Cellular Architecture for Wireless Indoor
Broadband Communication Systems in mm-
Wave Band

by

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in partial fulfillment of
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in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

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Abstract

A dynamic Time Division Multiple Access (TDMA) polling-base scheme is proposed for an indoor broadband wireless LAN. The protocol attempts to bridge the existing and rapidly-growing ATM technology to that of personal communications systems and should be capable of handling variable bit rate as well as constant bit rate connections. The system assumes a microcellular architecture with a low frequency reuse such as 3 or 4. To combat the severe co-channel interference, which is expected to be the dominant transmission impairment, switched sector-beam antennas are used on both portables and base stations.

The fixed-length frame gated-limited polling multiple access consists of a number of subframes corresponding to each of the sectors of the antenna. Portables are polled and serviced with a rate that is determined by their average bit rate and service requirements. The subframes may be randomized in order to randomize the interference and allow the error control procedures to bring the performance of the system to the required level. Selective ARQ is proposed to enhance the reliability of the transport link.

An analytical study is carried out for a simplified scenario where a terminal is polled and serviced by a central server. The study takes into account the ARQ retransmissions and the TDMA frame structure. Results such as the probability generating function of buffer size and bounds for the traffic delay are obtained. The effect of temporal dependences in the traffic stream (nonrenewal models) or lack of it (renewal models) is also studied.

The steady state performance of the system in terms of cell loss probability, call block and drop probabilities, traffic cell waiting time, and portable buffer occupancy are evaluated by simulation. A 4×4 cell microcellular squared open indoor environment is assumed. Results show that utilization figures ranging from 60% to 70% are achievable. The average raw cell loss probability is 10^{-3} to 10^{-2} , depending on the offered traffic load and the receiver signal-to-interference ratio threshold, can be dramatically improved

through the use of selective ARQ at low cost of slight increase in delay for traffic. Admission control and handoff procedures are recognized to be very critical in determining the overall performance of the system and should be carefully designed. For the suggested procedures, 10^{-2} call blocking probability is achieved at a load equal to about 60 Mb/s per microcell (or carried load of 0.52) for a signal-to-interference threshold of 8 dB. The call drop rate is 10^{-3} at that operating point.

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Ashraf Sharif Hasan Mahmoud

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1

Introduction

Great advances in the area of personal communication services have been achieved in the past two decades [14] from the first generation analog cellular phones to the second generation digital systems (IS-54, GSM, DECT). Attention is now being focused on the third generation systems that will not only carry voice streams but also many other types of data with the possibility of one wireless terminal capable of conveying all kinds of information (computer data, fax, video conferences, high resolution images, etc.) between any desired locations.

1.1 Objectives and Motivation

It seems this trend has to take advantage and actually grow in parallel to the already expanding presence of Broadband Integrated Services of Digital Networks (B-ISDN). The unification of the broadband communication with the wireless personal systems will make tetherless access to a wide range of broadband services possible. One application of this concept is the Wireless Local Area Network (WLAN) for offices and industrial environments. In this application, a number of high speed workstations are not only operating with a degree of connectivity equal to that provided by an equivalent wired network but also capable of receiving and sending traffic to/from sites existing on the larger wired establishment some thousands of miles or a few blocks away. The interface between the wireless LAN and the rest of the network is what makes it possible to view these wireless terminals or portables as extensions to the backbone network.

Another incentive for wireless LANs is the flexibility in terms of physical locations of portables and user terminals. The limited mobility (within buildings and walking speeds) that can also be supported is another advantage of wireless LANs over their wired

counterparts. These characteristics amount to little or no moving and/or rewiring costs when it comes to office (re)organization. Furthermore, the tetherless links are the option when permanent wiring is not considered for the cases of rented facilities or establishment of short term work groups requiring temporary connections.

1.2 System Context

Since 1990 the Canadian Institute of Telecommunications Research (CITR) has sponsored research on developing a broadband wireless indoor communication system operating in the millimeter wave band. The project aims to unite broadband communications with the emerging wireless personal communications and thus making possible untethered access to wide range of broadband and multimedia services.

The main objective of the research is to layout a system architecture and demonstrate the feasibility of a broadband indoor digital communications system capable of supporting Asynchronous Transfer Mode (ATM) traffic and bit rates up to 155.52 Mb/s for broadband LANs. The focus is on a radio system with carrier frequencies in the 20-60 GHz range. This is because of the relative abundance of bandwidth and the favorable regulatory environment in this range. The design includes a multiple access microcellular architecture accommodating traffic with wide range of bit rates and quality of service. The architecture also considers the interface between wireless access ports and the high-speed ATM backbone network. A modem configuration appropriate for the high-speed wireless indoor link is also part of the design together with propagations studies to characterize the channel. To accomplish these tasks, the project is divided into subprojects carried by subgroups with defined inputs and outputs among the subprojects.

One task that is very relevant to the subject of this thesis is the characterization of the radio frequency propagation in the mm-range. The study in [6] contains channel models and link budget calculations that have been developed for the wireless indoor environment. One major finding of this study is that the use of high gain (directional) antennas, such as switched multisector antennas, is essential in avoiding an excessive transmitter power requirement. The use of directivity is also useful in reducing the span of the multipath signals and the co-channel interference. The use of 16-sector antenna on both the base station and the user terminal is deemed an appropriate compromise between complexity and the benefits of directivity.

Another study that defines an important parameter for the subject of this thesis is the

modem design. With a gross rate of about 160 Mb/s and measured multipath delay spread of 10 to 120 nsec (i.e up to about 20 bit intervals) [31][67], there is potentially a very severe intersymbol interference (ISI) problem. The use of directive antennas may partially alleviate the problem as mentioned before, nonetheless, ISI remains significant. Equalization techniques may be used to eliminate the ISI problem, but their great complexity and high power consumption prohibits their use, especially in portable units. CITR researchers have proposed the use of the spread-spectrum commutation signalling [78][39] which fulfills the requirements of low cost and low power consumption. In addition to the commutation signalling method, the 160 Mb/s bit stream is divided into four 40 Mb/s parallel streams on four adjacent carrier frequencies. This partitioning is done to avoid the use of a very wide bandwidth receivers which may overstep the circuit technology. With a spreading factor of 5, a 160 Mb/s signal has a bandwidth of about 800 MHz which is on the order of one-fourth to one-third of the total 3 GHz bandwidth allocated for the system. This translates to a small reuse factor of 3 or 4 for any frequency reuse scheme. This reuse factor is low compared against existing wireless system and leads to a severe co-channel interference problem.

1.3 Thesis Organization

The purpose of this study is to propose and evaluate an architecture for such an application. The emphasis is on the protocol through which the wireless portables share access to the channel. A dynamic Time-Division Multiple-Access (TDMA) Time-Division Duplex (TDD) scheme is proposed to organize portables' and service ports' access to the channel and to carry both down link (from service ports to portables) and uplink (from portables to service ports) traffic. In this scheme portables are polled as often as their service requirements demand and then they are allocated certain portions of time on the channel.

This study attempts to evaluate the overall performance of such a network in terms of criteria figures (traffic cell loss, delay, etc.) for a given configuration (microcellular layout, traffic density and model, etc.). The study also considers other factors that are relevant to the system performance such as interference, antenna sectorization, handoff procedures, etc. The study is carried out analytically wherever possible and backed up by simulations for verification and extension of the results.

The thesis starts by describing the highlights of the first and second generation mobile

communication systems. It also describes some examples of existing wireless LANs. The third chapter looks at the wireless channel and the indoor one in particular in terms of propagation characteristics and some statistical models that can be used for modeling it. The second half of the chapter attempts to characterize the co-channel interference and the effect of macro diversity and antenna sectorization. In chapter four a multiple access protocol is suggested and described in some detail. This includes the frame structure, error control, and proposed packet formats. The chapter also highlights the terminal homing and handoff procedures. An analytical study of the proposed gated-limited polling is carried out in chapter 5. The considered scenario assumes a single terminal that is polled and served by a central server. The analysis takes into account the traffic model, the ARQ retransmissions, and the frame structure. A simple version of the protocol is simulated and the results are presented in chapter six. The effects of handoff, ARQ, and power control techniques are also shown to improve the performance of the system. Finally, chapter seven summarizes the results and the conclusions. It also includes the list of contributions.

2

Background and Literature Survey

2.1 Wireless Communication Systems

The last decade witnessed a rapid growth in the area of wireless communication systems, and new applications are being spawned at a great rate. These applications include analog and digital cordless phones, cellular mobile radio, personal communication networks, satellite radio systems, wireless local area networks, etc. The increasing popularity of these applications is mainly due to two reasons: the first is that these systems support user or customer mobility. Today's potential customer wants to make his telephone conversation, video conferencing, or even his data transfer a task of no or little overhead in terms of having to perform it at specific times or places. The need of tetherless communication, or portability, has been and is still the main drive for many researchers, laboratories, and giant enterprises to spawn wireless systems (new or previously existing but modified). Some of the applications named above provide this tetherless communication link in an outdoor environment and some are designed to perform mainly in an indoor environment. Secondly, especially in today's office or work environment, wireless systems may offer reduced cost of deployment of wired (copper or fiber optics) connections between offices and work places in the same building. Furthermore, office rearrangement and physical moves would be handled with minimum disruption of work [47].

Most of the wireless systems are designed based on two concepts: frequency reuse and cell splitting [44]. In frequency reuse, the overall coverage area is divided into cells or domains, not necessarily uniformly. In each of the domains a carrier radio frequency is used for communication the service ports (or base stations) and the mobile terminals (or

portable). The carrier frequency is reused in domains that are physically distant enough such that the co-channel interference, one of the main impairments in cellular systems, is not objectionable. This reuse helps better utilize the spectrum and cope with available or allocated radio bandwidth for that communication service. On the other hand, cell splitting is a measure in which the coverage area instead of being served by one relatively high power service port, is divided into smaller domains each served by a relatively lower power service port. Cell splitting, at least in the first generation systems, increased the capacity of the system at the expense of lower service quality in terms of more severe co-channel interference and more frequent handoffs between the new subdomains resulting in delays and greater chances of losing the communication link.

The first generation technology manifested itself in the early cordless phones and cellular mobile radio are the industry's first attempt at wireless communication systems. Examples of these early cellular systems are the *Advanced Mobile Phone System* (AMPS) [84], the *Total Access Communication System* (TACS), and the *Nordic Mobile Telephone* (NMT). In addition to the fact that they are characterized by analog voice transmission, these systems use one communication channel for both speech and network control messages (messages regarding handoffs and power control) which hinders system capacity and flexibility [27].

Second generation systems [28] were designed with the shortcomings of the first generation systems in mind. Mobile radio systems such as the European standard, the *Groupe Spécial Mobile* (GSM), the Japanese *Digital Cellular* standard (PDC), and the North American *Interim Standard 54* (IS-54) are based on digital voice technology. Moreover, dedicated channels are used for network control. Also, unlike the first generation cordless telephones which are vulnerable to interference, second generation cordless telephones are able to communicate with many base stations (cellular concept) and they automatically select the best available radio channel and thus are less vulnerable to interference. Examples of digital cordless telephony standards in this category are the *Digital European Cordless Telephone* (DECT), *Personal Handphone System* (PHS) and the *Cordless Telephony* (CT2) systems.

While the second generation applications are being finalized and deployed, many researchers are focusing on the third generation technology [12][13][11]. It seemed logical to try to merge the cordless, cellular, personal communication networks in one universal wireless communication network providing a variety of advanced information services

such as voice, facsimile, paging, video conferencing, etc. This type of network will provide the above services to outdoor and rural environments as well as indoor and workplace environments. Most likely [14], the infra structure of this network will require several complementary technologies. For example, a low-power tetherless access (deployed mostly within and around buildings for stationary and pedestrians) must be designed to complement current and future vehicular radio, mobile satellite, intelligent local exchange networks (including wireline networks), in a way such that access is unified and information exchange between network intelligence functions can be standardized and coordinated among infrastructure networks. Figure 2-1 shows a plausible scenario where a universal wireless network is deployed.

One example of such an effort is found in [55] where a European on going project supervised by the Research into Advanced Communications in Europe (RACE) is putting much effort into the Universal Mobile Telecommunication Systems (UMTS). The purpose of UMTS is to provide a wireless network of capacity 2 Mb/s for mixed types of traffic.

Table 2-1: Some Wireless Technologies [82] and [21]

System	AMPS	IS-54	GSM	CDMA	DECT	CT2	PHS
Multiple Access Scheme	-	TDMA/ FDMA	TDMA/ FDMA	CDMA/ FDMA (DS)	TDMA/ FDMA	FDMA	TDMA
Duplexing Method	FDD	FDD	FDD	FDD	TDD	TDD	TDD
Frequency Band (MHz)	824-849 869-894	824-849 869-894	890-915 935-960	824-849 869-894	1800-1900	864-868	18950-1918
Channel Spacing (KHz)	300-400	30	200	1250	1728	100	300
Modulation	Analog FM	$\pi/4$ DQPSK	GMSK	BPSK/ QPSK	GFSK	GFSK	$\pi/4$ DQPSK
Portable Peak Tx power (mW)	0.6,1.2,3.0 W	600	1.0 W	600	250	10	80
Speech Coding	-	VSELP	RPE-LTP	QCELP	ADPCM	ADPCM	ADPCM
Speech Rate (Kbps)	-	7.95	13	8 (variable rate)	32	32	32
Speech Ch/Rf Ch.	832	3 (6 with half rate coder)	8(6 with half rate coder)	-	12	1	4
Ch. Bit Rate (Kbps)	-	48.6	270.8	9.6	1152	72	384
Frame Duration (msec)	-	40	4.615	20	10	2	5

Figure 2-1: Universal mobile telecommunications systems

Table 2-2: Wireless LAN Vendors [66]

Vendors	Product	Remarks
Armatek	EasySpan	2.5 Mb/s; no license; supports Arcnet, 803.3, and 802.5
BICC	InfraLAN	4-Mb/s token ring; Auburn, MA; used by Shearson-Lehman
AT&T/NCR	WaveLAN	2-Mb/s system; spread spectrum; 11 chips per bit
Caliber Tek Cylink	Airlink	64, 128, or 256 Kb/s; 928 MHz spread spectrum; 10-mi radius
IBM (remarket)	Altair Plus	Resells Motorola's Altair; IBM is believed to be working on their wireless LAN
Infralink	Infralink	40 Kb/s; infrared scatter system; Arlington, VA
Motorola	Altair Plus	3.3 Mb/s; licensed at 18 GHz; 10BaseT; SNMP
O'Neil Comm.	LAWN	Low-speed Ultra-High Frequency (UHF) Ethernet; Princeton, NJ
Photonics	Photolink	200-Kb/s infrared system; San Jose/Campbell, CA
Proxim	RangeLAN	242-Kb/s spread spectrum; NetWare support Mountain View, CA
Symbol Techs.	Spectrum 1	
Spectrix		Infrared LAN
Telesystems SLW	Don Mills	1.3 Mb/s; Ethernet; scrambled for security; (Canada)
Ungermann-Bass	Altair Plus	Remarks Motorola's product
WinData	FreePort	5.7-Mb/s system; 32 chips per bit; Ethernet and token-ring support; resold by Cabletron.

2.2 Wireless Local Area Networks

Another emerging technology is the specialized low-peak power Wireless Local Area Networks (WLANs) with various data rates ranging from few kilobits per second to several mega bits per second [64]; some operate in the order of 10 Mb/s [5]. Although these WLANs are considered as an interpretation [14] of the many that belong to the second generation technology, they share distinguishing characteristics. These WLANs are designed with much higher capacities when compared to the voice-oriented systems, and are an attempt to provide service to multimedia capable terminals, so that they can be

easily integrated or be an extension to a Broadband Integrated Services Digital Network (B-ISDN).

Most of the already existing wireless LANs are mere wireless implementations of the IEEE 802.3 Ethernet and the IEEE 802.6 Token Ring protocols. They operate at moderate speeds less than 10 Mb/s. These shortcomings of the current wireless LANs limits their integration into B-ISDN and restricts the type of application that could be implemented. Some current wireless LANs vendors and their products are listed in Table 2-2.

The NCR WaveLAN¹ provides wireless connection of rates up to 2 Mb/s for personal computers [77]. The WaveLAN operates in one of the Industrial, Scientific, and Medical (ISM) Bands, namely 902-928 MHz and uses 11-chip per bit direct-sequence spread spectrum - DQPSK based modulation technique. Like the wireline based LANs, WaveLAN uses an Ethernet variety, Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) as an access protocol. With its two cross-polarized antennas etched onto a printed circuit board at the receiver and less than 1 W output power the system can provide coverage distances up to 800-600 feet for open environments and down to less than 30 feet for offices with concrete walls. The selection between the antennas is based on a post-processed signal quality level. To the best of the author's knowledge, the WaveLAN system (as well as the WalkLAN², a mobility supporting version of WaveLANs) is not based on a cellular concept. The capacity of the LAN in terms of number of personal computers in the WLAN is determined by the constraints similar to those in the wireline ethernet LAN.

Unlike the WaveLAN, the ALTAIR³ concept of WLANs is based on providing a radio connection between wireline LAN segments [5]. A user module resides on each segment and is responsible for communicating with a central module. User modules do not communicate directly. The system operates at 18 GHz and uses a 10 MHz channel to provide 15 Mb/s of raw capacity supporting a combined network traffic demand of approximately 3 Mb/s. ALTAIR, in theory, is based on a cellular concept where different central modules, serving different micro domains, use different carrier frequencies or are separated by a reuse distance (dependent on the indoor environment) on the order of 30 to

1. WaveLAN is a trademark of NCR Corporation.

2. WalkLAN is a trademark of NCR Corporation.

3. ALTAIR is a trademark of Motorola Inc.

50 meters.

To combat signal fading and exploit multipath diversity, ALTAIR uses a 6-sector directional antenna on both the user module and the central module, and employs a "best sectors combination" algorithm to choose the appropriate antenna sectors for communication. Time Division Duplexing (TDD) technique based on request/grant protocol is used to schedule transmissions among the user modules and the central module.

A third example of a wireless LAN is the FiRLAN which offers a raw capacity of 10 Mb/s and operates in the infrared band. The transceivers use sectorized antennas and rely on line-of-sight communication. Similar to WaveLAN, FiRLAN uses CSMA-CD technique to provide service for point-to-point applications.

New standards have been developed for wireless LANs [29][37][57][82] under the IEEE 802.11 in the United States and under ETSI/RES10 or High Performance Radio LAN (HIPER-LAN) in Europe. Japan is also considering standardizing two types of wireless LANs: one for rates less than 2 Mb/s and the other for rates greater than 10 Mb/s. The IEEE 802.11 and the HIPER-LAN are going to support different network architectures including point-to-point, point-to-multipoint, and broadcast services.

The IEEE 802.11 supports two types of topologies [37]: centralized and an ad-hoc one. In the centralized topology, base stations are spread over the coverage area to provide service for wireless terminals. These base stations act as an access point for a backbone network. In the ad-hoc architecture terminals on the floor communicate with each other (peer-to-peer) independent of the infrastructure and/or base stations. The standard specifies three types of physical layers to be used: 2.4 GHz ISM band with frequency hopping spread spectrum radio, 2.4 GHz ISM band with direct sequence spread spectrum radio, or infrared (IR) light. In addition, two data rates have been specified for each of the physical layers: 1 Mb/s and 2 Mb/s with the latter rate being optional. The primary access method specified is called Distributed Coordination Function (DCF) which is a derivative of CSMA-CA. However, delay-critical services are supported through the use of the optional Point Coordination Function (PCF) in which one station assumes an arbitrator position and coordinates access, using a polling mechanism, to the medium so that only one station is transmitting at any time.

On the European side, the HiperLAN standard [34] calls for 23.529 Mb/s gross bit rate operating at 5 GHz band with 150 MHz bandwidth that is divided into five channels. Similar to the IEEE 802.11, both centralized and ad-hoc topologies are supported. This

wireless LAN standard envisions short range coverage (10-100 m) for each radio, however, multihop routing is supported for communication across much longer distances. In the multihop routing case, some nodes are allowed to forward transmissions to other terminals in the LAN. In the physical layer, Gaussian Minimum Shift Keying (GMSK) is the chosen modulation method and a (31, 26) BCH code is used to achieve packet error rates below 10^{-3} . As for medium access protocol, again, it is based on the carrier sensing mechanism with provisions for prioritized and time-bounded services.

In the area of broadband wireless networks, there is AT&T's Broadband Ad-Hoc Wireless ATM Local Area Network or Broadband Ad-Hoc ATM Anywhere (BAHAMA) [20] [3]. The network consists of Portable Base Stations (PBS) that can assume an arbitrary topology to form a very high speed (Giga bits per second) backbone network with links being wired or wireless. The network of PBSs provide access to wireless mobile terminals with rates up to 20 Mb/s. Similar to the IEEE 802.11 and HiperLAN peer-to-peer communication is allowed and the main architecture of the network is an ad-hoc one with no emphasis on a centralized configuration. The purpose of the system is to provide seamless internetworking with other wired ATM local and wide-area networks. The system relies on multilevel Forward Error Correction (FEC) to combat errors on the wireless channel. This is in addition to ARQ which is proposed for the non real-time applications. The access method used is Distributed-Queueing Request Update Multiple Access (DQRUMA) and is a demand assignment TDMA access protocol [33]. Contention is still used in the method but only for traffic cells arriving to an empty terminal buffer. Uplink and downlink streams are multiplexed using Frequency Division Duplex (FDD) protocol.

Our last example of broadband wireless is the European Mobile Broadband System (MBS) [23] [80]. This system targets indoor as well as outdoor environments and operates in the 60 GHz range providing data rates as high as 160 Mb/s. It attempts to extend the B-ISDN to mobile users. This system uses FDMA/TDMA dynamic slot assignment method (based on slotted ALOHA). A form of selective ARQ is employed to reduce cell error rate to reasonable levels for ATM cells to be transported reliably.

The CITR project and in particular the subject of this study, the cellular architecture of the wireless broadband indoor communication system, differ in key points from some or all of the previously described wireless networks. Nevertheless, they still share some design criteria. For example, the CITR projects concentrates on providing a high capacity wireless link (up to about 160 Mb/s) for the indoor environment. The MBS also considers such high

rates. In the case of this study we opt for TDD method to multiplex up stream and down stream traffic while most of the other systems consider an FDD scheme. The choice of TDD facilitates signal and/or interference monitoring for user terminals and base stations as described in Chapter 4 and Chapter 6. This allows simpler handoff control. It also accommodates variations of instantaneous bandwidth allocated to the uplink and downlink in response to interactive traffic. One key issue that this thesis concentrates on, among other issues, is the combating of the high-levels of co-channel interference resulting from the low frequency reuse factor. Here we integrate this combating into the medium access protocol in the form of dividing the TDMA frame into segments where each is carried on one of the antenna sectors of the base station. Other means of avoiding or reducing the interference such as handoffs and power control are also evaluated.

Furthermore, this study chooses a polling-based scheme as one appropriate scheme to use, considering its simplicity and flexibility. Another study [50] [51] under the CITR project considers reservation-based methods in addition to polling. Polling and reservation techniques appear appropriate for reliable, simple, and flexible access for a mixture of continuous (synchronous) and bursty traffic [36]. The examples of wireless networks mainly base their Medium Access Control (MAC) on contention-based access methods. The adopted polling multiple access protocol is discussed in detail in Chapter 4.

Finally, this study does not consider terminal mobility management in contrast to AT&T's network or MBS since here we assume transportable terminals where motion is not supported during a communication session. Also, we adopt a centralized configuration where all communications passes through a base station. That is, peer-to-peer links are not supported.

2.3 ATM and Broadband Communications

In the past decade, the ATM has emerged as the transport of the present and future Broadband Integrated Networks [69]. ATM operation is based on transporting and switching constant-length packets called cells. These cells are 53 bytes long consisting of two parts: the payload which is 48 bytes of user data, and the ATM cell header occupying the first 5 bytes. The payload portion of the cell is unprotected. This is because ATM is designed for highly reliable links (such as fiber optics) where cell loss probability is in the order of 10^{-9} . The two ends of the connection are responsible for retransmissions if errors are detected or cells are lost; that is nodes along the route do not do any error control

functions. The simplicity and consistency of the ATM cells are the main characteristics of this protocol. Hardware switches can be designed at exceptionally high speeds taking advantage of the uniformity of the cell structures [41].

Being in essence a connection oriented protocol; i.e one can distinguish three phases of a user connection or call: call set up, information transfer, and call termination, ATM can provide the required flexibility in handling different types of traffic; each with its own service requirements. This is done through the four classes of services supported by the protocol: constant bit rate, variable bit rate, connection-oriented, and connectionless.

