A CDMA BASED HYBRID WIRELESS ARCHITECTURE
FOR SYMMETRIC AND ASYMMETRIC COMMUNICATIONS

by

Wilson Wai Shun Wong

A thesis submitted in conformity with the requirements
for the degree of Doctor of Philosophy;
Graduate Department of Electrical and Computer Engineering, in the
University of Toronto, Canada

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To my parents
Abstract

A CDMA Based Hybrid Wireless Architecture
for Symmetric and Asymmetric Communications by Wilson Wai Shun Wong.
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The objective of this thesis is to study a code division multiple access (CDMA) based hybrid wireless architecture in which broadcast systems using single frequency broadcasting are spectrally underlaid in an FDD-CDMA cellular network, for the provision of symmetric and asymmetric data services.

A novel duplex scheme called Space Division Duplex (SDD) is proposed to support asymmetric communications. The use of a hybrid FDD/SDD-CDMA system architecture is then explored for supporting symmetric and asymmetric data users, with the former served by a cellular network and the latter served by the broadcast systems. The cellular network utilizes FDD to provide wide area voice and low-bit-rate symmetric data services, while the broadcast systems utilize SDD to provide high-bit-rate asymmetric data services. Using per-cell capacity as the performance measure, the capacity performance of this system architecture is evaluated and compared with two other classical system architectures. The simulation results indicate that using adaptive array antenna structures at the broadcast system radio ports can improve capacity performance significantly and that more asymmetric data users can be supported at a given number of symmetric data users as the antenna beamwidth decreases. For example, when the number of symmetric data users is 30, the number of asymmetric data users increases from 16 to 32 when the antenna beamwidth decreases from 60° to 30°.

Finally, an iterative SIR-based power control algorithm is studied and its performance is accessed with the use of space diversity schemes. In particular, we have modeled the symmetric data users as voice users and the asymmetric data users as Internet users. When the voice user loading per sector is 80%, iterative power control with selection combining requires on average 12 access attempts for each Internet user compared to 18 access attempts with non-iterative power control. The best performance is achieved by using iterative power control with maximum ration combining, which requires on average 4 access attempts; and no significant degradation results until the voice user loading level is so high.
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<td>ADSL</td>
<td>Asymmetric Digital Subscriber Line</td>
</tr>
<tr>
<td>AMPS</td>
<td>Advanced Mobile Phone Service</td>
</tr>
<tr>
<td>AP</td>
<td>access point</td>
</tr>
<tr>
<td>ARIB</td>
<td>Association of Radio Industry Board, in Japan</td>
</tr>
<tr>
<td>ATM</td>
<td>asynchronous transfer mode</td>
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<tr>
<td>AWGN</td>
<td>additive white Gaussian noise</td>
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<tr>
<td>BS</td>
<td>base station</td>
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<tr>
<td>CATV</td>
<td>cable television</td>
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<td>CDMA</td>
<td>code division multiple access</td>
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<tr>
<td>CDF</td>
<td>cumulative distribution function</td>
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<td>DAB</td>
<td>Digital Audio Broadcasting</td>
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<td>DBCA</td>
<td>Distance Based Channel Allocation</td>
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<tr>
<td>DECT</td>
<td>Digital European Cordless Telephone</td>
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<tr>
<td>DS</td>
<td>direct sequence</td>
</tr>
<tr>
<td>DVB</td>
<td>Digital Video Broadcasting</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
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<tr>
<td>FCA</td>
<td>Fixed Channel Allocation</td>
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<td>FDD</td>
<td>frequency division duplex</td>
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<td>FDMA</td>
<td>frequency division multiple access</td>
</tr>
<tr>
<td>FM</td>
<td>frequency modulation</td>
</tr>
<tr>
<td>HFB</td>
<td>High Frequency Band</td>
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<tr>
<td>IF</td>
<td>intermediate frequency</td>
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<tr>
<td>IMT-2000</td>
<td>International Mobile Telecommunications for the year 2000</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>ISDN</td>
<td>Integrated Services Digital Network</td>
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<tr>
<td>ISP</td>
<td>Internet Service Provider</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
</tr>
<tr>
<td>IS</td>
<td>Interim Standard</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
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</tr>
<tr>
<td>LAN</td>
<td>local area network</td>
</tr>
<tr>
<td>LFB</td>
<td>Low Frequency Band</td>
</tr>
<tr>
<td>LMDS</td>
<td>local multipoint distribution system</td>
</tr>
<tr>
<td>LOS</td>
<td>line of sight</td>
</tr>
<tr>
<td>MAI</td>
<td>multiple access interference</td>
</tr>
<tr>
<td>MMDS</td>
<td>multichannel multipoint distribution system</td>
</tr>
<tr>
<td>MRC</td>
<td>maximum ratio combining</td>
</tr>
<tr>
<td>MSC</td>
<td>mobile switching centre</td>
</tr>
<tr>
<td>PACS</td>
<td>Personal Access Communications System</td>
</tr>
<tr>
<td>PBX</td>
<td>Private Branch Exchange</td>
</tr>
<tr>
<td>PDF</td>
<td>probability density function</td>
</tr>
<tr>
<td>PG</td>
<td>processing gain</td>
</tr>
<tr>
<td>PHS</td>
<td>Personal Handyphone System</td>
</tr>
<tr>
<td>PN</td>
<td>pseudo-noise</td>
</tr>
<tr>
<td>PSN</td>
<td>packet switched network</td>
</tr>
<tr>
<td>PSTN</td>
<td>public switched telephone network</td>
</tr>
<tr>
<td>PT</td>
<td>portable</td>
</tr>
<tr>
<td>QAM</td>
<td>quadrature amplitude modulation</td>
</tr>
<tr>
<td>QoS</td>
<td>quality of service</td>
</tr>
<tr>
<td>RCA</td>
<td>Random Channel Allocation</td>
</tr>
<tr>
<td>RP</td>
<td>radio port</td>
</tr>
<tr>
<td>SC</td>
<td>selection combining</td>
</tr>
<tr>
<td>SDD</td>
<td>space division duplex</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>TDMA</td>
<td>time division multiple access</td>
</tr>
<tr>
<td>TIA</td>
<td>Telecommunications Industry Association</td>
</tr>
<tr>
<td>UPR</td>
<td>Users' Performance Requirements</td>
</tr>
<tr>
<td>WWW</td>
<td>World Wide Web</td>
</tr>
</tbody>
</table>
List of Symbols

$E_b/N_0$  
bit-energy-to-noise ratio

$(E_b/N_0)_\text{req}$  
bit-energy-to-noise ratio requirement

$R$  
radius of a circular cell

$K$  
number of active PTs

$a$  
distance of a broadcast system receiver from the BS

$\alpha$  
normalized distance of a broadcast system receiver from the BS

$r$  
transmitter-receiver separation

$r_{\text{ref}}$  
close-in reference distance

$p_r$  
received power

$p_t$  
transmitted power

$\eta$  
path loss exponent

$r_s$  
radius of the small cell

$r_{so}$  
close-in reference distance of the small cell

$\eta_s$  
path loss exponent of the small cell

$10^{\Phi/10}$  
lognormal random variable representing shadowing effects

$\sigma$  
standard deviation

$\tau$  
time

$J_0(\cdot)$  
zero-order Bessel function of the first kind

$f_D$  
maximum Doppler frequency

$\nu$  
PT speed

$\lambda$  
wavelength of the RF carrier

$P_t$  
transmitted power of a PT

$B_i$  
base station $i$

$r_i$  
distance of a PT in cell $i$ from $B_i$

$\varepsilon_i$  
shadowing component between a PT in cell $i$ and BS $B_i$

$\gamma$  
adjacent cell interference spillover factor

$\chi$  
$(\ln 10)/10$

$P_B_i$  
transmitted power from BS $B_i$
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_C$</td>
<td>number of interfering cells</td>
</tr>
<tr>
<td>$\xi_i$</td>
<td>shadowing component between BS $B_i$ and the broadcast system receiver</td>
</tr>
<tr>
<td>$P_{max}$</td>
<td>BS's maximum transmitted power requirement</td>
</tr>
<tr>
<td>$G$</td>
<td>processing gain of the cellular network</td>
</tr>
<tr>
<td>$g$</td>
<td>processing gain of the broadcast system</td>
</tr>
<tr>
<td>$C$</td>
<td>number of regular cells</td>
</tr>
<tr>
<td>$p_{ik}$</td>
<td>the $k^{th}$ PT served by $B_i$</td>
</tr>
<tr>
<td>$b_{ij}$</td>
<td>the $j^{th}$ broadcast system RP in regular cell $i$</td>
</tr>
<tr>
<td>$q_{ijm}$</td>
<td>the $m^{th}$ broadcast system PT served by broadcast system RP $b_{ij}$</td>
</tr>
<tr>
<td>$P_{ik}$</td>
<td>transmitted power of PT $p_{ik}$</td>
</tr>
<tr>
<td>$Q_{b_{ij}}$</td>
<td>transmitted power of broadcast system RP $b_{ij}$</td>
</tr>
<tr>
<td>$J$</td>
<td>number of broadcast systems</td>
</tr>
<tr>
<td>$J_H$</td>
<td>number of HFB broadcast systems</td>
</tr>
<tr>
<td>$J_L$</td>
<td>number of LFB broadcast systems</td>
</tr>
<tr>
<td>$\mu_{0k}$</td>
<td>fraction of the transmitted power allocated to a given PT $p_{0k}$ from $B_0$</td>
</tr>
<tr>
<td>$\nu_{0jm}$</td>
<td>fraction of the transmitted power allocated to $q_{0jm}$ from $b_{0j}$</td>
</tr>
<tr>
<td>$K_s$</td>
<td>number of active symmetric data users</td>
</tr>
<tr>
<td>$K_a$</td>
<td>number of accessing asymmetric data users trying to access</td>
</tr>
<tr>
<td>$W_s$</td>
<td>spreading bandwidth</td>
</tr>
<tr>
<td>$\eta_iW_s$</td>
<td>receiver noise power at $B_i$</td>
</tr>
<tr>
<td>$t$</td>
<td>number of access attempts</td>
</tr>
<tr>
<td>$\delta$</td>
<td>step size of the iterative SIR-based power control algorithm</td>
</tr>
<tr>
<td>$1/\lambda_v$</td>
<td>mean time between call arrivals</td>
</tr>
<tr>
<td>$1/\mu_v$</td>
<td>mean call holding time</td>
</tr>
<tr>
<td>$T_t$</td>
<td>mean talkspurt period (ON-period)</td>
</tr>
<tr>
<td>$T_s$</td>
<td>mean silence period (OFF-period)</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Historical Perspective

Advanced Mobile Phone Service (AMPS) and its variations are often considered as the first generation analog wireless technologies. The major breakthrough of AMPS is the cellular concept itself. By organizing the frequencies in groups and establishing a frequency reuse pattern in clusters of cells, as well as the capability to hand off a call from one cell to another, brings to the birth of wireless industry. The cellular concept was conceived and developed in late 1970s [1], and the deployment of AMPS systems started in early 1980s. Following the AMPS’ lead, other parts of the world developed their respective first generation wireless standards. Whereas they generally differ by selecting a different channel bandwidth and/or different frequency band, the use of cellular concept, and analog frequency modulation (FM) radio is identical.

In 1988, the Telecommunications Industry Association (TIA) in the USA released cellular service requirements, known as the Users’ Performance Requirements (UPR) document. The key requirements include a ten-fold increase in capacity, and compatibility with the existing first generation cellular systems for dual mode operation. In 1989, a committee of the Telecommunications Industry Association (TIA) formulated IS-54 (Digital AMPS), the first North America digital cellular standard [2]. In the IS-54 standard, the committee adopted Time Division Multiple Access (TDMA) as the common air interface for all digital transmissions. The increase in
capacity of IS-54 over analog AMPS is only a factor of three, and it is short of meeting the capacity requirement of the UPR. Immediately following the appearance of the IS-54 TDMA standard, in 1990 San Diego based Qualcomm Inc. proposed a direct sequence-code division multiple access (DS-CDMA) spread spectrum cellular system which in July 1993 was adopted as the second North America digital cellular standard, known as IS-95 [3]. IS-54 and IS-95 are regarded as standards for the second generation digital wireless technologies.

1.2 DS-CDMA and IS-95 Overview

Spread spectrum techniques have been employed in military communications and radar systems for about 50 years. The primary purpose in military communications has been to combat the effects of jamming. In radar systems, the primary purpose has been to provide accurate ranging (delay measurement). In those early applications the multiple access aspects were not actively addressed. Recently the use of spread spectrum techniques has been revisited for multiuser communication in which all users share the same frequency band at the same time. To distinguish one user's transmission from another, each user's data symbols are modulated by a unique binary spreading sequence, which is often a pseudo-noise (PN) code. Each symbol is then composed of binary 'chips' which have a much shorter period than that of the original data symbol. The user's signal is thus "spread" onto a transmission bandwidth much wider than the original signal bandwidth. The ratio of these two bandwidths is commonly called the processing gain \( PG \). The signal of each user is separated or "despread" from the others at the receiver using a correlator keyed with the associated code sequence. Signals which do not match with the selected correlator despreading code sequence are not despread and contribute as interference. Therefore, the total interference is determined by the number of simultaneous active users; any reduction in the interference converts directly and linearly into an increase in capacity [4]. This technique is called DS-CDMA and forms the basis of the IS-95 standard. Many papers have been published on DS-CDMA over the years, and the first textbook devoted to
IS-95 appeared in 1993 [5].

IS-95 is a standard for DS-CDMA based cellular systems in the USA. We give a brief overview of the standard here; a more comprehensive discussion can be found in [3]. The IS-95 forward link (from base station [BS] to portable [PT]) operates in the 869-894 MHz band while the reverse link (from PT to BS) uses the 824-849 MHz band. The channel bandwidth is 1.25 MHz. Each forward link-reverse link pair is separated by 45 MHz. IS-95 employs DS spectrum spreading by multiplying each user’s narrowband waveform by a wideband signal. This wideband signal is generated by spreading codes consisting of sequences of 64 chips, associated with each symbol interval. The entire sequence of chips is used to modulate the carrier during each symbol period, resulting in a widened spectrum. The DS spread spectrum modulation technique is applied differently in the forward and reverse links.

In the forward link, IS-95 uses DS spreading with orthogonal 64-chip Walsh sequences. There are 64 orthogonal Walsh sequences and each user is assigned a different Walsh sequence to reduce the amount of interference seen at the PT. One Walsh sequence is reserved for continuous transmission of the pilot tone. Sending the pilot tone along with traffic allows the PT to coherently demodulate the received signal. All users’ transmissions occur synchronously from the BS, so these transmissions are also synchronized at any individual user’s PT. The use of a set of orthogonal sequences therefore ensures no cross-interference between transmitted forward link signals if we assume an environment where there is no multipath propagation. However, in an environment with multipath propagation the forward link signals interfere with one another. As the severity of the multipath increases, the advantages of using orthogonal sequences becomes less significant [6].

In contrast to the forward link which uses coherent detection and orthogonal spreading, the IS-95 reverse link employs noncoherent detection and nonorthogonal spreading. Generally, the PT is power-limited, thus transmission of a separate pilot tone to enable coherent detection is not attractive. In the reverse link, the Walsh sequences are employed to provide a noncoherent orthogonal sequence modulation technique. The Walsh modulator accepts the 6 bits needed to create an index for
the set of 64 orthogonal sequences which may be transmitted. The Walsh-modulated sequences are then randomized by a “data burst randomizer” and the randomized output is spread by a PN sequence generated by a long code generator. Since each user’s signal arrives at the BS via a different propagation path, orthogonality amongst all PTs in the reverse link is in general difficult to achieve. Therefore, asynchronous operation mode is adopted. This means that the receiver for each user will observe interference from all other users in the system. Hence, the number of users that can be simultaneously accommodated is usually limited by the asynchronous reverse link.

When considered purely as a multiple access technique over Additive White Gaussian Noise (AWGN) channels, CDMA will actually support fewer users within the same bandwidth as Frequency Division Multiple Access (FDMA) or Time Division Multiple Access (TDMA) techniques. However, certain technical aspects allow IS-95 CDMA to provide vastly increased spectral efficiency over the other two techniques:

1. Universal Frequency Reuse: In CDMA, universal frequency reuse applies not only to all users in the same cell, but also to those in all other cells. Adding new cells, as traffic intensity grows, does not require a revision of the frequency plans of existing cells.

2. Power Control: With universal frequency reuse, power control becomes an important system requirement for CDMA. The use of power control ensures that each PT transmits and receives just enough power while interfering with other PTs no more than necessary. In the reverse link, PTs are power-controlled by the BS of their own cell. This is to ensure that the PTs are received with equal power at the BS. The purpose of such control is to mitigate multiple access interference (MAI) by preventing the domination of any PT’s signal by that of any other PTs at the BS receiver, thus effectively realizing a fair distribution of MAI among all PTs within the cell. The potential for a significant discrepancy in received power is commonly referred to as the “near-far” problem, and can result in significant capacity degradation. In the forward link, power control takes the form of power allocation at the BS transmitter according to the needs
of individual PTs in their own cell. This requires measurement by the PT of its signal-to-interference ratio (SIR), defined as the ratio of the received power from its own cell to the total interference power received.

3. Rake Combining: Exploitation of multipath fading can be achieved through the use of a RAKE receiver which can resolve the frequency selective multipath channel into several frequency nonselective paths with different time delays (the time delay resolution equals the inverse of spreading code chip rate). The received signals from resolved paths are coherently combined in an optimum manner to enhance the radio link performance.

4. Soft Handoff: This is equivalent to site diversity technique involving multiple BSs used to reduce the adverse effects of multipath fading and path losses (distance-dependent propagation loss and shadowing loss). In CDMA, universal frequency reuse makes it possible for a PT to transmit and receive simultaneously from and to different BSs. In the forward link, for example, two BS signals can be combined to improve performance, as with Rake combining. In fact, we can regard the second BS signal as a delayed version of the first, generated actively and purposely, rather than as a delayed reflection of the first caused by the environment. In the reverse link, the two different BSs can normally demodulate the signals independently, and different signals can be added coherently using common combining techniques. This feature ensures more reliable handoff between BSs as a user moves from one cell to the adjacent cell, and provides near uniform quality within the coverage area and causes no disruption in communication during handoff.

5. Cell Sectorization: CDMA cellular systems are interference-limited; any decrease in interference can be linearly transformed into an increase in capacity. For example, with three antenna sectorizations per cell, each having 120° effective bandwidth, the interference seen by any antenna is approximately one-third of that seen by an omnidirectional antenna. This can be transformed into an increase in capacity by nearly a factor of 3. Although cell sectorization can be
utilized in FDMA or TDMA to reduce the interference, the trunking efficiency of dividing frequency channels in each sector also decreases. Revision of the frequency plans among different sectors is also required.

6. Voice Activity Detection: In human conversation the voice activity cycle is 35%. This voice activity can be monitored, a function which already exists in most digital vocoders nowadays. In CDMA all the users are sharing a common radio channel. When some users are not talking or silent, the others can benefit with less interference in the radio channel. Therefore the voice activity cycle reduces MAI by 65%; increasing the system capacity by nearly a factor of three. This activity monitoring includes not only the voice activity, but message or data traffic variability as well.

1.3 Third Generation CDMA - Expectations

Recent years have seen an unprecedented surge in the demand for and deployment of wireless communication services. First generation analog wireless technologies are gradually giving way to more efficient second generation digital wireless technologies. Simultaneously, emphasis is shifting from conventional voice service to a variety of services. Wireline communication systems provide a host of multimedia services like voice, data, image, video, etc. There is a considerable pressure on wireless communication systems to support these services in the near future. Because of this, there has been a considerable amount of wireless research over the past few years in the development of the third generation wireless technologies. Objectives and system framework of third generation wireless technologies go far beyond what is known from second generation wireless technologies such as IS-54 or IS-95, and include support of a wide range of services and data rates (up to 2 Mbps) with different quality of service (QoS) requirements, operation in mixed cellular environment (macro, micro, pico, outdoor, indoor) and flexibility in frequency and radio resource management, system deployment, and service provision. The raging debate on the third generation wireless technologies has been centered around the International Mobile Telecommu-
communications (IMT)-2000 activities in the International Telecommunication Union (ITU) which is seeking to develop a common worldwide wireless standard to realize objectives and requirements as mentioned above. DS-CDMA has been considered to be the most promising wireless access technique for IMT-2000.

Now, the question is what significantly higher capability the third generation CDMA can offer. If we look at the IS-95 CDMA systems being offered today, we can conclude that with the latest enhanced vocoders the systems offer fairly good voice services. Even though IS-95 has room for further capacity improvements and the voice coding technology will continue to progress, it is apparent that better voice service is not the significantly greater capability that may take the third generation CDMA a success. On the other hand, interest in high-bit-rate data access has increased rapidly, mainly due to the growth of Internet and other multimedia applications. Many solutions have been adopted to meet the increasing demand on data services, such as 56-kbps modem, Integrated Services Digital Network (ISDN), Asymmetric Digital Subscriber Line (ADSL), two-way cable television (CATV), fiber or hybrid fiber-coax to the home, etc. While most of these efforts have been focused on the wireline solutions, wireless access is another promising option, especially for those potential service providers who have no existing access infrastructures. More importantly, the wireless approach has the added value of mobility which offers the possibility to provide services to users both indoor and outdoor, both stationary and mobile. However, if we look at the present data capabilities of the IS-95 CDMA systems, we immediately notice the significant discrepancy in data rates between these systems and the wireline counterparts. For instance, the data rate of IS-95 ranges from 2.4 kbps to 9.6 kbps. At these rates, Internet surfing becomes very impractical. It is therefore generally accepted that the most significantly new capability for the third generation CDMA is a larger increase in data rate and a wider range of services that can be supported.

As we review the third generation CDMA proposals being proposed by Association of Radio Industry Board (ARIB) in Japan, European Telecommunications Standards Institute (ETSI) in Europe, and TIA in the USA, however, it is clear that
the most significant technological advance over the IS-95 standard lies in the choice of wider spreading bandwidth. Even though all the proposals have touted the capability of transmitting data rates up to 2 Mbps, most of these proposals use regular cellular structure, where large coverage area and large delay spread will limit the capacity and peak data rate that can be offered. These problems can be mitigated by using cells with reduced cell size and lower antenna height. As a result, the offered traffic capacity per unit area can be significantly improved and it is possible to achieve a data rate from several hundred kbit/s to multiple Mbit/s. In fact, systems that use small cells, such as Digital European Cordless Telephone (DECT), Personal Handyphone System (PHS), and Personal Access Communications System (PACS), have been suggested. All these systems have a cell radius less than 500 m and an antenna height lower than 10 m. Nevertheless, these systems have been optimized for circuit-switch voice telephony; while protocols for the Internet have evolved to be efficient for packet-switch data services. The designs for the two are essentially different. Voice telephony requires continuous transmission with no delays, while data services are best suited for discontinuous transmission and can tolerate moderate delays. Voice services can tolerate higher error rates than data can. Another difference worth mentioning is traffic nature. Traditional voice communication is based on using bi-directional symmetric channels for each user. This assumes each user has the same data rate in the forward and reverse links. However, this assumption is not justified in data services because they usually require uni- and/or bi-directional asymmetric data transfer, which means that the data rate is different in the forward and reverse links. It appears that the third generation CDMA proposals which base their design on bi-directional symmetric channels will render the support of high-bit-rate data services quite inefficiently. This creates certain anxiety on the part of wireless industry as it has yet to create a profitable wireless data business. However, personal computers and Internet services are experiencing explosive growth in the past few years due to low-cost high-performance computer technologies and attractive network applications. In particular, data/image-oriented Internet applications, such as World Wide Web (WWW), have gained widespread user acceptance and are becoming a domi-
nant service. It is our belief that a synergistic combination of wireless, computer, and Internet technologies can create a much higher demand for high-bit-rate data access.

1.4 Thesis Motivation and Organization

Since the IS-95 CDMA systems have just been deployed in the past few years, it is conceivable that a third generation CDMA system can be cost effective if it can offer backward compatibility with these second generation systems from the infrastructure perspective. As optimization of voice telephony and data services is so different that if we force to fit them into a single system framework, neither will perform to its full capability. By the advent of digital broadcast systems such as Digital Audio Broadcasting (DAB) [7] and Digital Video Broadcasting (DVB) [8], a new range of data services can be introduced besides conventional broadcasting. The services may vary from uni-directional audio visual services to bi-directional asymmetric Internet access. Combining the broadcast systems with a conventional cellular network is therefore a promising alternative for providing symmetric and asymmetric data services [9]-[10].

In this thesis, we propose a system architecture in which broadcast systems using single frequency broadcasting are spectrally underlaid in an FDD-CDMA cellular network. The broadcast systems coexist with the FDD-CDMA cellular network in the same geographical area and same allocated frequency bands. The FDD-CDMA cellular network is intended to provide wide area voice service, while the broadcast systems with limited coverage are used to provide high-bit-rate asymmetric data services. Each broadcast system is connected to a broadcast network and includes a set of radio ports which cover a geographical service area. The reason for introducing the broadcast systems to provide asymmetric data services instead of using upscaled cellular network design techniques is that the broadcast systems can be optimized differently from a voice system, because of different traffic natures and design constraints.

The thesis is organized as follows.

Chapter 2 presents an interference analysis for an ad-hoc broadcast system
located at an arbitrary position in a power-controlled CDMA cellular network which operates in a High Frequency Band (HFB) for forward link and a Low Frequency Band (LFB) for reverse link. Common to all forms of power control is the equalization of received power or received SIR at the BS and the PT disregard to the induced power distribution throughout the rest of the communication cell. As a result, a broadcast system receiver which operates in either the HFB or the LFB and is located somewhere inside the cell, may not benefit from the power control, and therefore is susceptible to the "near-far" effects. Our emphasis is on dealing with the interference received at the broadcast system receiver and on demonstrating the susceptibility of the broadcast system receiver to the "near-far" problem in both HFB and LFB.

