In compliance with the
Canadian Privacy Legislation
some supporting forms
may have been removed from
this dissertation.

While these forms may be included
in the document page count,
their removal does not represent
any loss of content from the dissertation.

Coverage Enhancement with Analog Fixed Relaying in Cellular Radio Networks

By

Xiaobin Tang, M.Eng.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements of the degree of

Master of Applied Science

Ottawa-Carleton Institute for Electrical and Computer Engineering

Department of Systems and Computer Engineering

Carleton University

Ottawa, Ontario

August 2003

© Copyright 2003, Xiaobin Tang

National Library
of Canada

Bibliothèque nationale
du Canada

Acquisitions and
Bibliographic Services

Acquisitions et
services bibliographiques

395 Wellington Street
Ottawa ON K1A 0N4
Canada

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

ISBN: 0-612-88898-3

Our file Notre référence

ISBN: 0-612-88898-3

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

Canada

Abstract

This thesis is focused on using analog technology to facilitate fixed-relaying in third and fourth generation wireless networks to provide ubiquitous high data rate coverage. An on-channel analog repeater model that amplifies both signal and noise has been introduced. Two different on-channel relaying schemes are discussed: Non-selective on-channel fixed relaying and selective on-channel fixed relaying. Diversity with Maximal Ratio Combining (MRC) is used. Coverage improvements obtainable with frequency reuse factor=1 and different interference suppression capabilities have been determined. Different factors affecting coverage, including variation in the feedback gain of relays, gain enhanced donor link, SINR threshold, cell radius, propagation exponent and number of relays and placement of those relays, have been examined. As well, we examined gain/stability requirements for on-channel relays and determined effect of interference to and from relayed signals as well as determining best relay placement. Our simulation results show that analog fixed relaying can significantly improve coverage in a cell. Non-selective analog fixed relaying has an appealing simplicity as well as great performance. We also compared its coverage performance with that of a digital relaying system.

Acknowledgements

First and foremost, I would like to express my sincerely gratitude to my thesis supervisor, Professor David Falconer of Carleton University, for his instruction, guidance, unwavering patience and support throughout this research work. His knowledgeable suggestions and passion have greatly motivated me to enjoy this process and significantly improved the end result.

In addition, I would like to thank Professor Halim Yanikomeroglu of Carleton University for his thoughtful arrangement, providing research device and some references. I am also grateful to Nortel Networks for their financial support in this research. As well, I am sincerely grateful to Mr. Narendra Mehta, Mr. John Knox of the Department of Systems and Computer Engineering, for their time and effort in installing the necessary software programs that were needed for this research. Finally, I also would like to thank the ladies from the Department for their kindly reminder of important deadlines.

Table of Contents

Abstract.....	ii
Acknowledge.....	iii
Table of Contents.....	iv
List of Figures.....	vii
List of Acronyms.....	xii
List of Symbols.....	xiii
 Chapter 1: Introduction	 1
1.1 Motivation.....	1
1.2 Objectives and Scope.....	3
1.3 Contributions	3
1.4 Organization.....	4
 Chapter 2: Relaying Concept	 6
2.1 Relaying in Cellular Radio Networks.....	7
2.2 Analog Repeaters.....	8
2.3 Coverage.....	12
2.3.1 Maximum Tolerable Path loss.....	12
2.3.2 Coverage Computation.....	14
 Chapter 3: Analog Fixed Relaying Scheme.....	 15
3.1 System Design.....	15
3.2 On-Channel Relay Model.....	17
3.3 Non-Selective Analog Fixed Relaying Scheme.....	18
3.3.1 Non-Selective Analog Fixed Relaying Path Modeling..	19

3.3.2	Mathematical Model of Non-Selective On-Channel Relay Network.....	21
3.4	Selective Analog Fixed Relaying Scheme	23
3.4.1	Relay Selection Criterion	24
3.4.2	Mathematical Model of Adaptive Gain Control.....	26
Chapter 4:	Simulation Model.....	31
4.1	Path Loss Model Selection.....	31
4.2	Enhanced Gain on Donor Link.....	32
4.3	Environment and Parameters Assumption.....	33
4.4	Simulation Algorithm.....	35
Chapter 5:	Simulation Results for Non-Selective Scheme.....	38
5.1	Impact of Feedback Gain and Locations of Relays on Coverage.....	38
5.2	Impact of Gain Enhanced Donor Link on Coverage.....	47
5.3	Impact of SINR Threshold on Coverage.....	54
5.4	Impact of Cell Radius on Coverage.....	58
5.5	Impact of Interference on Coverage.....	60
5.6	Impact of Propagation Exponent on Coverage.....	63
5.7	Impact of the Number of Relays on Coverage.....	65
Chapter 6:	Simulation Results for Selective Scheme.....	68
6.1	Impact of Feedback Gain and Locations of Relays on Coverage.....	68
6.2	Impact of Gain Enhanced Donor Link on Coverage.....	73
6.3	Impact of SINR Threshold on Coverage.....	78
6.4	Impact of Cell Radius on Coverage.....	81
6.5	Impact of Interference on Coverage.....	84
6.6	Impact of Propagation Exponent on Coverage.....	86
6.7	Impact of the Number of Relays on Coverage.....	88
6.8	Comparison with Digital Fixed Relaying Scheme.....	90
6.8.1	Simulation Parameters.....	91
6.8.2	Simulation Results of Analog Fixed Relaying	93
6.8.3	Simulation Results of Digital Fixed Relaying.....	95
6.8.4	Comparison of Results.....	97

Chapter 7: Discussions & Conclusions.....	99
7.1 Results Summary.....	99
7.2 Further Discussions.....	100
7.3 Suggestions for Future Research.....	102
References.....	104

List of Figures

Figure 2.1 Analog Fixed Relaying	8
Figure 2.2 On-Channel Repeater.....	9
Figure 2.3 Solutions of Isolating Antennas.....	10
Figure 2.4 Channel Allocations in a Translating Repeater System.....	11
Figure 3.1 System Design (with Six Fixed Relays).....	16
Figure 3.2 On-Channel Relay Model.....	17
Figure 3.3 Non-Selective Analog Fixed Relaying Path Modeling for Downlink.....	20
Figure 3.4 Scheme of Selective Analog Fixed Relaying.....	25
Figure 3.5 Relay Modeling.....	27
Figure 3.6 Path Modeling of Selective Analog Relaying	28
Figure 4.1 Enhanced Gain on the Donor Link.....	32
Figure 4.2 Flow Chart of Non-Selective Analog Fixed Relaying Process.....	36
Figure 4.3 Flow Chart of Selective Analog Fixed Relaying Process.....	37
Figure 5.1 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for feedback = 10^{-10} , 500 m cells without gain enhanced donor link).....	39
Figure 5.2 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for feedback = 10^{-12} , 500 m cells without gain enhanced donor link).....	40
Figure 5.3 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for feedback = 0, 500 m cells without gain enhanced donor link).....	41
Figure 5.4 Gains Distribution of 4 Relays at the $\frac{1}{2}$ Cell Radius for Non-Selective Relaying without Gain Enhanced Donor link.....	44
Figure 5.5 Gains Distribution of 4 Relays at the $\frac{3}{4}$ Cell Radius for Non-Selective Relaying without Gain Enhanced Donor link.....	45

Figure 5.6 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for feedback = 10^{-6} , 500 m cells without gain enhanced donor link).....	46
Figure 5.7 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for feedback = 10^{-8} , 500 m cells without gain enhanced donor link).....	47
Figure 5.8 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for feedback = 10^{-10} , 500 m cells with 14dB gain enhanced donor link).....	48
Figure 5.9 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for feedback = 10^{-12} , 500 m cells with 14dB gain enhanced donor link).....	49
Figure 5.10 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for feedback = 0, 500 m cells with 14dB gain enhanced donor link).....	50
Figure 5.11 Gains Distribution of 4 Relays at the $\frac{1}{2}$ Cell Radius for Non-Selective Relaying with 14dB Gain Enhanced Donor link.....	51
Figure 5.12 Gains Distribution of 4 Relays at the $\frac{3}{4}$ Cell Radius for Non-Selective Relaying with 14dB Gain Enhanced Donor link.....	52
Figure 5.13 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for feedback = 10^{-6} , 500 m cells with 14dB gain enhanced donor link).....	53
Figure 5.14 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for feedback = 10^{-8} , 500 m cells with 14dB gain enhanced donor link).....	54
Figure 5.15 User Coverage vs. SINR Threshold with Non-Selective Scheme (for feedback = 10^{-10} , 500 m cells without gain enhanced donor link).....	55
Figure 5.16 User Coverage vs. SINR Threshold with Non-Selective Scheme (for feedback = 10^{-12} , 500 m cells without gain enhanced donor link).....	56
Figure 5.17 User Coverage vs. SINR Threshold with Non-Selective Scheme (for feedback = 0, 500 m cells without gain enhanced donor link).....	57
Figure 5.18 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for feedback = 10^{-12} , 1000 m cells with 14dB gain enhanced donor link).....	58
Figure 5.19 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for feedback = 0, 1000 m cells with 14dB gain enhanced donor link).....	59
Figure 5.20 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for either interference factor = 1 or 0.5, feedback = 10^{-12} , 500 m cells without gain	

enhanced donor link).....	61
Figure 5.21 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for either interference factor = 1 or 0.5, feedback = 10^{-12} , 500 m cells with 14dB gain enhanced donor link).....	62
Figure 5.22 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for propagation exponent = 3.5, feedback = 10^{-12} , 500 m cells without gain enhanced donor link).....	63
Figure 5.23 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for propagation exponent = 3.5, feedback = 10^{-12} , 500 m cells with 14dB gain enhanced donor link).....	64
Figure 5.24 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for the number of relays: 0~16, feedback = 10^{-12} , 500 m cells without gain enhanced donor link).....	66
Figure 5.25 User Coverage vs. Number of Relays per cell with Non-Selective Scheme (for the number of relays: 0~16, feedback = 10^{-12} , 500 m cells with 14dB gain enhanced donor link).....	67
Figure 6.1 User Coverage vs. Number of Relays per cell with Selective Scheme (for feedback = 10^{-10} , 500 m cells without gain enhanced donor link).....	69
Figure 6.2 User Coverage vs. Number of Relays per cell with Selective Scheme (for feedback = 10^{-12} , 500 m cells without gain enhanced donor link).....	70
Figure 6.3 User Coverage vs. Number of Relays per cell with Selective Scheme (for feedback = 0, 500 m cells without gain enhanced donor link).....	71
Figure 6.4 User Coverage vs. Number of Relays per cell with Selective Scheme (for feedback = 10^{-6} , 500 m cells without gain enhanced donor link).....	72
Figure 6.5 User Coverage vs. Number of Relays per cell with Selective Scheme (for feedback = 10^{-8} , 500 m cells without gain enhanced donor link).....	73
Figure 6.6 User Coverage vs. Number of Relays per cell with Selective Scheme (for feedback = 10^{-10} , 500 m cells with 14dB gain enhanced donor link).....	74
Figure 6.7 User Coverage vs. Number of Relays per cell with Selective Scheme (for feedback = 10^{-12} , 500 m cells with 14dB gain enhanced donor link).....	75

Figure 6.8 User Coverage vs. Number of Relays per cell with Selective Scheme (for feedback =0, 500 m cells with 14dB gain enhanced donor link).....	76
Figure 6.9 User Coverage vs. Number of Relays per cell with Selective Scheme (for feedback = 10^{-6} , 500 m cells with 14dB gain enhanced donor link).....	77
Figure 6.10 User Coverage vs. Number of Relays per cell with Selective Scheme (for feedback = 10^{-8} , 500 m cells with 14dB gain enhanced donor link).....	78
Figure 6.11 User Coverage vs. SINR Threshold with Selective Scheme (for feedback = 10^{-10} , 500 m cells without gain enhanced donor link).....	79
Figure 6.12 User Coverage vs. SINR Threshold with Selective Scheme (for feedback = 10^{-12} , 500 m cells without gain enhanced donor link).....	80
Figure 6.13 User Coverage vs. SINR Threshold with Selective Scheme (for feedback =0, 500 m cells without gain enhanced donor link).....	81
Figure 6.14 User Coverage vs. Number of Relays per cell with Selective Scheme (for feedback = 10^{-12} , 1000 m cells with 14dB gain enhanced donor link).....	82
Figure 6.15 User Coverage vs. Number of Relays per cell with Selective Scheme (for feedback =0, 1000 m cells with 14dB gain enhanced donor link).....	83
Figure 6.16 User Coverage vs. Number of Relays per cell with Selective Scheme (for either interference factor = 1 or 0.5, feedback = 10^{-12} , 500 m cells without gain enhanced donor link).....	84
Figure 6.17 User Coverage vs. Number of Relays per cell with Selective Scheme (for either interference factor = 1 or 0.5, feedback = 10^{-12} , 500 m cells with 14dB gain enhanced donor link).....	85
Figure 6.18 User Coverage vs. Number of Relays per cell with Selective Scheme (for propagation exponent = 3.5, feedback = 10^{-12} , 500 m cells without gain enhanced donor link).....	87
Figure 6.19 User Coverage vs. Number of Relays per cell with Selective Scheme (for propagation exponent = 3.5, feedback = 10^{-12} , 500 m cells with 14dB gain enhanced donor link).....	88
Figure 6.20 User Coverage vs. Number of Relays per cell with Selective Scheme (for the number of relays: 0~16, feedback = 10^{-12} , 500 m cells without gain enhanced donor link).....	89

