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Traffic Handling Capability Study of a Broadband Indoor Wireless System Using CDMA Multiple Access

By
Chang Gang Zhang, Ph.D

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

Master of Science in Information and System Science

*Department of Systems and Computer Engineering
Carleton University
Ottawa, Ontario, Canada K1S 5B6*

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**TRAFFIC HANDLING CAPABILITY STUDY OF A BROADBAND
INDOOR WIRELESS SYSTEM USING CDMA MULTIPLE ACCESS**
submitted by

Chang Gang Zhang, Ph.D (Physics)

in partial fulfillment of the requirements
for the degree of Master's of Science in Information and System Science

Thesis Co-Supervisor

Thesis Co-Supervisor

Chair, Department of Systems and Computer Engineering

Carleton University

January 11, 1994

Abstract

The millimeter(mm) wave band (above 20 GHz) appears to be suitable for wireless access to broadband services, e.g. up to 20 Mb/s data rate, in an indoor environment due to the advantages of sufficient bandwidth, sparse usage, small RF device dimensions and favorable regulatory environment. CDMA (code division multiple access) may be an attractive technique because of its multiple access simplicity and other appealing features. In order to investigate the traffic handling capabilities of the future network providing desired quality of integrated services, this work presents a study of an indoor wireless network supporting high speed traffic using CDMA multiple access.

The results are obtained through the simulation of an indoor environment and the traffic capabilities of the wireless access to broadband 155.5 MHz ATM-SONET networks using the mm-wave band. A distributed system architecture is employed, and the system performance is measured in terms of call blocking probability and dropping probability. The impacts of the base station density, traffic load, average holding time, and variable traffic sources on the system performance are examined. The improvements of system performance by implementing various techniques such as handoff, admission control, power control and base antenna sectorization is also investigated.

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Chapter One

Introduction

1.1 Thesis Objectives

In the past few years, communications demand has been expanding rapidly. The progressing communications revolution is making this decade the "Telecommunications Decade". Only a few years from now, transcontinental calls will take full advantage of the enormous capacity of fiber-optic cable and switching equipment. The technology of the 21st century will provide high bandwidth telecommunications of video, text, data and images over fiber-optic networks. Due to the increased demand for communication services of all kinds, the Broadband Integrated Services Digital Network (BISDN) is receiving great attention.

Technology to support high-speed circuit switching is advancing rapidly, but circuit switching techniques can't efficiently carry bursty traffic. Resources are wasted when there is no information to transfer. Current circuit switching techniques are not well-adapted to support services at different information transfer rates.

New ATM (Asynchronous Transfer Mode) techniques, eliminating most of these shortcomings, are considered to be the most promising transfer techniques to implement BISDN[1]. ATM could potentially carry all services over a single, integrated, high-speed packet-switching fabric. ATM-based interfaces are extremely flexible, using signaling to dynamically reconfigure a mix of logical channels. An ATM channel is identified by a label carried in the header of a fixed-length cell, not by a position within a frame. Capacity can be dynamically allocated to any service. The service mix and information transfer rates are decoupled from characteristics of the physical interface and switching fabric. Synchronous Optical Network (SONET) is a proposed standard optical interface. Perhaps

it is the most significant current area of standardization impacting the telecommunications infrastructure.

The fiber-optic based wired communications link offers reliable broadband services. On the other hand, it has its own limitation in that terminals are restricted to fixed locations. In an indoor environment, besides restricting user mobility, network reconfiguration turns out to be a crucial problem for the wired network. To extend broadband services, a wireless LAN based on radio technology is a cost-effective solution. Research and development along this direction is ongoing.

There are many implemented or proposed indoor wireless communications systems. Unfortunately, few of them could be able to support multimedia traffic, and they are designed basically to accommodate voice and low bit rate data services. Due to the availability of wide uncongested bandwidth in the millimeter wave band (above 20 GHz), it could be a good transmission medium to meet the requirement of broadband services. So far, very limited work can be found in this area. As part of a series of efforts targeting the future broadband indoor wireless networks, this work investigates a broadband indoor wireless network using CDMA multiple access, and millimeter wave band.

There are a few factors influencing the selection and design of suitable multiple access techniques for these networks. These can be the traffic demand, number of users, channel bandwidth, cost, complexity, etc., and a set of performance measures such as call blocking probability, call dropping probability, co-channel interference and transmission quality. In order to achieve the desired service quality of the broadband SONET radio network for indoor use, it is important to investigate the system characteristics, to evaluate the access methods and traffic handling capabilities. These comprise the objectives of this thesis which in summary are:

- To develop a simulation tool based on known mm-wave propagation characteristics to analyze the traffic carrying performance of a microcellular radio architecture.
- To evaluate the performance of the system employing CDMA using this simulation tool.

1.2 Thesis Outline

The remainder part of this thesis is organized into five main chapters and a concluding chapter. Chapter two addresses the indoor wireless communications issues including background and brief history, radio channel characteristics, millimeter wave link, and wireless access to broadband networks.

Spread spectrum communications is described in chapter three. Chapter four begins by discussing multiple access techniques. Three commonly used multiple access schemes and associated advantages/disadvantages are described.

In chapter five, the design and architecture of our CDMA system is described in detail. This contains distributed system architecture, CDMA system model, mm-wave radio signal propagation, portable traffic model, and simulation method.

Results from a comprehensive study of the system are given in chapter six. Performance with different system configurations such as handoff, admission control, multi-traffic, power control, reception threshold, and sectorized antenna is presented, and analyses and discussions are also associated.

The last chapter presents some concluding remarks and suggestions for future work.

Chapter Two

Indoor Wireless Communications

This chapter addresses several issues of indoor wireless communications. Section 2.1 introduces the indoor environments, service requirements, and needs of wireless communication in indoor environments. Section 2.2 briefly reviews the history of indoor wireless system development and previous work. The general characteristics of indoor radio channels as a communication medium are discussed in section 2.3. The millimeter wave band as a new attractive communication link for indoor use to provide wireless access to broadband services is presented in section 2.4. Finally, we describe the wireless access to broadband networks in section 2.5.

2.1 Introduction

The indoor environment covers a wide range of structures characterized by proximity and communality of purpose[2]. Thus an indoor environment may be

- ✧ Office or apartment towers or smaller structures
- ✧ Campuses like hospitals, universities, and laboratories
- ✧ Building complexes
- ✧ Factories
- ✧ Residential houses
- ✧ Shopping centers

Indoor communications, viewed as systems, have three distinct yet interacting subsystems

- ◆ 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 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. To provide such highly integrated services, communication links are crucial. The question addressed here is the choice of a cost-effective multiple access approach to meet those requirements for ATM-based broadband wireless indoor communications.

Certainly wired or fibered networks such as FDDI and ATM-based LANs would do the job. They provide a sufficient bandwidth to support the traffic. But establishing the networks requires expensive wiring and reconfiguration. Beneath much of today's increasingly dense office electronic environment lies a tangled, confusing, virtually unmanageable maze of wiring. Various wires provide the advanced telecommunications links for indoor environments, but wire becomes a fundamental limitation. It costs mil-

lions of dollars to wire a new office building for communications. Just when everything is wired as requested, a new requirement often arises resulting in rewiring, then rewiring and still more rewiring. Beyond costs, performance itself is also a concern. Unshielded twisted pair wiring supports the 10 Mbps speeds adequate for today's LANs like Ethernet, but may not support the high speed reliable data highways envisioned for the coming years. Furthermore, wire restricts a user from moving around so that it can not support applications required such as flexibility. A less expensive, high-performance wireless alternative, functionally compatible with current systems, for indoor communications networks is badly needed.

The solution to the cabling problem that first comes to mind is to use radio frequencies for local communications, and in certain environments this is feasible. Wireless and personal communications services takes advantage of radio and network technologies to dramatically increase mobility and portability in telecommunications.

For mobile telephone systems, cellular radio is a method that has become an industry standard. Indoor environments can always be separated into microcells defined by floors and major walls in a building, each served by its own distinct wireless radio frequency. Such a wireless indoor communications system could be implemented as an extension of wired LANs.

The explosion in personal communications that has occurred in the last few years and the need to create high bandwidth wireless communication systems for the indoor environment has necessitated in-depth characterization of the indoor environment. The use of radio for indoor data and voice communications within office buildings, hospitals, factories, warehouses, convention centers, and apartment buildings is an attractive proposition. It would provide users with the convenience of freeing their phones and terminal from the cords tying them to specific locations within these buildings, thus allowing for portability and even mobility. It would also drastically reduce wiring in new buildings, and would provide the flexibility of changing or creating various communications services in existing buildings without the need for expensive, time-consuming rewiring. To effectively cope

with these requirements, an indoor communications system has to be reliable and flexible and have quality comparable to wired services.

2.2 Brief History

There is a growing interest in indoor wireless communications because of the attractive characteristics it offers. The advantages include easy establishment, reconfiguration or even redeployment of a complete radio system with minimum effort and cost. Undoubtedly one of the systems that can most benefit from a wireless connection is the Local Area Network, as a major component of the cost for a LAN is in providing a wired link to every terminal capable of transmitting at the high data rates required. Providing a wideband radio link to a number of terminals within an indoor environment is a non-trivial task.

The number of users for indoor use is rapidly growing in offices, manufacturing floors, shopping areas and warehouses. In the near future, one will expect to see several terminals clustered within a small indoor area. To avoid cable pulling to every foreseeable location, and to provide flexibility in the placement of terminals, the concept of wireless communication for indoor applications is appealing. There have been two independent approaches to implement this concept: one using infrared radiation, and the other using radio frequency. Optical and radio signals both employ electromagnetic waves. The depth of penetration of an electromagnetic signal is inversely proportional to the square root of its frequency, so optical signals can't pass through most of the objects around us, while radio signals can, at least to some extent.

There have been some projects investigating the use of infrared for local indoor communications, but most of the work has concentrated on the physical aspects of establishing a channel. In 1979, IBM Zurich developed a first wireless LAN using infrared radiation[3]. Much important work was performed, including establishing the concept of a 'satellite' system, in which areas each covered by a central satellite in a high location, which listens for messages from units on the floor on an uplink channel, and retransmits them on the

downlink. For areas that are larger than the range of a single satellite, overlapping satellite areas are used, and these satellites communicate with each other using a backbone cable-based network. In 1980, an infrared AM/FM system was developed for audio signals transmission[4]. As an extension, IBM Zurich developed a better infrared system using FSK modulation in 1981[5]. During the years 1983-1985, Fujitsu and Hitachi developed their own infrared networks in Japan[6]-[8]. In the mean time, HP labs developed an infrared network based on narrow beam line-of-sight transmissions[9]. At this point, all infrared systems employed carrier sense multiple access with collision detection (CSMA/CD). In those networks, a central satellite communicated with units on the floor. The units, which were simply terminals that needed to be easily movable, had their antennae pointing directly at the satellite. In 1986, Motorola built an infrared network with wide beam line-of-sight transmission and time division multiple access[10]. A similar system with narrow beam line-of-sight transmission was made in Bell labs[11]. The most recent infrared network was developed by Matsushita in 1988. It uses the narrow beam line-of-sight transmission for up link and wide beam for down link[12].

