SCs’ transmission requests for all the extra uplink time slots, such that the best
sector is active for the time slot. This method is referred to as *interference avoidance*, rather than *interference suppression*. The spatial filtering schemes, such as sector antennas and adaptive array antennas, try to *suppress* the co-channel interference for a given configuration of co-channel interferers, while the time slot allocation (TSA) strategies introduced in this chapter try to *avoid* the strong co-channel interference by exploiting the spatial distribution of SCs’ locations within a cell and the time orthogonal nature of TDMA frames.

### 4.2.1 Illustrative Example

To illustrate how the TSA strategies work, let us consider the cellular system shown in *Figure 4–1*. In this example, seven SCs are served during one frame, which are assumed to be distributed uniformly over the cell. For simplicity, only uplink time slots are illustrated in the figure. (See the uplink time slots shown in *Figure 4–1* (a).) The first seven time slots are assigned to seven SCs. The rest of three uplink time slots are assigned to the SCs, who request additional time slots. Let us consider the co-channel interference at the reference cell (CC0) introduced at the first extra uplink time slot. As shown in *Figure 4–1* (b), the active sector sees two co-channel cells in downlink cycle. Thus, the aggregate co-channel interference introduced via this sector is expected to be larger than that introduced via the sector which looks at less number of co-channel cells in downlink. (Do not type text in this document beyond here)
Figure 4–1: Illustrative example of TSA strategy. (a) The location of SCs to be served at the D-TDD frame. (b) D-TDD frame corresponding to the configuration of (a). (c) The active sector and the geographical configuration of co-channel interference. (d) The active sector corresponding to the newly assigned SC at the time slot of interest (e) The D-TDD frame corresponding to the configuration of (d). Note that, the number shown in a time slot represents the subscriber ID.
Figure 4–1 (cont.)

Co-channel Cell in uplink cycle

Co-channel Cell in downlink cycle
Figure 4–1 (cont.)
4.3 TSA Algorithms

We propose two TSA strategies: the MaxMin {SIR} and the Max {SIR}. The MaxMin {SIR} is a time slot strategy which maximizes the minimum expected value of SIR over extra uplink time slots region. Meanwhile, the Max {SIR} is a simple and efficient algorithm to improve the outage performance. As mentioned earlier, the objective of TSA is to suppress the co-channel interference such that the uplink SIR outage probability performance is improved.

4.3.1 System specification and assumptions

The following is assumed in our analysis. All the BSs share the frame resource information such as the number of downlink time slots, the active sector index table, etc. Hence, the reference BS knows when a co-channel cell starts downlink transmissions, and which sector will be turned on at each downlink time slot. SCs are allowed to transmit uplink (or downlink) transmission based on contention or reservation. However, initial call setup should be established, based on contention. For the call setup establishment, mini time slots can be considered. In a mini time slot structure, one or more time slots are divided into several time slots. Over several mini time slots, SCs send a transmission request to a BS. Then, a BS determines L-SCs from requests for uplink/downlink transmissions and broadcasts the results (See Figure 3-2 (b)). Also, we assume that the SCs are distributed uniformly over the cell coverage area. Once the initial
call setup is successful, the subsequent transmissions can be continued either on a contention or on a reservation basis, depending on the service requirements of each session. This scheme can be considered as a combination of slotted ALOHA and reservation. Our prime concern here is to address an efficient algorithm to assign uplink time slots so as to suppress the strong co-channel interference, rather than to meet fair queuing policy requirements. Hence, we assume that BS always succeeds to resolve $L$-SCs. Also, we assume that the frame information among BSs is shared by all BSs within the cellular systems such that the reference cell can assign uplink time slots, based on the two TSA strategies explained in the following.

4.3.2 SIR level estimation

TSA algorithms assign SCs to time slots, based on estimated SIR values. Also, SIR values used in TSA are estimated only based on the co-channel interference values from a co-channel BS on the downlink. We consider two types of SIR value estimation procedures: blind estimation and perfect estimation.

For blind estimation procedure, it is assumed that the link quality between a BS and the desired SC is not available at a BS. In this procedure, the SIR level is estimated based on the LMP values, i.e., the effect of fading is not considered for the estimation. Thus, the signal power level of a SC-$l$ is estimated as follows:

$$
\tilde{P}_{BLIND}(l) = G(\phi) - 10n_{cell} \log_{10} R_u,
$$

(4.1)
where $G(\phi)$ is the antenna gain in the direction of the desired SC, and $R_\theta$ is the distance between the reference BS and the SC. Since the geographical location of SCs within a cell is known to a BS, the signal power level can be estimated by a lookup table method.

For perfect estimation procedure, it is assumed that a BS knows the link quality between a BS and the desired SC. Since the link quality in fixed wireless environments varies slowly, the link quality measured by a SC during downlink transmission can be fed back to a BS at the next uplink transmission. We denote the signal level of the $l$-th SC as $\tilde{P}_{\text{CSI}}(l)$, which is assumed to be measured perfectly.

At the $m$-th extra uplink time slot, aggregate co-channel interference in dB can be obtained by taking account of all co-channel interferences originated from BSs, when sector-$s$ is active at the reference BS:

$$\tilde{I}(m,s) = 10 \log_{10} \left[ \sum_i \tilde{p}_i(m,s) \right], \quad (4.2)$$

where $\tilde{p}_i(m,s)$ is the interference from the $i$-th co-channel cell in downlink transmission when sector-$s$ is active at the reference BS, given by:

$$10 \log_{10} \tilde{p}_i(m,s) = G_i(\phi) + G_s(\phi) - 10 n_{\text{BB}} \log_{10} D_i. \quad (4.3)$$

Notice that, $\hat{I}(m,s)$ will be different for an active sector index $s$, which depends on the geographical location of a subscriber.