Chapter 3 applies the results of the interference analysis in Chapter 2 and studies the performance of CDMA broadcast systems spectrally underlaid in an FDD-CDMA cellular network. The broadcast systems coexist with the FDD-CDMA cellular network in the same geographic area and same frequency band. Interference scenarios between the cellular network and the broadcast systems in both HFB and LFB are identified. A detailed model and a simulation analysis are presented to evaluate received bit-energy-to-noise ratio \( (E_b/N_0) \) demonstrating the susceptibility to the "near-far" problem in both HFB and LFB. We also propose and compare a family of frequency allocation strategies for the CDMA broadcast systems: (1) Fixed Channel Allocation (FCA), (2) Random Channel Allocation (RCA), and (3) Distance Based Channel Allocation (DBCA), to ensure acceptable performance in the overall network.

In Chapter 4, we propose a novel duplex scheme called Space Division Duplex (SDD), which attempts to support traffic asymmetry by routing the low-bit-rate reverse link from a PT to an access point, and the high-bit-rate forward link from another access point to the PT. We explore the use of a hybrid FDD/SDD-CDMA system architecture for supporting symmetric and asymmetric data users, with the former served by a cellular network and the latter served by broadcast systems using single frequency broadcasting. The cellular network utilizes FDD to provide wide area voice and low-bit-rate symmetric data services, while the broadcast systems utilize
SDD to provide high-bit-rate asymmetric data services. This innovative approach is compared with other classical ones using per-cell capacity as the performance measure.

In Chapter 5, we consider the hybrid FDD/SDD-CDMA system architecture in which the asymmetric data users share the cellular network's reverse link with the symmetric data users. We assume that the asymmetric data users employ packet-mode access to transmit demand messages in relatively short bursts and are silent at other times, whereas the symmetric data users employ circuit-mode access. This imposes a significant challenge for performance optimization since accessing asymmetric data users can degrade the performance of currently active symmetric data users by introducing extra interference variations which reduce system capacity. We study the implementation and performance of a special version of iterative SIR-based power control algorithms in which the currently active symmetric data users are protected from interference by the accessing asymmetric data users. Moreover, as the accessing asymmetric data users are expected to have short duty cycles in the cellular network's reverse link, significant overhead may be required for iterative power control. We thus investigate the use of space diversity schemes to help reduce the high iteration overhead and access their performance jointly with the proposed iterative SIR-based power control algorithm.

Chapter 6 summarizes the main results of Chapters 2-5, and discusses some of the contributions of the thesis.

A final note is that parts of this thesis (Chapters 2-5) were published (or are accepted for publication) in [38]-[43]. The work in Chapter 4 is under preparation for patent application.
Chapter 2

Interference Analysis of an Ad-Hoc Broadcast System in a Power-Controlled CDMA Cellular Network

In this chapter, we present an interference analysis for an ad-hoc broadcast system located at an arbitrary position in a power-controlled CDMA cellular network which operates in the HFB for forward link and the LFB for reverse link. Our emphasis is on dealing with the interference received at a broadcast system receiver and on demonstrating the susceptibility of the broadcast system receiver to the "near-far" problem in both HFB and LFB. The results contributed toward the evaluation of outage probabilities of the broadcast system receiver under various propagation conditions and location considerations.

2.1 Power Control in CDMA

One of the crucial implementation requirements of CDMA cellular networks is the necessity for power control. For the reverse link, PTs are power-controlled by the BS of their own cell. This is to insure that the PTs are received with the same power at the
BS. The purpose of such control is to mitigate MAI in the reverse link by preventing the domination of any PT's signal by that of any other PTs at the BS receiver, thus effectively realizing a fair distribution of MAI among all PTs. The potential for a significant discrepancy in the PTs' received powers is commonly referred to as the "near-far" problem, and can result in significant performance degradation. For the forward link, power control takes the form of power allocation at the BS transmitter according to the needs of individual PTs in the cell of concern. This power allocation can in general be classified into two categories: (1) Power-based, and (2) SIR-based. In the former one, the BS distributes its transmitted power such that the received power at each PT is equal to a minimum required value, whereas in the latter one, the BS distributes its transmitted power such that the received SIR at each PT is equal to a required minimum value. As a consequence, the transmitted power for a PT in the cell fringe is relatively high; conversely, the transmitted power for a PT near the cell center is relatively low. Figure 2.1 shows the idea of forward and reverse link power control.

For the reverse link, since a BS is located in a fixed position in the cellular network, it receives the same MAI for its serving PTs, and therefore the BS's received SIRs among the PTs are all identical under the assumption of perfect received power control.
Common to all forms of power control is the equalization of received power or received SIR disregard to the induced power distribution throughout the rest of the communication cell. As a result, an ad-hoc broadcast system which operates in either the HFB or the LFB and is located somewhere in the cell, may not benefit from the power control, and therefore is susceptible to the “near-far” effects. Consider for example the situations depicted in Figure 2.2 and 2.3, where an ad-hoc broadcast system is deployed in a power-controlled CDMA cellular network. In Figure 2.2, both Scenario A and B give rise to the same transmitted power distribution. However, the broadcast system in Scenario B experience stronger interference from the PTs because they are located more closer to the broadcast system itself. Similarly, in Figure 2.3 the required BS transmitted power is higher in Scenario D because the PTs are located farther from the cell center. Therefore, the broadcast system experience higher interference from the BS in Scenario D than that in Scenario C. Consequently, the performance of an ad-hoc broadcast system in a power-controlled CDMA cellular network is highly dependent on the distribution of the PTs. Given an unfavorable distribution of PTs, the performance of the broadcast system can be seriously affected.

![Diagram of Scenario A and Scenario B](image)

Figure 2.2: Near-far effect for an ad-hoc broadcast system in the LFB.

2.2 System Model

We consider a standard, uniform, hexagonal layout with a BS at the center of every cell for the CDMA cellular network. A PT connects to the BS that offers the least
path loss. Forward and reverse link power control is employed by the chosen BS. We assume that the network is interference limited and that background noise is negligible. In real networks the background noise provides the reference from which absolute signal powers are set. Also note that we are solely concerned with DS-CDMA cellular networks.

To simplify the mathematical analysis, we approximate the hexagonal cells by circles of radius $R$ with a single centrally-located BS, $K$ active PTs, and a broadcast system receiver located at a distance $a$ ($a \leq R$) from the BS. The locations of the PTs in the cell are uniformly random and independent.

The circular cell geometry for analysis is shown in Figure 2.4.
2.3 Radio Propagation Model

Mobile radio signals are generally subject to rapid and large fluctuation. It is generally convenient to model the radio propagation into the following three main factors: distance dependent path loss, lognormal shadowing and multipath fading [18].

2.3.1 Distance Dependent Path Loss

Distance dependent path loss depends on the spatial distribution of the PT. As far as propagation conditions in typical cellular environments are concerned, we adopt the two-ray path loss model described in [19]. The received power for a transmitter-receiver separation of distance \( r \) in a cellular environment can be represented as

\[
p_r = p_t \left( \frac{r_{ref}}{r} \right)^\eta
\]

where \( p_r \) and \( p_t \) are the received and transmitted powers, and \( \eta \) is the path loss exponent of the cellular environment. \( r_{ref} \) defines a close-in reference distance to which the received signal powers at all farther distances can be compared. This use of \( r_{ref} \) is not strict, and in real channels will not be necessarily valid, since it depends on the antenna heights and patterns. However, for analysis of CDMA cellular networks, it is necessary to relate all of the power levels to some known reference power level, which is considered to depend on \( r_{ref} \) [20].

The simple model of (2.1) is accurate in areas with little terrain profile variation. Therefore the model is reasonable for conventional cellular networks which employ high antennas in flat service areas; but is not accurate in ad-hoc broadcast systems which employ small cells and low antennas.

Propagation in small cells follows a different law. Attenuation is quite close to free space due to a line-of-sight (LOS) path between the transmitter and the receiver. To cater for this circumstance we introduce a second path loss exponent for the small cell in our propagation model. The received power for a transmitter-receiver separation of distance \( r \) in a small cell can be represented as
\[
p_r = \begin{cases} 
  p_t \left( \frac{r_{so}}{r} \right)^{\eta_s} & \text{if } r \leq r_s \\
  p_t \left( \frac{r_{so}}{r_s} \right)^{\eta} \left( \frac{r}{r_s} \right)^{\eta} & \text{if } r > r_s 
\end{cases}
\]  
(2.2)

where \( \eta_s \) is the path loss exponent of the small cell. \( r_{so} \) and \( r_s \) are the close-in reference distance and the radius of the small cell, respectively.

2.3.2 Lognormal Shadowing

The path loss model we have just adopted can be augmented to incorporate the effects of shadow fading, which models a slow variation of the mean received power due to varying terrain and obstructions in the cell. Shadow fading can be accurately modeled by a zero-mean lognormal distributed random variable (normal in dB’s) derived from empirical results [21]. The path loss model in (2.1) or (2.2) can thus be augmented to a new path loss expression by multiplying the right hand of the equation by \( 10^{\Phi/10} \), which is a lognormal random variable representing shadowing effects. \( \Phi \sim N(0, \sigma^2) \) in dB.

2.3.3 Multipath Fading

Another propagation effect is multipath fading. As a PT moves through an area, the instantaneous received signal strength fluctuates rapidly as a result of multipath propagation. In general, the multipath propagation causes the received signal strength at the receiver to have a Rayleigh probability distribution and a uniformly distributed phase. This phenomenon is referred to as Rayleigh fading.

The autocorrelation function with an omnidirectional antenna is represented by [22]

\[
\rho_f(\tau) = J_0(2\pi f_D \tau)
\]  
(2.3)

where \( \tau \) is the time, \( J_0(\cdot) \) is the zero-order Bessel function of the first kind, and \( f_D \) is the maximum Doppler frequency. The maximum Doppler frequency is defined as \( f_D = v/\lambda \), where \( v \) is the PT speed and \( \lambda \) is the wavelength of the RF carrier.
Throughout this thesis we do not model the multipath fading, unless otherwise stated. It is generally assumed that the use of techniques such as interleaving, diversity reception and soft handoff as well as the employment of a RAKE receiver, can greatly mitigate the effects of multipath fading. At any rate we can assume the effects of multipath fading are encapsulated in the SIR requirement of the network.

2.4 Interference Power Distribution in the LFB

In this section, we derive the interference power from a uniformly distributed PT in a circular cell received at the broadcast system receiver which operates in the LFB. We assume that perfect reverse link power control is employed in the CDMA cellular network so that the PT's received power at the BS would be the same regardless of its location in the cell of concern.

Without loss of generality, we set the received power of a given PT at the BS of its own cell to be 1. Hence, the PT is power-controlled such that its transmitted power, $P_t$, is given by

$$P_t = \left( \frac{r}{r_{ref}} \right)^\eta$$  \hspace{1cm} (2.4)

2.4.1 Intracell Interference

![Diagram of intracell interference](image)

Figure 2.5: Plot for the computation of LFB intracell interference power distribution.

In order to determine the interference power received from an intracell PT we
consider the situation depicted in Figure 2.5. Here, the broadcast system receiver and the intracell PT are both located in the same cell. Using polar coordinates \((r, \phi)\), we assume that the broadcast system receiver is located at \((a, \pi)\) and the intracell PT is located at \((r_0, \phi_0)\). BS \(B_0\) in cell 0 is at the origin \((0, 0)\). From the law of cosines,

\[
b_0 = \sqrt{a^2 + r_0^2 + 2 a r_0 \cos \phi_0}
\]

(2.5)

The interference received at the broadcast system receiver from the intracell PT is given by

\[
I_{\text{intra}}(r_0, \phi_0) = \left( \frac{r_0}{b_0} \right)^\eta = \left( \frac{r_0}{\sqrt{a^2 + r_0^2 + 2 a r_0 \cos \phi_0}} \right)^\eta
\]

(2.6)

We are interested in calculating the cumulative distribution function (CDF) of the random variable \(I_{\text{intra}}(r_0, \phi_0)\) given the joint distribution function \(F_{r_0, \phi_0}\) of the random variables \(r_0\) and \(\phi_0\). The derivation is carried out in Appendix 2.8.1 and leads to the CDF of the interference received at \((a, \pi)\) from an intracell PT that is uniformly distributed in a circle of radius \(R\) centered at the origin. The CDF is given below.

\[
F_{I_{\text{intra}}}(z) = \begin{cases} 
0 & z < 0 \\
\frac{\alpha^2 z^\eta}{(1-z^\eta)^2} & 0 \leq z \leq \frac{1}{(1+\alpha)^\eta} \\
\frac{1}{2} + \frac{1}{\pi} \sin^{-1}\left( \frac{z^\eta(1+\alpha^2)-1}{2z^\eta \alpha} \right) & \frac{1}{(1+\alpha)^\eta} < z < \frac{1}{(1-\alpha)^\eta} \\
\frac{1}{2} + \frac{1}{\pi} \sin^{-1}\left( \frac{\alpha}{2} \right) + \frac{\alpha}{4\pi} \sqrt{4-\alpha^2} & z = 1 \\
1 - \frac{\alpha^2 z^\eta}{(1-z^\eta)^2} & \frac{1}{(1-\alpha)^\eta} \leq z < \infty
\end{cases}
\]

(2.7)

where \(\alpha = \frac{a}{R}\) and the range of \(\sin^{-1}(\cdot)\) is taken to be \(\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]\).
Figure 2.6: Plot for the computation of LFB intercell interference power distribution.

Figure 2.7: Plot for the computation of LFB intercell interference power distribution (after translation and rotation).
2.4.2 Intercell Interference

The intercell interference situation is depicted in Figure 2.6. Using polar coordinates \((r, \phi)\), we assume that the broadcast system receiver is located at \((a, \pi)\). BS \(B_i\) in cell \(i\) is located at \((D_i, \theta_i)\); and BS \(B_0\) in cell 0 is at the origin \((0,0)\). The intercell PT is at a distance \(r_i\) from BS \(B_i\). For ease of analysis, we shift the origin to \((D_i, \theta_i)\) and rotate with respect to this new origin such that the broadcast system receiver and BS \(B_i\) align on the same horizontal axis (see Figure 2.7). From the law of cosines,

\[
b_i = \sqrt{a^2 + D_i^2 + 2aD_i \cos \theta_i}, \quad b_i > R \tag{2.8}
\]

With reference to Figure 2.7, the interference received at the broadcast system receiver from the intercell PT is given by

\[
I_{\text{inter}}(r_i, \phi_i) = \left( \frac{r_i}{d_i} \right)^\eta = \left( \frac{r_i}{\sqrt{b_i^2 + r_i^2 + 2b_ir_i \cos \phi_i}} \right)^\eta \tag{2.9}
\]

where \(d_i\) is the distance between the intercell PT and the broadcast system receiver.

The CDF of the random variable \(I_{\text{inter}}(r_i, \phi_i)\) representing received interference from an intercell PT uniformly distributed in a circle of radius \(R\) centered at \((D_i, \theta_i)\) is derived in Appendix 2.8.1 and is given below.

\[
F_{I_{\text{inter}}}(z) = \begin{cases} 
0 & z < 0 \\
\frac{\beta^2z^{2/\eta}}{(1-z^{2/\eta})^2} & 0 \leq z \leq \frac{1}{(\beta+1)^\eta} \\
\frac{1}{2} + \frac{1}{\pi} \sin^{-1} \left\{ \frac{z^{2/\eta}(1+\beta^2)-1}{2z^{2/\eta}\beta} \right\} & \frac{1}{(\beta+1)^\eta} < z \leq \frac{1}{(\beta-1)^\eta} \\
\frac{1}{2} + \frac{1}{\pi} \sin^{-1} \left( \frac{\beta}{2} \right) + \frac{\beta}{4\pi} \sqrt{4 - \beta^2} & z = 1 \\
1 & z \geq \frac{1}{(\beta-1)^\eta}
\end{cases} \tag{2.10}
\]

where \(\beta = \frac{b_i}{R}\) and the range of \(\sin^{-1}(\cdot)\) is taken to be \([-\pi/2, \pi/2]\).
Assuming $\eta = 2, 3, 4$ and $\sigma = 0$ dB, we compare the analytic CDFs of received LFB intracell and intercell interference power at various broadcast system receiver locations with that obtained via computer simulation in Figures 2.8-2.13. Only the first tier of cells is considered in the intercell scenario. Portable locations are randomly generated in each cell according to the distributions in (2.33) and (2.34). The received interference power statistics at various broadcast system receiver locations are collected. Then all random variables are regenerated until 10000 interference power values have been calculated for each value of $\eta$ and $\alpha$. As the values of $\eta$ and $\alpha$ are varied the analytic expression remains in good agreement with simulation. It is also noticed in the figures that the variance of the received interference power increases with $\eta$. 
Figure 2.8: CDF of received LFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect reverse link power control: $\eta = 2$ and $\sigma = 0$ dB. Solid lines, analytic results. Points, simulation results.

Figure 2.9: CDF of received LFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect reverse link power control: $\eta = 3$ and $\sigma = 0$ dB. Solid lines, analytic results. Points, simulation results.

Figure 2.10: CDF of received LFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect reverse link power control: $\eta = 4$ and $\sigma = 0$ dB. Solid lines, analytic results. Points, simulation results.
Figure 2.11: CDF of received LFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect reverse link power control: $\eta = 2$ and $\sigma = 0$ dB. Solid lines, analytic results. Points, simulation results.

Figure 2.12: CDF of received LFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect reverse link power control: $\eta = 3$ and $\sigma = 0$ dB. Solid lines, analytic results. Points, simulation results.

Figure 2.13: CDF of received LFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect reverse link power control: $\eta = 4$ and $\sigma = 0$ dB. Solid lines, analytic results. Points, simulation results.
We define the adjacent cell interference spillover factor, $\gamma$, as the ratio of mean intercell interference to mean intracell interference as

$$\gamma = \frac{E[I_{1st tier}]}{E[I_{intra}]}$$  \hspace{1cm} (2.11)

Figure 2.14 illustrates the corresponding adjacent cell interference spillover factor, $\gamma$, for different broadcast system receiver locations under different path loss exponents $\eta = 2, 3, 4$ and $\sigma = 0$ dB. Observe that the spillover factor $\gamma$ decreases with $\eta$ at a given broadcast system receiver location $\alpha$. As $\eta$ increases, the PTs have to transmit higher powers in a power-controlled CDMA cellular network. Hence, the broadcast system receiver experiences higher intracell interference. Note that when the broadcast system receiver is located close to the cell centre, it experiences lower intercell interference as $\eta$ increases. On the other hand, when it is located close to the cell fringe, it experiences higher intercell interference as $\eta$ increases. This explains why for a given $\eta$, $\gamma$ decreases first but increases later as $\alpha$ increases.
Figure 2.14: Adjacent cell interference spillover factor, $\gamma$, for various broadcast system receiver locations under different path loss exponents $\eta = 2, 3, 4$ and $\sigma = 0$ dB.
2.4.3 Inclusion of Lognormal Shadowing

We are interested in extending the previous interference analysis which is based on the propagation model of (2.1) or (2.2), to include the shadowing effects. We assume $\eta$ and $\Phi$ are constant over all paths, and that the shadowing random variables are independent for different paths.

If the PTs are subject to lognormal shadowing, then the path loss between a PT and a BS with which it is communicating is given by $PL = (r/r_{ref})^{\eta} 10^{-\varepsilon/10}$ where $\varepsilon$ is a zero mean normal random variable with variance $\sigma^2$, representing the shadowing component between the BS and the PT in the cell of concern. If the BS compensates for shadowing through the use of feedback power control, then the transmitted power of the PT is given by

$$P_t = \left( \frac{r}{r_{ref}} \right)^\eta 10^{-\varepsilon/10} \tag{2.12}$$

In this case, the interference power received at the broadcast system receiver is given by

$$I_{intra}(r_0, \phi_0) = \left( \frac{r_0}{\sqrt{a^2 + r_0^2 + 2 a r_0 \cos \phi_0}} \right)^\eta 10^{(\delta_0 - \varepsilon_0)/10} \tag{2.13}$$

$$I_{inter}(r_i, \phi_i) = \left( \frac{r_i}{\sqrt{b_i^2 + r_i^2 + 2 b_i r_i \cos \phi_i}} \right)^\eta 10^{(\delta_i - \varepsilon_i)/10} \tag{2.14}$$

where $\varepsilon_0$ and $\delta_i$ are the shadowing components experienced by the broadcast system receiver from the intracell PT and the intercell PT respectively. Note that the first and second moments of $10^{(\delta_i - \varepsilon_i)/10}$ are given by

$$E(10^{(\delta_i - \varepsilon_i)/10}) = E(e^{\chi(\delta_i - \varepsilon_i)}) = e^{\chi \sigma^2} \tag{2.15}$$

$$E(10^{2(\delta_i - \varepsilon_i)/10}) = E(e^{2\chi(\delta_i - \varepsilon_i)}) = e^{4 \chi \sigma^2} \tag{2.16}$$

where $\chi = (\ln 10)/10$. 

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Figures 2.15-2.20 depict CDFs of received LFB intracell and intercell interference power at various broadcast system receiver locations under \( \eta = 4 \) and \( \sigma = 6, 8, 10 \) dB. Only the first tier of cells is considered in the intercell scenario. Of interest is the fact that power control amplifies the deleterious effect of shadowing at the broadcast system receiver. To see this, since \( \delta_i \) and \( \varepsilon_i \) are two independent zero mean normal random variables, the difference \( (\delta_i - \varepsilon_i) \) becomes another zero mean normal random variable but with variance \( 2\sigma^2 \), introducing a larger potential range of received interference powers. Therefore, the variance of the received interference power increases with \( \sigma \) as expected. Comparing the cases between without shadowing and with shadowing, the effect of shadowing is seen to flatten the CDF curves, an expected product of the location independent contribution to the received power variance represented by shadowing.
Figure 2.15: CDF of received LFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect reverse link power control: $\eta = 4$ and $\sigma = 6$ dB.

Figure 2.16: CDF of received LFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect reverse link power control: $\eta = 4$ and $\sigma = 8$ dB.

Figure 2.17: CDF of received LFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect reverse link power control; $\eta = 4$ and $\sigma = 10$ dB.
Figure 2.18: CDF of received LFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect reverse link power control: $\eta = 4$ and $\sigma = 6$ dB.

Figure 2.19: CDF of received LFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect reverse link power control: $\eta = 4$ and $\sigma = 8$ dB.

Figure 2.20: CDF of received LFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect reverse link power control: $\eta = 4$ and $\sigma = 10$ dB.
Figure 2.21 illustrates the corresponding adjacent cell interference spillover factor, γ, for various broadcast system receiver locations under path loss exponent η = 4 and different shadowing exponents σ = 6, 8, 10 dB. Recalling that $E(10^{(\delta-\varepsilon)/10}) = e^{(\varepsilon\sigma^2)}$, we note that the mean received intracell and intercell interference in the added presence of shadowing effects are both multiplied by $e^{(\varepsilon\sigma^2)}$. Hence, the ratio of the mean intercell interference to the mean intracell interference, γ, remains approximately the same with the values of σ. However, we also witness that at the given η = 4, γ decreases first but then increases as α increases.
Figure 2.21: Adjacent cell interference spillover factor, $\gamma$, for various broadcast system receiver locations under path loss exponent $\eta = 4$ and different shadowing exponents $\sigma = 6.8, 10$ dB.
2.5 Interference Power Distribution in the HFB

In this section, we determine the interference power from a BS for a uniformly distributed PT in a circular cell received at the broadcast system receiver which operates in the HFB. The BS allocates a fraction of its total transmitted power proportionally according to the needs of each PT in the cell of concern. This forward link power control aims at balancing the received power or the received SIR at each PT as discussed in Section 2.1.

![Diagram of interference power distribution in the HFB](image)

Figure 2.22: Plot for the computation of HFB interference power distribution.

Figure 2.22 depicts the interference scenario in the HFB. Using the same notation adopted in Section 2.4, we assume that the broadcast system receiver is at \( (a, \pi) \). BS \( B_i \) in cell \( i \) is at \( (D_i, \theta_i) \); and BS \( B_0 \) in cell 0 is at \( (0,0) \). The intracell PT is at a distance \( r_0 \) from BS \( B_0 \) and the intercell PT is at a distance \( r_i \) from BS \( B_i \). \( b_i \) is again expressed as given by (2.8). With reference to Figure 2.22, the total interference received at the broadcast system receiver consists of intracell interference due to BS \( B_0 \) and intercell interference due to other BSs (excluding \( B_0 \)); and is dependent upon the position of the broadcast system receiver in the cell. It is, therefore, a function of the distance between BS \( B_0 \) and the broadcast system receiver, \( a \). The function is given below.
\[ I(a) = P_{B_0} \left( \frac{r_{\text{ref}}}{a} \right)^\eta + \sum_{i=1}^{N_C-1} P_{B_i} \left( \frac{r_{\text{ref}}}{b_i} \right)^\eta \]

\[ = P_{B_0} \left( \frac{r_{\text{ref}}}{a} \right)^\eta + \sum_{i=1}^{N_C-1} P_{B_i} \left( \frac{r_{\text{ref}}}{\sqrt{a^2 + D_i^2 + 2 a D_i \cos \theta_i}} \right)^\eta \] (2.17)

where \( P_{B_i} \) is the total transmitted power from BS \( B_i \) and \( N_C \) (indexed from 0 to \( N_C - 1 \)) is the number of interfering cells in the coverage area.

### 2.5.1 Power Control Algorithms

Forward link power control takes the form of power allocation at the BS according to the needs of individual PTs in the cell of concern. In the following, we examine two power control algorithms.