An ATM based network is capable of providing bandwidth on demand, where each user is allocated a portion of the raw capacity based on its average rate of transmission. Different streams of cells from different sources are statistically multiplexed into the reliable high speed trunk. In this situation, a source is allocated a portion of the overall available capacity in proportion to its average rate of transmission.

Broadband services, the concern of the above paragraph, are those services that require a variety of capacities and delivery constraints. These are referred to as multimedia traffic [36]. Multimedia traffic require service rates ranging from relatively low rates 8 to 64 Kb/s for voice and telephony, to rates as high as 20 Mb/s for HDTV terminals. Some of these services such as telephony and video conferencing require synchronous links. While others are carried over asynchronous links such as computer data and file transfers. Table 2-3 shows some examples of multimedia traffic depicting the necessary capacity and some of the required service constraints.

Table 2-3: Some broadband services and their requirements.

Application	Service Type	Delay Sensitivity	Portable Speed	Cell Loss	Throughput
Voice Telephony	CO/CBR	Max = 60 msec	< 2 m/s	< 10^{-3}	8 - 32 Kb/s
Digital Audio	CO/CBR	Low delay jitter	< 2 m/s	< 10^{-4}	128 - 512 Kb/s
Teleconferencing (real time video)	CO/CBR, or CO/VBR	Max = 3 msec	< 2 m/s	< 10^{-4}	64 - 384 Kb/s
Computer Data	CL	Max = 250 msec	0	< 10^{-4}	0.1 - 1 Mb/s
File Transfer	CL	Max = 250 msec	< 2 m/s	< 10^{-5}	1 - 10 Mb/s
HDTV	CO/CBR	Low delay jitter	0	< 10^{-4}	10 - 20 Mb/s

CO: Connection oriented, CL: Connectionless, CBR: Constant bit rate, VBR: Variable bit rate.

3

Wireless Indoor Microcellular System Characteristics

Attracted by the abundance of spectrum and favorable regulatory environment, the CITR researchers embarked on a design project of a radio system with carrier frequencies in the 20-60 GHz band. Since few, if any, of the already existing cellular systems operate in this range, and because of lack of extensive characterization of the indoor signal propagation in this band, this design project establishes itself as a novel task in addition to being challenging.

Microcellular systems are based on the concept of frequency reuse as an efficient way to utilize the spectrum. With the abundance of bandwidth, it is reasonable to design a system with as many carrier frequencies as possible since this system will be capable of providing considerable traffic capacity and avoiding co-channel interference (as will be described later). Unfortunately, this is not the case. High cost and immature technology for devices operating in the mm-wave band necessitates keeping the frequency reuse to minimum. It is expected [19] that the system will operate with frequency reuse of 3 or 4. Each of the service ports in each domain or microcell is assigned one frequency for a long term. With such a small reuse factor, co-channel interference, undoubtedly, is the main capacity limiting factor at least in areas where microcells are not separated by walls or other barriers. System should depend on techniques devised to neutralize this limitation.

The first section of this chapter will summarize some of the characteristics of the mm-wave band; more studies are still being conducted to this date. The section will also describe some of the statistical models used in evaluating the indoor radio channel. The second section will focus on the characterization of the signal-to-interference ratio, SIR.

The SIR ratio is directly related to the bit error rate achievable on the wireless link and therefore to the quality of service. This ratio is studied using the average values for the signal and the interference, as well as using their instantaneous values. This section utilizes a technique developed by Schwartz and Yeh in [65] to characterize the sum of lognormal random variables. The study concludes by pointing out the significant rule of macro diversity and antenna sectorization in improving the quality of the wireless link.

3.1 Wireless Indoor Channel

3.1.1 mm-wave Band Characteristics

In the radio band of 20-60 GHz, here referred to by mm-wave band, signals propagation is ray-like [74] and is mainly dependent on attenuation from obstacles such as walls, dividers, people, etc. The mean received signal power, $\bar{P}$, decreases as a function of the distance d according to the general attenuation law

$$\bar{P} = P_0 / d^\alpha \quad (3.1)$$

where P_0 is a constant and α is the path loss exponent. In free space α is equal to 2. The value of α depends on the propagation environment. Todd et al. [76] have found out that the non-line of sight signals at 37.2 GHz decayed with distance to the exponent 3.5, whereas, the attenuation for corridors is less than that for free space when a line of sight component exists. This is due to the wave-guide effect and the enhancement of the signal strength by the reflected rays.

Data about the attenuation of different building material of signal power (for various frequencies ranging from: 10 to 60 GHz) is found in [26]. The graphs show that concrete has the highest attenuation factor when compared to wood, plywood, gypsum, glass and sheetrock, with more than 35 dB attenuation at 40 GHz and about 20 dB at 20 GHz. Whereas, sheetrock, a common material used for internal walls, has an attenuation of 4 and 2 dB for 40 and 20 GHz respectively. The same study concluded that the attenuation increases with frequency for all above mentioned building materials.

Large reflectors (such as glass windows, metal structures, etc.) present in the environment provide a bouncing surface for the signal rays and thus lead to the multipath effect. The multipath effect is also caused by diffractions. Melters in [49] has reported that

the wall reflectivity varies considerably with the wall material, as shown in Table 3-1.

Table 3-1: Measurements of Wall Reflectivity [49].

Material	Reflectivity (%)
Plasterboard (1 cm)	2
Chipboard (1.9 cm)	20
Concrete	16
Aluminum (1 mm)	> 99
Wood (20 mm)	2
Glass (3 mm)	16

In the multipath effect the signal transmitted from the transmitter, $s(t)$, is received at the receiver through many paths; each with different channel gain and delay [61]. This results in the signal being spread; the received signal $x(t)$ can be expressed as

$$x(t) = \sum_n \gamma_n(t) \exp(j\phi_n) s(t - \tau_n) \quad (3.2)$$

where $\gamma_n(t)$ is the channel gain, ϕ_n is a phase shift due to reflections, and τ_n is the delay. Each term of the summation corresponds to a signal path. Theoretically, the summation is carried over an infinite number of symbol durations, however, it is only significant over a finite duration of time called the delay spread (DS). DS is an indicator of the severity of the multipath effect.

Excessive DS (or spreading of the signal) causes an inter-symbol interference (ISI) problem. In the presence of the ISI, the receiver has to decide (at the decision instant) on a value that is the result of the desired received signal sample plus a noise component composed of a weighted sum of previous and future signal samples, and thermal noise. There are some anti-multipath techniques used to compact the ISI problem such anti-multipath signalling [78], adaptive equalization, antenna diversity, and directional antennas.

Another signal propagation impairment is caused by local scatterers or objects in close proximity to the receiver. In this phenomenon, the signal received bounces off the objects

close to the receiver resulting in relatively small (but large compared to the wave length) differences in the path lengths associated with each scattering signal. These differences amount to random phases causing the signal amplitude to become Rayleigh distributed [38]. However, when the line of sight (LOS) component exists the signal fading model is slightly different. Bultitude et al. in [8] have shown (via measurements) that fading on LOS paths with omni-directional antennas is mostly Rician on indoor channel with fixed terminals at 910 MHz and 1.7 GHz. Both propagation models, Rayleigh and Rician are described in the next subsection. In a recent work by Bultitude and Imbeau [7] at 40 GHz, results indicate that about 50% of the time on the indoor EHF channels, neither the Rician nor the Rayleigh models are appropriate.

As for delay spread measurements, Smulders and Wagemans in [67] conclude that for an indoor channel at 58 GHz, RMS DS lies between 15 and 45 nsec for small rooms, while it is between 30 to 75 nsec for large rooms. The study referred to in [7] concludes that an RMS DS of 28 nsec is associated with links with maximum length of 7.8 m in a hallway and a smaller-sized open office area.

3.1.2 Propagation Models

3.1.2.1 Large Scale Variations

The existence of obstacles, such as buildings and hills for outdoor communications, and walls and dividers for indoor communications leads to gradual change in the local mean of the signal. This is referred to as shadowing or large scale variations. It is confirmed by [56] and [58] that the change in the local mean follows the lognormal distribution. That is, the local mean of the radio signal strength when measured in dBs has a Gaussian probability distribution

$$f_X(x) = \frac{1}{\sqrt{2\pi}\sigma_x} \exp[-(x - m_x)^2 / (2\sigma_x^2)] \quad (3.3)$$

where x is the local mean of the signal in dB, m_x is the mean of the distribution and σ_x is the standard deviation. On the linear scale, the signal strength is given by

$$P = 10^{x/10} \quad (3.4)$$

P is lognormally distributed. The dB area mean, m_x , is the mean of the signal when the signal is measured in dBs, that is

$$m_x = \bar{x} = \overline{10 \log P} \quad (3.5)$$

The probability distribution function of the variable P is

$$f_P(P) = \frac{10 \log e}{\sqrt{2\pi} \sigma_x P} \exp [-(10 \log P - m_x)^2 / (2\sigma_x^2)] \quad (3.6)$$

where $\log$ is the base-10 logarithm function. It can be shown that the n^{th} moment of this distribution is given by

$$\begin{aligned} \overline{P^n} &= \int_0^\infty P^n f_P(P) dP \\ &= 10^{\frac{m_x n}{10} + a} n^2 \sigma_x^2 \end{aligned} \quad (3.7)$$

where $a = \log e (\ln 10)^2 / 200$, $\ln$ is the natural logarithm function. equation (3.7) clearly indicates that the mean of the linear variable P is dependent not only on the local mean of the logarithmic variable, m_x , but also on its standard deviation, σ_x . $\overline{P^n}$ increases exponentially with the square of the order, n^2 for $n > \frac{-m_x/10}{2a\sigma_x^2}$ if m_x is negative or for $n > 0$ if m_x is positive. The shadowing process is completely characterized by the standard deviation, σ_x , and the dB area mean, m_x , which is related to the area median ($\bar{P}$ given by equation (3.1)) by

$$m_x = 10 (\log \bar{P} - a \sigma_x^2) \quad (3.8)$$

The above equation is derived from equation (3.7).

For a particular environment, the shadowing process is characterized by the variability of the signal strength around the mean value. This variability, σ_x , ranges from as low as 6

dB for corridors to 12 dB for office areas with walls and dividers [2].

3.1.2.2 Small Scale Variations

The previous subsection described the variation in signal strength around the local area median due to large scale movement between the receiver and the transmitter while keep the separating distance fixed. However, when the movement is only few wavelengths, small scale variations are noticed. Movement of people or objects present in the vicinity produces the same effect. This variation is referred to as small scale variations. As mentioned in Section 3.1.1, some studies indicate that the signal statistics in a line of sight wireless indoor channel can be modelled with a Rician fading model [74]. This is a direct consequence of the small-sized cells and thus the existence of the line of sight (LOS) component. The probability distribution function (PDF) of the signal envelope is given by

$$p_R(r) = \frac{r}{\sigma^2} \cdot e^{-\left(\frac{r^2 + S^2}{2\sigma^2}\right)} \cdot I_0\left(\frac{Sr}{\sigma^2}\right); (r \geq 0) \quad (3.9)$$

where r is the test signal envelope, σ^2 is the average fading power, S is the peak value of the directly received signal, and $I_n(\cdot)$ is the modified bessel function of the 1st kind and n^{th} order.

The Rician distribution is characterized by the parameter K defined to be the ratio of the average specular power to the average fading power, that is

$$K = S^2 / (2\sigma^2) \quad (3.10)$$

This is in contrast to the outdoor/Radio Mobile environment where cell sizes are much larger and hence the LOS component often does not exist. The K parameter is equal to zero because $S = 0$. Substituting in equation (3.9) yields,

$$p_R(r) = \frac{r}{\sigma^2} \cdot e^{-r^2/2\sigma^2}; (r \geq 0) \quad (3.11)$$

which is the Rayleigh PDF.

The PDF of the instantaneous power is obtained using

$$p = r^2/2 \quad (3.12)$$

and performing a transformation of equation (3.9), the result is

$$p_P(p) = \frac{1}{\sigma^2} \cdot e^{-\left(\frac{2p+S^2}{2\sigma^2}\right)} \cdot I_0\left(\frac{\sqrt{2p}S}{\sigma^2}\right); (p \geq 0) \quad (3.13)$$

Again for mobile radio environment the PDF of the instantaneous power is obtained by setting S to zero in equation (3.13),

$$p_P(p) = \frac{1}{\sigma^2} \cdot e^{-p/\sigma^2}; (p \geq 0) \quad (3.14)$$

Statistics concerning the Rician model such as level crossing rate and fade duration are reported in [60] whereas those of the Rayleigh model are reported in [38]. Some experimental results regarding level crossing and fading durations are also reported in [7]. It is indicated there that there is 90% probability that all fades below the mean signal power by 10 dB have durations less than about 3 msec and the cross rate for this level is about 25 times per second.

3.2 Co-channel Interference and Outage Probability

As mentioned before, the cellular architecture has an advantage of utilizing the spectrum. Unfortunately, co-channel and adjacent channel interference problems develop. In the case of adjacent channel interference, adjacent frequency channels(s) -to the one of interest- is (are) being used in the nearby microcells. The imperfect filter characteristics mean that some power from those channels will spill into the band of interest. Among many methods of mitigating this effect are split symbol time equalization and cyclostationarity exploitation based techniques. However, this type of interference is not the subject of this study.

Co-channel interference is a result of reusing the same frequency channel in one or more microcells at some distance from the microcell of interest. This type of interference plays a significant role in determining the capacity of the cellular system, especially when it is the dominant signal impairment [4].

In a cellular communication system the quality of the communication link is not determined by the signal strength only, but by the ratio of desired signal power, P_d , to the sum of all powers of interfering signals, P_i s, that is

$$SNIR \approx SIR = P_d / \left(\sum_{i=1}^K P_i \right) \quad (3.15)$$

where P_i is the power of the signal associated with the i^{th} interferer. The above expression assumes that the thermal noise is negligible compared to the interference power which is the case for small frequency reuse factors. At the receiver end, it is required by the modulation scheme and receiver structure that the SIR be greater than some threshold value in order for the transmission to be correctly deciphered. When the experienced SIR is less than the SIR threshold, irrecoverable error patterns occur and thus the transmission is considered lost. This is referred to an outage. It is important in the design of the system to provide service to all users and reduce this outage probability as much as possible.

3.2.1 Average Signal to Average Interference Power

Consider the layout shown in Figure 3-1 to explain schematically the phenomenon of co-channel interference. The figure assumes square cell shapes and shows only the first layer of interferers. Not all co-channel domains of the first layer are at the same distance from the center of the cell of interest. The power of the interfering signal from the i^{th} co-channel domain (not considering shadowing or fading), P_{1i} , is inversely proportional to d_{1i}^α , where d_{1i}^α is the distance center-to-portable.

MacDonald in [44] presents details of the relations involved in the geometry of the cellular systems. Cox in [15] had showed that the ratio of the average signal power, $\bar{S}$, to the average interference power, $\bar{I}$, is approximated by

$$\bar{S}/\bar{I} = \frac{(4C')^{\alpha/2}}{4(1+2^{\alpha/2}) \sum_{i=1}^T \frac{1}{t^{\alpha-1}}} \quad (3.16)$$

Figure 3-1: Cell layout and co-channel interference.

Figure 3-2: Average signal to average interference power (with omnidirectional antennas).

C' is all possible cluster sizes (number of cells using distinct channels) that result in $\sqrt{C}$ being an integer and $C = i^2 + j^2$ for i and j are integers. However, this approximation is of acceptable accuracy for large values of C' . Exact expressions for uplink (equation (A.1)) and down link (equation (A.2)) $\bar{S}/\bar{I}$ for square areas are listed in the Appendix. The equations are graphed in Figure 3-2 and can be viewed as the worst case estimate of the $\bar{S}/\bar{I}$ on both the uplink and the down link since the portable is assumed at the microcell edge, the furthest possible position from the base station.

It is obvious that $\bar{S}/\bar{I}$ can be quite low for small values of frequency reuse factors such as $C = 3$ or 4, especially when dB margins for shadowing and Rayleigh fading are accounted for. A Monte Carlo simulation is also conducted to compute $\bar{S}/\bar{I}$ on both the uplink and down link averaged over all possible positions of users. For uplink a user is located at a random position in the cell of interest. Interfering users are also created at random locations each in one of the co-channel cells (only two layers of interferers is considered, i.e. 24 co-channel domains). The distances between the interfering users and the user of interest are computed and then the powers are calculated. In the case of downlink, a user is created at a random location in the cell of interest. The interference power is calculated based in the distances between the user's location and the interfering base stations. This procedure is repeated for 10^6 iterations. Results for different cluster sizes, C , and different cell radii are graphed in Figure 3-2. The radius of the excluded zone in a cell is 1 meter and the graphs are averaged over 10^6 iterations. Interestingly enough, the figures for the uplink and down link are the same. Not only that, but also the estimated $\bar{S}/\bar{I}$ is a function of the cell radius unlike the bound described by equation (3.16). This is expected since $\bar{S}$ is a function of cell radius, R , and so is $\bar{I}$. It should be emphasized that the Monte Carlo results and equations (A.1) and (A.2) are not really comparable, since the latter are for the worst (corners) positions in a cells while the former is averaged over all positions. However, both results do not account for shadowing or fading.

3.2.2 Characterization of Instantaneous SIR

Unlike the previous subsection which only looked at the average SIR, this subsection is considering the instantaneous SIR taking into account the shadowing process and also the Rayleigh/Rician fading. Rewriting equation (3.15) but considering the instantaneous

values,

$$\begin{aligned} SIR_{dB} &= 10\log P_d - 10\log \left(\sum_{i=1}^K P_i \right) \\ &= S_{dB} - I_{dB} \end{aligned} \quad (3.17)$$

where P_d is the desired signal power and P_i is the i^{th} interferer power. The outage probability defined as

$$F(CCI) = \text{Prob}[SIR_{dB} < \gamma_{dB}] \quad (3.18)$$

is going to be evaluated in using different approaches in the following subsections. γ_{dB} is the system signal-to-interference ratio or protection ratio in dBs.

Ignoring the Rayleigh fading, P_d and P_i are log-normally distributed as described by equation (3.6), hence S_{dB} is a normal random variable, but unfortunately, the same can

not be said about I_{dB} . This is because, $I_K = \sum_{i=1}^K P_i$ is not exactly a log-normal variable.

However, the next subsection will show that under some conditions, the sum of log-normal variables can be approximated by a log-normal variable. It will also describe a technique used to characterize I_{dB} .

3.2.2.1 Sum of Lognormal Random Variables

Studies in [22] and [52] have indicated that the distribution of the sum of finite number of log-normal random variables is well approximated, at least to the first order, by another log-normal distribution. Schwartz and Yeh in [65] have devised a procedure for estimating the mean and the standard deviation of $I_{K, dB}$, the sum of K log-normal random variables

in dBs, $I_{K, dB} = 10\log \left(\sum_{i=1}^K P_{oi} \right)$. Analytical formulae are developed to compute the exact mean and variance of the power sum of two log-normal components, P_{o1} and P_{o2} ,

$$I_{2, dB} = 10\log(P_{o1} + P_{o2}) \quad (3.19)$$

Assuming $I_{2, \text{dB}}$ to be Gaussian random variable (i.e. $P_{o1} + P_{o2} = 10^{I_{2, \text{dB}}/10}$ is log-normal), its first and second moments are computed as follows

$$\begin{aligned} m_{I_{2, \text{dB}}} &= m_{P_{o1}} + E [\ln (1 + e^{(P_{o2} - P_{o1})})] \\ \overline{m_{I_{2, \text{dB}}}^2} &= \sigma_{P_{o1}}^2 + m_{P_{o1}}^2 + E [2P_{o1} \ln (1 + e^{(P_{o2} - P_{o1})})] + E [\ln^2 (1 + e^{(P_{o2} - P_{o1})})] \end{aligned} \quad (3.20)$$

where $m_{P_{oi}}$ and $\sigma_{P_{oi}}^2$ are the mean and variance, respectively, of P_{oi} , $E[x]$ is the expectation of the random variable x , and $m_{I_{2, \text{dB}}}$ and $\overline{m_{I_{2, \text{dB}}}^2}$ are the first and second moments of $I_{2, \text{dB}}$. Having determined the parameters of $I_{2, \text{dB}}$, one can proceed to characterize $10 \log (P_{o1} + P_{o2} + P_{o3})$ or $10 \log (10^{I_{2, \text{dB}}/10} + P_{o3})$. This procedure is repeated until $I_{K, \text{dB}}$ is completely characterized or in other words, the mean, $m_{I_{K, \text{dB}}}$, and the variance, $\sigma_{I_{K, \text{dB}}}^2$, are known. The expressions given in equation (3.20) are derived and solved in [65]. The solution is presented in terms of infinite series involving the cumulative distribution function of the zero-mean unit-variance Gaussian random variable.

Figure 3-3: Characterization of sum of log-normal variables.

The procedure described above is carried out and K independent and identically distributed (iid) log-normal random variables are assumed each with a mean m and standard deviation σ . In addition to that a Monte Carlo simulation is also conducted. The results of these two experiments are summarized in Figure 3-3. Figure 3-3.a shows the estimated parameter $\sigma_{I_{dB}}$ using both: Schwartz and Yeh's approximation and the simulation for a wide range of σ . Also, the graph shows the effect of K , number of components. It can be noticed that the accuracy of the procedure deteriorates for large values of K and/or σ . For large K and/or σ values the deviation of the pdf of I_{dB} from the normal distribution assumed by the approximation method is depicted in Figure 3-3.c. The figure shows that there are mainly two places where the two pdfs differ, namely the head of the bell shape and the tails. The results are plotted against σ for $K = 6$ interferers, as it is the case in a cellular system with hexagonal cell shapes, in Figure 3-3.b. A second degree polynomial fit is performed on the simulation results and the coefficients of the polynomial are shown on the graph. This will be used in later sections when probability of outage is computed.

3.2.2.2 Single Interferer Approach

In this case I_{dB} in equation (3.17) is the result of only one interferer, P_{oi} and the co-channel interference probability is defined as

$$F(CCI) = \text{Prob} [P_{od}/P_{oi} < \gamma] \quad (3.21)$$

The Gaussian variable $10\log(P_{od})$ has mean equal to m_{od} , and a variance equal to σ_{od}^2 . Whereas, the mean and variance for the Gaussian variable corresponding to P_{oi} are m_{oi} and σ_{oi}^2 , respectively. Hence, the outage probability is given by [59],

$$\begin{aligned} F(CCI) &= \frac{1}{\sqrt{2\pi}} \int_{z_d/(\sqrt{2}\sigma_{eff})}^{\infty} \exp(-u^2/2) du \\ &= \frac{1}{2} \text{erfc}\left(\frac{z_d}{2\sigma_{eff}}\right) \end{aligned} \quad (3.22)$$

where $z_d = m_{od} - m_{oi} - \gamma_{dB} \cdot \sigma_{eff} = \sqrt{(\sigma_{od}^2 + \sigma_{oi}^2)}/2$. The previous result is obtained by [24], [18], and [63]. Safak and Prasad [63] derived the previous expression but assuming a correlation coefficient, ρ , between the desired and interfering signals. In this case, the effective standard deviation is equal to

$$\sigma_{eff} = \sqrt{(\sigma_{od}^2 + \sigma_{oi}^2 - 2\rho\sigma_{od}\sigma_{oi})}/2 \quad (3.23)$$

Outage probabilities, as a function of z_d are shown in Figure 3-4.a for different correlation factors. The graph is plotted for the case $\sigma = \sigma_{od} = \sigma_{oi}$. The correlation between desired signal and interferer signal decreases the outage probability. Further more, the outage probability increases with the standard deviation of the shadowing process, σ_{od} and/or σ_{oi} .

Considering Rayleigh fading in addition to the shadowing process, the co-channel interference probability as defined in equation (3.21) can be shown [63] to be

$$F(CCI) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{\exp(-u^2)}{1 + 10^{(z_d - 2\sigma_{eff}\mu)/10}} du \quad (3.24)$$

z_d and σ_{eff} are as defined for equation (3.22).

The two equations (3.22) and (3.24) are plotted in Figure 3-4.a and Figure 3-4.b respectively. It can be noticed that Rayleigh fading increases the probability of outage dramatically especially for low values of σ . For example, the outage probability for $\sigma=6$ dB and $z_d = 20$ dB is 10^{-2} with shadowing only, while the outage increases to 7.4×10^{-2} when Rayleigh fading is accounted for. The effect of Rayleigh fading can be mitigated by diversity techniques. Results derived in this section can be used in cases where there are more than one interferer. This is so because, as was shown in section 2.3, the overall distribution of sum of log-normals is very well approximated by a lognormal distribution.

