

Cambridge University Press

978-0-521-85768-0 - Coexistence in Wireless Networks: Challenges and System-Level Solutions in the Unlicensed Bands

Nada Golmie

Frontmatter

[More information](#)

Coexistence in Wireless Networks

The increasing popularity of wireless networks makes interference and cross-talk between multiple systems inevitable. This book describes techniques for quantifying this, and the effects on the performance of wireless networks operating in the unlicensed bands. It also presents a variety of system-level solutions, obviating the need for new hardware implementations. The book starts with basic concepts and wireless protocols before moving on to interference performance evaluation, interference modeling, coexistence solutions, and concluding with common misconceptions and pitfalls. The theory is illustrated by reference to real-world systems such as Bluetooth and WiFi. With a number of case studies and many illustrations, this book will be of interest to graduate students in electrical engineering and computer science, to practitioners designing new WLAN and WPAN systems or developing new techniques for interference suppression, and to general users of emerging wireless technologies.

Nada Golmie received her Ph.D. in Computer Science from the University of Maryland, College Park, in 2002. Since 1993 she has been a research engineer for the advanced networking technologies division at the National Institute of Standards and Technology (NIST). This publication, however, is not affiliated with her work there. Nada's research has led to over 100 papers published in professional conference proceedings and journals, and has contributed to industry-led consortia.

Cambridge University Press

978-0-521-85768-0 - Coexistence in Wireless Networks: Challenges and System-Level Solutions in the
Unlicensed Bands

Nada Golmie

Frontmatter

[More information](#)

Coexistence in Wireless Networks

Challenges and System-Level
Solutions in the Unlicensed
Bands

Nada Golmie



CAMBRIDGE
UNIVERSITY PRESS

Cambridge University Press
978-0-521-85768-0 - Coexistence in Wireless Networks: Challenges and System-Level Solutions in the
Unlicensed Bands
Nada Golmie
Frontmatter
[More information](#)

C A M B R I D G E U N I V E R S I T Y P R E S S
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 2RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521857680

© Cambridge University Press 2006

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without
the written permission of Cambridge University Press.

First published 2006

Printed in the United Kingdom at the University Press, Cambridge

A catalog record for this publication is available from the British Library

ISBN-13 978-0-521-85768-0 hardback
ISBN-10 0-521-85768-6 hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or
third-party internet websites referred to in this publication, and does not guarantee that any content on such
websites is, or will remain, accurate or appropriate.

Cambridge University Press
978-0-521-85768-0 - Coexistence in Wireless Networks: Challenges and System-Level Solutions in the
Unlicensed Bands
Nada Golmie
Frontmatter
[More information](#)

To my parents
To Geof

Contents

<i>List of illustrations</i>	<i>page</i> x
<i>List of tables</i>	xii
<i>Preface</i>	xiii
<i>List of abbreviations</i>	xvi
1 Introduction	1
1.1 Interference modeling and performance evaluation	2
1.1.1 Mathematical modeling	2
1.1.2 Experimental modeling	3
1.1.3 Simulation modeling	3
1.2 Interference avoidance and coexistence strategies	4
1.2.1 Industry led activities	5
1.2.2 Fair scheduling and wireless QOS research	5
2 Basic concepts and wireless protocol overview	7
2.1 Physical layer	7
2.1.1 Communication channel	7
2.1.2 Modulation and filtering	8
2.1.3 Channel propagation properties	9
2.1.4 Signal detection	10
2.1.5 Spread spectrum	10
2.2 Media access control layer	13
2.2.1 Channel partitioning	13
2.2.2 Access control protocol	16
2.2.3 Key design factors	22
2.3 Examples of wireless protocols	23
2.3.1 Bluetooth	23
2.3.2 IEEE 802.11b	27

