1

OF/DE

1

PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

A Simulation Traffic Study of Indoor Wireless Communications in the (20-60)GHz Band

by

V R Manikka Thyagarajan

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

Master of Engineering

Ottawa-Carleton Institute for Electrical Engineering
Faculty of Engineering
Department of Systems and Computer Engineering
Carleton University
Ottawa, Ontario, Canada K1S 5B6
January 4, 1993

© V R Manikka Thyagarajan, 1992

National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Author's name (in French)

Author's name (in English)

The author has granted an irrevocable non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of his/her thesis by any means and in any form or format, making this thesis available to interested persons.

L'auteur a accordé une licence irrévocable et non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de sa thèse de quelque manière et sous quelque forme que ce soit pour mettre des exemplaires de cette thèse à la disposition des personnes intéressées.

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

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

ISBN 0-315-84146-X

Canada

The undersigned hereby recommend to the Faculty of
Graduate Studies and Research acceptance of the thesis

*A Simulation Traffic Study of Indoor Wireless
Communications in the (20-60)GHz Band*

submitted by V R Manikka Thyagarajan
in partial fulfillment of the requirements for
the degree of Master of Engineering

Thesis Supervisor

Thesis Supervisor

Chair, Department of Systems and Computer Engineering

Carleton University
January 4, 1993

Abstract

Personal communications is a rapidly expanding field with many potential applications. The 20GHz to 60GHz (mm-wave) band appears to be a suitable choice for providing wireless indoor access to voice, data, video and other services, since it offers large bandwidth, current sparse usage, small RF device dimensions, and short range propagation suitable for microcellular system architectures. Reception of mm-wave signals in buildings is governed by attenuation by walls, doors, etc., by multipath effects due to scattering from the same, and by interference from other users. Time Division Multiple Access (TDMA) system operating with Time Division Duplex (TDD) is considered as a representative multiple-access algorithm.

This thesis discusses the results on the performance characteristics viz, blocking, co-channel interference, and transmission quality of indoor wireless communications in the (20-60)GHz band. Among the factors and parameters considered are traffic demand, density and types of users and their required bandwidths, numbers of frequencies assigned and various channel assignment algorithms. The results have been obtained through simulations of a typical indoor environment, with propagation parameters typical of the mm-wave propagation.

Acknowledgment

I have benefited, as have so many others, from Prof. Falconer's and from Prof. Hafez's powerful notions. They nurtured my early incoherent ideas, railed at me when I needed it, and patted me on the back (often undeservingly) to keep me going. Thanks to them, for the faith. Moreover, their relentless and always thoughtful questioning was often critical to honing of my ideas.

Of importance are all my friends who made my stay in Carleton interesting. A few deserve special thanks. Mrs. & Mr. Joseph, their brand of caring was inspiring. Srinivas, for all the bugging and specially for re-inventing UNIX to my requirements. Kathir & Arun for guiding me through my life as a Grad. student !

Any work is not only a product of current research and colleagues, our predispositions are the product of a lifetime. In that vein, my special thanks to my father, mother, brother and all my friends.

The last word of acknowledgment delightedly goes to the geniuses of Engineering whose work inspired me to learn, understand and appreciate the art of communications.

Contents

List of Figures	vii
List of Tables	viii
List of Graphs	ix
Glossary	x
Chapter 1 Introduction	1
1.1 Objective	1
1.2 Organization of the Thesis Report	3
Chapter 2 Indoor Wireless Communications	5
2.1 Overview	5
2.2 Present Wireless Systems	6
2.3 Requirements	6
2.4 20GHz to 60GHz Band	8
2.5 Multiple-Access Techniques	8
Chapter 3 Multiple-Access Techniques	12
3.1 Fixed Assignment	12
3.1.1 TDMA	12
3.1.2 FDMA	13
3.1.3 CDMA	13
3.2 Random Access	15
3.2.1 ALOHA	15
3.2.2 CSMA	16
Chapter 4 20GHz to 60GHz Band	17
4.1 Building Material Attenuation	17
4.2 Channel Propagation Parameters	19
4.3 Millimeter Wave Devices	19

Chapter 5	TDMA-TDD System Architecture	23
5.1	TDMA System	23
5.2	Radio Signal Propagation Model	28
5.3	Traffic Model	31
5.4	Simulation Methodology	33
5.4.1	Simulation Parameters	36
Chapter 6	Simulation Results and Analysis	38
6.1	System Behavior	39
6.1.1	Performance Measures	39
6.1.1.1	Blocking Probability	39
6.1.1.2	Interference Characterization	46
6.1.1.3	Transmission Quality	47
6.1.2	Behavior of Frequency Bands	55
6.1.3	Scatter Plot	55
6.1.4	Effect of Building Material	57
6.2	Effect of Traffic Parameters	59
6.2.1	Portable Traffic	59
6.2.2	Portable Density	61
6.2.3	System Utilization	63
6.2.4	Individual User Service	63
6.3	Scanning Algorithms	65
Chapter 7	Conclusions and Future Research	71
	Bibliography	74
	Appendix A	77
	Appendix B	79

List of Figures

2.1 Electromagnetic Spectrum	9
2.2 Basic Multiple-Access Techniques Tree	10
3.2 Direct Sequence Spread Spectrum	14
4.1 Block Diagram of a Millimeter wave Source (HP 83557A)	21
4.2 Block Diagram of a Millimeter wave Receiver	21
5.1 Building Topology 1 : Open Room	24
5.2 Building Topology 2 : Typical Office	25
5.3 Slot Assignment	25
5.4 Radio Signal Propagation Model	29
5.5 Traffic Model	32
5.6 Alternating State Process	34
5.7 TDMA Simulation Flow Chart	35

List of Tables

2.1 Present and Proposed Wireless Systems	7
2.2 20GHz – 60GHz Band Designation and Current Usage	9
4.1 Channel Parameters	18
6.1 System Specifications	38
6.2 BP I	41
6.3 Minimum SINR against Blocking and Traffic Demand	41
6.4 SINR Summary	45
6.5 Co-channel Interference Summary	48
6.6 SINR Performance Chart	52
6.7 Effect of Portable Traffic	60
6.8 System Utilization	64
6.9 Congestion : System B, Typical Indoor	64
B.1 Average Number of Active Portables : Open Room	80
B.2 Average Number of Active Portables : Typical Indoor	81

List of Graphs

4.1 Building Material Attenuation	18
6.1 BP II : Typical Indoor, System B	42
6.2 BP II : Open Room, System B	42
6.3 BP II : Typical Indoor, System 2.5B	43
6.4 BP II : Open Room, System 2.5B	43
6.5 Interference Characterization : Typical Indoor, System B	48
6.6 Interference Characterization : Open Room, System B	49
6.7 Interference Characterization : Typical Indoor, System 2.5B	49
6.8 Interference Characterization : Open Room, System 2.5B	50
6.8a CDF of I_d/I_s	50
6.9 CDF of Uplink & Downlink SINR : System B, Typical Indoor	52
6.10 CDF of Uplink & Downlink SINR : System B, Open Room	53
6.11 SINR Scatter Plot : System B, Typical Indoor	53
6.12 SINR Scatter Plot : System B, Open Room	54
6.13 Frequency Band Utilization	54
6.14 X-Y Scatter Plot	56
6.14a X-Y Scatter Plot	56
6.15 Effect of Building Material	58
6.16 Effect of Portable Traffic : Typical Indoor	58
6.17 Effect of Portable Traffic : Open Room	60
6.18 Effect of Portable Density : Typical Indoor	62
6.19 Effect of Portable Density : Open Room	62
6.20 Scanning Algorithms : Blocking in Typical Indoor	67
6.21 Scanning Algorithms : Blocking in Open Room	67
6.22 Scanning Algorithms : Interference in Typical Indoor	68
6.23 Scanning Algorithms : Interference in Open Room	68
6.24 Scanning Algorithms : Frequency Utilization in Typical Indoor	69
6.25 Scanning Algorithms : Frequency Utilization in Open Room	69
A.1 Effect of Power Control	78
B.1 Number of Active Portables : Open Room	80
B.2 Number of Active Portables : Typical Indoor	81

Glossary

ATM	Asynchronous Transfer Mode
BP	Blocking Probability
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CSMA	Carrier Sense Multiple Access
dB	Decibel
dBm	Decibel (relative to one milli-watt)
DS	Direct Sequence
DSB	Double Side Band
erl	Erlang
FDMA	Frequency Division Multiple Access
FH	Frequency Hopping
FSD	Frequency Switching Diversity
GHz	Giga Hertz
Hz	Hertz
IF	Intermediate Frequency
Kbps	Kilo- bits per second
Mbps	Mega-bits per second
MDS	Minimum Detectable Signal
MFD	Multiple Frequency Diversity
mm	Millimeter
RF	Radio Frequency
sec	Seconds
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
sq.m	Square Meter
SONET	Synchronous Optical Networks
TDD	Time Division Duplex
TDMA	Time Division Multiple Access

Chapter 1

Introduction

The innate need to communicate while on the move necessitates a tetherless, user friendly communication network. In the recent past, this has caused a rapid increase in the sales of cordless telephones and increasing support for mobile cellular systems. While there exists technology to economically transport the bulk of information the bottleneck is the nexus between the user equipment (portable) and the network. This has always remained expensive and restricted.

1.1 Objective

Recent years have witnessed an increased interest in local wireless access to voice/data communication networks [1],[2],[3]. Several factors influence the selection and design of suitable multiple-access techniques for these networks such as the traffic demand, number of users, channel bandwidth, cost, complexity, etc., and a set of performance measures such as blocking probability, co-channel interference and transmission quality. In order to achieve and maintain the desired quality of service it is important to evaluate the multiple-access system's initial access (channel allocation) and traffic handling capabilities.

The objectives of this thesis are

- ☐ To understand and define indoor wireless communications using millimeter waves.
- ☐ To form a radio signal strength equation using the available data on millimeter wave propagation in an indoor environment.
- ☐ To develop a simulation tool to analyze the performance of radio interface using the signal strength equation.
- ☐ To develop a portable traffic model for use in the simulation tool.
- ☐ To analyze Time Division Multiple Access (TDMA) system operating with Time Division Duplex (TDD) in millimeter wave indoor wireless environment using the

simulation tool. The factors and parameters considered for the analysis of TDMA-TDD are

1. Performance

- Blocking Probability.
- Co-channel Interference.
- Transmission Quality.

2. Teletraffic

- Portable Traffic.
- Portable Density.
- System Utilization.
- Individual User Service.

3. Scanning Algorithms

- Relative Ranking.
- First Fit.
- Close Fit.

Millimeter waves have been used mostly for satellite communications. The use of millimeter waves for terrestrial communications so far has not been a well experimented field. The increasing demand for broadband services along with highly congested lower frequency bands makes consideration of mm-waves for terrestrial radio communications very attractive. This thesis investigates the application of mm-waves for future indoor wireless communications. This study is limited to the available knowledge [4],[5],[6],[7] of the millimeter wave channel characteristics in an indoor environment. The purpose of this study is not to design a system using millimeter waves but to provide a test vehicle for analyzing the use of millimeter waves for future indoor wireless communications. This study deals with the establishment of wireless interface (multiple access) and the performance associated with it. The dynamics of a call like call dropping and statistical fading are not considered. Studies were made for two different building topologies, an open room and an office structure with different sized rooms, corridors and walls typical of an indoor environment.