It can be also noticed that the co-channel interference is quite high for relatively small frequency reuse factors. For example, for 10^{-2} outage $z_d = 20$ dB. But $m_{od} - m_{oi}$ for a cluster size of 3 is about 9 dB. Thus the receiver should work with a protection ratio equal

Figure 3-4: Co-channel interference probability (single interferer) [63].

to -11 dB. For a cluster size of 7 the protection ratio is about -4 dB. These SIR threshold values are much lower than the ones for typical TDMA/FDMA systems.

3.2.3 Co-channel Interference Results

To obtain co-channel interference probability results, a large floor is assumed to be uniformly divided into square microcells or domains. Each domain has a side of $\sqrt{2}R$ unit of length. Base stations or service ports are assumed to be located at the center of those domains. For the calculation of the outage probability, the user of interest is assumed to be located at the corner of its domain. The base station serving that domain compares the ratio of the received instantaneous power from the user of interest, P_d , to the sum of interferers powers, $\sum P_i$, to the SIR threshold value, γ_{dB} . The interferer is assumed at the center of the co-channel domain. At this stage the portable and service ports are assumed to have omni-directional antennas, i.e. the service port receives power from all directions.

As for the frequency reuse plan, Figure 3-5 summarizes the scenarios used. Since low frequency reuse factors are of interest only $C = 2, 4$, and 9 are considered. The figure also lists the number of interferers and their distance from the domain of interest, for the first four tiers of co-channel domains. All interferers are assumed to be active at all times. Results are shown in Figure 3-6 for $C = 2, 4$, and 9 . All the 4 layers (20 interferers) of interferers are assumed active. The standard deviation of the shadowing process, σ is taken to be 6 and 12 dB. The graph shows a strong agreement between the Monte Carlo simulation and the approximation described in the previous subsection. The approximation is carried out by replacing the sum of interferers by an equivalent interferer whose parameters are obtained using Schwartz and Yeh method. Then Rayleigh fading is imposed on this artificial component and equation (3.24) is used to evaluate the co-channel interference. As for the simulation results, they are averaged over 2×10^5 iterations where the interferers are assumed to be positioned at the centers of the co-channel domains. The results show that the first percentile of the outage figures occurs at extremely low values of protection ratio, γ_{dB} . Furthermore, the standard deviation of the co-channel component, σ , affects significantly the outage and so does the cluster size.

The effect of the tiers of the rings in strengthening the interference component is investigated for the case of $C = 4$. It is found that the source of most of the interference

power is the 1st tier and maybe the 2nd. Further tiers to the outside have negligible contribution. This is more accurate for smaller σ . In all the produced results the path loss exponent α is assumed to be equal to 3.5. As shown in [15] the outage probability is reduced as the exponent α is increased. This is a direct consequence of the fact that the signals becomes more confined to their domains. The reverse is also true. The effect of tiers of co-channel domains and their contribution to the interference probability is depicted in Figure 3-7. The figure shows also the effect of the path loss exponent α .

Figure 3-5: Squared-microcells layout and tiers of interferers.

Figure 3-6: Co-channel interference probability for different squared-microcells layout considering the first four tiers of interferers (omni-directional antennas).

Figure 3-7: Influence of the tiers of interferers and path loss exponent on the outage probability for a cluster size of four.

3.2.4 Macro Diversity and Sectorized Antennas

One can not but notice that the co-channel interference is exceptionally high for a typical range of SIR threshold values say 5 to 20 dB. However, the actual situation is not as grim as was presented. The portable, which is assumed at the corner of the domain of interest, is at the same minimum distance from four different base stations (primary servers). Each of these can provide service to the portable, if the transmissions are distinguishable. Due to the symmetry and the fact that each of the primary servers is associated with a different set of interferers fading independently, for a cluster size of 4, the overall outage probability is reduced to

$$P_1 = (\text{Prob} [S_{dB} - I_{dB} < \gamma_{dB}])^4 \quad (3.25)$$

This relation is depicted in the previous Figure 3-7. Higher orders of macro diversity are investigated by Cox in [15] but the method and results are evaluated for relatively greater values of frequency of reuse.

To evaluate the effect of macro diversity and sectorized antennas a Monte Carlo simulation is performed. In this case the user of interest is positioned randomly in the domain. Also, 20 co-channel users are positioned randomly each in its respective co-channel domain. All users and base stations are equipped with an antenna with S sectors. Since an ideal antenna characteristic (i.e. a sector only receives from the illuminated area) are assumed, the position of the co-channel user determines the antenna sectors combination used on the link between him and its domain. The user of interest may communicate with the base station in its domain or the nearby domain(s). The order of the macro diversity is 2 for cluster size of 2, and for cluster size of 4 it is 4. Signals' powers (with shadowing and Rayleigh fading imposed) are measured and SIR is computed at each of the potential home base stations for the user of interest. The greatest SIR value is picked as the one for the communication link. If this SIR is less than some protection threshold γ then an uplink outage event is registered. For the next iteration new random positions for users are generated and the whole process is repeated. The results generated are for 10^5 iterations.

Equation (3.25) can not be used to evaluate the macro diversity in the case described above. This is because the user of interest is not on the domain's corner and thus does not have identical chances of homing to each of the potential base stations. Results for cluster

size, $C = 2$ and 4 with different number of antenna sectors are summarized in Figure 3-8. The solid lines correspond to the result when the standard deviation of the shadowing process is taken to be 6 dB, whereas, results shown by the dashed lines consider $\sigma = 12$ dB. Figure 3-8.a shows that even for a cluster size as low as 2, with enough antenna sectors (6 or more), 10^{-2} outage can be achieved at very practical values of protection ratio. For example, for $S = 6$, 99% of the time the instantaneous SIR is greater than 4 dB even for a severe shadowing process with $\sigma = 12$ dB or greater than 10 dB for $\sigma = 6$ dB. The relationship between the number of antenna sectors and the protection ratio γ^* at which the 99% availability is possible is depicted in Figure 3-8.c. One interesting note is that the shadowing process ceases to be a significant factor in determining γ^* when the number of antenna sectors is greater than some number S^* . It seems that S^* equals 12 sectors for $C = 2$ whereas it is about 6 sectors for $C = 4$.

Figure 3-8: Outage probability with macro diversity and sectorized antennas.

4

Multiple Access Protocol

4.1 Introduction

As stated in Chapter 2, there is a growing need for wireless high speed networks that are capable of providing multimedia services. These high speed networks are seen as an extension of the already growing span of ATM networks. The goal of this thesis is to suggest a wireless architecture of a wireless broadband communication network that is capable of providing a wireless transport medium to communicate ATM traffic between terminals/ transportables (or sometimes referred to as users) and service ports. Carrying the intended services over the wireless medium and maintaining the quality required for multimedia applications is presenting new challenges that were not dealt within the first and second generation wireless communication systems. The indoor channel and the targeted frequency band, are the sources of communication impairments that should be alleviated by proposed architecture so that a user sees a transparent medium extending from his/her terminal to the other end of the communication link. The material found in this chapter is also published in references [45] and [46]. The second reference, compared to the first one, contains more detailed description of the protocol and describes interference monitoring and admission control procedures that are used to obtain the results presented in Chapter 6.

The architecture and the design of the multiple access have been influenced by many factors. These factors include:

- 1) The system coverage area is divided into microcells or domains of relatively small radii of 30~50 meters and those can shrink to about 10 meters in situations of dense portable user populations. A base station or service port is positioned in

each domain and acts as an access point to the ATM network. Terminals generate ATM traffic that is processed before it is carried on the wireless link. Processing is required to combat wireless link impairments. At the base station the processing is undone and the original stream of ATM cells is recovered and forwarded to the ATM network.

- 2) Broadband services require high bandwidth which is available at the 20 to 60 GHz range. Favorable regulatory circumstances exist for this band. Unfortunately, at this high frequency it is difficult to realize cheap and stable frequency sources or synthesizers. Thus it is assumed that the base stations and portable will only be using few frequencies: 3 or 4. That is the frequency reuse plan of the system is 3 or 4. Another limitation is the wide bandwidth required by the proposed anti-multipath modulation (commutation signaling) for this system. Furthermore, a fixed frequency plan is intended for the system. Base stations may change the frequency assignment at a slow pace every day or so after negotiations to minimize interference.
- 3) A wide range of multimedia traffic is expected. Variable bit rates as high as 20–30 Mb/s for high resolution compressed video and large files transfers and as low as 64 Kb/s for voice and facsimile services should be supported. This is in addition to the intermediate rates of 1–5 Mb/s that may be used for VCR-quality video among other applications. Traffic generated by these applications is packetized into ATM cells producing a constant or bursty rate of ATM cells depending on the nature of the traffic source. The wide range of bit and/or packets rates and the independence of the traffic sources rule out the consideration of purely contention-based multiple access techniques such as ALOHA or CSMA, or slot-reservation schemes like PMRA. A study of CDMA/ALOHA based technique, with moderate processing gain and no power control, is found in [87]. The study found out that the capacity of ALOHA/CDMA is about 8% of that of the raw wireless trunk rate. This is well below the non-interference-limited capacity.

- 4) Base stations and terminals access a trunk of 160 Mb/s and thus the required transmission bandwidth is on the order 160 MHz. If CDMA is considered then the use of processing gains as high as 100 translates into a bandwidth in the order of 16 GHz which is quite large and difficult to process. Even moderate processing gains such as 10 will yield a bandwidth of 1.6 GHz and that may result in great difficulties when the performance is to be enhanced through power control. Studies in [88], [75], and [85] indicate that a time-slotted multiple access is preferred to the moderate processing gain CDMA for broadband wireless indoor communication systems. However, spreading may be used to combat multipath [78][39].
- 5) Unequal access to the wireless link is granted to the different terminals depending on the traffic rates, priority schemes, quality of service, etc. Furthermore, the system should be able to adapt to sudden changes in traffic demand. This suggests a dynamic form of multiple access.

4.2 Polling-Based Multiple Access Technique

Considering the above mentioned factors, it was decided to use a dynamic polling-based TDMA scheme at least in the scope of this study. While other alternatives may still be used in other studies under CTR. The polling schemes also been chosen for other broadband LAN applications [86][32]. In addition to its simplicity, this type of central-control scheme allows the base station or server to possess a global view of the traffic conditions of all the portables in its domain without much cost and thus be able to provide the required degree of agile adaptability to sudden changes of load. The base stations and portables are equipped with sectorized antennas to combat co-channel interference. For the duration of a communication session the portable and the base use a specific combination of sectors that may be changed in cases where the propagation environment changes or a new co-channel interferer comes on line. In addition to being able to handoff from one sector to another on the same base station, the portable may choose to handoff from one base to another. The importance of the role of the combination of antenna sectorization and macro diversity (similar here to handoffs) was highlighted in section 3.2.4. The Motorola Altair system [5] uses a similar sectorized antenna approach.

Traffic cells from portables to base station (uplink) and traffic from base station to portables (down link) are transmitted in separate time slots within the proposed frame along with control envelopes. These transmissions are referred to as wireless envelopes. This means that a time-division duplex (TDD) method is used to multiplex the uplink and down link transmissions on the same wireless channel. This is in contrast to frequency-division duplex (FDD) where two different carriers are used; one for each direction. Considering the frequency band of interest and the state of the technology for millimeter-wave devices, TDD is more appropriate since it requires only one frequency synthesizer and receiver/transmitter hardware set.

4.2.1 Frame Format

Time axis is divided into slots of different durations depending on the transmission type. The base station in each domain is responsible for organizing the uplink and down link transmission into frames of fixed duration. The frame structure is shown in Figure 4-1.

As can be seen, the TDMA frame is divided into a sequence of S (S is the number of antenna sectors) subframes or sector segments. Each sector segment is started with a beacon envelope corresponding to an antenna sector and is transmitted using that particular sector. The envelope contains a synchronizing word specific to its sector. Following each beacon signal is a number of pre-specified registration slots. The remaining portion of the subframe is used for traffic transport between the base station and the portables. During each of the sector segments only the corresponding antenna sector is used for reception and transmission. Portables in a base station antenna sector coverage area are subscribed to the subframe of that sector. Thus the lengths of these subframes are not equal, but is proportional to the traffic demand of the serviced portables. However, the sum of all their lengths is fixed and equal to the frame length. The structure of the subframe is discussed in section 4.2.3.

Figure 4-1: Overall frame format.

Scheduling of the sector segments can be done in at least three ways. The first option is to make the order of the segments the same in every frame. This fixed strategy, may prove unfair to some portables since users on some sector segments will suffer from high co-channel interference and conditions will not improve until the segment is changed. On the other hand, other segments may have little or no interference. Secondly, the base station may choose to randomize the order of these subframes and thus any co-channel interference is essentially independent from frame to frame. This facilitates forward error correction or detection and retransmission procedures under conditions of heavy interference. Thirdly, the order of the sector segments can be chosen so that co-channel interference is minimized. This means the base station plans the order based on measurements of interference power (done at the base or by subscribed portables). This can be done by each of the base stations independently or through some coordination. The later assumes some form of communication among the base stations. The second strategy is chosen for analysis and simulation as described in the next chapters.

4.2.2 Beacon envelopes and Monitoring Function

In the first portion of every subframe the base station transmits beacon signals; one on every antenna sector at a fixed power level. These beacons enable the listening portable to determine and choose the best sector in terms of propagation conditions and traffic capacity availability. The beacon envelopes are transmitted at fixed power and their order is random (same with sector segments) so that the co-channel interference is independent. Also all frames are synchronized to start at the same time. All these factors help the portable to determine relative power from each base station. They also allow it to obtain a rough estimate of the signal to interference ratio (SIR).

Each beacon envelope contains a synchronization word characteristic of the particular antenna sector, a base station identifier, a sector identifier, the number of registration slots to follow, a list of terminals being polled in that frame, and current traffic status information for that sector.

During one or more of the beacon slots the portable can switch through its S antenna sectors and form a table of estimated channel quality figures. These figures may include relative power, expected SIR, and traffic conditions on the segment. When there are multiple paths and reflected components for the transmitted signals then the number of entries in the table is S^2 per carrier frequency. The time it requires the portable to collect

this information is a function of the time it requires to estimate power and the frame length as well.

When a portable is first powered on, it listens on its antenna sectors to evaluate potential home base stations. It also continues to listen on its sectors even after it tuned to a base/sector combination. It does that to evaluate alternative base stations for future handoffs when the link quality deteriorates. For each base/portable sector combination, the base signal level is determined from the corresponding beacon envelope. During times when the portable is not communicating with its own base, it passively monitors each of its own sectors. What it hears on each sector is potential interference from other portables and base stations picked up by that sector and, by reciprocity, potential interference from it to those other base stations and portables. It varies as the sector segments are randomly reordered, and as traffic fluctuates, but by averaging it the portable can form and update a table of current average signal to interference (SIR) levels, one for each of its antenna sectors. One entry for the i^{th} sector is p_i , the fraction of time the SIR is less than a certain threshold. After the listening period is over in the call set up stage, the portable ranks the base/sector combinations using p_i and SIR figures and attempts registration. It may happen that the best candidate combination is of poor quality figures then the portable is blocked. For a portable considering handoff, it maybe forced to drop the connection if a satisfactory link quality can not be found and the bad conditions on its current link persisted.

Once a portable decides on a base/sector combination it attempts registration by sending an uplink request cell in one of the pre-specified registration slots designated for the sector of interest. Such requests can come from previously unregistered portables, or from portables currently homing on a different base station and/or frequency, who wish a handoff to this frequency/base station/sector combination. Access to the registration slots is contention based and is done in a manner similar to that of slotted ALOHA protocol. That is the portable chooses, randomly, one of these slots and sends its registration request, which is a control envelope containing a synchronization word, the portable identification, the traffic related information. The latter consists of the rate it wishes to be polled at (e.g. once per frame, once every two frames, etc.), its traffic class and priority, and the transmit power level it requests from the base station. The positive acknowledgment or negative acknowledgment of the registration may be sent by the base station implicitly in the corresponding beacon signal in the next frame. Alternatively, those may be sent in the broadcast envelopes of the corresponding sector segment. Portables that experience collision or severe interference condition at the receiving base station try again the

registration procedure in the next frame. An indication of collision is the absence of the base station response for a certain duration of time, or time-out. The attempt of registering in the next frame assumes that the contention on the registration slots is negligible. However, if this is not the case, the base station may increase the number of those slots and/or portables resort to standard backoff procedures where the time of the next attempt is determined using a random process.

4.2.3 Polling Protocol in each Sector Segment

The structure of the sector segment is shown in Figure 4-2. The traffic part of the segment starts by a down link control envelope. The control envelope is followed by a number of down link broadcast envelopes. These envelopes carry information for all portables tuned to the corresponding antenna sector. The number of broadcast envelopes is communicated in the previous control envelope. After that the base station starts the polling cycle. Each user is polled according to the Gated-Limited service strategy [70] where the portable is allowed to transmit up to Y (Y is a positive integer) traffic cells in each cycle. Not all users subscribed to a particular subframe are polled in every frame. The frequency of polling is dependent on the traffic requirements of the portable and also on the traffic capacity available in that domain. The base uses the registration request to determine the initial frequency of polling.

For the i^{th} poll interval, the base station transmits a polling envelope which contains the identity of the destination portable, the maximum number of down link traffic envelopes to be transmitted to the portable, the maximum number of uplink traffic envelopes the portable is allowed to transmit in the current cycle, and a positive or negative acknowledgment of the uplink traffic envelopes sent in the previous cycle. The portable then receives the specified number of down link transmission and replies with an uplink control envelope. Finally, the portable can send (if it has traffic) a number of uplink envelopes not exceeding the maximum allowed. The portable uses the uplink control envelope to positively or negatively acknowledge the down link traffic envelopes. It also uses it to indicate to the base station if more or less bandwidth is required. This means that latency of responses from the base station to changes in the rate of traffic arrival at the portable are at least one frame. The polling interval is depicted in Figure 4-3.

Figure 4-2: Sector segments structure.

Figure 4-3: A polling interval with ARQ.

4.2.4 Error Control

Error control procedures are usually an essential part of the transmission transport where reliable communications are desired. This is the case with the wireless indoor channel: with impairments: fading, multipath (ISI), thermal noise, and server co-channel interference, error control procedures are more than essential to provide a transparent medium. Interfacing these wireless networks with ATM backbone networks means that the overall performance of the wireless segment should approach that of the typical wired ATM connection: low bit rates and cell loss probability, and limited delay. For example, error control procedures should be able to change the envelope loss probability from, say on the order of 10^{-2} or even 10^{-1} , to about 10^{-3} for synchronous services and to about 10^{-8} or less asynchronous services. Factors to be considered also in evaluating the procedures are the complexity, cost and the added delay to traffic stream. The procedures should also use minimal bandwidth leaving the greater part of the capacity for portables' use.

Given that the traffic transmissions on the wireless channel with envelope sizes anywhere from 400 ~ 600 bits ($2.5 \mu\text{sec} \sim 3.75 \mu\text{sec}$ at 160 Mb/s), events occurring on the channel can be classified into slow and fast events. Changes in propagation conditions are slow whereas, noise and co-channel interference are fast since they differ from one time slot to another. The slow impairments are dealt with most effectively by changing antenna sectors and/or handoff to another base station. This makes use of the macro diversity. To combat the noise and interference forward error correction (FEC), error detection and retransmission, or a combination of both can be employed.

Code diversity combining techniques have been studied in [10][68] and are promising. Exploiting macro diversity, each microcell is equipped with more than one antenna port and base station decides on the transmissions after the multiple copies of the coded envelope are received and decoded. However, the cost and complexity of this technique should be weighted against its advantages. Another FEC technique is Reed-Solomon (RS) coding where the transmitter accumulates m traffic cells and codes them generating n coded envelopes that are transmitted in different frames. Depending on the coding ratio, the receiver can still recover the original m cells even if some of the envelopes are lost. This procedure needs to be evaluated in terms of its resistance to interference and the added delay to the traffic stream.

As for error detection and retransmission, a cyclic redundancy check field can be used at the receiver to check for errors. Once an error is found a retransmission is requested. Variations of this ARQ technique have been considered for mobile radio systems in [47] [9] [30]. Especially a selective-ARQ version appears to be suitable and simple where only envelopes in error are retransmitted. The required overhead in terms of positive and negative acknowledgments can be carried over short control envelopes as explained in the previous subsection. Alternatively, these acknowledgments can be *piggybacked* i.e. embedded in the already exchanged envelopes. Since the propagation delay side-to-side of a service area of 50 meter in radius is only about 10% of the envelope transmission time, selective repeat transmissions can be acknowledged in the frame next to the one in which they were transmitted or some times in the same frame as it is the case with the down link traffic envelopes. The window size and the time-out parameters can be set to be equal to the round trip duration. An enhancement to the above pure ARQ scheme is to use hybrid ARQ [81] which employs a combination of FEC and retransmission.

4.2.5 Frame Length and Envelope Formats

To decide on the frame length, factors related to the propagation environment in addition to those related to the expected traffic services have to be considered. As mentioned in Chapter 3, channel measurements conducted by Bultitude in [7] indicated that the deep fades, occurring because of people movement and objects, last anywhere from ten to hundreds of msec and that the onset of a deep fade may take place in only a few msec. The observations are in favor of a frame length in the order of millisecond. Another factor that is also in favor of a short frame is the rate of temporal changes in the broadband traffic. On the other hand, the frame length should be long enough to avoid excessive overhead. It is expected that a frame length of length about millisecond to be appropriate.

The description of the multiple access suggested above, suggests the use of four different envelopes: beacon, polling, control and traffic envelopes. One possible format for all these envelopes is found in [46] and is as follows:

Beacon envelopes (32 bytes):	Sync words, characteristic of base and sector
	Base identifier
	Sector identifier
	Starting point of sector segment in current frame
	CRC

	Terminals polled in this frame
	Number of registration and broadcast slots
	Guard time
Polling envelopes (32 bytes):	Sync word, characteristic of base and sector Poll indicator and identifier of terminal being polled ACK/NAK of previous uplink envelopes Number of downlink envelopes to be sent Max. number of uplink envelopes allowed CRC
Traffic envelopes (64 bytes):	Sync word, characteristic of base and sector Envelope type (traffic) Sequence number Terminal identity Number of envelopes being sent this frame ATM cell, including ATM overhead CRC
Control and broadcast envelopes (32 bytes):	Sync word, characteristic of base and sector Envelope type (control) Sequence number Terminal identity ARQ information Management information, such as: <ul style="list-style-type: none">- request to set up, take down or change call status- request to change sector, base- traffic change request: priority or polling rate.- keep-alive for terminal with no traffic to send- Power control or current interference information- Current number of queued envelopes awaiting transmission

CRC

For 64-byte envelope durations, and for a transport bit rate of 160 Mb/s, the time duration of traffic envelopes is 3.2 μ s, and the time durations of beacon, polling and control envelopes are 1.6 μ s. To facilitate rapid adaptation to fades and changes in source bit rates, we propose a frame duration of about 800 μ s. A frame will in general include periods of silence due to guard times between uplink envelopes and to idle periods.

Recall that terminals are polled at a rate that is proportional to their average bidirectional bit rate. Hence if a 20 Mb/s terminal is polled once per frame, then a terminal with a rate R Mb/s is polled on average every $R/20$ frames. Of course, low bit rate terminals with stringent delay constraints may have to be polled more often than suggested in this scheme. The percentage of overhead per frame depends on the number of antenna sectors and on the average number of terminals polled per frame. Given the rate of polling described above, a terminal generates an average of 31.25 traffic envelopes per frame time. Assuming three overhead envelopes (beacon, registration and open poll envelopes) per sector segment and two overhead envelopes (poll and control envelopes) per terminal, the frame can support seven terminals on average, for 12 sector segments. The overhead in this case is $1.6\mu\text{sec} (3 \times 12 + 2 \times 7) = 80\mu\text{sec}$ or $80/800 = 10\%$ per frame. The overall efficiency assuming the 48 byte field of the data field of the ATM cell is encapsulated in 64 byte envelope is $(1 - 16/64) (1 - 0.1)$ which is 67.5%.

5

Performance Analysis and Approximations

5.1 Introduction

As mentioned in the previous chapter, the RF range proposed for this system makes the operation of CDMA in light of available hardware and technology quite difficult if not impossible. For the same reasons, multiple access methods based on multiple frequency carriers like FDMA are also ruled out. Furthermore, contention-based methods like ALOHA and CSMA-CA, in their simplest form, lead to unbounded delay and hence unsuitable for transporting real time traffic. They also suffer from low utilization and stability problems. However, some reservation protocols have been proposed for ATM-based networks (see for example [62]). In these protocols users or a particular group of users contend for time slots and then keep them for burst or call duration.