Figure 6.21 User Coverage vs. Number of Relays per cell with Selective Scheme (for the number of relays: 0~16, feedback = 10^{-12} , 500 m cells with 14dB gain enhanced donor link).....	90
Figure 6.22 User Coverage vs. SINR Threshold with Selective Analog Scheme (for feedback = 10^{-12} , 1000 m cells, 6 relays at the 2/3 cell radius with 14 gain enhanced donor link).....	93
Figure 6.23 User Coverage vs. SINR Threshold with Selective Analog Scheme (for feedback = 10^{-12} , 500 m cells, 6 relays at the 2/3 cell radius with 14 gain enhanced donor link).....	94
Figure 6.24 User Coverage vs. SINR Threshold with Digital Fixed Relaying Scheme (for 1000 m cells, 6 relays at the 2/3 cell radius).....	95
Figure 6.25 User Coverage vs. SINR Threshold with Digital Fixed Relaying Scheme (for 500 m cells, 6 relays at the 2/3 cell radius).....	96

List of Acronyms

AGC	Adaptive Gain Control
BER	Bit Error Rate
BS	Base Station
CDMA	Code-Division Multiple Access
DSP	Digital Signal Processing
FDMA	Frequency-Division Multiple Access
FDD	Frequency Division Duplex
GHz	Giga Hertz
HiperLAN2	High Performance Radio Local Area Network Type 2
LOS	Line-of-Sight
MAC	Medium Access Control
MHz	Mega Hertz
MIMO	Multiple Input Multiple Output
MRC	Maximal Ratio Combining
MTPL	Maximal Tolerable Path Loss
OFDMA	Orthogonal Frequency Division Multiplexing Access
RF	Radio Frequency
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
TDMA	Time-Division Multiple Access

List of Symbols

α	rms value
α^2	Time-average power of the received signal before envelope detection
σ	The standard deviation of lognormal shadowing
λ	The wavelength of carrier frequency
$\gamma_{\min}$	SINR threshold
$\gamma_{MT(\min)}$	The SINR threshold at a mobile terminal
d	Distance
d_0	The reference distance
g_{ii}	The feedback power gain of any node i
g_{ji}	The transmission power gain from node j to node i
i	Any node of a cellular radio networks
n	The propagation exponent
n_i	The noise power of any node i
k	Boltzman's constant (1.38×10^{-23} Joules / Kelvin)
s_i	The input signal power for any node i
A	The set of fixed relays
B	The transmission bandwidth
B_{DL}	The bandwidth of a mobile terminal
F	The noise figure

F_{BS}	The noise figure of a base station
F_{MT}	The noise figure of a mobile terminal
G	The amplifier gain of a selected relay
G_{BS}	The antenna transmission power gain for a base station
G_i	The combined amplifier and antenna power gain of any node i
G_{MT}	The receive antenna power gain for a mobile terminal
L_{MAX}	Maximal tolerable path loss
$L_{MAX(UL)}$	Maximal tolerable path loss for uplink
$L_{MAX(DL)}$	Maximal tolerable path loss for downlink
N	The number of nodes in a cellular radio networks
P_i	The output power from node i 's transmitting antenna
P_{BS}	The transmission power from a base station
P_{in}	The input power of selected relay i
P_I	The interference power coming from cochannel base station or relay
P_j	The output power from node j 's transmitting antenna
P_{MR}	The maximal output radiated power from a relay
P_{out}	The output power of selected relay i
P_T	The transmission power of base station
PL	The mean path-loss
R	Frequency reuse factor
T	The standard system temperature (290K)

X_1	Random variable for log-normal shadowing
X_2	Random variable for Rayleigh fading
Z	Random variable with Rayleigh distribution
$\mathbf{s}$	The matrix of the input signal powers
$\mathbf{n}$	The matrix of the internal noise powers
$\mathbf{n}_+$	The matrix of input noise powers
$\mathbf{r}$	The matrix of the received signal powers
$\mathbf{G}$	The matrix of the amplifier power gains
$\mathbf{I}$	Identity matrix
$\mathbf{N}$	The matrix of the amplified output noise powers
$\mathbf{P}$	The matrix of the amplifier output signal powers

Chapter 1: Introduction

Providing excellent system coverage is the primary requirement for all radio frequency (RF) systems design. A number of efforts have been made to provide as close to 100% reliable coverage as possible. The integration of relaying capability in conventional cellular radio networks realizes various benefits in the areas of deployment, connectivity and adaptability [14, 16].

1.1 Motivation

In the last few years, generic relaying wireless networks are most attractive to both industry and academia [16], including the “seed” concept in 3GPP [19, 25], coverage extension of HiperLAN2 through relays [15, 17, 22], user cooperative diversity [12, 13, 23, 24], etc.

In general, the recently proposed relaying technologies can be classified into: analog or digital relaying, fixed or mobile (peer-to-peer) relaying, etc.

In the analog relaying, a relay just amplifies the received signal and retransmits it to mobile terminals. In the digital relaying, a relay will digitally decode and re-encode the relayed signal before retransmission. In other words, the analog relaying is non-regenerative, while the digital relaying is regenerative [1, 14, 16]. Although people tend to consider that analog relaying would be inferior to digital relaying due to the amplified noise and interference propagation, recent research in [14, 21, 26] on the physical layer performance comparison of a number of multihop channels presents that

“this is not necessarily the case since a digital multihop channel may be limited by the hard detection at the worst hop which may cause a bottleneck” [16]. The advantage of analog relaying is especially noticeable when relaying is combined with diversity [14, 26]. This motivates the research on analog relaying.

In [3, 20, 24], a selected mobile terminal acts as a relay to communicate with the destination mobile terminal; this is a mobile (peer-to-peer) relaying technology. However, there are some difficulties to implement the peer-to-peer relaying within the upcoming cellular standards [16]. The most fundamental obstacle is that mobile terminals can not transmit and receive in the same frequency band in the FDD mode. Therefore, using mobile relaying in the traditional cellular networks requires the TDD mode of operation, otherwise all mobiles would require modification to be able to transmit and receive in both duplex frequency bands. Since FDD mode is used in almost all 3G cellular standards, mobile relaying is not feasible in this situation. Also, mobile terminals with relaying capability may be substantially more complicated [16]. Another primary obstacle with peer-to-peer relaying is that there is no guarantee for finding a suitable relay especially with lower density of the active terminals. This motivates the research on fixed relaying.

This thesis is concerned with using analog on-channel fixed relays in a cellular radio network to evaluate the system coverage improvement. In comparison with ongoing research in digital relaying technology, the analog relaying system can be planned and deployed easily and effectively due to no decoding and encoding. Because mobile terminals can not transmit and receive signal in the same frequency band in the FDD mode, they can not be used as an analog relay.

1.2 Objectives and Scope

This thesis is focused on analog on-channel fixed relaying technology. We try to:

1. Determine coverage improvements obtainable in a cellular system with frequency reuse factor = 1 from: non-selective on-channel fixed relaying and selective on-channel fixed relaying.
2. Determine coverage improvements obtainable with different interference suppression capabilities.
3. Examine gain/stability requirements for on-channel relays.
4. Examine effect of interference to and from relayed signals.
5. Compare with digital relaying on coverage.

1.3 Contributions

This thesis is concerned with on-channel analog fixed relaying in cellular radio networks. The major contributions of this thesis include:

1. Simulation analysis of an analog on-channel relay which can have an important role on coverage improvement.
2. A review of pertinent literature describing existing repeater and coverage models.
3. The definition and development of two novel on-channel analog fixed relaying schemes: non-selective and selective relaying.
4. The derivation of the mathematical model of the non-selective on-channel relaying and of Adaptive Gain Control (AGC) for the selective relaying.

5. The development of mathematical model of an on-channel relay which can be used in both non-selective relaying and selective relaying.
6. The generation of simulations that implement analog on-channel relaying for both non-selective and selective schemes.
7. A simulation analysis that verifies that non-selective relaying can have a significant impact on the system coverage.
8. A simulation analysis that verifies that selective relaying can have significant effect on the system coverage.
9. Discussions on advantages and disadvantages for the non-selective and selective relaying schemes.
10. A comparison with digital relaying researched at Carleton University.
11. The presentation of numerous implementation suggestions for non-selective and selective relaying schemes.
12. The presentation of various considerations that highlight a number of interesting areas for further research.

1.4 Organization

Chapter 2 provides a background to the relaying concept in cellular radio networks, including fixed and mobile relaying technologies, digital and analog relaying technologies. Different relays used in cellular radio networks have been summarized. Existing coverage model and studies have been discussed.

Chapter 3 presents the analog fixed relaying technology and develops an on-channel analog relay model. Two different analog fixed relaying schemes are

proposed and developed: the non-selective analog fixed relaying scheme and the selective analog fixed relaying scheme. A mathematical model for a non-selective on-channel relay network is developed and notation is introduced. Adaptive gain control for selective on-channel relay network is also proposed and developed.

Chapter 4 applies a path loss model to our simulation, introduces the concept of enhanced gain on the donor link and describes the environment parameters and assumptions utilized to simulate a system that provides relaying.

Chapter 5 presents the simulation results and discussions with respect to the various factors that can influence the system coverage performance for the non-selective relaying scheme.

Chapter 6 presents the simulation results and discussions with respect to the various factors that can affect the system coverage performance for the selective relaying scheme and provides a comparison with the digital fixed relaying based on coverage.

Chapter 7 provides some concluding remarks. The results of this thesis are summarized and considerations of designing the on-channel analog fixed relaying are suggested. Finally, a number of areas for future research are identified.

Chapter 2: Relaying Concept

This chapter is concerned with a brief background to the relaying technology. Classifications of relaying technologies have been briefly summarized.

In a traditional cellular radio network, many mobile wireless terminals communicate directly with a single fixed base station [2]. However, there are still some coverage dead spots that need to be covered [10], such as a deep valley, shadow of an intervening mountain or a man-made structure, for example, an underground shopping mall, subway station or tunnel. This problem can become more serious in third and fourth generation wireless networks due to the need to support high data rate [5, 29].

Generally, data transmission requires transmission power almost in proportion to its bit rate [2, 4]. As the transmission bit rate increases, practical area coverage decreases if the transmission power remains constant. Therefore, wide area coverage for high bit-rate data transmission, leads to the requirement for high base station density and this will significantly increase infrastructure cost [29]. The current solution to this problem is that the area coverage for high bit-rate data transmission is limited to the vicinity of the base stations to areas where line-of-sight (LOS) propagation is available, while conventional low bit-rate data transmission service can cover the entire cell. To enhance the area coverage at a reasonable infrastructure cost, relaying technology integrated in a conventional cellular network is a promising approach.

2.1 Relaying in Cellular Radio Networks

Relaying can be classified in several ways: (1) digital and analog relaying based on the signal retransmission method [1, 14, 16], (2) fixed and mobile relaying depending on the mobility of relay [3, 11, 14, 16, 27, 28], (3) intelligent and dumb relaying based on the selective capability [16, 30, 31] etc.

Digital relaying is regenerative. In digital relaying, the relay nodes digitally decode and re-encode the received signal. Digital relaying does not propagate noise. However, it possibly introduces decoding errors at each intermediate node. Thus it can degrade the system performance due to the added bit error rate (BER). Analog relaying is non-regenerative; it just amplifies and retransmits the received signal. In some papers, it was called amplified relaying [14]. It boosts noise as well as signal and introduces the possibility of decoding error only at the destination terminal.

In fixed relaying, the relay nodes are placed at some fixed locations (called “seeds” in 3GPP [19, 25]); each relay can be either digital or analog. Their electromagnetic compatibility and radio spectrum matters have been standardized in [18]. Their technical specification has been described in [19, 25]. There is need for fixed relaying infrastructure. On the other hand, in mobile (peer-to-peer) relaying, the relaying is performed by mobile terminals that have good links with their base station [3,16, 22,23,28]. Mobile terminals must be modified to have relaying capability. Peer-to-peer relaying doesn’t need any extra network infrastructure. However, it endures the problems of radio link reliability and network connectivity. It also involves the implementation of complicated routing algorithms inside each mobile terminal and a huge amount of communication signaling overhead [28].

Dumb relays, also called repeaters, are the conventional relays used for decades to improve system coverage in highly shadowed areas [8, 9, 10]. In dumb relaying, there is no need for channel selection, relay selection etc. The conventional blind dumb relaying may introduce significant multiple access interference [16]; therefore, carefully placing relay location has been an important issue. However, in intelligent relaying [3, 30, 31], only signals to/from users that need such assistance are relayed.

2.2 Analog Repeaters

Using analog repeaters (relays) in a conventional cellular radio networks with fixed location is illustrated in Figure 2.1. Additional infrastructure, (the provision of relays in fixed positions, with favorable coverage from one or more base stations) is needed in fixed relaying.

Figure 2.1 Analog Fixed Relaying

The link between the BS and relay is the donor link, while the link between relay and mobile terminal is the distribution link. Analog repeaters can be classified into on-channel and frequency-translating repeaters.

In the 1980's, an on-frequency (on-channel) repeater has been studied [8]. It was a narrow band RF amplifier that received and retransmitted simultaneously on exactly the same frequency. The on-channel repeater was strictly an RF device and did not decode and re-encode like a regular BS. Therefore, it was an analog repeater. Some application engineering considerations for on-channel repeater were suggested in [9]. An example of on-channel repeater is illustrated in Figure 2.2.

Figure 2.2 On-Channel Repeater

Since on-channel repeater receives and retransmits signal in the exactly same frequency, feedback from the output antenna to the input antenna is inevitable. The

lower the feedback is, the larger is the gain that the repeater can provide. Its two antennas must be highly isolated to minimize this feedback and make the on-channel repeater stable. Some solutions were offered in [7]: (1) Two antennas were set apart horizontally with some distance, shown in Figure 2.3 (a) (2) Two antennas were placed vertically apart with some distance, shown in Figure 2.3 (b) (3) Two antennas were put separately with a shield between them, shown in Figure 2.3 (c). The required isolation would be greater than the repeater's electrical gain by a factor known as the stability margin, typically 10-20dB, for unconditional stability [7]. In [7], the maximum repeater was limited by the gain achievable antenna isolation.

$$I > G + SM \quad , \quad (2.1)$$

where I = Antenna isolation (dB), G = Repeater's electrical gain (dB), and SM = Stability Margin (dB).