**Power-based Power Control**

In power-based power control, the BS distributes its transmitted power such that each PT receives the same power. Assuming **Equal Received Power** criterion in both HFB and LFB, we set each PT's received power to be 1. In other words, both BS and PT receive with the same power. Therefore, the transmitted power from BS \( B_i \) for a PT in cell \( i \) is given by

\[(P_{B_i})_{\text{power}} = \left( \frac{r_i}{r_{\text{ref}}} \right)^\eta \] (2.18)

where \( r_i \) is the distance between BS \( B_i \) and the PT.

(2.17) can now be rewritten as

\[ I(a) = I_{\text{intra}}(r_0, \phi_0) + \sum_{i=1}^{N_C-1} I_{\text{inter}}(r_i, \phi_i) \]

\[ = \left( \frac{r_0}{a} \right)^\eta + \sum_{i=1}^{N_C-1} \left( \frac{r_i}{\sqrt{a^2 + D_i^2 + 2 a D_i \cos \theta_i}} \right)^\eta \] (2.19)
We are interested in calculating the CDFs of the random variable \( I_{\text{intra}}(r_0, \phi_0) \) and \( I_{\text{inter}}(r_i, \phi_i) \) given the joint distribution functions \( F_{r_0,\phi_0} \) and \( F_{r_i,\phi_i} \). The derivation is carried out in Appendix 2.8.2 and leads to the CDFs of the interference power received at \((a, \pi)\) from BS \( B_0 \) and BS \( B_i \). The CDFs are given below.

\[
F_{\text{intra}}(z) = \begin{cases} 
0, & z < 0 \\
\alpha^2 z^{2/\eta}, & 0 \leq z < I_\alpha(1/\alpha) \\
1, & z \geq I_\alpha(1/\alpha) 
\end{cases}
\]  

(2.20)

\[
F_{\text{inter}}(z) = \begin{cases} 
0, & z < 0 \\
\beta^2 z^{2/\eta}, & 0 \leq z < I_\alpha(1/\beta) \\
1, & z \geq I_\alpha(1/\beta) 
\end{cases}
\]  

(2.21)

where \( \alpha = a/R \) and \( \beta = b_i/R \).

Figures 2.23 - 2.28 show CDFs of received HFB intracell and intercell interference power at various broadcast system receiver locations under perfect power-based forward link power control and \( \sigma = 0 \) dB.
Figure 2.23: CDF of received HFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect power-based forward link power control; $\eta = 2$ and $\sigma = 0$ dB.

Figure 2.24: CDF of received HFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect power-based forward link power control; $\eta = 3$ and $\sigma = 0$ dB.

Figure 2.25: CDF of received HFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect power-based forward link power control; $\eta = 4$ and $\sigma = 0$ dB.
Figure 2.26: CDF of received HFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect power-based forward link power control; \( \eta = 2 \) and \( \sigma = 0 \) dB.

Figure 2.27: CDF of received HFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect power-based forward link power control; \( \eta = 3 \) and \( \sigma = 0 \) dB.

Figure 2.28: CDF of received HFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect power-based forward link power control; \( \eta = 4 \) and \( \sigma = 0 \) dB.
Inclusion of Lognormal Shadowing

If the PTs are subject to lognormal shadowing, the required transmitted power from BS $B_i$ for a PT in cell $i$ is then given by

$$ (P_{B_i})_{power} = \left( \frac{r_i}{r_{ref}} \right)^\eta 10^{-\varepsilon_i/10} $$

(2.22)

where $r_i$ and $\varepsilon_i$ are the distance and shadowing component between BS $B_i$ and the PT.

In this case, the interference power received at the broadcast system receiver is expressed as

$$ I(a) = \left( \frac{r_0}{a} \right)^\eta 10^{(\xi_0-\varepsilon_0)/10} + \sum_{i=1}^{N_c-1} \left( \frac{r_i}{\sqrt{a^2 + D_i^2 + 2a\, D_i \cos \theta_i}} \right)^\eta 10^{(\xi_i-\varepsilon_i)/10} $$

(2.23)

where $\xi_i$ represents the shadowing component between BS $B_i$ and the broadcast system receiver.

Figures 2.29 - 2.34 show CDFs of received HFB intracell and intercell interference power at various broadcast system receiver locations under perfect power-based forward link power control; $\eta = 4$ and $\sigma = 6.8.10$ dB.
Figure 2.29: CDF of received HFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect power-based forward link power control; $\eta = 4$ and $\sigma = 6$ dB.

Figure 2.30: CDF of received HFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect power-based forward link power control: $\eta = 4$ and $\sigma = 8$ dB.

Figure 2.31: CDF of received HFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect power-based forward link power control; $\eta = 4$ and $\sigma = 10$ dB.
Figure 2.32: CDF of received HFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect power-based forward link power control: $\eta = 4$ and $\sigma = 6$ dB.

Figure 2.33: CDF of received HFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect power-based forward link power control: $\eta = 4$ and $\sigma = 8$ dB.

Figure 2.34: CDF of received HFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect power-based forward link power control: $\eta = 4$ and $\sigma = 10$ dB.
SIR-based Power Control

SIR-based power control aims at balancing and equalizing each PT’s received SIR and is known to increase system capacity. SIR-based power control reduces the BS’s transmitted power if the requested power from all PTs does not exceed $P_{max}$, the BS’s maximum transmitted power requirement; otherwise, the BS redistributes the transmitted power to provide the same link quality for all PTs regardless of their power requirements.

Consider a given intracell PT served by BS $B_0$. The SIR seen by the PT in the HFB is given by

$$
(SIR)_{HFB} = \begin{cases} 
\frac{(P_{B_0})_{SIR} \tau_0^{-\eta}}{\sum_{i=1}^{N_{C}} (P_{B_i})_{SIR} d_{i}^{-\eta}} & \text{without shadowing} \\
\frac{(P_{B_0})_{SIR} \tau_0^{-\eta}}{\sum_{i=1}^{N_{C}} (P_{B_i})_{SIR} d_{i}^{-\eta} \zeta_{i}^{10/\eta}} & \text{with shadowing}
\end{cases}
\tag{2.24}
$$

where $d_{i}$ and $\zeta_{i}$ represent the distance and shadowing component between BS $B_i$ and the intracell PT respectively; and $\tau_0$ and $\varepsilon_0$ represent the distance and shadowing component between BS $B_0$ and the intracell PT respectively.

Assuming **Equal Received SIR** criterion in both HFB and LFB, we set $SIR_{HFB}$ equal to $(SIR)_{LFB}$ in (2.25). The above procedures aim to make the communication quality in the forward link equal to that in the reverse link, thus balancing the performance of the forward link and reverse link.

The SIR seen by BS $B_0$ for the intracell PT in the LFB is given by

$$
(SIR)_{LFB} = \begin{cases} 
\frac{P_{t,0} \tau_0^{-\eta}}{\sum_{i=1}^{N_{C}} P_{t,i} d_{i}^{-\eta}} & \text{without shadowing} \\
\frac{P_{t,0} \tau_0^{-\eta}}{\sum_{i=1}^{N_{C}} P_{t,i} d_{i}^{-\eta} \nu_{i}^{10/\eta}} & \text{with shadowing}
\end{cases}
\tag{2.25}
$$

where $d_{i}$ and $\nu_{i}$ represent the distance and shadowing component between BS $B_0$ and the intercell PT served by BS $B_i$ respectively. $P_{t,i}$ is the transmitted power of the intercell PT served by $B_i$; and $P_{t,0}$ is the transmitted power of the intracell PT.

By setting $(SIR)_{HFB} = (SIR)_{LFB}$ and using the fact that $P_{t,i} = (P_{B_i})_{power}$, we have
\[ \sum_{i=1}^{Nc}(P_{Bi})_{SIR} \left( \frac{r_i}{d_i} \right)^{\eta} \]
\[ = \sum_{i=1}^{Nc}(P_{Bi})_{SIR} \left( \frac{r_0}{d_i} \right)^{\eta} \] without shadowing
\[ \sum_{i=1}^{Nc}(P_{Bi})_{SIR} \left( \frac{r_i}{d_i} \right)^{\eta} 10^{(\mu_i-\varepsilon_i)/10} \]
\[ = \sum_{i=1}^{Nc}(P_{Bi})_{SIR} \left( \frac{r_0}{d_i} \right)^{\eta} 10^{(\zeta_i-\varepsilon_0)/10} \] with shadowing

Unlike the power-based power control, the CDF of \((P_{Bi})_{SIR}\), which depends on the sum of ratios of ranked lognormal variables, does not lend itself to analysis. The difficulty in computing the CDF of \((P_{Bi})_{SIR}\) is that it depends on the CDFs of \(\left( \frac{r_i}{d_i} \right)^{\eta} 10^{(\mu_i-\varepsilon_i)/10}\) and \(\left( \frac{r_0}{d_i} \right)^{\eta} 10^{(\zeta_i-\varepsilon_0)/10}\), and vice versa. Given the CDFs of \(\left( \frac{r_i}{d_i} \right)^{\eta} 10^{(\mu_i-\varepsilon_i)/10}\) and \(\left( \frac{r_0}{d_i} \right)^{\eta} 10^{(\zeta_i-\varepsilon_0)/10}\), one can compute a corresponding CDF for the \((P_{Bi})_{SIR}\) and vice versa. We let \(\Lambda_i\) and \(\Lambda_0\) denote the CDFs of \(\left( \frac{r_i}{d_i} \right)^{\eta} 10^{(\mu_i-\varepsilon_i)/10}\) and \(\left( \frac{r_0}{d_i} \right)^{\eta} 10^{(\zeta_i-\varepsilon_0)/10}\) respectively. In the following, we implement an iterative algorithm to compute the CDF of \((P_{Bi})_{SIR}\).

1. Let \((P_{Bi})_{SIR} = 1\) for all \(i\).

2. Obtain the CDFs of \(\Lambda_i\) and \(\Lambda_0\) using observations of \(\left( \frac{r_i}{d_i} \right)^{\eta} 10^{(\mu_i-\varepsilon_i)/10}\) and \(\left( \frac{r_0}{d_i} \right)^{\eta} 10^{(\zeta_i-\varepsilon_0)/10}\) respectively.

3. Update the CDF of \((P_{Bi})_{SIR}\) using CDFs of \(\Lambda_i\) and \(\Lambda_0\) from Step 2.

4. Update the CDFs of \(\Lambda_i\) and \(\Lambda_0\). Test the distributions of \(\Lambda_i\) and \(\Lambda_0\) to ensure that they have converged. If so, go to Step 6, else go to Step 5.

5. Update the CDF of \((P_{Bi})_{SIR}\) from the CDFs of \(\Lambda_i\) and \(\Lambda_0\) computed in Step 4. Go to Step 4.


Figures 2.35 - 2.46 show CDFs of received HFB intracell and intercell interference power at various broadcast system receiver locations under perfect SIR-based forward link power control.
Figure 2.35: CDF of received HFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect SIR-based forward link power control; $\eta = 2$ and $\sigma = 0$ dB.

Figure 2.36: CDF of received HFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect SIR-based forward link power control; $\eta = 3$ and $\sigma = 0$ dB.

Figure 2.37: CDF of received HFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect SIR-based forward link power control; $\eta = 4$ and $\sigma = 0$ dB.
Figure 2.38: CDF of received HFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect SIR-based forward link power control: $\eta = 2$ and $\sigma = 0$ dB.

Figure 2.39: CDF of received HFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect SIR-based forward link power control: $\eta = 3$ and $\sigma = 0$ dB.

Figure 2.40: CDF of received HFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect SIR-based forward link power control: $\eta = 4$ and $\sigma = 0$ dB.
Figure 2.41: CDF of received HFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect SIR-based forward link power control; $\eta = 4$ and $\sigma = 6$ dB.

Figure 2.42: CDF of received HFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect SIR-based forward link power control; $\eta = 4$ and $\sigma = 8$ dB.

Figure 2.43: CDF of received HFB intracell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect SIR-based forward link power control; $\eta = 4$ and $\sigma = 10$ dB.
Figure 2.44: CDF of received HFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect SIR-based forward link power control; $\eta = 4$ and $\sigma = 6$ dB.

Figure 2.45: CDF of received HFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect SIR-based forward link power control; $\eta = 4$ and $\sigma = 8$ dB.

Figure 2.46: CDF of received HFB intercell interference power at various broadcast system receiver locations for a uniformly distributed PT in a circular cell under perfect SIR-based forward link power control; $\eta = 4$ and $\sigma = 10$ dB.
We note that the CDFs of received HFB intracell and intercell interference power are dependent on the location of the broadcast system receiver through $\alpha$. As $\alpha$ increases, the HFB intracell interference decreases because the broadcast system receiver is located further away from the intracell BS, but at the same time, the HFB intercell interference increases because the broadcast system receiver is getting closer to the intercell BSs in the surrounding cells.

Comparing the CDFs with that of the received LFB intracell and intercell interference power in Figures 2.8 - 2.20, we see that the CDFs of received HFB interference power is steeper in both power-based and SIR-based forward link power control, meaning that the variance of the received interference power is smaller in the HFB than that in the LFB. This is mainly attributed to a fundamental asymmetry between the LFB interference due to the PTs and the HFB interference due to the BSs, as PTs in general have arbitrary locations while BSs are fixed and regularly spaced.

We discover that the CDMA cellular network with SIR-based forward link power control injects higher interference to the broadcast system receiver than that with power-based forward link power control. For example, when $\alpha = 1.0$ and $\eta = 4.0$, it is 6.3 dB versus -1.5 dB at 0.9 Cumulative in intracell scenario without shadowing, and 7.5 dB versus 0 dB at 0.9 Cumulative in intercell scenario without shadowing. A similar trend can also be observed for the case when there is shadowing present. This is no surprise, because in SIR-based forward link power control the BS's transmitted power for a given PT depends on the PT's received SIR value. When the PT moves away from the intracell BS to the cell fringe, it receives higher interference from the intercell BSs and hence the intracell BS has to transmit higher power for the PT. When the PT is close to the intracell BS, it receives less interference from the intercell BSs and thus the intracell BS can transmit less power for the PT to maintain the same received SIR value. Given the assumption that the PT is uniformly distributed in the cell, the BS's transmitted power with SIR-based power control will be higher than that with power-based power control.


2.6 Outage Probability

A criterion for performance evaluation is the outage probability. It is defined as the probability of failing to achieve a SIR greater than a fixed threshold $SIR_{req}$, namely, $P_{out} = \text{Prob}\{SIR < SIR_{req}\}$.

Consider an ad-hoc broadcast system with a broadcast system receiver, which is received with signal power $q$. If we assume the broadcast system receiver uses a conventional matched-filter detector and prescribe a required SIR threshold $\Gamma$ below which the broadcast system receiver cannot operate satisfactorily, and with interference power $I$ from the CDMA cellular network (either in the HFB or the LFB), we can write the outage probability of the broadcast system receiver as

$$P_{out} = \text{Prob}(SIR < SIR_{req}) = \text{Prob}(q/I < \Gamma) \quad (2.27)$$

Figures 2.47 - 2.49 depict the outage probabilities of the broadcast system receiver as a function of $\alpha$ with different received signal power (from -10 dB to 10 dB) in both HFB and LFB. Ideal power control is assumed in the CDMA cellular network. In these figures, both $\sigma = 0$ dB (without shadowing) and $\sigma = 8$ dB (with shadowing) are compared. The results are obtained with a SIR threshold $\Gamma$ of -15 dB. It is found that the outage probability of the broadcast system receiver is highly dependent on $\alpha$. In the LFB, the smaller the $\alpha$ the better the outage performance; whereas in the HFB, the larger the $\alpha$ the better the outage performance. Also, the outage probability of the broadcast system receiver decreases with an increase in the received signal power. However, this implies an increase in the interference injected into the CDMA cellular network.

The power control algorithms employed by the CDMA cellular network in both HFB and LFB have an impact on the outage probability of the broadcast system receiver. In the LFB, each PT adjusts its transmitted power so that it is received at the BS with a constant power. This also equalizes the received SIR values at the BS for all PTs in the cell of concern. Nevertheless, this is not the case in the HFB because the PTs are arbitrarily located and interference seen at a particular PT is
dependent on where it is located. Therefore, equal received power among all PTs does not necessarily mean equal received SIR, and vice versa. In Section 2.5, we have presented two power control algorithms in the HFB. One is the power-based forward link power control which aims at equalizing the received power at the PT. The other one is the SIR-based forward link power control which aims at equalizing the received SIR at the PT. As shown in Figures 2.48 and 2.49, the outage performance of the broadcast system receiver is poorer when SIR-based forward link power control is employed. This implies that in the CDMA cellular network a BS on average needs to transmit higher power to a PT in order to balance the forward link SIR performance in the HFB and the reverse link SIR performance in the LFB.
Figure 2.47: Outage probability of the broadcast system receiver operating in the LFB under perfect reverse link power control.
Figure 2.48: Outage probability of the broadcast system receiver operating in the HFB under perfect power-based forward link power control.
Figure 2.49: Outage probability of the broadcast system receiver operating in the HFB under perfect SIR-based forward link power control.
2.7 Chapter Summary

We have presented the interference analysis for an ad-hoc broadcast system located at an arbitrary position in a power-controlled CDMA cellular network which operates in the HFB for forward link and the LFB for reverse link. The emphasis is on dealing with the interference received at a broadcast system receiver in both HFB and LFB. Intracell and intercell interference scenarios are considered, with distance dependent and lognormal shadowing models adopted for propagation path loss. The end products are CDFs of the interference power received at the broadcast system receiver for a uniformly distributed PT in a circular cell. These expressions are analytic for distance dependent propagation model but require numerical integration when lognormal shadowing model is introduced, and contribute toward the evaluation of outage probabilities of the broadcast system receiver under various propagation conditions and location considerations.

We conclude that power control employed in the CDMA cellular network actually increases “near-far” susceptibility at the broadcast system receiver by increasing the potential range of received interference powers from the PTs in the LFB and the BSs in the HFB respectively, and by increasing the variance of received interference powers resulting from lognormal shadowing in the CDMA cellular network wherein power control is employed to compensate shadowing. Our results form a performance guideline for optimizing an integration of conventional CDMA cellular network with broadcast systems for wireless multimedia services.
2.8 Appendix

2.8.1 Derivation of Interference Distribution Function in the LFB

$I_{\text{intra}}(r_0, \phi_0)$

We first derive the CDF of $I_{\text{intra}}(r_0, \phi_0)$ in the LFB.

Before proceeding, note that by symmetry it is only necessary to deal with the upper semi-circle in Figure 2.5. Further only the ratio of $a$ and $R$ is relevant and we therefore normalize $a$ w.r.t. $R$ and set $\alpha = a/R$ without loss of generality. Consider $I_{\text{intra}}(r_0, \phi_0)$ in (2.6). Replacing $r_0/a$ by $r$ and $\phi_0$ by $\phi$, we can express the equation in the following manner.

$$I_{\text{intra}}(r, \phi) = \left( \frac{r}{\sqrt{r^2 + 2 r \cos \phi + 1}} \right)^\eta \quad (2.28)$$

where $r \in [0, 1/\alpha]$ and $\phi \in [0, \pi]$. In the intracell scenario, $1 < 1/\alpha < \infty$.

$r$ and $\phi$ are independent random variables with marginal distributions given by

$$F_r(r) = \begin{cases} 
0 & r < 0 \\
\alpha^2 r^2 & 0 \leq r < 1/\alpha \\
1 & r \geq 1/\alpha 
\end{cases} \quad (2.29)$$

$$F_\phi(\phi) = \begin{cases} 
0 & \phi < 0 \\
\phi/\pi & 0 \leq \phi < \pi \\
1 & \phi \geq \pi 
\end{cases} \quad (2.30)$$

The problem now is to calculate the CDF of the random variable $I_{\text{intra}}(r, \phi)$ where $r$ and $\phi$ are independent random variables with the above readily calculated distributions.

Objective: Find the CDF of the random variable $I_{\text{intra}}(r, \phi)$.

Solution

Fix $r \in [0, 1/\alpha]$ and define $I_r(\phi) = I_{\text{intra}}(r, \phi)$.

Lemma A1.1 $I_r(\phi)$ is strictly increasing on $(0, \pi)$ for all $r \in [0, 1/\alpha]$. 

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Proof

\[
\frac{dI_r(\phi)}{d\phi} = \frac{\eta \, r^{\eta+1} \sin \phi}{(r^2 + 2 \, r \, \cos \phi + 1)^{\eta/2+1}} > 0 \text{ for } \phi \in (0, \pi)
\]

Note that for a given \( r \), \( I_r(\phi) \) is strictly increasing from \( I_r(0) \) to \( I_r(\pi) \) and therefore standard transformation techniques can be applied to calculate the CDF of \( I_r(\phi) \) where \( \phi \) is distributed as in (2.30). In particular, we have

\[
F_{I_r}(z) = \text{Prob}(I_r(\phi) \leq z) = \begin{cases} 0, & z < 0 \\ F_\phi(I_r^{-1}(z)), & 0 \leq z < I_r(\pi) \\ 1, & z \geq I_r(\pi) \end{cases}
\]

where the inverse function \( I_r^{-1}(z) \) is well defined on \( z \in [0, I_r(\pi)) \) because of the monotonicity of \( I_r(\phi) \). It is calculated by solving

\[
I_r(\phi) = \left( \frac{r}{\sqrt{r^2 + 2 \, r \, \cos \phi + 1}} \right)^\eta = z
\]

for \( \phi \) taking into consideration the allowed values of the variables involved.

We are thus led to the following lemma.

Lemma A1.2

\[
F_{I_r}(z) = \begin{cases} 0, & z < 0 \\ \frac{1}{\pi} \cos^{-1}\left[ \frac{r^2 (1-z^{2/\eta}) - z^{2/\eta}}{2 \, r \, z^{2/\eta}} \right], & 0 \leq z < I_r(\pi) \\ 1, & z \geq I_r(\pi) \end{cases}
\]

We can consider \( F_{I_r}(z) \) as a distribution function conditioned on the value of \( r \).

That is, \( F_{I_r}(z) = F_{I_{\text{intra}} | r}(z | r) \). A simple unconditioning allows us to write

\[
F_{I_{\text{intra}}}(z) = \int_0^{1/\alpha} F_{I_{\text{intra}} | r}(z | r) F_r(dr) = \int_0^{1/\alpha^2} F_{I_{\text{intra}} | u}(z | u) F_u(du) \quad (\text{by letting } u = r^2)
\]

where

\[
F_u(u) = \begin{cases} 0 & u < 0 \\ \alpha^2 \, u & 0 \leq u < 1/\alpha^2 \\ 1 & u \geq 1/\alpha^2 \end{cases}
\]
The integrals involve terms that can be integrated using elementary techniques. We are thus led to the following result.

**Theorem A1.3** The CDF of \( I_{\text{intra}}(r, \phi) \) where \( I_{\text{intra}}(\cdot, \cdot) \) in (2.28) and where \( r \) and \( \phi \) are independent random variables with marginal distributions given in (2.29) and (2.30) is given by

\[
F_{I_{\text{intra}}}(z) = \begin{cases} 
0 & z < 0 \\
\frac{\alpha^2 z^{2/\eta}}{(1-z^2/\eta)^2} & 0 \leq z \leq \frac{1}{(1+\alpha)^\eta} \\
\frac{1}{2} + \frac{1}{\pi} \sin^{-1} \left[ \frac{z^{2/\eta}(1+\alpha^2)-1}{2 z^{2/\eta} \alpha} \right] & 0 \leq z \leq \frac{1}{(1+\alpha)^\eta} \\
\alpha^2 z^{2/\eta} \left\{ \frac{1}{2} - \frac{1}{\pi} \sin^{-1} \left[ \frac{z^{2/\eta}(1+\alpha^2)-1}{2 z^{2/\eta} \alpha^2} \right] \right\} & \frac{1}{(1+\alpha)^\eta} < z < \frac{1}{(1-\alpha)^\eta} \\
\frac{1}{2} + \frac{1}{\pi} \sin^{-1} \left( \frac{\alpha}{2} \right) + \frac{3}{4 \pi} \sqrt{4 - \alpha^2} & z = 1 \\
1 - \frac{\alpha^2 z^{2/\eta}}{(1-z^2/\eta)^2} & \frac{1}{(1-\alpha)^\eta} \leq z < \infty 
\end{cases} 
(2.31)

The final CDF can be readily transformed back in terms of \( a \) and \( R \) by setting \( \alpha = a/R \) again.

\( I_{\text{inter}}(r_i, \phi_i) \)

We next derive the CDF of \( I_{\text{inter}}(r_i, \phi_i) \) in the LFB.

Again, we note that by symmetry it is only necessary to deal with the upper semi-circle of the interfering cell in Figure 2.7. Further only the ratio of \( b_i \) and \( R \) is relevant and we therefore normalize \( b_i \) w.r.t. \( R \) and set \( \beta = b_i/R \) without loss of generality. Consider \( I_{\text{inter}}(r_i, \phi_i) \) in (2.9). Replacing \( r_i/b_i \) by \( r \) and \( \phi_i \) by \( \phi \), we can express the equation in the following manner.

\[
I(r, \phi) = \left( \frac{r}{\sqrt{r^2 + 2 \frac{r}{r \cos \phi + 1}}} \right)^\eta 
(2.32)
\]

where \( r \in [0, 1/\beta] \) and \( \phi \in [0, \pi] \). In the intercell scenario, \( 0 < 1/\beta < 1 \).

\( r \) and \( \phi \) are independent random variables with marginal distributions given by
\[ F_r(r) = \begin{cases} 
0 & r < 0 \\
\beta^2 r^2 & 0 \leq r < 1/\beta \\
1 & r \geq 1/\beta
\end{cases} \]  
(2.33)

\[ F_\phi(\phi) = \begin{cases} 
0 & \phi < 0 \\
\phi/\pi & 0 \leq \phi < \pi \\
1 & \phi \geq \pi
\end{cases} \]  
(2.34)

The problem now is to calculate the CDF of the random variable \( I_{\text{inter}}(r, \phi) \) where \( r \) and \( \phi \) are independent random variables with the above readily calculated distributions.

