Cognitive Interference Management in 4G Autonomous Femtocells

By

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Doctor of Philosophy

Department of Electrical and Computer Engineering

University of Toronto

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Abstract

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We present a vision for 4G cellular networks based on the concept of autonomous infrastructure deployment. Cellular base stations, or femtocell access points, are deployed by network users without being constrained by the conventional cell planning process from the network operator. Autonomous deployment allows the network to grow in an organic manner which requires new methods for spectrum management. We study a framework for autonomous network optimization based on the method of cognitive interference management. In our model, a number of femtocells are co-channel deployed in an underlay macrocellular network. Instead of fully reusing
100% of the macrocellular resource, partial reuse is cognitively determined in femtocells based on their individual network environment. According to an interference signature perceived from the environment, a femtocell autonomously determines the appropriate channel allocation and minimizes the network interference. Upon the cognitive acquisition of the random infrastructure topology, base station pilot power is autonomously configured in order to maximize the cellular coverage. A series of network self-configuration procedures are discussed for automatic cell size adaptation and resource management. Our results show that the new approaches based on cognitive radio configuration facilitate the network optimization in terms of interference management, mobile handoff, pilot power control and network resource allocation. The proposed framework offers a 4G vision for spectrum management in an autonomous self-managed cellular architecture.
To My Fiancee: Yiming Wang
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# Contents

Abstract ii

List of Figures xi

List of Tables xii

List of Abbreviations xiii

1 Introduction 1

1.1 Overview . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 1
1.2 Autonomous Cellular Architecture . . . . . . . . . . . . . . . . . . . . 7
1.3 Comparison of Two Cellular Concepts . . . . . . . . . . . . . . . . . . . 9
1.4 Literature Review . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 13
1.5 Thesis Contribution and Organization . . . . . . . . . . . . . . . . . . . 17

2 Cognitive Interference Management in Autonomous Femtocell Networks 21
2.1 Femtocell-to-Macrocell Interference Scenario .................................... 23
   2.1.1 Cognitive Channel Reuse with Orthogonal Channelization ........ 23
   2.1.2 Analysis of Cognitive Channel Reuse Efficiency ..................... 31
   2.1.3 Cognitive Channel Reuse with Non-orthogonal Channelization 32
   2.1.4 Performance Results ............................................. 38
   2.1.5 Summary .................................................. 45

2.2 Femtocell-to-Femtocell and Macrocell-to-Femtocell Interference Scenarios ......................................................... 46
   2.2.1 Cognitive Channel Categorization ..................................... 47
   2.2.2 An Opportunistic Channel Reuse Scheduler .......................... 51
   2.2.3 Performance Results ............................................. 56
   2.2.4 Summary .................................................. 58

2.3 A Unified View on Cellular Network Optimization .................. 59

3 Pilot Power Management in Autonomous Femtocells .................. 63
   3.1 Optimization Model for Femtocell Pilot Management ................. 64
   3.2 An Autonomous Pilot Management Procedure .......................... 71
   3.3 Performance Results ............................................. 73
   3.4 Summary .................................................. 77

4 A MAC Protocol Design for Autonomous Cellular Resource Allo-
List of Figures

1.1 A Cellular Network .................................................. 2
1.2 Two Evolutional Paths to 4G ........................................ 6
1.3 Autonomous Cellular Network Topology .......................... 7
1.4 A Generalized Cellular Concept in 4G ............................. 11
1.5 A Software Dependent Cellular Architecture in 4G .............. 12
1.6 A Triple-Play Cellular Industry in 4G ............................ 14
1.7 Research Objectives for Autonomous Spectrum Management .... 18

2.1 Autonomous Femtocell Deployment in A Macrocell ............ 22
2.2 OFDMA Example with Cognitive Channel Reuse ................ 26
2.3 Procedure for Cognitive Spectrum Management .................. 28
2.4 Cellular Topology Used in Simulation ............................. 40
2.5 Public User Channel Outage of \{\text{SINR} \leq 5\text{dB}\} ................. 41
2.6 Public User Channel Outage of \{\text{SINR} \leq 8\text{dB}\} ................. 42
2.7 Percentage of Femtocells with Orthogonal Channel Reuse . . . . . . . 44
2.8 Femtocell Downlink Interference in A 3G Macrocell . . . . . . . . . 47
2.9 Interference Recognition in A 3G Femtocell . . . . . . . . . . . . . . 49
2.10 Channel Categorization and Reuse Priority . . . . . . . . . . . . . . 50
2.11 Cognitive Channel Allocation Procedure . . . . . . . . . . . . . . . 54
2.12 Femtocell Channel SINR Performance . . . . . . . . . . . . . . . . . 57

3.1 Femtocell Downlink Interference Scenario . . . . . . . . . . . . . . . 65
3.2 Autonomous BS Pilot Power Update Procedure . . . . . . . . . . . . 71
3.3 Optimized Cell Sizes for Five-Femtocell Deployment . . . . . . . . . 74
3.4 Optimized Cell Sizes for Ten-Femtocell Deployment . . . . . . . . . 75
3.5 Variance of Femtocell Coverage in Diameter . . . . . . . . . . . . . . 77

4.1 Three Basic Time Notions . . . . . . . . . . . . . . . . . . . . . . . . 82
4.2 Power Vector Allocation . . . . . . . . . . . . . . . . . . . . . . . . 83
4.3 Synchronized Power Allocation Vector . . . . . . . . . . . . . . . . . 84
4.4 Autonomous Cellular Resource Allocation Procedure . . . . . . . . 92
4.5 Average Downlink Frame Error Rate . . . . . . . . . . . . . . . . . . 94
4.6 Average Downlink Transmission Delay . . . . . . . . . . . . . . . . . 95
List of Tables

1.1 Comparison of Two Cellular Concepts ......................... 10

4.1 Simulation Parameters ........................................ 91
List of Abbreviations

4G the fourth generation of wireless cellular networks
EV-DO Evolution-Data Optimized
HSPA High Speed Packet Access
CDMA Code Division Multiple Access
Wi-Fi Wireless Fidelity
ACM Autonomous Control Module
LTE Long Term Evolution
WiMAX Worldwide Interoperability for Microwave Access
OFDM Orthogonal Frequency-Division Multiplexing
MIMO Multiple-Input and Multiple-Output
IP Internet Protocol
RNC Radio Network Controller
WCDMA Wideband Code Division Multiple Access
UMTS Universal Mobile Telecommunications System
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>IKEv2</td>
<td>Internet Key Exchange v2</td>
</tr>
<tr>
<td>IPsec</td>
<td>IP Security</td>
</tr>
<tr>
<td>AMPS</td>
<td>Advanced Mobile Phone System</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile communications</td>
</tr>
<tr>
<td>CSMA/CA</td>
<td>Carrier Sense Multiple Access with Collision Avoidance</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency-Division Multiple Access</td>
</tr>
<tr>
<td>BSC</td>
<td>Base Station Controller</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference plus Noise Ratio</td>
</tr>
<tr>
<td>LP</td>
<td>Linear Programming</td>
</tr>
<tr>
<td>TD-SCDMA</td>
<td>Time Division Synchronous Code Division Multiple Access</td>
</tr>
<tr>
<td>MAC</td>
<td>Media Access Control</td>
</tr>
<tr>
<td>SP</td>
<td>Service Period</td>
</tr>
<tr>
<td>PB</td>
<td>Power Bin</td>
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<tr>
<td>SS</td>
<td>Service Slot</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
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<tr>
<td>FER</td>
<td>Frame Error Rate</td>
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Chapter 1

Introduction

1.1 Overview

The concept of cellular communication emerged in 1960’s as an extension of the fixed telecommunication network to the wireless environment. A cellular network consists of a number of infrastructure base stations deployed throughout a service area. Each base station serves the mobile users around it as a shared access point to the backbone network. The service area of a base station is called a cell which is normally represented by a hexagonal grid. As shown in Figure 1.1, the cells are generally laid out in a non-overlapping pattern in order to cover a large service area such as a city or a country.

The cellular concept exploits the fact that the signal power decreases as it prop-
agates in space so that the same frequency carrier can be used in different cells. This solves the problem of accommodating a large number of users utilizing a limited block of spectrum. However, frequency reuse in different cells causes mutual interference in them. To manage this interference, a frequency reuse distance has to be configured based on the tolerable interference of mobile terminals. A cellular network has to be deployed according to a rigorous cell planning process performed by the network operator. Cellular parameters such as frequency reuse distance, cluster size and channel allocation in a cell need to be jointly configured in order to produce an optimized network planning strategy [1].

The evolution of the cellular systems has come through three generations over
the past 40 years [2]. We have seen the transition from the first generation (1G)  
to the second generation (2G) in 1980’s marked by analog communication being  
replaced by digital processing technology. Spread-spectrum based communication  
emerged in 1990’s and quickly became the dominant standard for the third genera-

tion (3G) technology which significantly improved the voice capacity over 2G. The  
recent 3.5G variations such as the Evolution-Data Optimized (EV-DO) and High  
Speed Packet Access (HSPA) standards renovated the 3G air interfaces in order to  
enhance their data carrying capability. Despite all these fast evolutions of the cellu-
lar technology, the method to deploy and manage a cellular network has remained  
somehow constant [2]. Base stations are regularly deployed by a network operator  
who uses its professional engineers to manually configure the network operation pa-
rameters. In a 3G Code Division Multiple Access (CDMA) based network, these  
parameters invariably include base station pilot power, base station antenna tilting  
angle, orientation of the antenna sectors in a cell, pilot neighbour list, pilot sequence  
offset in different cells and other operation parameters transmitted in the synchro-

nization channel. The configuration process of these cellular parameters is critical  
in optimizing the performance of a cellular network.

We now have an extensive research effort throughout the world targeting the  
next generation (the 4th generation or 4G) cellular systems. Except for the obvious  
goals for higher bit rate and greater cell capacity improvement, a 4G network is ex-
pected to have some different characteristics from the legacy cellular standards [2]. One 4G progression has come up with the idea of having a brand new cellular architecture that facilitates easier deployment of small base stations for organic cellular capacity improvement [3]. At the root of this approach is the idea of using small cells to increase the spectrum reuse density. The concept can be traced back to the cell splitting strategy proposed in [1] where a macrocell can be equally divided into multiple $N$ subcells and each of them has the same spectrum as that of the macrocell. Thus a factor of $N$ times capacity can be achieved in the network. The concept of microcell or picocell follows the similar idea of utilizing smaller cells for capacity improvement in high-demand traffic locations such as homes and offices. Nevertheless, a denser deployment of small cells will complicate the procedure for network configuration. More cost-effective approaches are required in order to facilitate easy deployment of a large number of low-power base stations in future cellular networks.

A good example of small cell deployment can be seen from the Wi-Fi technology. Low power access points can be autonomously deployed by network users and each access point defines a hotspot area with small coverage and high capacity. Mainly targeting ad hoc interconnection of a group of wireless users, the Wi-Fi standard was defined in the unlicensed spectrum band without rigorous network optimization like the cellular standards. However, some of Wi-Fi’s characteristics including
autonomous network deployment has made it quite successful in the marketplace. A future cellular network demands a new architecture that can facilitate the autonomous deployment of the infrastructure similar to Wi-Fi. Accordingly, novel methods will be required to enhance the robustness of the cellular air interface in terms of interference management and network optimization.

A novel method of deploying a cellular network has been introduced in [2], [3] and [4]. Small cellular base stations, or femtocells, are autonomously deployed by users in an underlay macrocellular network. An autonomous cellular concept allows the network to grow in an organic manner, which reduces the traditional work on infrastructure installation, network configuration and maintenance. However, not following a cell planing procedure, the deployment of the femtocells will cause non-regularized interference to the macrocell network. Therefore, the work for network optimization and interference management will have to be executed by an Autonomous Control Module (ACM) which adaptively allows network radio reconfiguration, power control and resource allocation.

To this end, we propose a dual-path progression of the future wireless technologies as shown in Figure 1.2. The upper path going through Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX) technologies represents a more or less straightforward evolution based on the current 3G standards. LTE and WiMAX can raise the cell capacity through a series of efforts
Figure 1.2: Two Evolutional Paths to 4G

such as air interface enhancement (e.g., Orthogonal Frequency-Division Multiplexing (OFDM) + Multiple-Input and Multiple-Output (MIMO) implementation), wider bandwidth allocation (e.g., up to 100MHz in LTE-advanced system), and IP-based architectural modification [5], [6], [7]. The traditional view for cellular spectrum management remains somehow unchanged and the objective is still to improve the cell capacity in terms of bits/s/Hz/cell.

The lower path shows a different progression by introducing an autonomous cellular architecture. The conventional cellular approaches have to be renovated in order to realize the objective for autonomous spectrum management. For example, when a large number of femtocells are randomly deployed by users, interference control has to be performed in an automatic manner based on the recognition of interference environment in the network. Smart power control and adaptive resource
allocation methods are required in order to optimize the network configuration. Therefore, the improvement of network intelligence becomes the new objective in an autonomously managed cellular network. We claim that the two evolutionary paths will converge and define a unified 4G air interface that achieves both high macrocell capacity in large service areas and smart hotspot management in small cellular scales.