Figure 2.3 Solutions of Isolating Antennas

Antenna isolation measurements for on-channel radio repeaters have been provided in [6]. In our research, we also use on-channel relays fixed in a cellular radio network and develop mathematical models for them, using feedback gain as an important parameter.

A frequency-translating repeater also has been mentioned in [7]. This kind of repeater used two different frequencies to receive and retransmit signal. Its channel allocation can be shown in Figure 2.4. It has no feedback from transmitting antenna to receiving antenna.

Figure 2.4 Channel Allocations in a Translating Repeater System

For the conventional cellular system, the BS and the mobile terminal will communicate directly on two simplex channels, Ch.1 & Ch.2. However, if frequency-translating repeaters are used in the system, two additional simplex channels (Ch.3 & Ch.4) are required to support the link. These additional channels will either increase the interference level in the system, or will reduce the pool of available channels in each cell.

Since there is no need for handover control management in an on-channel relay system, on-channel relays offer radio network operators a cost-effective means of improving service coverage. Their main implementation problem is in suppressing the feedback between the transmitting and receiving antennas.

2.3 Coverage

Coverage is dependent entirely on the status of bi-directional links between base stations and mobile terminals. Calculation formulas and enhancement methods for coverage have been presented in [1]. Coverage values derived from link status information are described in the remainder of this section.

Coverage enhancement methods are summarized as follows [1]:

1. Increasing base station antenna gain
2. Increasing mobile terminal antenna gain
3. Decreasing cell radius
4. Providing macrodiversity for mobile terminals
5. Increasing the system's maximum tolerable path loss (MTPL)
6. Adding repeaters or relays to provide alternate paths which bypass obstructions

2.3.1 Maximum Tolerable Path loss

In a conventional cellular system, the power at one certain mobile terminal is given by [4]

$$P_R = \frac{P_T G_T G_R}{L}, \quad (2.2)$$

where P_T is the transmission power and G_T is the transmission antenna gain for the base station, G_R is the receive antenna gain for the mobile terminal, and L is the total path loss between transmission and receive antennas, given by

$$L = L_{FS} L_a, \quad (2.3)$$

where L_{FS} is the free space path loss [2] and L_a is an additional (excess) path loss due to obstructions, atmospheric attenuation, etc.

The internal thermal noise power is given by

$$N = k \times T \times B \times F, \quad (2.4)$$

here $k = 1.38 \times 10^{-23} \text{ Joules / Kelvin}$ is Boltzman's constant, T is the standard system temperature (typically 290K), B is the transmission bandwidth in Hertz, and F is the noise figure.

Then, the signal to noise ratio (SNR) referenced at the receiving terminal is:

$$\gamma = \frac{P_R}{N} = \frac{P_T G_T G_R}{L k T B F}, \quad (2.5)$$

The link will have an acceptable BER (in the absence of interference) if the SNR satisfies the following:

$$\gamma = \frac{P_T G_T G_R}{L k T B F} > \gamma_{\min}, \quad (2.6)$$

This can be rewritten as:

$$L < L_{MAX} = \frac{P_T G_T G_R}{\gamma_{\min} k T B F}, \quad (2.7)$$

where L_{MAX} is the maximum tolerable path loss (MTPL).

To cover a mobile terminal in a cellular radio network, its path loss between the base station and the mobile terminal must meet the criterion in (2.7).

2.3.2 Coverage Computation

According to (2.7), a direct bi-directional link can be established between a base station and mobile terminal. For downlink, (2.7) can be rewritten as:

$$L < L_{MAX(DL)} = \frac{P_{BS} G_{BS} G_{MT}}{\gamma_{MT(min)} kTB_{DL} F_{MT}}, \quad (2.8)$$

where P_{BS} is the transmission power from a base station, G_{BS} is the antenna transmission power gain for the base station, G_{MT} is the receive antenna power gain for a mobile terminal, $\gamma_{min(DL)}$ is the SINR threshold at the mobile terminal, B_{DL} is the bandwidth of the mobile terminal and F_{MT} is the noise figure of the mobile terminal.

Thus, coverage C is computed as a function of MTPL L_{MAX} as follows:

$$C(L_{MAX}) = \frac{N_{cov}(L_{MAX})}{N_{MT}}, \quad (2.9)$$

where C is the coverage, N_{MT} is the total number of mobile terminals in a cell, N_{cov} is the number of mobile terminals that are covered which depended on L_{MAX} .

Chapter 3: Analog Fixed Relaying Scheme

This chapter deals with system design with analog fixed relays. Furthermore, we develop an on-channel relay model for use in this system. Then we define two analog fixed relaying schemes: one is the non-selective analog fixed relaying scheme, and the other is the selective analog fixed relaying scheme. For the non-selective scheme, we discuss non-selective analog fixed relaying path modeling, as well as mathematical model of non-selective on-channel relaying network. For the selective scheme, we give the link selection scheme using maximal ratio combining diversity and introduce the mathematical model of adaptive gain control.

3.1 System Design

A system consisting of several clusters with one hexagonal cell in each cluster is discussed in this thesis. Because there has been significant advances in interference cancellation algorithms and collocated antenna architectures which are generally referred to as smart antennas (such as MIMO and adaptive antennas) [16], we assume that the frequency reuse factor is $R=1$ and introduce an *interference factor* to represent interference from other cochannel base station and relays, which remains even after interference-suppression measures such as adaptive antenna arrays are employed.

We assume that a base station is in the center of each cell. Relays are uniformly distributed on a circle centered at the base station. First of all, different numbers of relays in each cell are investigated, from 0 to 8 relays. Secondly, four different distances

of these relays from the base station are discussed: from $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$ of the cell radius, and on the edge of the cell.

Figure 3.1 below provides an example of one system design for the analog fixed relaying scheme with six relays per cell. A base station is in the center of each cell. Six relays: ①, ②, ③, ④, ⑤ and ⑥ are distributed uniformly on a circle centered at the base station. The dashed circles are different sites of relays at distances $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$ of the cell radius and on the edge of the cell.

Figure 3.1 System Design (with Six Fixed Relays)

3.2 On-Channel Relay Model

We assume that there are N nodes in the system; each is either a base station node, relay node, or mobile terminal node. The on-channel relay model is developed below Figure 3.2 is an example model of node i for $i = 1, 2, \dots, N$. Input and output values in Figure 3.2 are powers. Gains G_i and g_{ii} are power gains.

Figure 3.2 On-Channel Relay Model

In Figure 3.2, each node has separate antennas receiving and transmitting simultaneously on the same channel. In a translating relay, the incoming signal would be translated to a different channel before being amplified and transmitted. For an on-channel relay, some signal power will be fed back from its transmitter to receiver.

Feedback gain is g_{ii} for node i , which is a critical parameter of the system. Our simulations include a range of values for g_{ii} , including $g_{ii} = 0$. The latter value would correspond to perfect isolation between transmitting and receiving antennas, or to the case of frequency-translation relays. G_i is the combined amplifier and antenna gain of each node. Received power of each node is the sum of powers received from $N-1$ other nodes ($\sum_{\substack{j=1 \\ j \neq i}}^N g_{ji} P_j + s_i$) where s_i is the input signal power for any node i . n_i is the noise power of node i . P_i is the output power from node i 's transmitting antenna.

In this thesis, we try to use the same relay model for a base station and a mobile terminal to make the algorithms of two schemes simple and clear. For downlink transmission, we assume that the base station node has no receiver, and that the mobile terminal only has receiver and noise without a transmitter.

3.3 Non-selective Analog Fixed Relaying Scheme

With a non-selective analog fixed relaying scheme, all of the relays in the system do not know each other's existence, and the base station broadcasts signals to mobile terminals. The relays pick up and retransmit these signals to all of the mobile terminals whether or not they need relaying. Mobile terminals will receive signals both from its base station and all of the cochannel relays.

With this scheme, lots of interference will be introduced. For example, if there are six relays used in a cell, a mobile terminal will receive 48 [6 from relays in the same cell + 6×(6 relays + 1 base station) from each of 6 neighboring cells =

$6 + 6 \times 7 = 48$] amplified echoes of signals emanating from the desired cell and 6 cochannel cells, assuming frequency reuse factor $R = 1$.

Advantages of non-selective relaying:

The non-selective analog fixed relaying scheme is easily implemented. Therefore it can cut the cost of implementing relays and terminals. No extra channel is needed in this scheme and there is no need for routing or relay selection. Those features can significantly simplify signaling overhead and MAC. Secondly, this scheme has built in multi-hopping technique, which will improve system coverage. As well, multi-hop also creates different paths and causes different delays with multipath forming diversity, which can be exploited by a receiver using RAKE, adaptive equalizer or OFDM. So that, non-selective relaying is generally used when there are distinct coverage holes.

Disadvantages of non-selective relaying:

On the other hand, the non-selective scheme has some drawbacks. Because it transmits all of received signals and noise, it indiscriminately amplifies noise as well as signals. This increases the probability of decoding error at the mobile terminal and reduces the SINR at mobile terminals, thus degrading the system coverage. Also, since no power control has been used in this scheme, inter-cell interference will increase and the system will not easily stay in stable status.

3.3.1 Non-selective Analog Fixed Relaying Path Modeling

We assume that there are N nodes in the system and each is either a base station node, relay node, or mobile terminal node. Each pair of nodes has transmission power

gain g_{ij} which corresponds to a certain path loss, for i and $j = 1, 2, 3, \dots, N$. In this thesis, node 1 is the base station node or source node and node N is the mobile terminal node or destination node. An example of non-selective analog fixed relaying path modeling for downlink is shown in Figure 3.3.

Figure 3.3 Non-Selective Analog Fixed Relaying Path Modeling for Downlink

In Figure 3.3, each pair of nodes has power gain g_{ij} . We assume $g_{ij} = g_{ji}$ where $i \neq j$.

For source and destination nodes: $g_{11} = g_{NN} = 0$; $g_{i1} = g_{Ni} = 0$, for downlink.

3.3.2 Mathematical Model of the Non-selective On-Channel Relaying Network

With the non-selective on-channel relaying scheme, we can get a mathematical model. For N nodes $i = 1, 2, \dots, N$, with amplifier power gains $\{G_i\}$ and path gains $\{g_{ij}\}$, node input signal powers $\{s_i\}$, amplifier output power $\{P_i\}$, internal noise powers $\{n_i\}$, and amplified output noise powers $\{N_i\}$.

$$\mathbf{g} = \begin{bmatrix} g_{11} & g_{12} & g_{13} & \dots & g_{1N} \\ g_{21} & g_{22} & g_{23} & \dots & g_{2N} \\ g_{31} & g_{32} & g_{33} & \dots & g_{3N} \\ \dots & \dots & \dots & \dots & \dots \\ g_{N1} & g_{N2} & g_{N3} & \dots & g_{NN} \end{bmatrix}, \quad (3.1)$$

where $g_{ij} = g_{ji}$ denotes path power gain from transmitter i to receiver j .

$$\mathbf{G} = \begin{bmatrix} G_1 & 0 & 0 & \dots & 0 \\ 0 & G_2 & 0 & \dots & 0 \\ 0 & 0 & G_3 & \dots & 0 \\ \dots & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & G_N \end{bmatrix}, \quad (3.2)$$

where G_i denotes amplifier power gain of node i .

$$\mathbf{s} = \begin{bmatrix} s_1 \\ s_2 \\ \dots \\ s_N \end{bmatrix}, \quad (3.3)$$

where s_i denotes the input signal power of node i .

$$\mathbf{P} = \begin{bmatrix} P_1 \\ P_2 \\ \dots \\ P_N \end{bmatrix}, \quad (3.4)$$

where P_i denotes the amplifier output power of node i .

$$\mathbf{n} = \begin{bmatrix} n_1 \\ n_2 \\ \dots \\ n_N \end{bmatrix}, \quad (3.5)$$

where n_i denotes the internal noise power of node i .

$$\mathbf{N} = \begin{bmatrix} N_1 \\ N_2 \\ \dots \\ N_N \end{bmatrix}, \quad (3.6)$$

where N_i denotes the amplified output noise power of node i .

If $i=1$ denotes base station, $g_{11} = n_1 = N_1 = 0$. If $i=N$ denotes terminal,

$$g_{NN} = n_N = N_N = 0.$$

According to path modeling and node modeling, we can get:

$$(1 - g_{ii}G_i)P_i - G_i \sum_{j \neq i} g_{ji}P_j = G_i s_i \quad \text{for } i = 1, 2, \dots, N \quad (3.7)$$

Therefore we can get the vector of transmitted powers:

$$\mathbf{P} = (\mathbf{I} - \mathbf{G}\mathbf{g}')^{-1} \mathbf{G}\mathbf{s} \quad (3.8)$$

Or,

$$(\mathbf{I} - \mathbf{G}\mathbf{g}')\mathbf{P} = \mathbf{G}\mathbf{s} \quad (3.9)$$

Then, vector of received powers:

$$\mathbf{r} = \mathbf{g}'\mathbf{P} = \mathbf{g}'(\mathbf{I} - \mathbf{G}\mathbf{g}')^{-1}\mathbf{G}\mathbf{s} \quad (3.10)$$

In a special case of no relaying,

$$\mathbf{r} = \mathbf{g}'\mathbf{P} = \mathbf{g}'\mathbf{G}\mathbf{s} \text{ and } P_i = 0 \text{ for } i > 1 \quad (3.11)$$

Subject to gain constraint for stability:

$$G_i = \min\left(\frac{0.1}{g_{ii}}, P_{MR}\right) \quad (3.12)$$

where P_{MR} = maximal output radiated power from a relay. This constraint implies that

the feedback loss $\frac{1}{g_{ii}}$ at each node is at least 10dB greater than the node's gain. Any

smaller value of $\frac{1}{g_{ii}}$ would bring the risk of instability [7, 8].