Now, the estimated SIR level in dB for the $l$-th SC at the $m$-th extra time slot can be obtained with/without CSI:

$$g_{\text{CSI}}(m,l) = \tilde{P}_{\text{CSI}}(l) - \tilde{I}(m,s), \quad (4.4.a)$$
The SIR levels estimated in Eq. (4.4) are used in TSA algorithms. In numerical evaluations, we will discuss the effect of channel estimation on the performance of TSA strategies. For the convenience of denotation, we denote \( g(m,l) \) as a collective representation of \( g_{\text{CSI}}(m,l) \) and \( g_{\text{BLIND}}(m,l) \).

### 4.3.3 MaxMin \{SIR\} Algorithm

The best pairing strategy that minimizes outage probability is to maximize the minimum value of \( g(m,l) \), i.e.:

\[
\text{Max}\{\text{Min}[g(m,l)]\}, \quad \forall m,l
\]

(4.5)

where \( m \) is the extra uplink time slot index, \( m \in \{1, 2, \cdots N\} \), and \( l \) is the subscriber index served for the frame, \( l \in L \). Note that, there may be the multiples of same elements in the set \( L \), since a certain SC may be served for multiple uplink time slots. The strategy searches the best pair of a SC and uplink time slot index for all extra uplink time slots in an exhaustive manner. The assignment algorithm is depicted in Figure 4–2. In the figure, \( \Theta(m,l) \) denotes an assignment operation, which assigns the element \( l \) in the set \( L \) to \( m \) in the set \( \Pi_{\text{Ext}} \). The operator “−” in Figure 4–2 denotes the set subtraction.

\[
g_{\text{BLIND}}(m,l) = \tilde{P}_{\text{BLIND}}(l) - \tilde{T}(m,s).
\]

(4.4.b)
Figure 4–2: Flow Chart for the MaxMin \{SIR\} Algorithm.
Since there may be more than two identical elements in the set $L$, only one of them is subtracted. After the assigning procedure is performed over $\Pi_{Ext}$, the remaining elements in $L$ are assigned over $\Pi_{Fix}$. Since this procedure maximizes the minimum $g(m,l)$, the outage probability is minimized. However, this strategy takes some intensive computations, as $N$ is increased, due to exhaustive search procedure. We use the outage performance employing the $MaxMin \{SIR\}$ algorithm as a benchmark.

### 4.3.4 Max $\{SIR\}$ Algorithm

Max $\{SIR\}$ Algorithm assigns the $l$-th SC at the $m$-th extra uplink time slot, which satisfies the following:

$$Max\{g(m,l)\}.$$  \hspace{1cm} (4.6)

This algorithm is devised on a heuristic manner, by observing the traffic distribution over $\Pi_{Ext}$. The expected number of co-channel interferer in downlink cycle at the $m$-th extra time slot is increased as the index $m$ is increased. Thus, the expected SIR value will be minimal at the $N'$-th extra uplink time slot. For this reason, the algorithm starts to perform the procedure from the $N'$-th extra uplink time slot, to provide the largest degree of freedom for a BS to choose. The subscriber is assigned, then, $L$ and $\Pi_{Ext}$ are updated. This procedure is repeated, until the first extra uplink time slot is assigned. This is illustrated in Figure 4–3. Since the Max $\{SIR\}$ performs the pairing search procedure on a time slot basis, it requires less computation than the $MaxMin \{SIR\}$. 
4.4 Numerical Results

For numerical evaluation, we use the cellular system and frame structure employed in chapter 3.

$S$-sector antennas are deployed at BS sites, where $S \in \{8, 12, 15\}$. At each sector, a square aperture antenna is deployed. Under uniform illumination, the far-field antenna pattern over azimuth plane is proportional to [50]:

\[ \text{Figure 4–3: Flow Chart for the Max \{SIR\} algorithm.} \]
where $\kappa$ is the wave number, $a$ is the lateral size of the aperture, and $\phi$ is the azimuth angle. Thus, the power gain pattern is given by: 

$$G(\phi) \propto 20\log_{10}\left(\frac{E(\phi)}{\sin\phi}\right).$$

To complete sectors, $S$-square aperture antennas are mounted such that the half power beam width (HPBW) points of antennas are overlapped. Thus, the normalized antenna beam pattern is fully characterized by the number of sectors. For instance, if the number of sectors is 8, the HPBW of each sector is 45 degrees. Also, the square aperture antenna with a HPBW of 20 degrees is deployed at the SC site to suppress the SC-to-SC co-channel interference.

The outage probability performance for two estimation procedures is compared in Figure 4–4. It is observed that the benefit of CSI is not so favorable when traffic dynamic gets large. Even for small traffic dynamics, it is observed that the benefit is not noticeable at the SIR threshold value of interest, e.g., say 17 dB. Thus, the proposed algorithms perform well without resorting to CSI estimation.

Figure 4–5 shows the performance comparison of the two TSA strategies: the Max $\{\text{SIR}\}$ and the MaxMin $\{\text{SIR}\}$. For comparison purposes, we used a 12-sector antenna at the BS sites, and a 20 degrees high-gain antenna at the SC sites.
Figure 4–4: The Effect of CSI on the performance of TSA.
The \textit{MaxMin} \{SIR\} algorithm is a more efficient algorithm than the \textit{Max} \{SIR\} algorithm in avoiding strong co-channel interference, $I_{bb}$, at the expense of higher complexity. As the traffic becomes more dynamic, the computation intensity is increased sharply. Meanwhile, the \textit{Max} \{SIR\} algorithm is simple and efficient. It is shown that the difference in the outage performance is not noticeable. At an outage probability of 1%,

\textit{Figure 4–5:} Comparison of Two TSA algorithms ($S = 12$).
the difference in the achievable SIR values between these two algorithms are about 1 dB and 0.3 dB for $N = 12$ and $N = 6$, respectively. Also, when $N = 3$, the difference is negligible. Thus, the $Max \{SIR\}$ algorithm performs well over a large range of traffic dynamic ($N$).

Figure 4–6 shows outage probability of a 15-sector antenna system with/without TSA. In the simulation, the $Max \{SIR\}$ was used. It is shown that the outage probability is improved substantially (14 dB improvement at an outage probability of 1%), when the TSA is employed. Usually, this requires fine spatial resolution in order to suppress co-channel interference at the expense of system complexity. However, using the simple TSA ($Max \{SIR\}$), outage probability performance can be substantially improved.