1.2 Autonomous Cellular Architecture

![Autonomous Cellular Network Topology](image)

Figure 1.3: Autonomous Cellular Network Topology

An autonomous cellular network is shown in Figure 1.3 which comprises the
following network infrastructure elements.

- Large base station: the regular base station deployed by a network operator with its full engineering capability. Cellular parameters such as frequency reuse distance, antenna tilting angle and base station pilot power have to be manually configured to optimize the spectrum management. A group of base stations are connected to a Radio Network Controller (RNC) which manages network resource allocation, pilot transmit power and mobile handoff between adjacent cells.

- Small base station/femtocell access point: the small cellular access point autonomously deployed by network users. They can operate either on the same spectrum band as the large base stations or on a separate frequency carrier. A femtocell access point can be easily attached to the Internet backbone through multiple interfaces such as DSL, TV cable, power line and Ethernet [4]. The service area of a femtocell is illustrated by small ellipse circles in Figure 1.3. The size of the coverage area depends on the maximum transmit power of a femtocell access point which normally ranges from 5mW to 100mW according to [8].

- Autonomous control module (ACM): the intelligent control module for autonomous spectrum management and dynamic resource allocation. As shown in Figure 1.3, an ACM server has control interfaces to both macrocell base stations and femtocell access points. Through an embedded software algorithm designed by either manufacturers or third-party network optimizer, ACM automatically config-
ures the cellular parameters as if the network can self-manage itself in an autonomous fashion. The control process may require ACM to recognize the change of the network topology and variation of the traffic distribution in the service area. Current wireless standards may require certain modification in order to meet a specific network optimization requirement.

In future cellular networks, a user-deployed femtocell access point can be very simple hardware equipment. The computational complexity resides in ACM which performs like the brain of the whole network. ACM first collects the network information such as the interference power from the individual infrastructure equipment, and then globally optimizes the configuration of channel assignment, pilot transmit power and antenna pattern for all base stations and access points. Under the central management of ACM, the entire infrastructure body organically configures itself and intelligently makes resource allocation to mobile users.

1.3 Comparison of Two Cellular Concepts

The autonomous cellular network differs from the traditional cellular concept in various aspects such as the way to deploy a network, the method to manage the interference and the criteria to measure the network performance. The traditional cellular concept was originally proposed by Bell Labs and designed to serve the voice users with certain mobility requirement. Therefore, the cellular spectrum was
regularly reused in space for continuous service provisioning over a large geographical area. The conventional objective of *cellular coverage extension* has led to some common characteristics over the 1 ∼ 3G cellular standards such as circuit-switched channelization in a cell, regular cell planning and rigorous network configuration for interference management.

<table>
<thead>
<tr>
<th></th>
<th>Traditional Cellular Network (1-3G)</th>
<th>Autonomous Cellular Network (4G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose of Spectrum Reuse</td>
<td>cellular coverage extension</td>
<td>cellular coverage enhancement</td>
</tr>
<tr>
<td>Infrastructure Deployment</td>
<td>uniform (by operators)</td>
<td>random (by users)</td>
</tr>
<tr>
<td>Cell Planning</td>
<td>regular</td>
<td>adaptive</td>
</tr>
<tr>
<td>Power Management</td>
<td>constant</td>
<td>autonomous</td>
</tr>
<tr>
<td>Resource Allocation</td>
<td>fixed</td>
<td>cognitive</td>
</tr>
</tbody>
</table>

Table 1.1: Comparison of Two Cellular Concepts

In an autonomous cellular network, cellular spectrum is spatially reused in an organic manner driven by network users. *Cellular coverage enhancement* becomes the new objective through autonomous femtocell deployment in the underlay macro-cell network. In comparison to the traditional cellular concept, more autonomous and self-management elements are introduced for spectrum management which led to different network characteristics as shown in Table 1.1. We view an autonomous cellular network a more general concept compared to the traditional cellular model.
proposed by Bell Labs. As shown in Figure 1.4, characterized by organic network growth, ad hoc cellular topology, cognitive resource reuse and autonomous interference management, an autonomous cellular concept defines the most modern view on cellular spectrum reuse and interference management. The Bell Labs’ model fits in the picture as a subset notion when fixed network parameters are manually configured by the network operator. In other words, an autonomous cellular network automatically reduces to the traditional cellular concept if the requirement for random base station deployment becomes less considered in the network. More autonomous elements will be introduced in future cellular networks with new requirement on network self-management and auto-configuration.

Figure 1.4: A Generalized Cellular Concept in 4G

To this end, the future cellular industry will hopefully take the similar trend as what we have seen from the computer industry, i.e. the software development gets
more separated from the hardware and plays more important roles in determining the system performance. In Figure 1.5, a software control layer is shown on top of the hardware infrastructure in a 4G cellular network. Through an open control interface between the two layers, computer software intelligently optimizes the network resource allocation and interference management. 4G cellular standards such as LTE and WiMAX will have an IP-based architecture with less hierarchy in the backbone network. This facilitates the implementation of cost-effective approaches for interference management based on software design and modification. Cellular hardware and software will jointly define an intelligent radio interface for autonomous mobile access in 4G.

Figure 1.5: A Software Dependent Cellular Architecture in 4G

Similar to the concept of modern computer technology, the efficiency and ro-
bustness of the software will eventually determine the performance of the cellular hardware infrastructure. In the future, the control software can be written and updated by professional companies according to some specific requirement from the network operator. As shown in Figure 1.6, a network optimizer will possibly spin off from the traditional cellular manufacturers and operators as a new business type in 4G. Rather than the manufacturers vending hardware equipments, a network optimizer provides advanced software solutions to the network operator. This will accordingly change the traditional role of a network operator in deploying, managing and maintaining a cellular network. Network optimization will be treated as an independent mission in 4G based on an open cellular architecture. The implementation of the new approaches such as software defined radio, cognitive radio and open source infrastructure [9] will facilitate the emergence of this new business in 4G era.

1.4 Literature Review

A user-deployed cellular network demands novel methods for spectrum management and network optimization. Existing research has focused on various issues such as base station pilot power control, network resource allocation and mobile user hand-off. All these approaches invariably require some autonomous radio configurability for network self-management. We take a complete summary of the existing results categorized by four areas in the following discussion.
• Autonomous Pilot Channel Management - Random deployment of a cellular network raised the issue of base station pilot power management. In traditional cellular networks the pilot channel is manually configured by the network operator. Constant pilot power configuration leads to a uniform mobile association pattern in each cell. In an autonomous cellular network, the cellular base stations are randomly deployed by customers which requires automatic pilot power management and adaptive cell size configuration. The work in [3], [10] and [11] discussed a sleep-pilot scheme to manage the pilot pollution level in an autonomous femtocell network. Base stations are in sleep mode until there is a wake-up signal received from a terminal. The base station who received the maximum power will respond to
that terminal. Similar work can be found in [12] and [13] where the objective has focused on maximizing the network coverage in a user-deployed cellular infrastructure topology.

- Adaptive Spectrum Allocation - The work in [14], [15], [16], [17], [18] and [19] studied adaptive frequency carrier allocation in order to manage the network interference between the macrocell and femtocells. The common idea is to view the femtocell network as a secondary tier from the macrocell and orthogonal frequency channels can be dynamically allocated to the two networks [20] and [21]. The shortcoming of these kind of approaches is the requirement for extra spectrum in handling the femtocell traffic [22]. So far, co-channel deployment of femtocells in an underlay cellular network is of the major interest to network operators [8], which makes the problem of interference management more complicated between the two networks.

- Autonomous Power Management - Co-channel deployment of femtocells in an underlay cellular network has been studied in [10], [23], [24], [25], [26] and [27]. The model in [10] considered a maximum number of 300 femtocells randomly deployed inside a $1000 \times 1000 \text{m}^2$ macrocell area. By keeping the femtocell coverage below 20 meters in diameter, the results showed dramatic network capacity improvement based on the Wideband Code Division Multiple Access (WCDMA) standard. The work in [28], [29], [30], [31], [32] and [33] continued the study on different power control strategies. Among them, the work in [28] undertook the most comprehensive
study on various types of interference scenarios in a WCDMA network. The results showed that the downlink interference from the femtocells to macrocellular users is the most critical problem in comparison to other interference scenarios.

- Mobile Handoff and Access - The work in [11], [34], [35] and [36] evaluated the mobile handoff performance based on 3G Universal Mobile Telecommunications System (UMTS) standard. Modified handoff procedures were studied with low signaling overheads in the IP backbone network. Both open access and closed access solutions were proposed with pros and cons to the network operators. By open access, a mobile terminal can access any of the femtocell access points in the network. In closed access, a femtocell is only used by a certain group of users as private access equipment. Apparently, the open access better helps absorb the macrocell traffic while introducing the new problem of billing the visiting users to a femtocell [8], [37], [38] and [39]. So far, the closed access approach has been widely accepted by the operators due to the ease of implementation. Meanwhile, a hybrid access mode allowing both open and closed access is under study in order to balance the benefits from the two approaches [40].

- Femtocell Security - As femtocells are supposed to be small access points directly attached to the IP backbone network, security issues arose as a concern in a user deployed network [41]. Various solutions have been discussed to address this issue including the implementation of IKEv2 (Internet Key Exchange v2) and the
In addition to these works mostly accomplished based on the 3G UMTS cellular standard, research in particular focusing on WiMAX femtocell solutions can be found in [43], [44], [45] and [46]. A good summary [8] developed a study about the femtocell’s impact to the future cellular industry from both technical and business perspectives. The autonomous femtocell deployment has been formally launched as a beyond 3G solution based on the current UMTS and future LTE-based cellular standards.

1.5 Thesis Contribution and Organization

In this thesis, we propose a novel framework for femtocell interference management. Note that femtocell deployment by users is essentially a spectrum reuse procedure in an underlay macrocellular network. Therefore, how to reuse the spectrum in order to maximize the spectral efficiency is the fundamental problem to solve. In the 1∼3G cellular systems, the degrees of spectrum reuse is generally measured by a single parameter called frequency reuse factor. The value of this factor determines the spatial separation of the co-channel cells based on the tolerable interference power on a mobile terminal. The typical values of this factor can be 1, 3, or 7 according to specific cellular standard under consideration (e.g., 1 for CDMA-based systems). Once the factor is determined it normally remains as a fixed value meeting
a particular cell planning requirement.

We study a flexible spectrum reuse scheme for femtocell deployment. The idea is to have an adaptive channel reuse factor based on the location of the femtocells within a macrocell. We name the scheme *cognitive femtocell* in the sense that the channel reuse pattern is cognitively determined according to each femtocell’s channel environment. A femtocell recognizes an *interference signature* from the network and intelligently reuses the proper channel modes to minimize the interference to the network. *Environment perception* and *interference recognition* are necessary procedures to facilitate cognitive interference management and resource allocation.

![Diagram of research objectives](image)

**Figure 1.7: Research Objectives for Autonomous Spectrum Management**

To this end, we show four objectives of our research in Figure 1.7 based on
autonomous environment perception and radio reconfiguration.

1. Based on the acquisition of an interference signature from the network environment, cognitive interference management is achieved through adaptive channel assignment and power allocation. (Chapter 2)

2. Based on the recognition of the mobile mobility pattern, autonomous mobile handoff is carried out between the macrocell and femtocells. (Chapter 2)

3. Based on the infrastructure topology recognition, pilot power of a femtocell access point is automatically updated by maximizing the femtocell coverage. (Chapter 3)

4. Based on the acquisition of global traffic distribution in the network, the transmit power of each femtocell is adaptively configured to balance the intercell resource allocation. A time-domain scheduler is studied achieving resource balance function in an autonomous cellular network. (Chapter 4)

Chapters 2-4 will layout a framework for cognitive spectrum management in a 4G autonomous cellular architecture. We will see that the ability of the environment perception and interference recognition are important cellular characteristics for future autonomous network deployment and optimization. Network performance in 4G will be not only depending on the capability of hardware equipment but also the
robustness of software. This will open a new area for cellular network optimization based on software development and autonomous radio configuration.
We consider a macrocell with a number of femtocells randomly deployed in it as shown in Figure 2.1. Each femtocell has a small signal coverage (e.g., 30 ~ 40 meters in diameter) determined by the maximum transmit power of the access point. We assume an open access network where mobile users can get associated with either the macrocell base station or any femtocell access point depending on their position in the area. Based on the pilot capturing effect, mobiles that are geographically close to a femtocell have greater chance to be served as femtocell users. Mobiles that are
not in vicinity to any of the access point will be served by the macrocell base station as *public macrocell users*. Note that the traditional pilot capturing effect may need certain modifications in order to produce an optimized mobile association result. The research work regarding pilot power optimization will be discussed in Chapter 3.

Figure 2.1: Autonomous Femtocell Deployment in A Macrocell

Suppose the femtocell access points operate on the same spectrum band as the macrocell base station. Three types of interference exist with different impact to the entire network capacity: interference from femtocells to macrocell, interference from macrocell to femtocells, and interference between femtocells. In this section, we focus on the first interference, i.e., the interference from the femtocells to the public macrocell users, which has the most critical impact to the network capacity.
as analyzed in work [28]. The reason is because the public users are normally far away from the macrocell base station and thus vulnerable to the local interference from the close-by femtocells.