Recently, some research results on high data rate infrared indoor communication systems have been reported. A group in the University of California at Berkeley is experimenting wireless infrared LANs at a bit rate of 100 Mbps[13]. A parallel research project is carrying on at University of Ottawa supported by Canadian Institute of Telecommunication Research (CITR) with mandate to study the potential of using infrared for transmission of ATM signals in broadband indoor wireless communications[14].

In an indoor application, infrared does not interfere with existing radio frequency systems and there is no FCC regulation for this particular band of electromagnetic spectrum. The FCC is only concerned with radio frequencies below 300 GHz. Infrared radiation is not essentially restricted to a room in which it is generated; it can not be detected outside a room and will not interfere with similar systems in neighboring offices. However, infrared is not suitable for very large offices or rooms with double blind corners. The data rate and the number of users in infrared systems is also restricted as compared to radio frequency systems.

Generally, the infrared systems use a part of the electromagnetic spectrum just below visible light as a transmission medium. Thus infrared is immune to radio interference. In addition, infrared components are small, inexpensive, and consume less power. Infrared frequencies are too high to be modulated for data transmission as radio frequencies are. Infrared, being light, also travels in line of sight path. It is absorbed by dark objects, scattered by light objects and directionally reflected by mirrors and shiny metals. The infrared indoor channels are very sensitive to the room size, physical shape of the room, location of the objects in the room, sunlight and fluorescent lights, and so on. Those factors stand as serious obstacles to infrared systems for applications other than slow-speed systems in open working environments[15].

For indoor communications using radio frequency, the vicinity of UHF, from 300 MHz-3 GHz, is suitable. Several radio propagation studies at 900 MHz within an office setting were made in 1982. The experimental results show a maximum received power fluctuation of around 25-30 dB. In other words, radio frequency propagation around 900 MHz suffers from frequency selective fading in indoor environment.

One of the conventional techniques to counteract the consequences of frequency selective fading is to increase the transmission bandwidth using spread spectrum techniques. Spread spectrum can reduce the interference of RF signal with any existing system and the detectability of the signals outside the office building. The experimental implementation of a direct sequence spread spectrum wireless terminal is reported by HP labs[16][17].

UHF spread spectrum indoor wireless communications systems suffer from critical bandwidth and spectrum reuse shortcomings that seem likely to prevent them from expanding beyond niche applications. Another serious problem for UHF is that RF energy at these frequencies tends to propagate through and around obstacles, reaching beyond the confines of the network it serves. It may be good for other applications, but it can't be contained within the confines of a microcell and therefore limits spectrum reuse, a requirement absolutely essential in a viable indoor wireless system.

Starting in the 1980's, first generation cordless telephones were developed for residential voice services. The speech transmission of those systems is analog frequency modulation, and there is little coordination between fixed network elements and wireless telephones. The most serious drawback of those systems is the operating range which is limited to tens of meters from a single base station. Another big problem is vulnerability to interference from other cordless phones. Most first generation cordless phones have access to only one channel and the user can do nothing to avoid interference from someone nearby using the same channel. Of the cordless telephones that have access to several channels, almost all rely on manual channel selection, by the user, to avoid interference. The frequency band assigned to those systems varies with different countries. It is 46 - 49 MHz in United States, 250 - 380 MHz in Japan, and around 50 MHz in Europe[18].

To overcome the limitations of first generation technology and satisfy the exploding demand for wireless access to communication networks, second generation cordless phones are coming into service in recent years. A few cordless telephone standards such as CT2, CT2+, and DECT have been developed. All these systems employ digital speech transmission and have dedicated channels for the exchange of control information between terminal and base station during a call. A cordless phone will be able to communicate with many base stations and it will automatically select the best available radio channel. They are designed to be interconnected to ISDN facilities to provide corresponding services. CT2 operates at frequency band 864 - 868 MHz, CT2+ has allocated frequency at 950 MHz, while DECT occupies a frequency band at 1.88 - 1.90 MHz[19].

At the beginning of 1990's, the research and development performed by Motorola's Wireless In-building Network technology group addressed the user requirements and technical challenges of the indoor environment. One of the major conclusions is 18 GHz radio is an appropriate choice for indoor communications[15].

Now the hardware and software technology that could make high speed wireless communications within an office, factory, or other in-building environment truly practical, cost-effective, and achievable has been developed.

The properties of 18 GHz band make it a good choice for networked cellular communications within buildings. This frequency band offers the bandwidth to handle the higher data speeds expected of future systems, as well as propagation characteristics suited to low-power in-building cellular networks. A novel intelligent six-sector antenna has solved the problem of providing clear, reliable signal capture, while the complex functions of microwave signal transmission, data switching, and radio frequency signal processing have all been implemented in VLSI circuits. On these technology bases, the ALTAIR system was developed by Motorola in 1991[20]. This system supports bit rates of 15 Mbps in a bandwidth of 10 MHz. A combination of 60 degrees antenna sectorization in the horizontal plane and selection diversity is used to combat the multipath effects. The selection of antenna beams in the transmitter and receiver is done by a central processor which monitors the signal quality in all 36 possible combinations (six beams at the transmitter and six at the receiver). The width of each beam in the vertical plane is also 60 degrees and therefore it does not provide complete coverage in elevation. Since the ALTAIR system is not designed to be portable, the base station units and the user units are mounted at fixed angles which take into account the limited coverage in elevation.

Starting in 1988, some research interest appeared in mm-wave channels. In particular the mm-wave band around 60 GHz was the subject of much investigation because of the specific attenuation due to atmospheric oxygen of about 15 dB/km, which might be advantageous with respect to frequency reuse in outdoor environments[21]-[23].

Extensive research activities are being conducted in Canadian Universities under the funding of CITR. The objective is to investigate various aspects of the mm-wave band, and to finally develop an ATM based wireless LAN. Under this structure, the previous work was largely concerned with single-frequency measurements[24]-[29]. Static wideband measurements have also begun. Studies have been done to estimate bit rate and performance requirements of broadband wireless links to LANs that may accommodate a wide range of multimedia traffic. These indicate that users may require peak bit rates on the order of 20 to 30 Mbps for high resolution compressed video, although the instantaneous bit rate required is variable[30]. The choice of multiple access strategy and microcellular architec-

ture is heavily influenced by technology considerations. A simulation study was completed to investigate indoor wireless communications in the 20 - 60 GHz band using TDMA multiple access[31]. On the other hand, an adaptive phased-array antenna, situated either at base stations or portable units, or both, is a recognized effective approach to combat multipath and interference problems in a dynamic way and to increase reliability in a broadband wireless indoor system[32][33]. Significant research results have been achieved for such an antenna technique by using a discrete element realization working at 21.6 GHz of an 8 elements linear phased array antenna[34][35]. To meet the requirements of communicating reliably through the indoor wireless multipath/fading channels with carrier frequencies of several tens of GHz with large bandwidths and with high data rates, suitable modulation schemes are likely to be spread spectrum, multicarrier system[36] and commutation signalling[37]. Investigations for this subject including coding schemes are also undergoing.

There are some reported results on the studies of mm-wave system protocols for bit rates of 100 Mbps or more in European universities[38]-[41].

2.3 Radio Channel Characteristics

In an indoor wireless communication system, the physical layer, as defined in the Open Systems Interconnection (OSI) seven layer model, is the indoor environment itself, as it appears to the radio signals that illuminate it, together with the radio transceiver that couples the information carrying signals into and out of this medium. This physical layer can also be referred to as the radio channel. Compared to wired media, the radio channel exhibits quite different characteristics.

The first distinction is that the connectivity provided by the radio channel is intermittent, whereas wired media normally provides a continuous physical connection. At the radio frequency, signal blockage due to moving people and equipment is the main source of

intermittent behavior in a typical office or factory environment. This problem can be dealt with by error checking and retransmission protocols.

The most distinctive, and troublesome, characteristic of radio signals is that they may travel from source to destination via many different paths. This means that a radio receiver actually sees the sum of many different forms of the transmitted signal. In the indoor environment, there are two types of multipath phenomena, each of which produces a different form of signal impairment. The first type of multipath is referred to as local scattering. In this scenario, signals to and from the base are scattered off objects, such as partition walls and office furniture. The main signal impairment produced by this local scattering is fading. A much more destructive form of multipath is produced by the reflective wall environment. The principal reflectors include the perimeter walls surrounding the entire work area, as well as the local scatterers referred to above. Since the overall dimensions of this work area are often comparable to the data wavelength, there will be a very significant difference in the arrival times of the direct and scattered signals. This delay spread multipath gives rise to a type of signal distortion that is referred to as Intersymbol Interference (ISI), since it is caused by the overlap of signals originally produced by adjacent data bits. For example, if the reciprocal of the bit rate R of a digital communication system operating through a multipath channel is less than the delay spread Δ between the first and last paths, i.e., when $R \Delta > 1$, severe intersymbol interference can occur. This is because the channel's response to previous symbols may be "ringing" during the current symbol's reception, the latter part of which in turn is masked by the response to successor symbols. This delay spread multipath also produces fading, but in a more complex form than is observed in the case of local scattering multipath. This fading arises from an interaction between the echo structure produced by the radio transceiver to limit the bandwidth of data signals.

In indoor environments, portables are moving slowly, and there is often a large number of reflective and obstructive materials in the vicinity. Therefore, bit errors due to random FM noise are negligible in indoor environments. Instead, multipath becomes the major cause of errors in indoor environments, since multiple reflections from walls, floors, and ceilings generate persistent radio wave echoes which cause inter-symbol interference, thus increas-

ing the bit error rate. Consequently, high bit rate digital indoor communication systems will experience frequent bit errors due to multipath when the symbol duration is of the same order as the delay spread of the propagation channel, unless anti-multipath techniques are employed. Conversely, if the delay spread is sufficiently small, we can ensure the data quality without any anti-multipath techniques.

There have been many schemes developed to deal with multipath problems in a wide variety of radio propagation environments. Adaptive equalization techniques have become widely used to counteract the ISI produced by a form of delay spread multipath. The equalizer counteracts multipath distortion in the time domain by introducing its own echoes, whose amplitudes and phases are automatically adjusted to cancel the ISI components produced by the radio channel. If the bandwidth of the receiving signal exceeds the coherence bandwidth of the channel, a receiver equipped with an equalizer can exploit the inherent diversity caused by delay spread multipath.

Spread spectrum is another effective scheme to deal with multipath problems. In this technique, each data bit is broken up into a series of smaller fragments known as chips. The same chip pattern is used to represent each bit at both the transmitter and receiver, and this pattern is chosen to be as random as possible for a fixed length binary sequence. This allows the receiver to reverse the effects of the chip level fragmentation in the transmitter by correlating the received signal with this common chip pattern. The key parameter in this type of system is the number of chips per bit, which is referred to as the processing gain. The expanded bandwidth creates a third wavelength scale, namely the chip wavelength. This reduction in critical wavelength is what makes it possible for a spread spectrum system to isolate and resolve echoes before they combine to produce fading and ISI. The spread spectrum techniques would be most effective against the mixture of local scattering and moderate delay spread multipath found in the typical indoor environments. The major drawback is the wide bandwidth occupied by such a signal and therefore reduction of the spectrum efficiency.

Antenna diversity techniques have long been established as the best method for overcoming the amplitude fading produced by local scattering multipath, and can also be used to

avoid, or at least minimize, the ISI problems produced by delay spread multipath. This ISI reduction effect can be enhanced by using directional antennas at each end of the link. In many respects, antenna diversity is the ideal technique for dealing with the multipath problem. First, there is no bandwidth penalty, and second, there is no need for the expensive and power hungry signal processors needed to do equalization.