The above eliminated all but the schemes based on sharing the available capacity by dividing the time axis. This study opts for statistical TDMA as opposed to classical TDMA because of expected benefits when the temporal variation of traffic is considered. Statistical TDMA can be achieved through a variety of techniques one of which is polling. Polling methods are based on the idea of a central server cyclically serving multiple terminals (or queues). Polling has received a great amount of attention since the advent of computer networks. Many of the service disciplines used in the context of polling have been analyzed and studied. An example of these studies is found in [71][72].

Among the many service disciplines, three are the basic ones: Exhaustive, Gated, and Limited polices. In exhaustive discipline, the service continues until the queue is empty.

Then the server switches to the next user. In the gated strategy, the buffer is not necessarily emptied. Only traffic present in the queue at the instant of polling is served. While traffic arriving during service time is queued. In contrast to the previous two policies, the limited service is a preemptive one. That is, only up to a fixed number of traffic cells or packets are served every frame. Depending on whether traffic arriving during service is served or not, limited policy can be either exhaustive-limited (E-limited) or gated-limited (G-limited). Limited-1, where at most one cell is served if any, is the one of the most studied limited policies for its analytic tractability. Analysis of the above mentioned policies in continuous and discrete-time is presented in [72]. The analysis mostly assume Poisson arrivals and is tightly coupled with the analysis of M/G/1 queues with vacation as in [73].

In [70] the main service disciplines are surveyed and ranked in terms of traffic delay as a measure of performance. It is shown that exhaustive policy leads to the least delay while limited-1 is the best in terms of fairness. More recently, the study in [50] evaluated the mean and variance performance of some polling systems with bursty sources such as Markovian ON/OFF process or Auto Regressive Moving Average (ARMA) video models.

In view of the requirements of real-time traffic, non preemptive schemes like exhaustive and gated are not suitable for delay sensitive traffic. This is because the cycle time is statistically unbounded. This study proposes a gated-limited method where a service limit of Y cells is imposed by the central server.

The intention of this chapter is to provide some approximate performance measure for the proposed multiple access, in view of the condition of the wireless indoor environment, considering a variety of traffic models. The queuing models discussed here approximate the behavior of the system by considering a one-microcell one-terminal situation. The effect of the external environment (such as interference and traffic conditions of other users) are all represented by two parameters, α , the probability that a transmission is corrupted by interference, and Y , the portion of the fixed-length TDMA frame the user of interest is allowed to occupy. While the first parameter, α , reflects, mainly, the quality of the wireless link and signal propagation, the second parameter, Y , reflects the capacity constraint and the traffic activity in the network. The following analysis will only consider the effect of α and Y on the performance of the network, but not the relation between them.

The analysis assumes a fixed-length frame that is divided into S sector segments or subframes. The user of interest is registered to one of these S subframes and a polling token is transmitted to him every time the subframe is scheduled for service. The position of the

user (assumed at the beginning of the subframe) within the subframe is fixed; however, the position of the subframe within the total frame is random. This gives rise to randomness in the inter-polling or intervisit time. Furthermore, it is assumed that the service limit for the user of interest is fixed and does not vary from a poll to the next. In case the user uses a number of time slots less than the service limit, then the remaining time slots are wasted. This produces a worst case scenario, since in a real system the service limit adapts to the needs of the user (defined by the variation in the instantaneous bit rate or the number of traffic cells waiting for transmission). Also, the unused time slots after a poll can be used to increase the service limit of the users who are yet to be serviced. The service limit adaptability is examined by simulations in the next chapter.

In addition to the analysis presented here, simulation results for the one-microcell one-user are used to support the analytic results and show that some of the approximations performed do not compromise the accuracy of the analysis. Results obtained throughout this chapter such as mean buffer size, mean traffic delay, full buffer occupancy probability (for the finite buffer case), utilization, etc. are useful in predicting the performance of the whole system which is simulated in the next chapter. Another important application of the derived formulas is in the design of the call admission procedure used at the base station controller. Next chapter will show that call admission procedure is one of the most critical procedures that highly affect the call block and call drop probabilities. A newly registering call will request a connection specifying its traffic parameters, such as bit rate statistics, and the acceptable quality of service. The controller then uses these parameters and the results of this chapter to compute some of the parameters of the expected quality of service, such as mean buffer size, average traffic delay, etc. The call is accepted if the available quality of service is equal or greater than that of the requested one. In some situations, a lower quality of service can be negotiated.

The organization of this chapter is as follows: first the basic queueing model is detailed. The second section describes the TDMA frame and the intervisit time, an important parameter that modulates the traffic arrival process to the queue. Traffic models are characterized in the third section. Then queueing analysis results are presented. The analytic details are contained in Appendix C. Only final results are shown here.

5.2 Queueing Model

As mentioned in the introduction, this section is going to present a simplified and approximate model for the proposed multiple access. Consider the queueing system

shown in Figure 5-1. In this system the cyclic server¹ sends a polling token to a wireless terminal (or user) every TDMA frame, which is correctly received with probability $(1 - \alpha)$. The polling token is corrupted by radio frequency interference (RF) from other transmissions with probability α . FL is the TDMA frame duration. The server allocates Y time slots for the terminal to transmit its traffic in the form of wireless envelopes. The service discipline considered here is the Y -limited gated discipline. That is, the traffic cells transmitted in a polling cycles are only those found in the terminal buffer at the instant the polling token is received and their number can not exceed Y . Let x_i be the buffer size (or the queue length) of the terminal upon receiving the polling token for the i^{th} time. The terminal determines the number of transmissions according to

$$b_i = \min(x_i, Y) \quad (5.26)$$

The wireless terminal generates traffic according to some model. Let the number of traffic cell generated during the intervisit time (from the $(i-1)^{\text{st}}$ to the i^{th} polling token receiving instants) be n_i cells, also let the number of traffic cells that were transmitted in the $(i-1)^{\text{st}}$ cycle and need to be retransmitted because of interference is l_{i-1} . Then the queue evolution equation can be written as

$$x_i = \begin{cases} 0 & i < 0 \\ n_i & i = 0 \\ x_{i-1} - b_{i-1} + l_{i-1} + n_i & i = 1, 2, \dots, \infty \end{cases} \quad (5.27)$$

The above assumes the presence of a modified selective automatic repeat request (S-ARQ) control for the transmissions between the base station and the terminal. Information pertaining to this data link control method are part of the polling token or transmitted separately on a wireless control envelope.

5.2.1 TDMA Frame and Intervisit Time

This analysis will assume a fixed length TDMA frame of length FL time slots, and the frame is divided into S sector segments that are randomized in order. A terminal is only

1. The terms server and base station will be used to denote the same entity.

polled in the sector segment in which it has registered. The intervisit time, I is defined as the duration between two consecutive polls. Here two distinct situations are recognized. The first is when the sector segments are equal in length. This is the case when traffic load is spatially symmetric, i.e all sectors of space are equally utilized. The second case, assumes that only one sector segment is occupied while the remaining ones have very little or no traffic. This case will be referred to as the asymmetric case. In Appendix C.1 the intervisit time distribution under the first assumption its generating function is shown to be

$$I(z) = M(S_1(z)) \quad (5.28)$$

where $M(z) = \frac{z(1-\alpha)}{1-\alpha z}$ for $|\alpha z| < 1$ and $S_1(z) = \sum_i e_i z^i$,

$e_i = \text{Prob [Intervisit Time} = i \text{ time slots given no token loss]}$

$$= \begin{cases} k/S^2 & i = k(FL/S), k = 1, 2, \dots, S \\ (2S-k)/S^2 & i = k(FL/S), k = S+1, \dots, 2S-1 \\ 0 & \text{else} \end{cases}$$

Figure 5-1: Queueing model.

A sector length in this symmetric case is FL/S time slots; FL is the length of the TDMA frame in time slots. Whereas it is given by

$$I(z) = M(S_2(z)) \quad (5.29)$$

when the asymmetric traffic condition is used. $S_2(z) = \sum_i e_i z^i$ and

$$e_i = \begin{cases} k/S^2 & i = kS_1, k = 1, 2, \dots, S-1 \\ (2S-k)/S^2 & i = kS_1 + S_2, k = 1, 2, \dots, S \\ 0 & \text{else} \end{cases}$$

S_1 and S_2 are the lengths of the free and busy sector segments, respectively. Note that, $FL = (S-1)S_1 + S_2$. The last distribution (equation (5.29)) can be closely approximated by the geometric distribution, i.e

$$I(z) = M(z^{FL}) \quad (5.30)$$

when S_2 is much greater than S_1 .

Figure 5-2 depicts some probability mass functions of the intervisit time for two values of cell loss probability: 1% and 10%. The frame is assumed to be 204 time slots in length (0.66 ms at 155.5 Mb/s) and is divided into 6 sector segments. It can be noticed that for the asymmetric case, the distribution can be approximated by a geometric probability mass function (pmf) whose mean is given by $FL/(1-\alpha)$. That is, the intervisit time in this case is roughly the frame length or multiples of the frame length.

Figure 5-2: Intervisit time, I , distribution for symmetric and asymmetric case considering two values for cell loss, α . Frame length, FL , is 204 time slots (0.66 ms at 155.5 Mb/s).

5.3 Traffic Models

It is of interest to find the performance of the system under many traffic conditions varying from relaxed ones to severe conditions on the other end of spectrum. Intuitively, burstiness, a characteristic exhibited by key services such as compressed videos and file transfers, gives rise to much worse performance when compared to responses to non bursty traffic. Although the mathematical underlying cause of burstiness in a traffic model is very complex, two main sources of burstiness are recognized: The first is the tail of the marginal distribution, and secondly, the autocorrelation or temporal dependences amongst arrivals. In [42] Livny et al. describe the impact of autocorrelation on the performance of queueing systems.

The types of models covered in this section can be categorized into two groups: The renewal type models, and the non-renewal type models [25]. In the first category Bernoulli and generalized Bernoulli models are considered, in addition to the periodic or constant bit rate model. Whereas, the second group contains the exponential ON/OFF and the Markov models. Historically, queueing theory dealt with the renewal offered traffic type. In this type, the autocorrelation function vanishes identically to zero for all non zero lags. Thus the only factor that influences burstiness in these models is the shape of the tail distribution. These renewal models are tractable analytically and one can, in most cases, find a closed form solution to the queueing problem at hand. When it comes to the non renewal models such as Markov and Markov-renewal models, temporal dependencies are introduced to the arrival sequence and potentially, these models can give rise to more burstiness than renewal type models. On the downside, as expected, closed form solutions are very difficult to obtain in most cases. However, there exist some techniques through which analytic results can still be obtained in the form of curves. Matrix Geometric method is one of those techniques. Unfortunately, this method quickly turns into a prohibitive computational task as the size of the queueing problem grows larger and larger.

Below is a description of the above listed models and characterizing of the arrival process when modulated by the polling process. That is the final probability mass function of the number of cells arriving during the intervisit time is evaluated. Details of the derivations for some models are found in Appendix C.

5.3.1 Bernoulli Traffic Model

This simple model assumes that a traffic cell (48 bytes of user data) arrives at any time slot

(of duration $500/R_{\text{total}}$ seconds; R_{total} is the link bit rate) with probability ϵ and is given by

$$\epsilon = \frac{R}{\frac{48 \times 8}{500} \times R_{\text{total}}} \quad (5.31)$$

where R is the source bit rate. Traffic cells arrivals are independent from one another. For example, for a 10 Mb/s source, ϵ is equal to 0.0837 (when $R_{\text{total}} = 155.52$ Mb/s). The generating function for the pmf of the modulated arrival process is given by

$$A(z) = I(1 - \epsilon + \epsilon z) \quad (5.32)$$

5.3.2 Generalized Bernoulli Traffic Model

As opposed to the previous model, traffic cells may arrive in batches at the beginning of the time slot with probability $\tilde{\epsilon}$, where

$$\beta \tilde{\epsilon} = \frac{R}{\frac{48 \times 8}{500} \times R_{\text{total}}} \quad (5.33)$$

β is the burst size (or average burst size). It is noted that if peak rate of the source is a fraction of the total link capacity, then more than one cell arrival in a time slot is not possible. However, this model may be justified if groups of cells are processed before being stored in the output buffer of the terminal.

The burst length, β , can be fixed for a particular source or allowed to assume any discrete random variable distribution. The two cases that are going to be considered here are when β is fixed and when it is geometrically distributed. When the burst has a constant length, β , then it can be easily seen that the generating function of the pmf is given by

$$A(z) = I(1 - \tilde{\epsilon} + \tilde{\epsilon} z^\beta) \quad (5.34)$$

However, when the batch size is geometrically distributed, the function is

$$A(z) = I(1 - \bar{\epsilon} + \bar{\epsilon} \frac{(1 - \xi)z}{1 - \xi z}) \quad (5.35)$$

where $\xi = 1 - 1/\beta$.

5.3.3 Periodic Traffic Model

If the source has a constant bit rate, it generates p ($p < 1$) cells every time slot (1 traffic cell every $\frac{1}{p}$ time slots). Hence during k time slots there will be $\lfloor pk \rfloor$ new traffic cells in the terminal's buffer, i.e the generating function is

$$A(z) = I(z^p) \quad (5.36)$$

$\lfloor x \rfloor$ is the greatest integer less or equal to x .

5.3.4 ON/OFF Exponential Model

According to this model, the traffic source switches between two states: ON and OFF. While on the ON state, the source generates information at a constant bit rate, whereas, its rate is zero when in the OFF state. The duration of the time it spends in either of these states is exponentially distributed with mean m . If T is defined to be the duration of the time the source is in active state for a given intervisit time, I , then it can be shown that T is distributed as

$$p_{T/I}(t) = \frac{\exp(-I/m)}{2} \left[\sum_{n=1}^{\infty} \frac{1}{m^n a_n! b_n!} \cdot (t^{a_n} (I-t)^{b_n} + t^{b_n} (I-t)^{a_n}) \right] \quad t \in (0, I) \quad (5.37)$$

$$+ \frac{\exp(-I/m)}{2} [\delta(t) + \delta(t-I)]$$

The quantity b_n is equal to the integer part of $n/2$, while a_n is equal to $(n-2)/2$ if n is even or $(n-1)/2$ if n is odd.

A special case of interest here is when the average duration of the ON/OFF periods is much greater than the average intervisit time, in this case only first few terms of the

summation in $p_{T/I}(t)$ are significant. When only the first two terms are taken into consideration the probability distribution function (pdf) reduces to

$$p_{T/I}(t) = \frac{1}{m} \left[1 - \frac{I}{2m} - \frac{I^2}{2m^2} \right] + \frac{\exp(-I/m)}{2} [\delta(t) + \delta(t-I)] \quad t \in (0, I) \quad (5.38)$$

Using the above two relations, one can compute the discrete pmf of the arrival process, $A(z)$, by integrating the function $P_T(t)$ over the interval $[n, n+1)$ to evaluate the probability of n cells arriving. Since $P_T(t)$ is in the form of power series plus some delta functions, the integration can be carried out without incurring numerical errors.

5.4 Queueing Analysis

Examining the queueing model depicted in Figure 5-1, under the Y -limited gated service discipline, the queue has the evolution equation (5.27). Furthermore, the sequence $\{x_i; i = 1, 2, \dots, \infty\}$ constitutes a Markov Chain. Defining the steady state probability distribution of the buffer size, at the polling instant, to be

$$q_k = \lim_{i \rightarrow \infty} \text{Prob}(x_i = k) \quad ; k = 0, 1, \dots, \infty \quad (5.39)$$

and $Q(z)$ to be the probability generating function, then it can be shown that

$$Q(z) = \frac{A(z) \left[z^Y \sum_{j=0}^{Y-1} q_j \cdot L_j(z) - Q_Y(z) \cdot L_Y(z) \right]}{z^Y - A(z) \cdot L_Y(z)} \quad (5.40)$$

where the function $A(z)$ is listed in the previous section for different kinds of traffic models, $L_k(z); k \in \{0, 1, \dots, Y\}$ is a generating function representing the ARQ process, and $Q_Y(z)$ is a function related to the service discipline. The detail of the functions appearing in equation (5.40) as well as the mean and mean square expressions are explained in Appendix C.

5.4.1 Mean Queue Length Results

Using formulae developed for the queueing model, the effect of utilization and cell loss probability on both the mean queue length and variance of queue length is studied. From the traffic models section, one can see that the average offered load to the system is given by $\bar{a} = \lim_{z \rightarrow 1} A^{(1)}(z)$ which is equal to the average number of traffic cells presented to the system each service cycle. The number of service slots available each cycle is Y . Hence, the average traffic intensity can be defined by

$$\rho = \frac{\bar{a}}{Y} \quad (5.41)$$

From Appendix C, the condition for the existence of the queue pmf is that $\bar{a} < (1 - \alpha)Y$, which means ρ can vary from 0 to $(1 - \alpha)$. Using the above notions, the results for mean buffer length and variance of buffer length are depicted in Figure 5-3 through Figure 5-6 for different types of traffic models and for two values of cells loss probability, namely, 10% and 1%.

It can be noticed that the two figures, the mean and the variance, increase slowly for small values of the traffic demand, and then exponentially when ρ approached $(1 - \alpha)$. Also, it is observed, that the Simple Bernoulli and the exponential ON/OFF with 0.1 ms. models have lower mean and variances than the other models for the same traffic demand. The batched-Bernoulli model have greater mean and variance than the exponential ON/OFF with 1.0 ms. for traffic intensities less than 50%. The positions are reversed for intensities greater than 50%.

Figure 5-3: Mean buffer size for different traffic models and with 10% cell loss probability (solid-line: simple Bernoulli model, dashed-line: batched Bernoulli model with mean burst size equal to 5 cells, dotted-line: ON/OFF model with mean ON/OFF period equal to 0.1 ms., dashed-dotted-line: ON/OFF model with mean ON/OFF period equal to 10 ms.

Figure 5-4: Mean buffer size for different traffic models and with 1% cell loss probability (solid-line: simple Bernoulli model, dashed-line: batched Bernoulli model with mean burst size equal to 5 cells, dotted-line: ON/OFF model with mean ON/OFF period equal to 0.1 ms., dashed-dotted-line: ON/OFF model with mean ON/OFF period equal to 10 ms.

Figure 5-5: Standard deviation of buffer size for different traffic models and with 10% cell loss probability (solid-line: simple Bernoulli model, dashed-line: batched Bernoulli model with mean burst size equal to 5 cells, dotted-line: ON/OFF model with mean ON/OFF period equal to 0.1 ms., dashed-dotted-line: ON/OFF model with mean ON/OFF period equal to 10 ms.).

Figure 5-6: Standard deviation of buffer size for different traffic models and with 1% cell loss probability (solid-line: simple Bernoulli model, dashed-line: batched Bernoulli model with mean burst size equal to 5 cells, dotted-line: ON/OFF model with mean ON/OFF period equal to 0.1 ms., dashed-dotted-line: ON/OFF model with mean ON/OFF period equal to 10 ms.

Table 5-1: Comparison between analytic and simulation results for mean and variance figures.
Utilization 78%.

ON/ OFF period (msec)	$\alpha = 1\%$				$\alpha = 10\%$			
	Analytic		Simulation		Analytic		Simulation	
	$\bar{q}$	σ_q	$\bar{q}$	σ_q	$\bar{q}$	σ_q	$\bar{q}$	σ_q
0.1	17.8	10.1	18.5	10.4	25.1	16.5	26.9	18.0
1	22.4	19.6	26.0	24.9	35.7	31.9	47.6	48.5
5	25.6	24.4	54.7	68.8	44.0	42.7	134.3	163.2
10	26.2	25.2	87.0	119.0	45.7	44.9	237.5	302.0

Another set of results are also shown in Table 5-1. It shows a comparison between the analytic and the simulation results for the exponential ON/OFF model. Simulation results are averaged over 10^6 iterations. The comparison shows that the analytic model provides good approximation of the performance of the system when the average ON/OFF period is one tenth or less of the average TDMA frame duration. However, the model greatly underestimates the buffer statistics when the average burst duration is comparable to the frame duration. The reason for this break down in the model is the increasingly introduced correlation in the arrival process with the increase of the burst length. The model analyzed above assumed independent arrivals from one polling cycle to the another. When the average burst length is comparable to the Intervisit time, then if the source is in the ON state when the i^{th} server visit occurred, with significant probability the source will still be in the ON state when the next visit occurs. That is the number of cells generated during the i^{th} and the $(i+1)^{\text{st}}$ intervisit times are not independent but correlated. It should be mentioned that when the other arrival models are used (all the ones described above except the ON/OFF model) the analytic results are exact.

In the next Section 5.5 a brief discussion on how to evaluate the system performance when the arrival process is fits or closely approximates a Markov Chain.

5.4.2 Tail distributions and Finite Buffer Results

The burstiness of the traffic model affects the tail of the buffer size distribution such that more burst models lead to longer distributions that decay at slower rates when compared to those generated by less bursty models. In Figure 5-7 some complementary cumulative distribution functions are given for some traffic models for a 10 Mb/s terminal ($\rho = 0.6$ roughly for all considered models). It can be noticed that the batched Bernoulli source has the longest tail, especially, when the batch sizes are geometrically distributed as opposed to constant size bursts. The slope of the complementary cumulative function decreases as the batch size increases. The shortest distribution corresponds to the case of constant bit rate source. In this figure, the exponential ON/OFF case is comparable to the simple Bernoulli case (the same as in the mean and variance results), however, the ON/OFF model becomes more bursty as the mean ON/OFF period increases as explained in the previous subsection.

Using the results developed in Appendix C for the finite buffer terminal, Figure 5-8 shows the probability that the buffer is full upon the visit of the server. Again, a 10 Mb/s terminal is considered and a service limit of 29 cells per polling cycle is enforced. As expected the batched Bernoulli model gives rise to the highest probability while the periodic model yields the smallest probability. This probability figure (buffer size equal to K at the polling instant) is proportional to the probability of dropping traffic cells due to lack of buffering space at the terminal.

Figure 5-7: Complementary cumulative distribution functions for buffer size with different traffic models using analytic results (Terminal rate = 10 Mb/s, cells loss prob. = 1% and service limit = 29 cells per polling cycle).

Figure 5-8: Probability of buffer being full for different traffic models: a) batched Bernoulli with mean batch = 5 cells and $\alpha = 10\%$, b) batched Bernoulli with mean batch = 5 cells and $\alpha = 1\%$, c) Bernoulli with $\alpha = 10\%$, d) periodic sources with $\alpha = 10\%$, e) Bernoulli with $\alpha = 1\%$, and f) periodic source with $\alpha = 1\%$.

5.4.3 Non-Uniform Polling Analysis

The strategy on the nonuniform polling was introduced in the previous chapter. According to this strategy a low bit rate terminal is polled less frequently than high bit rate terminals. If a low bit rate terminal is serviced every $\Psi \geq 1$ basic cycles (basic cycle corresponds to the fixed frame duration of FR time slots), then the probability generating function of its intervisit time, $I_\Psi(z)$ is related to the PGF of the intervisit time of the basic cycle, $I(z)$ by

$$I_\Psi(z) = z^{(\Psi-1)FR} I(z) \quad (5.42)$$

In relation of the arrival process, then $I_\Psi(z)$ replaces $I(z)$ in equations (5.32)-(5.36). The rest of the analysis and results are identical to that presented in Section 5.4.

5.5 Correlated Input Results

Correlation among traffic cell arrivals can lead to higher tail distributions of buffer size, as will be shown, even if the simplest arrival model is assumed. This can be seen from the results of the previous section where it was shown that batched Bernoulli is the burstiest of all nonrenewal models. To illustrate this point, the simple Bernoulli model is extended using the Transform-Expand-Sample (TES) method [48] to generate a number of correlated sequences of traffic arrivals. All these sequences have the same marginal pmf described by equation (5.32). The amount of correlation among subsequent arrivals is controlled by an “innovation” parameter which can be uniformly distributed on the interval $[-w, w]$. Zero correlation is obtained when w is equal to 0.5, while the correlation increases as w approaches zero. Figure 5-9 depict the autocorrelation function for the arrival sequence for different values of the parameter w while Figure 5-10 and Figure 5-11 depict the complementary cumulative distribution of the buffer size for these arrival sequences. The curves in Figure 5-10 correspond to $\rho = 0.60$. Comparing these curves with the ones in Figure 5-7, it is clear that correlation among arrivals leads to a slower decay in the tail of the pmf of the buffer size. Furthermore, these curves are sensitive to the service limit and cell loss parameters (or ρ). The same arrival sequences were used but with $Y = 25$ cell per polling cycle and $\alpha = 10\%$ (which corresponds to

$\rho = 0.76$), and the result is much greater tails as shown in Figure 5-11.