2.1 Femtocell-to-Macrocell Interference Scenario

In this section, we study a novel framework of cognitive channel reuse which effectively minimizes femtocells’ interference to public macrocell users. The idea is to view user-deployed femtocells as a secondary-tier system which autonomously reuses the orthogonal channels to the primary users in macrocell. Section 2.2 will continue to extend the framework in dealing with the other two interference scenarios. All discussion will be focused on downlink communication in the network.

2.1.1 Cognitive Channel Reuse with Orthogonal Channelization

We propose an interference management framework based on a cognitive channel reuse strategy. The target is to minimize the femtocells’ interference to the public users. In Figure 2.1, a number of public users are represented as the interference objects to the user-deployed femtocells. When a public user $i$ is served by the macrocell base station, the femtocells in its vicinity are viewed as potential interferers.
We first review the legacy method to manage the interference between users within a traditional macrocell. In systems such as Advanced Mobile Phone System (AMPS), Global System for Mobile communications (GSM) or CDMA, the cellular resource is channelized in a certain manner and assigned to different users within a common cell. We denote the downlink channel allocation to a particular user \( i \) as \( A_i = \{ f_i, t_i, c_i, s_i \} \) as shown in Figure 2.1, where \( A_i \) represents a particular channel allocation pattern for user \( i \) over four possible channel dimensions - frequency, time, code and space. Here each element in \( \{ f_i, t_i, c_i, s_i \} \) can be viewed as a vector that represents the channel allocation metric on the corresponding channel space. The joint use of these vectors will define a channel pattern for users based on specific cellular standard. In a GSM system for example, the resource pattern \( A_{GSM} = \{ f, t \} \) produces a two-dimensional frequency × time allocation matrix for voice users. In a UMTS High-Speed Downlink Packet Access (HSDPA) system, resources are allocated in three channel dimensions over \( A_{HSDPA} = \{ t, c, s \} \) provided that the antenna sectorization is also applied to the system. Along with the modern advance of the cellular technologies, cellular channel allocation is getting more flexible over multiple resource dimensions. In general, a particular channelization pattern \( A_i \) has to be unique for user \( i \), and for a different user \( j \neq i \), we have the classic orthogonal channelization process from the base station to multiple users in the same cell:
\( \mathcal{A}_i \perp \mathcal{A}_j \) \hspace{1cm} (2.1)

Now when a femtocell \( m \) is deployed in the same macrocell, it is supposed to reuse some of the macrocellular channels and treat them with proper power allocation. Now that a femtocell is of very low power, its downlink power only interferes to the close-by public users (red dashed line area in Figure 2.1). Our solution is to enable a femtocell to recognize those public users within a certain interference range and autonomously create an orthogonal channel pattern \( \mathcal{R}_m \) such that:

\( \mathcal{R}_m \perp \mathcal{A}_i \) \hspace{1cm} (2.2)

The above procedure is similar to (2.1) except that it must be executed on each femtocell in an autonomous manner. The reusable channel pattern \( \mathcal{R}_m \) on a femtocell \( m \) represents those resource modes that are orthogonal to channel \( \mathcal{A}_i \) of the public user \( i \). Unless for some random channel access technology like the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), a channel pattern \( \mathcal{A}_i \) can be found as a dedicated channel metric assigned to user \( i \) by the macrocell base station. Therefore, by performing the channelization in (2.2) a femtocell can totally avoid its interference to the close-by public users.

Here, the key point is the method to get the channel pattern \( \mathcal{A}_i \) on which the public user \( i \) will be interfered by femtocells. Normally this information is managed
by RNC in a 3G network who takes charge of channel allocation in macrocells. A femtocell can query RNC through ACM for the knowledge of $\mathcal{A}_i$ and then treat it as an *interference signature* which indicates the channel modes being used by the macrocell user $i$. Note that a particular femtocell $m$ does not necessarily need to query for all public users’ channel information. Instead, a femtocell access point $m$ should first perceive its environment and recognize the public users within a certain interference range (Figure 2.1). Then the channelization process of (2.2) can be implemented based on the acquired interference signature of the close-by public users. A detailed procedure for interference recognition will be discussed in later paragraphs.

![Figure 2.2: OFDMA Example with Cognitive Channel Reuse](image)

We discuss an example based on Orthogonal Frequency-Division Multiple Access (OFDMA) cellular standard where channels are allocated to users in a two-
dimensional \( \text{time} \times \text{frequency} \) matrix. We show such a channel matrix managed by a femtocell in Figure 2.2 in which the interference signature is illustrated by two red grids. Based on this recognition of the environment, all the orthogonal channels (the dark blue grids) can be safely reused in the femtocell without causing interference to the public users. One can view this scenario in a way that two public users \( i \) and \( j \) are both in vicinity to the femtocell of interest. Due to different distance to the femtocell, their interference signatures are marked with different strength on the corresponding channel mode (dark red v.s. light red grids). \( A_i \) and \( A_j \) are both unique channel patterns for the corresponding public user, which can be respectively identified by the femtocell access point. Note that because the public users are generally distributed in a macrocellular area, the chance for all of them getting close to a particular femtocell is a very low probability event. In other words, the scheme will not have to sacrifice a lot channels in a femtocell while effectively avoiding the interference to the public network. Therefore, the interference management from femtocell to macrocell is achieved in a geographically distributed manner based on each femtocell’s individual radio environment.

The procedure for interference signature acquisition plays a critical role for the above cognitive radio configuration. The way to determine a correct interference signature varies depending on the specific cellular standards under consideration. Figure 2.3 shows an example procedure based on OFDMA by having femtocells pe-
periodically listen to their uplink radios (step 1). Since public users normally have strong transmission power in uplink in order to communicate with the base station, a close-by femtocell access point can easily overhear this signal and mark the corresponding channel as an uplink interference signature (step 2). According to this uplink signature information, the femtocell can query ACM for the user IDs of these public users (step 3). Knowing the ID information, the next step is to acquire the downlink channel allocation patterns $A_i$’s that have been allocated to these public users by the macrocell base station (step 4). Every once in a while, a femtocell should re-sense the environment and update the downlink signature record due to mobility.
of the public users. By constantly maintaining a complete environment characterization, a femtocell cognitively reuses the orthogonal channel modes and adaptively avoids the interference to the macrocell network (step 5a). The maintenance of the interference signature matrix also helps recognize the mobility characteristics of the close-by public users, which assists the mobile handoffs between the macrocell and femtocell (step 5b).

The above procedure requires a query process from femtocells to ACM in the infrastructure backbone network. This may cause a time delay up to hundreds of milliseconds till the signature information is returned to the femtocell. When the backbone network is based on the Internet Protocol (IP), a round-trip query process may cause even longer delay due to the process of network queueing, IP packet encapsulation and decapsulation. Therefore, the scheme is supposed to be considered for slow/shadow fading level of channelization. This is the similar case in the traditional 2G/3G cellular networks where slow channelization in each macrocell is managed by the Base Station Controller (BSC)/(RNC) in the infrastructure network.

Here we have introduced a novel cellular feature for autonomous interference management: *radio cognition*. This concept is related to the *cognitive radio* concept that a terminal is able to cognitively sense the available frequency channels and opportunistically access the spectrum band [47], [48], [49]. The difference is that
we have proposed a more comprehensive radio configuring capability over frequency, time, code and space. When a strong interference signature is perceived from the environment, a femtocell should perform an orthogonal channelization process to protect it. A factor, $g_s$, is introduced as the threshold to facilitate this procedure. Femtocells who perceive a channel gain bigger than $g_s$ from a public user should automatically perform orthogonal channelization on the corresponding signature mode. Otherwise, the femtocell can safely reuse the signature channel. The value of $g_s$ actually determines the radio sensitivity of a femtocell. The lower the value is, the more sensitive a femtocell behaves to its network environment and thus lower interference is generated to the public macrocell users. The network performance determined by various configurations of $g_s$ will be studied in Section 2.1.4.

In a Time Division Duplex (TDD) system, the perceived uplink channel gain $g_s$ from a public user contains the identical information for downlink, which can be directly used to characterize the interference signature. In a Frequency Division Duplex (FDD) system, the uplink gain from a public user can be only used as a rough channel characterization for downlink. However, the proposed scheme is supposed to be functioning in a slow/shadow fading channel environment and the key point is to recognize the physical existence of the close-by public users as described in Figure 2.3. In this sense, a channel recognition procedure based on uplink environment listening is enough for cognitive channel configuration (Section 2.1.4). The precise
downlink channel gain to public users will be required when we develop the network capacity analysis in Section 2.1.3.

2.1.2 Analysis of Cognitive Channel Reuse Efficiency

The idea of cognitive channel reuse based on orthogonal channelization is to have each femtocell recognize the macrocellular interferers and cognitively avoid to reuse the same channels marked as an interference signature. In other words, a partial number of channels have to be sacrificed in a femtocell as long as some public users happen to be close by. It is necessary to study the average percentage of reusable channels in a femtocell - channel reuse efficiency. A femtocell is not supposed to lose too many channels due to the orthogonal channelization to public users in the macrocell.

We suppose that $N_p$ and $N_f$ are the number of public users and femtocells within a macrocellular area. For each public user $i$, a number of $h_i$ channels are allocated by the macrocell base station. According to a specific sensitivity threshold $g_s$, a certain interference range will be determined with $N_i$ femtocells being involved for orthogonal channelization (e.g., $N_i = 2$ in Figure 2.1). Because each of the $N_i$ femtocells will have to lose a number of $h_i$ channels in order to protect the public user $i$, the aggregate loss of the femtocell channels in a macrocell can be written as:
$h_{loss} = \sum_{i=1}^{N_P} h_i \cdot N_i$  \hspace{1cm} (2.3)

Now suppose that the same number of total channels $H$ are reused in both macrocell and femtocells, then a channel reuse efficiency parameter $\varepsilon$ can be found as:

$$\varepsilon = 1 - \frac{h_{loss}}{H \cdot N_f} = 1 - \frac{\sum_{i=1}^{N_P} h_i \cdot N_i}{H \cdot N_f}$$ \hspace{1cm} (2.4)

$\varepsilon$ represents the average percentage of reusable channels in a femtocell. Because the aggregate loss of femtocell channels $h_{loss}$ is bounded by the total number of femtocell channels $H \cdot N_f$ in a macrocell, we have: $\varepsilon \leq 1$. Note that a lower value of $g_s$, i.e. better femtocell sensitivity and thus bigger $N_i$, can lead to a lower efficiency of $\varepsilon$. In Section 2.1.4 we will study different configuration settings of the femtocell sensitivity threshold $g_s$ and their impact to the channel reuse efficiency $\varepsilon$ of femtocells.

\subsection{2.1.3 Cognitive Channel Reuse with Non-orthogonal Channelization}

In this section, we take a deeper study for non-orthogonal channel reuse in femtocells. The objective is to take extra capacity gain on the perceived interference signature as long as the power allocation can be appropriately optimized on those signature
channels. In other words, we study a framework that achieves a two-fold target. One is the primary objective to manage the interference from the femtocells to the public network, the other is to maximize the femtocell capacity under the achievement of the first objective.

Again, we use Figure 2.1 as the cellular layout where femtocells generate interference to the public network. Suppose that a public user $i$ defines a public interference signature $A_i$ and a total number of $M$ femtocells are within the interference region determined by $g_s$. Instead of having orthogonal channelization in each of these $M$ femtocells as discussed before, we want to find an optimized power allocation $\mathbf{p}^* = (p_1, p_2, ..., p_M)$ on $A_i$ for each femtocell $m = 1, 2, ..., M$, such that:

$$\max \sum_{m=1}^{M} C_m$$

subject to

$$\sum_{m=1}^{M} h_m \cdot p_m \leq P, \quad m = 1, 2, ..., M$$

The objective is to maximize the sum capacity $C_m$ of the $M$ femtocells on the common interference signature $A_i$. $P$ works as an interference threshold that strictly limits the aggregate interference from the femtocells to the public user $i$. Here, $P$ can be viewed as a Quality of Service (QoS) parameter that defines the maximum tolerable interference for sustaining a specific service for the public user $i$. The coefficient of $h_m$ is the channel gain from the $m$th femtocell to the target public user $i$. According to the previous discussion, $h_m$ can be easily obtained in a TDD system.
by uplink radio listening on a femtocell access point. In an FDD system, public
users are required to listen the downlink channel and feedback $h_m$ to the backbone
network.

The cell capacity of a femtocell $m$ is defined in the following according to Shan-
non’s channel capacity equation [50]:

$$C_m = r_{A_i} \cdot \log_2 \left(1 + \frac{g_m \cdot p_m}{N_{A_i,m} + \sigma_{A_i,m}}\right),$$

(2.6)

where $g_m$ denotes the channel gain from the access point $m$ to a single user in the
femtocell. $r_{A_i}$ denotes the total resource degrees of freedom on channel mode $A_i$.
As discussed before, the resource degrees of freedom can be measured based on a
joint allocation of multiple channel modes over frequency, time, code and space. As
for a particular cellular technology, the degrees of freedom allocated to a user is a
fixed pattern over a certain period of time (e.g., a few milliseconds for data and
several minutes for voice services). $N_{A_i,m}$ and $\sigma_{A_i,m}$ denote the received noise and
the aggregate interference power on the mobile receiver in femtocell $m$. The vector
$p = (p_1, p_2, ..., p_M)$ is the variable for optimization.