2.4 Millimeter (mm) Wave Link

The millimeter link refers to the frequency band whose wavelength is in the order of millimeters e.g. 20 - 60 GHz. Such a link looks to be a favorable choice for indoor communication. First of all, the millimeter wave band possesses some important characteristics[42]: propagation is mostly by line-of-sight; highly attenuated by atmosphere. In addition, it fits most of the crucial requirements of indoor communications such as

- ★ Sufficient bandwidth for the high data rates required in today's wired local area networks
- ★ Current sparse usage
- ★ Small radio frequency device dimensions
- ★ Short range propagation and high attenuation by exterior walls resulting in confinement of the signals.

Compared to conventional UHF bands, the advantage of mm-wave channel is the availability of a high information transport capacity. In addition, this frequency reuse is possible over very short distances, for example in adjacent rooms of an office floor. Because of this features and recent advances in GaAs technology, the mm-wave frequency band should be identified as a possible bearer for broadband data and video services as offered by fibre optics networks. The broadband nature is especially relevant because of the advent of Broadband Integrated Services Digital Network (BISDN). If an indoor radio

network is to be incorporated in BISDN, it should support data rates up to 155 Mbps. The necessary spectral space for this is, however, only available at frequencies above approximately 25 GHz. In particular, the mm-wave band around 60 GHz is the subject of much investigation[43] because of specific attenuation due to atmospheric oxygen of about 15 dB/km, which might be advantageous with respect to frequency reuse in outdoor environments.

The mm-wave band has advantages for micro-cell applications with respect to lower frequencies: bandwidth is large, small wave length facilitates miniaturization of components and antennas, penetration loss through building materials and low diffraction permits well defined demarcation of cells. Micro-cells have lower delay spreads than conventional cells since long path delays are less probable. Nevertheless, multi-path propagation and shadow fading in the mobile radio environment present a problem for transmission of data exceeding 1 Mbps[44]. However, the required bandwidth for inter-computer communications and high quality personal video applications is potentially much greater. (Reported experimental results show that delay spread in typical propagation environments is relatively insensitive to frequency.) The primary disadvantage of micro-cell architecture is the expense of all the base stations. This is compounded, as they must incorporate mm-wave components.

Fiber is wideband, low-weight, and low-cost. It brings an increase in data networking capability, ability to employ simple, compact, base stations and eases implementation of channel allocation and power control. The last two advantages arise since mm-wave and switching hardware may be centralized so micro base stations require only an optical/electrical transducer and perhaps a mm-wave amplifier. Additionally, excess absorption due to atmospheric oxygen, water vapor and rain may suppress long range interference between cells.

However, other important parameters regarding to propagation conditions are those which impact the ability of the channel to support high data rate and low power terminals; namely: the delay spread and the signal attenuation within a confined space.

There is little known information about the delay spread in indoor channels at mm-wave band, but a recent paper reporting the following results at 58 GHz[45].

Room Size (m)	Delay Spread (nsec)	
24.3 x 11.2	44	Wood walls
30 x 21	32	Acoustic soft material
43 x 41	58	Hall, concrete walls
33.5 x 32.2	55	Vax room, concrete walls
44.7 x 2.4	72	Corridor, concrete
9.9 x 8.7	40	Computer room, metal
12.9 x 8.0	18	Lecture room, wood walls
11.3 x 7.3	28	Laboratory, plastered concrete

The table above contains the approximate values of delay spread at the 50% point of the cumulative distribution function. As expected, the delay spread depends on the size of the room, type of walls and the contents of the room. In general, the delay spread is large for large rooms with concrete or metal walls, and is small for small rooms with soft material walls. Also, the presence of metallic objects in the room tends to increase the delay spread.

Excessive delay spread causes severe inter-symbol interference problem, and would require complicated anti-multipath signalling[37], adaptive equalization and /or anti-multipath phased array antennas. Implementing those techniques would increase system complexity. In addition, there are a number of disadvantages, high component cost, low generation efficiency, rapid fading in multi-path environment.

2.5 Wireless Access to Broad Band Network

In the past few years, BISDN has received increasing attention as a communication architecture capable of supporting multimedia applications. The key to a successful BISDN system is the ability to support a wide variety of traffic and diverse service and performance requirements. BISDN is required to support traffic requiring bandwidth ranging from a few kilobits per second to several hundred megabits per second. Some traffic such as interactive data and video, is highly bursty; while some traffic, such as large files, is continuous. BISDN is also required to meet diverse service and performance requirements of multimedia traffic. Real time voice requires rapid transfer through the network, but the loss of small amounts of voice information is tolerable. In many data applications, real time delivery is not of primary importance, but high throughput and strict error control are required. Some services, such as real time video communications, require error-free transmission as well as rapid transfer. BISDN should also be able to facilitate expected future services in a practical and easily expanded fashion.

Among the techniques proposed to implement BISDN, Asynchronous Transfer Mode (ATM) is considered to be the most promising transfer technique because of its efficiency and flexibility. In ATM, information flow is organized into fixed-size blocks called cells, each consisting of a header and an information field. Cells are transmitted over a virtual circuit, and routing is performed based on the Virtual Circuit Identifier contained in the cell header. The cell transmission time is equal to a slot length, and slots are allocated to a call on demand. ATM is a connection-oriented technique. It minimizes delay variation since cells belonging to the same call follow the same route. It also minimizes the processing required to make routing decisions.

As the demand for broadband communications services grows rapidly, the wireless access to broadband networks appears as a new research area which attracts attention. A recent forecast for the US market estimates the growth of integrated wireless office systems from zero in 1992 to over \$1-3 billion in 1997[46]. Broadband wireless access will afford potentially enormous bandwidth on demand to people on the move, using small portable

multimedia terminals. It will also be a solution to the problem of high rewiring/reconfiguring cost associated with high "churn" rates in modern offices.

To unite broadband communications with wireless personal communications, and make possible untethered access to wide range of broadband communications services, such as multimedia document communications, high resolution image or large file transfer, high resolution video conferencing, etc., the research and development on a broadband indoor wireless digital communications system capable of supporting ATM for broadband LANs has intensified a frontier and it will affect how we live and interact in the foreseeable future.

It is expected that wireless access to broadband networks will have its initial strongest appeal in office type environments, but that as costs diminish, it will also be heavily used in factories, hospitals, schools and residential environments. Several factors influence the design of wireless broadband networks such as the traffic demand, number of portable users, channel bandwidth, portable traffic fluctuations, cost, complexity, etc., and a set of performance measures such as co-channel interference, blocking and transmission quality. It is generally acceptable that future networks should provide a nearly open access to heterogeneous traffic produced by a diverse range of applications, but the exact characteristics and model of such traffic sources are still speculative. The density of portables in the service area and traffic variations are important parameters which determine the blocking and specify the capacity of the wireless system.

Chapter Three

Spread Spectrum Communications

The use of spread spectrum techniques for military communications has become quite commonplace over the past decade, and it was the potential use of spread spectrum in hostile environments that motivated most of the basic research in the subject for the past forty years. In recent years, there has been an even greater interest in understanding both the capabilities and the limitations of spread spectrum techniques for commercial applications. Entirely new opportunities such as wireless LANs, personal communication networks, and digital cellular radios have created the need for research on how spread spectrum systems can be reoptimized for most efficient use in these nonhostile environments. This chapter explains briefly the principles of spread spectrum communications, including different ways of spreading and the design of pseudorandom sequences.

3.1 Principles of Spread Spectrum Communications

A definition of spread spectrum that adequately reflects the characteristics of this technique is: Spread spectrum is a means of transmission in which the signal occupies a bandwidth in excess of the minimum necessary to send the information; the band spread is accomplished by means of a code which is independent of the data, and a synchronized reception with the code at the receiver is used for despreading and subsequent data recovery. There are many reasons for spreading the spectrum, and if done properly, a multiplicity of benefits can accrue simultaneously.

Since the desired signal can be recovered by correlating the signal at the receiver with the known code, the desired signal is protected against an interferer in the sense that it has an effective power advantage relative to the interferer. This power advantage is often propor-

tional to the ratio of the dimensionality of the space of code sequences to that of the data signal. This ratio is called processing gain which is equal to the ratio of the dimensionality of the possible signal space to the dimensions needed to actually transmit the signals. using the result that the dimensionality of a signal of duration T and of approximate bandwidth B_D is $2B_D T$, we see the processing gain can be written as

$$G_p = \frac{n}{D} \approx \frac{2B_{ss}T}{2B_D T} = \frac{B_{ss}}{B_D} \quad (3.1)$$

where B_{ss} is the bandwidth in Hertz of the spread spectrum signals and B_D is the minimum bandwidth that would be required to send the information if we did not need to imbed it in the larger bandwidth for protection.

A simple illustration of these ideas using random binary sequences will be used to bring out some of these points. Consider the transmission of a signal bit

$$\pm \sqrt{\frac{E_b}{T}} \quad (3.2)$$

with energy E_b of duration T seconds. This signal is one dimensional. As shown in Figures. 3.1 and 3.2, the transmitter multiplies the data bit $d(t)$ by a binary ± 1 chipping sequence $p(t)$ chosen randomly at rate f_c chip/s for a total of $f_c T$ chip/bit. The dimensionality of the signal $d(t)p(t)$ is then $n = f_c T$. The received signal is

$$r(t) = d(t)p(t) + l(t), 0 \leq t \leq T \quad (3.3)$$

ignoring, for the time being, thermal noise. The receiver performs the correlation

$$U \equiv \sqrt{\frac{E_b}{T}} \times \int_0^T r(t) p(t) dt \quad (3.4)$$

Fig. 3.1 Direct sequence spread spectrum system for transmitting a single binary digit.

Fig. 3.2 Data bit and chipping sequence.

and makes a decision as to whether $\pm\sqrt{E_b + T}$ was sent depending upon U being larger or smaller than 0. The integrand can be expanded as

$$r(t)p(t) = d(t)p^2(t) + I(t)p(t) = d(t) + I(t)p(t) \quad (3.5)$$

and hence the data bit appears in the presence of a code-modulated interferer.

If interference signal $I(t)$ is additive white Gaussian noise with power spectral density $N_{0I}/2$ (two-sided), so is $I(t)p(t)$, and U is then a Gaussian random variable. Since $d(t) = \pm\sqrt{E_b + T}$, the conditional mean and variance of U , assuming that $\pm\sqrt{E_b + T}$ is transmitted, is given by E_b and $E_b(N_{0I}/2)$, respectively, and the probability of error is

$$Q(\sqrt{2E_b + N_{0I}}) \quad (3.6)$$

This means that against white noise of unlimited power, spread spectrum serves no useful purpose. On the other hand, if the interferer power is limited the situation is different. Then, not having access to the random sequence, the interferer with available energy E_I can do better than to apply this energy to one dimension. For instance, if

$$I(t) = \sqrt{E_I + T}, 0 \leq t \leq T \quad (3.7)$$

then the received output is

$$U = E_b + \sqrt{E_b \cdot E_I} \cdot \frac{1}{n} \sum_{i=1}^n X_i \quad (3.8)$$

where the X_i 's are independent identically distributed random variables with $P(X_i=+1) = P(X_i=-1) = 1/2$, and n is the processing gain. An approximation of the bit error rate may be obtained by utilizing a central limit type of argument that says, for large n , U may be treated as if it were Gaussian. Then

$$P_e = P(U < 0) \cong Q\left(\sqrt{\frac{E_b}{E_I}} \cdot n\right) \quad (3.9)$$

The processing gain can be seen to be a multiplier of the signal-to-interference ratio. As it increases, the bit error rate reduces dramatically. A fundamental issue in spread spectrum is how this technique affords protection against interfering signals with finite power. The underlying principle is that of distributing a relatively low dimensional data signal in a high dimensional environment so that an interferer with a fixed amount of total power is obliged to either spread that fixed power over all the coordinates, thereby enduring just a

little interference in each coordinate, or else place all of the power into a small subspace, leaving the remainder of space interference free.