The preliminary investigation using the available data on signal propagation in an indoor environment and portable traffic statistics reveals that high path and wall attenuation necessitates short range propagation or micro-cellular system architecture with cell radius around 5 meters. Investigation also reveals that blocking is mainly due to co-channel interference. The attenuation caused by building materials (mostly walls) in a typical indoor environment reduces co-channel interference. In most cases (75% to 95%) the interference is caused by a single source. The absence of walls in an open room results in severe co-channel interference. As co-channel interference is the main communication impairment, the scanning and access algorithm (channel allocation) requires that accessing calls be spread evenly in all the frequency bands. This is because too many calls accessing a particular band results in overcrowding that band and hence more co-channel interference.

As the communication is short range and mostly line-of-sight, a power control strategy was adopted. The portables switch their transmitter power on sufficient Signal to Noise Ratio ($\text{SNR} \geq 50\text{dB}$) to a lower value (0dBm) from their normal value (10dBm). This strategy was found to have considerable power conservation (around 40%) and a performance increase of 2dB at the first percentile of blocking.

The time frame is divided into two blocks, one for uplink and another for downlink. Thus the duplex is achieved by independent uplink and downlink communications. The standard deviation of the difference between downlink and uplink SINR (local mean) is around 5dB. As the Cumulative Density Function (CDF) of downlink SINR is close to CDF of uplink SINR, a portable based scanning and access requires diversity for better performance. Diversity would enhance the signal at the receiver (port) and help to mitigate multipath fading once the port is selected.

The TDMA-TDD system in a typical indoor environment was found to offer 3% blocking (97% availability) to an offered load of 0.212 erlangs/sq.m corresponding to a system utilization of 54% for an SINR threshold of 20dB. Co-channel interference limits system utilization to 32% in an open room for 20dB SINR threshold.

1.2 Organization of the Thesis Report

This thesis is structured as concatenated modules. Chapter 2 provides an overview of indoor wireless communications and an introduction to multiple-access system archi-

techniques. Chapter 3 discusses in detail the important basic multiple-access techniques in a cellular environment. The 20GHz to 60GHz (mm-wave) channel from a signal strength perspective is analyzed in chapter 4. Chapter 5 explains the TDMA-TDD system architecture, traffic model, and the simulation methodology. Main results of the simulation tool are presented and analyzed in chapter 6. The last one, chapter 7 deals with conclusions and future research.

Chapter 2

Indoor Wireless Communications

The phrase “indoor wireless communications” is capable of a number of interpretations but the idea of a set of office functions miniaturized and packaged in such a way that they can be taken by the user wherever he goes sounds revolutionary. This chapter presents some of the significant features of indoor wireless communications and an introduction to one of its bottle-necks, the multiple-access scheme.

2.1 Overview

The indoor environment covers a wide range of structures characterized by proximity and communality of purpose [8]. Thus an indoor environment might be

- ☐ Office or apartment towers or smaller structures
- ☐ Campuses like hospitals, universities, and governmental or industrial laboratories
- ☐ Building complexes like groups of towers or groups of buildings
- ☐ Factories
- ☐ Residential houses
- ☐ Shopping centres

Indoor communications, viewed as systems, have three distinct yet interacting subsystems [9] viz,

- ☐ Communication system : multifunction telephones, electronic or voice mail, FAX, broadcast TV etc.,
- ☐ Office automation system : CAD/CAM, distributed data bases, graphics and video, text composition, video conferencing, computer communication facilities etc.,
- ☐ Building automation system : security/emergency services, automated air-conditioning and lighting, card controlled access, hallway information system etc.,

With current trends, an indoor communication system should be an integrated system, integrating as much as is feasible of telecommunications and telecomputing as possible into one single system. The main services to be integrated include but are not limited to

- ☐ Telephone services
- ☐ Computer communication services
- ☐ Security/Emergency services
- ☐ Video services

In summary, indoor communications are characterized by variable user density, variable bit rate and variable traffic requirements.

2.2 Present Wireless Systems

Some existing wireless systems and a few proposals [10] are tabulated in Table 2.1 to provide a comparison to indoor wireless communications. Some important functional differences between these present wireless systems/proposals and future indoor wireless communications are

- ☐ Attempt to use 20GHz to 60GHz band (mm-wave bands).
- ☐ Integrated voice, data, and video services.
- ☐ Higher data rate, data service rate up to 155.52Mbps (OC-3 ATM-SONET rate) will be attempted.

2.3 Requirements

Some important requirements of indoor wireless communications are

- ☐ Ubiquitous integrated duplex voice, data and video services.
- ☐ Light weight, user friendly, low power consumption portables.
- ☐ Large subscriber capacity with cost comparable to existing wireline service.
- ☐ Automatic channel assignment, control and monitoring in an integrated environment of wired and wireless systems.
- ☐ Widespread availability with toll quality service.
- ☐ Efficient co-ordinated use of radio spectrum.

	CT2	CT2+	DECT	GSM	PCN	IS-54	AMPS	UDPCS
Band (MHz)	864-868	944-948	1880-1900	890-915	1710-1785	824-849	824-849	-
				935-960	1805-1880	869-894	869-894	
Bandwidth (MHz)	4	4	20	50	150	50	50	60
Access Architecture	FDMA	FDMA	TDMA/ FDMA	TDMA/ FDMA	TDMA/ FDMA	TDMA/ FDMA	FDMA	TDMA/TDMA/ FDMA
Channel Spacing (KHz)	100	100	1728	200	200	30	30	300-400
# of freq channels	40	40	10	125	375	832	832	75
# users/freq channel	1	1	12	8	16	3 or 6	1	10
Total Duplex Channels	40	40	120	1000	6000	2496	832	750
Duplex Method	TDD	TDD	TDD	FDD	FDD	FDD	FDD	FDD
Channel Bit Rate (Kbps)	72	72	1152	270.833	270.833	48.6	-	500
Data Service(Kbps)	32	32	32-736	16	8	8	-	32-220
Speech Codec	ADPCM	ADPCM	ADPCM	RPE-LTP	RPE-LTP	VSELP	-	ADPCM
Bit Rate (Kbps)	32	32	32	22	6.7	13	-	32
Frame Time (msec)	2	2	10	4.6	4.6	20	-	2
Modulation	GMSK	GMSK	GMSK	GMSK	GMSK	$\pi/4$ DQPSK	Analog FM	DQPSK
Voice & Data	no	some	yes	yes	yes	-	no	yes
Peak Transmit Power (mW)	10	10	250	-	-	0.6,1.2,3.0 W	0.6,1.2,3.0 W	100-200
Cell Radius	40-140m	40-140m	40-140m	1-5 miles	0.4-5 miles	-	-	1000 feet

Table 2.1 Present and Proposed Wireless Systems [10]

2.4 20GHz to 60GHz Band

The (20 ~ 60) GHz band is also referred to in this thesis as the mm-wave band. This is because the wavelength ($\lambda = c/f$) of these frequencies are in the order of millimeters (mm), 15mm (20GHz) to 5mm (60GHz). Figure 2.1 depicts the electromagnetic spectrum and Table 2.2 explains the band designations [11] in 20GHz to 60GHz band and some of its current usage [12].

Some important characteristics [11] of mm-waves are

- Travel mostly by line-of-sight.
- Highly attenuated by atmosphere or rain.
- Various atomic, molecular, and nuclear resonance occur at microwave frequencies and are utilized in remote sensing, medical diagnosis and treatment, and cooking methods.

The 20GHz to 60GHz band (mm-wave) looks to be a favorable choice for indoor communication requirements because

- There is sufficient bandwidth for the high data rates required in today's wired local area networks.
- Current sparse usage.
- Small RF device dimensions.
- Short range propagation suitable for micro-cellular or pico-cellular system architectures.
- Favorable regulatory environment. High attenuation by exterior walls along with short range propagation at lower transmitter power results in confinement of the signals.

2.5 Multiple-Access Techniques

Multiple-access techniques are used to provide multiple simultaneous users with radio links of good transmission quality. The basic multiple-access techniques tree is shown in Figure 2.2. Fixed assignment assumes that all users require their own resources (channel) while random access assumes that the likelihood of many users using the network at any given instant is small and rely on multiple users contending for common

Figure 2.1 Electromagnetic Spectrum

Frequency (GHz)	Approx. Band Designation	Current Usage
18 - 26	K - band	Fixed Satellite Mobile Satellite Broadcasting Satellite Radiolocation Radio Astronomy Space Research etc.,
26 - 40	Ka - band	
40 - 60	U - band	

Table 2.2 20GHz – 60GHz Band Designation and Current Usage

Figure 2.2 Basic Multiple-Access Techniques Tree

resources (channel) to transmit information. Thus the main difference between fixed assignments and random access is that, in fixed assignment each user is assigned an independent channel (time, frequency or code) for communication whereas, in random access multiple users share a common channel in a way which leads to collision and hence are also referred to as contention systems.

Chapter 3

Multiple-Access Techniques

The important requirements of multiple-access are

- ☐ Port must receive the transmitted signal from the user (portable) in such a way that it interferes as little as possible with the reception of other signals.
- ☐ The signal must be so coded that once received there should be no ambiguity about the sender and the message it carries.

A brief explanation of various basic multiple-access techniques in fixed assignment and random access are presented in this chapter. For more information the reader is requested to refer to the various references cited for each technique.

3.1 Fixed Assignment

The three basic multiple-access techniques in fixed assignment are Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), and Code Division Multiple Access (CDMA). In general fixed assignment presents a better proposition when

- ☐ Required to handle large number of users and real time communication capabilities are required.
- ☐ Required to communicate, navigate, and control on a virtually continuous basis.
- ☐ Required to transmit bulk data (video text, high resolution graphics, etc.,).

3.1.1 TDMA

In TDMA, transmissions from several users would be time sequenced onto a common carrier frequency. The average bit rate of the users would normally be considered as the transmission rate and integer multiples of average bit rate could be accommodated by providing more than one slot in a frame for a user. The upper bound on the transmission rate from individual users is controlled by multipath propagation unless adaptive equalization is used. Additional bits are required for signalling, channel control,

synchronization, encryption and dead band between time slots to prevent overlaps between adjacent channels.

In synchronous TDMA the time frame is segmented into a fixed number of slots and each user is assigned a slot for transmission. In asynchronous TDMA messages are multiplexed in the order of their arrival. For identification of a message and its corresponding user an address is required and this necessitates a centralized control of messages which makes asynchronous TDMA less efficient.

TDMA has the comparative advantage of ease of implementation, cheap hardware. As the received data are time sequenced, it also has easy compatibility to subsequent real time data processing with least data loss and delay. Though TDMA has a flexible architecture it is susceptible to multipath at higher bit rates and frequency selective fading which can very much degrade its performance. It may also requires additional circuits for synchronization and equalization and requires overhead for bursty transmission and privacy.

3.1.2 FDMA

In FDMA, each user is assigned a frequency channel for duplex communications. In Multiple Frequency Diversity (MFD) the transmitted signal consists of the same information carried on several carrier frequencies within the allocated frequency channel. In Frequency Switching Diversity (FSD) the transmitted signal switches to a new frequency in a cyclical manner within the allocated frequency channel upon encountering a fade.

FDMA combats frequency selective fading but has the disadvantage of inflexibility (fixed resources) and costly hardware.