viii	Contents	
3	Interference performance evaluation	30
3.1	Interference model	31
3.2	Performance metrics	32
3.2.1	PHY layer performance measures	32
3.2.2	Higher layer performance measures	34
3.3	Factors affecting performance	35
3.3.1	Spectrum spreading	37
3.3.2	Hop rate	37
3.3.3	Traffic characteristics: offered load and packet size	37
3.3.4	Transmission power	40
3.3.5	Number of systems	42
4	Interference modeling: open loop	43
4.1	Theoretical BER estimation	43
4.2	Modeling BER in wireless channels	47
4.3	Packet error model	49
4.3.1	Case study: packet error model for Bluetooth with IEEE 802.11b interference	52
5	Interference modeling: closed loop	54
5.1	Usage definition	54
5.1.1	Usage models	55
5.1.2	Simulation scenarios	55
5.2	Application models	55
5.2.1	Bulk data	56
5.2.2	Application profiles	57
5.2.3	Traffic traces	58
5.3	Network topology	60
5.4	Channel model	62
5.5	Protocol layer modeling	63
5.5.1	MAC layer modeling	63
5.5.2	PHY layer modeling	65
5.5.3	Packet and signal processing simulation models interface	66
5.6	Simulation speed-up	67
5.7	Case study: evaluating IEEE 802.11 and Bluetooth interference	68
5.8	Comparing the simulation results with the analysis	71
6	Channel estimation and selection	76
6.1	Measurements	77
6.1.1	Physical layer measurements	77
6.1.2	Higher layer measurements	77

ix	Contents	
	6.2 Adaptive measurements	78
	6.2.1 Time average	79
	6.2.2 Combining measurements	80
	6.2.3 Thresholding techniques	82
	6.3 Implementation issues	83
	6.3.1 Channel classification	83
	6.3.2 Channel estimation feedback	84
	6.3.3 Channel estimation frequency	85
7	Effective coexistence strategies	88
	7.1 Knowledge of interference patterns	89
	7.2 Time division multiple access	90
	7.2.1 Fairness	91
	7.2.2 QOS support considerations	92
	7.2.3 Case study: Bluetooth interference aware scheduling (BIAS)	93
	7.2.4 Service priority	95
	7.3 Frequency division multiple access	103
	7.3.1 Space partitioning	104
	7.3.2 Time partitioning	105
	7.3.3 Case study: adaptive frequency hopping for Bluetooth systems	106
	7.4 Handovers	114
	7.4.1 Handover types	115
	7.4.2 Handover architecture	116
8	Myths and common pitfalls	117
	8.1 Power control	118
	8.1.1 Implementing PC in Bluetooth	120
	8.1.2 Lessons learned	124
	8.2 Modulation control	125
	8.2.1 Modulation control strategy in WLAN	126
	8.2.2 Lessons learned	131
	8.3 Parameter optimization	132
	8.3.1 Effects of packet fragmentation	132
	8.3.2 Effects of forward error correction	135
	8.3.3 Lessons learned	137
	<i>References</i>	138
	<i>Index</i>	143

Illustrations

2.1	Physical layer system components	<i>page</i> 8
2.2	Detection at receiver	10
2.3	Illustration of spread spectrum	11
2.4	MAC transmission and reception rules	13
2.5	Time division multiple access	14
2.6	Frequency division multiple access	14
2.7	Code division multiple access	15
2.8	Packet segmentation and encapsulation	16
2.9	Reservation-based access	17
2.10	Contention-based access	17
2.11	Stack visualization for collision resolution algorithms	19
2.12	Exposed and hidden nodes	23
2.13	Master TX/RX hopping sequence	24
2.14	Bluetooth packet format	25
2.15	WLAN frame transmission scheme	28
2.16	IEEE 802.11 frame format	29
3.1	Mutual interference between communication systems	31
3.2	Measuring interference	32
3.3	General shape of P_b versus E_b/N_0	33
3.4	Higher layer performance measures	34
3.5	Factors affecting the closed-loop interactions between victim and interferer systems	36
3.6	Effects of spread spectrum on victim performance	38
3.7	Effects of frequency hopping rate on victim performance	39
3.8	Traffic patterns	39
3.9	Effects of packet size on victim performance	41
3.10	Effects of transmitted power on performance	42
4.1	Conditional probability density function	45
4.2	Probability of bit error for a binary system	46
4.3	Two-state error model	48
4.4	Collisions at the victim's receiver	50
4.5	Frequency offset	51