**Objective:** Find the CDF of the random variable \( I_{\text{inter}}(r, \phi) \).

**Solution**

Fix \( r \in [0, 1/\beta] \) and define \( I_r(\phi) = I_{\text{inter}}(r, \phi) \).

Using the same methodology as in the previous section, we are thus led to the following lemma.

**Lemma A2.1** \( I_r(\phi) \) is strictly increasing on \((0, \pi)\) for all \( r \in [0, 1/\beta] \).

**Lemma A2.2**

\[ F_{I_r}(z) = \begin{cases} 
0, & z < 0 \\
\frac{1}{\pi} \cos^{-1} \left[ \frac{r^2 \left(1 - \frac{z^2}{\eta z^2/\eta}\right)}{2r} \right], & 0 \leq z < I_r(\pi) \\
1, & z \geq I_r(\pi)
\end{cases} \]

We can consider \( F_{I_r}(z) \) as a distribution function conditioned on the value of \( r \). That is, \( F_{I_r}(z) = F_{I_{\text{inter}}|r}(z|r) \). A simple unconditioning allows us to write

\[
F_{I_{\text{inter}}}(z) = \int_0^{1/\beta} F_{I_{\text{inter}}|r}(z|r) F_r(dr) \\
= \int_0^{1/\beta^2} F_{I_{\text{inter}}|u}(z|u) F_u(du) \quad \text{(by letting } u = r^2) \\
= \beta^2 \int_0^{1/\beta^2} F_{I_{\text{inter}}|u}(z|u) du
\]
where

\[ F_u(u) = \begin{cases} 
0 & u < 0 \\
\beta^2 u & 0 \leq u < 1/\beta^2 \\
1 & u \geq 1/\beta^2
\end{cases} \]

The integrals involve terms that can be integrated using elementary techniques. We are thus led to the following result.

**Theorem A2.3** The CDF of \( I_{\text{inter}}(r, \phi) \) where \( I_{\text{inter}}(\cdot, \cdot) \) in (2.32) and where \( r \) and \( \phi \) are independent random variables with marginal distributions given in (2.33) and (2.34) is given by

\[
F_{I_{\text{inter}}}(z) = \begin{cases} 
0 & z < 0 \\
\frac{\beta^2 z^{2/n}}{(1-z^{2/n})^2} & 0 \leq z \leq \frac{1}{(1+\beta)^n} \\
\frac{1}{2} + \frac{1}{\pi} \sin^{-1} \left[ \frac{z^{2/n}(1+\beta^2)-1}{2z^{2/n} \beta} \right] & \frac{1}{(1+\beta)^n} < z < \frac{1}{(3-\beta)^n} \\
\frac{1}{2} + \frac{1}{\pi} \sin^{-1} \left( \frac{3}{2} \right) + \frac{3}{4\pi} \sqrt{4 - \beta^2} & z = 1 \\
1 & z \geq \frac{1}{(3-\beta)^n}
\end{cases}
\]

(2.35)

The final CDF can be readily transformed back in terms of \( b_i \) and \( R \) by setting \( \beta = b_i/R \) again.

### 2.8.2 Derivation of Interference Distribution Function in the HFB

In this section, we derive the CDFs of \( I_{\text{intra}}(r_0, \phi_0) \) and \( I_{\text{inter}}(r_i, \phi_i) \) in the HFB.

By symmetry it is only necessary to deal with the upper semi-circle in Figure 2.22. We first consider \( I_{\text{intra}}(r_0, \phi_0) \) in (2.19). Since only the ratio of \( a \) and \( R \) is relevant, we therefore normalize \( a \) w.r.t. \( R \) and set \( \alpha = a/R \) without loss of generality. Replacing \( r_0/a \) by \( r \) and \( \phi_0 \) by \( \phi \), we have

\[
I_{\text{intra}}(r, \phi) = r^n
\]

(2.36)
where \( r \in [0, 1/\alpha] \) and \( \phi \in [0, \pi] \).

\( r \) and \( \phi \) are independent random variables with marginal distributions given by

\[
F_r(r) = \begin{cases} 
0 & r < 0 \\
\alpha^2 r^2 & 0 \leq r < 1/\alpha \\
1 & r \geq 1/\alpha 
\end{cases} \quad (2.37)
\]

\[
F_\phi(\phi) = \begin{cases} 
0 & \phi < 0 \\
\phi/\pi & 0 \leq \phi < \pi \\
1 & \phi \geq \pi 
\end{cases} \quad (2.38)
\]

The problem now is to calculate the CDF of the random variable \( I_{\text{intra}}(r, \phi) \) where \( r \) and \( \phi \) are independent random variables with the above readily calculated distributions.

**Objective:** Find the CDF of the random variable \( I_{\text{intra}}(r, \phi) \).

**Solution**

Fix \( \phi \in [0, \pi] \) and define \( I_\phi(r) = I_{\text{intra}}(r, \phi) \).

**Lemma B.1** \( I_\phi(r) \) is strictly increasing on \((0, 1/\alpha)\) for all \( \phi \in [0, \pi] \).

**Proof**

\[
\frac{dI_\phi(r)}{dr} = \eta r^{\eta-1} > 0 \quad \text{for} \quad r \in (0, 1/\alpha]
\]

\( I_\phi(r) \) is strictly increasing from \( I_\phi(0) \) to \( I_\phi(1/\alpha) \) and standard transformation techniques can thus be applied to calculate the CDF of \( I_\phi(r) \) where \( r \) is distributed as in (2.37). In particular, we have

\[
F_{I_\phi}(z) = \text{Prob}(I_\phi(r) \leq z) = \begin{cases} 
0, & z < 0 \\
F_r(I_\phi^{-1}(z)), & 0 \leq z < I_\phi(1/\alpha) \\
1, & z \geq I_\phi(1/\alpha)
\end{cases}
\]

where the inverse function \( I_\phi^{-1}(z) \) is well defined on \( z \in [0, I_\phi(1/\alpha)] \) because of the monotonicity of \( I_\phi(r) \). It is calculated by solving

\[
I_\phi(r) = r^\eta = z
\]

for \( r \) taking into consideration the allowed values of the variables involved.
We are thus led to the following lemma.

**Lemma B.2**

\[ F_{I_\phi}(z) = \begin{cases} 
0, & z < 0 \\
\alpha^2 z^{2/\eta}, & 0 \leq z < I_\phi(1/\alpha) \\
1, & z \geq I_\phi(1/\alpha) 
\end{cases} \]

We can consider \( F_{I_\phi}(z) \) as a distribution function conditioned on the value of \( \phi \). That is, \( F_{I_\phi}(z) = F_{I_{\text{intra}}|\phi}(z|\phi) \). A simple unconditioning allows us to write

\[
F_{I_{\text{intra}}}(z) = \int_0^\pi F_{I_{\text{intra}}|\phi}(z|\phi)F_{\phi}(d\phi)
\]

\[ = \frac{1}{\pi} \int_0^\pi F_{I_{\text{intra}}|\phi}(z|\phi) \, d\phi 
\]

\[ = \begin{cases} 
0, & z < 0 \\
\frac{1}{\pi} \int_0^\pi \alpha^2 z^{2/\eta} \, d\phi, & 0 \leq z < I_\phi(1/\alpha) \\
1, & z \geq I_\phi(1/\alpha) 
\end{cases} \]  

(2.39)

The integrals involve terms that can be integrated using elementary techniques.

We are thus led to the following result.

**Theorem B.3** The CDF of \( I_{\text{intra}}(r, \phi) \) where \( I_{\text{intra}}(\cdot, \cdot) \) in (2.36) and where \( r \) and \( \phi \) are independent random variables with marginal distributions given in (2.37) and (2.38) is given by

\[
F_{I_{\text{intra}}}(z) = \begin{cases} 
0, & z < 0 \\
\alpha^2 z^{2/\eta}, & 0 \leq z < I_\phi(1/\alpha) \\
1, & z \geq I_\phi(1/\alpha) 
\end{cases} \]  

(2.40)

The final CDF can be readily transformed back in terms of \( a \) and \( R \) by setting \( \alpha = a/R \) again.

Next we consider \( I_{\text{inter}}(r, \phi_i) \) in (2.19). Again, we normalize \( b_i \) w.r.t. \( R \) and set \( \beta = b_i/R \) without loss of generality. Replacing \( r_i/b_i \) by \( r \) and \( \phi_i \) by \( \phi \), we have

\[
I_{\text{inter}}(r, \phi) = r^\eta 
\]

(2.41)
where \( r \in [0, 1/\beta] \) and \( \phi \in [0, \pi] \).

\( r \) and \( \phi \) are independent random variables with marginal distributions given by

\[
F_r(r) = \begin{cases} 
0 & r < 0 \\
\beta^2 r^2 & 0 \leq r < 1/\beta \\
1 & r \geq 1/\beta
\end{cases} \quad (2.42)
\]

\[
F_\phi(\phi) = \begin{cases} 
0 & \phi < 0 \\
\phi/\pi & 0 \leq \phi < \pi \\
1 & \phi \geq \pi
\end{cases} \quad (2.43)
\]

To calculate the CDF of the random variable \( I_{\text{inter}}(r, \phi) \) where \( r \) and \( \phi \) are independent random variables with the above readily calculated distributions, we follow the same derivation presented above, and are thus led to the following result.

**Theorem B.4** The CDF of \( I_{\text{inter}}(r, \phi) \) where \( I_{\text{inter}}(\cdot, \cdot) \) in (2.41) and where \( r \) and \( \phi \) are independent random variables with marginal distributions given in (2.42) and (2.43) is given by

\[
F_{I_{\text{inter}}}(z) = \begin{cases} 
0, & z < 0 \\
\beta^2 z^2/\eta, & 0 \leq z < I_\phi(1/\beta) \\
1, & z \geq I_\phi(1/\beta)
\end{cases} \quad (2.44)
\]

The final CDF can be readily transformed back in terms of \( a \) and \( R \) by setting \( \beta = b_1/R \) again.
Chapter 3

Performance Study of CDMA Broadcast Systems in an FDD-CDMA Cellular Network

In this chapter, we apply the results of the interference analysis in the preceding chapter and study the performance of CDMA broadcast systems spectrally underlaid in an FDD-CDMA cellular network. The broadcast systems coexist with the cellular network in the same geographic area and same frequency band. Interference scenarios between the cellular network and the broadcast systems in both HFB and LFB are identified. A detailed model and a simulation analysis are presented to evaluate the received bit-energy-to-noise ratio \( (E_b/N_0) \) demonstrating the susceptibility to the "near-far" problem in both HFB and LFB. In order to ensure acceptable performance in light of the demonstrated "near-far" problem, we study a family of frequency allocation strategies exhibiting various levels of efficiency and complexity for use by the broadcast systems: (1) Fixed Channel Allocation (FCA), (2) Random Channel Allocation (RCA), and (3) Distance Based Channel Allocation (DBCA).
3.1 Assumptions and Notation

We consider an outdoor environment which is an open area divided into regular cells of square coverage, with FDD-CDMA BSs positioned on a uniform square grid as shown in Figure 3.1. The number of CDMA broadcast systems is variable and they are randomly distributed in each regular cell. There is little difference in performance between different cell geometries [23]. A cell wrapping technique can be used to avoid edge effects.

How to share precious radio resources between the cellular network and the broadcast systems is a key issue here. One possibility is to adopt a multiband CDMA approach [24] which requires some regulatory body to do frequency planning among different CDMA systems. However, frequencies that are exclusively allocated to a certain system, but remain unused due to low traffic in that system, represent a waste of radio resources. For this reason, another idea in which different CDMA systems are spectrally underlaid in the same frequency band has been proposed and analyzed in other contexts of wireless communications [25]-[26], and we explore this concept here for our system analysis.
Figure 3.1: Mixed cellular structure.
Performance study is based upon calculating the baseband $(E_b/N_o)$ at the receiver. The baseband $(E_b/N_o)$ is defined as

$$\left(\frac{E_b}{N_o}\right) = PG \left(\frac{S}{I}\right)$$

(3.1)

where $(S/I)$ is the signal-to-interference ratio, and $PG$ is the processing gain. Thermal noise is not considered here. Many factors must be considered to establish the required $(E_b/N_o)$ (denoted by $(E_b/N_o)_{req}$) like channel characteristics, type of modulation, diversity scheme, receiver structure, and coding/interleaving techniques.

In our system analysis, we assume that the processing gain of the FDD-CDMA cellular network is $G$ and the processing gain of the CDMA broadcast system is $g$. The total number of regular cells is $C$. An FDD-CDMA BS is located at the center of each regular cell serving $K$ FDD-CDMA PTs. $J$ broadcast systems are assumed to be uniformly distributed in each regular cell. Each broadcast system consists of an RP and $M$ broadcast system PTs. Use of omnidirectional antennas is assumed for all BSs and RPs. For the sake of clarification, we adopt the following notation. $h(x, y)$ is the channel gain from $x$ to $y$ in which $x$ or $y$ is represented by one of the following: $B_i$ (the FDD-CDMA BS in regular cell $i$), $p_{ik}$ (the $k^{th}$ FDD-CDMA PT served by FDD-CDMA BS $B_i$), $b_{ij}$ (the $j^{th}$ broadcast system RP in regular cell $i$), and $q_{ijm}$ (the $m^{th}$ broadcast system PT served by broadcast system RP $b_{ij}$). $P_B$, and $P_{ik}$ are the transmitted powers of FDD-CDMA BS $B_i$ and FDD-CDMA PT $p_{ik}$, respectively. $Q_{b_{ij}}$ is the transmitted power of broadcast system RP $b_{ij}$.

### 3.2 System Analysis

Two types of interference exist in both the cellular network and the broadcast systems. In addition to the usual self-system interference of individual cellular network and broadcast systems, there are also the cellular-to-broadcast and broadcast-to-cellular (or cross-system) interference. In this section, we consider the total interference (self-system and cross-system interference) in both the cellular network and the broadcast systems.
3.2.1 Cellular Network Performance

The interference power received by the cellular network from the broadcast systems is affected by many factors including the number of broadcast systems, their operating frequency (HFB or LFB), their positions, and their transmitted powers. We denote a broadcast system that employs the HFB for transmission as HFB broadcast system, and a broadcast system that employs the LFB for transmission as LFB broadcast system. In the following analysis, we assume that the numbers of HFB broadcast systems and LFB broadcast systems in each regular cell are $J_H$ and $J_L$ respectively. Obviously, $J = J_H + J_L$.

Without loss of generality, we take regular cell 0 as the reference cell in our analysis.

Forward Link

We first consider the capacity degradation of the cellular network when the broadcast systems employ the HFB for transmission. In this case, the HFB broadcast systems affect only the forward link performance of the cellular network. This interference scenario is depicted in Figure 3.2.

![Figure 3.2: Broadcast-to-cellular interference scenario with an HFB broadcast system. (Solid line: desired signal; Dashed line: interference signal from the HFB broadcast system).](image)
Let $\mu_{0k}$ denote the fraction of the transmitted power allocated to a given FDD-CDMA PT $p_{0k}$ from FDD-CDMA BS $B_0$. Then the signal power received at FDD-CDMA $p_{0k}$ is

$$S_f = \mu_{0k} P_{B_0} h(B_0, p_{0k}) \quad \text{for } k = 1, \ldots, K$$ (3.2)

The interference received at FDD-CDMA $p_{0k}$ consists of two parts: one due to the cellular network (denoted by $I_{cn}$) and the other due to the broadcast systems (denoted by $I_{bs}$). $I_{cn}$ consists of intracell interference due to FDD-CDMA BS $B_0$ in regular cell 0 and intercell interference due to FDD-CDMA BSs in the surrounding cells indexed from 1 to $C - 1$. Therefore,

$$I_{cn} = (1 - \mu_{0k}) P_{B_0} h(B_0, p_{0k}) + \sum_{i=1}^{C-1} P_{B_i} h(B_i, p_{0k})$$ (3.3)

On the other hand, $I_{bs}$ is the interference power at FDD-CDMA $p_{0k}$ accumulated from all HFB broadcast systems and is given by

$$I_{bs} = \sum_{i=0}^{C-1} \sum_{j=1}^{J_H} Q_{b_{ij}} h(b_{ij}, p_{0k})$$ (3.4)

Using (3.1), we can express the forward link $(E_b/N_o)$ of FDD-CDMA $p_{0k}$ as

$$\left( \frac{E_b}{N_o} \right) = \frac{G S_f}{I_{cn} + I_{bs}}$$

$$= \frac{G \mu_{0k} P_{B_0} h(B_0, p_{0k})}{(1 - \mu_{0k}) P_{B_0} h(B_0, p_{0k}) + \sum_{i=1}^{C-1} P_{B_i} h(B_i, p_{0k}) + \sum_{i=0}^{C-1} \sum_{j=1}^{J_H} Q_{b_{ij}} h(b_{ij}, p_{0k})}$$ (3.5)

The BS distributes its transmitted power according to the need of each PT in the cell of concern. This is achieved by employing forward link balancing power control which balances and equalizes the $(E_b/N_o)$ at each PT to increase system capacity. The idea is to obtain the required $\mu_{0k}$ for each PT, denoted by $(\mu_{0k})_{req}$, by setting $(E_b/N_o) = (E_b/N_o)_{req}$. 

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With forward link balancing power control, when the total power requested by the PTs is below the peak transmitted power, the BS will reduce its transmitted power, thereby reducing interference; otherwise, the BS will redistribute the power from the forward links with good quality to those with poor quality.

**Reverse Link**

Next, we consider the capacity degradation of the cellular network when the broadcast systems employ the LFB for transmission. In this case, the LFB broadcast systems affect only the reverse link performance of the cellular network. This interference scenario is depicted in Figure 3.3.

![Figure 3.3: Broadcast-to-cellular interference scenario with an LFB broadcast system.](image)

(Solid line: desired signal; Dashed line: interference signal from the LFB broadcast system).

Perfect reverse link power control maintains a constant received signal power at the BS for all PTs in the cell of concern. The power transmitted by a given FDD-CDMA PT $p_{0k}$ is $P_{0k}$. The received power of FDD-CDMA PT $p_{0k}$ at FDD-CDMA BS $B_0$ is given by

$$S_r = P_{0k} h(p_{0k}, B_0) \quad \text{for} \ k = 1, \ldots, K \quad (3.6)$$
The total interference received at FDD-CDMA BS $B_0$ consists of two parts: one due to the cellular network ($I_{cn}$) and the other due to the broadcast systems ($I_{bs}$). The interference from the cellular network can be obtained as follows.

\[
I_{cn} = \frac{(K - 1)S_r}{\text{intracell interference}} + \sum_{i=1}^{C-1} \sum_{k=1}^{K} P_{ik} h(p_{ik}, B_0) \tag{3.7}
\]

where the intracell interference is due to the FDD-CDMA PTs in regular cell 0 (excluding FDD-CDMA $p_{0k}$), and the intercell interference is due to the FDD-CDMA PTs in the surrounding cells indexed from 1 to $C - 1$.

In a similar manner, $I_{bs}$ is the interference power accumulated at FDD-CDMA BS $B_0$ from all LFB broadcast systems and is given by

\[
I_{bs} = \sum_{i=0}^{C-1} \sum_{j=1}^{J_i} Q_{b_{ij}} h(b_{ij}, B_0) \tag{3.8}
\]

Using (3.1), we can express the reverse link ($E_b/N_o$) of FDD-CDMA PT $p_{0k}$ as

\[
\left( \frac{E_b}{N_o} \right) = \frac{G S_r}{I_{cn} + I_{bs}} = \frac{G S_r}{(K - 1)S_r + \sum_{i=1}^{C-1} \sum_{k=1}^{K} P_{ik} h(p_{ik}, B_0) + \sum_{i=0}^{C-1} \sum_{j=1}^{J_i} Q_{b_{ij}} h(b_{ij}, B_0)} \tag{3.9}
\]

### 3.2.2 Broadcast System Performance

Similarly, the interference power received at a broadcast system from the cellular network depends on its operating frequency (HFB or LFB), and is therefore affected by the numbers of FDD-CDMA BSs and PTs, their positions, and their transmitted powers.

**HFB Broadcast System**

First, we consider the receiver performance of an HFB broadcast system. The interference scenario is depicted in Figure 3.4.
Without loss of generality, we consider a given HFB broadcast system PT \( q_{0jm} \) served by the corresponding broadcast system RP \( b_{0j} \) in regular cell 0. The received signal power at \( q_{0jm} \) is \( \nu_{0jm} Q_{b_{0j}} h(b_{0j}, q_{0jm}) \), where \( \nu_{0jm} \) is the fraction of the total transmitted power allocated to \( q_{0jm} \) from \( b_{0j} \).

The total interference is the sum of self-system interference received from all HFB broadcast systems and cross-system interference received from all FDD-CDMA BSs. Here we denote these again by \( I_{bs} \) and \( I_{cn} \), respectively. \( I_{bs} \) is given by

\[
I_{bs} = \sum_{i=0}^{C-1} \sum_{j=1}^{J_H} Q_{b_{ij}} h(b_{ij}, q_{0jm}) - \nu_{0jm} Q_{b_{0j}} h(b_{0j}, q_{0jm})
\]  

(3.10)

\( I_{cn} \) is given by

\[
I_{cn} = \sum_{i=0}^{C-1} P_{B_i} h(B_i, q_{0jm})
\]  

(3.11)

Using (3.1), we can express the received \( (E_b/N_o) \) at the HFB broadcast system PT \( q_{0jm} \) as
(\frac{E_b}{N_o}) = g \nu_{0jm} Q_{b_0j} h(b_{0j}, q_{0jm}) \\
\sum_{i=0}^{C-1} \sum_{j=1}^{J_R} Q_{b_{ij}, h(b_{ij}, q_{0jm})} - \nu_{0jm} Q_{b_0j} h(b_{0j}, q_{0jm}) + \sum_{i=0}^{C-1} P_B h(B_i, q_{0jm})
(3.12)

LFB Broadcast System

Next, we consider the receiver performance of an LFB broadcast system. The interference scenario is depicted in Figure 3.5.

![Figure 3.5: Cellular-to-broadcast interference scenario with an LFB broadcast system. (Solid line: desired signal; Dashed line: interference signal from the cellular network in the LFB).](image)

Let us consider a given LFB broadcast system PT $q_{0jm}$ served by the corresponding broadcast system RP $b_{0j}$ in regular cell 0. The received signal power at $q_{0jm}$ is $\nu_{0jm} Q_{b_0j} h(b_{0j}, q_{0jm})$, where $\nu_{0jm}$ is the fraction of the total transmitted power allocated to $q_{0jm}$ from $b_{0j}$.

The total interference again consists of two parts: the self-system interference ($I_{bs}$) from all LFB broadcast systems, and the cross-system interference ($I_{cn}$) from all FDD-CDMA PTs. $I_{bs}$ is given by
\[ I_{bs} = \sum_{i=0}^{C-1} \sum_{j=1}^{J_k} Q_{b_j} h(b_{ij}, q_{0jm}) - \nu_{0jm} Q_{bo_j} h(b_{0j}, q_{0jm}) \]  

(3.13)

\[ I_{cn} = \sum_{i=0}^{C-1} \sum_{k=1}^{K} P_{ik} h(p_{ik}, q_{0jm}) \]  

(3.14)

\[ \left( \frac{E_b}{N_o} \right) = \frac{g \nu_{0jm} Q_{bo_j} h(b_{0j}, q_{0jm})}{\sum_{i=0}^{C-1} \sum_{j=1}^{J_k} Q_{b_j} h(b_{ij}, q_{0jm}) - \nu_{0jm} Q_{bo_j} h(b_{0j}, q_{0jm}) + \sum_{i=0}^{C-1} \sum_{k=1}^{K} P_{ik} h(p_{ik}, q_{0jm})} \]  

(3.15)

\[ I_{cn} \] is the interference power from all FDD-CDMA PTs and can be obtained as follows.

Using (3.1), we can express the received \((E_b/N_o)\) at the LFB broadcast system PT \(q_{0jm}\) as

If there is only a single broadcast system in the cellular network, we can see that from (3.12) and (3.15) the main factor affecting the receiver performance of the broadcast system is the cross-system interference from the FDD-CDMA cellular network, which in turn depends on the operating frequency of the broadcast system. When the broadcast system employs the HFB for transmission, the cross-system interference is due to the FDD-CDMA BSs; but when the broadcast system employs the LFB for transmission, it is due to the FDD-CDMA PTs. Of interest is the fact that the FDD-CDMA BSs are always located at fixed positions, whereas the FDD-CDMA PTs are randomly located according to a certain distribution in the cellular network. The different spatial distributions create an asymmetry in the cross-system interference received at the broadcast system. This issue of interference asymmetry, however, has not received much attention and, to the best of our knowledge, has not been studied intensively. In the following section, we shall investigate this in depth.
3.3 Simulations For The Spatial \((E_b/N_0)\) Distribution

The objective of the simulations is to study the overall performance with the CDMA broadcast systems spectrally underlaid in the FDD-CDMA cellular network. The simulations consider many system variables and give statistics of received \((E_b/N_0)\) for both the cellular network and the broadcast systems. The simulation model consists of 25 regular cells of square coverage each with an FDD-CDMA BS at its center. A uniform grid of \(J\) broadcast system RPs are assumed in each regular cell. Portable locations are uniformly distributed for all cells. Distance dependent path loss and lognormal shadowing are assumed according to the propagation models described in Chapter 2. Mean signal and interference power levels and shadow fading are calculated, and SIR statistics are collected for the forward and reverse links. Then all random variables are regenerated until 100000 SIR values have been calculated.