Departing from the classical G/G/1 model where only the marginal distribution is of significance, many studies considered the effect of correlation on the queue statistics. Ahmadi and Guérin [1] in their introduction give a good survey of studies that considered correlated arrivals for continuous or discrete time queueing systems. Assuming the same model in Figure 5-1 applies and the input process is modeled by a Batched Markov Arrival Process (BMAP), a solution for the distribution buffer size is described. BMAP model assumes that arrivals during an intervisit time follow a Markov process with a finite number of states. The states in this chain correspond to the number of arrivals and the transition probabilities from a state to another characterize the second order statistics, the covariance, of the source in addition to the first order statistics, the marginal traffic arrival distribution. In other words, the system considered here is the BMAP/G/1 queue. To solve this queue a very powerful technique called "Matrix Geometric" technique is used. This technique was introduced by M. Neuts in [53] and then it was applied to BMAP/G/1 by Neuts and Lucantoni in [54] and [43] respectively.

Ahmadi and Guérin [1] present the solution procedure to a problem very similar to ours except that their queue evolution equation does not contain the ARQ term (refer to equation (5.27)). To solve the resulting queue they apply the theory of the matrix geometric technique and obtain the stationary buffer size distribution. Here their model is extended to include the retransmissions incurred because of the ARQ strategy and a new queue transition matrix is built. The queue transition matrix is the key matrix required for solving complex queue problems using the matrix geometric method. Details of the construction of this matrix and the solution procedure are found in Appendix C.5.

Figure 5-9: Autocorrelation function number of cells arriving during intervisit time for different values of the innovation parameter, w .

Figure 5-10: Buffer occupancy tail distribution for bernoulli arrivals with different auto-correlation functions. Terminal rate = 10 Mb/s, cell loss prob. 1%, TDMA frame = 204 slots (0.656 ms.), service limit = 29 cells/polling cycle.

Figure 5-11: Buffer occupancy tail distribution for bernoulli arrivals with different auto-correlation functions. Terminal rate = 10 Mb/s, cell loss prob. 10%, TDMA frame = 204 slots (0.656 ms.), service limit = 25 cells/polling cycle.

Figure 5-12: Complementary cumulative distribution functions of buffer size for Markov and renewal Bernoulli models: Solid line: $\rho = 0.67$, Markov model, Dashed-dotted line: $\rho = 0.67$, Bernoulli model, Dashed line: $\rho = 0.48$, Markov model, and dotted line: $\rho = 0.48$, Bernoulli model.

To apply the matrix geometric method to our queueing problem and considering the same bit rate and service limits (namely, 10 Mb/s and 25 or 29 cells per polling cycle) will result in square submatrices that have 9×10^6 elements. Defining and manipulating tens of these matrices is beyond the capability of the available computational resources. Thus we resort to scaling down the problem. Below we show the results for up to 2 Mb/s terminal with a service limit of 5 cells per polling cycle. The complementary distributions resulting from applying the solution procedure are shown in Figure 5-12 while mean and standard deviation figures are listed in Table 5-2. The table serves also as a comparison between simulation and analysis results. Simulation results are averaged over 10^6 iterations. It can be noticed that numerical errors are more evident as ρ increases. This is because of the large size of the submatrices that have to be considered. For example, for $\rho = 0.86$, the traffic source is represented by a 50 states Markov chain; and since Y is equal to 5, the components of the queue transition matrix are 23 distinct submatrices each of size 250×250 .

Table 5-2: Mean and standard deviation results for buffer size using a Markov traffic model (service limit = 5 cells per polling cycle, cell loss prob. = 10%)

Terminal Rate R Mb/s	Traffic Intensity ρ	Analytical		Simulation	
		$\bar{q}$	σ_q	$\bar{q}$	σ_q
0.5	0.29	1.1	1.2	1.1	1.2
1.0	0.48	2.3	2.0	2.3	2.0
1.5	0.67	4.7	4.4	4.7	4.6
2.0	0.86	14.4	16.1	16.5	17.8

6

Simulation Study and Results

6.1 Introduction

In this chapter a simplified version of the proposed multiple access protocol is evaluated using simulation techniques. The following two sections describe the system configuration and the basic procedures used by terminals or portables to acquire the wireless link and to transmit their traffic. Whereas, the fourth section presents the simulation results for four system architectures. It should be noted that simulating such a complex system and taking into account most of the events occurring in a real situation, required defining and setting values for many parameters that determine the behavior of the wireless system (such as portable tuning/listening parameters, power control measurements, etc.). A list of the simulation parameters and the used values is found in Appendix B.

6.2 Simulated System configuration

A square area of $100 \times 100 \text{ m}^2$, that can represent a floor plan in an office environment is considered. The area is divided into 16 microcells (referred to as domains) with 16 base stations or service ports (one in every domain) positioned on a uniform grid as shown in Figure 6-1. The figure shows also the frequency plan used among the service ports. This frequency plan is fixed and does not change during the simulation time. The geometric area of a domain is 625 square meter with radius of about 18 meters. Each service port will provide a maximum raw capacity (for uplink traffic) equal to the prime rate, 155 Mb/s. That is, each domain can have a traffic density as high as 0.249 Mb/s per square meter (this load includes overheads).

Figure 6-1: System layout and dimensions.

6.2.1 Propagation Model

Terminals and bases have 6-sector antennas; i.e. $S = 6$. Antenna directionality is assumed ideal, in the sense that any two transceivers receive each others signals only if they simultaneously use sectors that illuminate each other. The received mean power, P_d , at distance $d + d_{\min}$ meters from the transmitter (assuming normalized transmitted power) is

$$P_d = \frac{1}{(d + d_{\min})^\alpha} \quad (6.1)$$

where α is the path loss exponent and $d_{\min} = 1$ meter is the minimum distance between the transmitter and receiver. α is assumed to be 3.5 in the simulation. Signal shadowing and Rayleigh fading are considered as follows:

$$P_{r,sh}(\text{dB}) \sim N(10(\log P_{r,m} - a\sigma_{sh}^2), \sigma_{sh}) \quad (6.2)$$

where $P_{r,sh}(\text{dB})$ is a normally distributed random variable, related to the mean of the shadowed signal by $P_{r,sh} = 10^{(P_{r,sh}(\text{dB})/10)}$, σ_{sh} is the standard deviation of the shadowing process, and a is a constant equal to $\log_e(\ln 10)^2/200$ or 0.0115 as shown in subsection 3.1.2.1. σ_{sh} is assumed to 8 dB throughout the simulation. Finally, an exponentially distributed random number,

$$P_{r,Ray} \sim \text{Exponential}(P_{r,sh}) \quad (6.3)$$

with mean $P_{r,sh}$ is generated. $P_{r,Ray}$ is the received power at the receiver location.

6.2.2 Traffic Models

Each base station provides a maximum raw transport bit rate of 155 Mb/s while the applications on the portables generate data that is packetized in ATM cells (header of 5 byte and 48 bytes data segment). The ATM cell is then encapsulated in a wireless envelope that is 500 bits long, the duration of a time slot is 3.2 μsec at 155 Mb/s. The wireless envelope is the unit of transmission on the wireless link and it is the finest resolution of

time measure used in the simulation. It is referred to as "time unit". Furthermore, the overhead bits in every envelope are assumed to include control and ARQ, so that the simulated system has no control envelopes. All envelopes, including polling envelopes, are assumed to be of the same length.

The following two models were used in simulating the traffic generated by the applications.

6.2.2.1 Bernoulli Cell Arrivals

The Bernoulli model described in Section 5.3 is used to generate most of the simulation results. Its simplicity is appealing since it does not add significantly to the complexity of the simulation program. This model may represent variable bit rate sources with very low burstiness.

For a portable of rate R_i the number of ATM cell arrivals in each time slot, on average, is equal to $\frac{R_i/48 \times 8}{C/500}$ or $\frac{500}{48 \times 8} \frac{R_i}{C}$, which is less than one for $R_i < \frac{48 \times 8}{500} C$. Where C is the wireless link rate. Hence, a simple Bernoulli model assumes that the probability of a cell arriving is equal to

$$\text{Prob [cell arrival]} = \frac{500}{48 \times 8} \frac{R_i}{C} \quad (6.4)$$

6.2.2.2 Bursty Traffic Model

One of the widely used multi-media traffic models is the ON/OFF model [35][40][79]. This bursty model is used in some of the simulation scenarios. The model assumes that the source is the sum of N_s mini-sources; each is a two-state Markov process. The state occupancy time in the ON state is T_{ON} while it is T_{OFF} for the OFF state. The source is characterized with an activity ratio, AR , defined as the fraction of time spent in the ON state. While in the ON state, the mini-source generates information at a constant peak rate PR bit per second. It does not generate traffic while in the OFF state. It can be seen that the average rate for the source is given by

$$R = AR \times N_s \times PR \quad (6.5)$$

The values used in the simulation are $N_s = 15$, $AR = 0.375$, and $PR = 1.7778$ Mb/s. These figures yield a source of 10 Mb/s on average. T_{ON} is taken to be 33 ms or 5 ms.

6.2.3 Multiple Access Protocols

6.2.3.1 Frame structure

The frame structure proposed in Section 4.2 is simulated with the exception of broadcast envelopes since they are not used in the simulation. The simulated frame structure is shown in Figure 6-2 and is divided into $S = 6$ variable length subframes or sector segments. The order of subframes is random from frame to frame, to randomize interference hits. While the length of the frame is fixed, 204 slots or 0.66 msec, the length of the subframe is proportional to the sum of traffic loads of all portables subscribed to the corresponding antenna sector of the base station. Each subframe starts with a beacon envelope followed by three registration slots. The rest of the subframe is used for the polling cycle. Only uplink traffic is simulated.

The simulation assumes that time slots are aligned, i.e. base stations and user terminals are totally synchronized regarding the boundary of time slots. Furthermore, the base stations start their activities all at the same time stamp (in the beginning of the simulation) which means TDMA frames start and end at the same time stamp for all base stations. However, the structure and occupancy of these frames is different from one base station to another since they (the structure and occupancy) depend on users' locations and the traffic load that are random.

6.2.3.2 Polling Scheme

For each antenna sector of the base, there is a corresponding list of registered users or terminals. The base station sends a polling envelope to each of those users and waits for response. The polling service is done according to gated-limited discipline: only traffic cells present in the terminal buffer at the time the polling token is received are served. Cells or packets arriving during the service area are served in the next cycle. In each polling cycle the terminal is allowed to transmit a maximum number of cells equal to the smallest of the number of cells already in the buffer, and Y , where

$$Y = \left\lfloor \frac{\text{terminal bit rate}}{\sum \text{terminal bit rates in sector segment } i} N_i \right\rfloor \quad (6.6)$$

Figure 6-2: Frame structure and polling cycle.

where N_i is the number of traffic slots designated for the i^{th} sector segment, and $\lfloor x \rfloor$ is the greatest integer less or equal to the number x . The service limit, Y , described above is static, the use of dynamic service limits is described in Section 6.4.1.4.

6.3 Basic System

6.3.1 Homing, Registration, and Acknowledgment

In this subsection the call set up procedure is explained. In each simulation of a *system layout*, terminals are positioned randomly on the floor plan (refer to Figure 6-1). Terminals are powered-on and brought into the system gradually, within the duration of the first 10 to 100 frames, but at random instants of time. A powered-on terminal starts its activity by listening on its antenna sectors to the different service ports and ranking them according to cell loss probability (CLP) and signal-to-interference ratio (SIR). This is referred to as the homing or tuning phase. The portable builds a list of potential or candidate home stations. An elaborate tuning process will use the traffic conditions as one of the criteria when comparing against other home candidates. The tuning process continues for a number of time slots equal to five frames.

Choosing a home base station (determines the carrier frequency, base station antenna sector, terminal antenna sector), the terminal waits for the corresponding beacon signal corresponding to the antenna sector of interest (refer to Figure 6-2). The terminal sends a registration ATM cell in one of the three registration slots. The time slot is chosen randomly which gives rise to an ALOHA type of contention. Collision occurs when two or more terminals attempt sending registration envelopes in the same time slot. Collision does not necessarily mean that none of these envelopes is not received by the destination service port. A collided registration envelope may be correctly received if the corresponding signal power relative to the sum of all other powers (interferers) is greater than the receiver SIR threshold. The registration cell contains information about the terminal (address, type, etc.) and also about the type of traffic and its requirements or constraints (transmission rate, maximum delay, etc.).

Following the registration process, a terminal waits, a maximum of 408 time slots (equal to two frames), for an acknowledgment, if the service port decided to serve the terminal, or a negative acknowledgment, if the terminal is denied access to the port. The registering terminal, if did not receive an acknowledgment or negative acknowledgment

within two frames' duration, assumes that the registration cell was not correctly received and attempts a retransmission. Whereas if a negative acknowledgment was received, the terminal attempts registration with the next-base home candidate. Figure 6-3 shows the different states of a terminal.

The decision of accepting a terminal into a domain or denying it is the outcome of the admission control procedure executed by the home base station. The simulation program implements a simple procedure and uses some parameter values that seem to provide reasonable performance figures (in terms of call blocking and dropping probability). There are two criteria to accept a new connection that are used here: first there should be enough link capacity to give to the new user without adversely affecting the performance of the already registered ones. The second criterion is RF related. Base stations monitor interference power on every antenna sector in the unused time slots. Therefore, an antenna sector is always associated with an average interference power measured over the last five frame durations. When a user requests registration in the i^{th} sector segment (associated with $\bar{I}_i$ average interference), then the received signal power at the port from the user, P_i , should be greater than $\bar{I}_i + 3\sigma_{\text{sh}}$ if the user is establishing a new call. If the call is handed-off then P_i should be greater than $\bar{I}_i + \sigma_{\text{sh}}$, where σ_{sh} is the dB spread corresponding to the shadowing process. It should be noted that with power reciprocity in mind, the RF criterion together with the tuning process executed by the portable tries to minimize the interference caused by newcomers to already existing links and visa versa.

Although traffic only on the uplink is simulated, there are downlink transmissions that are simulated as well. These are the beacon signals and the polling tokens; and they are susceptible to interference. Hence, sometimes they are not received correctly. In the tuning and registration phase, a corrupted beacon slot means that a terminal will have to wait for another beacon signal leading to call set up delay. Whereas, an interference-corrupted polling token can mean delays in the call set up or simply missing a turn to transmit traffic.

Figure 6-3: Terminal states.

6.3.2 Blocking, Dropping, and Sign-off Events

The initial N terminals that are laid out on the floor plan in each system layout comprise what is referred to here as the *Demand Traffic*. That is, at the start of the simulation there are N terminals attempting to set up calls. After the call set up procedure is completed for all terminals, there will be terminals that simply did not find or retain a proper home service port, and consequently exited the simulation, because of capacity limitations and/or unfavorable link conditions (high cell losses, large delays, etc.). These conditions are function of the signal-to-interference (SIR) ratio threshold of the terminal receiver, as will be depicted in simulation results. In general, let the number of these terminals be denoted by $\overline{N_{\text{Signoff}}}$. The remaining active terminals generate what is referred to as the *Active Traffic*. Simulation of a single system layout is stopped when the statistics of the active terminals converge. A simple convergence criterion is used in obtaining the results in order not to add to the complexity of the simulation. The statistics are said to have converged if the last 10 readings of CLP, average waiting time for a traffic cell, and buffer occupancy figures do not differ by more than one percent amongst them.

One component of $\overline{N_{\text{Signoff}}}$ is $\overline{N_{\text{block}}}$. A blocking event occurs when a terminal exhausts all the entries in its candidates list. That is, none of the service ports in the candidates list granted service to the terminal. In this case, the terminal signs off and remains idle (out of the system; its statistics are not considered). If the system layout starts with N terminals, then after the tuning phase is completed $\overline{N_{\text{block}}}$ terminals will be blocked. The blocking probability is estimated as

$$P_{\text{block}}(N) = \frac{\overline{N_{\text{block}}}}{N} \quad (6.7)$$

where $\overline{N_{\text{block}}}$ is the number of the terminals blocked averaged over the number of simulated system layout.

There are two situations that can lead a terminal to sign off, one is the blocking event described in the first paragraph of this subsection, another is that conditions of the communication link deteriorate. In this situation, the terminal has already managed to set up a call, it is only that the arrival of new user(s) changed the interference conditions and thus the link conditions. When the link performance (CLP and/or polling token loss

probability) become unsatisfactory; this is indicated by the buffer instability experienced in the terminal, which is defined by the occurrence of 10 successive increases in the buffer contents observed when the buffer is sampled at 10-frame intervals. At this point the terminal considers changing the base station or performing a handoff.

The handoff, a completely user driven procedure, requires that the terminal possesses information regarding the base stations. This information is continuously gathered in terms of CLP and SIR figures on all antenna sectors and from all candidate service ports. The terminal uses the time slots in which it is not transmitting or receiving traffic for collecting statistics and building a list of candidates that represent base stations who could serve as alternative home base station in case of a handoff. If a handoff decision is made, the terminal goes through the list, one candidate at a time, in a similar manner to that used during the homing phase. That is, it sends a registration cell and waits for an acknowledgment or a negative acknowledgment. Even after performing the handoff, statistics for future handoff procedures are continuously gathered.

If conditions around the terminals are not favorable, that is every link it sets-up suffers from high interference power, the terminal attempts the handoff candidate for a maximum of three times. Once, all attempts are exhausted with no satisfactory quality of service is found, the terminal drops out of the system. The number of the drop-out terminals is denoted by $\overline{N_{drop}}$. This is the second component comprising the sign-off population of terminals, i.e

$$\overline{N_{signoff}} = \overline{N_{block}} + \overline{N_{drop}} \quad (6.8)$$

In the same manner as blocking probability, drop-out probability is estimated using

$$P_{drop}(N) = \frac{\overline{N_{drop}}}{N - \overline{N_{block}}} \quad (6.9)$$

where $\overline{N_{drop}}$ is number of dropped-out terminals averaged over the number of simulated system layouts.

In the results to be shown in the next section, a link drop event can occur even if the system does not support handoffs. This happens when a portable tunes to a base station and then the link quality (in terms of lost polling tokens) deteriorates as a result of interference from new terminals. This leads to monotonic increase in the buffer occupancy of the

portable and thus an unstable link. In this case, the link is dropped by the portable. When handoffs are supported, the portable considers an alternative link, otherwise, it exits the system.

The presented results are averages over a number of independent system layouts. This number ranges from 200 for a large number of terminals such as 130 to 500 for small number of terminals on the floor plan such as 30 or 20 terminals. This number of system layouts is used to compute the 95% confidence interval shown by error bars on some of the subsequent graphs.

In most of the presented results, performance figures are plotted against the carried traffic load. This load figure is obtained by averaging over all base stations the fraction of the data portion of the TDMA frame that is carrying interference-uncorrupted wireless envelopes. It should be noted that the simulation assumed that the maximum acceptable loading is set at 80% to avoid congestion and make the simulation time reasonable. The base stations used this load limit in executing the call admission procedure.

6.4 Simulation Results

Simulation results will be grouped into four groups; each is covered in each of the following four subsections. The first subsection assumes a basic system where no handoffs nor error control (ARQ) procedures are used to combat transmission impairments. The second and third subsections employ error control and handoff procedures, respectively. The fourth subsection shows the enhancements due to a simple power control algorithm.

Averaging over terminals positions, and shadowing and Rayleigh fading is carried out through averaging over system layouts. In each system layout, N terminals are randomly positioned on the floor plan. Power received by entity i from transmitting entity j is also calculated at the beginning for every pair of entities i and j , terminals and service ports. The power calculation is carried according to the propagation model suggested in Section 6.2.1. For the duration of the simulation of a system layout, neither the positions nor the corresponding propagation figures change. The only changing variable in that simulation is the interference experienced by the terminals and service ports, due to the mechanics of the system (traffic generating model, call set up procedure, handoff procedures, etc.).

6.4.1 Performance Figures with No Handoff and No ARQ

The results presented in this section correspond to the case where handoff and ARQ

procedures are not employed. That is, a terminal, if successfully homed on a service port, remains with that service port until the end of the simulation, even if the cell loss probability is high. However, a portable may drop the link if frequent polling-token loss leads to buffer instability.

The first graph shown in Figure 6-4 depicts the relation between the carried load and the offered load. The offered load is expressed in terms of Mb/s per domain. The demand traffic, in Mb/s per domain is given by

$$\text{demand traffic} = \frac{N \times 10 \text{ Mb/s}}{16 \text{ domains}} \quad (6.10)$$

whereas, the active traffic, in Mb/s per domain is given by

$$\text{active traffic} = \frac{(N - \overline{N_{\text{block}}} - \overline{N_{\text{drop}}}) \times 10 \text{ Mb/s}}{16 \text{ domains}} \quad (6.11)$$

where N is the initial number of terminals. Here, it is assumed that all terminals are of the same rate, 10 Mb/s. The curves have a knee at about 70 Mb/s per domain, indicating the beginning of the load saturation region; large increases in the offered load will lead to small increases in carried load. The system saturates for loads beyond 75 ~ 80 Mb/s per domain with maximum utilization is about 60%. The SIR thresholds have almost no effect for low values of traffic loads, whereas, they have a somewhat more significant effect beyond the saturation point. The lower the threshold is, the lower is the CLP and thus the greater is the utilization figure.

It is worth mentioning that although the raw capacity provided by the service port is 155.5 Mb/s, it is not all used to satisfy the demand traffic. The ATM header of 5 bytes segment added to the 48 byte data field and the encapsulation of the ATM cell in a wireless envelope of 500 bits, reduce this capacity by 23%. Another overhead factor is the control part of the frame (refer to subsection 3.1), which is about 12%, for total frame length of 204 time slots or 0.66 ms. Hence the available capacity for service is about 105 Mb/s per domain. However, when portables of 10 Mb/s each are used, a base station can serve only 8 or 9 portables at most depending on the cells loss rate and polling envelope loss probability. This makes 80 Mb/s or 90 Mb/s an upper limit on the available capacity under the simulation conditions.

The effect of randomized order of sector segments is shown through the figures listed

in Table 6-1. It can be noticed that without randomization the portables incur relatively high CLP, greater traffic delay, and greater buffer occupancy figures. The table depicted performance figures for a demand traffic of 75 Mb/s per domain or a carried load of about 60%.

Table 6-1: Effect of Randomized sector segments for demand traffic of 75 Mb/s per domain (120 terminals on the floor plan).

Performance Figure	Not Random	Random
CLP	$3.0 \times 10^{-2} \pm 1.6 \times 10^{-3}$	$1.2 \times 10^{-2} \pm 3.9 \times 10^{-4}$
Buffer (cells)	64 ± 8	20 ± 0.16
Delay (msec)	2.3 ± 0.3	$0.53 \pm 6.3 \times 10^{-3}$
Block Prob.	$3.5 \times 10^{-2} \pm 2.4 \times 10^{-3}$	$1.1 \times 10^{-1} \pm 3.3 \times 10^{-3}$
Drop Prob.	$6.0 \times 10^{-3} \pm 1.0 \times 10^{-3}$	$5.1 \times 10^{-3} \pm 8.0 \times 10^{-4}$
Carried Traffic	$0.56 \pm 5.2 \times 10^{-3}$	$0.55 \pm 2.4 \times 10^{-3}$

Figure 6-4: Throughput versus demand traffic with 16 domains, frequency reuse of 4, no handoffs, and no ARQ (ON/OFF sources 10 Mb/s terminals).

Figure 6-5: Cell loss probability for a wireless system with 16 domains, frequency reuse of 4, no handoffs, and no ARQ (solid line and dashed line: Bernoulli model, crosses and pluses: ON/OFF source).

Figure 6-6: Average waiting time: (a) and buffer occupancy: (b), for a wireless system with 16 domains, frequency reuse of 4, no handoffs, and no ARQ (solid line: Bernoulli & SIR = 8dB, dashed-line: Bernoulli & SIR = 20 dB, dotted line: ON/OFF & SIR = 8 dB, dashed-dotted line: ON/OFF & SIR = 20 dB).

6.4.1.1 CLP

Figure 6-5 depicts CLP curves for two SIR thresholds plotted against carried traffic load or throughput. A received wireless envelope or cell is considered lost if the signal power associated with desired cell relative to the interference power is less than a threshold value. This threshold is dependent on many factors: modulation scheme, coding technique, receiver structure, etc. The interference power is the sum of all the powers associated with the transmissions on the same carrier frequency and at the same time slot. Further more, the interferer should be transmitting on the antenna sector illuminating the antenna sector of the receiver. The received powers are assumed constant for the duration of the cell.

