

PERFORMANCE ANALYSIS, POWER
ALLOCATION AND SECRECY IN RELAYED
COMMUNICATION SYSTEMS

CHINMOY KUNDU



BHARTI SCHOOL OF TELECOMMUNICATION
TECHNOLOGY AND MANAGEMENT
INDIAN INSTITUTE OF TECHNOLOGY DELHI
INDIA

MARCH 2015

© Indian Institute of Technology Delhi (IITD), New Delhi, 2015

**PERFORMANCE ANALYSIS, POWER
ALLOCATION AND SECRECY IN RELAYED
COMMUNICATION SYSTEMS**

by

CHINMOY KUNDU

**Bharti School of Telecommunication Technology
and Management**

Submitted

in fulfillment of the requirements of the degree of

Doctor of Philosophy

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI
INDIA**

MARCH 2015

Certificate

This is to certify that the thesis entitled “**Performance Analysis, Power Allocation and Secrecy in Relayed Communication Systems**” being submitted by **Mr. Chinmoy Kundu** to the Bharti School of Telecommunication Technology and Management, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is the record of the bona-fide research work carried out by him under my supervision. In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

Date:

(Dr. Ranjan Bose)

Place:

Professor

Department of Electrical Engineering

Indian Institute of Technology Delhi

Hauz Khas, New Delhi 110016

India

Acknowledgements

First and foremost, I would like to gratefully acknowledge my supervisor Prof. Ranjan Bose for his immense support, patience, and encouragement. Without his guidance and scientific enlightenment this work would not have been possible.

I would like to express my sincere gratitude to my student research committee members Prof. Shankar Prakriya, Prof. Brejesh Lall, and Prof. Monika Aggarwal for many useful interactions and for their comments and suggestions on my work. I would like to specially thank Prof. Shankar Prakriya for his constant encouragement and invaluable feedback. I am also grateful to all the professors at IIT Delhi from whom I have learned a lot during the courses. I would also like to thank all members of the Bharti School of Telecommunication Technology and Management and Electrical Engineering department for their immense help.

To my good friends, thank you for being there for me through thick and thin, for sharing my joys and sorrows, for rejoicing in my successes and for helping me recover from my failures.

Most importantly, I express my heartfelt gratitude for my parents Mrs. Purnima Kundu and Mr. Kamal Baran Kundu, for their uncountable sacrifices for me, supporting my academic pursuits, and constantly encouraging to do well in my life. I also thank my sisters Mrs. Paramita Kundu and Mrs. Nivedita Kundu for their unceasing encouragement and loving support. I thank my uncle Mr. Parag Baran Kundu wholeheartedly; he helped me to accomplish what I am today. I would like to thank my grandmother Mrs. Sagarbala Kundu, uncle Mr. Malay Baran Kundu, and aunt Mrs. Sabitri Kundu for their endless love and care. I would also like to thank my aunt *late* Mrs. Sima Kundu for her kind blessings.

I place on record, my sense of gratitude to one and all who, directly or indirectly, have bestowed their helping hand in this endeavour.

Chinmoy Kundu

Abstract

In short distance communication technique like Ultra-Wideband (UWB) communication the log-normal fading model is a generally accepted channel model. In this thesis, we begin by proposing an alternate numerical approach to evaluate average symbol error probability in a log-normal channel. Average symbol error probability for maximal ratio combining Rake receiver in UWB multi-path channel is evaluated using the proposed numerical approach. It is shown that the proposed method is more general with comparable accuracy. We then propose multi-hop decode-and-forward relaying for range extension of UWB system using non-coherent transmitted reference UWB receiver. Distribution of individual hop signal-to-noise ratio is approximated by a log-normal distribution and subsequently end-to-end average bit error rate is evaluated analytically. It is found that the performance improvement in average transmit signal-to-noise ratio is not equal as the number of hop increases. It decreases with increase in hop number in the line-of-sight channel.

In an energy constrained multi-hop relaying network, the end-to-end quality-of-service must be optimized. Hence, joint optimization of power allocation and relay location is proposed for amplify-and-forward relaying over independent log-normal channels. The proposed optimization method maximizes the end-to-end average signal-to-noise ratio. It is observed that joint optimization can even outperform instantaneous signal-to-noise ratio based power allocation. Subsequently, joint optimization of power allocation and relay location is proposed for decode-and-forward relaying using the same system model of amplify-and-forward relaying. Optimization is now carried out in order to minimize the outage probability and end-to-end average bit error rate. All the optimization problems reformulated from the original problems

are shown to be convex except for the optimization of relay location in minimizing outage probability at the low signal-to-noise ratio scenario. It is then solved using properties of concave minimization. It is observed that performance improvement increases with increase in link unbalance and distance based allocation is most effective in performance improvement.