The system parameters used in the simulations are tabulated in Table 3.1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Cellular Network</th>
<th>Broadcast System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized Cell Dimension</td>
<td>(2 \times 2)</td>
<td>(0.2 \times 0.2)</td>
</tr>
<tr>
<td>Normalized Close-in Distance</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>Path Loss Exponent</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Shadowing Standard Deviation</td>
<td>8 dB</td>
<td>2 dB</td>
</tr>
<tr>
<td>Spreading Bandwidth</td>
<td>5 MHz</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Data Rate</td>
<td>8 kbps</td>
<td>128 kbps</td>
</tr>
<tr>
<td>Processing Gain</td>
<td>28 dB</td>
<td>16 dB</td>
</tr>
</tbody>
</table>

Table 3.1: System parameters used for studying the overall performance with the CDMA broadcast systems spectrally underlaid in the FDD-CDMA cellular network.

Simulation results are grouped under a few different headings. The analysis of various results is associated.
3.3.1 Performance of the Basic Cellular Network

Figure 3.6 illustrates the FDD-CDMA mean $\left( \frac{E_b}{N_0} \right)$ versus number of FDD-CDMA PTs per regular cell. The total number of regular cells is 25. We consider three different scenarios: Scenario A – FDD-CDMA PTs uniformly distributed in each regular cell; Scenario B – FDD-CDMA PTs uniformly distributed in a square cell with side equal to one half of the regular cell side; and Scenario C – FDD-CDMA PTs uniformly distributed at the regular cell boundary.

Figure 3.6: FDD-CDMA mean $\left( \frac{E_b}{N_0} \right)$ versus number of FDD-CDMA PTs per regular cell. Solid lines, FDD-CDMA PTs uniformly distributed in each regular cell (Scenario A). Dashed lines, FDD-CDMA PTs uniformly distributed in a square cell with side equal to one half of the regular cell side (Scenario B). Dotted lines, FDD-CDMA PTs uniformly distributed at the regular cell boundary (Scenario C).
From Figure 3.6, we see that the capacity in the forward link is about the same as that in the reverse link. We also notice that both links are quite sensitive to how the FDD-CDMA PTs are distributed in each regular cell. A commonly used value for $(E_b/N_o) = 7$ dB can be achieved at different values of the number of FDD-CDMA PTs, $K$, depending on how they are distributed in each regular cell. The worst case performance occurs in Scenario C in which the FDD-CDMA PTs are uniformly distributed at the regular cell boundary. In this case, the previous $(E_b/N_o)$ can only be achieved at $K = 60$. On the contrary, this $(E_b/N_o)$ can be achieved at $K = 80$ and $K = 100$ in Scenario A and Scenario B, respectively. In a power-controlled CDMA cellular network, PTs close to the BS transmit at lower powers, whereas those near the cell boundary transmit at higher powers. Therefore, if the FDD-CDMA PTs are uniformly distributed at the regular cell boundary, they will cause significant interference to the adjacent regular cells, thus reducing the capacity of the whole cellular network.

Plots of the estimated probability distribution of the $(E_b/N_o)$ under different FDD-CDMA PT distributions are presented in Figures 3.7-3.9 for $K = 80, 100, 120$. A typical objective is to provide adequate performance in at least 99% of all locations [27], i.e., $P_{out} = 0.01$. For example, in Figure 3.7 the outage probability can be attained at $(E_b/N_o) = 6.2$ dB in the forward link and $(E_b/N_o) = 6.6$ dB in the reverse link, given that $K = 80$. 

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Figure 3.7: FDD-CDMA ($E_b/N_0$) distribution for Scenario A, $K = 80, 100, 120$.

Figure 3.8: FDD-CDMA ($E_b/N_0$) distribution for Scenario B, $K = 80, 100, 120$.

Figure 3.9: FDD-CDMA ($E_b/N_0$) distribution for Scenario C, $K = 80, 100, 120$. 

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3.3.2 Performance of the Network with Broadcast Systems

Figures 3.10-3.12 present the FDD-CDMA mean \((E_b/N_o)\) performance versus normalized distance of a broadcast system from the intracell FDD-CDMA BS (denoted by \(\alpha\)) under different FDD-CDMA PT distributions and having the broadcast system’s normalized transmitted power (denoted by \(Q_b/P_B\)) as a parameter. It is noteworthy that \(Q_b/P_B\) has an adverse effect on the FDD-CDMA mean \((E_b/N_o)\) performance in the forward and reverse links. As \(Q_b/P_B\) increases, the FDD-CDMA mean \((E_b/N_o)\) decreases; and vice versa. On the other hand, if the \(Q_b/P_B\) can be kept below a certain level, for example, -20 dB, its influence on the cellular network is hardly noticeable.

Another observation is that the FDD-CDMA mean \((E_b/N_o)\) performance depends on the location of the broadcast system and its operating frequency, and is different in the forward and reverse links. As shown in the figures, the FDD-CDMA forward link \((E_b/N_o)\) decreases first with \(\alpha\), but increases later after a certain value of \(\alpha\). This is because, when the distance of the HFB broadcast system from the intracell FDD-CDMA BS increases, its interference received at the FDD-CDMA PTs also increases; but when the HFB broadcast system is located close to the regular cell boundary, fewer FDD-CDMA PTs are interfered and therefore the FDD-CDMA forward link performance improves. On the other hand, the FDD-CDMA reverse link \((E_b/N_o)\) increases first with \(\alpha\), but becomes saturated as \(\alpha\) becomes larger. The interference of the LFB broadcast system received at the intracell FDD-CDMA BS becomes more significant when it is located close to the regular cell centre, but becomes less noticeable when it is located closed to the regular cell boundary.

We also witness that for small values of \(\alpha\), the FDD-CDMA reverse link \((E_b/N_o)\) with an LFB broadcast system is lower than the FDD-CDMA forward link \((E_b/N_o)\) with an HFB broadcast system. However, after a certain value of \(\alpha\), the FDD-CDMA forward link \((E_b/N_o)\) then becomes lower than the FDD-CDMA reverse link \((E_b/N_o)\). For example, at \(Q_b/P_B = 0\) dB, this value is equal to 0.386, 0.212, and 0.754 in Scenario A, B, and C, respectively. The impact of this uneven influence on the cellular network can be attributed to the fact that the forward link performance is
very sensitive to where the HFB broadcast system is located relative to the FDD-CDMA PTs in the cell of concern. If the HFB broadcast system is located close to the FDD-CDMA PTs, this will severely degrade the forward link performance. Conversely, the reverse link performance depends only on the distance of the LFB broadcast system from the intracell FDD-CDMA BS, and $Q_b/P_B$ can be properly controlled so that its influence on the cellular network is still tolerable.
Figure 3.10: FDD-CDMA mean \((E_b/N_0)\) versus normalized distance of a broadcast system from the intracell FDD-CDMA BS with \(K = 80\) (Scenario A), \(M = 4\).

Figure 3.11: FDD-CDMA mean \((E_b/N_0)\) versus normalized distance of a broadcast system from the intracell FDD-CDMA BS with \(K = 80\) (Scenario B), \(M = 4\).

Figure 3.12: FDD-CDMA mean \((E_b/N_0)\) versus normalized distance of a broadcast system from the intracell FDD-CDMA BS with \(K = 80\) (Scenario C), \(M = 4\).
In Figures 3.13-3.15, we illustrate the broadcast system \((E_b/N_o)\) performance versus \(\alpha\) under different FDD-CDMA PT distributions and having \(Q_b/P_B\) as a parameter. Contrary to the FDD-CDMA \((E_b/N_o)\) performance, the broadcast system \((E_b/N_o)\) increases as \(Q_b/P_B\) increases, when the broadcast system employs either the HFB or the LFB for transmission. This phenomenon is intuitively reasonable because as \(Q_b/P_B\) increases, the interference from the cellular network is suppressed and therefore the broadcast system \((E_b/N_o)\) increases.

In each scenario, we observe that for small values of \(\alpha\), the \((E_b/N_o)\) performance of an HFB broadcast system is worse than that of an LFB broadcast system. But after a certain value of \(\alpha\), the \((E_b/N_o)\) performance of an LFB broadcast system then becomes worse than that of an HFB broadcast system. For instance, when \(Q_b/P_B = -20\) dB, this value is equal to 0.434, 0.263, and 0.786 in Scenario A, B, and C, respectively. This indicates that a broadcast system would prefer to employ the LFB for transmission when it is located close to the intracell FDD-CDMA BS; but when it is located farther away from the intracell FDD-CDMA BS, using the HFB for transmission would give a better \((E_b/N_o)\) performance.

Now, we investigate the effect of FDD-CDMA PT distributions on the \((E_b/N_o)\) performance of a broadcast system as \(\alpha\) varies. As we mentioned before, an HFB broadcast system is affected by the FDD-CDMA BSs which are placed at fixed positions in the service area. We see that the \((E_b/N_o)\) of the HFB broadcast system increases with \(\alpha\). As the distance of the HFB broadcast system from the intracell FDD-CDMA BS increases, the interference from the cellular network becomes less, indicating that the intracell FDD-CDMA BS has a more dominant effect on the HFB broadcast system than the intercell FDD-CDMA BSs. Note that we put the \((E_b/N_o)\) performance of the HFB broadcast system in all the three scenarios for the purpose of comparison.

On the other hand, an LFB broadcast system is affected by the FDD-CDMA PTs. The \((E_b/N_o)\) performance of the LFB broadcast system depends on how the FDD-CDMA PTs are distributed in the cellular network. In all the three scenarios considered, the \((E_b/N_o)\) of the LFB broadcast system decreases with \(\alpha\). This is not
surprising since in a power-controlled CDMA cellular network, PTs located farther away from the BS have to transmit higher powers to avoid the "near-far" problem. This power control scheme to counter the "near-far" problem in the cellular network, however, creates another "near-far" problem to the LFB broadcast system. As the LFB broadcast system is located farther from the intracell FDD-CDMA BS, it is more interfered by the high-transmitted-power FDD-CDMA PTs. In Scenario B, the FDD-CDMA PT density is four times larger than that in Scenario A due to the fact that they are distributed in a square cell of size equal to one half of the regular cell size. Therefore, the interference from the FDD-CDMA PTs on the LFB broadcast system is significantly higher in Scenario B when it is located within an $\alpha$ of 0.5 (i.e. one half of the regular cell size), but when the LFB broadcast system is located at after an $\alpha$ of 0.5, the effect from the FDD-CDMA PTs is hardly noticeable. In Scenario C, the $(E_b/N_0)$ of the LFB broadcast system decreases dramatically when it is located close to the regular cell boundary since the interference from both intracell and intercell FDD-CDMA PTs on the LFB broadcast system becomes more significant.
Figure 3.13: Broadcast system mean \((E_b/N_0)\) versus its normalized distance from the intracell FDD-CDMA BS with \(K = 80\) (Scenario A), \(M = 4\).

Figure 3.14: Broadcast system mean \((E_b/N_0)\) versus its normalized distance from the intracell FDD-CDMA BS with \(K = 80\) (Scenario B), \(M = 4\).

Figure 3.15: Broadcast system mean \((E_b/N_0)\) versus its normalized distance from the intracell FDD-CDMA BS with \(K = 80\) (Scenario C), \(M = 4\).
Figure 3.16 shows the FDD-CDMA cellular network \((E_b/N_o)\) distribution for Scenario A as a function of the \((E_b/N_o)_{req}\) with the number of broadcast systems using either the HFB or the LFB for transmission as a parameter. As the number of broadcast systems increases, the interference from the broadcast systems increases and therefore the outage probability of the cellular network increases too. We also notice that the outage performance of the FDD-CDMA cellular network is bounded by the cross-system interference due to the HFB broadcast systems. The variance of the FDD-CDMA forward link \((E_b/N_o)\) seems to be higher than that of the FDD-CDMA reverse link \((E_b/N_o)\), indicating that the forward link is more sensitive to the number of HFB broadcast systems than the reverse link to the number of LFB broadcast systems. This is mainly attributed to the fact that an FDD-CDMA PT is often within the coverage of a broadcast system; and the chance is even higher when the number of broadcast systems increases. If the broadcast systems employ the HFB for transmission, they will inject high interference to the surrounding FDD-CDMA PTs, thus seriously degrading the FDD-CDMA forward link performance. By a similar argument, the FDD-CDMA reverse link performance will be degraded significantly when the number of LFB broadcast systems near the intracell FDD-CDMA BS is large. However, for a given number of broadcast systems, only a small portion of them are actually located close to the intracell FDD-CDMA BS. This is because, under the assumption that the broadcast systems are uniformly distributed, the probability of having a broadcast system within a distance of \(r\) is equal to \(r^2\) (for example, at \(r = 0.2\), this probability is 0.04). Hence, the effect of LFB broadcast systems on the FDD-CDMA reverse link is less adverse than that of HFB broadcast systems on the FDD-CDMA forward link.

Figure 3.17 shows the broadcast system \((E_b/N_o)\) distribution for Scenario A as a function of the \((E_b/N_o)_{req}\) with the number of broadcast systems using either the HFB or the LFB for transmission as a parameter. As the number of broadcast systems increases, the interference from the broadcast systems increases and therefore the outage probability of the broadcast system increases as well. We also notice that the outage performance of an LFB broadcast system is worse than that of an HFB
broadcast system as the number of broadcast systems varies. Nevertheless, the outage performance of the LFB broadcast system is less sensitive to the number of LFB broadcast systems, whereas the outage performance of the HFB broadcast system is more sensitive to the number of HFB broadcast systems.

The above results show a contradicting performance between the FDD-CDMA cellular network and the CDMA broadcast systems in terms of the outage probability. HFB broadcast systems perform better than LFB broadcast systems in the FDD-CDMA cellular network, but they significantly degrade the FDD-CDMA forward link performance; on the other hand, LFB broadcast systems have less impact on the FDD-CDMA reverse link performance, but they perform worse in the FDD-CDMA cellular network. This motivates us in the next section to investigate frequency allocation strategies during the introduction of broadcast systems in the cellular network to ensure acceptable overall performance.
Figure 3.16: FDD-CDMA cellular network ($E_b/N_o$) distribution for Scenario A. $K = 80$, $M = 4$, $J = 4, 8, 16$, $Q_b/P_B = -20$ dB.
Figure 3.17: Broadcast system \((E_b/N_o)\) distribution for Scenario A, \(K = 80\), \(M = 4\), \(J = 4, 8, 16\), \(Q_b/P_B = -20\) dB.
3.4 Frequency Allocation Strategies

Existing and emerging picocellular networks, such as wireless PBX, private wireless networks on campus, in buildings or factories, often try to autonomously reuse the frequency channels allocated to the macrocellular networks. The prevention of mutual interference between picocells and macrocells is easily achievable when the macrocells employ Fixed Channel Allocation (FCA). Since each of the macrocells uses only a fixed subset of the total frequency spectrum under FCA, picocells can always scan to find stationarily available channels, wherever they are located [28].

Consider the CDMA broadcast systems spectrally underlaid in the FDD-CDMA cellular network. When a new broadcast system is deployed in a regular cell, the broadcast system has to determine which one of the FDD-CDMA frequency bands (HFB or LFB) to employ for transmission. We set out to design a family of frequency allocation strategies for the broadcast systems when they are being deployed in the FDD-CDMA cellular network. We propose the following three generic strategies:

3.4.1 Fixed Channel Allocation (FCA)

In FCA strategy, one of the FDD-CDMA frequency bands (HFB or LFB) is permanently assigned for all the broadcast systems. We denote the case when all broadcast systems employ the HFB for transmission as FCA (HFB), and the case when all broadcast systems employ the LFB for transmission as FCA (LFB). Note that these two cases constitute the performance bounds for the overall network and are adopted as baselines for purpose of comparison.

3.4.2 Random Channel Allocation (RCA)

In RCA strategy, a new broadcast system chooses from one of the FDD-CDMA frequency bands (HFB or LFB) randomly for operation. The obvious advantage of this strategy is its simplicity. On the other hand, it has to be designed for the worst case of the FDD-CDMA BS and PT distributions.
3.4.3 Distance Based Channel Allocation (DBCA)

In DBCA strategy, the frequency allocation is based on the distance of the broadcast system from the intracell FDD-CDMA BS. The idea is to partition the regular cell into two tiers, one is the inner tier and the other is the outer tier. This structure is similar to the reuse partitioning in FDMA systems suggested to improve capacity. By splitting a cell into two or more tiers, the cochannel reuse distance of the inner tiers, which is directly related with reuse pattern in FDMA systems, can be reduced and therefore more channels can be allocated in a cell [29]. With two separate frequency bands (HFB and LFB) in the FDD-CDMA cellular network, there are two possible configurations to allocate them to the broadcast systems in the inner and outer tiers. These two configurations are depicted in Figure 3.18. We use DBCA (L/H) to denote the case in which the broadcast systems in the inner tier employ the LFB for transmission and those in the outer tier employ the HFB for transmission; and DBCA (H/L) to denote the case in which the broadcast systems in the inner tier employ the HFB for transmission and those in the outer tier employ the LFB for transmission. We define the distance index $D$ as the ratio of the side of the inner tier to that of the outer tier. Depending on $D$ and on how the frequency bands are allocated, we can have different modified versions of the DBCA strategy. Obviously, the outage performance depends on $D$, the broadcast system location, and how both HFB and LFB are assigned in the regular cell.
3.4.4 Simulation Results and Discussions

In this section, we study the outage performances of both the FDD-CDMA cellular network and the CDMA broadcast systems using the proposed frequency allocation strategies.

Single Broadcast System

We first consider the case when there is a single broadcast system in the FDD-CDMA cellular network.

Figure 3.19 shows the outage probability of a broadcast system versus $\alpha$ using FCA strategy and RCA strategy for $q = 10$ dB, $\Gamma = -15$ dB and $\sigma = 8$ dB. In FCA (LFB) (marked by ‘x’), the outage probability increases as $\alpha$ increases. In FCA (HFB) (marked by ‘*’), however, the outage probability decreases as $\alpha$ increases. Due to the perfect power control in the cellular network, PTs located farther from their home BS in general transmit at higher powers. Therefore, an LFB broadcast system experiences more interference from the FDD-CDMA PTs when it is located close to the regular cell boundary. On the other hand, an HFB broadcast system experiences less interference from the intracell FDD-CDMA BS but experiences more interference from the intercell FDD-CDMA BSs when it is located close to the regular
cell boundary. As a result, we see that the FCA (HFB) curve becomes saturated when the HFB broadcast system is located close to the regular cell boundary. As for the RCA strategy, the outage performance curve is between that of FCA (LFB) and FCA (HFB).
Figure 3.19: Outage performance of a broadcast system versus its normalized distance from the intracell FDD-CDMA BS using FCA strategy and RCA strategy. $q = 10$ dB, $\Gamma = -15$ dB and $\sigma = 8$ dB.
Figures 3.20 and 3.21 depict the outage probabilities of a broadcast system versus $\alpha$ using DBC (L/H) and DBC (H/L) under different values of $D$ for $q = 10$ dB, $\Gamma = -15$ dB and $\sigma = 8$ dB. We vary $D$ from 0.1 to 1.0 with an increment of 0.1. In DBC (L/H), the LFB broadcast system in the inner tier experiences more interference from the FDD-CDMA PTs as it is located close to the regular cell boundary. Therefore, the outage probability increases as $\alpha$ increases for $\alpha < D$. The HFB broadcast system in the outer tier, however, experiences less interference from the intracell FDD-CDMA BS as it is located close to the regular cell boundary. Hence, the outage probability decreases as $\alpha$ increases for $\alpha > D$. Here, $D = 1.0$ corresponds to the case in which a broadcast system employs the LFB for transmission in all locations (i.e., FCA (LFB)). In DBC (H/L), the opposite is observed instead. The HFB broadcast system in the inner tier receives less interference from the intracell FDD-CDMA BS as it is located close to the regular cell boundary. Thus, the outage probability decreases as $\alpha$ increases for $\alpha < D$. The LFB broadcast system in the outer tier, however, experiences more interference from the FDD-CDMA PTs as it is located close to the regular cell boundary. Consequently, the outage probability increases as $\alpha$ increases for $\alpha > D$. Here, $D = 1.0$ corresponds to the case in which a broadcast system employs the HFB for transmission in all locations (i.e., FCA (HFB)).

The above result indicates that DBC (L/H) performs better than DBC (H/L) for a broadcast system in terms of outage probability. This can be observed from Figures 3.20 and 3.21 that if the broadcast system employs the HFB for transmission in the inner tier, it is greatly interfered by the intracell FDD-CDMA BS. On the other hand, if the broadcast system employs the HFB for transmission in the outer tier, it can avoid the interference injected from the high-transmitted-power FDD-CDMA PTs.
Figure 3.20: Outage performance of a broadcast system versus its normalized distance from the intracell FDD-CDMA BS using DBCA (L/H) strategy for different values of $D$. $q = 10$ dB, $\Gamma = -15$ dB and $\sigma = 8$ dB.
Figure 3.21: Outage performance of a broadcast system versus its normalized distance from the intracell FDD-CDMA BS using DBCA (H/L) strategy for different values of $D$. $q = 10$ dB, $\Gamma = -15$ dB and $\sigma = 8$ dB.
Multiple Broadcast Systems

We now consider the case when there are multiple broadcast systems in the FDD-CDMA cellular network.

Figures 3.22 and 3.23 depict plots of FDD-CDMA ($E_b/N_0$) distribution comparing DBCA with FCA and RCA for Scenario A, $K=80$, $J=32$, $M=4$, $Q_b/P_B = -20$ dB and $\sigma = 8$ dB. The FDD-CDMA forward link outage performance is upper bounded by the FCA (LFB), and lower bounded by the FCA (HFB); whereas the FDD-CDMA reverse link outage performance is upper bounded by the FCA (HFB), and lower bounded by the FCA (LFB). FCA (HFB) assigns all the broadcast systems permanently in the HFB; this strategy gives the worst performance in the FDD-CDMA forward link but the best performance in the FDD-CDMA reverse link. Similar argument holds for FCA (LFB) which gives the worst performance in the FDD-CDMA reverse link but the best performance in the FDD-CDMA forward link. In the RCA strategy the broadcast system selects the HFB or the LFB in a random manner; it is obvious that the outage performance curve is between that of the FCA (HFB) and FCA (LFB).

In the DBCA strategy we vary $D$ from 0.2 to 0.8 with an increment of 0.2. As $D$ increases, the area of the inner tier increases but that of the outer tier decreases. In DBCA (L/H), when $D$ increases, more LFB broadcast systems are located in the inner tier but fewer HFB broadcast systems in the outer tier, and therefore the FDD-CDMA cellular network experiences more interference from the LFB broadcast systems but less interference from the HFB broadcast systems. The outage performance of FDD-CDMA forward link improves but that of FDD-CDMA reverse link deteriorates. From Figure (3.22), we can see that the outage probability decreases greatly from $D = 0.6$ to $D = 1.0$ (equivalent to FCA (LFB)) in the forward link, and increases greatly from $D = 0.4$ to $D = 0$ (equivalent to FCA (HFB)) in the reverse link. In DBCA (H/L), when $D$ increases, more HFB broadcast systems are located in the inner tier but fewer LFB broadcast systems in the outer tier, and therefore the FDD-CDMA cellular network experiences more interference from the HFB
broadcast systems but less interference from the LFB broadcast systems. The outage performance of FDD-CDMA forward link deteriorates but that of FDD-CDMA reverse link improves. From Figure (3.23), we can see that the outage probability increases greatly from $D = 1.0$ (equivalent to FCA (HFB)) to $D = 0.6$ in the forward link, and decreases greatly from $D = 0$ (equivalent to FCA (LFB)) to $D = 0.4$ in the reverse link. The above observation implies that the FDD-CDMA forward link is more interfered by HFB broadcast systems located farther away from the intracell FDD-CDMA BS, whereas the FDD-CDMA reverse link is more interfered by LFB broadcast systems located close to the intracell FDD-CDMA BS.
Figure 3.22: FDD-CDMA $(E_b/N_o)$ distribution for Scenario A, $K=80$, $J=32$, $M=4$, $Q_b/P_B = -20$ dB, and $\sigma = 8$ dB. Comparison of DBCA (L/H) with FCA and RCA.
Figure 3.23: FDD-CDMA \( (E_b/N_0) \) distribution for Scenario A. \( K=80, J=32, M=4,\)
\( Q_b/P_B = -20 \) dB, and \( \sigma = 8 \) dB. Comparison of DBCA (H/L) with FCA and RCA.
Figures 3.24 and 3.25 depict plots of the broadcast system $E_b/N_0$ distribution comparing DBCA with FCA and RCA for Scenario A, $K=80$, $J=32$, $M=4$, $Q_b/P_B = -20$ dB, and $\sigma = 8$ dB. In DBCA (L/H), the outage performance deteriorates significantly from $D = 0.6$ to $D = 1.0$ (equivalent to FCA (LFB)). When $D$ increases, more LFB broadcast systems are located in the inner tier but fewer HFB broadcast systems in the outer tier, and therefore more LFB broadcast systems experience cross-system interference due to the high-transmitted-power FDD-CDMA PTs but fewer HFB broadcast systems experience cross-system interference due to the FDD-CDMA BSs. In DBCA (H/L), on the other hand, the outage performance improves greatly from $D = 0.6$ to $D = 1.0$ (equivalent to FCA (HFB)). When $D$ increases, more HFB broadcast systems are located in the inner tier but few LFB broadcast systems in the outer tier, and therefore more HFB broadcast systems experience cross-system interference due to the FDD-CDMA BSs but fewer LFB broadcast systems experiences cross-system interference due to the high-transmitted-power FDD-CDMA PTs.
Figure 3.24: Broadcast system \((E_b/N_0)\) distribution for Scenario A, \(K=80\), \(J=32\), \(M=4\), \(Q_b/P_B = -20\) dB, and \(\sigma = 8\) dB. Comparison of DBCA (L/H) with FCA and RCA.
Figure 3.25: Broadcast system \( (E_b/N_o) \) distribution for Scenario A. \( K=80, J=32, M=4, Q_b/P_B = -20 \text{ dB}, \) and \( \sigma = 8 \text{ dB} \). Comparison of DBCA (H/L) with FCA and RCA.
The above results have provided us some insight on how to select a suitable frequency allocation strategy for the CDMA broadcast systems spectrally underlaid in an FDD-CDMA cellular network. Both FCA (HFB) and FCA (LFB) are not recommended because of the “near-far” problem between the cellular network and the broadcast systems. In the former one, the FDD-CDMA forward link is seriously interfered by the HFB broadcast systems; and in the latter one, the LFB broadcast systems are seriously interfered by the high-transmitted-power FDD-CDMA PTs. The RCA is simple and easy to implement, but it is not designed for the worst case of FDD-CDMA BS and PT distributions and broadcast system locations. Although this strategy is better than FCA (HFB) in the FDD-CDMA forward link and FCA (LFB) in the FDD-CDMA reverse link, it is still far from optimum.