The interference factor $\sigma_{A_i,m}$ is treated as noise in the capacity equation because
of a unique channel characteristic in femtocells. Femtocells are normally deployed in
closed indoor areas with good signal protection by walls and floors. Femtocell users
are physically well covered by their own cell appeared as a hotspot area. Therefore,
users being served by a femtocell are generally guaranteed with very high Signal to Interference plus Noise Ratio (SINR) channels, and thus we can assume that the interference between two femtocells is treated as noise [10]. The summation of the noise-like interference power from a large number of femtocells is assumed to be a Gaussian variable with the variance of $\sigma_{A_i,m}$. A more theoretical proof about treating interference as noise in low interference regime can be found in the recent work [51].

Note that the above capacity equation (2.6) can be written in a more general form when time-varying function of each coefficient is considered, i.e.:

$$C_m(t) = r_{A_i}(t) \cdot \log_2(1 + \frac{g_m(t) \cdot p_m(t)}{N_{A_i,m}(t) + \sigma_{A_i,m}(t)}) \quad (2.7)$$

Each coefficient can be replaced by a function of time $t$ and the characteristic of each may vary over different time scales. In our discussion, we focus on the capacity optimization problem over a certain period of time (e.g., a couple of ms) during which none of those parameters get significant change in time. The optimization algorithm can be performed from one time block to next when the parameters are changing to a different state. Therefore we can safely remove the time index $t$ and use equation (2.6) for calculating a femtocell capacity over a particular signature $A_i$.

In addition, by considering the variable vector $p \geq 0$ and safely dropping $r_{A_i}$,
we finally have the following optimization problem to solve:

$$\max \quad \sum_{m=1}^{M} \log_2(1 + \frac{g_m \cdot P_m}{N_{A_i,m} + \sigma_{A_i,m}})$$  \hspace{1cm} (2.8)

$$s.t. \quad \sum_{m=1}^{M} h_m \cdot p_m \leq P, \quad m = 1, 2, \ldots, M$$

$$p_m \geq 0, \quad m = 1, 2, \ldots, M$$

The above formulation strictly constrains the maximum interference from the femtocells to a public user $i$ who has been allocated with channel $A_i$ by the macrocell base station. All the $M$ femtocells inside the interference range should rigorously optimize their transmit power by (2.8) when they reuse the channel mode $A_i$. All the others channels that are orthogonal to $A_i$ can be freely reused without interference to the public users as studied in Section 2.1.1.

We write the Lagrangian of the above problem in the following:

$$L(p, \lambda, \mu) = -\sum_{m=1}^{M} \log_2(1 + \frac{g_m \cdot P_m}{N_{A_i,m} + \sigma_{A_i,m}})$$

$$+ \lambda\left(\sum_{m=1}^{M} h_m \cdot p_m - P\right) + \sum_{m=1}^{M} \mu_m(-p_m), \quad (2.9)$$

where $\lambda$ and $\mu_m$ are Lagrangian multipliers and $\lambda \geq 0$, $\mu_m \geq 0$, $m = 1, 2, \ldots, M$. The optimal power allocation satisfies the Kuhn-Tucker condition:

$$\frac{\partial L(p, \lambda, \mu)}{\partial p} = \frac{-1}{1 + \frac{g_m P_m}{N_{A_i,m} + \sigma_{A_i,m}}} \cdot \frac{g_m}{N_{A_i,m} + \sigma_{A_i,m}} + \lambda \cdot h_m - \mu_m = 0$$  \hspace{1cm} (2.10)
Solving the above equation yields:

\[ p_m + \frac{N_{A_i,m} + \sigma_{A_i,m}}{g_m} = \frac{1}{\lambda \cdot h_m - \mu_m} \]  

(2.11)

By defining \( x^+ := \max(x, 0) \), the optimal power allocation:

\[ p_m^* = \left[ \frac{1}{\lambda \cdot h_m} - \frac{N_{A_i,m} + \sigma_{A_i,m}}{g_m} \right]^+ \]  

(2.12)

The above solution produces very important results for channel reuse in a femtocell. First, not all of the femtocells can reuse the interference signature perceived from their local environment. Those who have the reusing privilege must satisfy the condition of \( h_m \cdot \frac{N_{A_i,m} + \sigma_{A_i,m}}{g_m} \leq 1/\lambda \). As to the femtocells appearing as \( h_m \cdot \frac{N_{A_i,m} + \sigma_{A_i,m}}{g_m} \geq 1/\lambda \), no positive power should be applied from the capacity optimization point of view. Here, the product of the interference factor \( h_m \) and the weighted noise factor \( \frac{N_{A_i,m} + \sigma_{A_i,m}}{g_m} \) jointly characterizes a specific network environment for a particular femtocell \( m \). One femtocell should cognitively behave itself based on this environment characterization and accordingly allocate the transmit power determined by (2.12).

The procedure of an optimal power allocation follows a modified water-filling algorithm. Here the traditional common water level \( 1/\lambda \) for all water-filling channels is weighted by an extra interference metric \( h_m \). The difference between \( (1/h_m) \cdot 1/\lambda \) and the weighted noise term \( \frac{N_{A_i,m} + \sigma_{A_i,m}}{g_m} \) in each femtocell defines the optimized
power for allocation. Note that $h_m, m = 1, 2, ..., M$ represents the interference gain from a femtocell $m$ to the public user $i$, which characterizes a femtocell’s interference environment. A bigger value of $h_m$ means more significant interference to a public user, which leads to a less power allocation according to (2.12). This perspective is similar to the traditional water-filling algorithm where a fixed power volume is poured on multiple channels based on the individual’s SNR condition. In our solution, the two parameters of noise and interference matric characterize the full channel information for capacity optimization. One thing to note is that the noise factor normally behaves as a statistical network parameter without changing too much from one femtocell to another. Therefore the interference metric $h_m$ plays a much more important role in determining the optimal power allocation in femtocells. This well fits our intuition because the physical location of the femtocells which gives the interference gain $h_m$ acts as a critical factor in determining the interference power to public users.

2.1.4 Performance Results

We simulate the interference control performance with the following system parameters. A two-level piecewise path loss model (in dB) is used in the simulation to capture the femtocell-to-macrocell signal propagation effect [52]:

38
\begin{align*}
L(d) &= \begin{cases} 
L_1 + \gamma_1 \log_{10}(d) & d \leq d_1 \\
L_1 + \gamma_1 \log_{10}(d_1) + L_2 + \gamma_2 \log_{10}(d - d_1) & d > d_1,
\end{cases}
\end{align*}

and the outdoor macrocell path loss model is characterized by the following:

\begin{align*}
L(d) &= L_3 + \gamma_2 \log_{10}(d),
\end{align*}

where \(d_1 = 15\)m is the average indoor signal propagation distance. The corresponding path loss exponent \(\gamma_1 = 25\) and \(L_1 = 40\)dB. For the distance bigger than 15m, we use \(L_2 = 20\)dB to capture the signal loss by wall attenuation and \(\gamma_2 = 40\) as the outdoor path loss exponent. \(L_3 = 30\)dB. In our simulation, an extra Lognormal variable is added to the path loss model which captures the shadowing fading effect in the network. The deviations of this variable are respectively set to 4dB within the macrocell and 10dB from femtocells to macrocell.

Based on the above model, we layout a cellular network with a macrocell radius of 500m in the center and six surrounding ones as neighbouring cells with regular cell planning as shown in Figure 2.4. We suppose a frequency reuse factor of 1, which is the general case for 3G CDMA and WiMAX systems. We now randomly deploy a number of femtocells in each macrocell and want to study the channel SINR variation of the public users. In our simulation, we suppose that each femtocell has a maximum transmit power of 100mW and the macro base station implements a
maximum power of 200mW to serve each public user.

Figure 2.5 shows the SINR outage probability of a public user versus an increasing number of the femtocell deployment from 500 to 5000 in one macrocell. The SINR outage probability is defined as the relative frequency of the occurring events $\{\text{SINR} \leq 5\text{dB}\}$ out of 10000 experiments when a public user is randomly positioned in the center macrocell. We compare the performance of two approaches: one is to randomly reuse all cellular channels in femtocells without interference recognition; the other is to implement our method of cognitive channel reuse with orthogonality.
From Figure 2.5, the former approach causes a very quick increase of the SINR outage probability. When the number of femtocells goes beyond 2000/macrocell, the interference to public users can cause over an 60% SINR outage probability. However, cognitive femtocell approach always keeps the SINR outage in a very low probability level. The reason is clear to see because each femtocell recognizes the significant interferers in its vicinity and cognitively reuses the orthogonal channels to them. In addition, the sensitivity threshold $g_s$ is set to -60dB and -65dB respectively in our simulation representing two different sensitivity levels of the femtocell radio.
One can see that by configuring a 5dB higher sensitivity on femtocells even lower SINR outage probability is achieved because more public users can be recognized for interference avoidance.

Figure 2.6: Public User Channel Outage of \( \{\text{SINR} \leq 8\text{dB}\} \)

Figure 2.6 shows the public user outage performance when the channel \( \{\text{SINR} \leq 8\text{dB}\} \). Both of the approaches get severer channel outage for maintaining a 3dB stronger channel condition. However, by having a higher radio sensitivity by \( g_s = -65\text{dB} \) the SINR outage can still be well maintained in a low probability level \( (\leq 7\%) \). Again this is because each public user has announced a bigger interference range and
thus more femtocells in the range cognitively reuse the orthogonal channels to the
local environment. In practice, the performance of a public user such call dropping
probability can be adaptively improved by simply tuning $g_s$ parameter of femtocells
to a smaller value. In the following discussion we take a deeper look at the method
of setting a proper sensitivity threshold $g_s$ for femtocell configuration.

As what we discussed before, each public user announces an interference range
within which the femtocells have to perform orthogonal channel reuse. The size
of the range is determined by the value of $g_s$. For each public user, a certain
number of surrounding femtocells will have to sacrifice one channel for orthogonal
channelization. A smaller value of $g_s$ indicates a wider interference range and thus
a bigger percentage of femtocells will be involved for a channel loss.

We can see in Figure 2.7 that as the sensitivity threshold $g_s$ is getting smaller
from -52dB to -70dB this percentage increases from around 5% to 55%. As to $g_s$
= -60dB for example, one public user can cause 18% femtocells in one macrocell
to lose one channel. Now we consider a dense deployment of 5000 femtocells per
macrocell and 100 public users in the same area, then according to equation (2.3)
the total number of femtocell channels sacrificed for cognitive channel reuse are:

$$100 \times 5000 \times 0.18 = 9 \times 10^4$$

We further suppose that the total number of cellular channels $H$ is 200 for both
Figure 2.7: Percentage of Femtocells with Orthogonal Channel Reuse

the macrocell and femtocells. This can be viewed as a 2G cellular case such as CDMA IS-95 system which has 64 voice channels per sector and three sectors per macrocell. Then the total amount of femtocell channels per macrocell is:

\[ 5000 \times 200 = 1 \times 10^6 \]

Now according to equation (2.4), we can easily find the average capacity loss per femtocell due to the cognitive channel reuse with \( g_s = -60 \text{dB} \):

\[ \frac{9 \times 10^4}{1 \times 10^6} = 9\% \]

and the channel reuse efficiency \( \varepsilon = 1 - 9\% = 91\% \).
The above result implicates a very important conclusion about our cognitive channel reuse approach. By releasing a minor femtocell resource with cognitive radio configuration, the interference to public users can be efficiently reduced to a very low level. In our case study with $g_s = -60\text{dB}$, the SINR outage probability for 5dB case is well achieved below 10% even with a very dense deployment of the femtocells - 5000/macrocell. The average capacity sacrificed in each femtocell is only 9%. Note that a 9% channel loss is not a big deal in a femtocell because it normally serves a small number of users (e.g., 1 ∼ 4) and the channels are not likely to be fully used. In other words, a femtocell normally manages abundant amount of cellular channels and the key is how to use them in a proper way. To this end, our results offered an effective solution based on cognitive channel reusing. When femtocells are randomly deployed inside an underlay macrocell, they autonomously manage their interference to the public network based on environment listening and radio reconfiguration.

2.1.5 Summary

Autonomous cellular architecture has been expected to be a 4G method to deploy a cellular network. Different from the traditional cellular concept with regular cell planning, network users can facilitate the deployment of a cellular network in an ad hoc manner. By cognitive environment listening, the interference on each channel
mode is characterized by a unique signature. By looking over the signature metric on each channel mode, a femtocell access point can determine the proper resource allocation pattern autonomously managed by network control server. Our results showed that by adaptively tuning the radio sensitivity threshold, the method can adaptively control the femtocell interference level based on a specified interference management requirement. A femtocell normally manages the same amount of the channels as the macrocell base station yet with much fewer users to serve. Our solution offers a novel approach about properly reusing the abundant resource in femtocells and adaptively updating the channel pattern according to the dynamics of interference environment.