Also, considering that a system is rarely utilized perfectly, the fixed antenna layout based on a worst-case design may underutilize the system resources. Consequently, using TSA, combined with a sector antenna layout, provides a compromise between the system complexity and performance.

Figure 4–7 shows the SIR outage performance for the $Max \{SIR\}$ with different spatial resolution at a BS. The increase in the number of sectors results in a fine spatial resolution. Thus, BS has a larger degree of freedom to select the SC so as to avoid co-channel interference. Computer simulations show that the difference in achievable SIR value between an 8 sector and a 12 sector antenna is about 4.6 dB at an outage of 1%, when $N = 6$.

Finally, an outage performance comparison between a system employing the $Max \{SIR\}$ algorithm and that employing an adaptive array antenna (AAA) is made in Figure
4–6. Li et al. have employed adaptive array antennas, to suppress the co-channel interference in D-TDD systems [4, 5]. They have used adaptive array antennas at BS sites for uplink reception, while omni-directional antennas are used for downlink transmission. We adopt the same antenna layouts used in their work, to use a basis for performance comparison. Minimum mean square error (MMSE) scheme is used for adaptive beam forming. The simulation results show that only a 26-element adaptive array antenna system provides more than SIR value of 19.4 dB at the outage probability of 1% among the adaptive array antenna system layouts considered herein. Meanwhile, 15 sectors system provide more than 19 dB at the same outage probability, among TSA systems employing Max \{SIR\} algorithm.

For convenience, the possible system layouts to guaranty the target outage probability at the SIR threshold value of 17 dB are tabulated in Table 4–1. For instance, to maintain an uplink SIR outage probability of 1% at a threshold SIR value of 17 dB, a system employing the Max \{SIR\} algorithm requires at least 15 sectors, while a system employing an adaptive array antenna requires at least 26 sensor elements. Our simulation shows that the outage performance of a 15-sector antenna system with the Max \{SIR\} algorithm is almost comparable with that of a 26-element adaptive antenna system.
**Figure 4-6**: The effect of TSA (N=6). 15-Sector Antennas are employed at a BS site.
Figure 4–7: Effect of Spatial resolution at a BS site.
Figure 4–8: Outage Performance comparison between TSA systems and adaptive array antenna systems. MMSE beamforming is applied for adaptive array antenna systems.
4.5 Summary and Conclusions

In this chapter, we proposed novel methods to improve SIR outage probability of D-TDD system. Two kinds of TSA algorithms were developed; the MaxMin \{SIR\} and the Max \{SIR\}. The MaxMin \{SIR\} strategy provides higher improvements in the outage probability than the Max \{SIR\} strategy does, since it maximizes the minimum value of estimated SIR among all possible subscriber/time-slot assignments. However, enormous computational complexity is introduced as $N$ is increased. Meanwhile, the Max \{SIR\} algorithm requires less computation than MaxMin \{SIR\} algorithm. The difference in SIR outage performance between the two algorithms is not noticeable. In particular, the difference is negligible when the range of traffic dynamics ($N$) is small (e.g., for $N = 3$).
Our simulation shows that the Max {SIR} algorithm, combined with a sector antenna layout, provides substantial improvements in the outage probability. It is shown that the outage performance of a 15-sector antenna system with the Max {SIR} algorithm is comparable to that of a 26-element adaptive array antenna system. The proposed strategy shows a practical compromise between the complexity/cost and the required outage performance.
Chapter 5
Spectral Efficiency of TDD Fixed Cellular Systems

5.1 Introduction

In wireless systems, the radio spectrum available for services is extremely scarce. While the available spectrum is limited by federal communications commission (FCC) regulation, the physical impairments in wireless environments place high challenges to obtain high-speed reliable communication systems. Moreover, the ever-increasing demands on broad bandwidth require wireless systems to exploit spectrum efficiently. Spectral efficiency is a measure, which quantifies how efficient cellular networks utilize frequency spectrum. Thus, spectral efficiency has been of primary concern in the design of wireless communications systems. There have been intense studies about spectral efficiency of cellular system [22, 51, 52].

Conventionally, spectrum efficiency has been analyzed for the worst-case channel condition, i.e., the traffic pattern of uplink and downlink is assumed to be static and frame is assumed to be fully-loaded. In [51], the spectral efficiency is expressed in terms of [erlang/unit area], which is appropriate measure for voice traffic. However, the emerging multimedia traffic consists of voice traffic and data traffic as well. This integrated traffic shows different characteristics than voice only traffic. The nature of multimedia traffic is no longer static in its uplink and downlink bandwidth, and the
bandwidth is more biased to the downlink transmission. In section 1.1, we showed that statistical multiplexing gain can be obtained by adapting the boundary to its traffic pattern. In this context, the assumption of static traffic pattern in analysis of the spectral efficiency does not provide much insight for the dynamic asymmetric traffic. Consequently, the spectral efficiency needs to be expressed in other measure to reflect the new traffic characteristics. Recently, Alouini et al. have expressed spectral efficiency of cellular system employing adaptive modulation scheme in terms of [bps/Hz.m\(^2\)] to consider the effect of intense of data traffic offered to a unit area [52]. However, they have not considered the bandwidth variation between uplink and downlink traffic.

In this chapter, we evaluate the spectral efficiency of TDMA/TDD systems for dynamic traffic pattern in terms of [bps/Hz.m\(^2\)], to reflect the intense of the traffic and the effect of bandwidth variation, as well. Also, we investigate how the frame loading condition affects the spectral efficiency. Although the asymmetric and dynamic feature of multimedia traffic is expected to provide multiplexing gain in D-TDD system, the inherent effect of BS-to-BS co-channel interference degrades the channel condition severely, as shown in chapter 3. In our analysis, Max \{SIR\} algorithm is employed in D-TDD operation to suppress the effect of strong co-channel interference.