It can be noticed that CLP is ranging from 10^{-3} to 10^{-2} , which is quite expected for a cellular system with low frequency reuse and therefore, co-channel interference is very severe. Such high values of CLP are not compatible with the broadband services anticipated for wireless indoor systems unless error control is used. Target CLP values should be in the range of 10^{-5} to 10^{-3} (or lower with ARQ or FEC). Another note is that CLP improves as the SIR threshold of the receiver is reduced. The figure shows also the CLP for the system when the bursty model is used. It can be seen that the two models (Bernoulli and bursty) lead to the same CLP. It is also worth mentioning that, CLP is averaged over all traffic cells generated by all active terminals. In some instances, a terminal may experience very high CLP values such as 10% or even 40%. It can be noticed that CLP is still significant even at low traffic load. This is because the simulation program used a simple sector allocation algorithm, which did not necessary minimize interference in low traffic conditions. This occurred mainly when only one terminal is registered with a base station. The algorithm gives all the TDMA frame (except the overhead slots) to the terminal. Randomizing the order of sector segments, in this case, still results in traffic occupying the first portion of the frame.

On another experiment, a heterogeneous mix of terminal rates is used. This mix is composed of the following rates: 20% of terminals have bit rates of 25 Mb/s, 30% have rates of 10 Mb/s each, and the remaining 50% of terminals have rates of 5 Mb/s. The CLP results for this mix of traffic rates are approximately the same as that of the homogeneous case shown in Figure 6-5.

6.4.1.2 Waiting Time and Buffer Occupancy

Due to the randomness in the arrival process, associated with the generated traffic cells, and the service discipline used in these simulations, the traffic cells accumulate in the terminals' buffers. This queueing of traffic cells is characterized by the waiting and/or queue length probability distribution functions. Waiting time is estimated for all transmitted cells, whereas, buffer occupancy is recorded at the polling instant. Both figures are only measured for calls which were not dropped or blocked. Figure 6-6 (a) and (b) show the average waiting time for a traffic cell and the average buffer occupancy, respectively. It can be noticed that waiting time and buffer occupancy figures are on the order of a frame duration (or length in slots) or less. This is due to the light-to-moderate load condition and the short and fixed-length frame polling strategy that is used. For Bernoulli traffic these performance figures increase slowly for small values of offered traffic (less than 45 Mb/s per domain or a carried load of 0.4), and then rapidly for greater traffic loads. While for bursty model, the breaking point is at about 25 Mb/s or domain or at carried load of 0.3. The graphs also show the effect of the SIR threshold. The reason for the effect of SIR threshold is that with higher receiver SIR threshold more polling tokens are lost and thus more traffic is allowed to accumulate in the terminals' buffers. In this setup there were no buffer limits (neither time nor capacity) imposed.

Comparing the heterogeneous traffic mix with the homogeneous mix, the waiting time and buffer occupancy are almost identical for the two cases.

6.4.1.3 Call Blocking/Dropping and Utilization

As described in subsection 6.3.2 call blocking rate indicates the number of unsuccessful call setups, $\overline{N_{block}}$ out of the overall trials N , whereas, call drop (or $\overline{N_{drop}}$) is entirely due to unstable links. Call block and drop probabilities are estimated using equations (6.7) and (6.9), respectively. Figure 6-7 shows the curves for two SIR threshold values. It can be noticed that the effect of the blocking and dropping probabilities are sensitive to SIR threshold value.

For Figure 6-7 (a), a blocking probability of 1% is achieved for traffic loads of 0.42 and 0.52 (or 45 Mb/s or 60 Mb/s per domain) depending on the SIR threshold. However, 80 Mb/s is the maximum value for active traffic as depicted in Figure 6-8. That is the mechanics of the system does not allow more than that traffic per domain regardless of the initial number of terminals, N . Higher values of demand traffic will only result in greater

number of terminals being blocked or dropped, leaving only about 80 Mb/s per domain of traffic. When compared to the results corresponding to the heterogenous case, the results are the same. The call drop rate is almost one order of magnitude less than that of the block rate which is desirable.

Regarding the bursty model case (Figure 6-7 (b)), as expected, the call block probability is the same as the Bernoulli case while the call drop probability is much worse. The reason is that the latter's criterion is dependent on the buffer occupancy figure and the bursty mode gives rise to more variations in buffer occupancy when compared to the Bernoulli case. One parameter in the bursty model that affects its temporal behavior, and in turn the buffer occupancy, is the mean ON/OFF period. The relation of this parameter to the adopted drop criterion is also depicted in Figure 6-7 (b). The smaller the mean ON/OFF the less probable it is to find a monotonic increase in buffer size over the sampling time of the drop criterion, and therefore, the less the drop probability is. When the results are compared (for the Bernoulli case) with those of the heterogenous population, no or insignificant difference is found.

Figure 6-8 shows the relation between the demand traffic and the active traffic, both measured in Mb/s per domain. The curves show that each domain is capable of supporting an average of 75 to 80 Mb/s depending on the SIR threshold value.

Figure 6-7: Average call block/drop probability for Bernoulli: (a), and ON/OFF traffic: (b) for a wireless system with 16 domains, frequency reuse of 4, no handoffs, and no ARQ.

Figure 6-8: Average active traffic for a wireless system with 16 domains, frequency reuse of 4, no handoffs, and no ARQ.

6.4.1.4 Effects of Traffic Model Parameters and Polling Strategy

It goes without mentioning that any performance figure is affected by the many parameters and procedures used in the system; perhaps some more than others. In this subsection three new configurations are simulated and compared against results in previous subsection. The new setups are:

- I. The ON/OFF model has $T_{ON} = 5$ ms. as opposed to the 33 ms. used before. The rest of the parameters are the same.
- II. The ON/OFF model has $T_{ON} = 33$ ms. but the service limit imposed by the central server is proportional to the instantaneous bit rate rather than the average bit rate of the portable (equation (6.6)).
- III. Same as II but the admission policy of the base station allows the usage up to 100% of the available capacity as opposed to 80% used in previous subsection.

Results for the three different setups are shown in Figure 6-9 and Figure 6-10. The CLP for the new setups is the same as before. The previous results for the ON/OFF model indicated that it leads to high delay and buffer size; however, Figure 6-9 shows that this behavior is a function of the model characteristic and the service policy. When the mean activity period $T_{ON} = 33$ is reduced with respect to the frame duration, the correlation of arrivals from one frame to the next decreases and thus the delay and buffer occupancy are improved. Further improvements can be obtained if the service limit is calculated using the instantaneous bit rate instead of the average bit rate. This instantaneous rate (rate during the last service session) can be communicated to the base station in a dedicated wireless control envelope or impeded in one of the overhead fields in a regular traffic cell. Improvements are also evident in the call drop probability when Figure 6-7 (b) and Figure 6-10 are compared. The above three setups are only used in this subsection, the remainder of the results are for homogeneous population of 10 Mb/s terminals with Bernoulli traffic model, unless specified otherwise.

Figure 6-9: Traffic delay: (a) and buffer occupancy (b) for a wireless system with 16 domains, frequency reuse of 4, no handoffs, and no ARQ. SIR threshold is 20 dB. (solid-line: Setup I, dashed-line: setup II, dotted-line: setup III).

Figure 6-10: Call block and drop probability for a wireless system with 16 domains, frequency reuse of 4, no handoffs, and no ARQ. SIR threshold is 20 dB. (solid-line: Setup I, dashed-line: setup II, dotted-line: setup III).

6.4.2 Performance Figures with ARQ

In this section a system similar to that described and simulated in subsection 6.4.1 is considered, except that an added layer of error control, ARQ, is employed. Traffic cells that are transmitted are not discarded from the terminal's buffer immediately, but are saved. The polling token of the next frame acknowledges the reception of some or all of the cells transmitted in the previous frame. The cells that are correctly received are discarded from the buffer, while others, if any, are kept for another retransmission. According to this strategy, old traffic cells are always at the top of the queue and thus retransmitted first (first-come first-served) before transmissions of new ones are attempted. This helps keep the waiting time as small as possible.

It should be noted that ARQ is applied only to traffic transmissions (i.e. after initial call set up is completed). Furthermore, the relative increase of the raw transmissions as a result of the introduction of ARQ is not significant, for the magnitude of CLP figures experienced in this system, as will be shown.

6.4.2.1 CLP, Waiting Time, and Buffer Occupancy

With the ARQ procedure implemented here, there is no maximum delay or waiting time imposed on traffic cells. A cell can be retransmitted as many times as required to be received correctly. So, eventually, all traffic cells will go through and the overall CLP of the system is zero. The raw CLP figures range from 10^{-3} to a little more than 10^{-2} and are approximately equal to those in Figure 6-5 for the basic system with no handoffs and no ARQ. The set of curves exhibit the typical effect of the receiver SIR threshold. As for cell waiting time and buffer occupancy, the curves in Figure 6-11(a) and Figure 6-11(b) are slightly higher than those shown in Figure 6-6 (homogeneous traffic mix case).

Since the ARQ scheme implemented retransmits only the cells that are corrupted and hence called selective repeat ARQ, one can estimate the average number of transmissions, $\bar{R}$, for a traffic cell before it is correctly received using the following

$$\bar{R} = \frac{1}{(1-p)} \quad (6.12)$$

where p is the raw cell loss probability. This equation agrees well with the results obtained by simulation. These results, averaged over all transmitted cells, are shown in Figure 6-12.

As can be noticed, the overhead in terms of extra retransmissions is very small, however, the return in terms of improved CLP is very significant.

The drop probability, shown in Figure 6-13, due to (unstable links) has increased noticeably when compared to that of the basic system without ARQ (Figure 6-7). This is due to the fact that the drop criterion is based on buffer occupancy figures which are aggravated with ARQ for unstable links. Recall that the drop-event criterion in these two systems is based only on the portable's buffer status. On the other hand, the blocking probability with ARQ is the same as that for the basic system.

Figure 6-11: Average cell waiting time (a), and average buffer occupancy for a wireless system with 16 domains, frequency reuse of 4, no handoffs, and ARQ.

Figure 6-12: Average number of transmissions of a traffic cell for a wireless system with 16 domains, frequency reuse of 4, no handoffs, and ARQ.

Figure 6-13: Average call blocking and call dropping for a wireless system with 16 domains, frequency reuse of 4, with no handoffs, and ARQ.

6.4.3 Performance Figures with Handoff and ARQ Procedures

In this section's simulations a terminal is allowed to hand off from one base station to another, in search for a communication link that will provide a quality of service equal or better than a specified threshold. The criterion for handoff is the same as the call dropping criterion for the case of no handoff: the occurrence of 10 successive increases in buffer contents observed when the queue is sampled at 10-frame intervals. ARQ is still being used.

6.4.3.1 CLP, Waiting Time, and Buffer Occupancy

The raw cell loss probability results did not change significantly. About 20% increase is noticed for traffic loads higher than 50 Mb/s per domain or a carried load of 0.4. A similar increase occurred in the average waiting time buffer occupancy since the handoff procedure is accomplished over a minimum period of a frame or so. The effect of the receiver SIR threshold value is the same as that for the system with no handoff procedures.

The calls that are dropped (in the results of the previous two sections) can be saved by finding an alternative base station which can provide a satisfactory service. This is indicated by the lower call dropping rate as shown in Figure 6-14. The 10^{-2} mark of blocking probability corresponds to 0.42 and 0.52 carried traffic per domain, whereas the dropping probability is below 10^{-3} for SIR equal to 8 dB. This means, for SIR threshold of 8 dB, up to 70% of the available capacity can be used with satisfactory conditions. The compromise between call blocking probability and call dropping rate is achieved through the fine tuning of the parameters used in the admission control and the handoff procedures. In this study a stringent admission control procedure is used, so that call blocking is high, but the remaining users enjoy good quality links in terms of low level interference power. This makes the need for handoff very rare; handoffs are expected to be executed on a slow pace when new users appear or the signal path becomes obstructed. The admission procedure used here also applies a less strict criterion when accepting handed-off users.

Figure 6-14: Average call blocking and call dropping for a wireless system with 16 domains, frequency reuse of 4, with handoffs, and ARQ.

The design of the handoff procedure is critical to the performance of the system as a whole. This is indicated by some earlier versions of the simulation results. In those cases the portables executed handoff procedures more frequently (when compared to the results presented above) and resulted in some ripple effect where new handed-off users caused other users to opt for handoff and so on. The low frequency reuse factor helped in aggravating this effect since the slightest disturbance in the propagation conditions was felt by most of the co-channel users. As a result, much higher dropping probabilities (but lower blocking probabilities) were experienced.

6.4.3.2 Effects of Reduced Path Loss Exponent and Performance in Inner Domains

In another simulation for the system, the effect of the path loss exponent, α , is tested. Averaging the statistics over users positioned in the interior domains (central four domains in Figure 6-1) instead of averaging over all domains is also done. The results for cell loss probability and average blocking and dropping probabilities are depicted in Figure 6-15 (a) and (b) respectively. The signal-to-interference threshold used is 20 dB. Smaller path loss exponents aggravate the interference conditions and lead to increase in both the CLP and blocking and dropping rates. However the effect of the edge domains in biasing the results is not that significant as indicated by the closeness of the curves labeled interior domains and the ones labeled all domains. This can be justified by noticing that while users positioned in the interior domains may experience higher interference levels, they are within two domain radii from 9 base stations. The more alternatives in choosing a home base station with suitable service quality may alleviate the impairments caused by the extra interference. Whereas, users positioned in outer cells are within two domains radii from 4 or 6 base stations.

Figure 6-15: Average raw cell probability: (a), and average call blocking and call dropping probabilities for a wireless system with 16 domains, frequency reuse of 4, with handoffs, and ARQ.

6.4.4 Performance Figures with Power Control

Throughout the previous simulation experiments it is noticed that there are always some users that suffer from high interference powers and thus high CLP. On the other hand, there are users that experience very high SIR and thus have very low CLP. The goal is to improve the performance of users with high CLP while not affecting the performance of users with low CLP, or at least not disturbing it completely. One method to achieve this is to use power control.

A perfect power control algorithm will ensure that powers (or SIR) received are almost the same. In the current simulation a simple power control algorithm is employed. This algorithm is employed on the uplink and only after the call set up procedure is completed. Only two levels of transmission power are used: the normal level (0 dB reduction) and a lower level which is 20 dB less than the former level.

According to the algorithm, the service port maintains, for each terminal in its domain, a list of the most recent 1024 readings (five frames duration) of the SIR figure. Every 5-frame interval, the terminal performance is compared against a threshold Q : if the CLP is lower than Q and the measured average SIR is greater than 50 dB, then the terminal will be requested through the control channel to reduce its transmission power by 20 dB. Otherwise, the transmission power is kept at the same level. A terminal status may necessitate that transmission power level is increased back to the normal level after it has been reduced. In all the results presented Q is equal to 5×10^{-3} . The power control algorithm is used along with the ARQ and handoff procedures.

6.4.4.1 Raw Cell Loss Probability

As expected, the power control procedure, tends to prevent a user from using excess power that is unnecessary for the quality of the link. Such excess power only adversely affects the transmissions of other users. This can be seen in Figure 6-16 where histograms of the cell loss probability (averaged over all traffic cells generated by active users) are compared. Figure 6-16(a) and (c) are for the basic system with handoff, ARQ, and no power control procedures. Whereas, Figure 6-16(b) and (d) shows the results when the simple power control algorithm is used. It can be noticed in the histograms of (b) and (d) that the CLP figures, averaged over all users and all traffic cells, are concentrated towards the zero more than those in (a) and (c), and also they have less standard deviation (less

spread). The figures correspond to demand traffic of 25 Mb/s per domain ($N = 40$ terminals for (a) and (b)) and for 75 Mb/s per domain ($N = 120$ terminal for c) and d)). The frame used is 204 slot (0.66 msec) in length and the receiver threshold is 20 dB. A similar trend is noticed with histograms plotted for the CLP figures corresponding to the user with highest CLP. Table 6-2 summarizes these figures together with the ones shown in Figure 6-16. However, the improvement in raw CLP seems to diminish with decreasing SIR threshold values.

6.4.4.2 Other Performance Figures

Although power control procedure, at this stage, is only implemented on the uplink, down link transmissions are bound to benefit from it. For example, a polling token transmission to a particular user may have a better chance of being correctly received. This is so because some of the interfering transmission are uplink traffic cells. This, potentially, should lead to some reduction in the average waiting time and buffer occupancy. However, the simulation results do not show any improvement. This may be due to the insignificant improvement of the polling envelope loss.

Another area of improvement is the dropping probability. This is more apparent for SIR threshold equal to 20 dB. However, the blocking probability remained unchanged. As for link utilization, the introduction of power control led to an expected but slight increase of about 3% in the utilization figures for demand traffic loads greater than 60 Mb/s per domain.

It is also noticed that the frequency of power switching decreases slightly with the increase of the receiver's SIR threshold for the same traffic condition. This is expected since with the increase of the of SIR threshold (higher CLP) fewer terminals achieve quality of link conditions better than Q . The frequencies ranged from 2.5 to 3.5 switches per active terminal per second.

Figure 6-16: Histograms for the raw CLP figure (averaged over all traffic) with no power control: a), and c), and with power control procedure: b) and d). The results are for a wireless system with 16 domains, frequency reuse of 4, with handoffs, and ARQ.

Table 6-2: Summary of histograms for cell loss probability (frame length is 204 slots or 0.66 msec, and SIR threshold is 20 dB) for a wireless system with 16 domains, frequency reuse of 4, with handoffs, and ARQ.

	Cell Loss Probability for all users				Cell Loss Probability for user with highest CLP			
	No Power Control		with Power Control		No Power Control		with Power Control	
	mean	standard deviation	mean	standard deviation	mean	standard deviation	mean	standard deviation
Demand Traffic: 25 Mb/s per domain ($N = 40$)	8.7×10^{-3}	6.2×10^{-3}	4.1×10^{-3}	2.8×10^{-3}	1.4×10^{-1}	9.4×10^{-2}	5.0×10^{-2}	5.2×10^{-2}
Demand Traffic: 75 Mb/s per domain ($N = 120$)	2.2×10^{-2}	9.3×10^{-3}	1.2×10^{-2}	5.5×10^{-3}	4.4×10^{-1}	2.6×10^{-1}	1.3×10^{-1}	5.7×10^{-2}

7

Conclusions

7.1 Summary of the System Architecture

In the past decade wireless technology has witnessed a rapid growth due to the advances in digital communication field and semiconductor technology. One particular application that is receiving more and more attention is wireless LANs. This thesis explores a multiple access architecture for a broadband wireless LAN for an indoor environment and identifies key parameters that influence its performance. The system is designed to provide a transparent service over the unreliable wireless channel.

Working within the expectation of the sponsoring institute and the limits of the technology, certain major decisions had a great impact on the system architecture. First the system has to operate in the mm-wave band and secondly only a small frequency reuse factor is to be used which meant that co-channel interference is the main signal impairment. In addition to the technology dimension, the broadband services (HDTV, video conferencing, high quality audio, file transfers, still images, etc.) have their unique requirements as opposed to the narrowband services (mainly voice and modem connections) in terms of wide variety of traffic rate, tolerable delay limits, cell loss probabilities, etc.

To cope with challenges regarding the high interference levels, the proposed system employs switched multisector antennas on both the base station and the user terminal. This antenna directivity helps reduce transmitted power and alleviate, partially, the ISI problem faced in the indoor channel when high bit rates are transmitted. The reduction in transmitted power corresponds directly to a reduction in co-channel interference power. Furthermore, each of the antenna sectors is used to service a particular portion of the

TDMA frame called the sector segment. That is, for the duration of the sector segment, which depends on the traffic condition and may vary from frame to frame, the base station uses only the corresponding antenna sector. The order of these segments is randomized from one frame to the next to average the interference power and to facilitate the error control and ARQ procedures. Each sector segment starts with a beacon envelope which provides information to listening terminals regarding traffic load and interference on this particular segment. User terminals use this information plus that gathered from listening to other users to choose the base station/sector combination that will have the best link quality.

Other supplementary procedures supported by the system are handoff and power control. Handoff, initiated by the user terminal when the quality of service degrades below a certain threshold, allows the user terminal to change the home base station in search of a better link. The goal of the procedure is to reduce the impact of slow variations in the co-channel interference levels on the quality of service and ultimately reduce the call drop probability. This improvement is demonstrated in the simulation results. Power control, is a procedure that attempts to decrease excess transmission power and thus interference power. In the coming subsections handoff and power control procedures will be summarized in a more detailed manner.

Regarding the expected broadband services, dynamic TDMA-TDD in the form of polling provides a flexible multiple access method that can be made to meet the requirements of the expected types of carried traffic. The centralized decision-making process (at the central server or the base station) allows the system to possess a global view of the traffic conditions of users' terminals in the service area. This global view enables the server to set service parameters (polling rate, service limit, etc.) in an optimal way to meet the different service requirements. Furthermore, more coordination among different central servers is a possible way to obtain an incremental improvement in the performance of the system at an added cost of extra complexity.

In contrast to the exhaustive and gated polling policies, the adopted gated-limited policy is a preemptive one. This is in-line with the centralized multiple access, in the sense that the server preempts the channel from users or controls channel access through the use of appropriate service limits. This discipline imposes an upper bound on access delay (time to possess the channel) which is a requirement for delay sensitive and/or real-time traffic.

7.2 Summary of Results

7.2.1 Multiple Access Protocol

The multiple access proposed and evaluated in this thesis is based on dynamic TDMA-TDD and polling strategy. We choose a fixed-length frame, in the order of a millisecond, to upper bound access delay for delay critical or real-time services. Frame durations much less than a millisecond will greatly reduce the utilization of the system. Another factor that is also in favor of a short frame is the rate of temporal changes in the broadband traffic. As mentioned in the introduction of this chapter, the frame is divided into sector segments which vary in length in response to traffic load. The order of these sector segments may be random from frame to frame or coordinated among base stations to minimize co-channel interference. Simulation results in Table 6-1 show that for a traffic load of 75 Mb/s per domain, CLP is reduced from 3×10^{-2} to 1.2×10^{-2} when the order of the sector segments is randomized as opposed to being fixed. The average buffer size and traffic delay are also reduced from 64 cells and 2.3 ms to 20 cells and 0.53 ms, respectively.

With the chosen frame structure and length, the buffer occupancy for user terminals is in the range of 17 to 22 traffic cells, while the average cell delay is 0.4 to 0.6 ms, as shown in Figure 6-6. These results are for simple Bernoulli model, whereas, the results for the ON/OFF bursty model are as high as 50 cells and 1.6 ms for buffer occupancy and traffic delay, respectively. When exploiting the adaptability of the polling method, by varying the service limit in proportion to the instantaneous bit rate rather than the average bit rate, then the buffer occupancy dropped to 22 cells and traffic delay became 0.6 ms. These values are similar to those of the Bernoulli model and can be found in Section 6.4.1.4.

7.2.2 Traffic Models

The analysis in Chapter 5 considered two types of traffic models: renewal and non-renewal models. In the renewal category: constant bit rate model (periodic) as well as variable bit rate models such as Bernoulli and generalized Bernoulli models were considered. These models receive their significance from the fact that they are widely used in classical queueing theory. It should be noted that the analysis method is not restricted to the models mentioned in Chapter 5 but can be used with any traffic model that has an explicit probability generating function for the number of traffic cells arriving during a

time window. The batched Markovian arrival process (BMAP) represent a nonrenewal model that has been considered. Matrix analytic method was used to obtain the final probability distribution of the buffer occupancy.

In the simulation study in Chapter 6, again the two types of traffic models were represented by the Bernoulli model for the renewal class and the ON/OFF model for the nonrenewal class. The ON/OFF model is widely used in simulations of multimedia traffic [35][40][79]. The simulation considered homogenous as well as heterogeneous traffic rates. The results show that the overall cell loss probability is not very sensitive to the traffic generator model nor the traffic mixture. This is evident from the CLP graphs in Figure 6-5 and other results in Section 6.4.1.1, where CLP ranges from 10^{-3} to 10^{-2} for both Bernoulli and ON/OFF traffic models.

7.2.3 Queueing Analysis and Admission Control

The analytic study in Chapter 5 concentrated on characterizing the embedded queueing model in the proposed multiple access. The analysis considers a terminal serviced according to the gated-limited polling scheme and takes into account the ARQ retransmissions as well as the TDMA frame structure. For tractability, the analysis assumes static service limits which are expected to lead to worse performance than dynamic or adapting service limits. With dynamic service limits the server can exploit the unused portions of the TDMA frame in alleviating the traffic buildup in terminals yet to be serviced in the polling cycle. The simulation study considered dynamic service limits (subsection 6.4.1.4) and showed that traffic bursts of ON/OFF sources can be accommodated without leading to large increases in buffer size.