Vector of input noise power at the N nodes:

$$\mathbf{n}_+ = \mathbf{g}'\mathbf{N} = \mathbf{g}'(\mathbf{I} - \mathbf{G}\mathbf{g}')^{-1}\mathbf{G}\mathbf{n} \quad (3.13)$$

3.4 Selective Analog Fixed Relaying Scheme

In the selective analog fixed relaying scheme, each relay and base station knows of each other's existence, unlike with the non-selective analog fixed relaying scheme. Each relay sends a "BEACON" to inform a mobile terminal that a relaying service is available in the system. There are numbers of realistic selective schemes, and the following illustrates a practical and easily implemented one. If the link between a base station and a mobile has good quality, which means $SINR \geq \gamma_{\min}$ at the mobile terminal, then the mobile terminal can use the signal transmitted by its corresponding base station. If $SINR < \gamma_{\min}$, then the mobile terminal will check the donor links of its

surrounding relays and choose the best one based on selection criteria. Then the mobile terminal will use diversity with MRC algorithm to combine the signals received from the base station and from the relay. This combining can be done at the mobile by a RAKE receiver for CDMA systems, or by an adaptive equalizer for non-CDMA systems. For the selective relaying systems, the relayed signal is received with a significant delay relative to the signal received directly from the base station.

The selective relaying has several advantages:

First, interference is reduced in the selective scheme, since only one relay is selected to relay a given signal and other relays are kept in silence. Also, the selective scheme reduces propagation of noise and interference, because only one selected relay stays in working status. Finally, the selective scheme conserves energy of the relays which are not selected by the mobile terminal.

On the other hand, the selective relaying has also some disadvantages:

However, the selective scheme has the disadvantage of increasing the complexity of implementation of relays and terminals. This significantly increases the cost of infrastructure planning and deployment.

3.4.1 Relay Selection Criterion

In the selective analog fixed relaying scheme, each mobile terminal checks the link with its own base station. If this link has $SINR \geq \gamma_{\min}$ at the mobile terminal, then the terminal does not need relaying. If it has $SINR < \gamma_{\min}$, the terminal will select the link from a particular relay and base station based on a certain criteria. There are several

selection criteria, such as based on SINR, path loss or geographic distance between relay and mobile terminal, etc. In our research, we choose the path loss as the selection factor, based on the criterion:

$$p_s = \arg \max_{R \in A} \{g_{BR} g_{Rj}\} \quad (3.14)$$

Here, p_s is the selected path, A is the set of fixed relays, j is a certain mobile terminal, g_{Rj} is the gain between the candidate relay to the mobile terminal in need of relaying, and g_{BR} is the gain between the candidate relay and base station. Note that this is not necessarily optimal, since it does not include consideration of SNR or SINR. However it is simple to implement.

Figure 3.4 Scheme of Selective Analog Fixed Relaying

If only the $\max_{R \in A} \{ g_{Rj} \}$ is selected, the link will be worse with the worse link donor link due to the attenuated input power of the selected relay. Therefore, we assume the criterion in formula (3.14) is reasonable and practical.

Figure 3.4 provides an example of selective analog fixed relaying, in which six relays are used in each cell. A base station is in the center of each cell. Six relays: ①, ②, ③, ④, ⑤ and ⑥ are distributed uniformly on a circle centered at the base station. The dashed circles show different possible radii of the relays. Each shaded-in circled number is a randomly selected cochannel interfering relay.

When there are six relays used in the system, a mobile terminal will receive 12 [$6 \times (1 \text{ selected relay} + 1 \text{ base station})$ from each of 6 neighboring cells = $6 \times 2 = 12$] interferes. Comparing with the non-selective relaying, there are 48 interferes. In our simulations of the selective scheme, the location of the interfering relay from each cochannel cell is selected randomly.

3.4.2 Mathematical Model of Adaptive Gain Control

In the selective analog relaying system, in order to make the system stable and practical, the selected relay must adjust its amplifier gain to give a mobile terminal the best possible service. For instance, the selected relay i can be modeled in Figure 3.5. Physical environment is not taken into account.

Figure 3.5 Relay Modeling

In Figure 3.5, P_{in} represents the input power of selected relay i , P_{out} represents the output power of selected relay i , G_i represents the power gain of selected relay i , and g_{ii} represents the power feedback gain of selected relay i .

$$\begin{aligned}
 P_{out} &= G_i \times P_{in} + g_{ii} \times P_{out} \times G_i \\
 \Rightarrow P_{out} &= \frac{G_i}{1 - g_{ii} \times G_i} \times P_{in}
 \end{aligned} \tag{3.15}$$

$$\text{In order to make the system stable, } G_i < \frac{1}{g_{ii}} \tag{3.16}$$

A margin of safety is obtained by using a more restrictive criterion:

$$G_i < \frac{0.1}{g_{ii}} , \tag{3.17}$$

i.e. the feedback path loss should exceed the gain by at least 10dB.

We assume that a mobile terminal can be covered if its $SINR \geq \gamma_{\min}$, where $\gamma_{\min}$ is the required minimal SINR threshold. The relationship between a BS, selected relay, mobile terminal and interference node is shown in Figure 3.6.

An example of path modeling is shown in Figure 3.6, node 1 represents the base station, node 2 represents the selected relay with amplifier gain G , node 3 represents the mobile terminal, and node 4 represents the cochannel interference from a base station or relay. P_T is the transmission power of base station and P_I is the interference power coming from a cochannel base station or relay. n is the noise power of relay or mobile terminal.

Figure 3.6 Path Modeling of Selective Analog Relaying

On the other hand, if each relay has a maximal output power P_{MR} , then based on formula (3.15),

$$\frac{G}{1 - g_{22}G} P_T g_{12} \leq P_{MR} \quad (3.18)$$

We can get:

$$G \leq \frac{1}{g_{22} + \frac{P_T g_{12}}{P_{MR}}} \quad (3.19)$$

So, combining (3.17) and (3.19),

$$G \leq \min(\{0.1/g_{22}\}, \{ \frac{1}{g_{22} + \frac{P_T g_{12}}{P_{MR}}} \}) \quad (3.20)$$

If there is no relay, the SINR at the mobile terminal exceeds the threshold value;

i.e. if

$$\frac{S}{N+I} = \frac{P_T g_{13}}{n + P_T g_{43}} \geq \gamma_{\min}, \quad (3.21)$$

then the terminal is covered .Otherwise, relaying is needed and the terminal is covered

if:

$$\begin{aligned} \frac{S}{N+I} &= \frac{P_T (g_{13} + g_{12} \times \frac{G}{1 - g_{22}G} \times g_{23})}{n(1 + \frac{G}{1 - g_{22}G} g_{23}) + [P_I g_{43} + P_I g_{42} (\frac{G}{1 - g_{22}G}) g_{23}]} \\ &\geq \gamma_{\min} \end{aligned} \quad (3.22)$$

For example, assuming $\gamma_{\min} = 10$ (i.e. 10dB), so we get

$$G \geq \frac{10n - P_T g_{13} + 10P_I g_{43}}{10n(g_{22} - g_{23}) + P_T (g_{12}g_{23} - g_{13}g_{22}) + 10P_I (g_{43}g_{22} - g_{42}g_{23})} \quad (3.23)$$

Therefore, the terminal can be covered when relaying is needed and the selected relay amplify gain must meet formula (3.23).

When there are multiple cochannel interferes in the system, P_I will be substituted by the sum of interference powers from each cochannel cell. In my thesis, the *effective received interference level* = $P_I \times \text{interference factor}$.

Chapter 4: Simulation Model

This chapter presents path loss model selection, enhanced gain on donor link, the environment parameter and assumptions needed for simulating those scenarios mentioned in Chapter 3. Two types of assumptions are discussed. One is physical environment and system parameters for the non-selective analog fixed relaying scheme, while another is assumption for the selective analog fixed relaying scheme. Finally, we provide the simulation algorithms and flow charts of the overall simulation process.

4.1 Path Loss Model Selection

Power transmission gain is a critical parameter in our models that significantly affects coverage. The path loss determines the power gain of transmission in our simulations. Therefore the selection of the path loss model is very important in our simulations.

In an urban environment, there are lots of propagation path-loss models [2, 5]. The free-space path-loss model is the simplest one. In [3], this model was selected and modified with lognormal shadowing and Rayleigh fading which together characterize the radio propagation channel. This radio propagation path loss model can be represented by the following equation:

$$PL = \left(\frac{4\pi d_0}{\lambda}\right)^2 \times \left(\frac{d}{d_0}\right)^n \times X_1 \times X_2 \quad , \quad (4.1)$$

where PL is the mean path-loss, d_0 is a reference distance at free space; d is the

distance between the transmitter and the receiver, λ is the wavelength of the carrier frequency and n is the propagation exponent.

X_1 is caused by log-normal shadowing which has a log-normal distribution, so $Y = 10\log_{10}(X_1)$ has a normal distribution with zero mean and standard deviation σ .

X_2 is introduced by Rayleigh fading which has a chi-square distribution [3] which means $X_2 = |Z|^2$, where Z has a Rayleigh distribution [4].

4.2 Enhanced Gain on Donor Link

In order to improve system coverage, we introduce enhanced gain on the donor link in some of our simulations. It is shown on Figure 4.1.

Figure 4.1 Enhanced Gain on the Donor Link

In the simulations to which it is applied, we assume that there are directive antennas existing on both base station and relay. They certainly enhance the donor link path gain; therefore, equally they enhance the power transmission gain on the donor link. The enhanced donor link gain assumption also models the case of careful placement of each relay, so that it has a relatively unobstructed radio path to its base station.

4.3 Environment and Parameters Assumptions

We assume that the path loss model is the log-distance path loss model described in section 4.1 and consider the simulation environment is an urban environment. As for the carrier frequency estimate, we choose 2GHz [5].

For the non-selective scheme, we have the following assumptions:

- Simulation area: hexagonal cell with variation in cell radius either 1000 m or 500 m
- All fixed relays located equidistant from base station
- Frequency reuse factor is $R = 1$
- Path loss propagation exponent: $n = 4$, path loss = $20 \log\left(\frac{4\pi d_0}{\lambda}\right) + 10n \log\left(\frac{d}{d_0}\right)$
 $(d_0 = 10m)$
- Lognormal shadowing with a standard deviation: $\sigma = 8dB$

- Flat Rayleigh fading, which has an envelope distribution $f_y(y) = \frac{y}{\alpha^2} e^{-\frac{y^2}{2\alpha^2}}$,

$$y \geq 0, \alpha = \frac{1}{\sqrt{2}}$$

- RF Carrier = 2 GHz, transmission bandwidth: W=5MHz
- Thermal noise with a noise figure: F=8dB
- Maximum base station transmit power per node: 10W
- Maximum relay power per node: $P_{MR} = 1W$
- Feedback power gain g_{ii} varied from zero (no feedback, or translating relay) up

to 10^{-6} (∞ dB to 60 dB isolation).

- Interference canceling measures assumed e.g. selective antenna arrays or interference cancellation, so that:

$$\text{effective interference level} = \text{received interference} \times \text{interference factor},$$

where $0 \leq \text{interference factor} \leq 1$

- Thermal noise is considered at the receiver, noise power is given by (2.3)
- Downlink scenario only
- Doppler effects are ignored
- All relays are active
- There is interference from every adjacent cell
- Path gain enhancement on donor link (base to relay) varied to simulate favorable relay situation relative to base station.

Likewise, for the selective scheme, we have the exact same assumptions as for the non-selective scheme, excepting the following assumptions:

- A single relay is chosen for each terminal whose received SINR without relaying is below a given threshold, according to equation (3.14).
- There are two interferences in each adjacent cell: the base station and one relay
- Interference from adjacent cell relays in random location relative to its base station.

4.4 Simulation Algorithm

Re-transmission of on-channel analog repeater that amplifies both signal and noise is modeled without any change to the carrier frequency [1]. For each mobile user, it will be called covered if its $SINR \geq \gamma_{\min}$. For example, assuming $\gamma_{\min} = 10$ (i.e. 10 dB), so if $SINR \geq 10$, it will be covered.

Simulation is started without relaying for each mobile user in selective analog fixed relaying scheme. Relaying is incorporated when a certain mobile user needs relaying. The desired signal power is the sum of powers from the base station and the relay; i.e. maximum ratio combining is assumed.

The user coverage evaluation is based on the average of 1000 different terminals' locations with different shadowing random variables and 100 received SINR have been collected for each subscriber location, corresponding to 100 different realizations of the Rayleigh random variables. The 1000 different locations of a terminal model that 1000 mobile terminals are uniformly distributed in a hexagonal cell. To examine the simulation accuracy, we will check the standard deviation of the results in Chapter 5.

Figure 4.2 shows the detailed simulation process for non-selective analog fixed relaying scheme while Figure 4.3 shows the whole simulation process for the selective analog fixed relaying scheme.

Figure 4.2 Flow Chart of the Non-Selective Analog Fixed Relaying Process

Figure 4.3 Flow Chart of the Selective Analog Fixed Relaying Process

Chapter 5: Simulation Results for Non-Selective Scheme

In this chapter is concerned with the simulation results for the non-selective analog fixed relaying scheme. Seven different factors affecting coverage have been investigated: including feedback gain and locations of relays, gain enhancement on donor link, SINR threshold, cell radius, interference, propagation exponent and number of relays, while the effect of interference on coverage has been examined in all scenarios. As well, gains distributions have been determined for no relay feedback scenarios. The standard deviation of one special case has been analyzed.

5.1 Impact of Feedback Gain and Locations of Relays on Coverage

Figures 5.1-5.3 show the results of adjusting the feedback gain of each relay to examine its impact on coverage. Figures 5.4-5.5 show relay gains distributions of no relay feedback.

Figure 5.1 corresponds to relay feedback gain = 10^{-10} , Figure 5.2 corresponds to feedback gain = 10^{-12} , while Figure 5.3 corresponds to no feedback (relay feedback gain = 0). Placements of relays are adjusted from $\frac{1}{4}$ cell radius away, $\frac{1}{2}$ cell radius away, $\frac{3}{4}$ cell radius away from base station and on the edge of cell.