2.2 Femtocell-to-Femtocell and Macrocell-to-Femtocell Interference Scenarios

In this section, we continue to study the cognitive femtocell framework and deal with the rest of two types of interference i.e., the interference from macrocell to femtocells and interference between femtocells. An opportunistic channel scheduler is discussed based on the concept of cognitive channel reuse. Simulation results are evaluated based on the channel SINR comparisons under different channel management strategies.
2.2.1 Cognitive Channel Categorization

We consider a macrocellular area with a number of femtocells randomly deployed by users as shown in Figure 2.8. When a bunch of femtocells are closely deployed by users, their mutual interference may cause significant impact to the femtocell capacity. In this section we study an approach to improve the spectrum efficiency in femtocells based on cognitive channel management. Again, the discussion is focused on downlink communication.

As shown in Figure 2.8, the downlink interference $I(t)_{m,i}$ received by a user $i$ in femtocell $m$ at time $t$ is determined by the aggregate interference level on the corresponding channel mode $C(t)_{m,i}$. Note that once the channel pattern $C(t)_{m,i}$ is allocated to user $i$ in femtocell $m$, it normally remains unchanged for a while until
a particular service is finished. The traditional way to maintain service quality is to control the transmit power $p(t)_{m,i}$ of the channel such that:

$$\frac{p_{m,i}(t)|h_{m,i}(t)|^2}{I_{m,i}(t) + N_{m,i}} \geq \gamma_{m,i},$$

(2.13)

where $|h(t)_{m,i}|$ represents the channel amplitude from the femtocell $m$ to the user $i$ inside the coverage. $\gamma_{m,i}$ represents the user QoS requirement in terms of channel SINR. $N_{m,i}$ denotes the noise level at the terminal $i$.

Here $I(t)_{m,i}$ includes the aggregate interference from the neighbouring femtocells and the macrocellular base stations. In comparison to what we had in Figure 2.2, more sophisticated signature pattern can be perceived from the network environment. We redraw Figure 2.9 to illustrate an interference recognition example in a 3G femtocell. Again, the matrix can be viewed as the full channel resources that a femtocell manages to assign to its users. Here the 1st and 2nd channel dimensions represent a more general view of the channel allocation pattern in a typical 3G standard. One can view the two axes as time $\times$ code in a UMTS network or time $\times$ frequency in a WiMAX system based on OFDMA protocol etc. The interference signature is illustrated by the red grids with different power levels perceived from the environment (dark red v.s. light red grids).

Due to low transmit power of the femtocells, only the femtocells that happen to be closely deployed interfere with each other in a remarkable effect (e.g., the
femtocell cluster shown in Figure 2.8). The majority of the other femtocells widely distributed in the macrocellular area produce an aggregate noise-like interference. As illustrated in Figure 2.9 for example, a femtocell may see a bunch of channels being interfered with strong interference from the near neighbours and weaker ones from much further distances. A channel classification procedure can help determine the optimal channel reuse pattern. We show an example classification of the femtocell channels in Figure 2.10. The interference level on each channel mode can be perceived as a unique channel characterization and three channel categories are defined as follows:

- Interference-free channels: the channels that are 100% free of use because zero interference is perceived from the environment. This means that this category of channels are not reused anywhere in the whole network and thus automatically gain
Figure 2.10: Channel Categorization and Reuse Priority

the highest reuse priority. A femtocell should always starts serving its users by using these perfect channels without causing interference to others.

- Soft-interference channels: the channels that are only interfered by the majority of far-way femtocells. Each of them contributes to a small interference branch to the femtocell of interest and the aggregate effect behaves like a Gaussian distribution due to the Central Limit Theorem. A femtocell can opportunistically select the best channels for reuse, which generates smallest interference to the co-channel cells in far distances.

- Hard-interference channels: the channels that are not reusable because strong interference is caused from the neighbouring cells in vicinity (e.g., red grids in Figure 2.2). The interference signature of these channels is easily obtainable through the channel information exchange between adjacent cells. A femtocell should give the lowest priority to reuse these channels or always tries to orthogonalize the local channels (e.g., blue grids) to those channel signatures.
Note that the hard-interference channels are those normally reused in near vicinity and those with lower interference are reused in further distance. A cognitive femtocell is able to characterize the average channel reuse distance by constantly perceiving an interference signature from the environment. In spite of a random deployment of the femtocells, each access point can roughly obtain the knowledge about how a particular channel is spatially reused in other cells. This procedure helps automatically determine the proper channel allocation pattern in femtocells and meanwhile minimize the interference to the network.

Our simulation results in the performance section will verify that the soft-interference channels take the majority percentage of the channels in a femtocell network. This makes the power allocation an interesting problem to deal with as defined in the next section.

### 2.2.2 An Opportunistic Channel Reuse Scheduler

Suppose a femtocell $m$ manages a total number of $J$ channels in a 3G cellular network. Now we define an opportunistic scheduler that allocates the proper channel mode to serve the user $i$ ($1 \leq i \leq N_m$, $N_m = \text{the number of users in femtocell } m$). First the interference signature of each channel $1 \leq j \leq J$ can be cognitively characterized from the environment for user $i$ as:
\[ \alpha^{(j)}_{m,i} = \frac{|h^{(j)}_{m,i}|^2}{I^{(j)}_{m,i}}, 1 \leq j \leq J \]

where \( |h^{(j)}_{m,i}|^2 \) and \( I^{(j)}_{m,i} \) respectively denote the channel gain and the aggregate interference level on channel \( j \) when user \( i \) is served in femtocell \( m \). Noise is neglected in this case because the communication is considered as interference-limited. Our scheduler works to allocate the optimal channel \( j^* \) such that:

\[
\hat{j} = \arg \max_j (\alpha^{(1)}_{m,i}, ..., \alpha^{(j)}_{m,i}, ..., \alpha^{(J)}_{m,i}) \quad (2.15)
\]

Equation (2.15) produces an opportunistic identifier \( j^* \) that allocates the best channel mode to user \( i \) based on its own interference signature. Note that the scheduler represents the basic idea of the cognitive channel reuse discussed in the previous section. Based on the instantaneous interference signature perceived from the environment, a femtocell \( m \) cognitively determines the channel reuse pattern which produces the best signature benefit:

\[
\alpha^{(j^*)}_{m,i} = \frac{|h^{(j^*)}_{m,i}|^2}{I^{(j^*)}_{m,i}} \quad (2.16)
\]

One can view that a femtocell manages a candidate channel pool for each user as shown in Figure 2.10. The order of channels in the pool is unique for different users based on their individual interference signature perception. At a particular time when a femtocell \( m \) has multiusers to serve, the transmit power has to be
autonomously configured in order to minimize the interference to the network. We propose a simple optimization criterion as follows:

\[
\begin{align*}
\min & \quad \sum_{i=1}^{N_m} p_{m,i} \\
\text{s.t.} & \quad p_{m,i} \alpha_{m,i}^{(j^*)} \geq \gamma_{m,i}, \quad i = 1, 2, \ldots, N_m \\
& \quad p_{m,i} \geq 0, \quad i = 1, 2, \ldots, N_m
\end{align*}
\]  

(2.17)

The objective in (2.17) minimizes the sum power of femtocells at a particular scheduling time constrained by each user’s QoS requirement \(\gamma_{m,i}\). The problem turns out to be a linear programming (LP) problem as long as the optimal \(\alpha_{m,i}^{(j^*)}\) is cognitively determined by (2.15). The channel scheduler defined in (2.15) and the optimal power allocation determined in (2.17) together produces a procedure for autonomous resource management. We use Figure 2.11 to explain the whole process in the following discussion.

A femtocell access point constantly senses the radio environment (Step 1) and characterizes the interference signature from its neighbours (Step 2). The successful acquisition of the interference signature plays an important role in our discussion, and the way to get it varies depending on specific cellular standards. For example, users can feedback the channel information to help the access point know the channel condition similar to CDMA 1x EV-DO. Channel information can also be exchanged between femtocells to assist them to acquire the signature information. This process
Figure 2.11: Cognitive Channel Allocation Procedure

is supposed to be running as a loop according to a particular control period. The duration of the period may depend on specific wireless standard as well.

Upon knowing the interference environment, an opportunistic channel scheduler is implemented (Step 3) as defined in (2.15). The scheduler works to always pick the best channel for reuse which inversely causes low interference to other cells. Once the channel $j^*$ is determined with the highest reuse priority, the user QoS requirement will be evaluated based on the selected channel condition. If the channel
can satisfy the target service requirement, a valid power will be allocated to serve the user according to (2.17) (Step 5a). Otherwise, a handoff process is supposed to be triggered which switches the user to a different cell of better signal coverage (Step 5b). The optimal channel allocation $j^*$ is also supposed to be updated according to a loop time. The period of this process may also depend on specific wireless standard and the speed requirement to react upon the interference variation.

Normally the speed of power control in (Step 5a) is determined by the channel coherence time of a communication link. In a 3G macrocellular network, the mobiles are normally of high mobility and a fast power management is required based on the channel variation of the users. In 1xCDMA EV-DO and UMTS HSDPA standards, the users are opportunistically scheduled by the base station due to their individual channel variation in milliseconds level. A user that happens to see a channel ‘peak’ will be polled for data transmission and a multiuser diversity gain is achieved in each cell.

Now when we think of random femtocell deployment in an underlay macrocellular network, the channel condition of femtocells is not supposed to have too-fast variation. This is because the cell radius of each femtocell is normally of small range and the users are mainly nomadic without having fast motion. However, the aggregate interference pattern may be of big variance due to the statistical aggregation of hundreds of interference sources. To quickly acquire the accurate interference
signature is critical to the power management performance.

### 2.2.3 Performance Results

We study the interference control performance based on the same path loss model used in the previous section except that the Lognormal fading deviation is set to 12dB to characterize the femtocell-to-femtocell signal propagation. Also the same network topology from Figure 2.4 is used in simulation with the frequency reuse factor of 1 in all macrocells. We now uniformly deploy a number of femtocells and users in the center macrocell and want to study the channel SINR variation of the femtocell channels. In our simulation, we suppose that the macrocell base station and femtocells manage the same 100 channels and can respectively allocate 200mW and 1mW maximum transmit power on each channel. In addition, the traffic load in each femtocell on average requires 10% channel usage out of 100 channels in total.

Figure 2.12 shows the channel SINR outage probability versus an increasing number of the femtocell deployment from 100 to 1000 per macrocell. Uniform femtocell distribution is implemented in our simulation. Two SINR outage probabilities are respectively defined as the relative frequency of the occurring events of \( \{\text{SINR} \leq 10\text{dB}\} \) and \( \{\text{SINR} \leq 15\text{dB}\} \) out of 10000 experiments. In other words, we want to coin an experiment to study the capability of a femtocell maintaining a certain hotspot service quality, i.e. 10dB and 15dB, under different channel management
We compare the performance of two approaches: one is to randomly reuse all cellular channels in femtocells without interference recognition; the other is to implement our method of cognitive channel reuse. From Figure 2.12, the former approach causes very quick increase of the SINR outage probability in both two cases. One can see that it is very hard maintain a 15dB channel quality when the number of femtocells exceeds 200 in a macrocell. For the 10dB case, although the curve increases a bit slowly, a channel gets nearly 90% outage probability when the number
of femtocells reaches 400. The reason is obvious because a channel is randomly allo-
cated in a femtocell without the knowledge of the others. Neighbouring femtocells
in vicinity can cause significant interference to breakdown a target channel SINR.

On the contrary, the cognitive femtocell approach always keeps the SINR outage
in a low probability level. In a 1000 femtocells deployment scenario, the probability
can still be well kept below 10% and 20% respectively for maintaining 10dB and 15dB
channel qualities. The reason is because each femtocell recognizes the significant
interferers (hard interference channels) in its vicinity and cognitively reuses the
orthogonal channels to them. Co-channel interferences are mainly those propagated
from far locations which contribute trivial affect to the channel SINR variation.

2.2.4 Summary

In this section, we studied a method for femtocell interference management based
on interference perception and opportunistic channelization. We claim that the pro-
posed framework of cognitive channel reuse extends the traditional spectrum reuse
concept into a more general view. In legacy cellular networks, a block of spectrum
is used in one cell and reused in far locations in a regular fashion. Because of the
reuse distance configuration, a bunch of resource channels can be freely used inside
a cell with limited interference from far locations. In our framework for cognitive
channel reuse, the same procedure is carried out through a more flexible fashion.
Orthogonal cellular channels are allocated to a femtocell (same as in the traditional cell) and freely reused in a far distance where the interference gets lower than a specific level. The new characteristic in a cognitive femtocell is about the way to recognize the interference. In a cognitive channel reuse framework, the interference signature has to be perceived from the environment without a regular region appearing as a cell. A particular cellular channel can be freely reused in a femtocell as long as tolerable interference is recognized from the network environment. This approach is actually similar to the legacy channel reuse concept except that no radio cognitivity is required in traditional cellular systems. The reason is because the cellular infrastructure deployment has been well planned by the network operator and a so-called frequency reuse distance is manually configured in a regular way.