DBCA (L/H) with a small $D$ (e.g., $D \leq 0.6$) is best for the broadcast systems in terms of outage performance because the LFB broadcast systems in the inner tier and the HFB broadcast systems in the outer tier receive less interference from the high-transmitted-power FDD-CDMA PTs and the intracell FDD-CDMA BS, respectively. Nevertheless, FDD-CDMA forward and reverse links will be seriously affected because of cross-system interference due to the corresponding broadcast systems (see Figure 3.22). On the other hand, DBCA (H/L) with a small $D$ (e.g., $D \leq 0.6$) is best for the FDD-CDMA cellular network in terms of outage performance because the FDD-CDMA forward link and reverse link receive less cross-system interference due to the HFB broadcast systems in the inner tier and the LFB broadcast systems in the outer tier, respectively. However, the HFB broadcast systems and the LFB broadcast systems will be seriously affected by the intracell FDD-CDMA BS and the high-transmitted-power FDD-CDMA PTs, respectively (see Figure 3.23). Therefore, to maximize the outage performance of the FDD-CDMA cellular network and in the meantime to keep the outage performance of the CDMA broadcast systems at an acceptable level, the DBCA (H/L) should be adopted by the broadcast systems given that $D$ is properly adjusted. A good choice of $D$ is to set $D = 0.76$ under the assumption that the PTs are uniformly distributed throughout the service area.
Chapter Summary

We have presented a performance study of CDMA broadcast systems spectrally underlaid in an FDD-CDMA cellular network which operates in the HFB for forward link and the LFB for reverse link. Among our findings are the following:

- FDD-CDMA mean $(E_b/N_o)$ performance depends on the location of the broadcast system and its operating frequency, and is different in the forward and reverse links. For small values of $\alpha$, the FDD-CDMA reverse link $(E_b/N_o)$ with an LFB broadcast system is lower than the FDD-CDMA forward link $(E_b/N_o)$ with an HFB broadcast system. However, after a certain value of $\alpha$, the FDD-CDMA forward link $(E_b/N_o)$ then becomes lower than the FDD-CDMA reverse link $(E_b/N_o)$. The impact of this uneven influence on the cellular network can be attributed to the fact that the forward link performance is very sensitive to where the HFB broadcast system is located relative to the FDD-CDMA PTs in the cell of concern. If the HFB broadcast system is located close to the FDD-CDMA PTs, this will severely degrade the forward link performance. Conversely, the reverse link performance depends only on the distance of the LFB broadcast system from the intracell FDD-CDMA BS, and its transmitted power can be properly controlled so that its influence on the cellular network is still tolerable.

- For small values of $\alpha$, the $(E_b/N_o)$ performance of an HFB broadcast system is worse than that of an LFB broadcast system. But after a certain value of $\alpha$, the $(E_b/N_o)$ performance of an LFB broadcast system then becomes worse than that of an HFB broadcast system. With the assumption that the broadcast systems are uniformly distributed in each regular cell, HFB broadcast systems perform better than LFB broadcast systems in the FDD-CDMA cellular network, but they significantly degrade the FDD-CDMA forward link performance; on the other hand, LFB broadcast systems have less impact on the FDD-CDMA reverse link performance, but they perform worse in the FDD-CDMA cellular network.
A family of frequency allocation strategies exhibiting different levels of efficiency and complexity has been studied to ensure acceptable performance in the overall network: (1) Fixed Channel Allocation (FCA), (2) Random Channel Allocation (RCA), and (3) Distance Based Channel Allocation (DBCA). Both FCA (HFB) and FCA (LFB) are not recommended because of the "near-far" problem between the cellular network and the broadcast systems. In the former one, the FDD-CDMA forward link is seriously interfered by the HFB broadcast systems; and in the latter one, the LFB broadcast systems are seriously interfered by the high-transmitted-power FDD-CDMA PTs. The RCA is simple and easy to implement, but it is not designed for the worst case of FDD-CDMA BS and PT distributions and broadcast system locations.

To maximize the outage performance of the FDD-CDMA cellular network, and in the meantime to keep the outage performance of the CDMA broadcast systems at an acceptable level, the DBCA (H/L) can be adopted by the broadcast systems given that $D$ is properly adjusted. A good choice of $D$ is to set $D = 0.76$ under the assumption that the PTs are uniformly distributed throughout the service area.
Chapter 4

Hybrid FDD/SDD-CDMA System 
Architecture for Symmetric and 
Asymmetric Communications

In current cellular networks where the main application is voice telephony, same 
amount of frequency bandwidth has been assigned for the forward and reverse links. This is because voice traffic is symmetric, i.e., equal amount of traffic is assumed in the forward and reverse links. In future multimedia communication environment, however, this assumption is erroneous. In Internet access, for example, users are expected to send low bit-rate demand messages via the reverse link and receive high bit-rate texts/videos/images via the forward link. Hence, traffic asymmetry is foreseen between the forward link and the reverse link in multimedia services.

In this chapter, we present network concepts and capacity evaluation relative to the design of an innovative system architecture for symmetric and asymmetric communications. The chapter is organized as follows. Section 4.1 provides an assessment of conventional duplex schemes: Frequency Division Duplex (FDD) and Time Frequency Duplex (TDD), and discuss their limitations in handling asymmetric traffic. Section 4.2 proposes a novel duplex scheme for asymmetric communications - Space Division Duplex (SDD). In SDD, a simultaneous bidirectional flow of information is accomplished by assigning access points in different spatial locations to opposite
directions of transmission. Section 4.3 presents a hybrid FDD/SDD-CDMA system architecture for supporting symmetric and asymmetric data users, with the former served by a cellular network and the latter served by broadcast systems using single frequency broadcasting. The broadcast systems coexist with the cellular network in the same allocated frequency bands. The cellular network utilizes conventional FDD to provide wide area voice and low-bit-rate symmetric data services, while the broadcast systems utilize SDD to provide high-bit-rate asymmetric data services. This approach is compared with other classical ones using per-cell capacity as our performance measure.

4.1 Conventional Duplex Schemes

There are two conventional duplex schemes: Frequency Division Duplex (FDD) and Time Division Duplex (TDD), which are commonly employed in current wireless systems.

FDD employs two bands of frequency spectrum separated by a certain minimum bandwidth called guard band. A simultaneous bidirectional flow of information is accomplished by assigning the two frequency bands to opposite directions of transmission. The FDD mode has been adopted in most present-day cellular systems (e.g., IS-95, IS-54, IS-136), in which the forward and reverse links are transmitted in separate frequency bands. On the other hand, TDD requires only one frequency band for operation. Therefore, the TDD mode can only provide a quasi-simultaneous bidirectional flow, since while one direction is using the frequency band the other must be off. In the allocation process, TDD's strength lies in the fact that it is easier to find a single band of unassigned frequencies than it would be to find two bands of unassigned frequencies separated by the required guard band. TDD mode has already been employed in most cordless telephony systems nowadays (e.g., DECT, PHS), in which the forward and reverse links share the same frequency band, alternating between the two links at fixed time intervals separated by some guard time.

Fundamental limitations on the design parameters of a wireless system result
from the effects of the radio propagation environment. Radio scatters create multiple signals which arrive at the receiver with respect to each other in time and space, and result in multipath fading. This multipath fading causes the input signal strength at the receiver to vary widely in amplitude; and without countermeasures, it causes intersymbol interference and limits the maximum transmission rate through the radio channel. On a given frequency, the multipath propagation effect of a radio channel is reciprocal. Taking advantage of this inherent channel reciprocity in a TDD system, the receiver can analyze the received signal and give a more accurate measure of the present channel conditions. This facilitates the prediction of future channel conditions so that transmitter diversity can be exploited in the forward link transmission. For example, in selection diversity a BS selects the antenna which picks up the best signal from a given PT; then when the BS next transmits to the PT, it uses the same antenna. However, the TDD channel may change its impulse response during the forward and reverse link time phases, and therefore, the Doppler fading rate is critical to the performance of a TDD system. FDD, on the other hand, uses different frequency bands in the forward and reverse links. Since these two links are not instantaneously reciprocal, diversity antennas have to be employed at the BS and the PT to combat multipath propagation. As a PT is required to be small and compact, the need for multiple antennas at the PT could be viewed as a disadvantage for FDD. A detailed assessment of the strengths and the weaknesses of FDD and TDD is given in [30].

To handle asymmetric traffic in wireless systems, both FDD and TDD duplex schemes have been considered in the literature. For example, in FDD, it is possible to allocate multiple frequency bands in proportion to the traffic demand of each link. However, varying the number of allocated frequency bands of each link in an adaptive manner is not feasible since this would increase hardware complexity in an FDD system. Some other studies have dealt with the handling of asymmetric traffic in TDD systems [31]-[32]. The basic idea is that, the forward and reverse links are duplexed in the same frequency band in TDD; varying the forward and reverse link capacities can be attained by varying the partition between the links through a switching operation. However, TDD is a burst mode scheme; during the transmit
burst of TDD, the receiver must be switched out. Therefore, precise synchronization of the TDD transmit and receive bursts must be required. Without synchronization, it is possible for PTs operating in the same frequency band to have overlapping transmit and receive bursts. Lack of synchronization in these systems will reduce overall system capacity. Furthermore, transmission delay can affect the TDD system performance. This delay is caused by the fact that in a TDD frame the transmit burst must be followed by the receive burst, and vice versa. This separation adds delay into the transmission path. Delay caused by TDD can constrain the implementation of a system if delay requirements are stringent. Therefore, we see that both FDD and TDD have shortcomings in handling asymmetric traffic.

4.2 Space Division Duplex (SDD)

In this section, we proposes a novel duplex scheme for asymmetric communications - Space Division Duplex (SDD). In SDD, a simultaneous bidirectional flow of information is accomplished by assigning access points in different spatial locations to opposite directions of transmission. Figure 4.1 depicts the idea of the SDD protocol. In this figure, a PT is communicating with two different BSs (BS1 and BS2) on two separate frequencies ($f_1$ and $f_2$). The reverse link from the PT to BS1 is operated on $f_1$, while the forward link from BS2 to the PT is operated on $f_2$. Both links are simply a TDD with 100% duty cycle; with the reverse link in a fully transmitting mode and the forward link in a fully receiving mode. So, SDD can be viewed as a combination of the FDD and TDD duplex schemes. From a network point of view, BS1 and BS2 should be interconnected via some wireline infrastructure (e.g., CATV, ATM-based PSN, etc.) to complete the communication path.

SDD is very similar to the conventional duplex schemes (FDD and TDD) as they apply to spectrum considerations, radio design considerations, and radio implementation considerations for a wireless system. The main difference is the equipment utilization. An SDD system will require twice as many access points as an FDD or TDD system in order to complete the information flow, but the total number of
radio transceivers required is still the same. Nevertheless, we will see that if SDD is employed in an already existing cellular network, then one of the access points of the SDD system can be provided by the cellular BSs, thus minimizing the equipment utilization.

4.2.1 SDD for Asymmetric Communications

The SDD scheme is intended for asymmetric communications in which the forward and reverse links carry different or even time-varying data rates. In multimedia communication environment, the forward link usually carries more traffic and is at a higher data rate than the reverse link. In the following analysis, we show that under such scenario, the SDD scheme is better than the conventional duplex schemes in terms of transmission power requirement.

We consider the transmission of a signal over a flat terrain and assume that the signal propagates through a two-ray path. Figure 4.2 illustrates an FDD or
TDD system. \( d_1 \) is the distance between BS1 and the PT. Let us assume that BS1's transmitted power and data rate are \( P_{BS1} \) and \( R_{BS1} \) respectively, and that the PT's transmitted power and data rate are \( P_{PT} \) and \( R_{PT} \) respectively.

The received SNR \( (E_b/N_o) \) at BS1 is given by

\[
\frac{E_b}{N_o} = \frac{P_{PT}}{R_{PT}} \frac{k_1}{d_1^4 N_1}
\]  

(4.1)

And the received \( (E_b/N_o) \) at the PT is given by

\[
\frac{E_b}{N_o} = \frac{P_{BS1}}{R_{BS1}} \frac{k_1}{d_1^4 N}
\]  

(4.2)

where \( N_1 \) and \( N \) are thermal noise powers at BS1 and the PT respectively \(^1\), and \( k_1 \) is a constant which depends on the antenna gains and heights of BS1 and the PT.

For the same \( (E_b/N_o) \) requirement at BS1 and the PT, we have

\[
P_{BS1} = \frac{R_{BS1} N}{R_{PT} N_1} P_{PT}
\]  

(4.3)

Figure 4.3: An SDD system.

In Figure 4.3 we have an SDD system with BS2 at a distance \( d_2 \) from the PT. Let us assume that BS2's transmitted power and data rate are \( P_{BS2} \) and \( R_{BS2} \) respectively.

The received \( (E_b/N_o) \) at BS1 is again given by

\(^1\)Here we assume a noise-limited environment. However, the analysis can also be applied to an interference-limited environment in which \( N_1 \) and \( N \) can be replaced by \( I_1 \) and \( I \), the interference powers at BS1 and the PT respectively.
And now the received \( \frac{E_b}{N_o} \) at the PT is given by

\[
\frac{E_b}{N_o} = \frac{P_{PT}}{R_{PT}} \frac{k_1}{d_1^4 N_1}
\] (4.4)

\( k_2 \) is a constant which depends on the antenna gains and heights of BS2 and the PT.

For the same \( \frac{E_b}{N_o} \) requirement at BS1 and the PT, we have

\[
\frac{E_b}{N_o} = \frac{P_{BS2}}{R_{BS2}} \frac{k_2}{d_2^4 N}
\] (4.5)

From (4.3) and (4.6), we can deduce that,

1. \( R_{BS1} = R_{BS2} \Rightarrow P_{BS2} < P_{BS1} \)

2. \( P_{BS1} = P_{BS2} \Rightarrow R_{BS2} > R_{BS1} \)

under the condition that \( \left( \frac{k_1}{k_2} \right) \left( \frac{d_2}{d_1} \right)^4 < 1 \). In particular, if \( k_1 = k_2 \), this condition becomes \( d_2 < d_1 \). In other words, by making \( d_2 < d_1 \), an SDD system requires less forward link transmitted power than a conventional duplex system under the same forward link data rate requirement. It can also support higher forward link data rate under the same forward link transmitted power requirement. So, in order to handle asymmetric traffic in a power-efficient manner, we can route a PT’s low bit-rate reverse link via BSs in large cells (e.g., macro/microcells) and its high bit-rate forward link from BSs in small cells (e.g., picocells). This motivates the use of SDD in a CDMA cellular network for providing asymmetric data services.

4.3 Hybrid FDD/SDD-CDMA System Architecture

4.3.1 System Description

Figure 4.4 illustrates the cellular structure for the hybrid FDD/SDD-CDMA system architecture, with a cellular network and broadcast systems coexisting in the same
geographical area. The cellular network is to provide wide area voice and low bit-rate symmetric data services, while the broadcast systems are to provide high bit-rate asymmetric data services. A wireline infrastructure that can interconnect the cellular network and the broadcast systems is depicted in Figure 4.5. We envision the use of broadband transmission facilities such as CATV broadcast network to interconnect the broadcast systems. The BSs are star-connected to a mobile switching center (MSC) which provides a gateway to the public switched telephone network (PSTN). This interconnection configuration can minimize the infrastructure cost because the distribution network for the broadcast systems is shared with an existing wireline infrastructure, and therefore can add a degree of flexibility in the provision of the broadcast systems.

![Cellular structure for the hybrid FDD/SDD-CDMA system architecture.](image)

Figure 4.4: Cellular structure for the hybrid FDD/SDD-CDMA system architecture.

**FDD-CDMA Cellular Network**

The cellular network intended for full coverage is a wideband **FDD-CDMA** air interface. Two equal frequency bands are assigned for symmetrical two-way communication: one is the HFB and the other is the LFB. The carrier frequencies from the HFB are allocated to the forward link and those from the LFB are allocated to the reverse link.
In the forward link, the cellular network uses orthogonal spreading and coherent detection. Each user is assigned a different orthogonal code channel to reduce the amount of interference seen at the PT. This provides perfect separation among the signals from different PTs. If orthogonality is fully preserved between code channels, interference from PTs of the same cell can be suppressed at the receiver, at least for the case where multipath does not exist. A pilot tone is usually provided in the forward link and this is done by reserving one orthogonal code for its continuous transmission. Sending the pilot signal along with the traffic allows the PTs to determine and react to the channel characteristics while performing coherent detection. In the reverse link, asynchronous operation mode is adopted. Since each received signal arrives at the BS via a different propagation path, orthogonality amongst all PTs is in general difficult to achieve.

**SDD-CDMA Broadcast System**

The broadcast system, on the other hand, employs a wideband SDD-CDMA air interface. It utilizes the same frequency bands as the FDD-CDMA counterpart, i.e., HFB for the forward link and LFB for the reverse link.
Figure 4.6 illustrates the system model of a broadcast network (e.g., CATV, DAB, DVB, etc.) connecting to the broadcast systems. Each broadcast system consists of a set of RPs which cover a certain service area in the cellular network. The RPs in a broadcast system communicate with an access point (AP). Each AP serves as a regional broadcast node and is connected to the broadcast network, which interacts with a number of ISPs. The ISPs are connected to the global Internet through routers. Using the SDD protocol, a PT transmits low-bit-rate demand messages (e.g., requests, acknowledgements) to the cellular network's BSs in the LFB and receives high-bit-rate web page download (e.g., texts, videos, images) from the broadcast system's RPs in the HFB. This system model has a few advantages. First, since the PTs transmit information via the cellular network but not via the broadcast network, they do not need a broadband power amplifier which consumes much power. Therefore, the PTs do not require a large and heavy battery, and can be made less expensive. Second, it is possible to provide the PTs with dual-mode capabilities, i.e., they can access symmetric data services via the cellular network and asymmetric data services via the broadcast system. In addition, since the broadcast network has been more prevalent than other network backbones like ATM-based PSN, the broadcast system can be gradually deployable and growable. From an economical point of view, this greatly reduces the initial setup and implementation costs.

In order to set up a user connection, a PT must first determine a serving RP in
the broadcast system. To distinguish among different RPs in a broadcast system, we adopt a two-layer (long and short) spreading code assignment for the pilot spreading codes. A long spreading code is uniquely assigned to each broadcast system so that interference from other broadcast systems can be modeled as Gaussian random-like noise. RPs in a broadcast system are distinguished by different short spreading codes, and therefore an RP can be easily identified by its unique pilot tone which is a combination of a unique long spreading code and a short spreading code. All broadcast systems are allocated the same set of short spreading codes, thus facilitating spatial reuse of codes among different broadcast systems.

All RPs connected to an AP simultaneously broadcast their respective pilot tones in the HFB. By constantly monitoring the received signal strengths of the pilot tones, the PT can decide which RP to receive information. The RP selection is performed jointly by the cellular network and the broadcast network as follows.

1. The PT monitors the received signal strengths of the pilot tones it detects. If the received pilot-to-interference ratio from an RP is above a certain threshold (e.g., $T_{add}$), the PT sends an “ADD” request to the cellular network to add the RP. Conversely, if the pilot-to-interference ratio drops below another threshold (e.g., $T_{del}$), the PT sends a “DEL” request to the cellular network to delete the RP.

2. The cellular network sends the request to the broadcast network’s interface unit which determines the RP for which the action (“ADD” or “DEL”) should be performed.

3. If the request is “ADD”, the interface unit signals the RP to start the forward link transmission. If the request is “DEL”, the interface unit signals the RP to stop the forward link transmission.

In the forward link, RPs in each broadcast system can act collectively as widely separated antennas of an adaptive antenna array, thus providing a form of transmitter diversity to combat fading. The small-scale Rayleigh fading of the signal will be
statistically independent on the propagation channels from the serving RPs. These signals can be combined at the PT using array processing techniques which involve either switching or combining.

### 4.3.2 Network Model

![Network Model Diagram](image)

Figure 4.7 outlines a network model of the hybrid FDD/SDD-CDMA system architecture. The model consists of three main parts—Internet, ISP, and network providers (cellular network and broadcast network). An interface unit is provided between the cellular network to which the BSs are connected and the broadcast network to which the APs are connected.

When a PT wants to access asymmetric data services in the broadcast system, it first transmits a demand message to a cellular BS. The interface unit receives the demand message from the PT via the cellular network, and transmits it to the ISP via the broadcast network. The Internet supplies to the ISP the requested information.
which can consist of audio, video, text, graphics, still pictures, or combination of these. The ISP then transmits the requested information via the broadcast network to an AP with which the PT is associated.

### 4.4 Capacity Evaluation

We call the above proposed architecture with FDD-CDMA cellular network and SDD-CDMA broadcast systems as System I. For the purpose of comparison, we also consider two other system architectures, namely, System II and System III. System II employs an FDD/FDD-CDMA system architecture, and System III employs only FDD-CDMA cellular network to support symmetric and asymmetric data users.

The detailed analysis presented is for System I only, but the resultant equations can be applied, with just a few modifications, to System II and System III as well. The total number of regular cells is \( C \) indexed from 0 to \( C - 1 \) and a cellular BS is located at the center of each regular cell. In each regular cell, there are \( J \) broadcast system RPs, \( K_s \) symmetric data users and \( K_a \) asymmetric data users. The following notation is adopted for the analysis. \( h(x, y) \) is the channel gain from \( x \) to \( y \) in which \( x \) or \( y \) is represented by one of the following: \( B_i \) (the BS in regular cell \( i \)), \( p_{ik} \) (the \( k^{th} \) symmetric data user served by BS \( B_i \)), \( b_{ij} \) (the \( j^{th} \) RP in regular cell \( i \)), and \( q_{im} \) (the \( m^{th} \) asymmetric data user served by RP \( b_{ij} \)). \( P_B \) is the transmitted power of BS \( B_i \), and \( P_{ik} \) is the transmitted power of symmetric data user \( p_{ik} \). \( Q_{b_{ij}} \) is the transmitted power of RP \( b_{ij} \), and \( Q_{im} \) is the transmitted power of asymmetric data user \( q_{im} \).

#### 4.4.1 Symmetric Data User Performance

The forward and reverse links of a symmetric data user are connected to the cellular network via a BS. Without loss of generality, we take BS \( B_0 \) in regular cell 0 as the reference BS.

**Reverse Link**

The received power of symmetric data user \( p_{0k} \) at BS \( B_0 \) is
\[ S_s = P_{0k} h(p_{0k}, B_0) \quad \text{for } k = 1, \ldots, K_s \] (4.7)

The total interference received at BS \( B_0 \) consists of self-system interference from all interfering symmetric data users in the cellular network (denoted by \( I_{ss} \)), and cross-system interference from all interfering asymmetric data users in the broadcast systems (denoted by \( I_{sa} \)). The self-system interference is given by

\[ I_{ss} = (K_s - 1)S_s + \sum_{i=1}^{C-1} \sum_{k=1}^{K_s} P_{ik} h(p_{ik}, B_0) \] (4.8)

and the cross-system interference is given by

\[ I_{sa} = \sum_{i=0}^{C-1} \sum_{m=1}^{K_a} Q_{im} h(q_{im}, B_0) \] (4.9)

If the asymmetric data users in regular cell 0 are also power-controlled by BS \( B_0 \), then \( I_{sa} \) becomes

\[ I_{sa} = K_a S_s + \sum_{i=1}^{C-1} \sum_{m=1}^{K_a} Q_{im} h(q_{im}, B_0) \] (4.10)

**Forward Link**

We let \( \mu_{0k} \) denote the fraction of BS \( B_0 \)'s transmitted power allocated to symmetric data user \( p_{0k} \). Then the signal power received at \( p_{0k} \) is

\[ S_s = \mu_{0k} P_{B_0} h(B_0, p_{0k}) \quad \text{for } k = 1, \ldots, K_s \] (4.11)

The self-system interference consists of intracell interference due to BS \( B_0 \) and intercell interference due to the BSs in the surrounding regular cells. Therefore,

\[ I_{ss} = (1 - \mu_{0k}) P_{B_0} h(B_0, p_{0k}) + \sum_{i=1}^{C-1} P_{Bi} h(B_i, p_{0k}) \] (4.12)

and the cross-system interference is the interference accumulated from all broadcast system RPs and is given by
4.4.2 Asymmetric Data User Performance

In the SDD approach, the reverse link of an asymmetric data user is connected to the cellular network via a BS and utilizes its reverse link radio resource, whereas the forward link of this user is routed from the broadcast network via a broadcast system RP. Without loss of generality, we take broadcast system RP $b_0$ in regular cell 0 as the reference RP.