Figures 5.1-5.3 have the following in common: hexagonal cell radius = 500 m, with the non-selective analog fixed relaying scheme, number of the relays is varied from 0 to 8, SINR threshold = 10 dB, maximal output power of base station is 10W while maximal output power of relay is 1 W. For the case of Figure 5.1, the relay gains

are observed to be at the limit of $\frac{0.1}{10^{-10}} = 10^9$. Likewise, for the case of Figure 5.2, the

relay gains are observed to be at the limit of $\frac{0.1}{10^{-12}} = 10^{11}$; for the case of Figure 5.3,

they are limited only by maximal power of 1 watt. In Figure 5.1-5.3, the top curves are obtained by assuming *interference factor* = 0.2 while the bottom curves are obtained by assuming no interference (*interference factor* = 0). Four curves of each group correspond to four distinct placements of relays.

Figure 5.1 User Coverage vs. Number of Relays per cell with Non-selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-10} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W without Gain Enhancement on Donor Link.)

In Figure 5.1, the four curves are almost overlapped unless the number of fixed relays is beyond 3. This result shows that there is only a slight improvement in coverage (approximately 4% enhancement on coverage for 8 relays) when there are relays put in the system.

Figure 5.2 User Coverage vs. Number of Relays per cell with Non-selective Analog Fixed Relaying Scheme (for Feedback Gain = 10^{-12} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W without Gain Enhancement on Donor Link.)

In Figures 5.2-5.3, we would expect to see a coverage improvement due to decreased feedback gain. We see that placing relays on $\frac{3}{4}$ or $\frac{1}{2}$ cell radius is best,

depending on the amount of interference suppression and number of relays per cell. The best positions of relays may be changed based on different maximum transmission powers of the base station and relays. This result shows how sensitive the system performance is to the placement of relays. For 10^{-12} feedback and no feedback, they have almost same coverage improvement.

Figure 5.3 User Coverage vs. Number of Relays per cell with Non-selective Analog Fixed Relaying Scheme (for Feedback Gain = 0, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W without Gain Enhancement on Donor Link.)

In Figure 5.2 and Figure 5.3, for 4 relays, with no relaying, coverage decreases from about 76% to about 60% as the interference factor is changed from 0 to 0.2. For 8

relays with the best placement, the corresponding coverage decrease is from about 80% to about 69%.

As well, in Figures 5.1-5.3, we see that the $4/4$ cell radius curves decrease with number of relays, even for the case where there is no cochannel interference. The reason is that all of relays retransmit all of signals and noises from which they have received in non-selective relaying (in equations (3.8) and (3.10)) , but the amplifier gains of relays are at the limit of equation(3.12). When relays are on the edge of a cell, the transmission power gains on the donor link are very small. To make a mobile terminal be covered, the required amplifier gains of the relays are higher than for other cases, such as $1/4$, $1/2$ and $3/4$ cell radius. However, due to the limitation in equation (3.12), the relays cannot achieve the required amplifier gains and the mobile terminal cannot be covered. So the noise level increases with the number of relays, if they are at maximal gain, this implies using less than maximal gain might give better coverage at least as good as for no relays.

To determine the accuracy of our simulations, we run 10 times for the simulation of feedback $=10^{-12}$ case (corresponding to Figure 5.2). For the best placements of 4 relays, those results are shown in Table 1.

Number of Running times	1	2	3	4	5	6	7	8	9	10
User Coverage	0.6607	0.6620	0.6716	0.6347	0.667	0.6589	0.657	0.6553	0.6512	0.6487

Table 1 Relays Located on the $1/2$ of cell radius for Non-Selective Relaying without Gain Enhanced Donor Link

Let $\hat{c}$ denote the average estimator for the coverage performance when relays are located in the $1/2$ cell radius with feedback $=10^{-12}$, which can be computed as follows:

$$\hat{c} = \frac{0.6607 + 0.6620 + 0.6716 + \dots + 0.6512 + 0.6487}{10} = 0.6567$$

Therefore, the sample variance of $\hat{c}$ can be calculated as follows:

$$s^2(\hat{c}) = \frac{(0.6607 - 0.6567)^2 + (0.662 - 0.6567)^2 + \dots + (0.6487 - 0.6567)^2}{9}$$

$$= 0.00010637$$

Then, the estimator variance: $\hat{\sigma}^2(\hat{c}) = \frac{s^2(\hat{c})}{10} = 0.000010637$

Thus, the standard deviation of this case is: $\hat{\sigma}(\hat{c}) = 0.0033$.

To examine the gains distribution for Figure 5.3 case, we observed two scenarios: 4 relays are located on the $\frac{1}{2}$ or $\frac{3}{4}$ cell radius. There are $4 \times 1000 \times 100 = 400,000$ gain values for each scenario. For the $\frac{1}{2}$ cell radius scenario, probability of gains distribution is shown in Table 2; gains distribution is shown in Figure 5.4. For the $\frac{3}{4}$ cell radius scenario, probability of gains distribution is shown in Table 3; gains distribution is shown in Figure 5.5.

Gains Value(dB)	G<=85	85<G<=95	95<G<=105	105<G<=115	115<G<=125	G>125
Probability	4499/400000 ≈ 1.12%	42622/400000 ≈ 10.66%	130397/400000 ≈ 32.6%	146251/400000 ≈ 36.56%	66475/400000 ≈ 16.62%	9756/400000 ≈ 2.44%

Table 2 Probability of Gains Distribution of 4 Relays Located on the $\frac{1}{2}$ Cell Radius for Non-Selective Relaying without Gain Enhanced Donor Link

In Table 2, we see that 32.6% of gains are from 95 dB to 105 dB and 36.56% of gains are from 105 dB to 115 dB. Only about 1% of gains are less than 85 dB and 2% of gains are larger than 125 dB. In Figure 5.4, we see that no gain is larger than 130 dB and the largest probability of gain is 4.2% in 105 dB. Note that gain of each relay is limited by the maximal transmission power.

Figure 5.4 Gains distribution of 4 relays located on the $\frac{1}{2}$ cell radius for non-selective on-channel relaying without gain enhanced donor link

In Table 3, we see that 37.91% gains are from 105 dB to 115 dB and 34.22% gains are from 115 dB to 125 dB. Only about 2.5% are less than 95 dB and 9% are less than 125 dB. In Figure 5.5, we see that no gain is larger than 130 dB and the largest gain probability of gain is 4.2% in 110 dB.

Gains Value(dB)	$G \leq 95$	$95 < G \leq 105$	$105 < G \leq 115$	$115 < G \leq 125$	$G > 125$
Probability	10116/400000 $\approx 2.53\%$	66425/400000 $\approx 16.61\%$	151636/400000 $\approx 37.91\%$	136866/400000 $\approx 34.22\%$	34957/400000 $\approx 8.74\%$

Table 3 Probability of Gains Distribution of 4 Relays Located on the $\frac{3}{4}$ Cell Radius for Non-Selective Relaying without Gain Enhanced Donor Link

Figure 5.5 Gains Distribution of 4 Relays Located on the 3/4 of Cell Radius for Non-Selective On-Channel Relaying without Gain Enhanced Donor Link

Comparing Table 2 with Table 3, we see that desired gains in Table 2 are less than that of in Table 3. This means that the $\frac{1}{2}$ of cell radius scenario requires lower amplifier relay gains than does the $\frac{3}{4}$ of cell radius scenario to cover a mobile terminal.

For relay feedback larger than 10^{-10} , results are shown in Figures 5.6-5.7. Figure 5.6 corresponds to feedback gain = 10^{-6} , while Figure 5.7 corresponds to feedback gain = 10^{-8} . We see that system coverage has no improvement from relays with feedback gains larger than -100dB.

Figure 5.6 User Coverage vs. Number of Relays per cell with Non-selective Analog Fixed Relaying Scheme (for Feedback Gain = 10^{-6} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W without Gain Enhancement on Donor Link.)

We get the conclusion that relays used in non-selective relaying system must have high separation between transmitter and receiver (>100 dB). To get better coverage improvement, we recommend that the separation should larger than 120 dB.

Figure 5.7 User Coverage vs. Number of Relays per cell with Non-selective Analog Fixed Relaying Scheme (for **Feedback Gain** = 10^{-6} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W without Gain Enhancement on Donor Link.)

5.2 Impact of Gain Enhanced Donor Link on Coverage

Figures 5.8-5.10 show the results of adjusting the feedback gain of each relay with 14 dB gain enhancement on donor link to examine its impact on coverage. Figure 5.8 corresponds to feedback gain = 10^{-10} , Figure 5.9 corresponds to feedback gain =

10^{-12} , while Figure 5.10 corresponds to no feedback (feedback gain = 0). We keep other assumptions the same as Figures 5.1-5.3. Figures 5.11-5.12 show relay gains distributions of no relay feedback scenario.

Figure 5.8 User Coverage vs. Number of Relays per cell with Non-selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-10} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14dB Gain Enhancement on Donor Link.)

In Figures 5.8-5.10, the $\frac{3}{4}$ cell radius curves have the best coverage for feedback gain of 10^{-10} , 10^{-12} and 0. Comparing Figures 5.8-5.10 with Figure 5.1-5.3, we can find

that the system performance has more significant improvement with gain enhancement than without gain enhancement on the donor link (for 4 relays at the $\frac{3}{4}$ cell radius and *interference factor* = 0.2, approximately from 60% to 68% as feedback = 10^{-10} , and from 63% to 76% as feedback = 10^{-12} and no feedback).

Figure 5.9 User Coverage vs. Number of Relays per cell with Non-selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-12} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14dB Gain Enhancement on Donor Link.)

For no relay feedback, we also observed two scenarios to see the gains distributions: 4 relays are located on the $\frac{1}{2}$ or $\frac{3}{4}$ cell radius. For the $\frac{1}{2}$ cell radius

scenario, probability of gains distribution is shown in Table 4; gains distribution is shown in Figure 5.11. For the $\frac{3}{4}$ cell radius scenario, probability of gains distribution is shown in Table 5; gains distribution is shown in Figure 5.12.

Figure 5.10 User Coverage vs. Number of Relays per cell with Non-selective Analog Fixed Relaying Scheme(for Feedback Gain = 0, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14dB Gain Enhancement on Donor Link.)

Gains Value(dB)	$G \leq 75$	$75 < G \leq 85$	$85 < G \leq 95$	$95 < G \leq 105$	$G > 105$
Probability	27960/400000 ≈ 6.99%	106378/400000 ≈ 26.6%	155196/400000 ≈ 38.8%	85809/400000 ≈ 21.5%	24657/400000 ≈ 6.16%

Table 4 Probability of Gains Distribution of 4 Relays Llocated on the $\frac{1}{4}$ Cell Radius for Non-Selective Relaying with 14dB Gain Enhanced Donor Link

Figure 5.11 Gains Distribution of 4 Relays Located on the $\frac{1}{2}$ Cell Radius for Non-Selective On-Channel Relaying with 14dB Gain Enhanced Donor Link

In Table 4, we see that 26.6% of gains are from 75 dB to 85 dB; 38.8% of gains are from 85 dB to 95 dB and 21.5% of gains are from 95 dB to 105 dB. Only about 7% of gains are less than 75 dB and about 6% are large than 105 dB. In Figure 5.11, we see that gain has largest probability 4.2% in 88 dB.

In Table 5, we see that about 11% of gains are from 75 dB to 85 dB; about 33% of gains are from 85 dB to 95 dB and 35.8% of gains are from 95 dB to 105 dB. Only about 1% of gains are less than 75 dB and about 19% are large than 105 dB. In Figure 5.12, we see that the largest probability of gain is 4.2% in 95 dB.

Gains Value(dB)	$G \leq 75$	$75 < G \leq 85$	$85 < G \leq 95$	$95 < G \leq 105$	$G > 105$
Probability	4839/400000 $\approx 1.21\%$	44382/400000 $\approx 11.11\%$	132152/400000 $\approx 33.04\%$	143320/400000 $\approx 35.83\%$	75307/400000 $\approx 18.83\%$

Table 5 Probability of Gains Distribution of 4 Relays Located on the $\frac{3}{4}$ Cell Radius for Non-Selective Relaying with 14dB Gain Enhanced Donor Link

Figure 5.12 Gains Distribution of 4 Relays Located on the $\frac{3}{4}$ Cell Radius for Non-Selective On-Channel Relaying with 14dB Gain Enhanced Donor Link

Comparing with scenarios of section 5.1, we see that desired gains are less than that of section 5.1. With gain enhanced donor link, it can significantly improve coverage with lower relay amplifier gains.

For relay feedback larger than 10^{-10} , results are shown in Figures 5.13-5.14. Figure 5.13 corresponds to feedback gain = 10^{-6} , while Figure 5.14 corresponds to feedback gain = 10^{-8} . We see that system coverage has no obvious improvement.

Figure 5.13 User Coverage vs. Number of Relays per cell with Non-selective Analog Fixed Relaying Scheme (for Feedback Gain = 10^{-6} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14dB Gain Enhancement on Donor Link.)

We get the conclusion that relays used in non-selective relaying system with gain enhanced donor link also must have high separation between transmitter and receiver (>100 dB). To get better coverage improvement, we recommend that the separation should larger than 120 dB. This conclusion is consistent with that of section 5.1.

Figure 5.14 User Coverage vs. Number of Relays per cell with Non-selective Analog Fixed Relaying Scheme (for Feedback Gain = 10^{-8} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14dB Gain Enhancement on Donor Link.)

5.3 Impact of SINR Threshold on Coverage

In section 5.1 and 5.2, measured SINR threshold at certain mobile terminal is a constant 10dB. However, in this section, we adjust the SINR threshold to see what will happen with system coverage performance. We would expect that better coverage would occur due to decreased SINR threshold. Figures 5.15-5.17 show the observed

complementary cumulative distribution function of SINR. The curves can be interpreted as displaying coverage as a function of minimum required SINR.