### 2.3 A Unified View on Cellular Network Optimization

In this section we develop a more unified view to study the two cellular concepts, i.e. the traditional cellular model that has been widely used in 1 ~ 3G networks and the autonomous architecture for 4G cellular deployment. In the conventional concept, the metric of capacity/cell has been used as the tool for network performance measurement which led to the following objective:
The objective is to invariably maximize the capacity in each cell subject to some
regular cell planning requirement. The requirement is a general term representing
the technical considerations in deploying and configuring a traditional cellular net-
work. Technically speaking, it consists of the configuration parameters of cell size,
frequency reuse and antenna sectorization and so on. We have seen the cellular
evolution from the 1G to 3G through the implementation of the advanced cell plan-
ning and air interference technologies, e.g., the progression from the frequency reuse
factor of 7 in GSM system to 1 in CDMA system. In other words, to squeeze more
bits/s from the limited spectrum has been pursued as the system design objective
in traditional cellular networks.

The autonomous cellular model is expected to have some different aspects be-
cause autonomous base station deployment facilitates more flexible spectrum reuse
in space. When the cellular infrastructure can be deployed by users in a random
fashion, the target of maximizing the cellular capacity will be automatically con-
sidered in irregular geographical areas not like hexagonal cells. A flexible spectrum
reuse pattern makes the following optimization model a more generalized form from
(2.18):

\[
\text{max} \quad \text{Capacity/Macrocell} \quad (2.18)
\]

\[\text{s.t.} \quad \text{Regular Cellular Planning Requirement}\]
max \quad \text{Capacity}/(\text{Autonomous Cell Unit}) \quad (2.19)

s.t. \quad \text{Autonomous Cell Planning Requirement}

By maintaining the similar objective in optimizing the cellular capacity, the spatial unit of a macrocell in (2.18) is replaced by an autonomous cell unit in an autonomous cellular network. An autonomous cell unit, e.g., a femtocell, indicates a geographical area in which the spectrum resource has to be orthogonalized as that of the channelization in a macrocell. With regular cell planning in a macrocell a block of spectrum is orthogonalized within a cell and freely reused in far locations where the co-channel interference is below a certain level. In an autonomous cellular network, this channel reuse distance will have to be perceived from the environment in a cognitive fashion. In other words, an autonomous cell planning procedure will be required to determine an automatic frequency reuse pattern in the network. Cells in an autonomous network may not necessarily be the traditional physical areas centered at base stations, but autonomously formed as the logic cells through base station cooperation. This generalizes the traditional cellular objective in (2.18) and validates the necessity of our study on cognitive femtocells. A base station can adaptively control the channel reuse pattern in an autonomous cell unit. Without a concrete cell planning requirement manually configured by the network operator, a cell planning pattern has to be autonomously determined by the intelligent control
module of the network. A specific procedure has been discussed in Chapter 2.2 where three channel categories were discussed in an autonomous femtocell network: hard interference channels, soft interference channels and interference free channels. The channel allocation and power control parameters should be constantly updated in order to dynamically maintain the optimal resource gain in autonomous cell units.

In future work, we are going to show that an autonomous cellular model, in a general sense, represents a more continuous spectrum reuse pattern in spatial domain. Our results are supposed to show this continuity and visualize the reused resource distribution in space. The traditional cellular concept ends up with a more geographically regular reuse of the cellular resource according to the old factor of channel reuse distance.
Chapter 3

Pilot Power Management in Autonomous Femtocells

In the previous chapter, we studied the method for interference management on traffic channels in a user-deployed cellular network. In this chapter, we slightly shift the interests to femtocell’s pilot channel management. This is another important issue for autonomous network optimization because the pilot power allocation determines the cell size and thus the mobile association pattern in the network. So far, it is not clear about the standard to configure a cell size when access points are randomly deployed without cell planning. Research work on this topic can be found in [10] and [11] where a simple power control scheme was proposed based on the usage of each femtocell. When femtocell users are in idle mode (e.g., not in a
call), the pilot power is reduced by 10dB in order to reduce the pilot pollution level in the network. The approach lacks the necessary consideration on some critical parameters that come up with a particular infrastructure deployment, such as the concrete cellular topology and specific channel environment in femtocells.

We study an optimization method that maximizes the cell size coverage for user-deployed femtocells. The algorithm periodically updates the pilot power configuration based on each femtocell’s channel path loss and global traffic distribution in the network. Radio cognitivity still plays an important role in getting the knowledge of neighbour list and interference metric from network environment.

3.1 Optimization Model for Femtocell Pilot Management

Suppose we have $N$ user-deployed femtocells in a certain geographical area under autonomous cellular management as shown in Figure 3.1. We want to find a method to automatically configure the pilot power for each femtocell. Although the access points are deployed by users in a random way, each of them is supposed to periodically sense the neighbouring pilots and recognize the co-channel femtocells in vicinity.

We denote two vectors $\mathbf{p} = (p_1, p_2, ..., p_N)^T$ as pilot power and $\mathbf{r} = (r_1, r_2, ..., r_N)^T$
as cell radius for a particular femtocell \(i, i \in N\). Here the cell radius \(r_i\) represents the distance from the access point \(i\) to the cell boundary beyond which a certain received SINR threshold is no longer satisfied. In some circumstances, a cell radius may not be clearly defined as a constant value due to the random channel fading and interference. In our discussion, we suppose that the cell radius is the average distance from a femtocell access point to its users in handoff position.

Our objective is to find the optimal pilot power vector \(p^*\) which determines the cell radius \(r_i\) for each femtocell \(i\), such that:
\[
\begin{align*}
\text{max} & \quad t \\
\text{s.t.} & \quad r_i \geq t, \quad i = 1, 2, \ldots, N \\
& \quad 0 \leq p_i \leq p_{\text{max}_i}, \quad i = 1, 2, \ldots, N
\end{align*}
\]

where \( t \) is a newly introduced scalar variable. The above optimization is equivalent to a Max-Min problem: \( \text{max} \ \text{min} \ r_i, \ i = 1, 2, \ldots, N \), which maximizes the minimum femtocell radius in the network. \( p_{\text{max}_i} \) defines the maximum pilot power in each cell \( i \) which constrains the cell radii solved from (3.1). The above objective function equalizes all femtocells’ coverage by maximizing the smallest cell size in the network. This objective is important for pilot management in a fairness point of view because any femtocell is not supposed to suffer much smaller cell coverage than others.

According to (3.1), all user-deployed access points cooperate to smooth out the potential big variance of cell sizes in an arbitrary infrastructure topology. This objective is much more flexible than setting a constant cell radius of 10 meters for all femtocells as studied in previous work [10] and [11]. In addition, both the femtocell-to-macrocell and femtocell-to-femtocell interference are considered in our model in the following discussion.

Now we introduce a function \( \mathcal{F}_i(p) \) to replace the radius expression \( r_i \) in (3.1) and the primal problem becomes:
\[
\begin{align*}
\text{max} & \quad t \\
\text{s.t.} & \quad F_i(p) \geq t, \quad i = 1, 2, ..., N \\
& \quad 0 \leq p_i \leq p_{\text{max}_i}, \quad i = 1, 2, ..., N 
\end{align*}
\]

The function of \( F_i(p) \) maps the variable power vector \( p \) to each of the cell radius \( r_i \). We can use this replacement because a particular pilot power allocation pattern \( p \) uniquely determines each femtocell size in the network.

In order to define \( F_i(p) \) for each cell \( i = 1, 2, ..., N \), we denote the cell radius \( r_i \) as the distance between the access point \( i \) and a reference mobile located at \( l = (x, y)^T \) in cell \( i \). As shown in Figure 3.1, such a reference mobile is illustrated by a terminal that is normally on the edge of the cell and probably in the handoff process. \( x \) and \( y \) are the two-dimensional coordinates that denote the physical location of the reference mobile terminal in cell \( i \). We show the received SINR on the reference mobile as:

\[
C_i = \frac{p_i \cdot g_i(r_i)}{\sum_{j \neq i} p_j \cdot g_{j,i}(l) + n_i} \quad i, j = 1, 2, ..., N 
\]  

(3.3)

In addition to \( p_i \) denoting the pilot strength of the \( i \)th access point, \( g_i(r_i) \) represents the channel gain from the access point \( i \) to the reference mobile and is a function of their distance \( r_i \). \( g_i(r_i) \) can be obtained by the signal path loss model which is a unique channel characterization of cell \( i \). \( p_j \) and \( g_{j,i}(l) \) for \( j \leq N \) and \( j \neq i \) denote
the pilot power and the downlink interference gain from the $j$th cell to the reference mobile in cell $i$. $C_i$ is a weight parameter to balance different femtocell sizes based on specific traffic distribution in the network. The bigger setting of $C_i$ will make larger cell size configuration for femtocell $i$. Finally, $n_i$ denotes the received noise power on the reference mobile terminal.

The measurement of the interference gain $g_{j,i}(l)$ can be easily performed in a CDMA cellular system. A reference mobile in soft handoff process can simultaneously talk to multiple neighbouring access points/base stations, which makes both information of $p_j$ and $g_{j,i}(l)$ easy to know by the network controller.

Then, from equation (3.3) we get the expression of $\mathcal{F}_i(p)$ as:

$$\mathcal{F}_i(p) = r_i = g_i^{-1}\left(\frac{1}{p_i} \cdot C_i \cdot \left[ \sum_{j \neq i} p_j \cdot g_{j,i}(l) + n_i \right]\right), \quad i, j = 1, 2, ..., N \quad (3.4)$$

where the function of $g_i^{-1}(\cdot)$ denotes the inverse function of finding the cell radius from the pilot power based on the path loss function $g_i(\cdot)$. Therefore, the original problem in (3.2) can be written as:

$$\max t \quad (3.5)$$

$$s.t. \quad g_i^{-1}\left(\frac{1}{p_i} \cdot C_i \cdot \left[ \sum_{j \neq i} p_j \cdot g_{j,i}(l) + n_i \right]\right) \geq t, \quad i, j = 1, 2, ..., N$$

$$0 \leq p_i \leq p_{\text{max}_i}, \quad i = 1, 2, ..., N$$

The convexity and mathematical tractability of the above problem are deter-
mined by specific path loss expression $g_i(r_i)$ for each cell $i$. Note that $g_i(r_i)$ is a monotonically decreasing function, i.e. bigger cell radius $r_i$ always leads to smaller channel gain of path loss. Therefore, the problem (3.5) can be rewritten as the following:

$$\begin{align*}
\max & \quad t \\
\text{s.t.} & \quad \frac{1}{p_i} \cdot C_i \cdot \left[ \sum_{j \neq i} p_j \cdot g_{j,i}(1) + n_i \right] \leq g_i(t), \quad i, j = 1, 2, \ldots, N \\
& \quad 0 \leq p_i \leq p_{\max i}, \quad i = 1, 2, \ldots, N
\end{align*}$$

In order to find the solution for problem (3.6), we assume that the path loss characterization $g_i(\cdot)$ in each femtocell $i$ has the same mathematical expression. Then, the maximization on scalar $t$ can be replaced by the minimization on $g(t)$ and the problem (3.6) can be written as:

$$\begin{align*}
\min & \quad g(t) \\
\text{s.t.} & \quad \frac{1}{p_i} \cdot C_i \cdot \left[ \sum_{j \neq i} p_j \cdot g_{j,i}(1) + n_i \right] \leq g(t), \quad i, j = 1, 2, \ldots, N \\
& \quad 0 \leq p_i \leq p_{\max i}, \quad i = 1, 2, \ldots, N
\end{align*}$$

Finally, the problem (3.7) is equivalent to the following expression:
\[
\begin{align*}
\min & \quad \max \quad \frac{C_i \cdot [\sum_{j \neq i} p_j \cdot g_{j,i}(l) + n_i]}{p_i}, \quad i, j = 1, 2, \ldots, N \\
\text{s.t.} & \quad 0 \leq p_i \leq p_{\text{max}i}, \quad i = 1, 2, \ldots, N
\end{align*}
\] (3.8)

which is a convex and linear fractional programming (LFP) problem [53]. There are a couple of methods to solve an LFP problem by either transforming it to an equivalent linear programming (LP) problem or solving a sequence of linear programs through only re-computing the local gradient of the objective function. In our problem (3.8), we also need to know the factor \( g_{j,i}(l) \) which determines the interference power gain from adjacent cells \( j \) to the reference mobile in cell \( i \). In next section, we propose a discrete-time power updating procedure in order to find the optimal cell coverage \( r^* \) and pilot power configuration \( p^* \). The position of the reference mobile in each cell is updated in a periodical manner, which facilitates the search for optimal solution.

Our formulation (3.8) incorporates two cellular factors for pilot power optimization in a user-deployed cellular network. First, each of the femtocells should be able to characterize its channel environment through a unique characterization of \( g(r) \). This can be done by different means based on specific cellular standard under consideration. For example, in a Time Division Synchronous Code Division Multiple Access (TD-SCDMA) network, the uplink communication is synchronized on chip level which allows the access point to measure the signal path loss in a cell. Second, by implementing different weight parameters \( C_i \) to femtocells, the cell sizes can be
adaptively balanced according to specific resource allocation requirement.