In the analysis, we consider two types of modulation schemes. The fixed modulation scheme is widely employed for most commercial mobile cellular systems. In this scheme, the modulation level is fixed all the time, regardless of channel variation. This modulation scheme is suitable for delay sensitive traffic, e.g. voice telephony, where constant bit rate transmission may be preferred. Meanwhile, adaptive modulation scheme
has been known as a means to increase the spectral efficiency of link capacity, due to its adaptability to the link quality. As shown in chapter 2, adaptive modulation scheme can improve the spectral efficiency of wireless data system substantially. Since the adaptation may require buffering in transmission, this scheme is suitable for delay tolerant traffic, e.g. data communications. In this chapter, we investigate the effect of both modulation schemes on the spectral efficiency of TDD operations.

The rest of this chapter is organized as follows. In section 5.2, we explain traffic model and frame loading used in this chapter. In section 5.3, we define spectral efficiency for both TDD systems. We analyze the effect of frame loading on the spectral efficiency. In section 5.4, we provide numerical results to compare spectral efficiency of TDD schemes. Finally, we conclude with summary of our investigations in section 5.5.

5.2 Frame Loading Condition

In chapter 3 and chapter 4, we evaluated SIR outage probability of D-TDD systems, when frames are fully loaded. For conventional analysis, the frame is assumed to be fully loaded, so that the analysis is robust for the worst-case. However, the frame loading condition would vary according to the traffic pattern. For instance, even for the same dynamic traffic pattern, D-TDD frame may be fully loaded, while S-TDD frame may be partially loaded.

In our analysis, we assume both TDD operations support $L$-SCs. Some of $L$ subscribers may request more than one time slot in the transmission of either direction. We use the same frame structure in chapter 2, however, the number of extra time slots is
assumed to be \( L \). The bandwidth requested from \( L \)-SCs is assumed to be the same for both TDD systems. This means that the total number of uplink time slots (or, downlink time slots) requested from \( L \) subscribers is the same for both TDD modes operations. The requested time slots are accommodated, if there are available time slots in the frame. Since the nature of data traffic is usually asymmetric and bursty, the bandwidth ratio of uplink to downlink varies from frames. In D-TDD operation, the dynamic partitioning between uplink and downlink transmission enables to accommodate the additional requests of the transmission bandwidth of one direction, if there is available timeslot in the transmission of the other direction. Meanwhile, in S-TDD operation, since the bandwidth (the number of time slots) is fixed, the requested time slots, which exceed the predefined bandwidth, can not be served for the frame, even if there are idle time slots in the transmission of the other direction.

In D-TDD system analyzed in this chapter, we assume that the frame accommodates all uplink time slot requests \((n_{Up})\). The spectral efficiency of TDMA system depends on the number of active time slots: the spectral efficiency would be improved as the active time slots are increased. However, the increase of active extra uplink time slots results the effect of BS-to-BS co-channel interference dominant, which severely degrades SIR outage performance. Thus, we are interested in the effect of time slot occupation on the spectral efficiency of D-TDD systems. We define frame loading reflecting the time slot occupation as:

\[
\text{Frame loading}\% = \frac{N_F - N_{idle}}{N_F} \times 100, \quad (5.1)
\]
where \( N_F \) is the number of time slots in a frame, and \( N_{\text{Idle}} \) denotes the number of idle time slots in a D-TDD frame. We assume that the idle time slots are located over \( \Pi_{\text{Ext}} \), and \( N_{\text{Idle}} \in [0, L] \). Thus, the frame is fully loaded if \( N_{\text{Idle}} = 0 \), while there is no variation between the uplink and the downlink bandwidth, if \( N_{\text{Idle}} = L \).

For the given frame loading condition \((N_{\text{Idle}})\), the number of uplink time slots in a D-TDD is expressed as:

\[
n_{\text{Up}} = L + N', \tag{5.2}
\]

where \( N' \) is the number of uplink time slots additionally requested from some of \( L\text{-SC} \), and is given as \( U[0, N] \), and \( N \) is given as:

\[
N = \min(N_{\text{Ext}}, N_F - N_{\text{Idle}} - 2L), \tag{5.3}
\]

where \( N_{\text{Ext}} \) is the total number of uplink time slots allowed in a D-TDD frame. The variation of the traffic is related to \( N \). Thus, large value of \( N \) represents that traffic is more dynamic.

Meanwhile, S-TDD system can not utilize the bandwidth as efficiently as D-TDD, since the switching point is fixed all the time, i.e., the transmission bandwidth of one direction can not be shared by the transmission of the other direction, regardless of its availability. Typically, the bandwidth ratio of uplink to downlink traffic is asymmetric and dynamic in multimedia applications. Thus, the network operator needs to be careful in choosing the switching point in S-TDD operation, such that the bandwidth utilization is maximized. We choose the number of uplink time slots in a S-TDD frame is the same as the average number of uplink time slots in a fully loaded D-TDD frame. Thus, the
extra uplink time slots in S-TDD ($N_S$), i.e. the uplink time slots excluding the first $L$-uplink time slots, are defined as:

$$N_S = \left\lceil \frac{N_{EU}}{2} \right\rceil,$$

(5.4)

where $\lceil \cdot \rceil$ selects the largest integer which is closest to the argument.

In the analysis, we assume that the dynamic traffic in D-TDD systems is offered to S-TDD systems. Thus, in S-TDD systems, when $N'$ is larger than $N_S$, the number of time slots which exceeds $N_S$ is delayed to the next frame or dropped for transmission, permanently, depending on the traffic management rule defined in the network systems.

5.3 Spectral Efficiency

Conventionally, spectral efficiency has been measured in Erlangs/Hz·$m^2$ [51]. Since the traffic present in the network behaves alike and requires the same quality in conventional voice network, the measure which reflects the occupation of traffic per cell (in Erlangs) is enough to characterize the spectral efficiency of such networks. However, the emerging multimedia traffic consists of several classes, which requires different QoS. Thus, the conventional measure, which considers the traffic of one class only, is no longer a proper measure for the new traffic.