In Figures 5.15-5.17, Figure 5.15 corresponds to feedback gain = 10^{-10} , Figure 5.16 corresponds to feedback gain = 10^{-12} , while Figure 5.17 corresponds to no feedback (feedback gain = 0). We only consider that there are 4 relays in the system while keeping other assumptions the same as Figures 5.1-5.3.

Figure 5.15 User Coverage vs. SINR Threshold with Non-selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-10} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W , number of relay : 4 without Gain Enhancement on Donor Link.)

In Figure 5.15, the four curves are almost same. These results show that coverage is not sensitive to locations of placed relays in the cell when relay feedback is higher than 10^{-10} . These results are consistent with those of Figure 5.1 for 4 relays and SINR threshold =10 dB. At the same time, we can discover that coverage significantly improves from about 50% to about 75% as the SINR threshold drops from 12dB to 6 dB

Figure 5.16 User Coverage vs. SINR Threshold with Non-selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-12} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W , number of relay : 4 without Gain Enhancement on Donor Link.)

as *interference factor*=0.2. This result shows that coverage is very sensitive to SINR threshold. It also indicates that the ability of a system to adapt its coding and modulation rate to available SINR will tend to optimize coverage.

Figure 5.17 User Coverage vs. SINR Threshold with Non-selective Analog Fixed Relaying Scheme(for Feedback Gain = 0, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W , number of relay : 4 without Gain Enhancement on Donor Link.)

However, in Figures 5.16-5.17, for 120dB and ∞ dB feedback isolation respectively, we see a larger difference among different locations of relays put in the

cell. There is a 10% difference in coverage between placing 4 relays on best and worst locations with SINR threshold = 12 dB as feedback = 10^{-12} and interference factor = 0.2.

5.4 Impact of Cell Radius on Coverage

In this section, we adjust the cell radius from 500 m to 1000 m to examine its impact on coverage. Figure 5.18 corresponds to feedback gain = 10^{-12} , while Figure 5.19 corresponds to no feedback. Other assumptions are same as in Figures 5.9-5.10.

Figure 5.18 User Coverage vs. Number of Relays per cell with Non-selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-12} , 1000 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14 dB Gain Enhanced Donor Link.)

Comparing Figure 5.18 with Figure 5.9, we find that system has significant coverage degradation due to the increased cell radius, approximately from 59% to 31% with no relaying, as well as from about 76% to about 46% for 4 relays put in the $\frac{3}{4}$ cell radius as interference factor = 0.2. Likewise, comparing Figure 5.19 with Figure 5.10, approximately from 59% to 31% with no relaying, as well as from 76% to 46% for 4 relays at the $\frac{3}{4}$ cell radius with interference factor = 0.2.

Figure 5.19 User Coverage vs. Number of Relays per cell with Non-selective Analog Fixed Relaying Scheme(for Feedback Gain = 0, 1000 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14 dB Gain Enhanced Donor Link.)

We see that there is only 6% difference between *interference factor* = 0.2 and *interference factor* = 0 with large 1000 m cells while there are 16% difference with small 500 m cells for no relaying. We get the conclusion that the larger each cell is, the greater the role played by noise, rather than interference, in determining coverage.

5.5 Impact of Interference on Coverage

In previous sections, we determined effects of *interference factor* = 0.2 and *interference factor* = 0 on coverage. In this section, we adjust *interference factor* to 0.5 and 1 to see its effect on coverage, assuming constant relay feedback = 10^{-12} and keeping other assumptions the same as section 4.3. The *interference factor* = 1 means that no interference cancellation has been exploited in the system and coverage has been affected by maximal interference.

Figures 5.20 and 5.21 show these results. Figure 5.20 corresponds to the scenario without gain enhanced donor link, while Figure 5.21 corresponds to the scenario with 14dB gain enhancement on donor link. The top curves show the results with maximal interference *interference factor* = 1 while the bottom curves show the results with *interference factor* = 0.5.

In Figure 5.20, with no relaying, coverage increases from about 38% to about 50% as *interference factor* is changed from 1 to 0.5. For 8 relays located in the $\frac{3}{4}$ of cell radius, the corresponding coverage increase is from about 56% to 63%.

Figure 5.20 User Coverage vs. Number of Relays with Non-selective Analog Fixed Relaying Scheme (for either interference factor = 1 or 0.5, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1W without Gain Enhancement on Donor Link.)

Likewise, in Figure 5.21, for 8 relays placed at the $\frac{3}{4}$ of cell radius, the corresponding coverage increase is from about 73% to 80%.

Comparing Figure 5.20 with Figure 5.2 and Figure 5.21 with Figure 5.9, we see that the more interference, the worse coverage. Coverage is sensitive to received

interference at mobile terminals. Best placements of relays depend on not only interference but also number of relays.

Figure 5.21 User Coverage vs. Number of Relays with Non-selective Analog Fixed Relaying Scheme (for either interference factor = 1 or 0.5, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1W with 14dB Gain Enhancement on Donor Link.)

5.6 Impact of Propagation Exponent on Coverage

In other sections, we assume the path loss propagation exponent is a constant $n = 4$. In this section, we adjust it to $n = 3.5$ examine its effect on coverage, assuming constant relay feedback $= 10^{-12}$ and keeping other assumptions the same as section 4.3.

We consider two scenarios: without gain enhanced donor link and with 14 dB gain enhancement on donor link, shown in Figures 5.22 and 5.23. Figure 5.22 corresponds to the scenario without gain enhanced donor link, while Figure 5.23

Figure 5.22 User Coverage vs. Number of Relays with Non-selective Analog Fixed Relaying Scheme (for propagation exponent = 3.5, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1W without Gain Enhancement on Donor Link.)

corresponds to the scenario with 14dB gain enhancement on donor link. We would expect to see coverage improvement due to decreased propagation exponent.

In Figure 5.22, we see that the $\frac{3}{4}$ cell radius is the best placement of relays. Comparing Figure 5.22 with Figure 5.2, with no relaying, coverage increases from about 59% to about 67% for *interference factor* = 0.2 as the propagation exponent is adjusted from 4 to 3.5. For 4 relays put in the $\frac{3}{4}$ of cell radius, the corresponding

Figure 5.23 User Coverage vs. Number of Relays with Non-selective Analog Fixed Relaying Scheme(for propagation exponent = 3.5, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1W with 14 dB Gain Enhancement on Donor Link.)

coverage increase is from about 64% to about 74% as *interference factor* = 0.2. For 8 relays located in the $\frac{3}{4}$ of cell radius, the corresponding coverage increase is from about 69% to about 80%. We get conclusion that coverage is very sensitive to propagation exponent for non-selective relaying without gain enhancement on donor link.

In Figure 5.23, we also see that placing relays on the $\frac{3}{4}$ cell radius away from base station is the best choice for this scenario. Comparing Figure 5.23 with Figure 5.9, for the best placements of 4 relays, the corresponding coverage increase is from about 63% to about 82% as *interference factor* = 0.2. For 8 relays, the corresponding increase is from 69% to 88%. We note that coverage is sensitive to propagation exponent for non-selective relaying with gain enhancement on donor link.

5.7 Impact of the Number of Relays on Coverage

In previous sections, we examined the number of relays from 0 to 8. In this section, we extend the maximal number from 8 to 16 see what will happen if the number of relays is much greater than 8, assuming constant relay feedback = 10^{-12} and keeping other assumptions same as section 4.3. Results are shown in Figures 5.24 and 5.25.

Figure 5.24 corresponds to the scenario without gain enhanced donor link, while Figure 5.25 corresponds to the scenario with 14dB gain enhancement on donor link. In Figure 5.24, we see that coverage gradually decreases as the number of relays is

greater than 7, except placement of relays on the edge of a cell. Best coverage can be obtained as 6 relays are placed in a cell

In Figure 5.25, we see that coverage almost has no change as the number of relays is greater than 10. Best coverage is achieved as 10 relays are put in a cell. However, for no gain enhancement on donor link, worse coverage is achieved when there are more than 10 relays put in the system. Note that the more relays there are, the stronger interference and noise a mobile terminal will receive.

Figure 5.24 User Coverage vs. Number of Relays with Non-selective Analog Fixed Relaying Scheme(for the number of relays: 0~16 , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1W without Gain Enhancement on Donor Link.)

Figure 5.25 User Coverage vs. Number of Relays with Non-selective Analog Fixed Relaying Scheme(for the number of relays: 0~16 , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1W with 14 dB Gain Enhancement on Donor Link.)

Chapter 6: Simulation Results for Selective Scheme

This chapter describes the simulation results for the selective analog fixed relaying scheme. Seven different factors of affecting coverage have been examined: including feedback gain and locations of relays, gain enhancement on donor link, SINR threshold, cell radius, interference, propagation exponent and number of relays, while the effect of interference on coverage has been examined in all scenarios. As well, a comparison of coverage with a digital fixed relaying is provided in section 6.8.

6.1 Impact of Feedback Gain and Locations of Relays on Coverage

In Figures 6.1-6.3, the feedback gain of each relay has been evaluated to examine its impact on coverage. Figure 6.1 corresponds to feedback gain = 10^{-10} , Figure 6.2 corresponds to feedback gain = 10^{-12} , while Figure 6.3 corresponds to no feedback (feedback gain = 0). Locations of relays are adjusted from $\frac{1}{4}$ cell radius away, $\frac{1}{2}$ cell radius away, $\frac{3}{4}$ cell radius away from base station and on the edge of cell.

Figures 6.1-6.3 have the following in common: hexagonal cell radius = 500 m, with selective analog fixed relaying scheme, number of relay is varied from 0 to 8, SINR threshold = 10 dB, maximal output power of base station is 10W while maximal output power of relay is 1 W. In Figures 6.1-6.3, the top curves are obtained by assuming *interference factor* = 0.2 while the bottom curves are obtained by assuming no interference (*interference factor* = 0). We see only 2% coverage enhancement in

Figure 6.1.

Figures 6.2-6.3 show that $\frac{1}{2}$ cell radius is the best placement for no feedback and 10^{-12} feedback. One reason is that relays placed at $\frac{1}{2}$ cell radius can provide common better links for all of mobile terminals because we assume that parameters and environment are same for donor link and distribution link. Another reason is that only one relay is used in a cell.

Figure 6.1 User Coverage vs. Number of Relays per cell with Selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-10} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W without Gain Enhancement on Donor Link.)

In Figure 6.2 and Figure 6.3, we would expect to see a coverage improvement due to decreased feedback gain. With no gain constraints due to feedback, the system performance has slight improvement than with 10^{-12} feedback gain. For 4 relays at the

$\frac{1}{2}$ cell radius, coverage improves from about 68% to about 70% for *interference factor*=0.2; from about 80% to about 84% for *interference factor*=0.

Figure 6.2 User Coverage vs. Number of Relays per cell with Selective Analog Fixed Relaying Scheme (for Feedback Gain = 10^{-12} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W without Gain Enhancement on Donor Link.)

In Figure 6.2, we see that system coverage is very sensitive to cochannel interference from other cells. For 4 relays placed at the $\frac{1}{2}$ cell radius, coverage is about 68% with *interference factor* = 0.2, while it is about 80% with *interference factor* = 0. There is about 12% coverage difference. In Figure 6.3, we see the same feature.

Figure 6.3 User Coverage vs. Number of Relays per cell with Selective Analog Fixed Relaying Scheme (for Feedback Gain = 0, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W without Gain Enhancement on Donor Link.)

Comparing Figure 5.2 with Figure 6.2, Figure 5.3 with Figure 6.3, we do not see much difference between selective relaying and non-selective relaying. The selective relaying only has slight coverage improvement (about 4%) than non-selective relaying. Note that non-selective relaying has built in multi-hopping technique, while selective relaying only selects one relay to amplify and retransmit signal to a mobile terminal.

For relay feedback larger than 10^{-10} , results are shown in Figures 6.4-6.5. Figure 6.4 corresponds to feedback gain = 10^{-6} , while Figure 6.5 corresponds to feedback gain = 10^{-8} . There are no coverage improvements. This implies that relays used in the selective relaying system also must have high separation between transmitter and

Figure 6.4 User Coverage vs. Number of Relays per cell with Selective Analog Fixed Relaying Scheme (for Feedback Gain = 10^{-6} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W without Gain Enhanced Donor Link.)

receiver (>100 dB). To achieve better coverage improvement, we recommend that the separation should larger than 120 dB. This result is consistent with the non-selective relaying.

Figure 6.5 User Coverage vs. Number of Relays per cell with Selective Analog Fixed Relaying Scheme (for Feedback Gain = 10^{-8} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W without Gain Enhanced Donor Link.)

6.2 Impact of Gain Enhanced Donor Link on Coverage

In Figures 6.6-6.8, we adjust the feedback gain of each relay with 14 dB gain enhancement on donor link to examine its impact on coverage. Figure 6.6 corresponds to feedback gain = 10^{-10} , Figure 6.7 corresponds to feedback gain = 10^{-12} , while Figure

6.8 corresponds to no feedback (feedback gain = 0) while we keep other assumptions the same as Figures 6.1-6.3.

Figure 6.6 User Coverage vs. Number of Relays per cell with Selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-10} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14dB Gain Enhancement on Donor Link.)

For 10^{-12} feedback gain and no feedback gains, $\frac{3}{4}$ cell radius is the best placement for the relays with 14 dB donor enhancement; in contrast to the case which $\frac{1}{2}$ cell radius is the best placement for the relays without donor enhancement in section 6.1. Note that the gain enhanced donor link reduces the path loss on the donor link; thus

the received power at a relay is stronger than without the gain enhanced donor link.

Figure 6.7 User Coverage vs. Number of Relays per cell with Selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-12} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14dB Gain Enhancement on Donor Link.)

Comparing Figures 6.6-6.8 with Figures 6.1-6.3, we can find that the system performance has significantly improvement with gain enhanced donor link, compared to the case without the gain enhanced donor link (approximately from 60% to 67% for feedback = 10^{-10} , from 62% to 78% for feedback = 10^{-12} and no feedback with

interference factor = 0.2 as 4 relays are placed on the $\frac{3}{4}$ cell radius). Those results show what impact on coverage with gain enhanced donor link.