Reverse Link

The reverse link analysis of the asymmetric data users is the same as that of the symmetric data users, since they are both power-controlled by the cellular network. The received power of asymmetric data user $q_{im}$ at BS $B_0$ is

$$ S_a = Q_{im} h(q_{im}, B_0) = S_s \text{ for } m = 1, \ldots, K_a $$

(4.14)

The self-system interference (denoted by $I_{aa}$) is the interference accumulated from all interfering asymmetric data users and is given by

$$ I_{aa} = (K_a - 1)S_a + \sum_{i=1}^{C-1} \sum_{m=1}^{K_a} Q_{im} h(q_{im}, B_0) $$

(4.15)

The cross-system interference (denoted by $I_{as}$) is the interference accumulated from all interfering symmetric data users and is given by

$$ I_{as} = K_s S_s + \sum_{i=1}^{C-1} \sum_{k=1}^{K_s} P_{ik} h(p_{ik}, B_0) $$

(4.16)

Forward Link

We let $\nu_{0jm}$ denote the fraction of broadcast system RP $b_0$'s transmitted power allocated to asymmetric data user $q_{0m}$. Then the signal power received at $q_{0m}$ is

$$ I_{sa} = \sum_{i=0}^{C-1} \sum_{j=1}^{J} Q_{b_{ij}} h(b_{ij}, P_{0k}) $$

(4.13)
The self-system interference is the interference accumulated from all broadcast system RPs and is given by

$$S_a = \nu_{0jm}Q_{b0j}h(b_{0j}, q_{0m}) \quad \text{for} \ m = 1, \ldots, K_a$$  \hspace{1cm} (4.17)

The cross-system interference from all cellular BSs is expressed as

$$I_{aa} = \sum_{i=0}^{C-1} \sum_{j=1}^{J} Q_{bij} h(b_{ij}, q_{0m}) - \nu_{0jm}Q_{b0j}h(b_{0j}, q_{0m})$$  \hspace{1cm} (4.18)

4.5 Simulation Approach and Numerical Results

The simulation approach we used determines the values of received $(E_b/N_a)$ for different system architectures. The simulations simultaneously consider many system parameters and give statistics of $(E_b/N_a)$ for the symmetric data users and the asymmetric data users randomly located throughout each regular cell. The simulation model consists of 25 regular cells of square coverage each with a cellular BS at its center. A uniform square grid of 16 broadcast system RPs are assumed in each regular cell. Use of omnidirectional antennas is assumed for all BSs and RPs. Portable locations are randomly generated for all cells. Distance dependent path loss and lognormal shadowing are assumed according to the propagation models described in Chapter 2. Mean signal and interference power levels and shadow fading are calculated and SIR statistics are collected for the forward and reverse links. Then all random variables are regenerated until 100000 SIR values have been calculated. We assume that the symmetric data users and the asymmetric data users access the corresponding BS and RP respectively with the strongest signal strength. This provides a form of macroscopic diversity against lognormal shadowing and thus gives better coverage performance.

The system parameters used in the simulations for comparing capacity among different system architectures are tabulated in Table 4.1.
Table 4.1: System parameters used in the simulations for comparing capacity among different system architectures.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Cellular Network</th>
<th>Broadcast System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized Cell Dimension</td>
<td>$2 \times 2$</td>
<td>$0.2 \times 0.2$</td>
</tr>
<tr>
<td>Normalized Close-in Distance</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>Path Loss Exponent</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Shadowing Standard Deviation</td>
<td>8 dB</td>
<td>2 dB</td>
</tr>
<tr>
<td>Fraction of Pilot Power</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Spreading Bandwidth</td>
<td>5 MHz</td>
<td>5 MHz</td>
</tr>
<tr>
<td>User Profile</td>
<td>Symmetric</td>
<td>Asymmetric</td>
</tr>
<tr>
<td>Forward Link Data Rate</td>
<td>8 kbps</td>
<td>128 kbps</td>
</tr>
<tr>
<td>Reverse Link Data Rate</td>
<td>8 kbps</td>
<td>8 kbps</td>
</tr>
</tbody>
</table>

4.5.1 Performance of FDD-CDMA Cellular Network

Figure 4.8 shows the capacity performance of an FDD-CDMA cellular network in both HFB and LFB with only symmetric data users under different shadowing standard deviations. The HFB is used for the forward link, whereas the LFB is used for the reverse link. We observe that the capacity decreases when the shadowing standard deviation increases. In particular, shadowing has a more significant effect on the HFB capacity. The strong dependence of the HFB capacity on the propagation characteristics can be explained as follows. Forward link power control distributes the BS transmitted power according to the needs of individual PTs. Shadowing variations cause each PT to require either more or less transmitted power from the serving BS. Hence, the overall capacity changes dramatically when the propagation conditions vary. Unlike the HFB capacity, shadowing has relatively little impact on the LFB capacity, since the shadowing variation in the received signal of each PT is power-controlled by the serving BS.

Figure 4.9 shows the capacity performance of the same cellular network for different $(E_b/N_0)_{req}$ at $\sigma = 8$ dB. As shown in the graph, the capacity is greatly
increased by a reduction in \((E_b/N_o)_{req}\). With \((E_b/N_o)_{req} = 5\) dB for the forward link and \((E_b/N_o)_{req} = 7\) dB for the reverse link, we see that about 70 symmetric data users can be supported.
Figure 4.8: Capacity performance of the FDD-CDMA cellular network with only symmetric data users for different shadowing standard deviations.
Figure 4.9: Capacity performance of the FDD-CDMA cellular network with only symmetric data users for different values of $(E_b/N_o)_{req}$. 
4.5.2 Capacity Plane of Different System Architectures

We now consider the capacity achieved for different system architectures. Using (3.1), we can express the \( (E_b/N_o) \) ratio as follows.

For the symmetric data users,

\[
\left( \frac{E_b}{N_o} \right)_s = PG_s \left( \frac{S_s}{I_{ss} + I_{sa}} \right)
\]  (4.20)

And for the asymmetric data users,

\[
\left( \frac{E_b}{N_o} \right)_a = PG_a \left( \frac{S_a}{I_{aa} + I_{as}} \right)
\]  (4.21)

where \( PG_s \) and \( PG_a \) are processing gains for the symmetric data users and the asymmetric data users respectively. To guarantee the users' quality of service performance, their \( (E_b/N_o) \) ratios have to be greater than their required \( (E_b/N_o)_{\text{req}} \).

Figure 4.10-4.12 illustrate the capacity plane or the permissible \( (K_s, K_a) \) region for different system architectures in both HFB and LFB. We notice that in all the system architectures considered, the capacity is bound by the forward link performance in the HFB. In other words, there is residual reverse link capacity left unused in the LFB. This can be explained as follows. When there are only symmetric data users in each system architecture, the forward and reverse links would take up approximately the same amount of radio resource in the HFB and LFB, respectively. However, when there are asymmetric data users with higher forward link data rates as well, more radio resources in the HFB would be taken up and this makes the forward link the limiting direction. In particular, System III, with only the cellular network to support symmetric and asymmetric data users, gives the worst forward link capacity performance. This is because the asymmetric data users would require much higher transmitted power from the cellular BSs.

In System I and System II, each asymmetric data user's forward link is served by a broadcast system RP and thus lower transmitted power from the broadcast system RP is required. Therefore, the forward link capacity performances in System I and System II are the same. Nevertheless, we see that System I has more reverse link
capacity than System II. In System I, the reverse link of an asymmetric data user is power-controlled by a cellular BS, thus minimizing the cross-system interference injected into the cellular network. In System II, however, the reverse link of the asymmetric data user is power-controlled by a broadcast system RP and this would inject larger amount of cross-system interference into the cellular network under favorable propagation conditions.
Figure 4.10: Capacity plane for System I: FDD/SDD-CDMA system architecture.
Figure 4.11: Capacity plane for System II: FDD/FDD-CDMA system architecture.
Figure 4.12: Capacity plane for System III: only FDD-CDMA cellular network.
4.5.3 Performance Enhancement with Adaptive Antennas

From the previous subsection, we discover that with the use of omnidirectional antennas, System I and System II support the same number of symmetric data users and asymmetric data users simultaneously, due to the fact that both system architectures' capacities are bound by the forward link performance in the HFB. However, we see that System I has more residual reverse link capacity unused in the LFB. Hence, if we can improve the forward link performance in the HFB, System I will be able to have a higher capacity than System II. One way to accomplish this is through the use of array antenna structures at the broadcast system RPs. By combining the outputs of the individual antennas in an array, a single effective antenna can be created with gain and directional characteristics that are optimized to enhance a particular user's signal while simultaneously rejecting interferers, resulting in greater capacity and improved service quality.

In general, we can differentiate array antenna structures into two categories: fixed-beam antenna structures and adaptive array antenna structures. A fixed-beam antenna structure uses an array of antennas to create a group of antenna beams that together result in omnidirectional coverage. For example, see Figure 4.13, which shows a three-sector cell employing a four-beam fixed-beam antenna structure in each sector. Each antenna beam contains a fixed beam pattern with the greatest sensitivity located in the centre of the beam and less sensitivity elsewhere. When a PT enter a particular cell, the structure scans the output of each beam and selects the beam with the strongest signal strength. Throughout the call, the structure monitors the signal strength and switches to other beam as required. Additionally, multiple beam outputs can be combined to provide diversity.

The adaptive array antenna structures take a different approach. They employ an array of antennas which are combined at baseband using complex weights. These weights are chosen to maximize SIR by sophisticated signal processing algorithms which can be interpreted as trying to both maximize the antenna beam pattern in the direction of the desired signal and minimize the beam pattern in the direction of the
interfering signals, and to continuously update the beam patterns based on changes in both the desired and interfering signals. The ability of continuously changing the antenna beam patterns separates the adaptive approach from the fixed type. Figure 4.14 illustrates an important aspect of the adaptive array antenna structures that apply to the broadcast system RPs in the hybrid FDD/SDD-CDMA system architecture. The figure shows the antenna beam patterns for two broadcast system PTs in a 120° sector of a broadcast system RP with two interfering cellular PTs. A four-element adaptive array is used. Each of the two beam patterns in the figure is optimized at the receiver of each broadcast PT.

Fixed-beam antenna structures are less complex and easier to implement. However, there are some limitations. Since the antenna beams are fixed, the signal strength varies as the PT moves through the beam. As the PT moves toward the far...
azimuth edges of a beam, the signal strength can degrade rapidly before the PT is switched to another beam. Another limitation occurs because a fixed-beam antenna structure cannot distinguish between a desired signal and an interfering signal. If the interfering signal is at approximately the centre of the selected beam, the interfering signal can be enhanced far more than the desired signal and therefore SIR for the desired signal will degrade accordingly. In contrast, an adaptive array antenna structure is able to distinguish between a desired signal and an interfering signal, and dynamically minimize interference and maximize desired signal reception. The ability to track desired PTs with main lobes and interfering PTs with nulls insures that the performance of the wireless systems is constantly maximized.

Our simulation analysis is focused on the use of adaptive array antenna structures at the broadcast system RPs in System I, to investigate the capacity performance with the same system parameters in Table 4.1. Figure 4.15 shows the improvement in capacity performance of System I with the use of adaptive array antenna structures. The upper bound of the overall capacity that can be achieved in System II is also plotted for comparison (labeled as System II bound). With the use of omnidirectional antennas at the broadcast system RPs, the capacity of System I is less than that of System II bound and its deviation from the bound is more noticeable when the number of symmetric data users is small in the system architecture. The simulation results indicate that using adaptive array antenna structures at the broadcast system RPs can improve capacity performance significantly and that more asymmetric data users can be supported at a given number of symmetric data users as the antenna beamwidth decreases. For example, when the number of symmetric data users is 30, the number of asymmetric data users increases from 16 to 32 when the antenna beamwidth decreases from 60° to 30°.
Figure 4.15: Overall capacity plane for System I: FDD/SDD-CDMA system architecture.
4.6 Chapter Summary

We have proposed a novel duplex scheme for asymmetric communications - Space Division Duplex (SDD). In SDD, a simultaneous bidirectional flow of information is accomplished by assigning access points in different spatial locations to opposite directions of transmission. By routing a PT's low bit-rate reverse link via BSs in large cells (e.g., macro/microcells) and its high bit-rate forward link from BSs in small cells (e.g., picocells), an SDD system requires less forward link transmitted power than a conventional duplex system under the same forward link data rate requirement. It can also support higher forward link data rate under the same forward link transmitted power requirement.

We have presented a hybrid FDD/SDD-CDMA system architecture (System I) for supporting symmetric and asymmetric data users, with the former served by a cellular network and the latter served by broadcast systems using single frequency broadcasting. The broadcast systems coexist with the cellular network in the same allocated frequency bands. The cellular network utilizes FDD to provide wide area voice and low-bit-rate symmetric data services, while the broadcast systems utilize SDD to provide high-bit-rate asymmetric data services. Using per-cell capacity as the performance measure, we have evaluated the capacity performance of System I and compared it with two other classical system architectures (System II and System III).

Our simulation results show that in all the system architectures considered, the capacity is bound by the forward link performance in the HFB, and there is residual reverse link capacity left unused in the LFB. System III, with only the cellular network to support symmetric and asymmetric data users, gives the worst forward link capacity performance. This is because the asymmetric data users would require much higher transmitted power from the cellular BSs. In System I and System II, each asymmetric data user's forward link is served by a broadcast system RP and thus lower transmitted power from the broadcast system RP is required. Therefore, the forward link capacity performances in System I and System II are the same. Nevertheless,
we see that System I has more reverse link capacity than System II. In System I, the reverse link of an asymmetric data user is power-controlled by a cellular BS, and thus minimizing the cross-system interference injected into the cellular network. In System II, however, the reverse link of the asymmetric data user is power-controlled by a broadcast system RP and this would inject larger amount of cross-system interference into the cellular network under favorable propagation conditions.

With the use of omnidirectional antennas, System I and System II support the same number of symmetric data users and asymmetric data users simultaneously, due to the fact that both system architectures' capacities are bound by the forward link performance in the HFB. By implementing adaptive array antenna structures at the broadcast system RPs, we see that there is a significant improvement in the capacity performance of System I and that more asymmetric data users can be supported at a given number of symmetric data users as the antenna beamwidth decreases.
Chapter 5

Joint Power Control and Space Diversity for Demand Access Channels

Internet access has proliferated dramatically from universities to homes and businesses over the past few years. Data/image-oriented Internet applications, like WWW, have gained widespread user acceptance and are becoming a dominant service. One of the distinguishing features of these applications is that they require uni- and/or bi-directional asymmetric data transfer as well as high bit-rate transmission. In WWW, for example, PTs are expected to send low-bit-rate demand messages (e.g., requests, acknowledgements) via the reverse link and receive high-bit-rate web page download (e.g., text, video, graphics) via the forward link. In the preceding chapter, we proposed a hybrid FDD/SDD-CDMA system architecture for supporting symmetric and asymmetric data users, with the former served by a cellular network and the latter served by broadcast systems using single frequency broadcasting. Using per-cell capacity as the performance measure, we showed that this system architecture could be an attractive technique in future generation wireless networks for providing symmetric and asymmetric data services in a spectrum-efficient manner.

In this chapter, we consider the hybrid FDD/SDD-CDMA system architecture in which the asymmetric data users share the cellular network’s reverse link with the
symmetric data users. We assume that the asymmetric data users employ packet-mode access to transmit demand messages in relatively short bursts and are silent at other times, whereas the symmetric data users employ circuit-mode access. This imposes a significant challenge for performance optimization since accessing asymmetric data users can degrade the performance of currently active symmetric data users by introducing extra interference variations which reduce system capacity. In CDMA, one way to achieve maximum capacity is by using iterative power control in order to optimize the SIRs of several simultaneous users [4]. We study the implementation and performance of a special version of iterative SIR-based power control algorithms in which the currently active symmetric data users are protected from interference by the accessing asymmetric data users. Moreover, as the accessing asymmetric data users are expected to have short duty cycles in the cellular network's reverse link, significant overhead may be required for iterative power control. We thus investigate the use of space diversity schemes to help reduce the high iteration overhead and access their performance jointly with the proposed iterative SIR-based power control algorithm.

5.1 Iterative SIR-based Power Control Algorithm

In this section, we introduce an iterative SIR-based power control algorithm with active link protection which provides protection for the symmetric data users that are currently active, in the sense that it maintains their SIRs above their required threshold \( SIR_{req} \) at all times, while allowing the asymmetric data users to try to access the cellular network. Moreover, if the latter cannot be served they are simply rejected, without hurting the currently active symmetric data users in the process.

5.1.1 System Model

The total number of regular cells is \( C \) indexed from 0 to \( C - 1 \). In each regular cell, the number of active symmetric data users is \( K_s \) and the number of accessing asymmetric data users trying to access is \( K_a \). We adopt the same notation used in
The received power of active symmetric data user $p_{ik}$ at BS $B_i$ is $h(p_{ik}, B_i) P_{ik}$. We assume that the received powers from all active symmetric data users in regular cell $i$ is common and given by $P_i$, for BS $B_i$, i.e.,

$$P_i = h(p_{ik}, B_i) P_{ik} \quad \text{for } k = 1, \ldots, K_s$$

(5.1)

We prefer to work with the quantities $\{P_i\}$ since they are fewer than $\{P_{ik}\}$ and this leads to a simpler analytic treatment. However, it should be straightforward to recover information on $P_{ik}$ from $P_i$ via (5.1).

The total interference received at BS $B_i$ consists of two parts: the intracell interference from all interfering symmetric data users in regular cell $i$, and the intercell interference from all interfering symmetric data users in regular cell $c \neq i$. Let $I_{i,\text{intra}}$, $I_{i,\text{inter}}$ and $I_i$ denote the intracell, intercell, and total interference for regular cell $i$ respectively. Thus,

$$I_{i,\text{intra}} = (K_s - 1) P_i$$

(5.2)

$$I_{i,\text{inter}} = \sum_{c=0, c \neq i}^{C-1} \sum_{k=1}^{K_s} h(p_{ck}, B_i) P_{ck}$$

(5.3)

$$I_i = I_{i,\text{intra}} + I_{i,\text{inter}} + \eta_i W$$

(5.4)

where $\eta_i W$ is the local receiver noise power at BS $B_i$, and $W$ is the spreading bandwidth.

Therefore, the SIR for active symmetric data user $p_{ik}$ in regular cell $i$ is given by

$$\text{SIR}_{ik} = \frac{P_i}{(K_s - 1) P_i + \sum_{c=0, c \neq i}^{C-1} \sum_{k=1}^{K_s} h(p_{ck}, B_i) P_{ck}}$$

(5.5)

$p_{ik}$ is said to be active if $\text{SIR}_{ik} \geq \Gamma$, $\Gamma$ being the required SIR threshold.
5.1.2 Algorithm Design

We shall describe the iterative SIR-based power control algorithm below and list some of its useful properties. Without loss of generality, we consider the $m^{th}$ accessing asymmetric data user in regular cell $i$, i.e., $q_{im}$, who tries to access the cellular network by transmitting a demand message at a certain power level $Q_{im}$. If the access attempt is not successful, the same message is sent again. We assume that the channel is known and static during each access attempt. The number of access attempts is denoted by $t$ where $t = 1, 2, 3, \ldots$.

The iterative SIR-based power control algorithm updates the transmitted power levels $\{P_{ik}(t+1), Q_{im}(t+1)\}$ in regular cell $i$ at the $(t+1)^{th}$ access attempt in steps indexed by $t = 1, 2, 3, \ldots$, according to the following rules:

\[
\begin{align*}
\Delta P_{ik}(t+1) &= \delta \frac{SIR_{ik}(t)}{P_{ik}(t)} \quad \text{for } k = 1, \ldots, K_s \\
\Delta Q_{im}(t+1) &= \delta Q_{im}(t) \quad \text{for } m = 1, \ldots, K_a
\end{align*}
\]  

(5.6)

where $\delta$ is the step size of the power control algorithm such that $\delta > 1$.

$SIR_{ik}(t)$ is the signal-to-interference ratio $SIR_{ik}$ for active symmetric data user $p_{ik}$ during the $t^{th}$ update and is given by

\[
SIR_{ik}(t) = \frac{P_i(t)}{I_i(t)}
\]  

(5.7)

where $P_i(t)$ is the desired received power level for all active symmetric data users in regular cell $i$ during the $t^{th}$ update. Obviously, $P_i(t) = h(p_{ik}, B_i) P_{ik}(t) \forall k \in$ regular cell $i$. $I_i(t)$ is the total interference power received at BS $B_i$ during the $t^{th}$ update and is given by

\[
I_i(t) = (K_s - 1) P_i(t) + \sum_{c=0, c \neq i}^{C-1} \sum_{k=1}^{K_s} h(p_{ck}, B_i) P_{ck}(t) + \sum_{c=0}^{C-1} \sum_{m=1}^{K_a} \chi_{cm}(t) h(q_{cm}, B_i) Q_{cm}(t)
\]  

(5.8)

where $\chi_{cm}(t)$ is the activity indicator for the $m^{th}$ accessing asymmetric data user in regular cell $c$ during the $t^{th}$ update, i.e., $\chi_{cm}(t) \in \{0, 1\}$ and $\chi_{cm}(t) = 1$ if and only if
this user is active during the $t^{th}$ update.

The iterative SIR-based power control algorithm has the following useful properties:

**Proposition 5.1** For any fixed $\delta \in (1, \infty)$, we have that $\forall k \in \text{regular cell } i$

$$SIR_{ik}(t) \geq \Gamma \rightarrow SIR_{ik}(t+1) \geq \Gamma$$  \hspace{1cm} (5.9)

**Remark 5.1** Proposition 5.1 shows that initially active symmetric data users remain active throughout the evolution of the algorithm. Therefore, each active symmetric data user's link quality is protected while the asymmetric data users are trying to gain access to the cellular network.

**Proposition 5.2** For any fixed $\delta \in (1, \infty)$, we have that $\forall k \in \text{regular cell } i$

$$P_{ik}(t+1)/P_{ik}(t) \leq \delta$$  \hspace{1cm} (5.10)

**Remark 5.2** Proposition 5.2 shows that the overshoots of the power control algorithm are bounded by $\delta$, which is typically slightly larger than 1. Therefore, the transmitted powers of active symmetric data users can only increase in a controlled smooth manner, to accommodate the accessing asymmetric data users that are powering up.

**Proposition 5.3** For any fixed $\delta \in (1, \infty)$, we have $\forall m \in \text{regular cell } i$

$$SIR_{im}(t+1) \geq SIR_{im}(t)$$  \hspace{1cm} (5.11)

**Remark 5.3** Proposition 5.3 shows that, at each step of the power control algorithm, the SIR of every accessing asymmetric data user is non-decreasing and improves continuously. Therefore, the SIR may rise at some step above its required threshold, in which case the cellular network can receive correctly the demand message from the accessing asymmetric data user.
5.1.3 Packet Access

When an accessing asymmetric data user transmits a demand message, the cellular network will evaluate if it is received correctly or not. This evaluation is done based on the information obtained from the power control algorithm.

Considering the $m^{th}$ accessing asymmetric data user in regular cell $i$, $q_{im}$, a necessary condition has to be satisfied for the message to be received correctly. During the $t^{th}$ access attempt, the received power of $q_{im}$ at BS $B_i$ is $h(q_{im}, B_i) Q_{im}(t)$. The message is correctly received if the following condition is satisfied.

$$\frac{h(q_{im}, B_i) Q_{im}(t)}{I_i(t)} \geq \gamma$$

(5.12)

where $\gamma$ is the required SIR threshold for all asymmetric data users.

5.2 Space Diversity

In cellular mobile radio systems, signal fading due to both the time variance and frequency selectivity of the multipath fading channel [33] and the interference in the cellular environment have a degrading effect on the system performance. The value of the SIR at the receiver thus varies with time and with frequency. As the interference power varies, the value of the SIR at the receiver varies depending on the actual interference situation. Low values of the SIR, which may result from deep fades of the channel or large interference power, can lead to insufficient service quality or even to an interrupt of the communication link. A large variance of the SIR at the receiver can result from a large variance of the signal power, as well as a large variance of the interference power.

The aim of the diversity is to reduce the variance of the SIR at the receiver in order to improve the system performance. This aim is achieved by providing the receiver with two or more signal contributions which bear the same information and which have values of the SIR being realizations of, if possible, independent random variables SIR. These signal contributions are combined at the receiver. The variance
of the SIR of the combined received signal is reduced as compared with the variance of the SIR of each signal contribution due to an averaging over two or more different channel transmission conditions or interference situations. In the case of an averaging over different transmission conditions, the variance of the SIR is reduced by reducing the variance of the signal in the SIR. In the case of an averaging over different interference situations, the variance of the SIR is reduced by reducing the variance of the interference in the SIR. For combining the signal contributions at the receiver, well-known linear combining methods can be applied [34].

Diversity can be provided in the three dimensions: frequency domain, time domain or space domain, resulting in frequency, time or space diversity, respectively. Frequency diversity is useful if the channel is frequency selective and time diversity is useful if the channel is time variant. In the case of space diversity, antenna, angle, and cell site diversity can be distinguished. Antenna diversity is useful if the reception conditions depend on the location, i.e., if the channel is time variant. Concerning antenna diversity, one can distinguish the cases that the distance \( \Delta \) between the different receiver antennas is smaller than the wavelength \( \lambda (\Delta < \lambda) \), in the order of the wavelength \( \lambda (\Delta \approx \lambda) \), and much larger than the wavelength \( \lambda (\Delta >> \lambda) \). In the first case, the signal contributions received at the antennas are correlated. In the second case, the signal contributions are approximately uncorrelated, but the propagation path loss and lognormal shadowing are roughly the same for the antennas. In the third case, the signal contributions are uncorrelated and experience different propagation path loss and shadowing conditions. Distances \( \Delta \approx \lambda \) and \( \Delta >> \lambda \) between the different receiver antennas can only be achieved in the reverse link and not in the forward link.