As a proper measure for spectral efficiency of multimedia system, Alouini et al have defined the spectral efficiency as the sum of average bit rate (bits/sec) per unit bandwidth (Hz) per unit area ($m^2$) supported by a cell’s base station, i.e. [52]:
\eta = \frac{\sum_{i=1}^{n} \delta_i C_i}{\pi \cdot (D/2)^2}, \quad \text{[bit/sec/Hz/m^2]} \tag{5.5}

where \( \delta \) is a fraction of bandwidth assigned to the \( i \)-th channel with respect to bandwidth for a cell; \( C_i \) is a capacity of the \( i \)-th channel expressed in [bit/sec/Hz], \( n \) is a number of active channel; and \( D \) is frequency reuse distance.

In a TDMA system, bandwidth of the \( i \)-th channel, \( \delta_i \), is a fraction of time that the \( i \)-th time slot occupies out of frame time, whereas in FDMA system, it is a fraction of frequency band that the \( i \)-th channel occupies out of total frequency band given to a cell. Usually, the bandwidth of a channel is identical for all channels in a cell. For a TDMA/TDD system, therefore, \( \delta_i \) is given by:

\[
\delta \equiv \delta_i = \frac{T_s - T_G}{T_F} = \frac{1 - \mu_G}{N_F}, \tag{5.6}
\]

where \( T_s \) is time slot interval; \( T_F \) is a TDD frame time; \( T_G \) is guard time; and \( \mu_G = T_G/T_s \).

Since our interest is on the spectral efficiency of TDD systems for dynamic traffic pattern, we consider a cellular system with a typical geographic configuration. The cellular system parameters such as frequency reuse, cell size, etc., will be fixed throughout the analysis in this chapter. In consequence, the denominator of Eq. (5.5) is common for all spectral efficiency representation herein. Thus, for notational convenience, we define the spectral efficiency (\( \eta_{n} \)) of the cellular system considered in this chapter as:
\[ \eta_N = \sum_{i=1}^{\infty} \delta_i C_i = \delta \sum_{i=1}^{\infty} C_i. \quad \text{[bit/sec/Hz]} \quad (5.7) \]

### 5.3.1 Fixed Modulation Systems

In wireless systems, information rate is determined to guarantee the required link quality (e.g., BER) to the SCs within cell coverage. Since the channel condition varies, the information rate is conventionally determined for the worst-case channel. For the delay sensitive traffic, constant information rate transmission may be preferred. Fixed modulation scheme, which keeps the modulation level throughout the communications, is suitable for this type of traffic.

In fixed modulation system, the modulation level is determined by the link quality of cellular system, which is evaluated by SIR outage probability [22]. We decide the modulation level from Shannon’s well-known capacity formula [53] given as:

\[ C = \log_2 (1 + \gamma), \quad \text{[bit/sec/Hz]} \quad (5.8) \]

where \( \gamma \) is the threshold SIR value at the target outage probability of 1%. Since the SIR outage performance of D-TDD system is limited by uplink performance, we analyze spectral efficiency of TDD system for uplink reception only. Now, uplink spectral efficiency of TDMA/TDD system is simply given as:

\[ \eta_N = \delta \cdot E[n_{up}] \cdot C, \quad \text{[bit/sec/Hz]} \quad (5.9) \]

where \( E[n_{up}] \) is the expected number of active uplink time slots.
In a D-TDD system, boundary between uplink and downlink transmission is varying according to traffic pattern. If traffic is dynamic and a frame is fully load, therefore, the expected number of occupied time slots are increased. From Eq. (5.2), the expected number of active uplink time slots is expressed as:

\[ E[n_{up}] = \frac{2L + N}{2}. \]  

(5.10)

By substituting Eq. (5.10) into Eq. (5.9), uplink spectral efficiency of D-TDD system is simply given as:

\[ \eta_N = \frac{2L + N}{2} \times \delta \cdot \bar{C}. \]  

[bit/sec/Hz]  

(5.11)

It should be noticed that the effect of co-channel interference becomes more severe, as the maximum number of uplink time slots are increase. This is due to that fact that the more extra uplink time slot increases the expected number of downlink co-channel cells, which is the dominant source of co-channel interference.

Meanwhile, due to dynamic traffic pattern, S-TDD frame may not be fully loaded, even if D-TDD frame is fully loaded. Considering this, the spectral efficiency of S-TDD system is expressed as:

\[ \eta_N = \delta \cdot E[n_{up}] \cdot \bar{C} \]  

[bit/sec/Hz]

\[ = \delta \cdot \bar{C} \cdot \left\{ L + \frac{1}{N+1} \left[ \sum_{i=1}^{x} (N-i+1) \right] \right\}, \]  

(5.12)

\[ = \delta \cdot \bar{C} \cdot \left[ L + \frac{x(2N-x+1)}{2(N+1)} \right], \]

where \( x = \text{min}[N,N_s] \).
Compared to D-TDD system, the expected number of time slots is small, which results in less bandwidth utilization. However, in S-TDD system, there is no base-to-base co-channel interference. Therefore, SIR outage performance of S-TDD system is better than that of D-TDD system.

### 5.3.2 Adaptive Modulation Systems

Recently, adaptive modulation has drawn much attention as a means to increase link capacity [54]. In adaptive modulation scheme, transmission rate is adapted to link quality, i.e. SIR level. In other words, when channel suffers strong deteriorations, transmitter lowers its modulation level such that the required link quality (target BER) is met. Meanwhile, when channel is observed to be favorable, transmitter increases its modulation level to deliver more information. Thus, link capacity of adaptive modulation is much higher than that of fixed modulation. Since this modulation may require buffer at the transmission, it is more suitable for the delay tolerant bursty data traffic.