It is necessary to hide the pattern by which the data is spread. This is usually done with a pseudonoise (PN) sequence which has the desired randomness properties and which is available to the cooperating transmitter and receiver, but denied to other undesirable users of the common spectrum.

There are two primary spread spectrum techniques, direct sequence spread spectrum, an amplitude modulation technique, and frequency hopping spread spectrum, a frequency modulation technique. The goal of both of these techniques is to take the power to be transmitted and spread it over a very wide bandwidth so that the power per unit bandwidth is minimized. When this is accomplished, the transmitted spread spectrum power received by an existing user, having a relatively narrow bandwidth, is only a small fraction of the actual transmitted power.

The feature of spread spectrum that results in interference reduction is that the spread spectrum receiver actually spreads the received energy of any interferer over the same wide bandwidth while compressing the bandwidth of the desired received signal to its original bandwidth.

Note that for any spread spectrum system to operate properly, it is necessary for the receiver to acquire the correct phase position of the incoming waveform, and it must continually track that phase position so that loss of lock will not occur. The two processes of acquisition and tracking form the synchronization subsystem of a spread spectrum receiver. The former operation is typically accomplished by a search of as many phase positions as necessary until one is found which results in a large correlation between the phase of the incoming signal and the phase of locally generated spreading sequence at the receiver. The latter operation is often performed with a delay-locked loop. The importance of the combined synchronization process cannot be overstated; for if synchronization is not both achieved and maintained, the desired signal can not be despread.

The original application of spread spectrum techniques to anti-jam uses continues to be important and widely used in the military. In fact its use appears to be growing in the military and furthermore, its covert features are additionally being used. The biggest growth area is in civilian applications[47]. In particular, indoor radio[48], cellular radio[49], and, the more general personal communication systems, are being actively considered as good applications of spread spectrum techniques. Numerous systems are already commercially available and others are undergoing field trials. In the following, we describe the two primary methods of spreading.

3.2 Frequency Hopping Spread Spectrum

FH spread spectrum utilizes the large spectrum provided for spread spectrum systems by periodically changing the carrier frequency of the transmitted signal. The changing is called hopping. If the entire allocated bandwidth is, say, 1000 times wider than the bandwidth of the transmitted signal, then during a given time interval the signal can be transmitted at any one of 1000 possible frequencies. The result is reduced interference to any existing user. For example, if an existing narrow band user occupies one of the 1000 frequency slots, then interference with the existing user occurs only 1/1000 of the total time (assuming uniform distribution of interference). During the remaining time, the transmission has hopped to different frequencies and does not cause interference.

3.3 Direct Sequence Spread Spectrum

DS spread spectrum achieves a spreading of the spectrum by modulating the original signal with a very wide band signal relative to the data bandwidth. This wideband signal is chosen to have amplitudes, +1 and -1, and these amplitudes are switched, in a pseudorandom manner, periodically. Both bits and chips are represented as rectangular functions in

both time and frequency, whereas they are quite rounded in frequency but fairly rectangular in time.

At the receiver, the received signal plus interference plus system noise goes through a despreading process. The despreading involves multiplying the received signal plus interference and noise by the despreading function. If the despreading is done correctly, the original spread signal compresses back to a power spectrum equal to that of the original spread signal. This despread signal goes to the standard demodulator type for that particular form of modulation. Such a process that despreads the received signal causes the spectrum of the interference and noise to be spread. Thus, at each equally spaced time interval, a decision is made as to whether the wideband modulating signal should be +1 or -1. A pseudorandom sequence is generated electronically, which is known a priori to the transmitter and receiver to perform modulation and demodulation.

3.4 Pseudorandom Sequences

Both the FH and DS modes of spread spectrum use pseudorandom sequences to generate the spreading sequence. While there are many different possible sequences, the most commonly used are maximal-length linear-shift register sequences, often referred to as Pseudo Noise (PN) sequences. The characteristics of these sequences are indeed noise like, because the properly designed spreading sequences will have the following properties:

- ★ In a long sequence, about $1/2$ the chips will be +1 and $1/2$ will be -1
- ★ The length L of a run of r chips of the same sign will occur about $L/2^r$ times in a sequence of N chips
- ★ The autocorrelation of the sequence $PN(t)$ and $PN(t+t')$ will be very small except in the vicinity of $t'=0$
- ★ The cross correlation of any two sequences will be small

One form of the PN sequence generated by linear feedback shift registers is the maximal length sequence or m-sequence. The period of a linear feedback shift register depends on the generating polynomial and its degree. If the maximal length sequence is periodically repeated, the resulting autocorrelation function is also periodic. The length of the m-sequence is important for various applications. The direct sequence spreading process results in the symbol consisting of N chips of duration T_c each and it is assumed that N is an integer. Thus $T_s = NT_c$, where T_s is a symbol period. The period of the m-sequence is

$$T_m = L_m \times T_c \quad (3.10)$$

Normally there are two cases of interest. One is if the m-sequence and symbol periods are equal. The other is if the m-sequence period is much larger than that of the symbol. Intermediate cases are of not practical interest because of their complexity.

In this work, we use spread spectrum for multiple access which is considered in more detail in the next chapter. Due to the system design concern, our primary interest is in long codes. For instance, with a 1.55 Gchip/s spreading of a 155 Mbps binary modulation, we can use an m-sequence with order $r = 50$ linear feedback shift register. The length of such a sequence turns to be $L_m = 2^r - 1 = 1.13 \times 10^{15}$. At 1.55 Gchip/s, the sequence period is $T_m = 202$ hours. On the other hand, synchronization can also relatively be easy to perform for long m-sequences. As long as two codes derived from different phase of the same m-sequence differ in timing by greater than a chip period, then the cross correlation between the two functions is of the form of the sidelobes of the m-sequence's autocorrelation. As it is known that the long m-sequences generated by a linear feedback shift register have a vulnerability to determination of the parameters of the linear feedback shift register. So they are not secure to use for some applications. But for the multiple access applications, this may be a good choice to simplify the system.

3.5 Further Remarks

The limitations of spread spectrum are due to technology and therefore can be overcome. The limitation in DS spread spectrum is the ability to spread the spectrum using a very high chip rate. Today, the maximum chip rate attainable using CMOS is 70 Mc/s. However, commercially available GaAs FET devices can operate at 2 Gc/s. The limitation to FH spread spectrum is the ability of a frequency synthesizer to change frequencies quickly without generating spurious signals. Today, numerically controlled oscillators can generate such a signal, but only at hop rates up to 1 Mc/s and over 20 MHz bandwidth.

Spread spectrum modulation has the ability to resolve delayed multi-path components and either eliminate or use them to provide diversity. Moreover, it supports CDMA and facilitates soft handover between cells and base station micro-diversity to suppress shadow fading. In CDMA, the channel quality that each user sees gradually degrades as the number of actively transmitting users increases

Spread spectrum is not only usable, it is useful. It will be possibly used as the basic means of communication for applications such as personal communications like the PCN, and wireless BISDN.

The use of spread spectrum is indeed spreading. Since the technology is readily put into VLSI chips and low power transmission can be employed, spread spectrum equipment is becoming low cost and small volume, two essential ingredients for commercial equipment.

Chapter Four

Multiple Access Techniques

4.1 Introduction

In a wireless local area network, communications between nodes are established through radio links. The radio spectrum is a scarce resource that is rationed out by international agreement. A particular frequency allocation is assigned to a particular class of user. The total resource is actually a two dimensional resource in time and frequency. The best utilization of the time-frequency resource has always been a challenge for telecommunication system development. To accommodate more users within a limited bandwidth resource, or to let more users share a common link, regulating the access to the shared link is an important task. Many multiple access schemes have been developed. Multiple access techniques are used to provide multiple simultaneous users with radio links of good transmission quality. Generally, the important requirements of multiple access are

- Base station must receive the transmitted signal from the user 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.

Basically, our resource is consisting of two dimensional space of time and frequency. The different way of utilizing such a space leads to different multiple access techniques. In the following, we present three primary multiple access methods, i.e., frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple

access (CDMA) in section 4.2, 4.3, and 4.4, respectively. In addition to those fixed assignments, random access techniques are also explained in section 4.5.

Figure 4.1 Frequency division multiple access in time, frequency space.

4.2 FDMA

An obvious way to support multiple users is through frequency division wherein a different center frequency is used for each user signal. In time and frequency space it operates as shown in Figure 4.1. Each frequency channel can be assigned to one point-to-point communications link. If multiple users are transmitting to a single receiver, such as arises on a satellite uplink, then this process is called frequency division multiple access. In FDMA, all users transmit simultaneously, but use disjoint frequency bands[50]. If a single transmitter sends multiple signals on multiple carriers, the process is called multi-tone.

Multi-tone can combat frequency selective fading but has the disadvantage of inflexibility and costly hardware.

Figure 4.2 Time division multiple access in time, frequency space.

4.3 TDMA

Time sharing is another traditional means of sharing the time-frequency resource as shown in Figure 4.2. In TDMA, transmission 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 signaling, channel control, synchronization, encryption and guard 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[50]. 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 centralized control of messages which makes asynchronous TDMA less efficient.

TDMA has the comparative advantage of ease of implementation, and inexpensive hardware. As the required data are time sequenced, it also is compatible with 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.

4.4 CDMA

The third way of utilizing the time-frequency plane for multiple signals is through spread spectrum techniques. It is displayed in figure 4.3. In CDMA, each user is assigned a unique time-frequency waveform or code that is used for transmission or reception[50][51]. A large number of CDMA signals share the same frequency spectrum. The data signal is multiplied by the code and this implies a convolution of the two signals in the frequency domain. The signals are separated by using a "correlator" which accepts only signal energy from the selected binary sequence and despreads its spectrum. The other user's signals, whose codes do not match, are not despread in bandwidth and as a result, contribute only to the noise. If the 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 transmis-

sion bandwidth beyond what is required to transmit the data. The ratio of transmission bandwidth to the data rate is called processing gain. The means by which the spectrum is spread is crucial. There are several band spreading techniques for spread spectrum systems. However, for interference limited multiple access systems such as mobile radio and portable radio, Direct Sequence (DS) and Frequency Hopped systems are the two most suitable[52][53]. In the following, we discuss more about the DS and FH.

Figure 4.3 Code division multiple access in time, frequency space.