3.1.3 CDMA

In CDMA [13] [14] each user is assigned a unique time-frequency waveform or code that is used for transmission or reception. The data signal is multiplied by the code (spreading signal) and this implies a convolution of the two signals in the frequency domain. If data signal is narrow band compared to the spreading signal, the transmitted signal will have the spectrum of the spreading signal. Thus in CDMA the data signal is spread where spreading refers to expanding the transmission bandwidth beyond what is

$$\text{Direct Sequence} = \text{Data bits} \oplus \text{Spreading Sequence}$$

$$15 \text{ chips/bit} = 11.8 \text{ dB spreading gain}$$

Figure 3.2 Direct Sequence Spread Spectrum [15]

required to transmit the data. The ratio (W/R) of transmission bandwidth (W) to data rate (R) is called the processing gain. There are two types of spreading techniques viz., the Direct Sequence (DS) and Frequency Hopping (FH). In DS, spreading is achieved by multiplying the data sequence by a pseudorandom sequence whose symbol rate (chip rate) is many times the data rate. In FH the signal remains at a frequency for a bit or block of bits and hops to a new frequency anywhere in the spreading bandwidth in a pseudorandom pattern for the next bit or blocks of bits.

In CDMA [16] addressing and privacy are built in. The cells (receivers) are placed on the basis of signal strength rather than on geographical basis. This technique exhibits frequency diversity, in that at any given time the probability that a majority of the frequency components are simultaneously in a deep fade is very small. Interference rejection capabilities of this system depend on the processing gain

CDMA presents an attractive proposition to overcome channel impairments but has problems of inefficient spectrum usage, tight adaptive power control to overcome near/far effect, and high chip rate (e.g. 300Mbps) for data rate of 10Mbps.

3.2 Random Access

The two important random access strategies are ALOHA and Carrier Sense Multiple Access (CSMA). In general random access presents a better proposition when

- ☐ User demands have statistical nature.
- ☐ Required to handle more bursty users with minimum delay and comparatively less bandwidth.
- ☐ Expandability, flexibility, suitability to time varying loads and simplicity of implementation are required.

3.2.1 ALOHA

In unslotted or pure ALOHA the user transmits whenever it has data to be sent and this results in collision. Colliding packets are destroyed or erased and hence require re-transmission. This limits the throughput of unslotted ALOHA to $0.184 (1/2e)$ [17]. This was modified by a requirement that a user must transmit only at the beginning of a slot and not whenever it has data. This is slotted ALOHA and has a maximum throughput of $0.368 (1/e)$ [17].

It was the notion of complete connectivity among all users with little or no central co-ordination that prompted ALOHA. However ALOHA sacrifices throughput and delay. It is found to be more effective in cells of smaller area as the near/far effect [18],[19] improves throughput and lessens delay.

3.2.2 CSMA

In CSMA [20] the user listens to the channel to see if any one else is transmitting and on sensing an idle channel transmits its own data. In persistent CSMA [20] the user first listens to the channel to see if anyone else is transmitting. If the channel is busy, the user keeps sensing the channel continuously. Whenever it finds the channel idle the user transmits its data. When a collision occurs the user waits a random interval of time and starts all over again.

In non-persistent CSMA [20], if the channel is already in use, the user does not continuously sense it for the purpose of seizing it immediately. The user waits a random amount of time before retrying. If no one else is transmitting, the user begins doing so itself immediately.

Chapter 4

20GHz to 60GHz Band

Ray-like [5] radio signal propagation in mm-wave band (20GHz to 60GHz) depends [4] mainly on

- ☐ Attenuation by walls, space dividers, doors, windows, furniture, etc., and occasionally by people.
- ☐ Multipath effects due to scattering from walls, ceilings, floors, furniture, people etc.,
- ☐ Channel propagation parameters.

Since the frequency band (20GHz to 60GHz) is wide there is a large variation in attenuation and channel parameters and this along with the consideration for frequency selective fading [21] necessitate splitting up the frequency band into smaller bands. In this thesis the 20GHz to 60GHz band is split into four adjacent bands (20–30, 30–40, 40–50, 50–60) of 10GHz each. This chapter characterizes the mm-wave indoor channel from a signal strength perspective using the available measurements and discusses the channel parameters considered in the simulation.

4.1 Building Material Attenuation

The attenuation versus frequency for most of the common building materials of one inch thickness are depicted in graph 4.1 [4]. Relatively low attenuation is offered by sheetrock to radio signals while concrete offers extremely high attenuation. The use of sheetrock for internal walls is a common practice in office buildings and this might contribute to significant co-channel interference. On the other hand concrete floors and outside walls will provide efficient screening from external interferences.

The received power may suffer dips or fades due to the combining of out of phase signals arriving by different paths. In most cases this fading can be taken care of by providing high power margins or by space diversity reception. Signals arriving at the port antenna by reflection have longer propagation time than the line-of-sight signals and can cause signal smear and intersymbol interference when the bit rate is near or above the channel's coherence bandwidth.

Graph 4.1 Building Material Attenuation

Reference : L.Golding and A.Livne, "RALAN - A Radio Local Area Network for voice and data communications," Proc. of IEEE Globecom, 1988.

Frequency Band (GHz)	Line of Sight Path Exponent (γ_f)	Free Space Loss at One meter (L_{ref}) in dB
20 - 30 (f_1)	1.80 to 1.90	58.2 to 62.0
30 - 40 (f_2)	1.70 to 1.80	62.0 to 64.5
40 - 50 (f_3)	1.60 to 1.70	64.5 to 66.4
50 - 60 (f_4)	1.50 to 1.60	66.4 to 68.0

Table 4.1 Channel Parameters

4.2 Channel Propagation Parameters

The radio signals are attenuated at d^γ where d is the distance from the portable to the port in meters and γ is the path exponent. The attenuation with distance is calculated [7] as

$$L(d) = L_{ref} + 10\gamma_f \log_{10}(d) \text{ dB} \quad \dots \dots (1)$$

where L_{ref} is the free space loss at one meter from the transmitter and is defined [7] as

$$L_{ref} = 10\log_{10}P_{tran} - 10\log_{10}P_{rec} \text{ dB} \quad \dots \dots (2)$$

where P_{tran} is the transmitted power (Watt) and P_{rec} is the received power (Watt) at one meter from the transmitter. Free space loss is calculated using the equation [22]

$$P_{rec}/P_{tran} = G_T G_R (\lambda/4\pi r)^2 \quad \dots \dots (3)$$

where G_T and G_R are the antenna gains of the transmitter and the receiver respectively. With $G_T = G_R = 1$, L_{ref} could be defined as

$$L_{ref} = -10\log_{10}[\lambda/4\pi]^2 \text{ dB} \quad \dots \dots (4)$$

where λ is the wavelength in meters. Obstacles to the line-of-sight radio path in the service environment cause high attenuation. Obstacles could either be materials or human body interference. Human body interference causes approximately 25dB to 30dB attenuation [4],[7] in all frequency bands. The variations in path exponent [6] and free space loss at one meter as a function of frequency are summarized in Table 4.1.

Since these large scale variations are obtained by averaging instantaneous signal samples measured in a small area, the corresponding signals are called local area mean or local mean signals [22],[23]. The path exponent decreases with frequency and is below the free space value. Wave guide effect is observed in the corridors and the path exponent [7] varies between 1.1 to 1.5.

4.3 Millimeter Wave Devices

This section discusses the state of the technology transmitter/receiver characteristics in the mm-wave band under consideration. For the last ten years, mm-wave device

technology has been mainly developed for defense programs. The main characteristics of mm-wave components are that they are [21] small, and that a given antenna aperture yields a narrower beamwidth, high precision, and better resolution. The important requirements of mm-wave devices for use in indoor wireless communications are :

- [1] Sufficient output power.
- [1] Full band coverage.
- [1] Low output harmonics.
- [1] Compatibility with other existing devices.

The parameters mentioned in this section are mainly to specify the range of values supported by the state of the technology.

Figure 4.1 is the block diagram of a particular mm-wave source, the HP 83557 A. The millimeter wave source [21] normally has a microwave signal source, amplifier/doubler, and a coupler/detector. The mm-wave signals are obtained from a low frequency (microwave) source as they are more stable, have low phase noise and are easy to amplify. The conversion gain [21] of the amplifiers (around 20%) requires a high power microwave source for direct multiplication of the microwave frequency to the required millimeter wave value. Since the power output from the microwave source is limited ($\leq 8W$), two amplifying/doubling stages are usually needed to obtain a frequency around 60GHz. The power output at the first amplifier/doubler (25GHz to 36GHz) is around 11dBm to 15dBm, and that at the second amplifier/doubler (50GHz to 74GHz) is around 8dBm to 12dBm. The levelled output [21] of the source is around -3dBm. A typical transmitter in addition to the mm-wave source would have a balanced up-converter (from IF to RF), a band pass filter, and a power amplifier.

The block diagram of a mm-wave receiver is shown in Figure 4.2. The millimeter wave receivers [24] have a microwave source, an amplifier/doubler, a sub-harmonic mixer, and low noise amplifiers. The sub-harmonic mixer [25] uses a nonlinear element with symmetric conductance in order to achieve down-conversion (from RF to IF) for which the effective local oscillator frequency is twice the true local oscillator frequency. The power amplifiers have a gain around 10dB for input power between 6dBm to 18dBm. The DSB noise figure of the receiver is between 4dB and 8dB. The minimum detectable

Figure 4.1 Block Diagram of a Millimeter wave Source (HP 83557A)

Figure 4.2 Block Diagram of a Millimeter wave Receiver

signal (MDS) of the receiver is

$$MDS = N_{IH} + BW_{IF} + NF \text{ dB} \quad (5)$$

where N_{IH} is the temperature dependent noise (-174dBm/Hz), BW_{IF} is the IF receiver bandwidth in dB, and NF is the noise figure of the receiver in dB. The receiver thermal noise (N_{RX}) is given by

$$N_{RX} = 10\log_{10}(KT_0) + 10\log_{10}(BW_{IF}) \text{ dB} \quad (6)$$

where K is the Boltzman's constant ($1.374 \times 10^{-23} \text{ joule/}^{\circ}\text{K}$), T_0 is the room temperature (290°K), and BW_{IF} is the receiver IF bandwidth (in Hz).

Chapter 5

TDMA-TDD System Architecture

This chapter describes a TDMA-TDD system architecture that was simulated for a mm-wave indoor wireless system and discusses the important system parameters considered in the simulation. The simulation methodology is also discussed in detail.

5.1 TDMA System

The purpose of indoor wireless communications is to provide high quality voice, data and video services in areas with varying subscriber densities by efficient use of radio spectrum. This is done with a fixed grid of radio equipment, called radio access ports or simply ports. The relative positioning and interconnection of the ports, and their cooperation in the establishment and maintenance of radio links with small, low power subscriber radios, greatly influence the service quality and system economy. Maximum subscriber capacity would be obtained by frequency reuse [22],[26],[27] where radio channel assignments are repeated throughout the service area.

The indoor environment includes [8] single-tenant office buildings, single-tenant laboratories, multi-tenant office buildings, shopping centres, factories etc.,. Thus for any analysis of indoor communications the typical environment must include small rooms to specify single-tenant offices and a few large rooms to specify conference rooms or laboratories or multi-tenant offices. Wall attenuation is a dominant channel parameter [4] that emphasizes on building topology. Two floor plans are considered for analysis. The first is an open room without any walls as in Figure 5.1. The second model in Figure 5.2 is designed to represent some typical indoor propagation conditions such as small or single-tenant rooms, large conference rooms, corridors and a variety of wall materials. This floor plan is similar to a part of the Systems and Computer Engineering Department of Carleton University. The number and positioning of the ports depend on the floor plan. The two figures show the building topology and placement of ports in the service area as considered in the simulation.