Figure 6.8 User Coverage vs. Number of Relays per cell with Selective Analog Fixed Relaying Scheme(for Feedback Gain = 0, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14dB Gain Enhancement on Donor Link.)

Comparing Figure 5.9 with Figure 6.7, Figure 5.10 with Figure 6.8, we do not see much difference between selective relaying and non-selective relaying. The selective relaying only has slight coverage improvement (about 6%) than non-selective relaying. Note that non-selective relaying has built in multi-hopping technique, while

selective relaying only selects one relay to amplify and retransmit signal to a mobile terminal.

For relay feedback larger than 10^{-10} , results are shown in Figures 6.9-6.10. Figure 6.9 corresponds to feedback gain = 10^{-6} , while Figure 6.10 corresponds to feedback gain = 10^{-8} .

Figure 6.9 User Coverage vs. Number of Relays per cell with Selective Analog Fixed Relaying Scheme (for Feedback Gain = 10^{-6} 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14dB Gain Enhanced Donor Link.)

In Figures 6.9-6.10, we see that system coverage has no improvement on coverage. We get the same conclusion that high separation between transmitter and

receiver is needed (>100 dB) to achieve significant coverage improvement. We recommend that the separation should larger than 120 dB. This conclusion is consistent with that of non-selective relaying.

Figure 6.10 User Coverage vs. Number of Relays per cell with Selective Analog Fixed Relaying Scheme (for Feedback Gain = 10^{-8} 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14dB Gain Enhancement on Donor Link.)

6.3 Impact of SINR Threshold on Coverage

In this section, we change the SINR threshold to see what will happen with system coverage performance. We would expect that better performance would occur due to decreased SINR threshold.

In Figures 6.11-6.13, Figure 6.11 corresponds to feedback gain = 10^{-10} , Figure 6.12 corresponds to feedback gain = 10^{-12} , while Figure 6.13 corresponds to no feedback (feedback gain = 0). We assume that there are 4 relays in the system while keeping other assumptions the same as Figures 6.6-6.8.

Figure 6.11 User Coverage vs. SINR Threshold with Selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-10} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W , number of relay : 4 without Gain Enhancement on Donor Link.)

In Figure 6.11, the four curves are almost same. This results shows that coverage is insensitive to placement of relays in the cell when relay feedback is greater than 10^{-10} . At the same time, we see that coverage significantly improves from about 50% to

about 74% as SINR threshold drops from 12dB to 6 dB. This result shows that coverage is very sensitive to SINR threshold.

However, in Figures 6.12-6.13, we see significant differences among different locations of relays put in the cell. Similar to the case of non-selective relaying, the results indicate that adapting modulation and coding rates to the SINR may maximize coverage.

Figure 6.12 User Coverage vs. SINR Threshold with Selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-12} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W , number of relay : 4 without Gain Enhanced Donor Link.)

Figure 6.13 User Coverage vs. SINR Threshold with Selective Analog Fixed Relaying Scheme(for Feedback Gain = 0, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W , number of relay : 4 without Gain Enhanced Donor Link.)

6.4 Impact of Cell Radius on Coverage

In this section, we adjust the cell radius from 500 m to 1000 m to examine its impact on coverage. Figure 6.14 corresponds to feedback gain $=10^{-12}$, while Figure 6.15 corresponds to no feedback. Other assumptions are same as in Figures 6.7-6.8.

Figure 6.14 User Coverage vs. Number of Relays per cell with Selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-12} , 1000 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14dB Gain Enhanced Donor Link.)

Comparing Figure 6.14 with Figure 6.7, we find that system has significant coverage reduction due to doubled cell radius. The corresponding coverage reduction is approximately from 59% to 31% with no relaying. For 4 relays at the 3/4 cell radius, the corresponding coverage reduction is from 78% to 46% for interference factor = 0.2. Also, comparing Figure 6.15 with Figure 6.8, the corresponding coverage degradation is

approximately from 59% to 31% with no relaying ; for 4 relays at the 3/4 cell radius, the correspond coverage degradation is from about 78% to about 47% as interference factor = 0.2.

In Figures 6.14 and 6.15, we find that there are only about 6% difference between *interference factor* = 0.2 and *interference factor* = 0 with large 1000 m cells while there are about 16% difference with small 500 m cells. Therefore, we know that the larger each cell is, the smaller the effect interference has relative to noise.

Figure 6.15 User Coverage vs. Number of Relays per cell with Selective Analog Fixed Relaying Scheme(for Feedback Gain = 0, 1000 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W with 14dB Gain Enhanced Donor Link.)

6.5 Impact of Interference on Coverage

Likewise in section 5.1.5, in this section, we adjust *interference factor* to 1 and 0.5 to see its effect on coverage, assuming constant relay feedback $=10^{-12}$ and keeping other assumptions the same as section 4.3.

Results are shown in Figures 6.16 and 6.17. Figure 6.16 corresponds to the scenario without gain enhanced donor link, while Figure 6.17 corresponds to the scenario with 14dB gain enhanced donor link.

Figure 6.16 User Coverage vs. Number of Relays with Selective Analog Fixed Relaying Scheme(for interference factor = 1 and 0.5, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1W without Gain Enhancement on Donor Link.)

In Figure 6.16, with no relaying, coverage increases from about 38% to about 50% as *interference factor* is changed from 1 to 0.5. For 8 relays placed at the $\frac{1}{2}$ cell radius, the corresponding coverage increase is from about 52% to 64%.

Figure 6.17 User Coverage vs. Number of Relays with Selective Analog Fixed Relaying Scheme (for interference factor = 0.5 and 1, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1W with 14dB Gain Enhancement on Donor Link.)

In Figure 6.17, for 8 relays put in the $\frac{3}{4}$ of cell radius, the corresponding coverage increases from about 76% to 84% as the *interference factor* is changed from

1 to 0.5.

Comparing Figure 6.16 with Figure 6.2 and Figure 6.17 with Figure 6.7 respectively, we see that the more interference, the worse coverage. We conclude that coverage is also sensitive to interference for the selective on-channel relaying.

6.6 Impact of Propagation Exponent on Coverage

In this section, we adjust propagation exponent from $n = 4$ to $n = 3.5$ determine its effect on coverage, assuming constant relay feedback $= 10^{-12}$ and keeping other assumptions same as section 4.3.

We consider two scenarios: without gain enhanced donor link and with gain enhanced donor link, shown in Figures 6.18 and 6.19. Figure 6.18 corresponds to the scenario without gain enhanced donor link, while Figure 6.19 corresponds to the scenario with 14dB gain enhanced donor link. We would expect to see coverage improvement due to decreased propagation exponent.

In Figure 6.18, we see that the $\frac{1}{2}$ cell radius is the best placement of relays. Comparing Figure 6.18 with Figure 6.2, with no relaying, coverage increases from about 59% to about 67% for *interference factor* = 0.2 as the propagation exponent is changed from 4 to 3.5. For 4 relays placed on the $\frac{1}{2}$ cell radius, the corresponding coverage increase is from about 68% to about 75%. For 8 relays, the corresponding coverage improvement is from about 72% to about 78%. We conclude that coverage is sensitive to propagation exponent for selective relaying without gain enhancement on donor link. This result is consistent with that of non-selective relaying.

Figure 6.18 User Coverage vs. Number of Relays with Selective Analog Fixed Relaying Scheme(for propagation exponent = 3.5, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1W without Gain Enhanced Donor Link.)

In Figure 6.19, we see that the $\frac{3}{4}$ cell radius is the best placement of relays. Comparing Figure 6.19 with Figure 6.7, for 4 relays put on the $\frac{3}{4}$ cell radius, the corresponding coverage increase is from about 76% to about 82%. For 8 relays, the corresponding coverage improvement is from about 87% to 91%. This implies that coverage is not so sensitive to propagation exponent for selective relaying with gain

enhanced donor link as that of without gain enhanced donor link. This result is consistent with that of non-selective relaying with gain enhanced donor link.

Figure 6.19 User Coverage vs. Number of Relays with Selective Analog Fixed Relaying Scheme(for propagation exponent = 3.5, 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1W with 14dB Gain Enhanced Donor Link.)

6.7 Impact of the Number of Relays on Coverage

In this section, we adjust the maximal number from 8 to 16 see its effect on coverage, assuming constant relay feedback = 10⁻¹² and keeping other assumptions same as section 4.3. Results are shown in Figures 6.20-6.21.

Figure 6.20 User Coverage vs. Number of Relays with Selective Analog Fixed Relaying Scheme(for the number of relays: 0~16 , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1W without Gain Enhanced Donor Link.)

Figure 6.21 corresponds to the scenario without gain enhanced donor link, while Figure 6.17 corresponds to the scenario with 14dB gain enhanced donor link.

In Figures 6.20-6.21, we see that coverage saturates, as the number of relays increases above 10. We get conclusion that using more relays will have no effect on

coverage as the number of relays is greater than 10.

Figure 6.21 User Coverage vs. Number of Relays with Selective Analog Fixed Relaying Scheme(for the number of relays: 0~16 , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1W with 14 dB Gain Enhanced Donor Link.)

6.8 Comparison with Digital Fixed Relaying Scheme

This section is concerned with a comparison with digital fixed relaying researched at Carleton University [32]. Huining Hu provides the results of digital

relaying.

The frequency reuse factor is one. The cellular system has seven clusters. Each cell has fixed 6 relays located on the 2/3 cell radius. The base station uses 64-QAM to modulate and demodulate the signals. Channels available in the system are partitioned in six groups. Each relay is distributed with one group of the channels. To improve the throughput and provide the high data rate coverage, adaptive modulation and adaptive coding are used in relays and mobile terminals. Only one best relay is selected. The relay selection scheme is based on either distance, path loss or SINR. Diversity with maximal ratio combining is used. Receiving signal is a combination from both the BS and the selected relay. Perfect donor link transmission is assumed.

6.8.1 Simulation Parameters

Analog and digital Relaying have the following common parameters:

- Simulation area: hexagonal cell with variation in cell radius from 1000 m to 500 m
- Frequency reuse factor is $R=1$
- Path loss propagation exponent: $n=4$, path loss: $= 20\log(\frac{4\pi d_0}{\lambda}) + 10n\log(\frac{d}{d_0})$

$$(d_0 = 10m)$$

- Lognormal shadowing with a standard deviation: $\sigma = 8dB$
- Flat Rayleigh fading, which has an envelope distribution $f_Y(y) = \frac{y}{\alpha^2} e^{-\frac{y^2}{2\alpha^2}}$,

$$y \geq 0, \alpha = \frac{1}{\sqrt{2}}$$

- RF Carrier = 2 GHz, transmission bandwidth: $W=5\text{MHz}$
- Thermal Noise with a noise figure: $F=8\text{dB}$
- Maximum base station transmit power per node: 10W
- Maximum relay power per node: 1W
- Variation single SINR threshold: from 4 dB to 26 dB
- Interference factor is 0.1 or 0.2
- Number of relays in the system is 6 which is fixed relays located equidistant on the $2/3$ cell radius away from base station
- Downlink scenario only: since the requested data rate from this direction is much higher than the uplink case
- Maximal Ratio Combining diversity is used at mobile terminals

They have the following different parameters:

(1) For analog relaying :

- 14 dB gain enhancement on donor link. Donor link is not perfect; there is some path loss according to equation (5.1)
- Variation in feedback gain of relays: from 10^{-10} to 0
- Selective scheme is used

(2) For digital relaying:

- Omnidirectional antennas (with a gain of 1) for both the base station, fixed relay and mobile terminal
- No power control: because when adaptive modulation and adaptive coding scheme is used, power control does not contribute much towards the throughput

increase.

- Perfect (noiseless) donor link transmission

6.8.2 Simulation Results of Analog Fixed Relaying

Figures 6.22-6.23 show simulation results of analog fixed relaying. Figure 6.22 corresponds to cell radius 1000 m while Figure 6.23 corresponds to cell radius 500 m. Different curves express the different results with different feedback of relay.

Figure 6.22 User Coverage vs. SINR Threshold with Selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-12} , 1000 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W , number of relay : 6 with 14 dB Gain Enhancement on Donor Link.)

In Figure 6.22 for SINR threshold = 10 dB, the best coverage is about 59% while the worst is about 39% for interference factor = 0.2; similarly, the best is about 60% and

the worst is about 40% for interference factor = 0.1.

In Figure 6.23 for SINR threshold = 10 dB, the best coverage is about 85% while the worst is about 72% as interference factor = 0.2; likewise, the best is about 88% and the worst is about 76% as interference factor = 0.1.

Figure 6.23 User Coverage vs. SINR Threshold with Selective Analog Fixed Relaying Scheme(for Feedback Gain = 10^{-12} , 500 m cells, maximal output power of base station: 10W, maximal output power of relay: 1 W , number of relay : 6 with 14 dB Gain Enhancement on Donor Link.)

In Figures 6.22-6.23, we can see that the system has the same SINR distribution as the relay feedback is less than 10^{-12} . This implies that the system will have almost same coverage improvement as antenna separation is larger than 120 dB. This result is consistent with previous results.

6.8.3 Simulation Results of Digital Fixed Relaying

Figures 6.24-6.25 show simulation results of digital fixed relaying (those results provided by Huining Hu).

Figure 6.24 User Coverage vs. SINR Threshold with Digital Fixed Relaying Scheme(1000 m cells, number of relay : 6)

Figure 6.24 corresponds to cell radius 1000 m, while Figure 6.25 corresponds to cell radius 500 m. Different curves express the different results with different feedback of relay.

Figure 6.25 User Coverage vs. SINR Threshold with Digital Fixed Relaying Scheme (500 m cells, number of relay : 6)

In contrast to the analog relaying, there is no feedback existing in the digital relaying system. In Figures 6.24-6.25, different curves represent different results of different maximal output powers of relays. The system has the worst performance without relaying and the best performance when relay power is 1W. 1W is the maximal power used by the corresponding analog relaying system.