4.4.1 Direct Sequence CDMA (DS CDMA)

In this technique spreading is achieved by multiplying the data sequence by a pseudorandom sequence whose symbol rate is many times the data rate. Consider N users that are to be supported simultaneously by means of DS multiple access. Each transmitter is assigned a different spreading code, $C_j(t)$, $j = 1, 2, \dots, N$. At the j th receiver, such as illustrated in

Figure 4.4, the corresponding N signals $S_N(t)$ are received. At the receiver, these N signals interfere with each other. Figure 4.5 is an attempt to illustrate this condition with each of the users shown spread over the total band and piled up one upon the other. Also shown is a single non-spread but narrow band signal which can operate with adequate performance provided that N_0 plus the total interference signals are sufficiently small.

Figure 4.4. model of a DS multiple access receiver for the j th user signal.

The receiver shown in Figure 4.4 wants to obtain the j th signal and therefore uses the j th code, $C_j(t)$ for the despreading operation. The despreading process can be described as a correlation process. Therefore, it is desired that the cross correlation between $C_j(t)$ and $C_i(t)$ ($i \neq j$) is low and the autocorrelation between $C_j(t)$ and itself should be very large.

Direct sequence code division multiple access has been proposed for wireless networks including digital cellular. It has been recognized that power control is important for its performance. Suppose now the users all transmit the same power but are at different dis-

Figure 4.5. Conceptual representation of multiple DS spread users in a spread band.

tances, d_U , from the j th receiver. The received power relative to the power from the j th transmitter would then be

$$S_U = \left(\frac{d_j}{d_U} \right)^\alpha S_j$$

where α is a propagation constant which depends on the transmission conditions for the particular link. From Figure 4.5, it is seen that one user located closer to the receiver than the j th transmitter causes a considerable degradation in performance. Therefore a strong signal received from a near-end portable will mask the weak signal from a far-end portable. The number of users supported falls very quickly. This is the well known near-far problem associated with DS multiple access. Thus power control is the single most important system requirement for CDMA, since only by control of power of each user can resources be shared equally among users and capacity maximized.

CDMA systems tend to be self-interference limited. That is, in attempting to have many users communicate simultaneously, the mutual interference sets a limit on the number of simultaneously active users. To the extent that not every user in the network is always transmitting, the capacity of the system is increased. Note that this argument is also applied to FDMA and TDMA systems, but there is a fundamental difference. In these latter systems, some type of central control is needed to implement a demand assignment protocol; in CDMA, no such control is necessary. Alternatively, if such control is indeed used, one still achieves a performance advantage in CDMA because of this effect that is not achieved with either conventional FDMA and TDMA. This is because with CDMA, if a given user stops talking, and no new user wants to access the channel at that particular instant of time, then all the remaining users on the channel experience less interference.

A major disadvantage of DS spread spectrum system is the requirement of synchronization and tracking of the phase of the received signal. This task is very difficult in the presence of fast fading. Fortunately, this difficulty does not exist in an indoor communication environment which does not exhibit fast fading characteristics. On the other hand, the multipath propagation becomes the major channel impairment for this case, and this type of impairment can result in intersymbol interference (ISI)[50].

4.4.2 Frequency Hopping Multiple Access

In this scheme, each of the users is assigned a different hopping pattern so that they each have a different PN sequence. The hopping patterns are chosen to have a uniform distribution between the possible frequency channels. The receiver receives the desired hop signal for which it is dehoppping with the appropriate hop pattern. It also receives signals from the other users. The total hopping frequency channels are called chips. There are two basic hopping patterns; one called fast hopping which makes one or more hops for each symbol. The other is called slow hopping which makes one or more symbols for each hop. In general, the transmission rate is the symbol rate. The symbol rate is equal to the bit rate at a binary modulation and transmission.

Figure 4.6 Conceptual representation of multiple FH spread users in a spread band.

Due to the limitation of today's technology, the frequency hopping is usually slow. Occasionally, there will be a collision in which one or more of the other user hops falls within the frequency channel and within the hop period of the dehopper as shown in Figure 4.6. It is desired to reduce the probability of collision between users to a minimum. If all users have frame synchronization, then a set of hop patterns can be devised that result in no collision. If these condition pertain but there is no frame synchronization, the number of collisions can be kept small by judicious choice of the generating PN sequences. Frequency hopping does not suffer as much from the near-far problem.

4.5 Random Access

The two most important random access techniques are ALOHA and Carrier Sense Multiple Access (CSMA) which are described in the following.

4.5.1 ALOHA

The ALOHA was the first multiple access protocol built at the University of Hawaii in the early 1970s. The ALOHA protocol is used by users that transmit on a common channel and that listen to the same channel. There are two versions of the ALOHA: slotted and pure. In the pure ALOHA the user transmits whenever it has data to be sent and this can result in collision. Colliding packets are destroyed or erased and hence require re-transmission. This limits the throughput to 18%. In the modified version of slotted ALOHA, the time axis is divided into time slots with durations equal to the time required to transmit a packet on the channel. Users are allowed to transmit only at the beginning of a time slot, and therefore the throughput is doubled. The trade off is that the slotted ALOHA is more difficult to implement than the pure ALOHA. Generally, ALOHA is the simplest multiple access method providing good connectivity among users. However, it sacrifices throughput and delay. It is found to be more effective in the cells of smaller area.

4.5.2 CSMA

CSMA is used by Ethernet as a media access protocol which specifies that a user with data to transmit must proceed as follows:

- Wait until the channel is idle
- When the channel is idle, transmit and listen while transmitting.
- In the case of a collision, stop data transmission, transmit a jam signal, and then wait for a random delay and GO TO first step.

CSMA is more efficient than ALOHA, but it may suffer longer delay when it is applied to a network with a long propagation time.

4.6 Summary

Multiple access provides a way to the best utilization of bandwidth resources. Among the previously mentioned access techniques, each has its plus and minus depending upon the applications. In general fixed assignment presents a better proposition for application which are

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

Random access better fits applications where

- User demands have a statistical nature.
- Expendability, flexibility, suitability to time varying loads and simplicity of implementation are crucial.
- More bursty users with minimum delay and comparatively less bandwidth are needed to be handled.

On the other hand, certain combinations of these techniques are also made to support some systems. In this work, we combined spread spectrum with ALOHA to serve as a multiple access method for indoor broadband communications system. The performance of such an access scheme through our study will be reported later.

Chapter Five

CDMA System Architecture

This chapter describes the architecture of a broadband indoor wireless communications system using a mm-wave link and a CDMA access protocol. Section 5.1 presents a distributed system architecture and its major advantages for indoor applications against a centralized system architecture. The detailed design issues of the simulated indoor system are described in Section 5.2. The mm-wave radio signal propagation characteristics are presented in Section 5.3. Traffic model and simulation methodology are described in Section 5.4, and 5.5, respectively.

5.1 Distributed System Architecture

An indoor communication system via radio links is characterized as wireless local area network (WLAN). The architecture of WLAN requires characteristics which can be broadly stated as easy to install, use, maintain, high performance, and low cost. Compatibility is the key to the installation, use, and maintenance requirement. In order for a WLAN to be installed in an existing network, it must be compatible with the existing network in terms of physical and logical interfaces, functionality, and operation, especially with respect to bridges, routers, and gateways. The wireless interface must fit inside any existing computing product or connect to an existing product via a standard interface. The wireless interface should be transparent to existing network operating systems and application software. It must also conform to network management standards and be compatible with network management products. The high performance requirement is more than just a high bit rate and low delay. In particular, the wireless system must be able to compensate for intermittent signal fading caused by moving obstacles and interference due to multipath effects.

As an extension of a backbone fiber based local area network, a WLAN generally employs a medium access control protocol to enable multiple portables to share the same radio or optical wireless channel, and provides connectivity to mobile portables. To provide coverage in a large building using low-power radio transmissions, and to meet those above mentioned requirements, there are two architectural approaches in wireless LAN design.

The first one is a conventional centralized strategy in which the building area is divided into microcells, and they are connected through a backbone LAN, as illustrated in Figure 5.1.

Figure 5.1 Centralized Wireless LAN Architecture

Different radio channels are assigned to adjacent microcells to minimize interference. Each radio channel is re-used at microcells separated by several microcell diameters. In each microcell, all portables communicate over the same radio channel using a specific multiple access protocol, and access the backbone LAN via a single point on interconnec-

tion. This is a wireless in-building system architecture proposed by Motorola. A typical instance of such a wireless system based on Motorola's wireless in-building network is ALTAIR[54]. Portables do not directly communicate with one another in the microcell. Each base station typically located near the center of a microcell acts as a relay point between portables or between a base station and wired backbone. It also allocates bandwidth for transmission of packets, filters and routes all packets in the microcell, and provides an interface to the enterprise network.

The centralized architecture has an advantage that the internetworking between the WLAN and the backbone LAN is relatively straight forward. However, configuration and management of the centralized network with respect to changes in network coverage and mobility of terminals are complicated by the need for frequency coordination between microcells and handoff of portables moving across microcell boundaries.

The second one is a distributed strategy proposed by Leung[55] in which the same radio channel is used over the entire coverage area, with multiple base stations interconnecting portables to the backbone LAN. This architecture eliminates the need for frequency coordination, and greatly eases network configuration and management. For instance, adding portables in the existing network coverage area is straightforward, with no more involvement of network management functions than is necessary for fixed portables. In particular, portable mobility is easily accommodated without using complicated handoff mechanisms as required in cellular architectures. Moreover, a random access to the wireless channel with spread spectrum signaling can take advantage of its ability to overcome fading. However, the number of portables within a certain area may be limited by the available network throughput capacity per unit area. Since the throughput available in a given area is limited by the cluster of base stations providing overlapping coverage of that area, the throughput may be increased within certain limits by reducing the coverage of each base station in that area, and increasing the number of base stations. This is similar to the idea of cell splitting in cellular networks.

We investigate a distributed architecture using the mm-wave band as a radio link for the broadband system. Mm-wave radios may be expensive, therefore it is not economic at all

for a base station or a portable to use more than one frequency at a time. In our proposed architecture, only one frequency is used in the whole system.

Figure 5.2 Distributed Wireless LAN Architecture

Now we look at the system architecture in more detail. Figure 5.3 shows a block diagram of each system component and the functionality associated. A multimedia portable equipped with radio transceiver generates source information which can be voice, data, and video. Source coding block performs digital signal processing. This includes sampling and data compression. One notices that the minimum sampling rate will depend on channel statistics. Advanced data compression techniques can reduce the multimedia source rate down up to 16 kbps (compressed voice) and 20 Mbps (compressed HDTV). Therefore, we take a data rate of 20 Mbps as a maximum rate in this work. The next block organizes bits into standard ATM cell format, i.e., 53 octet with 48 octet data and 5 octet header. Modulation and spreading are performed sequentially in the next stage. Finally the signals are transmitted at an antenna through the mm-wave link. The fading character of

the indoor channel impairs the transmission quality. Spread spectrum signaling and channel coding can effectively combat fading, but the use of intelligent antennas with diversity is also necessary to improve transmission quality. At the base station, signals received by an antenna are despread and demodulated first. Then a powerful processor performs diversity operation. System controls such as media access, retransmission protocol, power control, admission control, etc., are carried out at base station as well. Finally the recovered ATM cells are forwarded by the base station to an ATM switching center, and are sent to destinations through SONET.

Fig. 5.3 System block diagram with associated functions.