For a certain antenna position, the various multipath components will add either constructively or destructively according to the relative phase of the signal concerned. However, the effects of fading can be substantially mitigated through the use of antenna diversity. In the hybrid FDD/SDD-CDMA system architecture, however, it is not always possible to follow this rule of thumb, especially for the accessing asymmetric data users who are either stationary or slowly moving. When they are in a
deep fading attenuation, several iterations will be required by the power control algorithm to update the transmitted power levels for the active symmetric data users and the accessing asymmetric data users in order to achieve the desirable performance. However, as the accessing asymmetric data users are expected to have short duty cycles in the cellular network's reverse link, significant overhead will be required for the iterative power control algorithm. This implies reduced traffic capacity in the system architecture. In this work, we exploit the use of space diversity in the form of multiple antenna elements in the cellular network's reverse link, in conjunction with the proposed power control algorithm, to reduce the high iteration overhead required for the accessing asymmetric data users.

As mentioned above, the use of multiple antenna elements at the receiver is fairly easily exploited. In essence, multiple copies of the transmitted stream are received and can be efficiently processed via switching or combining techniques. In the switching techniques, the selection of the antenna branch are based on some reliable signal quality measurement like SIR. In the combining techniques, received signals from different antenna branches are linearly combined in a weight-and-sum process, normally ensuring that they are in phase with one another. Two common receiver antenna diversity techniques are considered. One is selection combining (SC) and the other is maximum ratio combining (MRC). In SC, the signal quality metric is monitored simultaneously on all antenna branches and the strongest one is selected for reception. This means that only one of the antenna branch signals is used for demodulation, while the rest of the antenna branch signals are discarded. MRC involves weighting all the antenna branch signals in proportion to the received power level prior to the addition operation. In this way, more weight is given to the antenna branch with the highest received power level, thus maximizing the output SIR of the diversity combiner.
5.3 Simulation Description

We study the performance of the iterative SIR-based power control algorithm with the use of space diversity for the accessing asymmetric data users based on an event-driven simulation. The following simulation model is used to evaluate the reverse link performance of the hybrid FDD/SDD-CDMA system architecture. The system studied is a $5 \times 5$ regular square cell layout wrapped around to eliminate the edge effects. A cellular BS is placed at the centre of each cell and three sectors per cell are considered. Users are uniformly distributed throughout each cell and each user connects to the BS with the strongest pilot tone. Handoff is assumed to occur instantaneously. During the duration of the call, the user keeps monitoring the pilot-to-interference ratio; and handoff decisions are made at regular pilot strength measurement interval. Perfect reverse link power control is assumed for the symmetric data users. Three-branch receiver antenna diversity is used to reduce the effect of Rayleigh fading. Two different diversity control configurations are considered here: SC and MRC of antenna branches; and we assume different antenna branches are uncorrelated.

Details of the simulation environment are as follows.

5.3.1 Traffic Models

Voice Service

The symmetric data users are assumed to be voice users which are modeled as Poisson arrivals (i.e., exponential interarrival time) with exponential holding time. If the mean time between call arrivals is $1/\lambda_v$ seconds and the mean call holding time is $1/\mu_v$ seconds then the traffic to the cellular network is $A = \lambda_v/\mu_v$. Let $K$ be the random variable representing the number of active voice calls in the cellular network at steady state. Then $K$ has the Poisson distribution

$$P(K = k) = e^{-A} \frac{A^k}{k!}$$  \hspace{1cm} (5.13)

Within each duration of a voice call, the voice activity can be modeled by an ON/OFF source model with the following traffic parameters: $T_i$ the mean talkspurt
period (ON-period) and \( T_s \) the mean silence period (OFF-period). In this paper, we adopt a mean holding time of 3 minutes and a mean idle time of 15 minutes for the voice users, with an activity factor of 0.375 [35].

**Internet Service**

The asymmetric data users are assumed to be Internet users who are actively accessing Internet applications. We employ a call-level traffic model to describe the traffic behavior of the Internet users similar to that of the voice users. That is, the arrivals of Internet users (e.g., Internet sessions) are modeled as Poisson arrivals (i.e., the idle time of an Internet user can be modeled by an exponential distribution). The holding time of an Internet session can be modeled by a Pareto distribution which is found to match very well with recent studies on Internet traffic [36]. One well-known Pareto distribution, which we refer to as \( \text{Pareto}(a, b) \), has the following probability density function (PDF):

\[
\begin{align*}
    f(t) &= \frac{a \left( \frac{1}{b} \right)^a}{(t + \frac{1}{b})^{a+1}} \\
    E[t] &= \frac{1}{(a - 1)b}
\end{align*}
\]

The Pareto distribution has two parameters, \( a \) and \( b \). \( a \) describes the "heaviness" of the tail of the distribution, and \( b \) is set based on the mean of the distribution. For illustration here, we choose a particular Internet application scenario, namely web browsing, in which the mean holding time is assumed to be 20 minutes with \( a = 1.35 \). The mean idle time is varied from 10 minutes to 60 minutes to control the traffic loading. The activity factor is taken to be 0.01.

**5.3.2 Mobility Model**

Each PT chooses a random starting location and direction of travel at the beginning of the call. It travels in a straight line until the call is completed. Starting location is uniformly distributed over the entire area of the cell; direction of travel is uniformly
distributed in \([0, 2\pi]\). Call holding time and PT speed are taken to be constant.

Table 5.1 summarizes the system parameters for the numerical results.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>NOMINAL VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path Loss Exponent</td>
<td>4</td>
</tr>
<tr>
<td>Shadowing Standard Deviation</td>
<td>8 dB</td>
</tr>
<tr>
<td>PT Speed</td>
<td>0.56 km/h</td>
</tr>
<tr>
<td>Number of BSs</td>
<td>25</td>
</tr>
<tr>
<td>Number of Sectors/BS</td>
<td>3</td>
</tr>
<tr>
<td>Normalized Cell Dimension</td>
<td>(2 \times 2)</td>
</tr>
<tr>
<td>Normalized Close-in Distance</td>
<td>0.1</td>
</tr>
<tr>
<td>((E_b/N_0)) Threshold</td>
<td>7 dB</td>
</tr>
<tr>
<td>Power Control Step Size (\delta)</td>
<td>1 dB</td>
</tr>
<tr>
<td>Spreading Bandwidth</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Frame Length</td>
<td>10 ms</td>
</tr>
<tr>
<td>User Profile</td>
<td>Voice</td>
</tr>
<tr>
<td>Data Rate</td>
<td>8 kbps</td>
</tr>
<tr>
<td>Call Arrival</td>
<td>Poisson</td>
</tr>
<tr>
<td>Mean Idle Time</td>
<td>15 minutes</td>
</tr>
<tr>
<td>Call Duration</td>
<td>Exponential</td>
</tr>
<tr>
<td>Mean Holding Time</td>
<td>3 minutes</td>
</tr>
<tr>
<td>Activity Factor</td>
<td>0.375</td>
</tr>
<tr>
<td></td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 5.1: System parameters used for studying the performance of the iterative SIR-based power control algorithm in conjunction with the use of space diversity.

5.4 Numerical Results

Figure 5.1 shows the outage probability of the hybrid FDD/SDD-CDMA system architecture with only voice users. It can be seen from this plot that the capacity is
168 voice users per sector at 5% outage and 144 voice users per sector at 1% outage. The outage is computed assuming an \((E_b/N_0)\) threshold of 7 dB.
Figure 5.1: Outage probability of the hybrid FDD/SDD-CDMA system architecture with only voice users.
We now consider the hybrid FDD/SDD-CDMA system architecture with also the Internet users and access the performance of the iterative SIR-based power control algorithm in conjunction with the use of space diversity schemes. We assume that there are 4 Internet users per sector each operating in packet mode at 64 kbps with a mean idle time of 60 minutes, unless otherwise stated.

Figure 5.2 shows the average number of access attempts for an Internet user versus voice user loading per sector with different receiver antenna diversity configurations and power control algorithms. All the receiver antenna diversity configurations and power control performance were simulated with two antenna branches. For the case with non-iterative power control, the transmitted power is set exactly 10 dB higher than the interference measured from the pilot tone. The iterative power control process is performed independently by each PT assuming perfect SIR measurements, and we assume that the initial power is set at the level obtained by non-iterative power control. We see that the performance of non-iterative power control is not robust against cochannel interference that is admitted later. For example, when the voice user loading per sector is 80%, SC with iterative power control requires on average 12 access attempts for each Internet user compared to 18 access attempts with non-iterative power control. The best performance, obviously, is achieved by using iterative power control with MRC diversity, which requires on average 4 access attempts: and no significant degradation results until the voice user loading level is so high. Non-iterative power control produces limited improvement, because it does not update the transmitted power in response to the bursty Internet users, which may cause excessive interference to the currently active voice users. For the numerical results reported here, it is clear that significant performance enhancement can be achieved by employing iterative power control and MRC diversity.
Figure 5.2: Average number of access attempts for an Internet user versus voice user loading per sector with different receiver antenna diversity configurations and power control algorithms.
Figure 5.3 shows the average number of access attempts for an Internet user versus voice user loading per sector under different Internet user loads with iterative power control and MRC diversity. The voice and Internet traffic parameters are the ones specified in Table 5.1. The Internet user mean idle time is varied from 10 minutes to 60 minutes. In general, the average number of access attempts increases when the Internet user mean idle time decreases; in other words, when the Internet user load increases. Moreover, the amount of increment depends on the relative loading between the voice users and the Internet users. For example, when the voice user loading per sector is 40%, the average number of access attempts increases from 2 to 3.5. However, when the voice user loading per sector is 80%, the average number of access attempts increases from 4.1 to 12.4, i.e., an increase of about three times.

Figure 5.4 shows the overall system capacity for different number of voice and Internet users per sector with iterative power control and MRC diversity. The voice and Internet traffic parameters are the same as those specified in Table 5.1. The mean idle time of Internet users is taken to be 10 minutes here. Up to 144 and 168 voice users can be supported at 1% and 5% outage, respectively, without Internet users as reported in Figure 5.1. For each Internet user added into the system, there is about a reduction of 6.5 and 4 voice users per sector at 1% and 5% outage, respectively. Fewer voice users are replaced by an additional Internet user at a higher outage criterion. In other words, more voice users can be supported for each additional Internet user as a higher level of outage can be tolerated.
Figure 5.3: Average number of access attempts for an Internet user versus voice user loading per sector under different Internet user loads with iterative power control and MRC diversity.
Figure 5.4: Outage probability of the hybrid FDD/SDD-CDMA system for different numbers of voice and Internet users per sector with iterative power control and MRC diversity.
So far, we assumed the power control step size of $\delta = 1dB$. Figure 5.5 shows the average number of access attempts for an Internet user versus power control step size $\delta$ under different voice user loading per sector with iterative power control and MRC diversity. It can be found that the value of $\delta$ should be around 1 dB, otherwise, the number of access attempts increases because of large fluctuations in the interference powers.

Figure 5.6 shows the average number of access attempts for an Internet user versus voice user loading per sector for the case of employing iterative power control and MRC diversity: with and without mobility. The PT speed is chosen to be between 0 and 56 km/h. With user mobility, not only the absolute performance becomes worse, but also the performance sensitivity to voice user loading. The performance sensitivity increases as the voice user loading increases, as compared to that without user mobility. At high voice user loading, the signal variations caused by user mobility give rise to more performance variation, resulting in severe performance degradation. Therefore, the average number of access attempts for each Internet user is higher when user mobility is present.
Figure 5.5: Average number of access attempts for an Internet user versus power control step size $\delta$ under different voice user loading per sector with iterative power control and MRC diversity.
Figure 5.6: Average number of access attempts for an Internet user versus voice user loading per sector with iterative power control and MRC diversity: with and without mobility.
5.5 Chapter Summary

We have considered the hybrid FDD/SDD-CDMA system architecture for supporting symmetric and asymmetric data users, with the former served by a cellular network and the latter served by broadcast systems using single frequency broadcasting. The asymmetric data users employ packet-mode access to transmit demand messages in relatively short bursts and are silent at other times, whereas the symmetric data users employ circuit-mode access. To protect currently active symmetric data users from interference by accessing asymmetric data users, we have studied the implementation of a special version of iterative SIR-based power control algorithms and accessed its performance in conjunction with the use of space diversity schemes.

The reverse link performance of the hybrid FDD/SDD-CDMA system architecture with the use of power control and space diversity has been evaluated by computer simulations. In particular, we have modeled the symmetric data users as voice users and the asymmetric data users as Internet users. When the voice user loading per sector is 80%, SC with iterative power control requires on average 12 access attempts for each Internet user compared to 18 access attempts with non-iterative power control. The best performance is achieved by using iterative power control with MRC diversity, which requires on average 4 access attempts; and no significant degradation results until the voice user loading level is so high. Non-iterative power control produces limited improvement, because it does not update the transmitted power in response to the bursty Internet users, which may cause excessive interference to the currently active voice users. Therefore, it is clear that significant performance enhancement can be achieved by employing iterative power control and MRC diversity.

Our simulation results also show that up to 144 and 168 voice users can be supported at 1% and 5% outage, respectively, without Internet users. For each Internet user added into the system, there is about a reduction of 6.5, 4 voice users per sector at 1% and 5% outage, respectively. Fewer voice users are replaced by an additional Internet user at a higher outage criterion. When the Internet user load increases, the average number of access attempts for an Internet user increases too. The amount of
increment depends on the relative loading between the voice users and the Internet users.

We also have found that the power control step size should be around 1 dB, otherwise, the number of access attempts increases because of large fluctuations in the interference powers.

With user mobility, not only the absolute performance becomes worse, but also the performance sensitivity to voice user loading. The performance sensitivity increases as the voice user loading increases, as compared to that without user mobility. At high voice user loading, the signal variations caused by user mobility give rise to more performance variation, resulting in severe performance degradation. Therefore, the average number of access attempts for each Internet user is higher when user mobility is present.
Chapter 6

Conclusions

6.1 Summary

Future generation wireless networks are expected to handle an integrated mix of multi-media services like voice, data, image, video, etc. In particular, data/image-oriented Internet applications have gained widespread user acceptance and are becoming a dominant service. One of the distinguishing features of these applications is that they require asymmetric data transfer as well as high bit-rate transmission. To this end, the main objective of this thesis is to study an innovative system architecture for providing symmetric and asymmetric data services in a spectrum-efficient manner.

By the advent of digital broadcast systems such as DAB and DVB, a new range of date services can be introduced besides conventional broadcasting. The services may vary from uni-directional audio visual services to bi-directional asymmetric Internet access. Combining the broadcast systems with a conventional cellular network is therefore a promising alternative for providing symmetric and asymmetric data services.

We have presented the interference analysis for an ad-hoc broadcast system located at an arbitrary position in a power-controlled CDMA cellular network which operates in the HFB for forward link and the LFB for reverse link. Common to all forms of power control is the equalization of received power or received SIR disregard to the induced power distribution through the rest of the communication cell. As a
result, a broadcast system receiver which operates in either the HFB or the LFB and is located somewhere inside the cell, may not benefit from the power control, and is therefore susceptible to the "near-far" effects. Our emphasis is on dealing with the interference received at the broadcast system receiver in both HFB and LFB. We have demonstrated that the power control employed in the CDMA cellular network actually increases "near-far" susceptibility at the broadcast system receiver by increasing the potential range of received interference powers from the PTs in the LFB and the BSs in the HFB respectively, and by increasing the variance of received interference powers resulting from lognormal shadowing in the CDMA cellular network wherein power control is employed to compensate shadowing.

The CDFs of the interference power received at the broadcast system receiver for a uniformly distributed PT in a circular cell have been developed. Both intracell and intercell interference scenarios are considered, with distance dependent and log-normal shadowing models adopted for propagation path loss. The distributions are analytic for distance dependent propagation model but require numerical integration when lognormal shadowing model is introduced, and contribute toward the evaluation of outage probabilities of the broadcast system receiver under various propagation conditions and location considerations.

Based on the interference analysis, we have studied the performance optimization of CDMA broadcast systems in FDD-CDMA cellular bands. The broadcast systems coexist with the cellular network in the same geographic area and same frequency band. Two types of interference exist in both the cellular network and the broadcast systems. In addition to the usual self-system interference of individual cellular network and broadcast systems, there are also the cellular-to-broadcast and broadcast-to-cellular (or cross-system) interference. FDD-CDMA mean \((E_b/N_0)\) performance depends on the location of the broadcast system and its operating frequency, and is different in the forward and reverse links. For small values of \(\alpha\), the FDD-CDMA reverse link \((E_b/N_0)\) with an LFB broadcast system is lower than the FDD-CDMA forward link \((E_b/N_0)\) with an HFB broadcast system. However, after a certain value of \(\alpha\), the FDD-CDMA forward link \((E_b/N_0)\) then becomes lower than
the FDD-CDMA reverse link \( (E_b/N_o) \). The impact of this uneven influence on the cellular network can be attributed to the fact that the forward link performance is very sensitive to where the HFB broadcast system is located relative to the FDD-CDMA PTs in the cell of concern. If the HFB broadcast system is located close to the FDD-CDMA PTs, this will severely degrade the forward link performance. Conversely, the reverse link performance depends only on the distance of the LFB broadcast system from the intracell FDD-CDMA BS, and its transmitted power can be properly controlled so that its influence on the cellular network is still tolerable.

For small values of \( \alpha \), the \( (E_b/N_o) \) performance of an HFB broadcast system is worse than that of an LFB broadcast system. But after a certain value of \( \alpha \), the \( (E_b/N_o) \) performance of an LFB broadcast system then becomes worse than that of an HFB broadcast system. With the assumption that the broadcast systems are uniformly distributed in each regular cell, HFB broadcast systems perform better than LFB broadcast systems in the FDD-CDMA cellular network, but they significantly degrade the FDD-CDMA forward link performance; on the other hand, LFB broadcast systems have less impact on the FDD-CDMA reverse link performance, but they perform worse in the FDD-CDMA cellular network.

A family of frequency allocation strategies exhibiting different levels of efficiency and complexity has been studied to ensure acceptable performance in the overall network: (1) Fixed Channel Allocation (FCA), (2) Random Channel Allocation (RCA), and (3) Distance Based Channel Allocation (DBCA). Both FCA (HFB) and FCA (LFB) are not recommended because of the “near-far” problem between the cellular network and the broadcast systems. In the former one, the FDD-CDMA forward link is seriously interfered by the HFB broadcast systems; and in the latter one, the LFB broadcast systems are seriously interfered by the high-transmitted-power FDD-CDMA PTs. The RCA is simple and easy to implement, but it is not designed for the worst case of FDD-CDMA BS and PT distributions and broadcast system locations.

To maximize the outage performance of the FDD-CDMA cellular network, and in the meantime to keep the outage performance of the CDMA broadcast systems at
an acceptable level, the DBCA (H/L) should be adopted by the broadcast systems given that $D$ is properly adjusted. A good choice of $D$ is to set $D = 0.76$ under the assumption that the PTs are uniformly distributed throughout the service area.

Motivated by combining the broadcast systems with a cellular network for providing wireless multimedia services, we have proposed a hybrid FDD/SDD-CDMA system architecture for supporting symmetric and asymmetric data users, with the former served by the cellular network and the latter served by broadcast systems using single frequency broadcasting. The cellular network utilizes FDD to provide wide area voice and low-bit-rate symmetric data services, while the broadcast systems utilize SDD to provide high-bit-rate asymmetric data services. In the SDD approach, the reverse link of an asymmetric data user is connected to the cellular network via a cellular BS and utilizes its reverse link radio resource, whereas the forward link of this user is routed from the broadcast network via a broadcast system RP.

We have presented network concepts of the hybrid FDD/SDD-CDMA system architecture (System I). Using per-cell capacity as the performance measure, we have evaluated its capacity performance and compared it with two other classical system architectures (System II and III). We have shown that in all the system architectures considered, the capacity is bound by the forward link performance in the HFB, and there is residual reverse link capacity left unused in the LFB. System III, with only the cellular network to support symmetric and asymmetric data users, gives the worst forward link capacity performance. This is because the asymmetric data users would require much higher transmitted power from the cellular BSs. In System I and System II, each asymmetric data user's forward link is served by a broadcast system RP and thus lower transmitted power from the broadcast system RP is required. Therefore, the forward link capacity performances in System I and System II are the same. Nevertheless, we see that System I has more reverse link capacity than System II. In System I, the reverse link of an asymmetric data user is power-controlled by a cellular BS, and thus minimizing the cross-system interference injected into the cellular network. In System II, however, the reverse link of the asymmetric data user is power-controlled by a broadcast system RP and this would inject larger amount
of cross-system interference into the cellular network under favorable propagation conditions.

With the use of omnidirectional antennas, System I and System II support the same number of symmetric data users and asymmetric data users simultaneously, due to the fact that both system architectures' capacities are bound by the forward link performance in the HFB. By implementing adaptive array antenna systems at the broadcast system RPs, we see that there is a significant improvement in the capacity performance of System I and that more asymmetric data users can be supported at a given number of symmetric data users as the antenna beamwidth decreases. Therefore, the hybrid FDD/SDD-CDMA system architecture could be an attractive technique in future generation wireless networks for providing symmetric and asymmetric data services in a spectrum-efficient manner.

We further consider the case in which the asymmetric data users employ packet-mode access to transmit demand messages in relatively short bursts and are silent at other times, whereas the symmetric data users employ circuit-mode access. This imposes a significant challenge for performance optimization since accessing asymmetric data users can degrade the performance of currently active symmetric data users by introducing extra interference variations which reduce system capacity. In CDMA, one way to achieve maximum capacity is by using iterative power control to optimize the SIR. We have studied the implementation and performance of a special version of iterative SIR-based power control algorithms in which currently active symmetric data users are protected from interference by accessing asymmetric data users. Moreover, as the accessing asymmetric data users are expected to have short duty cycles on the cellular network's reverse link, significant overhead may be required for iterative power control. Therefore, we have investigated the use of space diversity schemes to help reduce the high iteration overhead and access their performance jointly with the proposed iterative SIR-based power control algorithm.

The reverse link performance of the hybrid FDD/SDD-CDMA system architecture with the use of power control and space diversity has been evaluated by computer simulations. In particular, we have modeled the symmetric data users as voice users
and the asymmetric data users as Internet users. When the voice user loading per sector is 80%, SC with iterative power control requires on average 12 access attempts for each Internet user compared to 18 access attempts with non-iterative power control. The best performance is achieved by using iterative power control with MRC diversity, which requires on average 4 access attempts; and no significant degradation results until the voice user loading level is so high. Non-iterative power control produces limited improvement, because it does not update the transmitted power in response to the bursty Internet users, which may cause excessive interference to the currently active voice users. Therefore, it is clear that significant performance enhancement can be achieved by employing iterative power control and maximum ratio combining diversity.

The simulation results have also shown that up to 144 and 168 voice users can be supported at 1% and 5% outage, respectively, without Internet users. For each Internet user added into the system, there is about a reduction of 6.5, 4 voice users per sector at 1% and 5% outage, respectively. Fewer voice users are replaced by an additional Internet user at a higher outage criterion. When the Internet user load increases, the average number of access attempts for an Internet user increases too. The amount of increment depends on the relative loading between the voice users and the Internet users.

With user mobility, not only the absolute performance becomes worse, but also the performance sensitivity to voice user loading. The performance sensitivity increases as the voice user loading increases, as compared to that without user mobility. At high voice user loading, the signal variations caused by user mobility give rise to more performance variation, resulting in severe performance degradation. Therefore, the average number of access attempts for each Internet user is higher when user mobility is present.
6.2 Contributions

Traditional cellular telecommunications, where the main application is voice telephony, is based on a symmetrical two-way channel. This is because voice traffic is symmetric, i.e., equal amount of traffic is assumed in the forward link and the reverse link. In future multimedia communication environment, this assumption is erroneous. For example, in Internet access, PTs are expected to send low bit-rate acknowledgements/requests via the reverse link and receive high bit-rate texts/videos/images via the forward link. Hence, traffic asymmetry is foreseen between the forward link and the reverse link in multimedia services.

The contributions of this thesis are as follows. First, we have proposed a CDMA-based hybrid wireless architecture for symmetric and asymmetric communications. The architecture is to combine CDMA broadcast systems with a conventional CDMA cellular network for the provision of symmetric and asymmetric data services. Second, we have proposed the SDD concept for asymmetric communications in the hybrid wireless architecture. SDD attempts to support traffic asymmetry by routing the low-bit-rate reverse link from a PT to a cellular BS for sending acknowledgements or requests, and the high-bit-rate forward link from a broadcast system RP to the PT for receiving web page download such as text, audio, video, or graphics. Finally, to protect currently active symmetric data users from interference by accessing asymmetric data users, we have studied the implementation of a special version of iterative SIR-based power control algorithms and accessed its performance in conjunction with the use of space diversity schemes.

A final note is that the SDD concept has been considered in cable modem industry. For example, we refer to the cable modem system described in [37]. Starting with the ISP, connecting to the ISP LAN is some form of downstream router. The digital output is converted by a 64QAM modulator which provides a 44 MHz IF signal to the transmitter. This signal occupies a 6 MHz bandwidth. The residential user receives the signal via a distribution network (e.g., Local Multipoint Distribution System [LMDS], Multichannel Multipoint Distribution System [MMDS]), and the
cable modem at the residential premise is connected by means of Ethernet to the computer or multiple computers on an Ethernet LAN. The cable modem return path is over the dial up telephone network to a modem bank and an upstream router. This return path carries both upstream acknowledgements and requests of the downstream packets.

6.3 Future Work

Some areas in this work have the potential for further research. They are given below:

- The work so far assumed that the broadcast system is broadcasting information over a single frequency channel. One can also conceive an environment in which the broadcast system has a large bandwidth which is divided into multiple frequency channels. It is apparent that proper use of these channels can result in better performance.

- In the broadcast systems, mechanisms to efficiently transmit information to the PTs are of significant importance. Algorithms for scheduling broadcasts, with the goal of minimizing the access attempts, should be investigated.

- As noted earlier, the SDD concept has been considered in cable modem industry. It is therefore interesting to investigate its applicability to wireless industry from an implementation point of view. How to engineer the hybrid FDD/SDD-CDMA system architecture and design a wireless modem that builds upon the system architecture are important issues.
References