Relaying not only increases the area of interception it can even provide diversity benefit to the eavesdropper. Thus, towards the end of the thesis, a dual-hop amplify-and-forward system is considered in Rayleigh fading channel with an eavesdropper. We consider maximal ratio combining and selection combining diversity by the eavesdropper. Closed-form expressions for upper, lower bounds and approximate secrecy outage are derived. In order to achieve the same performance of selection combining, maximal ratio combining requires relatively higher signal-to-noise ratio at lower rate. It is also interesting to observe that either one of the dual-hop link can equally limit the secrecy outage performance.

Relay selection can further improve the secrecy outage performance. Secrecy outage probability of optimal, traditional and suboptimal relay selection schemes is evaluated for a dual-hop regenerative multi-relay system in Rayleigh fading channel. Partial relay selection schemes are introduced. An optimal relay selection scheme is proposed which does not require any instantaneous channel information. Improvement in eavesdropper link quality affects the secrecy outage more when the required secrecy rate is low. It is also interesting to observe that either of the source-relay or the relay-destination link quality can equally limit the secrecy outage performance.

Contents

Certificate	i
Acknowledgements	iii
Abstract	v
List of Figures	xiii
List of Tables	xvii
List of Abbreviations	xix
1 Introduction	1
1.1 Introduction	1
1.2 Wireless Channels	2
1.3 Fading Channel Models	4
1.3.1 Log-normal Fading Model	4
1.3.2 Rayleigh Fading Model	5
1.4 Signal Relaying	6
1.4.1 Amplify-and-Forward (AF)	7
1.4.2 Decode-and-Forward (DF)	7
1.5 Cooperative Diversity	8
1.6 Secure Communication	8
1.7 Motivation	9
1.8 Contributions	9

1.9	Organization of Thesis	11
2	Related Work	15
2.1	UWB Communication	15
2.2	Average Probability of Error over Log-normal Channel	16
2.3	Relayed Communication	17
2.4	Optimal Power Allocation	19
2.5	Secrecy in Relayed Communication	20
2.6	Relay Selection for Secrecy	21
2.7	Summary	23
3	Alternate Method of Averaging in Log-normal Channel with Appli- cation to UWB Communication	27
3.1	Introduction	27
3.2	System Model	28
3.3	Alternate Averaging Method	30
3.4	ASEP in UWB Channel	31
3.5	Numerical Results	33
3.6	Summary	36
4	Performance Analysis of Multi-hop UWB Transmitted Reference System using DF Relays	39
4.1	Introduction	39
4.2	Review of UWB TR Receivers	40
4.3	System Model	41
4.4	Signal and Channel Model	42
	4.4.1 Signal Model	42
	4.4.2 Channel Model	43
4.5	End-to-End Performance	45
	4.5.1 Received SNR at Each Hop	45
	4.5.2 Received SNR Distribution and ABER Performance	47

4.6	Numerical Results	48
4.7	Summary	54
5	Joint Optimal Power Allocation and Relay Location for Multi-hop AF Relaying over Log-normal Channel	57
5.1	Introduction	57
5.2	System Model	58
5.3	OPA Based on ASNR	59
5.3.1	OPA for the Fixed Relay Location	60
5.3.2	Optimize Relay Location for the Fixed PA	61
5.3.3	Joint PA and Relay Location Optimization	62
5.4	OPA Based on ISNR	63
5.5	Analysis of Outage Probability	64
5.6	Numerical Results	65
5.7	Summary	69
6	Joint Optimal Power Allocation and Relay Location for Multi-hop DF Relaying over Log-normal Channel	71
6.1	Introduction	71
6.2	System Model	72
6.3	Outage Optimal Allocation	73
6.3.1	High SNR Scenario	74
6.3.1.1	PA for the Fixed Relay Location	74
6.3.1.2	Optimal Relay Location for Fixed PA	76
6.3.1.3	Joint Optimal PA and Relay Location	77
6.3.2	Low SNR Scenario	78
6.3.2.1	PA for the Fixed Relay Location	79
6.3.2.2	Optimize Relay Location for Fixed PA	80
6.3.2.3	Jointly Optimize PA and Relay Location	80
6.4	Optimization of ABER Upper Bound	81