Port	One Freq./Port	Three Freq./Port
•	f_1	f_1, f_2, f_3
◊	f_2	f_2, f_3, f_4
■	f_3	f_3, f_4, f_1
—	f_4	f_4, f_1, f_2

Figure 5.1 Building Topology 1 : Open Room

Port	One Freq./Port	Three Freq./Port
●	f_1	f_1, f_2, f_3
◇	f_2	f_2, f_3, f_4
■	f_3	f_3, f_4, f_1
▬	f_4	f_4, f_1, f_2

Figure 5.2 Building Topology 2 : Typical Office

Figure 5.3 Slot Assignment

The total allocated spectrum is divided into N equal bandwidth TDMA-TDD channels of different carrier frequency. N ($=4$) is also referred to as the number of channels or cluster size. The four frequencies, f_1, f_2, f_3, f_4 are assumed to be in the 20–30, 30–40, 40–50, and 50–60 GHz bands respectively. The four frequencies are separated by 10GHz to investigate the effect of different propagation conditions at different frequencies on the traffic. A real system could have frequencies closer together. Each frequency channel at the port serves multiple users by time division multiplexing. Each frequency channel supports $2k$ dedicated time slots supporting k uplink and k downlink call paths or k two way call paths (TDD) or users.

The general frequency reuse pattern adopted in the simulation is a square with the four frequencies on the four corners. Deviations to above could be observed when there are high attenuation walls in between. In such cases assignments were made with optimal co-channel frequency separations. Two fixed frequency assignments per port are considered : one frequency channel per port and three frequency channels per port.

The number of time slots in a TDMA-TDD channel depends on signalling rate and baseband rate. The maximum signalling rate due to multipath characteristics found within a building is 3MHz to 4.5MHz [4],[6]. Two systems with different baseband rates are considered for analysis. One with a baseband rate of 64Kbps ($B^\dagger$) and the other at a baseband rate of 160Kbps (2.5B). The former system is mainly to take into account the possibility of all low bit rate portable users in specific environments. With a signalling rate of 3.2MHz the number of TDD users are 25 for a baseband rate of B Kbps and 10 for a baseband rate of 2.5B Kbps. The user rate in the one frequency channel per port system is B Kbps and the user rate in the three frequency channels per port is 2.5B Kbps. Each slot in the frame is assigned independently. Assignment of more than one slot to a user to accommodate multiples of the base rate is also possible. The slot assignment in a 10 TDD users per frame is as shown in Figure 5.3.

Studies indicate [4] that the movement of people in a room may affect the multipath signal structure, and proximity to the antenna may affect its radiation pattern. Therefore, the antenna has to be placed at heights above 6 feet from the floor. In this study the port antenna is assumed to be mounted at a height of approximately 10 feet above the floor.

[†] B refers to the "B-channel" rate of 64Kbps in narrowband ISDN.

The objective of multiple-access is to provide multiple simultaneous users with radio links of good transmission quality by maximizing signal power, minimizing noise and interference and also providing alternate choices when the best slot is busy. Interference can either be co-channel or adjacent channel. Co-channel interference in the mobile to port direction [22],[28] occurs when two portables simultaneously transmit in the same frequency channel and slot but to different ports. Co-channel interference is reduced by maximizing the distance between co-channel ports, while minimizing the distance between portables and their selected ports. Adjacent channel interference is negligible as the frequency channels are assumed to be separated by 10GHz.

A portable based scanning and access strategy (i.e. allocation of frequencies and slots to users) is adopted. The ports are assumed to transmit periodically a short data sequence or beacon signal so that the portable can measure the signal strength and decode port identity. The portable scans all the four frequencies, making power measurements in each. The measurements are stored in a short term memory. The portable selects the port and corresponding frequency with the highest power. A representative scanning and access algorithm for three frequency channels per port can be summarized as :

Step 1 Portable selects three ports based on average signal strength. With three frequency channels per port there are ninety slots and this provides enough choice to the portables.

Step 2 Rank the nine channels by their relative power to form candidate list.

Let $i=1$.

Step 3 Portable picks a channel (i) from the candidate list and listens to that frequency (idle slot tone) for idle time slots.

☐ YES : GO TO Step 4

☐ NO

- (IF $i < 8$)

Let $i = i + 1$

GO TO Step 3

- (IF $i = 9$)

Call blocked (BP 1)

Return user to user set

Step 4 Check Signal to Interference plus Noise Ratio (SINR)

□ SINR $\geq$ Threshold

GO TO Step 5

□ SINR < Threshold

<> ● Check for idle slot tone in channel 'i'

* YES

GO TO Step 4

* NO

o (IF i < 8)

i = i + 1

GO TO ●

o (IF i = 9)

Call blocked (BP II)

Return user to user set

<> (IF i = 9)

Call blocked (BP II)

Return user to user set

Step 5 Occupy the slot for a period equal to holding time

Other scanning algorithms are discussed in section 6.3.

5.2 Radio Signal Propagation Model

The radio signal propagation model is based on experimental data gathered in an indoor environment [4],[6],[5] with mm-wave (20GHz to 60GHz) link between ports and the portable radio users[†]. The schematic radio signal propagation model is as shown in Figure 5.4. When a portable receives service from a port the local mean signal power at the port is

$$S_i = S_{TX} + G_{RX} + G_{LX} - L_{f,i} - L(d_i) \text{ dBm} \quad (7)$$

[†] Local experimental data [7] became available towards the end of this investigation

Figure 5.4 Radio Signal Propagation Model

where $1 \leq i \leq k$ being the slots considered. d_i (meters) is the distance between the portable and the port with the i th slot. S_{TX} is the average portable transmitter power⁵ (dBm), G_{RX} is the port antenna gain (3dB), G_{TX} is the portable antenna gain (3dB), $L(d_i)$ is the path loss (dB), $L_{f,i}$ accounts for attenuation (dB). The frequency dependent attenuation is given by

$$L_{f,i} = L_{WALL} + L_{HUMAN} \text{ dB} \quad (8)$$

where L_{WALL} is the building material attenuation (in dB) as in Graph 4.1. All walls are of one inch thickness. L_{HUMAN} is the human body attenuation (25dB - 30dB) [4],[7]. 25% of the calls accessing the network are assumed to experience human body attenuation.

A power control strategy is employed where line-of-sight (SNR $\geq$ 50dB) portables accessing the port transmit at 0dBm whereas the non-line-of-sight (wall or human attenuation) portables transmit at 10dBm. By maintaining a lower transmitter power, the line-of-sight portables cause little interference and also save power (Appendix A). All portable antennas have the same omni-directional patterns in azimuth. The path loss between the portable and the port with the i th slot is given [7] by

$$L(d_i) = L_{ref} + 10\gamma_f \log_{10}(d_i) \text{ dB} \quad (9)$$

where L_{ref} is the loss at a given distance (1 m) from the portable antenna and γ_f is the path loss exponent which is frequency channel dependent and are as in Table 4.1.

The expression for the local mean signal power of co-channel interfering ports is similar to that of desired serving ports. The local mean at the l th port due to the n th co-channel interfering portable is

$$I_{ln} = S_{TX} + G_{TX} + G_{RX} - L(d_{ln}) - L_{f,(ln)} \text{ dBm} \quad (10)$$

d_{ln} is the distance from the n th co-channel portable to the l th port, $L_{f,(ln)}$ is the corresponding attenuation. The total local mean interfering power at the l th port is the

⁵ The average power represents the average power over all time slots, including the time when a portable is not transmitting. The peak power could be much higher than the average power. It would be the average power multiplied by $2k$, where k is the number of one-way time slots

power sum of all co-channel interfering portables.

$$I_{tot} = 10 \log_{10} \sum_{n=1}^m 10^{I_{tn}/10} \text{ dBm} \quad \dots \dots (11)$$

where m denotes the number of active co-channel portables at the calculated instant.

The signal to interference ratio (SIR) is

$$\text{SIR}_i = S_i - I_{tot} \text{ dB} \quad \dots \dots (12)$$

and signal to interference plus noise ratio (SINR) is

$$\text{SINR}_i = S_i - 10 \log_{10} [10^{I_{tot}/10} + 10^{N_{RX}/10}] \text{ dB} \quad \dots \dots (13)$$

where N_{RX} (in dBm) is the receiver (port) thermal noise and is calculated as per Equation 6. The vacant slot with maximum SINR is selected from the serving slots.

$$\Phi = \max (\text{SINR}_1, \text{SINR}_2, \dots, \text{SINR}_k) \quad \dots \dots (14)$$

5.3 Traffic Model

Figure 5.5 is the discrete event traffic model. A port either acts as a k -server-blocked-call-cleared facility or as a $3k$ -server-blocked-call-cleared facility [29]. There are M users in the user set and they are equally divided into voice and data. The data users are split into three groups as explained below. Each idle user in the user set independently generates access attempts with average rate λ . When an access request is made and the selected port has an idle time slot, the request is processed by the port. Otherwise the access is blocked and the user is returned to the user set. The traffic statistics are

- Type I (50%) : Offers 0.11 erlangs/portable , exponentially distributed holding time with 180 sec. mean [30]. These could be voice users.
- Type II (35%) : Offers 0.25 erlangs/portable, uniformly distributed holding time between 60 sec. to 600 sec. with 300 sec. mean. This could represent time sharing systems.

Figure 5.5 Traffic Model

- Type III (5%) : Offers 0.33 erlangs/portable, uniformly distributed holding time between 300 sec. to 1200 sec. with 720 sec. mean [31]. These portables could be interactive data transfer terminals.
- Type IV (10%) : Offers 0.5 erlangs/portable, uniformly distributed holding time between 5 sec. to 60 sec. with 30 sec. mean. These could be bursty portables like security/emergency etc.,

The interarrival time between access attempts are exponentially distributed with mean $1/\lambda$ and hence the call attempt process approaches Poisson when the user set is large [30]. The portables are uniformly spread in the service area (X-Y space). There are two (one voice and one data) users in every 10 sq.m. in the service area.

The activity of the portables are modeled as alternating state process as in Figure 5.6. The portable can either be in an idle (on-hook) state when it is not in use, or in an active (off-hook) state when someone is making a call. This model is called the ON-OFF process [30] as active periods are always separated by an idle period.

5.4 Simulation Methodology

The computation intensive call-by-call stochastic simulation is written using SIMSCRIPTTM and C. The high-level flow chart is as shown in Figure 5.7. First the two fixed parameter files : the attenuation parameter file and the system file are loaded. The attenuation parameter file contains the attenuation data of various building materials attenuation (L_{WALL}) and the system file contains the path law exponent (γ_f) and system parameters (L_{ref} , L_{HUMAN} , G_{TX} , G_{RX} , S_{TX}). Next the simulation variation files : the port configuration file and the topology file are read. The port configuration file contains the details of port placement and assigned frequency channels and the topology file contains wall, window and furniture placement and material detail.

A user is placed at a random position in the service area and access is attempted. On a successful access, a new user record is created and the system state is updated for additional co-channel interference. On a failed access, lesser SINR than threshold or non availability of slot, the blocking statistics are updated and the user is returned to the user set. In the event of a call termination, the user record is deleted and the user is

Figure 5.6 Alternating State Process

Figure 5.7 TDMA Simulation Flow Chart

returned to the user set. The system state is updated by removing the corresponding co-channel interference.

This simulation is a call by call or static simulation in the sense that the local signal power is evaluated at the call setup and fixed for the duration of the call. The static simulation deals with the establishment of the multiple-access (call set up) and the performance associated with it. In an alternative, slot by slot or dynamic simulation the fading or changes in signal power during the call duration are also considered. The reading are recorded after the system reaches steady state. The system is assumed to reach the steady state after 1000 call attempts. The dynamic simulation deals with the performance of the system after the call setup.