### 3.2 An Autonomous Pilot Management Procedure

![Figure 3.2: Autonomous BS Pilot Power Update Procedure](#)

Based on the proposed optimization model, we study a practical procedure for autonomous pilot management in a 3G cellular network as shown in Figure 3.2. All femtocells are supposed to register themselves to a network controller ACM managed...
by the network operator. The software in ACM solves the optimization problem (3.5) and sends commands for pilot power configuration. The whole control procedure is considered to follow two stages under different traffic conditions as discussed in the following.

When traffic load is low in a femtocell, the access point can enter sleep mode in order to reduce the pilot pollution to its neighbours (Step 1). An access point in sleep mode is supposed to turn off its downlink radio when no traffic shows up for a certain period of time. The uplink radio of the access point listens to the pilot signals from the neighbouring co-channel cells and build up a neighbour list as the environment characterization (Step 2). Based on the result from environment listening, a femtocell estimates the signal propagation model \( g(\cdot) \) for solving the optimization problem (3.5).

When traffic goes high in a femtocell, pilot management needs to be optimized according to (3.5). Femtocells in sleep mode can be woken up by mobile users who has data to transmit (Step 3). The wake-up signal is received by a number of access points that forward the signal identification together with the signal strength received to the network controller. The controller then determines the access point that received the maximum signal and commands that access point to respond to the user and initiate a connection with that user. Once a femtocell is chosen to be woken up (Step 4), its pilot strength must be initiated to a minimum value.
Then, based on $g_i(\cdot)$ and $C_i$ for each cell $i = 1, 2, ..., N$, the ACM can iteratively update the pilot power allocation by a discrete power level $\Delta p$ in each cell according to (3.5) (Step 6 and 7). The updating process keeps going until the network converges at the time when all the cell sizes reach their optimal configuration, i.e. $r = r^*$ (Step 8). The whole procedure is supposed to take a while to finish depending on the network scale and the computational capability of ACM.

### 3.3 Performance Results

We simulate the performance of our algorithm, i.e. a femtocell access point automatically updates its pilot power until either the optimal cell radius $r^*$ is satisfied or the maximum pilot power $p_{\text{max}}$ is reached. In a WCDMA cellular system, $p_{\text{max}}$ is normally set to 10% of the total transmit power of a base station. In our simulation, we set the maximum transmit power of a femtocell access point 150mW which gives $p_{\text{max}} = 15$mW.

The pilot power update has been simulated as a discrete time process. We set the identical initial power $p_{\text{min}}=1$mW for all femtocells and a step unit $\Delta p=0.5$mW is updated during each runtime of the procedure represented in Figure 3.2. For simplicity, $C_i$ is set to 1 for all femtocells which means no biased cell size configuration is considered in the network. In practice, this parameter can be adaptively configured reflecting the relative traffic density across cells. Also, the same path loss model
from Chapter 2.2.3 is used in the simulation and the channel parameters in each cell are assumed to be the same. In practice, different channel parameters may be applied to femtocells based on their individual signal propagation effect.

We randomly deploy five femtocells and 200 users in a 100×100m² simulation area. Access points are forced to be placed at least 15 meters apart from each other, which is a reasonable consideration for indoor femtocell deployment. The scenario actually represents an example for sparse infrastructure deployment and the result of cell size optimization is shown in Figure 3.3. All cells are of roughly the same size.

Figure 3.3: Optimized Cell Sizes for Five-Femtocell Deployment

We randomly deploy five femtocells and 200 users in a 100×100m² simulation area. Access points are forced to be placed at least 15 meters apart from each other, which is a reasonable consideration for indoor femtocell deployment. The scenario actually represents an example for sparse infrastructure deployment and the result of cell size optimization is shown in Figure 3.3. All cells are of roughly the same size.
with the implementation of maximum pilot power $p_{\text{max}} = 15\text{mW}$. This is because cells are well spread out in space with little interference between each other. Each access point allocates the highest pilot power to maximize the individual cell radius according to (3.5), and associate the largest number of users in vicinity. Users that are not covered by any of the femtocells are still served by the macrocell base station (not shown in the Figure) as public users.

![Figure 3.4: Optimized Cell Sizes for Ten-Femtocell Deployment](image)

Figure 3.4: Optimized Cell Sizes for Ten-Femtocell Deployment

Now we double the femtocell deployment density to ten in the same $100 \times 100\text{m}^2$ area and maintain the number of mobiles unchanged as 200. After autonomous
adaptation to the new infrastructure topology according to (3.5), cell size configuration shows different result as shown in Figure 3.4. Access points that happen to be closely deployed in the central-right and left areas automatically reduce the pilot power and shrink their cell size. Cells that are more spread out in other areas still allocate full pilot power due to lower interference among them. Compared to the simulation results in [10] with constant cell size configuration, our algorithm adaptively determines the pilot power allocation according to the dynamic change of infrastructure topology. Without regular cell planning in the simulation area, the algorithm works to well balance the size of different cells with minimum size variance. This is because the objective in (3.5) already maximizes the smallest cell size in the network.

Now we vary the number of femtocells deployed in the simulation area from 0 to 20 and study the variance of the cell coverage in the network. The result is shown in Figure 3.5 which compares two pilot power configuration schemes. One is to have a constant pilot power of 15mW in each femtocell and the other is based on our autonomous pilot update algorithm. We find that smaller cell variance is achieved in the network with our scheme. When the number of femtocells increases to 20 in 100×100m² area, autonomous cell configuration keeps the cell variance below 8m while the traditional method causes a bigger value up to 14m. Low cell size variance is automatically achieved by the Max-Min operation in (3.5), which offers equalized
Figure 3.5: Variance of Femtocell Coverage in Diameter

service coverage for different femtocell users in the network.

3.4 Summary

In this chapter, we studied a method to configure the femtocell pilot power in an autonomous cellular network. The method can be applied to various cellular standards when channel propagation model is easy to measure from the network environment. Performance results showed the effect of auto-configuration of the cell sizes based on the knowledge of signal propagation model and network traffic distribution.
Chapter 4

A MAC Protocol Design for

 Autonomous Cellular Resource Allocation

In Chapters 2 and 3, we have studied two critical issues in a user-deployed cellular network, i.e. cognitive interference management and autonomous pilot power management. Now, our work leaves the third problem interesting to study, which is about cellular resource assignment across different cells. In traditional cellular networks with regular cell planning, cellular resource is basically allocated to different cells in a uniform manner. In autonomous cellular networks, spectrum resource is spatially reused in a random way and traffic requirement in each cell is of big
difference from others. In this chapter, we design a Media Access Control (MAC) protocol which schedules packet transmission in each cell and balances resource allocation between neighbouring cells. Compared to the existing work [54] and [55] our scheduler works in a much simpler manner requiring less exchange of the channel information between neighboring cells. Performance results are evaluated by simulation in a cellular WiFi system with autonomous infrastructure deployment.

In our discussion, we focus on downlink communication in a cellular network and interference management is realized by power control between co-channel cells. In Section 4.1, we first study a generic downlink power allocation model in an autonomous cellular network. Based on each user’s QoS requirement, the downlink transmit power in each cell is optimized for interference minimization. In Section 4.2 and 4.3, we present a practical MAC protocol design which facilitates the realization of cooperative power allocation in different cells.

4.1 Generic Model for Downlink Power Management

We assume that $K$ co-channel cells are randomly deployed in a geographical area as shown in Figure 3.1. Omni-directional antennas are implemented on both the base station and mobiles such that power radiation in downlink is isotropic in each cell.
For each base station \( k \) serving the \( i \)th user \( i_k \), its downlink transmit power \( p_{k,i_k} \) needs to produce a receive power margin over the total co-channel interference. We denote \( \gamma_{k,i_k} \) as the expected SINR threshold for the \( i \)th user in the \( k \)th cell, which reflects the QoS requirement determined by higher layer applications. Our purpose is to find the minimum transmit power allocation in each cell which satisfies each user’s QoS requirement. This leads to the very generic formulation of the following optimization problem:

\[
\begin{align*}
\text{min} & \quad \alpha \\
\text{s.t.} & \quad p_{k,i_k} \leq \alpha \cdot P_{\text{max}}, \quad k = 1, 2, \ldots, K \\
& \quad \sum_{j \neq k} p_{j,i_j} \cdot g_{j,i_k} \cdot g_{j,i_k} + n_{k,i_k} \geq \gamma_{k,i_k}, \quad j, k = 1, 2, \ldots, K \\
& \quad p_{k,i_k} \geq 0, \quad k = 1, 2, \ldots, K \\
& \quad \alpha \geq 0,
\end{align*}
\]

where the constraints in (4.2) limit the transmit power of each base station by a multiplying factor of \( \alpha \). The minimization of \( \alpha \) automatically minimizes the power allocation for each base station. Here we have supposed that \( P_{\text{max}} \) is same for all base stations deployed by users. The group of constraints in (4.3) guarantees the QoS requirement for each user \( i_k \) in the \( k \)th cell. \( g_{k,i_k} \) denotes the channel gain from the \( k \)th base station to its own mobile user \( i_k \). For \( j \neq k \), \( p_{j,i_j} \) denotes the transmit power of the neighbouring \( j \)th base station to its own \( i_j \)th user, and \( g_{j,i_k} \).
is the downlink interference gain from the \( j \)th base station to the user \( i_k \) in the interested cell \( k \). Therefore, the whole term of \( p_{j,i_j} \cdot g_{j,i_k} \) represents the received downlink interference power from the \( j \)th base station to the current user \( i_k \) in cell \( k \). The optimization variables are scalar \( \alpha \) and the \( K \times 1 \) power allocation vector \( \mathbf{p}; p_{k,i_k}, g_{k,i_k}, g_{j,i_k} \) and \( P_{max} \) are constants. Here we have assumed that the SINR constraints in (4.3) are such that the problem exists at least one feasible solution.

Formulation (4.1) gives the most generic description of the problem, i.e. when a certain transmission scheduling to users \((i_1, i_2, ..., i_K)\) is determined in all \( K \) cells at a particular time, the optimal power allocation is to minimize the margin of \( p_{k,i_k}/P_{max} \) over all base stations. The minimal vector \( \mathbf{p}^* \) produces the lowest power radiation of each base station in order to meet the QoS requirement for the current user being served in each cell.

The above problem is not easy to solve in practice because of its mathematical tractability and the unknown parameters of \( g_{j,i_k} \) for \( j \neq k \), i.e. the instantaneous interference gain from each neighbouring base station to the scheduled user of interest. Because the total downlink interference always comes at the same time from each neighbouring base station, it is not realistic to know the interference level of each interfering neighbouring base station in order to solve the problem. Previous research work [54] has proposed a scheduling scheme that maximized the cellular spectrum efficiency provided each interference metric is known in a fixed cellular
network without user mobility.

4.2 A MAC Protocol Design for Cellular Power Allocation

Since the instantaneous co-channel interference metric is hard to obtain by users, we want to do some regular channelization that facilitates power allocation to base stations. We first break the total base station transmit power into $N$ different levels $p = (p_1, p_2, \ldots, p_N)$, $p_1 \leq p_2 \leq \ldots \leq p_N$, with some constant power gap, e.g. 2dB. Then we want to come up with a protocol that manages the the allocation of the power vector $p$ in each cell. We define a notion of service period ($SP$) in time domain as shown in Figure 4.1, which represents the period of updating the power allocation to base stations. A pilot or beacon frame defines the start of an $SP$ similar to the concept of service interval (SI) in the IEEE 802.11e standard [56]. An $SP$
can be further partitioned into $N$ power bins ($PB$) with equal length over time. At the start of each $PB$, a short pilot frame is broadcast to users announcing the transmit power used in the following $PB$ time, which takes one of the $N$ values from the power allocation vector $p$. A network controller takes charge of power vector assignment to different base stations in a synchronized manner in time domain, which allows each base station to give a regular announcement of an *interference map* to its neighbours. The minimum length of $PB$ configuration depends on the speed of channel variation in the network. Mobile users that are served inside a $PB$ duration are supposed to see a constant channel envelope, which leads to a couple of milliseconds in a fast fading channel environment.

Figure 4.2: Power Vector Allocation

Figure 4.2 illustrates an example protocol for power vector allocation. Suppose that five co-channel cells are deployed by users in a certain geographical area where
the two shaded cells represent the areas with relatively high traffic requirement. A
good power allocation scheme intuitively leads to the results shown in Figure 4.2
where the shaded cells can obtain the vectors with reversed power allocation pattern.
Other cells exemplified for less traffic requirement have no need for full power vector
allocation. The time layout of $SP$ and $PB$ has to be perfectly lined up with good
synchronization as shown in Figure 4.3. This can be done by a network controller
(e.g., RNC or ACM) that coordinates the transmission activity in different cells
and manages the power vector allocation for each base station. By coordinating the
power allocation pattern on different base stations, their cell sizes keep compensating
from each other to mitigate the mutual interference in the network.