The WLAN consists of multiple wireless portables transmitting over the same (uplink) radio channel (frequency) to the base stations, and receiving over a different (downlink) radio channel (frequency) from the base stations. Each portable is equipped with a wireless transceiver, and employs the wireless channel medium access control protocol to communicate with the base stations within its range. The channel signaling rate is 155.5 Mbps, i.e., OC-3 of ATM SONET. Therefore, portables first convert source information generated at different rates depending on applications into ATM frame format then transmit over the channel. Each base station incorporates a processing unit which buffers and forwards incoming frames according to the internetworking protocol, a wireless transceiver for communication with portables within its coverage area using the wireless channel medium access control protocol, and a LAN interface for communication with other base stations over the LAN using medium access control protocol for the LAN. As sufficient numbers of base stations have to be attached to the backbone LAN at fixed locations throughout the building to provide multiple site radio coverage of all possible locations of the portables. Multiple connections may exist between each portable and base station within its range, providing site diversity. The usable connections for each portable vary with time as changes occur in propagation conditions and the portable's location. The site diversity enhances the probability of successful reception for each frame.

5.2 CDMA System Model

The purpose of indoor wireless communications is to provide high quality voice, data and video services in an area with varying subscriber densities by efficient use of radio spectrum. This is done with a fixed grid of radio equipment, called base stations. The relative positioning and interconnection of the base stations based on a certain indoor environment, and their cooperation in the establishment and maintenance of radio links with small, low power subscriber radios, influence the service quality and system economy.

We consider an indoor wireless network model which consists of a number of base stations uniformly distributed in the service area of 50×50 square meters as shown in Figure

5.4. This floor design represents a typical indoor signal propagation environment such as a large conference room. The number of base stations is variable. Depending upon the traffic load, the arrangement can be made to provide adequate radio coverage over a single floor.

Fig 5.4 Open room building topology

The signalling bandwidth for uplink is about 2 GHz. The same bandwidth of different frequency is needed for downlink, i.e., frequency division duplex rather than time division duplex is used to avoid doubling the bandwidth and aggravating the delay spread problem. For mm-wave band, the bandwidth resource is abundant, but mm-wave radios are quite expensive. Using a CDMA access strategy could be more economical because fewer frequencies are used. Generally we can choose any fraction within 20-60 GHz band. In this work, we allocated channel bandwidth in the frequency range of 20 GHz to 30 GHz. This is a common channel shared by all base stations. To make the wireless link compatible with the backbone OC-3 ATM-SONET network, the same ATM cell format, i.e., 54 bytes per cell including overhead and redundant code bits (48 data + 5 ATM header + 1 wireless headers, adopted in the wireless link. The wireless header contains signalling bits which

takes care of the realization of call setup, admission control, power control, and multimedia traffic handling. The wideband system can support multimedia traffic, i.e., base stations operating at an OC-3 rate of 155 Mbps receive transmissions from various portables and forward them to a wired backbone LAN. The implicit assumption here is that the wireless transceivers are assumed capable of transporting this net rate, plus the overhead for error control coding and link management. Portables can be mobile voice phone sets, data servers, and video desktops. They generate various types of traffic that is packetized into a common ATM cell format.

Studies indicate that [56] the movement of people in a room may affect the multipath signal structure, and that 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 base station antenna is assumed to be mounted at a height of approximately 10 feet above the floor.

Perfect synchronization is assumed, implying that the intended receiving base station always has knowledge of the code of the transmitting portable. Since high rate video transmission has the most significant impact on system performance, we focused our major efforts on the video traffic (assumed data rate 20 Mbps) in this work. The transmitted bit rate is 155 Mbps and thus the corresponding duty cycle is 7.75, i.e., each terminal is only transmitting about 1/8 of the time. Thus cochannel interference is partly alleviated by this duty cycle and partly by the spread spectrum processing gain.

Service requests are generated uniformly in the whole service area. We used spread spectrum signalling and random ALOHA as a wireless channel medium access control protocol. Both uplink and downlink radio channels are configured as multipoint/broadcast channels shared by all portables and base stations, which access the respective channels under regulation of the wireless channel medium access control protocol. A portable can generate a call or receive a call from a base station; however, CDMA capacity is limited by the uplink capacity[57], hence, only the uplink is considered in this work.

Due to technology limitations, we assume the achievable chip rate of spread spectrum is 1.55 Gchip/s. In other words, we have a processing gain of only about 10. To simplify the

signal processing of base stations, an assumption is also made that a single long code is assigned to every user which uses its own portion of the long code. Direct sequence spread spectrum signaling using a single pseudo-noise (PN) spreading code is employed over the channel to take advantage of its multipath rejection and signal capturing properties. By using spread spectrum signaling, multipath and multiaccess interference signals are attenuated by the processing gain when they are out of phase by more than one chip with the signal to which the receiver is in synchronization. Such a low processing gain may not provide enough protection against interference. But using asynchronous random access with spread spectrum signalling is based on the assumption that the network traffic load is not so high that the probability of two users starting transmission within a chip period is negligibly small.

In our indoor environment, the signal suffers from fading, shadowing loss, and also intersymbol interference (ISI) caused by multipath. Besides using spread spectrum and micro-diversity techniques, we assume that those effects could be further overcome by advanced antenna technology[15] and powerful channel coding[58]. We consider the co-channel interference to be the major source of communication impairment. At a base station, the detection signal to interference ratio of -12 dB (equivalent to $E_b/N_0 = 7$ dB, given the duty cycle of 7.75) is taken as a reception threshold which corresponds to a bit error rate of 10^{-3} [57]. Although this criterion was proposed by Qualcomm to qualify the voice communication, we assume that this threshold is also suitable for high data rate traffic when powerful long constraint-length channel coding and interleaving are exploited. The weakness of the low processing gain can be compensated to some extent by taking advantage of micro-diversity. The objective of multiple access is to provide multiple simultaneous users with radio links of good quality by maximizing signal power, minimizing noise and interference. In our system, we used a relatively high base station density in order to have sufficient network throughput to handle high user density. As a result any portable can access the four closest base stations, and the base station having the best signal strength can forward the signal to the backbone LAN. The service requests arrive according to a Poisson pattern.

5.3 MM-Wave Radio Signal Propagation

Radio signal propagation in the 20-60 GHz band depends mainly on: attenuation by walls, space dividers, doors, windows, furniture, people, etc.; Multipath effects due to scattering from walls, ceilings, floors, furniture, people etc. [59][60].

In this study, the worst open building case was considered, the mm-wave propagation inside building is ray-like and the attenuation behaves as $R^{-\gamma}$ where R is the distance from the portable to the base station and γ the path exponent that varies with frequency. In the frequency range of our interest, i.e., 20-30 GHz band, the γ is chosen to be in the range of 1.9-2.1[27]. Other effects are ignored in this study. The base station antenna is assumed to be mounted at a height of approximately 10 feet above the floor.

At a base station j , the received local mean signal power from the desired portable i is

$$S_{ji} = S_{TX} + G_{RX} + G_{TX} - L(R_{ji}) \text{ dBm} \quad (5.11)$$

where $i \leq m$ (the number of active portables in the system), and $j \leq N$ (the number of base stations). R_{ji} (meter) is the distance between the i th portable and the j th basestation. S_{TX} is the portable transmitter power (0 dBm). G_{RX} and G_{TX} are the antenna gains for a portable and a base station, respectively. We assume that all portables transmit at the same power level, and their antennas have the same omni-directional patterns in azimuth and the same gain. Two types of base station antennas are studied:

- omni-directional antenna with zero gain;
- sectorized antenna with ideal angular antenna gain.

The path loss is given by

$$L(R_{ji}) = \left(10\gamma \log(R_{ji}) + (-10) \log \frac{P_r(1m)}{P_t} \right) \text{ dB} \quad (5.12)$$

where $P_r(1m)/P_t$ is the normalized received power at a separation distance of one meter. According to wide-band measurements of indoor radio channel, the worst value of this term is approximately -80 dB[43]. In our case, we take it as -62 dB[31].

In our spread spectrum system, the total radio frequency spectrum is shared by all portables. Hence, a desired transmission is interfered with by all active portables in the system. This is so called multiuser interference. The local mean signal power at the l th base station due to the n th co-channel interfering portable takes the same expression as the desired signal

$$I_{ln} = S_{TX} + G_{RX} + G_{TX} - L(R_{ln}) \text{ dBm} \quad (5.13)$$

where R_{ln} is the distance from the n th co-channel portable to the l th base station. Exact modeling of the multiuser interference especially in a fast multipath fading environment still remains an open problem. In this study, the multiuser interference is modeled approximately as an uncorrelated Gaussian random process so that their power spectral densities add. The total local mean interfering power at the l th basestation is the power sum of all co-channel interfering portables.

$$I_{tot} = 10 \left(\log \sum_{n=1, n \neq i}^m 10^{\frac{I_{ln}}{10}} \right) \text{ dBm} \quad (5.14)$$

where m denotes all active co-channel portables at the instant of calculation. Note that $n = i$ is excluded from the sum. The signal to interference plus noise ratio is

$$SINR_{ji} = (S_{ji} - 10 \log [10^{I_{tot}/10} + 10^{(N_{RX})/10}]) \text{ dB} \quad (5.15)$$

where N_{RX} (dBm) is the thermal noise level at the receiver which is assumed to be approximately -82 dBm. The i th portable measures $SINR$ and selects four serving base stations

$$\Phi_i = \max (SINR_{i1}, SINR_{i2}, SINR_{i3}, SINR_{i4}) \quad (5.16)$$

If the $SINR$ measured at base stations exceeds a prespecified detection threshold $SINR_{Th}$, the call can be successfully set up, and a reliable communication is said to be established. The value of the $SINR_{Th}$ is chosen to provide some level of acceptable communication performance. In a spread spectrum system, $SINR_{Th}$ is a function of

- E_b/N_0 required to achieve a vocoder bit error rate specification
- The available processing gain, which is determined by the spreading bandwidth, W , and the information rate, R_b

Thus the $SINR_{Th}$ is expressed as

$$SINR_{Th} = \frac{E_b/N_0}{(\alpha W)/R_b} \quad (5.17)$$

where α is the duty cycle, and $SINR_{Th}$ is assumed to be at least -12 dB for establishment of a reliable communication. This value of $SINR_{Th}$ translates to an E_b/N_0 of 7 dB, given a 7.75 duty cycle.

5.4 Traffic Model

Broadband services will be extremely diverse in terms of traffic characteristics as well as grade of service requirements. Network design is driven by traffic and performance considerations. Many types of services spanning a broad range of bandwidths will be soon supported by the emerging BISDN. In addition, this network will have the capability and flexibility in the transport media of assigning bandwidth dynamically on demand, however, it is just this variety of services, flexibility, connection types, and different degrees of responsiveness which bring new interesting and challenging design problems. In particular, traffic models will need to be developed to evaluate the end-to-end user perceived performance and to appropriately assign network resources.

A diversity of services will coexist in a heterogeneous environment producing complex traffic patterns which need to be carefully characterized and modelled in order to design cost-effective broadband networks. Therefore, traffic characterization arises as a fundamental issue in all concentration BISDN points such as access points, multiplexers, switches, etc. as well as in the optimum design of variable bit rate (VBR) encoders ranging from videophony and progressive image transmission to full motion video applications.