xi	List of illustrations	
4.6	Bluetooth probability of packet error with WLAN interference	53
5.1	On-off traffic source	56
5.2	Traffic trace capture and configuration set-up	59
5.3	Four-node network topology	60
5.4	Multi-WLANs and Bluetooth piconets	61
5.5	Traffic flow directionality	61
5.6	Event driven simulations	64
5.7	Generic MAC state machine	65
5.8	Communication system generic model	66
5.9	MAC/PHY simulation interface	66
5.10	Period of stationarity	67
5.11	Bluetooth and 802.11 DSSS 11 Mbit/s interference	69
5.12	Impact of WLAN interference on Bluetooth	72
5.13	Impact of WLAN interference on Bluetooth	73
6.1	BER measurement histogram	81
6.2	Frequency status table	84
6.3	Estimation interval	85
6.4	Explicit estimation	87
6.5	Implicit estimation	87
7.1	Interference aware scheduling	93
7.2	Master packet transmission flow diagram	95
7.3	Multislave Bluetooth piconet and two WLAN nodes	99
7.4	Delays at the slave and master	101
7.5	Probability of packet loss	103
7.6	Space partitioning	105
7.7	Time partitioning	106
7.8	Bluetooth adaptive frequency hopping patterns	107
7.9	Bluetooth packet loss	110
7.10	Bluetooth goodput and TCP delay	111
7.11	WLAN probability of packet loss	113
7.12	Horizontal versus vertical handovers	115
8.1	Signal received at node i	119
8.2	Bluetooth transmitted power	122
8.3	Effects of adaptive power control on Bluetooth performance	123
8.4	Effects of power control on the other (interference) system	125
8.5	WLAN FTP performance	128
8.6	Bluetooth HTTP performance	130
8.7	Effects of packet fragmentation on victim system	133
8.8	Effects of packet transmission interval on victim system	134
8.9	Effects of error correction on packet loss	135
8.10	Effects of error correction rate on packet loss	136

Tables

2.1	Bluetooth packet types	<i>page 26</i>
2.2	Summary of error occurrences in the packet and actions taken when errors are not corrected	27
5.1	Example of parameter profile	58
5.2	FTP capture statistics	59
5.3	Traffic directionality scenarios	62
5.4	Typical path loss exponents	63
5.5	BER for an 802.11b 1 Mbit/s receiver and Bluetooth interference	68
5.6	Simulation parameters	69
5.7	SIR computation	72
6.1	Measurements summary	79
7.1	Definition of parameters used in the scheduling algorithm	97
7.2	BIAS pseudo-code	97
7.3	Application profile parameters	100
7.4	Experiment summary	100
7.5	Application profile parameters	109
7.6	Experiment summary	109
7.7	Bluetooth voice performance	113
8.1	Bluetooth device power classes	121
8.2	Experiment summary	127
8.3	Application profile parameters	127

Preface

Wireless networks are rapidly becoming a part of the ubiquitous computing environment, and whether they are enterprise networks or in public hot spots (for example in airports, hotels, homes), often they are deployed in infrastructureless environments. The rapid specification development phase and the tight time to market cycle that follows leave little room for performance enhancements and proper coexistence consideration.

Why did I write this book?

Having gone through a somewhat complete performance analysis and coexistence development cycle for wireless network technologies being developed by the IEEE 802 standard working groups, and having gained some experience on the topic, I feel compelled to share it with other network engineers and researchers that are pursuing similar objectives. In particular, I would like to share the methodologies developed and the lessons learned from this process with others embarking on a similar quest.

The audience for this book includes: (1) researchers interested in performance evaluation and interference mitigation techniques; (2) wireless systems engineers and practitioners designing wireless communication systems; (3) users of wireless networks.

This book is unique because it focuses on a system level view of the problem of interference and its solution space. Generally, interference is dealt with at the physical layer. There are several outstanding books that focus on the accurate characterization of the wireless channel in addition to the development of physical layer techniques for filtering and anti-jamming. By considering a system level view for the interference problem and providing methods for evaluating interference at the system level including the medium access control layer, the transport, and the application layers, this effort is intended to (1) complement previous work aimed at the physical layer, (2) provide more accurate tools for quantifying interference and its impact on the

system performance, and (3) develop a catalog of coexistence techniques that could be applied in various environments and for different technologies.

About the organization of this book

The structure of this book is as follows.

Chapter 1 provides an introduction to the subject of coexistence in wireless networks.

Chapter 2 covers some of the basic concepts and the design choices in the development of physical and media access control layer protocols. Examples for select technologies of interest, such as Bluetooth and IEEE 802.11b, are given in order to illustrate the concepts described.

Chapter 3 defines an interference model in the context of this book. Some of the major building blocks for conducting a performance analysis study are discussed, including the terminology, performance metrics, and the system parameters affecting the performance.

Chapter 4 consists of an open-loop interference model. In this chapter approximations for evaluating interference at the victim’s receiver while ignoring the interactions between the interferer and the victim system are given. This open-loop evaluation consists of a mathematical analysis technique based on a probability of packet collision in time and frequency.