The results of the analysis (probability generating functions, mean and variance of buffer size, bounds for average delay, etc.) can be used directly by the call admission procedure to avoid congestion and to guarantee an acceptable traffic delay or buffer overflow probability. For example, a new registering terminal declares its connection parameters (average bit rate, variance of bit rate, tolerable delay, maximum buffer size, etc.) and the expected quality of service (CLP, average delay, etc.). These parameters can be used by the base station or the central server to estimate average traffic delay and expected buffer occupancy or even the cell drop probability when the terminal buffer size is given. The estimates are based on the load on the sector segment and the interference level on the corresponding antenna sector. As mentioned before, the base station monitors

interference continuously on each of its antenna sectors, while expressions such as equation (C.34) and equation (C.50) can be used to estimate occupancy and delay related figures. If the required quality of service is met, then the connection may be accepted; otherwise it is rejected or a lower quality of service is negotiated.

7.2.4 Handoff and Power Control Technique

The handoff procedure is critical to the performance of the overall system. It is the measure used to combat co-channel interference resulting from newly arriving users, and keep cell losses under a certain threshold value. In the simulated system, terminals monitor the quality of wireless link through monitoring the size of their traffic buffer. Monotonic increase over a period of time 100 frames (about 70 ms) duration is an indication of excessive loss of polling token and/or traffic cells. This triggers the terminal to handoff to another base station. The decision employs information that is collected and updated continuously by the terminal about interference measured during its silence periods. In the base station, lesser strict criteria are applied to accept a handoff call than those used to accept a newly originating call. This helps reduce call drop probability. From simulation trials and the results in subsection 6.4.3, the implemented procedure has a dramatic effect in determining the call drop probability while the admission control affects directly the blocking probability and indirectly the dropping probability. The design of these procedures and determination of the parameters and the thresholds used in triggering them is very important. The compromise between the call block probability and the call drop probability is achieved through the fine tuning of these parameters. Simulation results (Figure 6-14) show that with ARQ and handoffs a call block probability of 10^{-2} is achieved at a load equal to about 60 Mb/s per microcell (or carried load of 0.52) for a signal-to-interference threshold of 8 dB. The call drop probability is 10^{-3} at that operating point.

When call admission control allows the usage of all available capacity without keeping some reserve (see subsection 6.4.1.4), the call block probability is reduced. However, the population becomes very sensitive to interference (buffer sizes of terminals become very susceptible to instabilities) and thus call drop probability increases. The reverse is also true; when call admission control is conservative, leading to relatively high call block probabilities, most likely the reserve capacity will be enough to absorb traffic fluctuation and/or ARQ retransmissions.

Regarding power control, the algorithm tested in the simulation is simple; it uses only two levels of power: normal and 20 dB attenuated. Moreover, each base station and portable decides independently on the power level. The improvement obtained is about 50% reduction in cell loss probability. A more elaborate algorithm where probably more than two levels are used may prove more beneficial. Again, coordination between the two ends of the communication link may be required to achieve more enhancements.

7.2.5 Error Control

Wireless channel is not a reliable channel in comparison with the wireline channels. Signal fading and shadowing due to motion, and to large and small obstructing structures lead to errors in the received traffic cells. The system should compensate and provide a transparent service. The simulation results showed the effect of the receiver signal-to-interference threshold on many of the performance figures such as CLP, buffer occupancy, traffic delay, call block/drop probability. The study considered a relatively high threshold value (20 dB) and a moderate one (8 dB). The actual threshold of a receiver is a function of modulation/demodulation techniques, coding algorithm, etc. The CLP with no ARQ ranges from 10^{-3} to a little over 10^{-2} depending on the offered load and the receiver signal-to-interference threshold.

Selective automatic repeat request (ARQ) proved to be a simple method to combat errors at a little cost incurred in retransmissions. The raw CLP is the same as before and the average number of retransmissions per traffic cell (refer to Figure 6-12) is not significant. ARQ combined with forward error correction (FEC) algorithms may be another option but at an added cost of complexity.

7.3 Future Research

The objective of this study is to present an overall microcellular architecture of a wireless indoor broadband communications systems operating in the mm-wave band. For the purposes of this study some assumptions were necessary to simplify the tackled problem and to be able to obtain reasonable results in a limited time. However, if a particular aspect of this project is to be further analyzed, more detailed and realistic models can be used to obtain more accurate results. An example of such an area is the signal propagation in the indoor environment and the antenna model. The simulations conducted here considered sectorized antennas with ideal directivity, in addition to that, no reflections were taken into

consideration. A more accurate approach will be to allow for non-ideal behavior of the sector antennas and to account for signal reflections off walls and other objects.

The study proposes handoff as a remedy technique for interference generated by new comers, but not as a procedure to support mobility of users. Simply, the system assumes no mobility during the communication session. However, this might not be true for all types of user terminals, especially with hand-held terminals. More study should be done to consider mobility on the ground. As users move from the coverage area of one base station to another, the system should preserve and correctly maintain the traffic stream from the moving terminal to the other end. Other areas that can be expanded are the power control and the ARQ-plus-FEC procedure. As mentioned before, this study concentrated on a simple implementation of these procedures and demonstrated their potential benefit to the performance of the system.

On the analytical side of the study, we assumed a simple model for cell loss process in which cell losses are independent from a time slot to the next. Although this model maybe justified for cases where cell interleaving completely eliminates bursts of errors, there can be situations when signal fades are longer than the interleaver width resulting in correlation amongst cell losses. This can be considered by modifying the cell loss model to account for this correlation. Another issue is the service limits. To simplify the analysis, we considered static service limits, while in a practical situation these limits are dynamic and change from one polling cycle to the next, reflecting the variable traffic load. Hence, a more realistic model should consider the interaction amongst the different terminals.

Finally, the system layout described in this study is tailored for an indoor environment. Recently, research is focusing on broadband communication systems for the outdoor environment [17][16]. One example is the Local Multi-point Distribution Service (LMDS) which is predicated to operate in the 28 GHz range and as an alternative to the Fiber To The Curb (FTTC) systems. A research topic will be the extension of the proposed multiple access scheme to the LMDS system, if possible. Already some proposals suggest the use of a combination of contention-based and polling-based access methods to serve the broadband two-way traffic supported by these systems.

7.4 List of Contributions

1. Designing and demonstrating a multiple access protocol based on a fixed-length dynamic TDMA-TDD frame and on gated-limited polling that is appropriate for interference-limited environment. The design is summarized in Chapter 4. The

design includes a specific structure (beacon signals, registration slots, sector segments) and incorporates co-channel combatting mechanisms such as randomized order of segments and continuous monitoring of interference.

2. Proposing and testing handoff and power control techniques that improve the performance of the wireless LAN. Detailed description of both procedures are found in Section 6.3.2 and in Section 6.4.4. The handoff technique is based on continuous monitoring of SIR values on all antenna sectors on the part of the wireless terminal. This monitoring is aided by the beacon signals transmitted by the base stations at the beginning of each TDMA frame.
3. Building a complete modular simulation program for verifying the proposed microcellular architecture (microcells layout, antennas arrangement, multiple access protocol, etc.). The software also implements and tests ARQ, handoff, and power control procedures. Because of the modularity and flexibility of the program, variations of the protocol and the latter procedures can be simulated without significant modifications to the original program. The data structures used in designing the simulation program facilitate tracing of the execution and statistics collection.
4. Studied analytically an infinite-buffer queue with ARQ. The queue uses a gated-limited service discipline. The analysis takes into account the first order statistics of the traffic source and the TDMA frame structure. The main result is an exact probability generating function of the queue size, which is given in Section 5.4 and Section C.3.1. Consequently, expressions for the number of transmitted cells per polling cycle and cells in error are also obtained (equation (C.38) and equation (C.39), respectively). Mean buffer occupancy and estimate of traffic delay are given in equation (C.34) and equation (C.50), respectively.
5. Simpler expressions, when frame is under-utilized or traffic mostly occupies one sector segment, are obtained in Section C.3.2. These expressions specify the

probability generating function, and the mean and variance of buffer occupancy.

6. A finite-buffer queue model is formulated in equation (C.47) and the corresponding linear system of equations governing the probability mass function is set up in equation (C.48).
7. Analysis of an ON/OFF source and the derivation of the probability distribution of the number of traffic cells generated by such a source. The analysis is carried out in Section C.2.1 and the final result is given by equation (5.37).
8. Extension of Ahmadi's model to accommodate ARQ, as shown in equation (C.52), and building a new queue matrix structure to consider BMAP traffic models. This structure is given by equation (C.54).

A

Co-channel Interference and Square Cells Layout

A.1 Average Signal to Average Interference Ratio

Consider square cells of radius R each (or side length is $\sqrt{2}R$) as shown in Figure A-1. For cluster formations that are squared in area (i.e. $C = 1^2, 2^2, 3^2, \dots$), the cluster side length is $\sqrt{2}CR$. The co-channel domains belonging to the t^{th} layer are positioned uniformly on the sides of a bigger square whose side length is $2t\sqrt{2}CR$. Moreover, the number of these domains is equal to $2tC$.

To find the average signal to average interference power ratio on the uplink, the portable is assumed at the corner of the cell of interest: coordinates $(0, R)$. Hence the signal power is $R^{-\alpha}$ where α is the path loss exponent. Using symmetry, on one side of the square representing the t^{th} layer of co-channel domains, one can locate one co-channel source (labeled as (a) in the figure) at distance $t(\sqrt{2}CR)$ from the center $(0, 0)$. Another, labeled as (b) is at distance $\sqrt{2}t(\sqrt{2}CR)$. Further more, there are two sets of domains, labeled as (c) and (d), that are symmetric about the line joining the domain (a) and $(0, 0)$. The number of co-channel sources in each set is equal to $t-1$ and the distance of the i^{th} domain (counting from left) from origin is $\sqrt{(i\sqrt{2}CR)^2 + (t\sqrt{2}CR)^2}$. Adding all the interferer's powers, SIR on the uplink (considering T layers of co-channel domains) is given by:

Figure A-1: Square cells layout and layers of interferers (uplink case).

$$SIR = \left[4 \sum_{i=1}^T \left[\frac{1}{(tL)^\alpha} + \frac{1}{(\sqrt{2}tL)^\alpha} + 2 \sum_{i=1}^{t-1} \frac{1}{(\sqrt{(tL)^2 + (iL)^2})^\alpha} \right] \right]^{-1} \quad (\text{A.1})$$

where $L = \sqrt{2C}$.

For the down link, the powers are measured at the portable location. Using symmetry again (refer to Figure A-2), the down link average signal-to-interference is given by

$$SIR = \left[\sum_{t=1}^T \left[\frac{1}{d_{c_1}^{\alpha}} + \frac{1}{d_{c_2}^{\alpha}} + 2 \sum_{i=1}^{2t} \frac{1}{d_{i,s_1}^{\alpha}} + 2 \sum_{i=1}^{2t-1} \frac{1}{d_{i,s_2}^{\alpha}} \right] \right]^{-1} \quad (\text{A.2})$$

where

$$d_{c_1} = (2\sqrt{C}t - 1),$$

$$d_{c_2} = (2\sqrt{C}t + 1)$$

$$d_{i,s_1} = \sqrt{(\sqrt{C}i)^2 + (\sqrt{C}(2t-i) - 1)^2}$$

$$d_{i,s_2} = \sqrt{(\sqrt{C}i + 1)^2 + (\sqrt{C}(2t-i))^2}$$

Figure A-2: Square cells layout and layers of interferers (down link case).

B

Simulation Parameters

B.1 Simulations Parameters

- GRIDLIMITX:	width of the simulated floor layout.
- GRIDLIMITY:	length of the simulated floor layout.
- STATSDELTA:	maximum acceptable variance in the statistical readings before convergence is assumed.
- NOOFSTATTRIALS:	number of reading that should not vary amongst themselves by no more than STATSDELTA before convergence is assumed.
- NOOFBASESTATIONS:	number of base stations in the simulation floor.
- NOOFPORTABLES:	number of the portables on the simulated floor.
- PATHLOSS:	path loss propagation exponent, α .
- $d_{\min}$:	minimum distance between a portable and a service port.
- SHADOWINGSIGMA:	σ_{sh} , standard deviation of the shadowing process.
- SIRTHRESHOLD:	$SIR_{\text{threshold}}$, the minimum signal-to-interference ratio required to correctly receive a wireless envelope.
- NOSIGNALSIR:	no signal level.
- PRIMERATE:	raw capacity provided by the service port.
- ATMDATA:	number of bits in the data field of the ATM cell.
- WIRELESSCELL:	number of bits in the wireless envelope.
- MAXREGISTRATIONSLLOT:	number of registration slots per sector segment.
- NOOFSECTORS:	number of antenna sectors per base or portable. Also it is the number of sector segments or subframes per frame.
- FRAMELENGTH:	number of slots per frame, L .
- MAXTOFORACK:	number of time units, a portable waits for the acknowledgment

	envelope from the home service port, before timing out (retransmitting the registration packet).
- MAXHOMINGATTEMPTS:	number of time units the portable listens for the service ports before choosing a home base station (initial registration).
- MAXLISTENINGCELLS:	number of time units during which the portable listens for the transmissions and collecting statistics. When the period has elapsed it decides whether to handoff or not.
- PCCHECKPERIOD:	the period used in checking whether there is a need or not for power control procedure.
- POWERCONTROLLEVEL:	reduction in transmission power level, if power control is used.
- BASEWINDOWCOCHANNEL:	the window length in time slots, over which the power control criteria are averaged.
- MINAVERAGESIRATM:	minimum signal-to-interference level required before power control is invoked.
- MAXPOLLINGWAIT:	number of time units a portable waits without receiving a polling token. If this period has elapsed, it assumes that it was cut off its home base station and performs a handoff.
- MAXPLTTKCLP:	maximum allowable polling-token loss probability for a portable. If token loss rate is higher, the transportable considers handoff.
- MINTRAFFICCLP:	maximum allowable cell loss probability figure for a home/handoff candidate.
- MAXTRAFFICCLP:	Q , maximum allowable traffic cell loss probability for a portable. If cell loss probability is higher, the transportable considers handoff.
- MAXNOOFHOMINGS:	max number of times a portable is allowed to link to the same base station during handoff.
- STABILITYLIMIT:	minimum number of consecutive monotonic readings of buffer occupancy required before declaring a link to be unstable. The check is done every 10 frames duration.

The following table lists the values used for the parameters.

Table B-1: Simulation Parameters.

Parameter	Value	Parameter	Value
GRIDLIMITX	100 meter	GRIDLIMITY	100 meters
STATSDelta	0.01	NOOFSTATTRIALS	5
NOOFBASESTATIONS	16	NOOFPORTABLES	ranging from 5 ~ 130
PATHLOSS, α	3.5	$d_{\min}$	1 meter
SHADOWINGSIGMA, σ_{sh}	8 dB	SIRTHRESHOLD, $SIR_{\text{threshold}}$	8 ~ 20 dB
NOSIGNALSIR	-1000 dB	ATMDATA	48*8 bits
PRIMERATE	155.4 Mbps	MAXREGISTRATIONSLLOT	3 time slots
WIRELESSCELL	500 bits	FRAMELENGTH, L	204 time slot
NOOFSECTORS	6	MAXHOMINGATTEMPTS	$5L$
MAXTOFORACK	$2L$	PCCHECKPERIOD	$5L$
MAXLISTENINGCELLS	$5L$	BASEWINDOWCOCHANNEL	$5L$
POWERCONTROLLEVEL	20 dB	MAXPOLLINGWAIT	$5L$
MINAVERAGESIRATM	50 dB	MINTRAFFICCLP	0.01
MAXPLTTKCLP	0.01	MAXNOOFHOMING	3
MAXTRAFFICCLP, Q	0.05~0.005	STABILITYLIMIT	10

C

Queueing Analysis and Traffic Models

C.1 Intervisit Time Probability Mass Function

The intervisit time distribution is an important parameter that modifies the traffic arrival process and thus its evaluation is of extreme importance. As stated in Chapter 5, the distribution is evaluated for two distinct cases: symmetric and asymmetric spatial traffic distributions. For both cases, consider a TDMA frame that is FL time slots long. It is divided into S sector segments or subframes. The order of these segments is randomized from frame to another. Polling a specific user who is signed to a particular segment is done by sending him a token when the service of the segment commences. The token is correctly received with probability $(1 - \alpha)$.

When the sector segments are equal in length (each is FL/S time slots), then the probability mass function for intervisit time given there is no loss of token is

$$\begin{aligned} e_i &= \text{Prob [Intervisit Time} = i \text{ sector segments/no token loss]} \\ &= \begin{cases} i/S^2 & , i = 1, 2, \dots, S \\ (2S - i)/S^2 & i = S + 1, \dots, 2S - 1 \\ 0 & \text{else} \end{cases} \end{aligned} \quad (\text{C.1})$$

This can be readily deduced from the fact that the position of the sector segment in a frame is determined by a uniformly distributed discrete random variable. Hence, the distance

between two successive positions is given by the convolution of two identical discrete uniform random variables. The corresponding generating function of (C.1) is given by

$$S_1(z) = \sum_{i=1}^{2S-1} e_j z^i \quad (\text{C.2})$$

However, the terminal may miss a random number of polls or turns because of interference. The number of polls until the first correct reception of the token, $\bar{m}$, is geometrically distributed with the following probability mass function,

$$\text{Prob} [\bar{m} = i] = \alpha^{i-1} (1 - \alpha) \quad ; i = 1, 2, \dots, \infty \quad (\text{C.3})$$

and the corresponding generating function is

$$M(z) = \frac{(1 - \alpha)z}{(1 - \alpha z)} \quad (\text{C.4})$$

Combining equations (C.2) and (C.4), the generating function of the intervisit time (in sector segments length) is given by

$$I(z) = M(S_1(z)) \quad (\text{C.5})$$

which when written in a polynomial form is

$$I(z) = \frac{(1 - \alpha)}{\alpha} \sum_{i=1}^{\infty} \alpha^i \left(\sum_{j=1}^{2S-1} e_j z^j \right)^i \quad (\text{C.6})$$

but one can show that

$$\left(\sum_{j=1}^{2S-1} e_j z^j \right)^n = \sum_{k=n}^{n(2S-1)} e_{n,k} z^k \quad (\text{C.7})$$

where

$$e_{n,k} = \begin{cases} 0 & k = 1, 2, \dots, n-1 \\ \sum_{j=1}^{k-1} e_{n-1,k-j} e_j & k = n, n+1, \dots \end{cases} \quad \text{and } e_{1,k} = e_k.$$

Hence, $I(z)$ can be written as

$$I(z) = \sum_{i=1}^{\infty} c_i z^i \quad (\text{C.8})$$

where $c_i = \frac{(1-\alpha)}{\alpha} \sum_{j=\lceil \frac{i}{2S-1} \rceil}^i \alpha^j e_{j,i}$ $i = 1, 2, \dots, \infty$. $\lceil x \rceil$ is the smallest integer

greater or equal to x . c_i is the probability that the intervisit time is equal to i sector segments. This completely specifies the required pmf.

Considering the second case where the sector segments are not equal in length. $S-1$ of them are of length S_1 time slots and one is $S_2 = FL - (S-1)S_1$ time slots long. Again, this time using time slots to start with, the generating function for the pmf of intervisit time given no loss of token is given by

$$S_2(z) = \sum_{i=1}^{\infty} e_i z^i \quad (\text{C.9})$$

$$\text{where } e_i = \begin{cases} k/S^2 & i = kS_1, k = 1, 2, \dots, S-1 \\ (2S-k)/S^2 & i = kS_1 + S_2, k = 1, 2, \dots, S \\ 0 & \text{else} \end{cases}$$

The final generating function of the pmf of intervisit time is obtained as in equation (C.5),

$$I(z) = M(S_2(z)) \quad (\text{C.10})$$

C.2 Traffic Models

C.2.1 ON/OFF Exponential Model

The bursty source considered here alternates between two states: an ON state and an OFF state. During the ON state, the source generates information at a constant bit rate of $R_{ON} = 2R$ bits per second, whereas it has a zero rate when it is in the OFF state. The duration of the ON (OFF) states τ_{ON} (τ_{OFF}) is a random variable that follows the exponential distribution with mean m time units. The average bit rate of the source is R bit per second.

It is required to find out the probability mass function of the number of traffic cells generated by a bursty source during the intervisit time (i.e the arrival process is modulated by the polling mechanism). That is, what is $A(z)$ for this source?

The plan is to find density function of the sum of the time(s) the source is in the ON state for a given intervisit time, I . This is equivalent to finding the probability that i traffic cells arrive conditioned on I , the intervisit time, and then using the pmf of I , the deconditioning is carried out.

In a given window of I time slots, the traffic sources changes its states a random number of times, n , as shown in Figure C-1. Because of the exponential distribution of the ON and OFF periods, n has a Poisson distribution, i.e

$$\text{Prob}[n = i] = \frac{(I/m)^i}{i!} \exp(-I/m) \quad (\text{C.11})$$

Furthermore, the number of cells generated during I are only due to the sum of ON periods occurring during I (probably plus a fraction of a traffic cell; however, this fraction is ignored). Let this sum be denoted by T . Then from Figure C-1, if the beginning of the window is taken as the origin of the time axis then T is computed by

$$T = \begin{cases} x_2 - x_1 + x_4 - x_3 + \dots + x_n - x_{n-1} & n \text{ even} \\ x_2 - x_1 + x_4 - x_3 + \dots + I - x_n & n \text{ odd} \end{cases} \quad (\text{C.12})$$

if the window starts with an OFF period, or

Figure C-1: Bursty traffic source model.

$$T = \begin{cases} x_1 + x_3 - x_2 + x_5 - x_4 + \dots + I - x_n & n \text{ even} \\ x_1 + x_3 - x_2 + x_5 - x_4 + \dots + x_n - x_{n-1} & n \text{ odd} \end{cases} \quad (\text{C.13})$$

if the window starts with an ON period.

The vector $\underline{x} = (x_1, x_2, \dots, x_n)$ is the order statistic of a vector sample of size n from the uniform distribution on the interval $(0, I)$, and its joint p.d.f. is given by¹

$$f(x_1, x_2, \dots, x_n) = \begin{cases} n!/I^n & \text{if } 0 < x_1 < x_2 < \dots < x_n < I \\ 0 & \text{else} \end{cases} \quad (\text{C.14})$$

Now using equation (C.14), it is required to compute the density function, $f_T(t)$, of the variable T defined by equations (C.12) and (C.13). The classical method, of finding the cumulative distribution $\text{Prob}[T \leq t]$ and then differentiating it with respect to t , requires that one find the general solution for

$$\iint \dots \int \frac{n!}{I^n} dx_1 dx_2 \dots dx_n \quad (\text{C.15})$$

when the integrals are computed over the region constrained by $0 < x_1 < x_2 < \dots < x_n < I$ and the equations leading to T . Obtaining the integral limits proved to be a very difficult task and pursuing this lead was not possible. A second method² is used here to derive $f_T(t)$. This method relies on the moment generating function $F_T(s)$ defined as

$$F_T(s) = E[\exp(-sT)] \quad (\text{C.16})$$

Evaluating $F_T(s)$ requires also evaluating an n -integrals expression but the limits in this case are trivial as shown below: for example when the first branch of equation (C.12) is used to define T , then

1. This formulation of the problem is due to Prof. Peter Galko at the department of Electrical Engineering in Ottawa University.

2. This method is suggested by Prof. Adnan Awad at the department of Science in Jordan University for Women.

$$F_T(s) = \int_0^I \int_0^{x_1} \dots \int_0^{x_{n-1}} \frac{n!}{I^n} \exp(-s(x_2 - x_1 + x_4 - x_3 + \dots + x_n - x_{n-1})) dx_1 dx_2 \dots dx_n \quad (C.17)$$

The multiple integrals above involve exponential terms and are easy to evaluate. After computing $F_T(s)$, $f_T(t)$ is found by the inverse laplace transformation.

It can be shown (by iterative solution) that the density function of T when the window starts with an OFF period is given by

$$f_{T, \text{OFF}}(t) = \begin{cases} \frac{1}{I} & n = 1 \\ \frac{n!}{I^n} \frac{t^{a_n} (I-t)^{b_n}}{a_n! \cdot b_n!} & n = 2, 3, \dots, \infty \end{cases} \quad (C.18)$$

where:

$$a_n = \begin{cases} (n-2)/2 & n \text{ even} \\ (n-1)/2 & n \text{ odd} \end{cases}$$

$$b_n = \left\lfloor \frac{n}{2} \right\rfloor, \lfloor x \rfloor \text{ is the greatest integer smaller or equal to } x.$$

and when the window starts with an ON state, the density function is given by

$$f_{T, \text{ON}}(t) = \begin{cases} \frac{1}{I} & n = 1 \\ \frac{n!}{I^n} \frac{t^{b_n} (I-t)^{a_n}}{a_n! \cdot b_n!} & n = 2, 3, \dots, \infty \end{cases} \quad (C.19)$$

$f_{T, \text{ON}}(t)$ and $f_{T, \text{OFF}}(t)$ exist only in the interval $(0, I)$. To complete the previous two density functions, there also two discrete components that arise when n is equal to zero. These are

$$\frac{1}{2} \exp(-I/m) (\delta(t) + \delta(t-I)) \quad (C.20)$$

Figure C-2 depicts those density function for some values of n when the length of the window is one.