6.4.1	OPA for the Fixed Relay Location	82
6.4.2	Optimize Relay Location for Fixed PA	83
6.4.3	Joint PA and Relay Location Optimization	84
6.5	Performance Improvement using Unbalanced Links	85
6.5.1	Performance Improvement using OPA for Fixed Relay Locations	85
6.5.2	Performance Improvement using Optimized Relay Location for Fixed PA	86
6.5.3	Performance Improvement using Joint PA and Relay Location Optimization	88
6.6	Numerical Results	88
6.7	Summary	93

7 Secrecy Outage of Dual-hop AF Relay System with Diversity Combining at the Eavesdropper 95

7.1	Introduction	95
7.2	System Model	96
7.3	Mathematical Preliminaries	98
7.4	Secrecy Outage: Correlated Assumption	101
7.4.1	MRC at Eavesdropper	101
7.4.1.1	Lower Bound	101
7.4.1.2	Upper Bound	104
7.4.1.3	Approximate Analysis	105
7.4.2	SC at Eavesdropper	107
7.4.2.1	Lower Bound	107
7.4.2.2	Upper Bound	108
7.4.2.3	Approximate Analysis	108
7.5	Secrecy Outage: Independent Assumption	110
7.5.1	MRC at Eavesdropper	111
7.5.2	SC at Eavesdropper	112
7.6	Asymptotic Analysis	113

7.6.1	Correlated Assumption	114
7.6.2	Independent Assumption	116
7.7	Numerical Results	120
7.8	Summary	126
8	Secrecy Outage of Dual-hop Regenerative Multi-relay System with Relay Selection	127
8.1	Introduction	127
8.2	System Model	128
8.3	Secrecy Outage of Dual-hop Single Relay System	130
8.4	Secrecy Outage of Relay Selection Schemes	131
8.4.1	Optimal Selection: ICSI of All Links are Known (<i>OS</i>)	131
8.4.2	Traditional Selection: <i>R-E</i> Link ICSI is Unknown (<i>TS</i>)	132
8.4.3	Suboptimal Selection: ICSI of S-R and R-D Link and Average R-E Link is Known (<i>SS-RE</i>)	134
8.4.4	Suboptimal Relay selection: Only R-D Link ICSI is Known (<i>SS-RD</i>)	135
8.4.5	Suboptimal Selection: Only S-R Link ICSI is Known (<i>SS-SR</i>)	138
8.4.6	Proposed Selection (<i>PS</i>)	139
8.5	Asymptotic Analysis	139
8.5.1	Single Relay: Balanced Case	140
8.5.2	Single Relay: Unbalanced Case	141
8.5.3	Optimal Selection: Balanced Case	142
8.5.4	Optimal Selection: Unbalanced Case	142
8.6	Numerical Results	143
8.7	Summary	147
9	Conclusions and Future Work	149
9.1	Conclusions	149
9.2	Future Work	153

Bibliography	155
A Evaluation of μ_γ and σ_γ	169
B Convexity Conditions of P_{out} Upper Bound in Equation (6.7)	171
B.1 Convexity in β_k	171
B.2 Convexity in d_k	172
B.3 Joint Convexity in β_k and d_k	172
C Convexity of P_{out} Upper Bound in Equation (6.7) at High SNR	175
D Convexity Analysis of Equation (6.24) at Low SNR	177
D.1 Convexity in β_k	177
D.2 Convexity in d_k	178
D.3 Joint Convexity in β_k and d_k	178
E Convexity or Concavity of Equation (6.24) at Low SNR	179
Publications	181
Technical Biography of Author	183

List of Figures

3.1	Comparison of various Gaussian Q-function averaging method in log-normal channel.	34
3.2	Probability density function of log-normal “power sum” distribution following approach (C) for different number of resolvable multi-paths.	35
3.3	ASEP comparison of different “power sum” approximation with proposed numerical averaging in UWB channel.	36
4.1	Multi-hop relaying strategy.	41
4.2	ABER comparison of different hops using STR receiver in LOS and NLOS channel.	50
4.3	ABER comparison of different hops using ATR receiver in LOS and NLOS channel.	51
4.4	ABER comparison of different hops using DTR receiver in LOS and NLOS channel.	51
4.5	Multi-hop ABER comparison of STR, ATR and DTR receivers in LOS channel.	53
4.6	Comparison of ABER of different hops with distance in STR receiver for LOS and NLOS channel.	54
5.1	Comparison of OA techniques for $K = 2$ with $\sigma_1 = 4$ and $\sigma_2 = 8$ dB.	66
5.2	Comparison of OA techniques for $K = 2$ with $\sigma_1 = 4$ and $\sigma_2 = 10$ dB.	67
5.3	Comparison of OA techniques for $K = 2$ and $K = 4$ system with identical links having $\sigma = 6$ and $\sigma = 8$ dB.	68