In adaptive modulation system, data rate is adapted according to channel state. Thus, data rate for the $i$-th time slot is not constant. To analyze, we use average information rate defined as:

$$\bar{C}_i = \int_{\frac{1}{\gamma_i}}^{\gamma_i} \log_2 (1 + \gamma_i) f(\gamma_i) d\gamma_i,$$

where $f(\gamma_i)$ is a probability density function of SIR at the $i$-th time slot. Since the distribution of interference power in D-TDD is heterogeneous over extra time slot region,
it is convenient to analyze $\eta_N$ over two regions, $\Pi_{Fix}$ and $\Pi_{Ext}$. Thus, the spectral efficiency of TDD system when adaptive modulation is employed is provided as:

$$
\eta_N = \sum_{i=1}^{n_{fix}} \delta \cdot C_i
= \delta \cdot L \cdot C_{Fix} + \delta \cdot \sum_{n=1}^{N} \sum_{i=1}^{N} C_i \cdot Pr ob(n) \\
= \delta \cdot L \cdot C_{Fix} + \frac{\delta}{N+1} \sum_{n=1}^{N} \sum_{i=1}^{N} C_i
$$

(5.14)

where $C_{Fix}$ is data rate over $\Pi_{Fix}$.

In D-TDD systems, the second term in right hand side (RHS) of Eq. (5.14) is given by:

$$
\frac{\delta}{N+1} \sum_{i=1}^{N} (N-i+1) \cdot C_i.
$$

(5.15)

By substituting Eq. (5.15) into Eq. (5.14), spectral efficiency of D-TDD system is obtained as:

$$
\eta_N = \delta \cdot L \cdot C_{Fix} \cdot \frac{1}{N+1} \sum_{i=1}^{N} (N-i+1) \cdot C_i.
$$

(5.16)

Similarly, in S-TDD System, the second term in RHS of Eq. (5.14) is

$$
\frac{1}{N+1} \sum_{i=1}^{x} (N-i+1) \cdot C_{L+i},
$$

(5.17)

where $x = \min[N, N_s]$.

Now, from Eq. (5.17) and Eq. (5.14), spectral efficiency of S-TDD system is expressed as:
\[
\eta_N = \delta \cdot \left\{ L \cdot \bar{C}_{Fix} + \frac{1}{N+1} \left[ \sum_{i=1}^{N} (N-i+1) \cdot \bar{C}_{L+i} \right] \right\}.
\] (5.18)

In the analysis, we assume that the channel state is available at the transmitter such that the modulation level can be properly determined. Since our primary interest in this section is to investigate and compare the spectral efficiency of TDD systems employing adaptive modulation, the channel estimation scheme and the effect of channel estimation error are beyond of our concern. The spectral efficiency of TDD systems employing adaptive modulation evaluated in the next section will show the upper bound that the system can obtain for the dynamic traffic.

### 5.4 Numerical Results

In [3], it is stated that the SIR outage probability of S-TDD system is the same as that of FDD system, provided that S-TDD system is synchronized. Since we assume that the frame is synchronized in our analysis, the spectral efficiency of S-TDD system herein can be considered as that of FDD system, provided that the guard time of S-TDD and guard band in FDD system are same.

In our simulation, we use the same cellular structure and frame structure in the chapter 3. The following parameters are additionally used or modified. The cell radius is assumed to be 1 [km]. Each TDD frame is divided into 36 time slots and serves 12 SCs \((L = 12)\). We also assume that frames are synchronized. We use guard time of 30.5 [\mu sec]
and frame time of 20 msec (i.e. $\mu_G = 5.5 \times 10^{-2}$). At BS sites, 15 sector antennas are employed, and HPBW of 20-degree high gain antennas are employed at SC sites.

The spectral efficiency of TDD systems with fixed modulation scheme is compared in Figure 5–1, Figure 5–2, and Figure 5–3, for different traffic variations, i.e., $N_{Ext} \in \{3,6,12\}$ respectively. The data rates for different frame loading and traffic pattern are determined from SIR outage performance. SIR value at 1%-outage is used in our analysis.

First, let us observe the effect of TSA strategy on the spectral efficiency of D-TDD systems. The spectral efficiency of D-TDD, which does not employing TSA strategy, is improved as the time slot occupation is increased to a certain frame loading. However, the spectral efficiency curve falls sharply as the frame is highly occupied. This is due to the presence of BS-to-BS co-channel interference. Meanwhile, it is observed that the spectral efficiency of D-TDD systems employing TSA strategy does not vary sharply for a large range of frame loading.

The spectral efficiency of D-TDD systems with or without TSA strategy is identical, when $N_{Idle} > N_{Ext}$ . This is because there is no BS-to-BS co-channel interference. Especially, drastic improvement is observed in Figure 5-3. It is observed that 9 times higher spectral efficiency is obtained by employing TSA strategy when the frame is fully loaded.
Figure 5–1: Spectral efficiency employing fixed modulation ($N_{Ext} = 3$).
Figure 5–2: Spectral efficiency employing fixed modulation ($N_{Ext} = 6$).
Another aspect of interest is the comparison of spectral efficiency between D-TDD system and S-TDD system. Unlike D-TDD system, the spectral efficiency of S-TDD is observed to be increased as the percent of frame loading is increased. Compared the D-TDD systems without TSA strategy, S-TDD system can utilize the spectrum much efficiently. This is because that the effect of co-channel interference sacrifices the benefit of statistical multiplexing in D-TDD system, unless TSA strategy is employed. However,

Figure 5–3: Spectral efficiency employing fixed modulation ($N_{Ext} = 12$).
as shown in Figure 5–2, D-TDD system employing TSA strategy shows higher spectral efficiency than S-TDD system does, for fairly large range of frame loading. Especially, at the frame loading of 90 %, approximately 15% higher spectral efficiency is obtained in D-TDD system over S-TDD system by employing TSA strategy.

Now, let us observe the spectral efficiency of TDD systems, when adaptive modulation scheme is employed Figure 5–4 to Figure 5–6 show the simulation results. The benefit of adaptive modulation over fixed modulation is that it can exploit the time variation of wireless channel, thus, significant improvement can be obtained in D-TDD system, where large channel variation is present due to dynamic partitioning. Drastic improvement is observed for the D-TDD system employing adaptive modulation, even without TSA strategy. For instance, 26 times higher spectral efficiency is obtained over fixed modulation system, when $N_{Eut} = 12$ and frame is fully loaded.