In Figure 6.24, the best coverage is about 72% when SINR threshold = 10 dB

with interference factor = 0.2. Similarly, coverage is about 80% with interference factor = 0.1.

In Figure 6.25, the best coverage is about 88% when SINR threshold = 10 dB for interference factor = 0.2. Also, coverage is about 92% for interference factor = 0.1.

6.8.4 Comparison of Results

According to those above results both analog and digital relaying, we see that digital relaying has obviously better coverage than analog with large cell 1000 m radius while both systems have little coverage difference with 500 m cell radius. Note that digital and analog relaying have different assumptions for donor link. In digital relaying, perfect transmission on donor link was assumed. However, in analog relaying, we assumed that there is no perfect transmission on donor link, there is path loss (equation (5.1), see section 6.8.1). Since the path loss is proportional to the distance between base station and relay or mobile terminal, there is larger path loss with large cell 1000 m radius than that of with small cell 500 m radius.

On-channel analog relaying is easier to implement than digital relaying in terms of signal processing complexity. It has the following advantages: on-channel relay has no explicit routing or scheduling needed. This feature simplifies signaling overhead and MAC. Therefore, it will improve the data transmission efficiency. For non-selective on-channel relaying, relays simply retransmit signals to all of mobile users whether or not they need relaying, it has built in multi-hop technology.

Likewise, it has the following disadvantages: on-channel relay propagates noise as well as signal; this generally limits the maximum signal to interference plus noise

ratio at mobile terminals and leads to service degradation. On the other hand, it has potential instability due to feedback from transmitter back to receiver. Its stability will be achieved by strictly isolating transmitter and receiver antennas with shielding, directivity and distance. Another drawback is that relay must control AGC by output power to ensure the system stable. On-channel relay will also increase inter-cell interference due to shorter paths from relays (but not due to increased channel use).

Chapter 7: Discussions and Conclusions

7.1 Results Summary

The simulation results presented in this thesis provide system coverage performance due to different factors with analog on-channel relays. Whether or not there is a potential benefit from employing analog fixed relaying in a fully loaded digital cellular network was investigated.

In particular, we determined coverage improvements obtainable in a cellular system with frequency reuse factor = 1 from both non-selective on-channel fixed relays and selective on-channel fixed relays.

Our simulation results show that significant coverage improvements can be obtained. For example:

1. From 31% for no relaying to > 52% for 8 fixed on-channel non-selective relays per 1000m radius cell, with 14 dB enhanced donor link gain (section 5.4).
2. From 59% for no relaying to > 84% for 8 fixed on-channel non-selective relays per 500m radius cell, with 14 dB enhanced donor link gain (section 5.2).
3. From 31% for no relaying to > 60% for 8 fixed on-channel selective relays per 1000 m radius cell, with 14 dB enhanced donor link gain (section 6.4).
4. From 59% for no relaying to > 88% for 8 fixed on-channel selective relays per 500 m radius cell, with 14 dB enhanced donor link gain (section 6.2).
5. The selective relaying has slight better coverage improvement than that of the non-selective relaying: about more 6% with 14dB enhanced gain donor link and about more

4% without enhanced gain donor link (chapter 5 and chapter 6).

6. Interference with different suppression factors has affected coverage with about 12-16% (chapter 5 and chapter 6).

7. Gains are close to those achieved with digital relaying for small cells (section 6.8).

Therefore, based on our simulations, we recommend the following system design considerations:

1. For the selective scheme, we suggest that there are at least 4 to 6 fixed selective relays per cell, at about $2/3$ to $3/4$ cell radius distance from base station, with good (enhanced gain) links to base stations (section 5.2).
2. For the non-selective scheme, non-selective relays can also improve coverage, even though optimum cell radius depends on cell size (section 5.1). We suggest using smaller cell radius.
3. Analog on-channel relays should have high degree of isolation between transmitter and receiver (e.g. > 120 dB) (section 5.1 and 5.2). When feedback gains of relays $> 10^{-10}$, there is no coverage improvement.
4. For systems with aggressive frequency reuse, fixed relays should have fixed beam-shaping capability to suppress interference from fixed neighbor relays and base stations by at least $> 80\%$ (~ 7 dB) (chapter 5 and chapter 6).
5. The smaller the required SINR, the better is system coverage. Adaptive modulation and coding can be exploited to enhance coverage (section 5.3 and 6.3).

7.2 Further Discussions

According to our research, analog fixed relaying in a cellular network seems

promising. However, we only investigated simple log-distance path loss model and parameters and environment. It would be interesting to see how sensitive these results are to different environment and parameter assumptions. For example, by changing the log-distance path loss model to different other models in [2] or [5] or considering the physical environment factors into the model, such as building, raining and trees, etc., to improve the on-channel model. As well, it may be more suitable to select Ricean channel model instead of Rayleigh channel. These and other parameters need to be refined and further simulations need to be done so that we have a basis for making practical comparison.

Furthermore, in our simulation, we discussed the special case for frequency reuse factor = 1 and assumed omniscells. If we change the cell design to sectored cells, we could take a three/six-sectored cell, and create some overlap by using realistic antenna patterns. Therefore, would it be useful to locate the relays at the intersections of the sectors or at the farther edges of the cell? If relays are located at the intersections of sectors, would it make sense for them to be accessible to users in the overlapping sectors? We need further simulations to examine all of these considerations.

One other issue concerns the mobility assumption, where in our simulations we have discussed low-speed mobility. In a highly dynamic environment with high-speed mobility, adding Doppler for mobility is more useful.

Different diversity algorithms, which are alternatives to maximal ratio combining diversity, are one other issue. For example, we could choose selective combining instead of maximal ratio combining diversity. Selective combining means that the received signal power at a mobile terminal is that of strongest signal instead of the sum

of powers of all received signals. Or, we could change the relay selection scheme based on SINR instead of gain. How would coverage results be affected?

Finally, the lognormal shadowing standard deviation for donor link should perhaps be lower than that of distribution link. We should increase correlated shadowing on distribution link. One more issue should be considered is which multiple-access should be employed OFDMA or CDMA or TDMA for selective relaying?

7.3 Suggestions for Future Research

To determine further insights into the impact of analog relaying in a cellular network on system coverage performance, the following future research are suggested:

1. Using path loss models in [2] or [5] instead of log-distance path loss model to determine the impact on coverage.
2. Choosing a Ricean channel model instead of a Rayleigh channel to examine the effect on coverage.
3. Improving the on-channel model with some physical environment factors into the model, such as building, raining and trees, etc.,
4. Coverage analysis on the impact of using sectored cells instead of omni-cells, directional relays instead of omni-relays.
5. Coverage analysis on the impact of Doppler for mobility instead of low-speed mobility.
6. Performance impact due to other combining options other than maximal ratio combining diversity.
7. Performance impact due to different lognormal shadowing between donor link and

distribution link.

8. Employ relay selection scheme based on SINR or geographic distance instead of transmission gains on both donor link and distribution link.
9. Effect due to various multiple access schemes, such as OFDMA or CDMA or TDMA for selective relaying.
10. Using directive antennas on both of between base station and relays, between relays and mobile terminals.

References

- [1] Jean-Paul DeCruyenaere, *Radio Coverage of Mill-Wave Broadband Wireless Access Systems in Suburban Areas*, PhDs thesis, Department of Systems and Computer Engineering, Carleton University, 2000
- [2] T.S.Rappaport, *Wireless Communications: Principles and Practice*, Prentice Hall PTR, 1996
- [3] Van M. Sreng, *Coverage Enhancement through Two-hop Relaying in Cellular Radio Systems*, Masters thesis, Department of Systems and Computer Engineering, Carleton University, 2002
- [4] J.G.Proakis, *Digital Communications*, McGraw-Hill, New York, Fourth Edition, 2001
- [5] W. Mohr, R. Luder, K.Mohrmann, "Data Rate Estimates, Range Calculations and Spectrum Demand for New Elements of Systems Beyond IMT-2000 ", WPMC, Honolulu, October 2002
- [6] W.T.Slingsby, J.P.McGeehan, "Antenna Isolation Measurements for On-frequency Radio Repeaters", *IEE International Conference on Antennas and Propagation*, April 1995
- [7] W.T.Slingsby, J.P.McGeehan, "A High-Gain Cell Enhancer", *Proceedings of the IEEE Vehicular Technology Conference*, Vol. 1, pp756-758, May 1992
- [8] V.S.Kaunismma, "On Frequency Radio (OFR) Repeater as Fade Filler", *IEEE Vehicular Technology Conference*, Vol. 2, pp.528-531, June 1989
- [9] B.J.Leff, "Application Engineering Considerations for Cellular Repeaters", *IEEE Vehicular Technology Conference*, Vol. 2, pp. 532-534, June 1989
- [10] E.H.Drucker,"Development and Application of a Cellular Repeater", *IEEE Vehicular Technology Conference*, pp. 321-325, June 1988
- [11] Mazen O. Hasna, Mohamed-Slim Alouini, "A performance study of dual-hop transmissions with fixed gain relays", *Acoustics, Speech, and Signal Processing, (ICASSP '03), IEEE International Conference*, Vol. 4, pp.1310-1314, April 2003
- [12] Andrew Sendonaris, Elza Erkip, Behnaam Aazhang, "User Cooperation Diversity-Part I: System Description", <http://eeweb.poly.edu/~elza/>

- [13] Andrew Sendonaris, Elza Erkip, Behnaam Aazhang, "User Cooperation Diversity-Part II: Implementation Aspects and Performance Analysis",
<http://eeweb.poly.edu/~elza/>
- [14] J.Boyer, *Multihop Wireless Communications channels*, Masters thesis, Department of Systems and Computer Engineering, Carleton University, 2001
- [15] Branimir Vojcic, *Ad-Hoc Networks*, Lecture Notes, George Washington University, October 2000, <http://www.ece.seas.gwu.edu/people/fac/vojcic.html>
- [16] Halim Yanikomeroglu, "Fixed and Mobile Relaying Technologies for Cellular Networks", in *Proceedings of the Second Workshop on Applications and Services in Wireless Networks (ASWN'02)*, Paris, France, July 2002
- [17] WWRF/WG4/Ad-hoc Networking Subgroup, White Paper, Draft Version 0.8, June 2002
- [18] ETSI EN 301 908-11 V.0.0.5, *Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Base Stations (BS), Repeaters and User Equipment (UE) for IMT-2000 Third Generation cellular networks; Part 11: Harmonized EN for IMT-2000 CDMA Direct Spread (UTRA FDD) (Repeaters) covering essential requirements of article 3.2 of the R&TTE Directive*, September 2002
- [19] 3GPP TS 25.106 V5.2.0, *3rd Generation Partnership Project; Technical Specification Group Radio Access Networks; UTRA Repeater Radio Transmission and Reception (Release 5)*, September 2002
- [20] V.Sreng, H. Yanikomeroglu, and D.D.Falconer, "Capacity Enhancement Through Two-hop Relaying in Cellular Radio Systems", *IEEE Wireless Communications and Networking Conference (WCNC'02)*, Vol. 2, pp. 881-885, 2002
- [21] J. Boyer, D. Falconer, H. Yanikomeroglu, "A theoretical characterization of the multihop wireless communications channel without diversity", *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Vol. 2, pp. E-116-E-120, October 2001
- [22] Branimir Vojcic, Raymond Pickholtz, Dezso Vekassy, Michael Souryal, "Throughput Analysis of Cellular Multihop Networks", George Washington University, <http://www.ece.seas.gwu.edu/people/fac/vojcic.html>
- [23] Mazen O. Hasna, Mohamed-Slim Alouini, "Performance analysis of two-hop relayed transmissions over Rayleigh fading channels", *IEEE 56th, Vehicular Technology Conference*, Vol. 4, pp1992-1996, September 2002
- [24] Mazen O. Hasna, Mohamed-Slim Alouini, "Application of the harmonic mean

statistics to the end-to-end performance of transmission systems with relays”, *IEEE Global Telecommunications Conference*, (GLOBECOM '02.), Vol. 2, pp.1310 –1314, November 2002

[25] 3GPP TR 25.956 V5.0.0, *3rd Generation Partnership Project; Technical Specification Group Radio Access Networks; UTRA Planning Guidelines and System Analysis (Release 4)*, March 2002

[26] J. Boyer, D. Falconer, H. Yanikomeroglu, “A theoretical characterization of the multihop wireless communications channel with diversity”, *IEEE GlobeCom Conference (GLOBECOM'01)*, 2001

[27] T. Ohta, S. Inoue, Y. Kakuda, “An adaptive multihop clustering scheme for highly mobile ad hoc networks”, *The Sixth International Symposium on Autonomous Decentralized Systems, ISADS*, pp. 293 –300, 2003

[28] Hui Li, Dan Yu, “Comparison of ad hoc and centralized multihop routing”, *The 5th International Symposium on Wireless Personal Multimedia Communications*, Vol. 2, pp. 791 –795, October 2002

[29] A. Fujiwara, S. Takeda, H. Yoshino, T. Otsu, “Area coverage and capacity enhancement by multihop connection of CDMA cellular network”, *IEEE 56th Proceedings, Vehicular Technology Conference*, 2002, Vol. 4, pp. 2371 -2374 September 2002

[30] T.J. Harrold, A.R. Nix, “Intelligent relaying for future personal communication systems”, *IEE Colloquium on Capacity and Range Enhancement Techniques for the Third Generation Mobile Communications and Beyond (Ref. No. 2000/003)*, pp. 9/1 - 9/5, February 2000

[31] T.J. Harrold, A.R. Nix, “Performance analysis of intelligent relaying in UTRA TDD”, *IEEE 56th Proceedings, Vehicular Technology Conference*, Vol. 3, pp. 1374 – 1378, September 2002

[32] Huining Hu, *Performance Analysis of Cellular Networks with Digital Fixed Relays*, Masters thesis, Department of Systems and Computer Engineering, Carleton University, 2003