5.4.1 Simulation Parameters

The input parameters to the simulation can be split into system parameters, portable traffic parameters, radio signal propagation parameters, and building topology parameters. The various parameters in each of these divisions are listed below. The values within the brackets specify those used in the simulation.

System Parameters

<i>TOT</i>	Total access attempts [$10^5 - 10^6$]
<i>SINR_{thr}</i>	SINR threshold value [10dB - 20dB]
<i>MDS</i>	Minimum Detectable Average Signal at the Receiver -118dBm for 64Kbps user rate -114dBm for 160Kbps user rate
<i>N</i>	Frequency cluster size [4]
<i>N_{select}</i>	Number of ports to select for initial access
<i>DENS</i>	Portable density [one voice & one data every $10m^2$]
<i>D</i>	Portable distribution in service area [uniform]
<i>BS_{hgt}</i>	Port or base station height from ground [10 feet]
<i>S_{TX}</i>	Average transmitter power line of sight calls [0dBm] non line of sight calls [10dBm]

c	Number of carriers per port [1 or 3]
k	Number of users per TDMA/TDD carrier [10 or 25]
n	Random number seed [1-6]
NSD	Number of calls to reach steady state [1000]

Portable Traffic Parameters

$Traffic/Portable$	Traffic per portable in erlangs
$1/\mu$	Mean call holding time in minutes
$HOLD_{dist}$	Call holding time distribution
$HOLD_{max}$	Maximum call holding time in minutes
$HOLD_{min}$	Minimum call holding time in minutes

Radio Signal Propagation Parameters

L_{ref}	One meter intercept [as in Table 4.1]
γ_f	Path loss exponent [as in Table 4.1]
N_{RX}	Receiver thermal noise -126dBm for 64 Kbps user rate -122dBm for 160 Kbps user rate
L_{HUMAN}	Human attenuation [25 dB - 30 dB]
L_{WALL}	Wall attenuation [as in Graph 4.1]

Building Topology Parameters

$LENT$	Length of the service area in metres
$BRTH$	Breath of the service area in metres
N_{BS}	Number of base stations or ports
N_{WALLS}	Number of walls
$X1_{WALL}, Y1_{WALL}$	Wall begining co-ordinates
$X2_{WALL}, Y2_{WALL}$	Wall ending co-ordinates
MAT	Material of the wall
X_{BS}, Y_{BS}	Base station or port location - (x,y) co-ordinates

Chapter 6

Simulation Results and Analysis

This chapter deals with the analysis of various results produced using the simulation tool to study TDMA-TDD behavior in an indoor environment. The results of the simulation are grouped under three different headings viz, system behavior, effect of traffic parameters and access scanning algorithms. The first, system behavior, depicts the TDMA-TDD's performance in an indoor environment. The effect of traffic parameters explain the operation of TDMA-TDD under various traffic conditions. The third, scanning algorithms, analyzes various TDMA-TDD scanning algorithms' applicability in an indoor environment.

System Specification	User Rate	Signalling Rate	# of TDD users per frequency	# of frequencies per port
B	64 Kbps	3.2 Mbps	25	One
2.5 B	160 Kbps	3.2 Mbps	10	Three

Table 6.1 System Specifications

The analyses in this chapter is carried out for two different sets of TDMA-TDD system parameters as explained in Table 6.1. The two benchmarks considered for analysis are normal traffic and one erlang per portable traffic and are as explained in the Appendix B. These two conditions depict the normal and maximum load the system is likely to carry for a given portable density due to variations in portable traffic. Hence the system performance at any instant would be in between these two boundaries. Two different building topologies, i.e. open room where co-channel interference will be maximum and an indoor environment with different sized rooms and corridors typical of an office environment are considered.

6.1 System Behavior

This section analyzes the effect of system parameters such as number of frequencies per port and portable transmitter power on TDMA-TDD's performance under extreme traffic conditions. Performance criteria selected for evaluation of TDMA-TDD behavior in an indoor environment are blocking probability, co-channel interference and transmission quality. By positioning the user at many uniformly separated locations in the service area, a measure of performance over the service area is achieved. These performance statistics are also referred to as area-averaged statistics. The effect of transmitter power control on system performance is analyzed in Appendix A. As the radio signal propagation in 20GHz to 60GHz depends on attenuation of building materials [4] a study on effect of building materials on system performance is carried out in section 6.1.4. Utilization of the four (20–30, 30–40, 40–50, 50–60 GHz) frequency bands is compared in section 6.1.2.

6.1.1 Performance Measures

Due to extreme power limitations of the portables, the portable to port radio link (uplink) is important. Interference and blocking are assessed for uplink and transmission quality is assessed at the portable location (downlink) to validate portable based scanning and access.

6.1.1.1 Blocking Probability

A portable attempting an access scans the available frequency channels. It selects the strongest three ports (or corresponding frequencies) on signal strength averaging for initial access attempts. The portable listens (idle slot tone) to the frequency channels in these three ports to find whether there are idle time slots. If there are, it signals the port using an idle time slot and requests service. The port processes the information and decides the time slot (slots) to be assigned. Otherwise, the port sends a negative acknowledgment and the user returns to the user set.

Blocking of communication on a link could occur when there are no idle time slots as determined by the ports in the selected frequency channels. Blocking could also occur when the received signal SINR (or corresponding Bit Error Rate) at the port is less than the threshold. Blocking due to the former is referred to as BP I and that due to the latter as BP II.

In TDMA, BP I refers to call access attempts that were unsuccessful due to the unavailability of idle time slots. So BP I is of significance as it is governed by fixed system parameters like the number of time slots per frequency and number of frequencies per port. A high value of BP I implies inadequate system resources for the traffic conditions and could be modified only by redesigning the whole multiple-access system. BP II is power dependent and varies significantly with variations of building materials and co-channel interference.

BP I for the two different systems and the two different topologies are summarized in Table 6.2. The results are for two extreme conditions of normal traffic and one erlang per portable traffic. The values in Table 6.2 indicate that the parameters (user density, traffic/user, system parameters etc..) considered are such that the probability of finding all time slots occupied (BP I) is extremely small (zero for all practical purposes) for the assumed user density of two (one voice and one data) users per 10 sq.m. Therefore blocking will mainly occur due to co-channel interference (BP II).

BP II (CDF of uplink SINR) against traffic demand are shown in Graphs 6.1 – 6.4. The CDF of uplink SINR gives the probability of blocking. The performance of one frequency channel per port (system B) is better than the three frequency channel per port (system 2.5B) as interference is less due to less frequency reuse. Comparing graph 6.1 for the typical indoor and graph 6.2 for the open room, the closeness of CDF of uplink SINR for normal and one erlang per portable traffic in typical indoor indicates the sensitivity to the confining effect of the high attenuation wall materials.

As highly reliable transmission is expected over the service area, the tail of the distribution is important for reliable service. Table 6.3 illustrates the calculated SINR at the port as a function of traffic per portable at lower percentile values of blocking for the considered user density of two (one voice and one data) users per 10 sq.m. The calculated SINR values for system B in both typical indoor and open room environments are around the minimum acceptable SINR values of 10dB to 20 dB. But for system 2.5B the calculated SINR values are below the minimum acceptable values. Even if the receiver (port) is capable of detecting the signal when SINR is around -40dB, there will still be a blocking of 1% for system 2.5B in an open room.

A parameter δ (in dB), could be defined as the difference in SINR between normal and one erlang per portable traffic for a fixed blocking value. The normal and one erlang

System	Topology	BP I for Normal Traffic	BP I for 1 erl. Traffic
B	Open Room	0,0	0,0
	Typical Indoor	0,0	0,0
2.5 B	Open Room	0,0	0,0
	Typical Indoor	0,0	0,0

Table 6.2 BP I

Blocking Probability	SINR in dB corresponding to the Blocking Probability							
	Typical Indoor				Open Room			
	Normal Traffic		One erl. Traffic		Normal Traffic		One erl. Traffic	
	B	2.5 B	B	2.5 B	B	2.5 B	B	2.5 B
1 %	0.88	18.54	- 5.42	-11.94	18.72	-30.24	-13.68	-42.85
2 %	10.15	34.49	4.43	-7.24	20.27	-29.01	-12.09	-41.87
3 %	32.87	35.92	11.95	-4.57	21.28	-27.99	-11.18	-41.24
4 %	35.32	36.81	29.18	-1.87	22.18	-27.07	-10.42	-40.71
5 %	36.34	37.52	33.10	1.13	22.94	-26.03	-9.82	-40.28

Table 6.3 Minimum SINR against Blocking and Traffic Demand

Graph 6.1 BP II : Typical Indoor, System B

Graph 6.2 BP II : Open Room, System B

Graph 6.3 BP II : Typical Indoor, System 2.5B

Graph 6.4 BP II : Open Room, System 2.5B

traffic per portable are the minimum or normal and the maximum traffic the system is likely to experience for a given portable density and traffic statistics. This parameter δ explains the sensitivity of the system to temporal portable traffic fluctuations. A smaller value of δ (say $\leq 5\text{dB}$) implies that the TDMA-TDD system is robust to temporal traffic fluctuations and could easily accommodate more traffic. A higher value of δ indicates that the system has already saturated for the assumed traffic statistics.

For 5% blocking using Table 6.3, δ for system B (system 2.5B) in an open room is 32.76 (14.25) and in a typical indoor is 3.24 (36.39). Hence the smaller value of δ for system B in a typical indoor environment indicates that this TDMA-TDD system is robust to portable traffic fluctuations and could easily accommodate more traffic. Though the values of δ for system 2.5B are less than system B in an open room, the calculated SINR values are below the minimum acceptable SINR values (10dB to 20dB). Hence system B with calculated SINR values closer to minimum acceptable SINR values and with smaller δ at lower percentile values of blocking offer better performance than system 2.5B.

The response of the TDMA system to portable traffic fluctuations could be analyzed by considering three distinct regions of BP II (Graph 6.1–6.4) as in Table 6.4. Region 1 refers to values of SINR below 20dB. With normal traffic only about 21% of the portables are active whereas for one erlang per portable traffic all the portables are active in the service area. Hence severe interference is more probable for one erlang per portable traffic. As co-channel interference is the main communication impairment, the situation of high interference pushes the SINR value to this region. Open room specifies the condition of maximum co-channel interference and more than 80% (system B) of the calls have SINR less than or equal to 20dB for one erlang per portable traffic. In system 2.5B due to more frequency reuse and hence high co-channel interference more than 95% of the calls in both normal and one erlang per portable traffic fall in this region. For system B in a typical indoor environment only 4% of the calls fall in this region because of isolation afforded by the interior walls. Due to isolation offered by interior walls system B offers better performance in a typical indoor environment.

Region 2 refers to the value of SINR between 20dB and 60dB. Except for system B in an open room there is only a little variation, about 10%, in the number of calls with

System	Topology	Traffic per portable	Probability that received SINR is in		
			Region 1 $\text{SINR} \leq 20$	Region 2 $20 < \text{SINR} < 60$	Region 3 $\text{SINR} \geq 60$
B	Open Room	Normal	0.018	0.960	0.022
		1 erlang	0.831	0.160	0.009
	Typical Indoor	Normal	0.025	0.583	0.392
		1 erlang	0.034	0.617	0.349
2.5 B	Open Room	Normal	0.968	0.009	0.023
		1 erlang	0.994	0.003	0.003
	Typical Indoor	Normal	0.011	0.462	0.428
		1 erlang	0.236	0.584	0.180

Table 6.4 SINR Summary

SINR falling in this region for normal and fully loaded conditions. This holds true for both one and three frequency channels per port. But for system B in open room about 80% of the calls get transferred from Region 2 (moderate interference) to Region 1 (severe interference).