6.1	Outage probability comparison of optimal allocation strategies with equal allocation for a $K = 2$ hop system for $\sigma_1 = 8, \sigma_2 = 5$ dB and $\sigma_1 = 5, \sigma_2 = 3$ dB.	90
6.2	Outage probability comparison of optimal allocation strategies with equal allocation for a $K = 3$ hop system with $\sigma_1 = 8, \sigma_2 = 6, \sigma_3 = 4$ dB and $\sigma_1 = 7, \sigma_2 = 6, \sigma_3 = 4$ dB.	91
6.3	ABER comparison of optimal allocation strategies with equal allocation for a $K = 2$ hop system for $\sigma_1 = 8, \sigma_2 = 5$ dB and $\sigma_1 = 5, \sigma_2 = 3$ dB.	92
6.4	ABER comparison of optimal allocation strategies with equal allocation for a $K = 3$ hop system with $\sigma_1 = 8, \sigma_2 = 6, \sigma_3 = 4$ dB and $\sigma_1 = 7, \sigma_2 = 6, \sigma_3 = 4$ dB.	93
7.1	System Model for analyzing secrecy outage probability of a dual-hop communication system using AF relay.	97
7.2	Lower and upper bounds of secrecy outage probability for MRC diversity combining using analysis with correlated assumption at the eavesdropper.	121
7.3	Lower and upper bounds of secrecy outage probability for SC diversity combining using analysis with correlated assumption at the eavesdropper.	121
7.4	Comparison of secrecy outage probabilities of SC and MRC diversity combining for unbalanced case using analysis with correlated assumption.	123
7.5	Comparison of secrecy outage probabilities of SC and MRC diversity combining for unbalanced case using analysis with independent assumption	123
7.6	Comparison of secrecy outage probabilities of SC and MRC diversity combining for balanced case using analysis with correlated assumption.	125
7.7	Comparison of secrecy outage probabilities of SC and MRC diversity combining for balanced case using analysis with independent assumption.	125

8.1	Dual-hop multi-relay regenerative system where one of the relay is selected to forward the source information.	128
8.2	Secrecy outage probability of single relay balanced case.	144
8.3	Secrecy outage probability of single relay unbalanced case.	145
8.4	Secrecy outage probability comparison of various relay selection schemes with N	146
8.5	Secrecy outage probability comparison of various relay selection schemes with different eavesdropper link SNRs.	147

List of Tables

6.1	Outage optimal power allocation factors for equal relaying distance at high SNR, received ASNR per hop and convexity threshold for different P_T/N_0 in dual-hop system with $\sigma_1 = 8$ dB and $\sigma_2 = 5$ dB.	90
7.1	Bounds and approximate secrecy outage probability of MRC diversity combining at the eavesdropper.	106
7.2	Bounds and approximate secrecy outage probability of SC diversity combining at the eavesdropper.	109
8.1	Secrecy outage probability of various relay selection schemes.	137

List of Abbreviations

Acronym	Meaning
ABER	Average Bit Error Rate
AF	Amplify-and-Forward
ARake	All-Rake
ASEP	Average Symbol Error Probability
ASNR	Average Signal-to-Noise Ratio
ATR	Average Transmitted Reference
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CF	Characteristics Function
CSI	Channel State Information
CTS	Clear-to-Send
dB	Decibel
DF	Decode-and-Forward
DTR	Differential Transmitted Reference
EA	Equal Allocation
EGC	Equal Gain Combining
ICSI	Instantaneous Channel State Information
ISI	Inter Symbol Interference
ISNR	Instantaneous Signal-to-Noise Ratio
JOA	Joint Optimal Allocation
LOS	Line-of-Sight

LT	Long Term
MGF	Moment Generating Function
MRC	Maximal Ratio Combining
NLOS	Non Line-of-Sight
OA	Optimal Allocation
OPA	Optimal Power Allocation
ORL	Optimal Relay Location
PA	Power Allocation
PAM	Pulse Amplitude Modulation
PDF	Probability Distribution Function
PPM	Pulse Position Modulation
PSD	Power Spectral Density
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QoS	Quality-of-Service
RV	Random Variable
RTS	Ready-to-Send
S-V	Saleh-Valenzuela
SC	Selection Combining
SCSI	Statistical Channel State Information
SNR	Signal-to-Noise Ratio
ST	Short Term
STR	Simple Transmitted Reference
TR	Transmitted Reference
UWB	Ultra-Wideband