In contrast to the substantial improvement in fixed modulation systems, the benefit of TSA strategy on the spectral efficiency of D-TDD system is not significant. This is due to the fact that the objective of TSA strategy is to maximize the minimum value of SIR, not to maximize the SIR values at extra uplink time slots. Nevertheless, as in the fixed modulation system, spectral efficiency of D-TDD system employing TSA strategy is higher than that of S-TDD system for fairly large range of frame loading, when adaptive modulation is employed. At the frame loading of 83.3 %, approximately 8% higher spectral efficiency is obtained in D-TDD system over S-TDD system, when $N_{Eut} = 6$ . (See Figure 5–5). However, it is also observed that the spectral efficiency of D-TDD system is inferior to that of S-TDD, when $N_{Eut} = 12$ .
Figure 5–4: Spectral efficiency employing adaptive modulation ($N_{Ext} = 3$).
Figure 5–5: Spectral efficiency employing adaptive modulation \(N_{E_{th}} = 6\).
Figure 5–6: Spectral efficiency employing adaptive modulation \((N_{\text{Ext}} = 12)\).
5.5 Summary and Conclusions

In this chapter, we compared the spectral efficiency of TDD systems for dynamic traffic and various frame loading conditions. We investigated the effect of TSA on the spectral efficiency of D-TDD systems. Also, we compared the spectral efficiency of D-TDD system to that of S-TDD system. In our analysis, we considered two different modulation schemes: fixed modulation, which is suitable for delay sensitive traffic, and adaptive modulation, which is suitable for delay tolerant traffic.

For convenience, we list the observations in the following:

- In fixed modulation systems:
  1. The spectral efficiency of D-TDD system is degraded, as the frame is fully loaded. Especially, the spectral efficiency curve of D-TDD system drops sharply as the occupied time slots are increased, unless TSA strategy is employed.
  2. The benefit of TSA is substantial. As much as 9 times higher spectral efficiency is obtained in D-TDD systems by employing TSA strategy, when $N_{Ext} = 12$ and the frame is fully loaded.

- In adaptive modulation systems:
  1. The benefit of adaptive modulation in D-TDD systems is drastic. It is observed that 26 times higher spectral efficiency can be obtained over fixed modulation system by employing adaptive modulation, when $N_{Ext} = 12$ and frame is fully loaded.
2. Although benefit of TSA is not significant, spectral efficiency of D-TDD system employing TSA strategy is higher than that of S-TDD system for fairly large range of frame loading, as in the fixed modulation system.

As a conclusion, D-TDD system can take advantage of statistical multiplexing gain of dynamic traffic by adapting the boundary to the varying traffic bandwidth in its two-way transmission. However, strong effect of BS-to-BS co-channel interference should be suppressed to have the benefits of dynamic characteristics of traffic. When the proposed TSA is employed in D-TDD system, the merit of variable boundary can be obtained for a fairly large range of frame loading, compared to S-TDD system.
Chapter 6

Summary and Future Research Directions

6.1 Summary of Results

The following is a list of summary of works in this thesis.

1. We developed an analytical model of co-channel interference in D-TDD fixed wireless systems. We showed that the distribution of co-channel interference in D-TDD systems is bimodal, which is different than that in S-TDD systems, and the distribution varies at time slots over the extra time slot regions. According to our investigation, the benefit of D-TDD system can not be justified in cellular network due to the strong BS-to-BS co-channel interference, when omni-directional antennas are employed at BS and SC sites.

2. Using our analytic model, it is observed that an enormous number of sectors (or antenna sensor elements) to suppress the co-channel interference in D-TDD systems is needed, when interference suppression method is applied alone. To obtain the target SIR outage probability of 1% at the SIR threshold of 17 dB, antenna beamwidth of 3.4 degree is required, which means that more than 106 sectors are required in sector antenna systems, while approximately 30 element antennas are required in adaptive array antennas systems.
3. We proposed a novel interference management method for interference avoidance. This method employs TSA, combined with sector antennas at BS sites. We devised two types of time slot allocation strategies to improve the SIR outage performance of D-TDD systems. MaxMin \{SIR\} is the best pairing search algorithm, which may require enormous computations as the number of extra uplink time slots is increased. Thus, this algorithm may not be appropriate for the largely dynamic traffic. In our analysis, we use the performance results obtained employing this algorithm as the benchmark. Another algorithm, Max \{SIR\}, does not incur enormous increase in computation, as the dynamic range of the traffic is increased. We showed that the difference in performance between the two algorithms is negligible.

4. We compared the performance of TSA to that of adaptive array antennas. Our simulation shows that the performance using TSA with a 15-sector antenna is comparable to that using UCA adaptive array antenna with 26 sensing elements. We evaluated the spectral efficiency of TDD cellular systems. It is observed that the spectral efficiency of D-TDD can be improved significantly by employing TSA strategy. For instance, for fixed modulation system, as much as 9 times higher spectral efficiency is obtained by employing TSA strategy, when \(N_{Ex} = 12\) and frame is fully-loaded. When the proposed TSA is employed in D-TDD system, the merit of statistical multiplexing can be obtained for a fairly large range of frame loading, compared to S-TDD system.
6.2 Future Research Directions

In this section, we suggest several topics for future research regarding TSA strategy and D-TDD systems.

6.2.1 Co-operative fixed cellular networks

In this thesis, we observed that BS-to-BS interference degrades SIR outage performance severely, thus, the capacity of D-TDD is far below being acceptable, unless a countermeasure is employed to counteract the adverse effect of strong co-channel interference.

Two interference management methods were considered: interference suppression and interference avoidance. While these methods are performed in spatial domain, interference cancellation, which suppresses the effect of co-channel interference in signal processing domain, is worth being considered. Since interference cancellation scheme can be performed at the receiver independent of the resource allocation strategy, it can be employed alone or combined with any of the other interference management methods, to improve the capacity of the system.

To illustrate how the interference cancellation method improves the D-TDD system, let us consider a fixed cellular network (See Figure 6–1), which shares the information among co-channel BSs. In such co-operative cellular networks, the reference BS (CC0 in Figure 6–1) is assumed to know the downstream information at co-channel cells in their downlink duty cycles (CC3 and CC5 in Figure 6–1). In this example, CC3
and CC5 are in downlink cycle. Since the reference cell (CC0) knows the downlink information in those co-channel cells via RNC, CC0 can subtract the effect of the interfering signals at the received signal, provided that the channel state information between those cells are available.