Figure 4.3: Synchronized Power Allocation Vector

Based on this approach, the downlink power control problem in (4.1) can be
replaced by two procedures of power vector allocation to each base station and user
scheduling based on a particular power allocation pattern in each cell. Such a channelization protocol regularizes the interference pattern in the network which makes intercell scheduling easier to implement in comparison to the generic problem (4.1). A base station needs to schedule users to the right \( PB \) with a constant interference level received from its neighbouring cells. This facilitates the interference management based on the easy management of power vector allocation to different base stations.

Now we want to study the method to determine the power allocation vector for each base station. The synchronized power allocation pattern from Figure 4.3 can be represented by a \( K \times N \) matrix as follows:

\[
P = \begin{bmatrix}
p_{11} & p_{12} & \ldots & p_{1N} \\
p_{21} & p_{22} & \ldots & p_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
p_{K1} & p_{K2} & \ldots & p_{KN}
\end{bmatrix},
\]

where each row vector represents the power allocation in each \( PB \) during an \( SP \) and each column vector denotes the power allocation to different base stations within a certain \( PB \) duration. \( K \) is the total number of cells in the whole service area and \( N \) is the number of \( PB \) in one \( SP \). In practice, the bigger value of \( N \) leads to a finer channelization pattern. The optimized power allocation for each base station \( k \) is to find the correct permutation of elements in each row vector \( p_k \) such that:
\[
\min \quad \max \quad \sum_{k=1}^{K} p_{k,n}, \quad n = 1, 2, \ldots, N \tag{4.7}
\]

The above Min-Max problem minimizes the sum transmit power of all base stations during each PB duration. The optimal solution \(P^*\) characterizes the complete power allocation pattern for all base stations during an SP. The length of one SP should be around the same magnitude of the average channel coherence time such that the channel condition in terms of (downlink channel gain) / (total interference power) can remain roughly constant during an SP. In Figure 4.3, one SP is exemplified by 12 ms which can be translated to a terminal moving speed of 42 km/h on the 900 MHz carrier frequency in a Rayleigh fading environment.

Now that the transmit power from each base station is regularized over time, a user can easily measure a channel SINR vector \(\gamma = (\gamma_1, \gamma_2, \ldots, \gamma_N)\) in an SP based on the received PB pilot signal. Knowing the channel condition in each PB a user can send back \(\gamma\) in uplink in order to facilitate the base station to schedule users in the next SP time period.

### 4.3 Scheduler Design for Base Stations

In this section we study a scheduler that allocates mobile users to the right PB in a cell based on their channel measurement \(\gamma\) and data traffic requirement. So far two
vectors $p^*$ and $\gamma$ have been determined at each base station. The vector $p^*$ specifies the transmission power pattern in one $SP$, during which the channel conditional is characterized by the SINR vector $\gamma$. We equally divide the length of each $PB$ into $L$ different service slots ($SS$) as shown in Figure 4.1. Each $SS$ represents the unit resource time $T_{SS}$ assigned to users. We denote the element $c_{i,j}$ of the variable $M \times N$ matrix $C$ as the number of $SS$ allocated to the $i$th mobile in the $j$th $PB$:

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1N} \\ c_{21} & c_{22} & \cdots & c_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ c_{M1} & c_{M2} & \cdots & c_{MN} \end{bmatrix}, \quad (4.8)$$

where $M$ is the number of users in the cell of interest and $N$ is the number of $PB$s inside one $SP$. The matrix $C$ fully specifies the transmission slot allocation for each mobile in each $PB$. Each row vector $(c_{m1} \ldots c_{mN})$ denotes the $SS$ allocation for user $m$ in each $PB$s; And the elements summation of the column vector $(c_{1j} \ldots c_{Mj})^T$ represents the total number of the $SS$ inside a specific $PB$ time $n$, such that:

$$\sum_{m=1}^{M} c_{m,n} \leq L, \quad n = 1, 2, \ldots, N \quad (4.9)$$

The optimal scheduler $C^*$ is such that:
where the constraints in (4.11) guarantees a complete finish of the user $m$’s traffic $B_m$ in the following SP, which is determined by the service requirement of the user. The function $R(\cdot)$ transforms the achievable data rate from the channel SINR $\gamma_{m,n}$ based on some acceptable bit error rate (BER). Constraints in (4.12) bounded the total available number of SS in one PB and (4.13) guarantees the non-negative number of SS allocation.

The optimization objective (4.10) minimizes the total downlink transmission time given a certain amount of traffic requirement in each cell. This implicates that mobiles with better SINR condition will be allocated to stronger PB’s. Along with the optimization requirement from (4.7) which allocates complementary transmit power between cells, the above scheduler automatically creates orthogonal transmissions when the aggregate cell traffic is low. When the traffic load goes up in the network, the intercell channelization turns from orthogonal to sub-orthogonal based on the QoS constraints defined in (4.11). Cells with low traffic automatically release
their power resource to other high traffic cells. The algorithm generalizes the work in paper [55] which simply performs orthogonal channelization between co-channel cells with low spectrum efficiency.

The optimization problem (4.10) can be transformed into a standard linear programming format in the following discussion. We align the row vectors in matrix \( \mathbf{C} = \{ \mathbf{c}_1^T, \mathbf{c}_2^T, \ldots, \mathbf{c}_M^T \} \) and make it to a single vector \( \mathbf{c} \):

\[
\mathbf{c} = \begin{bmatrix}
\mathbf{c}_1 \\
\vdots \\
\mathbf{c}_M
\end{bmatrix} = \begin{bmatrix}
c_{11} \ldots c_{1N} \ldots c_{M1} \ldots c_{MN}
\end{bmatrix}^T \quad (4.14)
\]

To get the same expression in (4.11), we define an \( M \times (M \cdot N) \) matrix \( \mathbf{A}_1 \):

\[
\mathbf{A}_1 = T_{ss} \cdot \begin{pmatrix}
\mathbf{R}_{11} & \ldots & \mathbf{R}_{1N} & 0 & \ldots & 0 & 0 & \ldots & 0 \\
0 & \ldots & 0 & \mathbf{R}_{21} & \ldots & \mathbf{R}_{2N} & 0 & \ldots & 0 \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
0 & \ldots & 0 & 0 & \ldots & 0 & \mathbf{R}_{M1} & \ldots & \mathbf{R}_{MN}
\end{pmatrix} \quad (4.15)
\]

and a \( M \times 1 \) vector \( \mathbf{b}_1 = [B_1 \ldots B_M]^T \). Then, the first constraint (4.11) can be expressed in a vector production form:

\[
\mathbf{A}_1 \mathbf{c} \succeq \mathbf{b}_1 
\]
Similarly, we can define an $M \times (M \cdot N)$ matrix $A_2$:

$$A_2 = \begin{pmatrix}
1 & 0 & \ldots & 0 & 1 & 0 & \ldots & 0 \\
0 & 1 & 0 & \ldots & 0 & 1 & 0 & \ldots \\
\vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\
0 & \ldots & 0 & 1 & 0 & \ldots & 0 & 1
\end{pmatrix}$$

(4.17)

and an $M \times 1$ vector $b_2 = L \cdot 1$. Then, the second constraint (4.12) can be expressed as:

$$A_2 c \preceq b_2$$

(4.18)

Therefore, the original optimization problem (4.10) can be written in the following standard linear programming form, which can be easily solved either analytically or by software programs.

$$\begin{align*}
\min & \quad 1^T c \\
\text{s.t.} & \quad A_1 c \succeq b_1 \\
& \quad A_2 c \prec b_2 \\
& \quad c \succeq 0
\end{align*}$$
Parameter | Value
---|---
Length of SP | 10ms
Number of PB in one SP | 4
Number of SS in one PB | 5
AP Transmission Rate | 54Mbps
AP Transmit Power | 20dBm, 17dBm, 15dBm, 13dBm
Number of APs | 5
AP Deployment | Random
Simulation Area | 2500m²
Packet Arrival Model | Poisson
Data Packet Payload | 500Bytes
ACK Packet Payload | 14Bytes
RTS/CTS | Yes

Table 4.1: Simulation Parameters

4.4 Performance Results

The downlink performance is studied by simulation in a multi-cell WiFi (IEEE 802.11a) system. Five co-channel access points are randomly placed in a $50 \times 50$m² area as shown in Figure 4.2 and simulation parameters are displayed in Table 4.1. Fifteen mobiles are uniformly deployed in each cell to share the maximum 54Mbps radio transmission rate. Each access point has four synchronized PB channel allocation with the transmit power levels: 20dBm, 17dBm, 15dBm, and 13dBm. In practice, the transmit power in each PB can be adaptively changed by the network controller according to the specific traffic load distribution in the network. In our
simulation, we make them fixed values for simplicity. The allocation of $PB$ for each access point follows the method in (4.7). And each access point schedules the mobile uses based on the optimization algorithm in (4.10). The signal path loss model used in simulation is characterized by the following equation:

$$L(d) = L + \gamma \log_{10}(d),$$

where $L = 30$dB, $\gamma = 3.5$ and the Lognormal fading deviation is set to 8dB.

---

![Figure 4.4: Autonomous Cellular Resource Allocation Procedure](image-url)
Now we discuss a procedure used in our simulation in Figure 4.4 which realizes autonomous power allocation and resource scheduling in each cell. At the initial stage when cell traffic is low, all access points set their transmit power to the lowest level $p_1$ which generates minimum interference to neighbouring cells (Step 1). When cell traffic increases, each access point periodically checks the QoS satisfaction from each user based on the optimization constraint (4.11) (Step 2). If there is a need to increase the resource allocation to handle more cell traffic, the access point autonomously updates its transmit power vector by adding 2dB into its lowest $PB$ (Step 3). Then, the global power allocation matrix needs to be updated following the algorithm (4.7) (Step 4). After the power vector gets updated in each cell, resource scheduling is implemented by solving the optimization problem (4.10) (Step 5). Each access point is supposed to autonomously update the transmit power and cellular resource allocation in a periodic manner (Step 6).

With the above settings, we compare the performance of our protocol and the ordinary IEEE 802.11 standard based on CSMA/CA. We show the performance of the center cell shown in Figure 4.2. First, we study a case that the aggregate traffic load in four neighbouring cells is set to 20Mbps, which is supposed to coin a low network interference scenario. From the blue curves in Figure 4.5, we see that the increase of the downlink transmission frame error rate (FER) is much slower with our scheduling approach. This is because of the fact that the optimized channel
allocation determined by (4.7) and (4.10) creates orthogonal intercell channels over time. When we change the interference environment to a worse case with doubled traffic load to 40Mbps in neighbouring cells, the benefit gap becomes even larger. This is because the interference has been well managed by creating sub-orthogonal intercell channelization across the five cells. The cell sizes well compensate with each other that reduces the co-channel interference.

![Graph](image)

Figure 4.5: Average Downlink Frame Error Rate

The performance of average packet transmission delay is shown in Figure 4.6. Again, blue curves show that the average downlink transmission delay gets worse for both cases as the traffic load increases in low interference environment. However,
an average of 20% throughput gain is achieved by our protocol within the bounded delay of 50ms. This is because the packet retransmissions caused by the MAC layer packet collision have been effectively reduced.

![Figure 4.6: Average Downlink Transmission Delay](image)

With a doubled traffic load in the neighbouring co-channel cells, a worse delay performance is represented by the red curves in Figure 4.6. One can see that with our control approach, the delay performance is less sensitive to the traffic increase in cells. And a bigger throughput benefit can be achieved within the same bounded delay value compared to the previous case. This converges to the FER results that our channelization and scheduling protocol better improves the network performance.
in high network interference scenarios.

4.5 Summary

In this chapter we proposed an intercell channelization scheme that manages network interference and balances radio resource allocation across cells. The scheme can be implemented as an add-on control function to some of the existing cellular standards. A network controller creates orthogonal/sub-orthogonal channels with adaptive power allocation in different cells. Unlike the CDMA 1x EV-DO technology, the scheme is supposed to be more applicable in static or slow fading channel environment, e.g., femtocell application scenarios. When the global traffic distribution parameter is known in a cellular network, the transmit power of each cell should be adaptively adjusted to meet the resource balance requirement. The scheme may also be used in cellular MIMO systems where the spatial channel multipaths are rich and the power control can be applied as an effective method for interference management.
Chapter 5

Conclusion

In this work, a 4G method of deploying a cellular network is introduced based on the concept of autonomous network management. Interference management, cell size configuration, mobile handoff management and network resource allocation must be carried out in an autonomous manner based on the knowledge of network environment. A cellular framework that covers the above issues is developed based on the method of network listening and cognitive radio configuration. Future cellular networks are supposed to be more software dependent. Optimization algorithms can be easily applied to hardware equipment, which offers strong radio configurability for cellular spectrum management.

Future work will be focusing on the uplink study based on the idea of cognitive channel allocation. Network capacity will be studied based on different strategies for
user access, i.e. open, closed and hybrid. Other network factors will be considered in the model for pilot power management, such as the traffic distribution in cells and mobile handoff requirement between macrocell and femtocells.
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