Traffic characterization aims at the establishment of the appropriate parameters and performance measures for the broadband services that will be required in network design. In this direction, multimedia traffic has been modelled in several papers[61]-[64]. The discrete-time Markov chain approach was used to model not only a single type of multimedia traffic, but rather several different classes with different characteristics[61]. For voice sources, the Markov chain approach is appealing, since it enables us to model this highly bursty process by a simple two state Markov chain. Similarly, a continuous-time, discrete-state Markov chain can easily be used to characterize the alternating arrival process. One state would represent the on period while the other state would represent the off period, where the holding time in each state is exponentially distributed.

The characteristics of the video signal depends primarily on two factors:

- The nature of the video scene (e.g, low-activity video scenes such as video conferences or high-activity motions with scene changes)
- The type of VBR coding technique employed (e.g., motion compensated discrete transfer, interframe DPCM, etc.)

Video sources generate very bursty traffic with high bit rates for scenes with high motion. Moreover, video traffic has stringent quality of service requirements in terms of cell loss rate and cell delay jitter. The Markov chain models are also used to model the video traffic with or without scene changes[63][65]. To this point, we would mention that developing a simple model which can characterize the correlations and burstyness of the multimedia traffic such as integrated voice and video traffic streams is still a challenging task.

In the present work, we are not intending to take statistical advantage of traffic characteristics due to greatly increased complexity. We consider that sources are bursty or non-bursty, have short or long holding times. The simple traffic model was employed. It is a continuous model with exponentially distributed holding time. In other words, once a portable accesses the channel, it will keep transmitting until all packets have been transmitted. As a matter of fact, if detailed statistics of traffic could be counted, the performance of the system would be better because of CDMA multiple access which has less interference when the source is in an off mode.

Now we describe a discrete event traffic model considered in the simulation. There are M (250) users in the user set and they transmit or receive 20 Mbps video calls. This is the primary source rate in this study. This implies a significant degree of continuous traffic. Multi-rate sources are also investigated. Each idle user in the user set independently generates access attempts with an average rate λ calls/sec. The value of λ is variable depending on offered traffic. The inter-arrival time between access attempts is exponentially distributed with mean $1/\lambda$, and the call arriving process approaches Poisson when the user set is large. The portables are uniformly distributed in the service area. The mobility of portables is not considered in this study. The whole traffic load is video data with exponentially distributed holding time of 30 minutes mean per call.

The access scheme is CDMA. Any given portable selects a set of four base stations based on average signal strength calculation and requests transmission. Upon receiving the request, the four base stations measure the average signal strength to be received relative to the total interference signal strength. If this ratio is above the detection threshold, the transmission is authorized, and the portable will occupy the allocated channel for the duration of the call. During the process of transmission, new arrivals may come into the system and cause interference. It may lead the signal to interference ratio of the transmitting portable to drop below the detection threshold, forcing this call to drop. Since the state of each base station is updated in terms of signal to interference ratio, whenever there is an arrival or a departure, it is always possible that some calls have to be dropped before their completion as the result of S/NR variations.

5.5 Simulation Method

The computation intensive call-by-call stochastic simulation is written using Simscript II.5 and C. The simulator models the actual behavior of an indoor broadband communication system. The system operation aspects include call arrival, channel assignment, hand-off, power control, admission control, etc. Discrete event driven simulation was chosen for the model representation. Three classes of events were selected to describe the system behavior: 1) call arrival events that represent the random arrival of calls at each portable; 2) call drop events for updating uncompleted calls at each active portable; 3) call completion events that occur at the end of a call. Fig. 5.5 shows the event transition diagram of the simulation. The simulation flow is depicted in Fig. 5.6. Precisely speaking, 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 generated and the system state is updated for the additional co-channel interference. By updating the system state, we mean every active portable's signal to interference ratio at its serving base is updated. Whenever the updated *SINR* goes below the threshold, the call has to be dropped and then returns to the user set. A failed access is due to lesser *SINR* than threshold. The blocking statistics are updated and the user is returned to the user set. The readings are recorded after the system reaches steady state. The simulation tool was tested and verified module by module. The main inputs to the simulator are: number and locations of the fixed base stations; number of portables; transmitter and receiver parameters; number of carriers; offered load per portable and average call duration.

Fig. 5.5 Event transition diagram. Event 1: Call arrival. Event 2: Call drop. Event 3: Call completion.

Fig. 5.6 Flow chat of the simulation program.

Chapter Six

Simulation Results and Discussions

The objective of this simulation is to study the traffic handling capability of a broadband indoor wireless communication system using mm-waves and a CDMA access protocol. Conventionally, the performance measures of such a local area network are the throughput and the delay. In this work, we focused on the network throughput aspect. The selected criteria for evaluation of the system in an indoor environment are blocking probability and dropping probability under various traffic conditions. 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 simulation results are grouped under several different headings. The analyses of various results on the broadband CDMA system are included. The network performance in terms of delay will be targeted in a future work.

6.1 Performance of the Basic System

A portable attempting an access scans the four closest base stations, and selects the best one based on signal strength averaging for initial access attempts. It then sends an access request to those base stations. Upon receiving the request, those base stations process the information and check their current *SINR* level. Access is granted by the base station with maximum *SINR*, as long as it is above the threshold. Otherwise, none of them have resource to support services and a negative acknowledgment is received by the user and it thus returns to the user set. Blocking of a request is registered when the received *SINRs* at all these base stations are below the detection threshold.

In CDMA, the blocking probability depends on power level, base station density, traffic condition, transmission channel, traffic type, etc. All those system parameters are controlled in the simulation such that the blocking will mainly be caused by multiuser interference, i.e., the traffic load relative to the number of base stations in the system. The free access character of CDMA makes the system relatively simple. On the other hand, the ongoing transmissions are not well protected. During the service period of time, the quality of the service may deteriorate as the result of new subsequent users. When the interference is serious enough to cause the *SINR* of that ongoing call to be dropped below the threshold, then the call is dropped. Similarly, the dropping probability is also primarily decided by multiuser interference and base station density. Figure 6.1 illustrates blocking

Figure 6.1 Blocking and dropping probabilities vs. offered traffic load for an indoor basic system under fixed base station density of 32/1000

probability and dropping probability vs. the offered traffic loads under a fixed base station density of 32/1000 square meters. The traffic load is defined as the total number of active users at a given instant of time, on an average basis, multiplied by the user rate, divided by

the service area. Because of long holding time (average 30 minutes) and access scheme, the system suffers from a high dropping probability. Increasing the traffic load causes both blocking and dropping to increase. It seems that the basic system can support a traffic load no higher than about 0.4 Mbps/square meter or 12 Mbps per base station.

Figure 6.2 Blocking and dropping probabilities vs. base station density for an indoor basic system under a fixed traffic load of 0.4 Mbps/square meters.

Figure 6.2 presents the blocking and dropping probability vs. base station density for a given traffic load at 0.4 Mbps/square meter. It is understood that increased base station density will provide better service coverage and enhance the network throughput. Thus it improves system performance accordingly. The simulation results in this figure indicate that significant improvement can be achieved when base station density exceeds 20/1000 square meter, corresponding to traffic of about 20 Mbps per base station. In other words, certain number of base stations are necessary to support a desired traffic load, above this value the better improvement can be achieved.

Figure 6.3 Offered traffic load vs. base station density for an indoor basic system under fixed blocking probability of 1% and dropping probability of 3%.

Figure 6.3 illustrates how traffic load varies with base station density for a fixed value of the blocking probability of 1% and that of the dropping probability of 3%. As seen from the figure, below a certain value of base station density, 20/1000 square meter in our case, increasing the base station density only improves system capacity a little. However, a linear relation is observed beyond that value. Note that the possible performance limit for the system under certain circumstances is observed. As the base station density increases beyond 40/1000 square meters, the capacity tends to saturate. This agrees with the previous observation in which the infrared was used as a transmission link and CSMA was employed as a multiple access protocol[68]. The important message here is that the operation of system should be restricted to the linear range, i.e. the base station density be limited from 20-40/1000 meter square, provided that 1% blocking and 3% dropping are acceptable performance.

To this point, we have assumed that the high rate video traffic has an exponentially distributed holding time with 30 minutes mean. Different mean holding times were also examined in this work, but it was limited to a reasonable range. In our simulation program, the mean holding time is an adjustable system parameter. Therefore, the variations of the average holding time could be investigated. By fixing the traffic load at 0.4 Mbps/square meter, and the base station density at 32/1000 square meters, we ran simulations at various average holding times. The results (BI and DI) are shown in Figure 6.4. The interesting conclusion drawn from this figure is that (1) the system performance in terms of blocking and dropping probabilities improves as the mean holding time decreases; (2) the higher dropping than blocking is an inherent nature of the system and it is apparently not directly caused by longer holding time.

It is understood that a longer holding time could lead to better utilization of the channel, but the chances of call blocking and dropping would become larger in general. Our

Figure 6.4 Blocking and dropping probabilities vs. average holding time for a given traffic load of 0.4 Mbps/meter square, and a fixed base station density of 32/1000 square meters. The curves BI, DI, BII and DII stand for blocking and dropping probabilities of systems with or without handoff, respectively.

simulation results indicated higher dropping probability even for relatively short holding time. One might attribute it to higher traffic load. Our previous results have shown that this is not the case. As a matter of fact, this is due mainly to two reasons. First it is the access scheme. Second, it is an outcome of the lack of power control. We are using CDMA with very small processing gain. So the protection of the desired signal is rather fragile. In addition, without power control, any ongoing transmission could be terminated due to nearby new comers. Certainly a higher dropping probability should always be avoided for a practical system. It seems that some other effective mechanisms have to be implemented to achieve this goal.

6.2 Performance of the Basic System With Handoff

In order to alleviate the effect of a higher dropping probability, we implemented a handoff mechanism according to which whenever an active portable's transmission is jeopardized by other interferers, it starts a search algorithm. All nearby base stations are checked. If there exists any other base station providing better service, then it switches over. Thereby, a local higher load can be shared by nearby available resources. To what extent the performance can be improved with this handoff mechanism is a question of interest.

Figure 6.5 presents the simulation results of this system in terms of blocking and dropping probabilities under a fixed base station density of 32/1000 square meters. To compare with the basic system, the simulation results under the same condition are also given in the same figure. It shows that the improvement of blocking probability is rather small, but the dropping probability improvement is more significant. Similar to Figure 6.2, the effect of system performance on base station density is also investigated. Under a given traffic load, both blocking and dropping probabilities decrease as the base station density increases. The curves in Figure 6.6 look like the ones in Figure 6.2, but they are shifted down a certain amount. From this graph, we see that the dropping is significantly reduced, especially for larger base station density. For traffic with different mean holding time, the handoff improvement is different as well. In Figure 6.4, this effect is presented as curves

Figure 6.5 Blocking and dropping probabilities vs. traffic load for a basic system with (BII and DII) or without (BI and DI) handoff under a fixed base station density of 32/1000 square meters.

BII and DII representing blocking and dropping probabilities. In contrast to basic system (BI and DI), the handoff is more effective for traffic with shorter mean holding time.