Region 3 depicts the condition of little or no interference and the SINR is controlled by signal attenuation and receiver noise. The no or little interference condition could be observed if the co-channel ports are wide apart or if there are high attenuation walls in between co-channel ports. Hence a good percentage of calls in a typical indoor environment fall in this region. As there are fewer active portables in normal traffic, the percentage of calls falling in this region is more for normal traffic than for one erlang per portable traffic.

In the subsequent sections unless otherwise specified blocking probability refers to BP II. In all the graphs of blocking probability the extreme left point indicates BP I.

6.1.1.2 Interference Characterization

Indoor wireless communications must provide service to areas with high portable density using the available spectrum. In effect, it is necessary to reuse [22],[26] the radio channel in a planned way to accommodate the portable capacity. In the cellular frequency reuse strategy, a portable in any cell operating on any radio channel is subjected to co-channel interference [22],[28],[32] from other portables operating on similar channels in the surrounding cells. The severity of co-channel interference determines the degree of reuse.

The ratio I_{max}/I_{total} , refers to the ratio of the single maximum co-channel interfering signal to the sum of all the co-channel interfering signals. The CDF of this ratio is a useful measure to determine the nature of interference. The simulation was run for normal and one erlang traffic per portable with one and three frequency channels per port. The CDF of the ratio are as plotted in Graphs 6.5 – 6.8. Table 6.5 summarizes the co-channel interference for the assumed user density of two (one voice and one data) users every 10 sq.m..

A portable trying to access a port experiences co-channel interference in the uplink (port to portable) only if there are active portables on similar frequency channels in the surrounding cells. Interference present refers to the percentage of calls that experience

co-channel interference. The number of calls experiencing interference is less for one frequency per port than for three frequencies per port due to its larger co-channel port separation. Co-channel interference when present might be due to one or more interferers depending on the number of active portables on similar frequency channels in the surrounding cells. In both the systems interference due to one interferer only dominates for normal traffic. The system with three frequencies per port (system 2.5B) experience severe interference in maximum load (one erlang per portable traffic) condition (Graphs 6.7 & 6.8). The system with one frequency per port (system B) has high tolerance to interference (Graphs 6.5 & 6.6) in normal traffic and maximum load conditions.

From Table 6.5 the interference due to one interferer dominates in most of the situations. But in the case of open room at maximum loading for both system B and system 2.5B, more than 90% of the time interference is due to more than one interferer. For these situations an attempt to characterize the interference with respect to a dominant interferer is carried out in this section. $I_d (=I_{max})$ is defined as the signal strength in dBm of the dominant interferer among the group of interfering signals and I_r as the signal strength sum in dBm of the remaining interfering signals. The ratio I_d/I_r in dB is the ratio of dominant to remaining interference. If a dominant interferer is defined as the signal with signal strength more than twice ($I_d/I_r \geq 3\text{dB}$) that of the remaining signals then from Graph 6.8a for system B in an open room interference could be characterized for 64% of the time and 22% of the time for system 2.5B. Graph 6.8a illustrates the severity of interference in system 2.5B.

6.1.1.3 Transmission Quality

A portable attempting an access scans the available frequency channels. The portable selects the frequency channel with maximum SINR for initial access. The portable listens to that channel to find whether there are idle time slots. If there are, it signals the port using an idle time slot and requests service. The port processes the information and decides the time slot (slots) to be assigned. Once the channel is selected the Signal to Interference plus Noise Ratio (SINR) calculated at the users's position characterize the transmission quality perceived by the user.

Transmission quality is given by the cumulative distribution (CDF) of SINR. The CDF gives the probability of successful access for a given SINR value. The tail of the

System	Topology	Traffic per portable	Interference Present		No interference
			Due to one interferer only	Due to more than one interferer	
B	Open Room	Normal	50.80%	4.11%	45.09%
		1 erlang	8.60%	90.36%	1.04%
	Typical Indoor	Normal	60.63%	4.22%	35.75%
		1 erlang	78.63%	19.74%	11.63%
2.5 B	Open Room	Normal	16.19%	74.21%	0.60%
		1 erlang	4.88%	94.80%	0.32%
	Typical Indoor	Normal	66.34%	17.39%	16.27%
		1 erlang	44.86%	54.81%	0.33%

Table 6.5 Co-channel Interference Summary

Graph 6.5 Interference Characterization : Typical Indoor, System B

Graph 6.6 Interference Characterization : Open Room, System B

Graph 6.7 Interference Characterization : Typical Indoor, System 2.5B

Graph 6.8 Interference Characterization : Open Room, System 2.5B

Graph 6.8a CDF of I_d/I_s

distribution is important for reliable access. Since highly reliable transmission over the service area is desired, performance is compared at the lower percentile values of the cumulative distribution of SINR. The CDF of SINR (local mean) achieved by uplink (portable to port) and that by the downlink (port to portable) are shown in Graphs 6.9 & 6.10.

A parameter Δ (in dB) could be defined as the difference between the downlink and the uplink SINR values at maximum loading (one erlang/portable traffic) for a fixed blocking probability. The value of Δ determines the closeness of uplink and downlink SINR. A small value of Δ implies that the uplink SINR is close to or same as downlink SINR. This would ensure a high two way transmission quality for either port or portable based initial access. A high value of Δ implies that for a portable or port based initial access the SINR calculated at the user position need not be close to or same as that at the port. Hence for high values of Δ both uplink and downlink SINRs need to be calculated and compared for initial access which might be a complicated initial access algorithm. Table 6.6 summarizes the value of Δ at the third percentile of blocking for system B at maximum loading. The small value of Δ (0.73) indicates the closeness of uplink and downlink SINR and confirms that either a port based or portable based initial scanning and access would be of use in indoor wireless communications.

The SINR scatter plot (Graphs 6.11 & 6.12) of downlink SINR against uplink SINR shows variability in the uplink performance that accompany downlink access for each access. Most of the variability between uplink and downlink performance is related to independent uplink/downlink interference mechanism and path difference of the interfering signals. For a portable based initial scanning and access, if the minimum downlink SINR of concern is 10dB and the maximum SINR of concern is 25dB then the standard deviation of the difference between downlink and uplink SINR for system B in typical indoor is 4.97dB and in open room is 2.09dB. Hence a portable based scan and access requires diversity for better performance. Diversity would enhance the signal at the port and help to mitigate multipath fading once the port is selected. Hence for system B the diversity scheme implemented at the receiver (port) should have a minimum performance gain of 4.97dB in a typical indoor and 2.09dB in an open room.

System	Building Topology	Link	SINR (local mean) in dB at one erl./Portable
B	Typical Indoor	Downlink	29.91
		Uplink	29.18
		$ \Delta $	0.73

Table 6.6 SINR Performance Chart

Graph 6.9 CDF of Uplink & Downlink SINR : System B, Typical Indoor

Graph 6.10 CDF of Uplink & Downlink SINR : System B, Open Room

Graph 6.11 SINR Scatter Plot : System B, Typical Indoor

Graph 6.12 SINR Scatter Plot : System B, Open Room

Graph 6.13 Frequency Band Utilization

6.1.2 Behavior of Frequency Bands

As the 20GHz to 60GHz band is wide there are significant variations in path exponent, shadow fading and building material attenuation as shown in Table 4.1 and Graph 4.1. This results in variations in utilization of the four frequency bands (20–30 (f_1), 30–40 (f_2), 40–50 (f_3), 50–60 (f_4) GHz). Many calls accessing a particular frequency band would result in increased co-channel interference in that frequency band. Little use of a frequency band would be an overhead without any service and result in over crowding other bands. So the system design should consider the optimum assignment of frequency bands to various ports so that there is uniform usage of all frequency bands.

Graph 6.13 shows the band utilization under normal traffic and fully loaded conditions. There is definitely an uneven usage of frequency bands for both normal and one erlang per portable traffic. High path attenuation along with high wall attenuation at upper bands (40GHz - 60GHz) forces most of the calls to access the lower bands (20GHz - 40GHz). This uneven spread of calls in various bands necessitates a study of various access scanning algorithms (portable based or centralized) that might optimize the usage of various frequency bands. It might be interesting to see the effect of this optimization on multiple-access system performance. The average SINR for each band was around 55dB for both normal and one erlang per portable traffic.

6.1.3 Scatter Plot

The X-Y scatter plot with respect to serving ports of all accessing user positions is a useful measure to determine co-channel interference and also antenna placement and hand-off [32] requirements. The X-Y scatter plot of user positions with respect to port A as shown in Figure 5.2 (Typical Indoor) and in Figure 5.1 (Open Room) are shown in Graphs 6.14 and 6.14a respectively. Since all the portables accessing Port A are uniformly distributed in the service area, the points were gathered between zero to ninety degrees to obtain the sample space. The user positions that are farthest from the serving ports cause the greatest co-channel interference.

Graph 6.14 X-Y Scatter Plot

Graph 6.14a X-Y Scatter Plot

The access scanning algorithm selects the port with the strongest (relative ranking) SINR. Hence all portables accessing the port (Graph 6.14) are closer to the port and within the four walls surrounding the port. This is mainly because the wall material, concrete, offers very high attenuation (Graph 4.1) to radio signal propagation. This necessitates placement of a port antenna in the room. Thus a room of concrete walls results in confinement (screening effect) of radio signal to that room and hence lesser co-channel interference or better performance at the cost of more port antenna placements (at least one per each room [5]).

Unlike the previous case, in Graph 6.14a due to absence of walls in an open room the portables are not closer to the serving ports. The portables that are farther away from the serving port cause high co-channel interference and also have higher probability of moving away from the port and hence, may necessitate a hand-off.

6.1.4 Effect of Building Material

The attenuation offered by various building materials to the radio signal propagation path at 20GHz to 60GHz varies widely with materials like sheetrock, glass, gypsum and plywood offering less attenuation and materials like wood and concrete offering very high attenuation as depicted in Graph 4.1. The effect of these materials would be a significant factor as high attenuation materials like concrete cause confinement of radio signals to the room and so less co-channel interference even if the next co-channel port is located nearby. This also necessitates less inter port separation or a smaller cell size in the service area for acceptable system performance. But lower attenuation materials in the service area necessitate larger cell size or a large inter port separation due to heavy co-channel interference.

To study the effect of building materials on TDMA-TDD system performance two extreme conditions of all concrete walls and all sheetrock walls of the building shown in Figure 5.2 are considered. All walls are one inch thick. Graph 6.15 explains the effect of building material on the system performance. In fully loaded traffic conditions the portables in an all sheetrock wall building experience more severe interference than the portables in all concrete wall building. This clearly demonstrates the screening effect of concrete walls. Unlike mobile communication systems where the frequency reuse depends on shadow

Graph 6.15 Effect of Building Material

Graph 6.16 Effect of Portable Traffic : Typical Indoor

fading [33], the placement of port antennas, frequency reuse and inter port separation depends strongly on the building material for indoor communication systems.

6.2 Effect of Traffic Parameters

The indoor environment might be [8] an office or apartment towers, university or government campuses, factories, building complexes etc.,. Hence the number of building occupants (tenants) or portable density vary from building to building. The new communication [30] services depart from the conventional telephone services in three essential aspects. They can be multi-media, multi-point and multi-rate. The ultimate goal of Indoor wireless communications is to support these services. At present indoor communications are expected to provide [9] a communication system, an office automation system and a building automation system. Hence the density of portables in the service area and traffic variations are important features of indoor communications and this section examines the effect of portable traffic and portable density on TDMA-TDD system performance. The analysis in this section is carried out for system B only.