Specifically, the received signal at the reference BS over extra uplink time slot region is given by:

\[
y(t) = \sum_{k=0}^{\alpha} h_k \cdot S_k(t) + n(t)
\]

(6.1.a)

\[
y(t) = h_0 S_0(t) + \sum_{i \in \text{BS}} h_i \cdot S_i(t) + \sum_{j \in \text{SC}} h_j \cdot S_j(t) + n(t),
\]

(6.1.b)

where \( S_k(t) \) is the signal output at the \( k \)-th transmitter; \( h_k \) is complex channel path gain from the \( k \)-th transmitter to the BS at the reference cell; \( n(t) \) is an AWGN term; \( \alpha \) is the total number of interferers. In RHS of Eq. (6.1.b), the first term represents the received signal from desired SC, the second term represents the aggregate interfering signal from co-channel cells in downlink duty cycle, and third term represents the aggregate interfering signal from co-channel cells in uplink duty cycle. Since CC0 knows \( S_i(t) \) via RNC, the second term can be subtracted from \( y(t) \), provided that CC0 can estimate \( h_i \) perfectly. Thus, the SIR outage is greatly improved. Interestingly, after the subtraction, the number of co-channel interferers is less than that in fully loaded S-TDD systems, thus, the SIR performance is improved, even more. Thus, efficient channel estimation will improve the capacity of co-operative D-TDD network by employing an interference cancellation method.
The drawback of the co-operative D-TDD network is that it requires large number of signaling between co-channel BSs, so that the downlink information is shared among co-channel BSs. For instance, let us consider the example shown in Figure 6–1. While the reference cell is in uplink reception, the CC3 and CC5 are already in downlink transmission. To cancel the interfering signals coming from CC3 and CC5, the reference cell CC0 asks to share the downlink data sequences to RNC. Considering that the number
of BS-to-BS interferers is increased as the extra uplink time slot index of interest is increased, the bandwidth request number to share these downlink data sequences may be quite large at the last uplink time slot. Thus, the signaling information required at the reference BS is increased as the number of interferers in downlink cycle at the time slot of interest. One remedy to relieve the amount of signaling is to employ the proposed TSA strategy, which tries to reduce the effective number of BS-to-BS interferers. Employing TSA provides benefit for channel estimation, as well. Since the complexity of channel estimation is increased significantly, as the number of interferers is increased, the proposed TSA strategy, which reduces the number of interferers, alleviates the computational burden of the channel estimation procedure.

6.2.2 Call Admission Control and resource allocation for QoS guarantee

The proposed TSA strategy takes advantage of degree of freedom provided by the spatially distributed SCs’ location. Thus, the performance of TSA strategy depends on the number of SCs served in a frame, which determines the degree of freedom. In this thesis, we assume that the $L$-SCs are already resolved by a certain call admission control strategy.

In wireless data packet networks a call admission control strategy that allows a packet whose channel quality is good through, may increase the throughput of the network, while the packet whose channel quality is relatively poor is delayed. When delay-sensitive and delay-tolerant traffic coexist in the network, the call admission control and the radio resource allocation strategy affect the QoS, seriously. Especially, D-
TDD shows different statistical behavior in distribution of SIR, compared to the conventional S-TDD or FDD systems. Thus, more attention should be paid to the design of call admission and resource allocation strategies.

6.2.3 TSA for mobile networks

The proposed TSA strategy in this thesis is to improve the SIR outage probability in fixed wireless cellular networks. Due to the dynamic partitioning, the deleterious effects of strong co-channel interference are not an exception in D-TDD mobile cellular networks.

The SC-to-SC co-channel interference is suppressed in fixed wireless network, by employing high-gain antennas at the SC sites. However, in a mobile network, it is practically impossible to deploy high-gain antennas at the SC sites due to mobility. Also, the expensive RF components and enormous power consumption to compute beampattern make it even worse to employ adaptive array at the SC sites. Especially, power consumption is an increasingly important consideration in mobile environments. Thus, the simplest design suggests deploying omni-directional antennas at the handset. However, the omni directional propagation characteristics create a dominant SC-to-SC co-channel interference when the desired SC is in downlink, while the closest SC at co-channel cell is in uplink transmission cycle [2] (See Figure 6–2).

As in the fixed wireless network, TSA strategy can be considered to improve the SIR outage performance of mobile system. However, since another entity, SC-to-SC co-channel interference degrades the performance, the objective of TSA should be modified
to consider the entity. Also, phased array antennas can be used at BS sites, instead of sector antennas, since a large number of sectors results in too many handoffs in mobile environments.

Figure 6–2: Illustration of SC-to-SC co-channel interference.

6.3 List of Contributions

The following is a list of papers, which are published, submitted or in preparation:

Journal Papers:


Conference Papers:


BIBLIOGRAPHY


38. J. Yun, W. Jeong, and M. Kavehrad, “Throughput performance analysis of automatic repeat request strategies combined with adaptive rate transmission,”


Wun-Cheol Jeong was born on October 26, 1971 at Cheong-Ju, Korea. He received the B.S. degree in Electrical Engineering from Kon-Kuk University, Seoul, Korea, in 1996. He was a recipient of Kon-Kuk Univ. Fellowship Awards for his excellent academic achievements, and he graduated cum laude. He enrolled in graduate program at the Department of Electrical Engineering at the Pennsylvania State University, University Park, in August 1997, where he received the M.S. degree in May 1999. He has been a member of the Center for Information and Communications Technology Research (CICTR) since 1998. During pursuing of his masters degree, he worked for the broadband indoor wireless infrared (IR) communications, while he focused on interference management schemes for multimedia traffic in wireless applications during Ph. D. program. Since 1999, he has worked as a graduate research assistant in the Department of Electrical Engineering at the Pennsylvania State University. His research interests include wireless communications, information theory, and digital signal processing. Wun-Cheol Jeong is a member of the IEEE and IEEE Communication Society.