6.3 Performance of the System with Admission Control

As we have seen previously the system exhibits higher dropping probability than blocking probability. This is certainly an unwanted behavior. We have attributed this to small processing gain and the absence of power control. On the other hand, it may be useful to look at an extreme case, i.e., admission control by which the dropping probability can be completely eliminated. This can be realized by employing a central controller which

Figure 6.6 Blocking and dropping probabilities vs. base station density under a given traffic load of 0.4 Mbps/square meter for a system with (BII and DII) or without (BI and DI) handoff.

regulates each service request. A portable intended to transmit has to communicate with the central controller first, upon receiving the request the controller then communicates with each base station to see the effect of incoming transmission on all currently served portables. If none of the active portables' transmission quality is going to be degraded to an unacceptable threshold due to this incoming portable, then a permission is granted. Otherwise, it is blocked. The results are presented in Figure 6.8 . Apparently, the dropping is eliminated at a large expense of blocking probability. Technically, such a central controller may not be viable, because of extra processing overhead. But some performance bounds can be obtained from such an extreme case.

Figure 6.7 Blocking and dropping probabilities vs. base station density under a given base station density of 32/1000 square meters for a system with (BII) or without (BI and DI) admission control.

Besides this control scheme, a simpler admission control technique was also implemented as an alternative in which the admission threshold for every portable was increased by one dB and all ongoing transmissions remain the same threshold for good quality of service. In other words, instead of 7dB admission, now the admission level was raised to 8dB, and the threshold for maintaining a call was still kept at 7dB. With this control mechanism, the simulation results are displayed in Figure 5.8. We can see that blocking probability suffers a small penalty but dropping probability is improved 50%. In practice, this may be a good technique to be considered.

Figure 6.8 Blocking and dropping probabilities vs. base station density under a given base station density of 32/1000 square meters for a system with (BII and DII) or without (BI and DI) admission control (8dB admission threshold).

6.4 System Performance with Different Types of Traffic

So far, we have only investigated system behavior under an extreme traffic condition, i.e., a single type of high rate video traffic. We have collected useful information on such a worst case. But in the real world, a broadband system will support integrated multi-media traffic. To see the effect of different types of traffic, a simulation was conducted for five types of traffic. The traffic statistics are

Type I: 45% of traffic with 64Kbps data rate, and an exponentially distributed holding time of 3 minutes mean, corresponding to voice users.

Figure 6.9 Blocking probabilities of 5 types of traffic vs. offered traffic load for a fixed base station density of 14.4/1000 square meters.

Type II: 5% of traffic with 128 Kbps data rate, and an exponentially distributed holding time of 4 minutes mean, corresponding to low bit rate data users.

Type III: 15% of traffic with 0.5 Mbps data rate, and an exponentially distributed holding time of 5 minutes mean, corresponding to bursty data users.

Type IV: 15% of traffic with 5 Mbps data rate, and an exponentially distributed holding time of 30 minutes mean, corresponding to interactive data users.

Type V: 20% of traffic with 20 Mbps data rate, and an exponentially distributed holding time of 60 minutes mean, corresponding to video users.

Simulation results are shown in Figure 6.9 and Figure 6.10. The interesting thing is that the blocking probabilities are about the same for different types of traffic, but the dropping probabilities are quite distinct only for the two high rate traffic types which are significantly larger than the other three types of traffic.

Figure 6.10 Dropping probabilities of 5 types of traffic vs. offered traffic load for a fixed base station density of 14.4/1000 square meters.

The same traffic model was used to investigate the traffic handling capability of mm wave broadband indoor wireless system employing TDMA access[69]. The simulation studies of TDMA system indicated that type V portables experience maximum blocking due to its maximum bandwidth requirement per access, the other types portables also have quite different level of access blocking, depending upon the bandwidth requirement of access. It is understood that TDMA system allocate time slots to users carrying different types of traffic. High bit rate users would consume more slots than lower bit rate users, and therefore the access blocking probability is higher. In our system using CDMA access, blocking is the outcome of insufficient power level at an instant of access. This is a primary reason why different types of traffic experience about the same level of blocking.

On the other hand, TDMA system does not have dropping. As soon as the slot is signed to a specific user, the transmission is guaranteed. While in CDMA system, it is a different

scenario. High bit rate users are more vulnerable due to longer holding time. This is what it is seen in Figure 5.10, i.e., users of different bit rate suffer different degree of dropping.

6.5 Performance with Power Control

In a CDMA system all users transmit in the same frequency channel and hence the received spectrum at the base station shows a quite uneven distribution. The differences in power levels cause each communication link to have different degrees of communication quality. Also the effect of the stronger signal on the weaker one due to cross correlation could cause unacceptable degradation for the weaker signal. The high dropping probability of our system seen previously is also attributed to the absence of power control. Hence power control is necessary to equalize the received power at the base station and maintain an acceptable communication quality, although the implementation of power control may have some practical difficulty for fading channel. For an indoor communication system, it may not be that hard due to the lower speed of portables. We implemented a power control scheme in our system in order to see the impact of power control on system performance. The power control is based on each micro cell. Each base station covers a certain service area. All active portables appearing in the same cell have their power adjusted to the same signal level. Because of the small size of micro cell, the dynamic range of power control is not big.

The simulation results are displayed in Figure 6.11 . Compared to the performance of a basic system represented by BI and DI, Both blocking and dropping probabilities are improved significantly. The dropping probability is reduced more than blocking probability. It is not surprising to see the performance improvement introduced by power control. For a CDMA system, power control is an effective way to combat near-far problem and reduce the dropping probability accordingly. On the other hand, implementation of power control leads to higher data processing overhead, and tracking the power of mobile units in a fading environment is difficult, especially when the speed of a mobile unit is high.

Figure 6.11 Blocking and dropping probabilities vs. offered traffic load under a given base station density of 32/1000 square meters for a system with (BII and DII) or without (BI and DI) power control.

6.6 System Performance with Sectorized Base Antennas

The utilization of sectorized antennas tends to increase the system capacity. Our previous results indicate that a system with relatively small processing gain may have difficulty in supporting a high traffic load. By implementing sectorized antennas for the base stations, the system performance should be improved. In our model system, we still keep omnidirectional antennas for the portables, and antennas with three sectors are used for the base stations. For systems with CDMA multiple access, using sectorized antennas increases the

Figure 6.12 Blocking and dropping probabilities vs. offered traffic load under a given base station density of 1/100 square meters for a system with (BII and DII) or without (BI and DI) three sectored base-site antennas.

resources or reduces the cell area. Each sector is still operating at the same frequency, but it senses less interference, because only those active portables located inside the same sector will be sources of interference.

The system performance is simulated with a single type of traffic source, i.e. 20Mbps data rate and 30 minute mean holding time. The results are shown in Figure 6.12 . It is seen that the improvement in terms of blocking and dropping probabilities, compared to the basic system, is significant. Even at a higher offered load of 1.2 Mbps/square meters, the blocking and dropping probabilities are well below 10^{-2} , while the blocking probability is much smaller. The interesting thing is that as the traffic load increases, the dropping probability initially increases, then turns flat showing some kind of saturation. Compared

to the blocking probability, the dropping probability is still bigger. Once again, we see that higher dropping probability is associated with the absence of power control. Even with sectorization, the problem does not seem to be solved, but it has become very much less serious. At a load of 1.1 Mbps/square meter, the blocking probability approaches the dropping probability. The results here imply that sectorization is a promising approach to increase the system capacity. A blocking and dropping probability of about 1 Mbps/square meter can be obtained with the assumed base station density of 32 base stations per 1000 square meters or 96 sectors per 1000 square meters. The resulting traffic per base station is $1/0.032-0.034$ Mbps per base station, or about 11 Mbps per sector.

Chapter Seven

Conclusions and Some Suggestions for Future Work

7.1 Conclusions

Simulation studies have been carried out of the traffic characteristics of CDMA wireless systems operating at mm-wave frequencies for broadband traffic (video traffic of data rate 20 Mbps) in a worst open building environment where co-channel interference, the main communication impairment is maximum. 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. Therefore, signal attenuation of the line-of-sight component in the indoor environment is calculated based on previously published results. A distributed system architecture is used so that each portable can take advantage of micro-diversity in accessing the channel. An OC-3 bit rate of 155 Mb/s of ATM-SONET standard is taken as a line rate. The achieved chip rate is assumed to be 1.55 Gchip/s. The media access protocol is direct sequence CDMA and the reception threshold is assumed to be 7 dB to achieve a bit error rate better than 10^{-3} . The blocking and dropping probabilities are taken as the system performance measures.

The simulation tool was tested and verified by various means. Each module was individually tested for known results. Results were compared by changing the random seed in the simulation and very good agreement was observed. Various system behaviors were investigated by the simulation tool. The effects of portable density, base station density, mean holding time on system performance were evaluated. The system's traffic handling capability was measured. Useful results were obtained to serve as a good reference for future system development.

The simulation results indicate that lower processing gain without implementing power control, the CDMA protocol has limited efficiency, and hence the traffic handling capability of the system is relatively low with about 0.4 Mbps/square meter or 12Mbps/base station for given base station density of 32/1000 square meters. Longer mean holding time is not a primary cause of low throughput. In certain range of base station density from 20/1000 to 40/1000 square meters, almost linear increase of throughput can be obtained by increase the base station density.

By implementing power control and soft-handoff, both dropping and blocking probabilities are improved considerably. Admission control may be a good option to avoid a high dropping probability. Sectorized base antenna techniques can enhance the system traffic handling capability significantly. Our studies demonstrated that three sectored base antennae can increase traffic density from 0.4 Mbps per square meter to 1.0 Mbps per square meter at a given base station density of 32/1000 square meters. It is 2.5 times more traffic capacity.

As we mentioned in the previous chapter that a simulation study was performed for a system using TDMA access under similar circumstance. Comparison of two systems, several points should be addressed. Firstly, the TDMA system with reservation could have better performance in terms of the traffic density supported for this specific application. TDMA may not be efficient because of the high bit rate variation exhibited by multimedia terminals. Some form of reservation or adaptive allocation of time slots must be instituted to take advantage of the bit rate variations and to accommodate the delay requirements. Secondly, a CDMA system could be less efficient in supporting broadband traffic density due mainly to small processing gain. Even a small processing gain will result in a very wide bandwidth signal and will require very high speed signal processing. Thirdly, a TDMA system does not exhibit a dropping problem, which is serious for a CDMA systems. Fourthly, a tight power control could also be a practical difficulty for a CDMA system.

In summary, CDMA would be a good access protocol to provide reasonable performance for wireless access to broadband network, but power control and base sectorized antenna are essential techniques to be implemented.

7.1 Some Suggestions for Future Work

Wireless access to broadband networks is a new expanding research area. Many important characteristics remain open for further study. Our preliminary work shall be a useful reference for some future work. From knowledge and experience we gained through our work, we can provide some suggestions for further studies in this area:

- 1) As hardware technology advances, high chip rate ICs will be available for commercial use. This will make higher processing gain achievable. With such a high processing gain, we could further investigate our system. For example, we can consider to taking better advantage of CDMA, and then have better network throughput.
- 2) More realistic indoor environments such as factory, apartment buildings, business offices with various kinds of walls and dividers can be implemented with some further efforts. System performance under those environments can be evaluated.
- 3) Mobility of certain type users like voice terminals can be taken into account.
- 4) More detailed simulation software can be built to track the transmission of each ATM cell, and statistics of multimedia traffic can be collected of various cell losses.
- 6) Study of the system performance under more complicated channel model such as fading and shadowing can be made to investigate more realistic situation.
- 7) Polling is another attractive access scheme which can be modified to allow for polling the whole class of low data rate terminals, with fixed time allocation to each terminal within that class. The performance of this scheme can be further investigated to see if it is a better access method against CDMA or TDMA.

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