6.2.1 Portable Traffic

Indoor wireless communications are expected to handle [8] telephone services, computer communication services, video services and security/emergency services. Thus the traffic offered by the portables varies from bursty services like smoke detection, fire alarm, simple surveillance to moderate traffic services like voice and computer communications. This wide variation in the traffic offered by the portables in the service area places stringent requirements on the capacity of multi access system to handle traffic variations.

The robustness of TDMA-TDD to traffic variations is analyzed by varying the traffic (erlangs/portable) of all the portables in the service area from a small value of 0.05 to the maximum possible value of one keeping the relative proportions of the different kinds of portables as in section 5.3. The blocking probability for various SINR threshold values are recorded.

Graph 6.17 Effect of Portable Traffic : Open Room

Blocking Probability	Traffic per Portable (in erlangs) corresponding to the blocking probability			
	Typical Indoor		Open Room	
	10 dB	20 dB	10 dB	20 dB
1 %	0.03	0.02	0.425	0.275
2 %	0.275	0.05	0.475	0.32
3 %	1.0	0.925	0.502	0.34

Table 6.7 Effect of Portable Traffic

The service offered by the multiple-access system to portable traffic variations are as given in Graphs 6.16 and 6.17. As highly reliable transmission is expected over the service area, performance of the system is determined by sampling the blocking probability at lower percentile values. Table 6.7 depicts the traffic per portable at the first, second, and third percentile of blocking. With 97% availability the TDMA-TDD system could support in a typical indoor (open room) environment 1.0 (0.34) erlangs per portable for a SINR threshold of 20dB at 64Kbps user rate (System B). The indoor communication system is able to offer acceptable service even if each portable is active 50% (0.5 erlangs) of the time. The lower traffic per portable in typical indoor for 1% and 2% blocking is presumably due to the fact that the attenuating walls restrict access to most ports, whereas for the open room case, most (all) of the ports are accessible to any portable.

6.2.2 Portable Density

Portable density refers to the concentration of portables in the service area. Concentration of portables in the service area varies from building to building [8] like less concentrated single-tenant laboratories and single tenant office buildings usually owned by the corporations for corporate purposes and highly concentrated shopping centres, multi-tenant buildings and factories. Tetherless access provides freedom of movement to the users and this results in temporal variations of portable density in the service area.

The density of the portables in the service area are varied from two (one voice and one data) every 90 sq.m. to two (one voice and one data) every 1 sq.m. with the traffic parameters as mentioned in section 5.3. The service offered by the TDMA system to changes in portable density are as given in Graphs 6.18 and 6.19. With 97% availability this TDMA-TDD system in a typical indoor (open room) environment could support an offered traffic of 0.19 (0.061) erlangs per sq.m or less for a SINR threshold of 20dB. The same for SINR threshold of 10dB is 0.2 (0.065) erlangs per sq.m or less.

A simple extrapolation of the results in the previous two sections would be that as long as the average traffic per portable in a typical indoor (open room) is less than or equal to 0.92 (0.6) erlangs and the offered traffic per sq.m is less than or equal to 0.19 (0.061) erlangs 97% availability would be offered by this TDMA-TDD system for a SINR threshold of 20dB.

Graph 6.18 Effect of Portable Density : Typical Indoor

Graph 6.19 Effect of Portable Density : Open Room

6.2.3 System Utilization

Required capacity could be achieved either by making full use of the available resources or by providing enough excess resources to meet the capacity requirements. A better system design is one that has the required resources and makes full use of it. Hence, system utilization could be defined as the maximum traffic the system could support (for a given blocking probability) to the total traffic the system could carry if interference is ignored. In the case of typical indoor (open room) environment there are 19 (25) ports, each port is assigned a single frequency in system B, and each channel could support 25 users. So the total traffic that the system could carry in a typical indoor (open room) is $19 \times 1 \times 25 = 475$ (625) erlangs. Table 6.8 lists system utilization for a few values of system blocking. Co-channel interference limits system utilization to around 50% at 95% availability.

6.2.4 Individual User Service

Congestion can be measured or defined [30] in two ways. The first method measures how fully utilized the resources are, given by the fraction of time that all resources are used. This measure is also called time congestion or system blocking. Time congestion could be measured by sampling the multiple-access system at random times and finding the fraction of sampling times when the system is fully utilized.

The second method measures how often a resource request is denied in all resource requests. This measure is also called call congestion or call blocking. Call congestion could be measured by sampling the multiple-access system at the time of access and finding the fraction of uncompleted access.

Call congestion is of significance as it depicts the quality of service offered by the multiple-access system to an individual user. Call congestion would be an important system design parameter at higher traffic conditions. In this section congestion is used to refer to call congestion.

To measure congestion the call access attempts of each user in the user set M (240) is recorded to calculate the fraction of uncompleted access. The minimum, maximum and average values in the user set are as recorded in Table 6.9 for a SINR threshold value of 20dB for system B in a typical indoor environment. Over the entire traffic range, 0.1 to 1.0 erlangs per portable the maximum value changes by less than a factor of two

Blocking Probability	System Utilization corresponding to the blocking			
	Typical Indoor		Open Room	
	10 dB	20 dB	10 dB	20 dB
1 %	1.52 %	1.01 %	34 %	22 %
2 %	13.4 %	3.2 %	37.9 %	25.6 %
3 %	48 %	46.74 %	40 %	27.2 %
5 %	58.1 %	53.1 %	44 %	32 %

Table 6.8 System Utilization

Traffic per Portable in erlangs	CONGESTION		
	SINR = 20 dB		
	min	avg	max
1.0	0.0	0.0124	0.0656
0.9	0.0	0.0064	0.0547
0.8	0.0	0.0043	0.0516
0.7	0.0	0.0033	0.0476
0.6	0.0	0.0026	0.0476
0.5	0.0	0.0022	0.0448
0.4	0.0	0.0018	0.0421
0.3	0.0	0.0016	0.0402
0.2	0.0	0.0014	0.0388
0.1	0.0	0.0013	0.0380

Table 6.9 Congestion : System B, Typical Indoor

Fifth percentile value of call congestion (95% individual user availability) is attained at an offered traffic of 0.144 erlangs per sq.m for a SINR threshold of 20dB, whereas the same value for statistical service criterion is 0.2102 erlangs per sq.m. The average value of call congestion are close to Blocking Probability as in Graph 6.1.

6.3 Scanning Algorithms

Indoor wireless communications require a balance between radio transmission quality and high user capacity. High user capacity is achieved by frequency reuse. The transmission impairments include co-channel interference and signal attenuation. A user who wishes to connect to a local network must have the portable radio select a channel and initiate an access protocol. At the time of turn on the portable has no information about the strength or quality of the channels. The portable should gather, process, and use the information from radio signal measurement to select the appropriate port or ports on which to start the call. It is desired to have the portable quickly (without perceptible delay) and reliably identify a channel with which it can access the network with good transmission quality. The type of radio measurements to be made, their processing and the criteria to be applied to them from the point of view of the portable are discussed in this section.

The port periodically transmits a short data sequence or beacon, so that the portable can measure the signal strength and decode the port identity etc., To access, the portable rapidly scans the frequency channels making power measurements on each. The strongest port on a channel is the serving port with the remaining signals being co-channel interference. The corresponding SINR is stored in a short term memory. Once the measurements are made, the scanning algorithm should decide on a channel set with

- ☐ Good two way transmission quality.
- ☐ Minimum distance between the user and the accessed port to minimize the co-channel interference.
- ☐ Alternate channel choices if the first choice is blocked.

Three scanning algorithms are simulated and their performances are compared. The three scanning algorithms are relative ranking, first fit, and close fit.

Relative Ranking

In relative ranking, frequency channels (or corresponding ports) are ranked according to the measured SINR. The channel with the highest SINR is selected for initial access. If it is blocked, the second ranked choice is selected etc.,

First Fit

In first fit algorithm, the channels are scanned in a random order (non repeating scan) and the first channel having SINR greater than or equal to a preset threshold is selected for initial access. If all channels in the system are scanned without finding one that meets the threshold requirements, the access fails.

Close Fit

Close fit algorithm is a modification of relative ranking. The portable ranks the channels according to the measured SINR to identify the candidates for access. From the ranked candidates the channel with signal strength closest to the preset threshold is selected for initial access. If it is blocked, the next channel with SINR close to the threshold is selected etc.,

Performance Comparison

System B in a typical indoor environment and in an open room is considered for analysis. The performance measures considered for evaluating the scanning algorithms are blocking probability, co-channel interference, and frequency utilization.

Graphs 6.20 and 6.21 illustrates the blocking probability for the three scanning and access schemes in a typical indoor and in an open room respectively. Though the blocking in an open room is high, it is considered for evaluating the initial scanning and access schemes as it offers an environment of maximum co-channel interference, the main communication impairment in an indoor environment. For the receiver (port) SINR threshold of 20dB, first fit offers the better performance both in the typical indoor and in the open room.

Graph 6.20 Scanning Algorithms : Blocking in Typical Indoor

Graph 6.21 Scanning Algorithms : Blocking in Open Room

Graph 6.22 Scanning Algorithms : Interference in Typical Indoor

Graph 6.23 Scanning Algorithms : Interference in Open Room

Graph 6.24 Scanning Algorithms : Frequency Utilization in Typical Indoor

Graph 6.25 Scanning Algorithms : Frequency Utilization in Open Room

Graphs 6.22 and 6.23 illustrates the effect of co-channel interference against traffic for the three scanning and access algorithms under consideration. First fit has a higher tolerance to co-channel interference than the other two schemes. The reason for the first fit's better performance under maximum loading (one erlang/portable traffic) in typical indoor and in open room is explained by Graphs 6.24 and 6.25 respectively for the considered user density of two (one voice and one data) users every 10 sq.m. First fit spreads the calls more evenly in all the four bands than the other two access and scanning algorithms. The standard deviation of the frequency utilization in a typical indoor (open room) environment for relative ranking, first fit and close fit are 4.8339 (5.8218), 2.2554 (2.8166) and 3.3744 (2.8249) respectively. The even spreading in first fit results in no overcrowding of any particular band and hence lesser co-channel interference or better performance.

Chapter 7

Conclusions and Future Research

A simulation tool to analyze the behavior of TDMA-TDD in mm wave indoor wireless communications has been developed and tested. The simulator can analyze the performance, traffic capabilities, and scanning algorithms of TDMA TDD in mm wave indoor wireless communications. Studies were conducted using the simulation tool on an indoor environment with large and small sized rooms and corridors typical of an indoor environment and on an open room where co-channel interference, the main communication impairment is maximum.

Using the available traffic data and with the available knowledge of the channel the simulator based analysis reveals that the use of millimeter waves for indoor wireless communication would be a favorable choice. Short range propagation due to high path attenuation along with the high attenuation of building materials almost forces the communication link to be line-of-sight for better performance. This requires placement of at least one port antenna per room. This requirement generally results in the allocation of resources in excess of the requirements. Hence the system does not saturate for normal and maximum loading for a given user density. With resources usually in excess of the requirements the main communication impairment is the co-channel interference. This limits system utilization to around 50% at 95% availability.

A power control strategy where, line-of-sight calls ($\text{SNR} \geq 50\text{dB}$) switch their portable transmitter power to 0dBm whereas non-line-of-sight calls transmit at 10dBm was tried out in the simulation. This results in a 2dB performance advantage due to reduced co-channel interference and power conservation about 40% of the time (Appendix A).