Chapter 5 describes a closed-loop modeling environment in order to capture the mutual effects of interference on each end device including the protocol interactions. A modeling and simulation methodology is presented that includes the number of devices and their placement on a two-dimensional grid, setting the transmission power of the radios, and defining the traffic distribution pertaining to the applications considered.

Chapter 6 discusses channel estimation and selection techniques that constitute the basis for most interference mitigation techniques. Several metrics for channel estimation are presented and explained, including packet or frame loss, received signal strength, and packet acknowledgment. These metrics are then used as criteria for channel selection and interference avoidance.

Chapter 7 describes proven techniques to mitigate interference. The emphasis is on dynamic and system level mechanisms that are able to adapt to the interference environment. The techniques overviewed can be broken up into two broad categories. The first category of solutions consists of temporal and/or spectral sharing of the spectrum. The second category of solutions is about adaptation and the possibility of choosing either the radio or the network that is best suited to the environment.

Chapter 8 includes some common myths and misconceptions associated with interference mitigation solutions. The main goal is to shed some light on the lessons learned while researching and developing solutions.

Acknowledgments

I would like to thank David Su at the National Institute of Standards and Technology, who has supported my professional endeavors. I would also like to thank my colleagues at NIST and many exceptional people whom I collaborated with over the years. Their enthusiasm and dedication provided an enriching and stimulating environment for me to learn from and pursue research.

I am indebted to my dad for always believing in me. His pride, love, and encouragement have been and continue to be a constant source of inspiration in my life.

I would like to thank two people who hold a special place in my life. I am especially grateful to my mom, Raja, and my husband, Geof, for their unconditional love, infinite support, and for putting up with me during the writing of this book. It is due to their constant encouragement that I have been able to complete this project.

My gratitude goes to Phil Meyler from Cambridge University Press, whose idea it was for me to write this book and who made it all happen with his very able team of technical and production editors, including Emily Yossarian, Anna Littlewood, Emma Pearce and Irene Pizzie.

Abbreviations

ACK	acknowledgment message
ACKLoss	acknowledgment loss
ACL	asynchronous connectionless link also in Bluetooth
AFH	adaptive frequency hopping
AP	access point
API	application program interface
ARQ	automatic repeat request
AWGN	additive white Gaussian noise
BER	bit error rate
BIAS	Bluetooth interference aware scheduling
BT	Bluetooth technology
CCA	clear channel assessment (used in 802.11)
CCK	complementary code keying
CDMA	code division multiple access
CPU	central processing unit
CRC	cyclic redundancy check
CSMA/CA	carrier sense multiple access/collision avoidance
CTS	clear-to-send
DCF	distributed coordination function (in 802.11)
DIFS	DCF interframe space
DS	direct sequence spread spectrum
FCS	frame check sequence
FDM	frequency division multiplexing
FDMA	frequency division multiple access
FEC	forward error correction
FER	frame error rate
FH	frequency hopping spread spectrum
FIFO	first in first out queueing
FST	frequency status table
GFSK	Gaussian frequency shift keying
GHz	gigahertz

xvii **List of abbreviations**

GMSK	Gaussian minimum shift keying
GPS	global positioning system
GSM	global system for mobile communications
IEEE 802.11	a set of IEEE standards for WLANs
IEEE 802.15	a set of IEEE standards for WPANs
ISM	industrial, scientific, and medical frequency band
LD	limiter–discriminator receiver
LIFO	last in first out queueing
LLC	logical link control layer
LMP	link management protocol
MAC	medium access control layer
MANET	mobile ad hoc network
MHz	megahertz
NACK	negative ACK
OFDM	orthogonal frequency division multiplexing
PDF	probability density function
PDU	payload data unit
PHY	physical layer
PLoss	packet loss
QOS	quality of service
RF	radio frequency
RR	round robin scheduling
RSNI	received signal to noise indicator
RSSI	received signal strength indicator
RTS	request-to-send
SCO	synchronous connection-oriented link in Bluetooth
SIFS	short interframe space
SIR	signal to interference ratio
SNR	signal to noise ratio
TCP/IP	transmission control protocol/internet protocol
TDM	time division multiplexing
TDMA	time division multiple access
TPL	transmit power level
UMTS	universal mobile telecommunications system
UNII	unlicensed national information infrastructure band
Wi-Fi	wireless fidelity, generic designation for an IEEE 802.11 network
WLAN	wireless local area network
WMAN	wireless metropolitan area network
WPAN	wireless personal area network