Figure C-2: Density functions for the random variable T for different values of n ($I = 1$).

From the above relations, the density function of T conditioned on the length of the window, I , is given by

$$p_{T/I}(t) = \frac{\exp(-I/m)}{2} \left[\sum_{n=1}^{\infty} \frac{1}{m^n a_n! b_n!} \cdot (t^{a_n} (I-t)^{b_n} + t^{b_n} (I-t)^{a_n}) \right] + \frac{\exp(-I/m)}{2} [\delta(t) + \delta(I-t)] \quad (C.21)$$

The marginal pdf of T , $p_T(t)$, is computed by deconditioning (C.21) over the pmf of I .

C.3 Queueing Analysis

C.3.1 Symmetric Spatial Distribution of Traffic with Infinite Buffer

Considering the queueing model depicted by Figure 5-1, the buffer evolution equation is given by

$$x_i = \begin{cases} 0 & i < 0 \\ n_i & i = 0 \\ x_{i-1} - b_{i-1} + l_{i-1} + n_i & i = 1, 2, \dots, \infty \end{cases} \quad (C.22)$$

where x_i is the buffer size (or the queue length) of the terminal upon receiving the polling token for the i^{th} time and n_i is the number of cells generated during the intervisit time (from the $(i-1)^{\text{st}}$ to the i^{th} polling token receiving instants). The variable l_i is the number of cells that are corrupted by interference and need to be retransmitted while b_i is the number of cells served in the polling cycle and is determined according to the Y -limited gated service discipline, i.e

$$b_i = \min(x_i, Y) \quad (C.23)$$

Y is the service limit.

The sequence of variables $\{x_i; i = 1, 2, \dots, \infty\}$ constitute a Markov Chain with state transition probabilities

$$\begin{aligned}
 p_{j,k} &= \text{Prob} [x_{n+1} = k / x_n = j] \\
 &= \begin{cases} \sum_{l=0}^k a_{k-l} L_{jl} & k \geq 0, j \leq Y, l \leq j \\ \sum_{l=0}^{k-j+Y} a_{k-j+Y-l} L_{Yl} & k \geq j-Y > 0, l \leq Y \\ 0 & \text{else} \end{cases} \quad (\text{C.24})
 \end{aligned}$$

where

$$\begin{aligned}
 L_{jl} &= \text{Prob} [l \text{ cells in error when } j \text{ are transmitted}] \\
 &= \begin{cases} \binom{j}{l} \alpha^l (1-\alpha)^{j-l} & ; l \leq j \\ 0 & \text{else} \end{cases} .
 \end{aligned}$$

a_i = Probability that i traffic cells arrive during intervisit time, and

α is the cell loss probability.

Note that the transition probabilities do not depend on the polling cycle index, n .

Let the steady state probabilities for the buffer size be

$$q_k = \lim_{i \rightarrow \infty} \text{Prob} (x_i = k) \quad ; k = 0, 1, \dots, \infty \quad (\text{C.25})$$

and define the generating function $Q(z)$ as

$$Q(z) = \sum_{k=0}^{\infty} q_k z^k \quad (\text{C.26})$$

But q_k can be written using the transition probabilities as

$$q_k = \sum_{j=0}^{\infty} q_j p_{jk}; k = 0, 1, \dots, \infty \quad (\text{C.27})$$

or

$$q_k = \sum_{j=0}^{Y-1} q_j \sum_{l=0}^k a_{k-l} L_{jl} + \sum_{j=Y}^{k+Y} q_j \sum_{l=0}^{k-j+Y} a_{k-j+Y-l} L_{Yl} \quad (\text{C.28})$$

Applying equation (C.26) to equation (C.28) and rearranging terms yields

$$Q(z) = \frac{A(z) \left[z^Y \sum_{j=0}^{Y-1} q_j \cdot L_j(z) - Q_Y(z) \cdot L_Y(z) \right]}{z^Y - A(z) \cdot L_Y(z)} \quad (\text{C.29})$$

where:

$A(z) = \sum_{i=0}^{\infty} a_i z^i$, the generating function describing the arrival process.

$L_j(z) = \sum_{i=0}^j L_{ji} z^i = (1 - \alpha + \alpha z)^j$, generating function describing the ARQ process.

$$Q_Y(z) = \sum_{j=0}^{Y-1} q_j z^j$$

$\{q_j; j = 0, 1, \dots, Y-1\}$ are the first Y points of the required distribution. They are solved for exploiting the analytic property of $Q(z)$ in the region enclosed by $|z| = 1$ as follows. The denominator of $Q(z)$ has Y zeros within the circle $|z| = 1$. Let these zeros be denoted by $\{z_m; m = 0, 1, \dots, Y-1\}$. Note that $z_0 = 1$ is one zero located in the circle. The remaining zeros can be found using Lagrange's theorem

$$z_m = \sum_{n=1}^{\infty} \frac{\exp\left(\frac{2\pi n m \sqrt{-1}}{Y}\right)}{n!} \frac{d^{n-1}}{dz^{n-1}} \{A(z) L_Y(z)\}^n \Big|_{z=0} \quad (\text{C.30})$$

for $m = 1, 2, \dots, Y-1$. Since $A(z)$ and $L_Y(z)$ are polynomials then the derivative term

is relatively easy to evaluate. More conveniently, packages like Matlab can be used to find the roots of $z^Y - A(z) L_Y(z)$.

Having $\{z_m; m = 0, 1, \dots, Y-1\}$, the numerator of equation (C.29) should also vanish when $z = z_m$. This leads to a set of $Y-1$ equations of the form

$$\sum_{j=0}^{Y-1} q_j \{z_m^Y L_j(z_m) - z_m^j L_Y(z_m)\} = 0 \quad ; m = 1, 2, \dots, Y-1 \quad (\text{C.31})$$

The last needed equation to complete the square linear system is obtained from the fact that $Q(1) = 1$, or

$$\sum_{j=0}^{Y-1} q_j (Y-j) = Y - \frac{\bar{a}}{1-\alpha} \quad (\text{C.32})$$

where $\bar{a} = \lim_{z \rightarrow 1} A^{(1)}(z)$. Solving the Y equations in (C.31) and (C.32), uniquely determined the unknowns $\{q_j; j = 0, 1, \dots, Y-1\}$. This completely specifies the generating function $Q(z)$.

On the stability issue, one can show by applying Rouché's theorem on the expression of $Q(z)$, that the following condition

$$\bar{a} + \alpha Y < Y \quad (\text{C.33})$$

is necessary for the existence of $Q(z)$. This condition can be interpreted as the average number of arrivals from the traffic source $\bar{a}$ plus the number of erroneous cells, αY , should be less than the maximum available portion of the TDMA allocated for the user, Y .

The mean buffer size can be obtained by

$$\begin{aligned} \bar{q} &= \lim_{z \rightarrow 1} Q^{(1)}(z) \\ &= \frac{N^{(2)}(1) \cdot D^{(1)}(1) - N^{(1)}(1) \cdot D^{(2)}(1)}{[D^{(1)}(1)]^2} \end{aligned} \quad (\text{C.34})$$

while the mean square is given by

$$\overline{q^2} = \lim_{z \rightarrow 1} Q^{(2)}(z) - \bar{q} \quad (\text{C.35})$$

and

$$\lim_{z \rightarrow 1} Q^{(2)}(z) = \frac{M^{(3)}(1)G^{(2)}(1) - M^{(2)}(1)G^{(3)}(1)}{12[D^{(1)}(1)]^4} \quad (\text{C.36})$$

where:

$F^{(i)}(.)$ is the i^{th} derivative of $F(.)$ with respect to z . $N(z)$ and $D(z)$ are the numerator and denominator of equation (C.30), respectively.

$$M^{(3)}(1) = N^{(3)}(1)D^{(1)}(1) - N^{(1)}(1)D^{(3)}(1)$$

$$M^{(2)}(1) = N^{(2)}(1)D^{(1)}(1) - N^{(1)}(1)D^{(2)}(1)$$

$$G^{(3)}(1) = 6D^{(1)}(1)D^{(2)}(1)$$

$$G^{(2)}(1) = 2[D^{(1)}(1)]^2$$

$$\begin{aligned} N^{(3)}(1) = & \{ Y(Y-1)(Y-2)(1-\alpha^3) + 3\bar{a}Y(Y-1)(1-\alpha^2) + \\ & 3(\bar{a}^2 - \bar{a})Y(1-\alpha) \} Q_Y(1) + \{ 3Y(Y-1)\alpha(1-\alpha) - \\ & 3(\bar{a} - \bar{a})(1-\alpha) \} Q_Y^{(1)}(1) + 3(1-\alpha^2)(-Y-\bar{a})Q_Y^{(2)}(1) - \\ & (1-\alpha^3)Q_Y^{(3)}(1) \end{aligned}$$

$$\begin{aligned} N^{(2)}(1) = & \{ 2Y\bar{a}(1-\alpha) + Y(Y-1)(1-\alpha^2) \} Q_Y(1) - \\ & 2\bar{a}(1-\alpha)Q_Y^{(1)}(1) - (1-\alpha^2)Q_Y^{(2)}(1) \end{aligned}$$

$$N^{(1)}(1) = Y(1-\alpha)Q_Y(1) - (1-\alpha)Q_Y^{(1)}(1)$$

$$D^{(3)}(1) = Y(Y-1)(Y-2)(1-\alpha^3) - (\bar{a}^3 - 3\bar{a}^2 + 2\bar{a}) - 3(\bar{a}^2 - \bar{a})\alpha Y - 3\alpha^2 \bar{a} Y(Y-1)$$

$$D^{(2)}(1) = Y(Y-1)(1-\alpha^2) + \bar{a}(1-2\alpha Y) - \bar{a}^2$$

$$D^{(1)}(1) = Y(1-\alpha) - \bar{a}$$

$$\bar{a} = \lim_{z \rightarrow 1} A^{(1)}(z) = \sum_{i=0}^{\infty} i \cdot a_i, \text{ the mean traffic cells arrivals during intervisit time.}$$

$$\bar{a}^2 = \sum_{i=0}^{\infty} i^2 \cdot a_i, \text{ the mean square of traffic cells arrivals during intervisit time.}$$

$$\bar{a}^3 = \sum_{i=0}^{\infty} i^3 \cdot a_i, \text{ the mean cubed of the traffic arrivals during intervisit time.}$$

$$Q_Y(1) = \sum_{i=0}^{Y-1} q_i$$

$$Q_Y^{(1)}(1) = \sum_{i=0}^{Y-1} i \cdot q_i$$

$$Q_Y^{(2)}(1) = \sum_{i=0}^{Y-1} i(i-1) \cdot q_i$$

$$Q_Y^{(3)}(1) = \sum_{i=0}^{Y-1} i(i-1)(i-2) \cdot q_i$$

Knowing the probability distribution of the buffer size, one can find the steady state probability distribution of the other variables that appear in the buffer evolution equation

(C.22), namely, b , the number of cells served in each visit, and l the number of corrupted cells each transmission (b and l are the steady state versions of b_i and l_i , respectively).

From equation (C.23), the probability mass function of b is given by

$$\text{Prob}[b = i] = \begin{cases} q_i & ; i = 0, 1, \dots, Y-1 \\ \sum_{k=Y}^{\infty} q_k & ; i = Y \\ 0 & ; \text{else} \end{cases} \quad (\text{C.37})$$

or more conveniently put in a generating function form,

$$B(z) = Q_Y(z) + (1 - Q_Y(1))z^Y \quad (\text{C.38})$$

Since l is has a binomial distribution for a given value of b , then its probability generating function is

$$L(z) = B(1 - \alpha + z\alpha) \quad (\text{C.39})$$

C.3.2 Asymmetric Spatial Distribution of Traffic with Infinite Buffer

In this case, it is assumed that one of the S sector segments of the frame is heavily utilized while the others are free or have very little traffic. In this case the service limit on the terminal occupying the busy sector segment is very large compared to the symmetric case, and would justify the following equation for the buffer evolution

$$x_i = \begin{cases} 0 & i < 0 \\ n_i & i = 0 \\ n_i + l_i & i = 1, 2, \dots, \infty \end{cases} \quad (\text{C.40})$$

i.e the buffer is emptied each time it is served. Again here, the sequence of variables $\{x_i; i = 1, 2, \dots, \infty\}$, where x_i is the buffer size at the i^{th} polling instant, constitute a Markov Chain with state transition probabilities

$$p_{jk} = \begin{cases} \sum_{l=0}^k a_{k-l} \cdot L_{jl} & : 0 \leq k \leq j \\ \sum_{l=0}^j a_{k-l} \cdot L_{jl} & : 0 \leq j \leq k \end{cases} \quad (\text{C.41})$$

Hence, the steady state probability distribution of the queue is given by equation (C.27), or

$$q_k = \sum_{j=0}^{k-1} q_j \sum_{l=0}^j a_{k-l} \cdot L_{jl} + \sum_{j=k}^{\infty} q_j \sum_{l=0}^k a_{k-l} \cdot L_{jl} \quad (\text{C.42})$$

The generating function obtained from the above expression has the functional form

$$Q(z) = Q(1 - \alpha + \alpha z) \cdot A(z) \quad (\text{C.43})$$

Through direct substitution, one can easily show that the following is a solution to the functional equation

$$Q(z) = \prod_{k=0}^{\infty} \tilde{A}(\alpha^k (1-z)) \quad (\text{C.44})$$

where $\tilde{A}(z) = A(1-z)$.

From equation (C.43), the average length is given by

$$\bar{q} = \frac{\bar{a}}{(1-\alpha)} \quad (\text{C.45})$$

and the variance is

$$\sigma_q^2 = \frac{\bar{a}^2}{(1-\alpha)^2} + \frac{\bar{a}\alpha(2\bar{a}+1-\alpha)}{(1-\alpha)(1-\alpha^2)} - \frac{\bar{a}^2}{(1-\alpha)^2} \quad (\text{C.46})$$

where $\bar{a}$ and $\bar{a}^2$ are the first and second moments of the arrival process, respectively.

C.3.3 Symmetric Spatial Distribution of Traffic with Finite Buffer

The same queueing model considered above is used here. The only difference is that the buffer size of a terminal is limited to K traffic cells. Again, the sequence of variables $\{x_i; i = 1, 2, \dots, \infty\}$ constitute a Markov Chain but with the following transition probabilities

$$\begin{aligned}
 p_{j,k} &= \text{Prob} [x_{n+1} = k / x_n = j] \\
 &= \begin{cases} \sum_{l=0}^{\min(k,j)} a_{k-l} L_{jl} & k < K, j < Y \\ \sum_{l=0}^{\min(k-j+Y, Y)} a_{k-j+Y-l} L_{jl} & k < K, k \geq j-Y \geq 0 \\ \sum_{k=K}^{\infty} \sum_{l=0}^{\min(k,j)} a_{k-l} L_{jl} & k = K, j < Y \\ \sum_{k=K-j+Y}^{\infty} \sum_{l=0}^{\min(k,j)} a_{k-l} L_{jl} & k = K, j \geq Y \\ 0 & \text{else} \end{cases} \quad (C.47)
 \end{aligned}$$

and the steady state distribution is given by

$$q_k = \sum_{j=0}^{\infty} q_j p_{jk}; k = 0, 1, \dots, K \quad (C.48)$$

Using equation (C.48) together with $\sum_{k=0}^K q_k = 1$, a linear system of $K+1$ equation is generated and solved for the probability distribution of the buffer size.

C.4 Traffic Delay Estimation

The conventional approach based on Little's formula would require finding the expected number of cells in the buffer at any instant of time. For Poisson Arrivals (continuous time case) Burke's theorem and the PASTA property (Poisson Arrivals See Time Averages)

facilitate obtaining the queue size distribution at an arbitrary time instant. However, for the queueing model considered here, this seems not tractable and thus the exact mean delay is unavailable. Instead, upper and lower bound are given in this section.

From the queue mechanics, one can note the following: the buffer is being filled during intervisit time and then emptied during service time (there might be arrivals during the service time). So, intuitively, the mean number of cells in the buffer at an arbitrary time is less than the mean number of traffic cells at the polling instant and is greater than that when the service ends. i.e

$$\bar{d} \leq \bar{n} \leq \bar{q} \quad (\text{C.49})$$

where $\bar{d}$, $\bar{n}$, and $\bar{q}$ are the buffer means at the server departure instant, arbitrary time instant, and server visit (polling) instant, respectively. Hence from Little's Formula

$$w_L \leq w \leq w_U \quad (\text{C.50})$$

where w_L and w_U are the lower and upper bounds of the mean traffic delay. w is the exact mean delay. The terms in equation (C.50) are obtained by dividing the corresponding terms in equation (C.49) by the average arrival rate of traffic cells per unit time.

The upper bound in equation (C.50) was computed in a previous section while the lower one can be computed from the evolution equation of the queue. Considering equation (5.27), the mean number of cells remaining in the buffer is given by

$$\bar{d} = \bar{q} - \bar{b} + \bar{l} + \bar{a} \quad (\text{C.51})$$

where $\bar{b}$, $\bar{l}$, and $\bar{a}$ are the means of the number of cells transmitted, corrupted, and arrived during service time, respectively. Knowing the distribution of the buffer size at the polling instant (i.e. $\{q_k; k = 0, 1, \dots, \infty\}$) the distributions of b and l are known (equations (C.38) and (C.39)) and hence the means are known. $\bar{a}$ is found by multiplying $\bar{b}$ by the rate of traffic arrival per time slot. The above completely specifies the lower bound on traffic delay.

C.5 BMAP/G/1 Model and Matrix Geometric Technique

Consider our queue evolution equation, namely,

$$X_{i+1} = \max(0, X_i - Y) + L_i + R_i \quad ; i = 0, 1, \dots \quad (\text{C.52})$$

which is rewritten here in a different form than the one in equation (C.22). R_i here is a sequence of correlated batch arrivals. L_i is a term describing the ARQ, and follows a binomial distribution with parameters $\min(X_i, Y)$ and α , the cell loss probability. The same system is considered by Ahmadi and Guérin [1] but with L_i equal to zero.

Let R_i be generated through a Markov chain with a finite number of states $\{0, 1, 2, \dots, N-1\}$ where the k^{th} state corresponds to the event of k traffic cells arriving¹. Furthermore, let p_{ij} be the transition probability between state i and j , $0 \leq i, j \leq N-1$. Using these definitions, (X_i, R_i) forms a discrete time Markov chain. The transition probability matrix of this chain has a block-partitioned structure similar to that of an M/G/1 queue, which is of the form

$$Q = \begin{bmatrix} B_0 & B_1 & B_2 & \dots & B_{M-1} & 0 & 0 & 0 & \dots \\ A_0 & A_1 & A_2 & \dots & \dots & A_M & 0 & 0 & \dots \\ 0 & A_0 & A_1 & \dots & \dots & A_{M-1} & A_M & 0 & \dots \\ 0 & 0 & A_0 & A_1 & \dots & \dots & \dots & A_M & 0 & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \end{bmatrix} \quad (\text{C.53})$$

where A_i for $0 \leq i \leq M$ and B_i for $0 \leq i \leq M-1$ are square nonnegative submatrices. This is true when the following mapping is used: the transition probability from state (i_1, j_1) to state (i_2, j_2) is the entry in the $(Ni_1 + j_1)^{\text{th}}$ row and the $(Ni_2 + j_2)^{\text{th}}$ column of the matrix Q . i.e the states $\{(i, j) : 0 \leq i, 0 \leq j \leq N-1\}$ are ordered lexicographically as

1. The study in [1] considers a more general definition of the Markov chain in the sense that state k corresponds to $s_k \geq 0$ traffic cells arriving. However, since our arrival process will vary from 0 to $N-1$ traffic cells, we chose the definition that state k corresponds to the arrival of k traffic cells.

$\{(0, 0), (0, 1), \dots, (0, N-1), (1, 0), (1, 1), \dots, (1, N-1), \dots\}$.

From the evolution equation one can deduce that the transition probability is given by

$$\tilde{q}_{(i_1, j_1), (i_2, j_2)} = \begin{cases} p_{j_1, j_2} L_{i_1, k} & i_2 = \max(0, i_1 - Y) + j_2 + k \\ 0 & \text{else} \end{cases} \quad (\text{C.54})$$

$k = 0, 1, \dots, \min(i_1, Y)$, Y is the service limit every polling cycle, and p_{j_1, j_2} is the transition probability associated with the correlated traffic stream, i.e. it is the probability that a batch of j_2 cells arrive given that the previous batch was j_1 cells. As before, the variable $L_{i, k}$ is the probability that k cells are in error when i are transmitted. Substituting in equation (C.54) and building the matrix Q , and after recognizing the block structure, one finds out that the submatrices A_i and B_i are of size $YN \times YN$ and M is equal to $\left\lceil \frac{N}{Y} \right\rceil + 1$, where $\lceil x \rceil$ is the smallest integer greater or equal to x .

It should be noted that the matrix Q is stochastic and its invariant probability vector q can be obtained through solving the system described by $Qq = q$ and $\varepsilon q = 1$, where ε is a row of ones. However, since the dimensions of Q are infinite, the matrix geometric technique relies on the submatrices to obtain the vector q , which is defined by

$$q = \left[q_0^T \ q_1^T \ \dots \ q_p^T \ \cdot \right]^T \quad (\text{C.55})$$

$$q_p = \left[q_{Yp, 0} \cdot \dots \cdot q_{Yp, N-1} \ q_{Yp+1, 0} \cdot \dots \cdot q_{Yp+1, N-1} \cdot \dots \cdot q_{Yp+Y-1, 0} \cdot \dots \cdot q_{Yp+Y-1, N-1} \right] \quad (\text{C.56})$$

and

$$q_{i, j} = \lim_{n \rightarrow \infty} \text{Prob} \{x_n = i, R_n = j\} \quad ; i \leq 0, 0 \leq j \leq N-1 \quad (\text{C.57})$$

The solution method is as follows:

1) Define the following matrices

$$A = \sum_{i=0}^M A_i$$

$$G(z) = \sum_{i=0}^M z A_i G^i(z)$$

$$K(z) = \sum_{i=0}^{M-1} z B_i G^i(z)$$

The matrix $G(z)$ is the transform of the number of traffic cells served during the busy period, where $K(z)$ is the transform of the first passage times from level 0 back to level 0. The corresponding stochastic matrices to $G(z)$ and $K(z)$ are G and K respectively, and these are computed using these formulae:

$$G_{k+1} = \sum_{i=0}^M (I - A_1)^{-1} A_i G_k^i$$

$$K = \sum_{i=0}^{M-1} B_i G^i$$

Once G and K are computed, then the corresponding stationary vectors, g and k are computed where

$$Gg = g \quad \text{and} \quad eg = 1$$

$$Kk = k \quad \text{and} \quad ek = 1$$

2) A vector, $\underline{\beta}$ is computed using $\underline{\beta} = \sum_{i=0}^M i A_i e^T$.

3) A vector, $\underline{\mu}$ is computed using $\underline{\mu} = (I - G + eg) [I - A + (e - \underline{\beta})g]^{-1} e^T$

4) A vector k_1 is computed using $k_1 = e + \sum_{i=1}^{M-1} \left(B_i \sum_{j=0}^{i-1} G^j \right) \underline{\mu}$.

5) Finally, the vectors g_i , $i = 0, 1, \dots$ are computed using

$$q_0 = \frac{k}{k k_1}$$

and

$$q_i = \left[q_0 \bar{B}_i + \sum_{j=1}^{i-1} q_j \bar{A}_{i+1-j} \right] (I - \bar{A}_1)^{-1}$$

$$\text{where, } \bar{A}_i = \sum_{j=i}^M A_j G^{j-i} \text{ for } 0 \leq i \leq M, \bar{B}_i = \sum_{j=i}^{M-1} B_j G^{j-i} \text{ for } 0 \leq i \leq M-1.$$

Using the vectors q_i and there definition the stationary queue length distribution is given by

$$\text{Prob [Queue length} = n] = \sum_{j=0}^{N-1} q_{n,j}.$$

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