The duplex communication is achieved by independent uplink and downlink communication paths. The variability (local mean) between the downlink and uplink transmission is around 5dB. This is due to independent uplink and downlink interference mechanism and path difference of the interfering signals. Hence for a portable based scanning and access diversity is required for better performance. Portable based scanning and selection of three frequency channels for initial access provides enough alternative

choices to the portable and appears to be adequate. As the available spectrum is large the initial access and scanning algorithm has an important requirement of evenly distributing the accessing calls in the available spectrum for better performance.

The simulation tool was tested and verified by various means. Each module was individually tested for known results and consistency checks of the completed code were made by taking snapshots of data structures during execution. The number of active portables in the system with changes in portable traffic was compared against analytical values and good agreement was observed as shown in the Appendix B. The results were also compared by changing the random number seed in the simulation and very good agreement was observed. Cross comparison of the results were also made to check the validity of the results. The effect of offered traffic on system performance where the offered traffic was varied by varying the traffic per portable and maintaining the portable density constant and vice versa was tested. The agreement of results could be observed by comparing the corresponding points in Graphs 6.16 and 6.18. The simulation tool was found to produce reliable results.

The simulation tool could be used to study various building topologies and to study the impact of system parameters on performance. This work could be extended to dynamic channel allocation and its performance could be studied. On availability of wide band channel measurements this simulation could be extended to study wireless access to ATM-SONET networks. This simulation would be an important tool to study the impact of new channel propagation parameters, effect of diversity reception, various combination of portable traffic, various signalling and corresponding baseband rates on TDMA-TDD's performance in an indoor environment using millimeter waves.

The important results of this investigation on the use of mm-waves for indoor wireless communications using a TDMA-TDD system could be summarized as

- (1) High path and building material attenuation necessitates short range propagation or micro-cellular system architecture with cell radius of 5 meters.
- (2) As the communication is short range and mostly line-of-sight a power control strategy was adopted. The line-of-sight calls transmit at 0dBm and the non-line-of-sight calls transmit at 10 dBm. This was found to have a performance increase of 2dB at the first percentile of blocking and power conservation around 40% of the time.

- Blocking is mainly due to co-channel interference. The system with one frequency channel per port (system B) offers better performance than the three frequency channels per port (system 2.5B) due to its larger co-channel frequency separation.
- Co-channel interference when present is mostly (50% to 80%) due to one source only in a typical indoor environment for a user density of two (one voice and one data) every 10 sq.m..
- High attenuation of building materials (walls) result in confinement of radio signals and hence, reduced co-channel interference in a typical indoor environment. Whereas the absence of walls in an open room results in severe co-channel interference.
- The closeness of the CDF of downlink and uplink SINR indicates that a portable based initial scanning and access is sufficient. The standard deviation of the difference between downlink and uplink SINR (local mean) is around 5dB. Hence the portable based initial scanning and access requires diversity reception at the port for better performance.
- With 97% availability the TDMA-TDD system could support M ($M = 240$ in typical indoor and $M = 500$ in open room) users with 0.925 (0.34) erlangs/portable traffic for a SINR threshold value of 20dB in a typical indoor (open room) environment at 64Kbps user rate.
- With 97% availability the TDMA-TDD system could support an offered traffic of 0.19 (0.061) erlangs/sq.m. for a SINR threshold value of 20dB in a typical indoor (open room) environment at 64Kbps user rate.
- With 95% availability the system utilization is around 53% (32%) for a SINR threshold of 20dB in a typical indoor (open room) environment at 64Kbps user rate.
- Most of the calls tend to access the lower frequency bands due to its lesser path and building material attenuation. For better performance the initial scanning and access algorithm requires that all accessing calls be spread evenly in all the frequency bands. The first fit due to its random picking of frequency channel results in more even distribution of the calls in all the frequency bands than relative ranking or close fit

Bibliography

- [1] D.C.Cox, "Universal digital portable radio communications," *Proc. of IEEE*, vol. 75, pp 436-477, Apr. 1987.
- [2] H.Ochsner, "DECT-Digital European Cordless Telecommunications," *Proc. of IEEE Vehicular Technology Conference*, pp 718-721, 1989.
- [3] T.Hattori, A.Saski and K.Momma, "Emerging Technology and service enhancement for cordless telephone systems," *IEEE Communications Magazine*, pp 53-58, Jan. 1988.
- [4] L.Golding and A.Livne, "RALAN - A Radio Local Area Network for voice and data communications," *Proc. of IEEE Globecom*, pp 48.1.1-48.1.5, 1988.
- [5] A.R.Tharek and J.P.McGeehan, "Indoor propagation and bit error rate measurements at 60 GHz using phase-locked oscillator," *Proc. of IEEE Vehicular Technology Conference*, pp 127-133, 1988.
- [6] S.E.Alexander and Pugliese, "Cordless communication within buildings : results of measurements at 900 MHz and 60 GHz," *British Telecom Technical Journal*, vol. 1, pp 99-105, July 1983.
- [7] G.A.Kalivas, M.El.Tanany and S.A.Mahmoud, "Millimeter-wave channel measurements for Indoor wireless communications," *Proc. of IEEE Vehicular Technology Conference*, pp 609-612, 1992.
- [8] M.R.Finley Jr., A.Karakura and R.Nbogni, "Survey of Intelligent Building concepts," *IEEE Communications Magazine*, pp 18-23, Apr. 1991.
- [9] S.Fujie and Y.Mikami, "Construction aspects of Intelligent Buildings," *IEEE Communications Magazine*, pp 50-57, Apr. 1991.
- [10] S.A.Wilkus, "Standards and regulatory aspects of wireless local communications," *IEEE Workshop on wireless LANs*, Worcester, May 1991.
- [11] D.M.Pozar, *Microwave Engineering*, Addison Wesley series in Electrical and Computer Engineering, Massachusetts, 1990.

- [12] D.L.Schilling, L.B.Milstein, R.L.Pickholtz, M.Kullback and E.Miller, "Spread Spectrum for Commercial Communications," *IEEE Communications Magazine*, vol. 29, pp 66-79, April 1991.
- [13] D.L.Schilling, "Theory of Spread Spectrum Communications," *IEEE Trans. on Communications*, vol. 30, pp 855-884, May 1982.
- [14] M.K.Simon, J.K.Omura, R.A.Scholtz and B.K.Levitt, *Spread Spectrum Communications*, vol. 1 and 2, Rockville : Computer Science, Massachusetts, 1985
- [15] S.J.Lipoff, "Implementation issues for wireless spread spectrum data communication links for use in license free applications," *IEEE Workshop on wireless LANs*, Worcester, May 1991.
- [16] M.Kavehrad and P.J.MacLane, "Spread Spectrum for Indoor digital radio," *IEEE Communications Magazine*, vol. 25, pp 32-40, June 1987.
- [17] L.Kleinrock, *Queing Systems*, vol. 1 and 2, Wiley Interscience, New York, 1975.
- [18] D.J.Goodman, "The near/far effect in local ALOHA radio communications," *IEEE Trans. on Vehicular Tech.*, vol. 36, pp 19-27, Feb. 1987.
- [19] B.Ramamurthi, Adel A.M.Saleh and D.J.Goodman, "Perfect Capture ALOHA for Indoor radio communications," *IEEE Journal on Selected areas in Communications*, vol. 5, pp 806-814, June 1987.
- [20] A.S.Tanenbaum, *Computer Networks*, Prentice Hall, Englewood Cliffs, 1981.
- [21] M.M.Sayed, G.F.Anderson, "50-to-110-GHz High-Performance Millimeter Wave Source Modules," *Hewlett-Packard Journal*, pp 50-64, April 1991.
- [22] W.C.Jakes, *Microwave Mobile Communications*, Wiley Interscience Publications, New York, 1974.
- [23] W.C.Y.Lee, *Mobile Communications Engineering*, McGraw-Hill Book Company, New York, 1982.
- [24] L.Raffaelli, E.Stewart, "Millimeter-wave monolithic components for automotive applications," *Microwave Journal*, pp 22-32, Feb. 1992.
- [25] K.Krishnamurthy and D.R.Conn, "Conversion gain and stability of a resonant tunneling diode harmonic mixer," *Microwave and Optical technology letters*, vol 4, pp 212-216, April 1991.

- [26] V.H.MacDonald, "The Cellular Concept," *Bell System Technical Journal*, vol. 58, pp 15-41, Jan. 1979.
- [27] R.H.Frenkiel, "A high capacity Mobile Radiophone System model using a coordinated small-zone approach," *IEEE Trans. on Vehicular Tech.*, vol. 19, pp 173-177, May 1970.
- [28] D.C.Cox, "Cochannel Interference considerations in frequency reuse small coverage-area radio systems," *IEEE Trans. on Communication*, vol. 30, pp 135-142, Jan. 1982.
- [29] R.B.Cooper, *Introduction to Queueing Theory*, second edition, North-Holland, New York.
- [30] J.Y.Hui, *Switching and Traffic theory for Integrated Broadband Networks*, Kluwer Academic Publishers, Massachusetts, 1990.
- [31] P.F.Pawlita, "Two decades of data traffic measurements : A survey of published results, experiences and applicability," *Proc. of International Teletraffic Conference*, pp 5.2A.5.1-5.2A.5.9, June 1988.
- [32] J.D.Parsons and J.G.Gardiner, *Mobile Communication Systems*, Blackie and Son Ltd., London, 1989.
- [33] R.C.Bernhardt, "RF Performance of macroscopic diversity in Universal digital portable radio communications: Signal strength considerations," *Proc. of IEEE Globecom*, pp 1002-1005, 1985.

Appendix A

Power Control

Power control, line-of-sight ($\text{SNR} \geq 50\text{dB}$) calls transmit at 0dBm whereas the non line-of-sight calls transmit at 10dBm was used in the simulation. This has a two folded impact on the system performance viz, line-of-sight calls transmit at low power and hence considerably reduce co-channel interference and the reduction in power also prolongs the battery life. The effect of power control was tested for system B in a typical indoor environment at maximum loading. Of the total calls accessing the network 38% were line-of-sight and hence a corresponding conservation of power. From Graph A.1 at 1% blocking there is 2dB performance increase due to reduction in co-channel interference by power control.

Graph A.1 Effect of Power Control

Appendix B

Traffic per Portable

The number of active portables at normal traffic and one erlang per portable traffic are illustrated for the Open Room (B.1) and Typical Indoor (B.2). The graphs (Graph B.1 and B.2) are obtained by sampling the number of active calls in the TDMA-TDD system at random instants during the simulation. The tables (Table B.1 and B.2) represent the average values calculated analytically. The values in the graph and the table agree quite closely.

B.1 Open Room

Graph B.1 Number of Active Portables : Open Room

Portable Type	# of Portables	Traffic/Portable (erlangs)	Average # of active Portables at any given instant	
			Normal Traffic	One Erlang Traffic
Type I	250	0.11	27	250
Type II	175	0.25	43	175
Type II	25	0.33	8	25
Type IV	50	0.50	25	50
Average # of active portables (of all four types) at any given instant			103	500

Table B.1 Average Number of Active Portables : Open Room

B.2 Typical Indoor

Graph B.2 Number of Active Portables : Typical Indoor

Portable Type	# of Portables	Traffic/Portable (erlangs)	Average # of active Portables at any given instant	
			Normal Traffic	One Erlang Traffic
Type I	120	0.11	13	120
Type II	84	0.25	21	84
Type III	12	0.33	4	12
Type IV	24	0.50	12	24
Average # of active portables (of all four types) at any given instant			50	240

Table B.2 Average Number of Active Portables : Typical Indoor

END

15-1 2-93

FIN