A Study of MAC Protocols for Long Range Wireless Networks

THE AUSTRALIAN NATIONAL UNIVERSITY

Jeta Vedi

Research School of Physical Sciences and Engineering

Australian National University

A thesis submitted for the degree of

Master of Philosophy

March 2006

Declaration

The contents of this thesis are the results of original research and have not been submitted for a higher degree to any other university or institution.

A part of the work in this thesis has been published

Jeta Vedi, Gerard Borg. MAC Performance Analysis in Long Range Wireless Local Loops. In *Proceedings of* 3^{rd} *IEEE and IFIP International Conference on Wireless and Optical Communications Networks*, Bangalore, India 2006.

This thesis is the result of my work performed jointly with Dr. G. Borg. All sources used in the thesis have been furthermore acknowledged.

20 June 2008

Acknowledgements

Many thanks to my supervisor, Dr Gerard Borg, for his guidance during my time at the Research School of Physical Sciences and Engineering.

Thanks also to my family for their caring support.

Abstract

The disparity in telecommunications services between urban and rural areas continues to be a contentious issue. However, the possibility of using vacant UHF spectrum for long range wireless networks may offer a practical solution. This thesis explores Medium Access Control (MAC) protocol design for such networks, with particular focus on the BushLAN wireless regional area network.

We show random access schemes are not suitable for channel sharing in networks with hidden nodes and long propagation delays. The optimal form of p-persistent CSMA/CA from the IEEE 802.11 standard is found to offer less channel utilisation than an equivalent contention free method, TDMA/TDD. We recommend slotted Aloha be used for a control channel to allocate contention free data channel access as demanded from network subscribers.

Two contention free MAC protocols, with full duplex base stations and half duplex subscriber stations are then proposed. The first MAC, TDMA/FDD, uses TDMA on both the uplink and downlink channels. The second MAC, TDMA/FDMA, uses TDMA on the downlink and FDMA for the uplink. We evaluate the throughputs for both MACs and find they are comparable on the downlink, but FDMA provides superior uplink performance, and can support a significantly greater coverage area than TDMA. We conclude the most suitable MAC layer protocol for BushLAN is TDMA/FDMA.

Throughput results for TDMA/FDMA under VoIP, HTTP and SMTP traffic loads are also obtained. We show that TDMA/FDMA provides satisfactory capacity for each application without saturating the MAC layer.

Contents

List of Figures

Abbreviations

ACK Acknowledgement

BA Basic Access

BEB Binary Exponential Backoff

BS Base Station

CA Collision Avoidance

CD Collision Detection

CDMA Code Division Multiple Access

CSMA Carrier Sense Multiple Access

CTS Clear to Send

CW Contention Window

DCF Distributed Coordination Function, part of IEEE 802.11

DCF Distributed Coordination Function

DIFS Distributed InterFrame Space

FDD Frequency Division Duplexing

FDMA Frequency Division Multiple Access

HTTP Hypertext Transfer Protocol

LAN Local Area Network

MAC Medium Access Control

MTU Maximum Transmission Unit

P_s Probability of successful transmission over the channel

P_{tr} Probability of transmission over the channel

QoS Quality of Service

RTS Request to Send

SIFS Short InterFrame Space

SMTP Simple Mail Transfer Protocol

SS Subscriber Station

T_c Time taken for a collision in a CSMA system, cycle time in a TDMA system

TCP Transmission Control Protocol

TDD Time Division Duplexing

TDMA Time Division Multiple Access

T_f Time taken for a TDMA frame

T_s Time taken for a successful transmission

Chapter 1

Introduction

The growth of the Internet and the increasing demand for broadband access is driving improved methods of communication and business. Broadband services such as DSL, cable modem and wireless access have been widely deployed in urban and metropolitan areas. The telecommunications market has been able to provide regular network upgrades in tandem with the evolution of the Internet to these areas by upgrading existing infrastructure, as the high population density justifies the large capital costs involved. These may include factors such as equipment, cable and spectrum (55).

By contrast, the inadequate provisioning of communications services in rural and regional Australia has been a contentious issue, resulting from a lack of economically feasible technological solutions (60). The costs involved in cable and satellite are too large, while current terrestrial wireless solutions such as the popular Wifi (IEEE 802.11) (53) and LMDS (27) operate in a microwave frequency range unsuitable for the long distances and sparsely populated regions in the bush.

However, recent developments by regulators such as the FCC (51), and industry bodies such as the IEEE 802.22 Working Group on Wireless Regional Area Networks (WRANs) (12), into the potential application of UHF TV bands for long range broadband communications may be a promising solution. UHF has a long wavelength that allows the signal to travel over large distances, and is also capable of diffracting around objects such as hills, vegetation and buildings. These properties make it ideal for applications such as TV broadcasting, where approximately 5 MHz of bandwidth provides coverage of around 100 kilometres (15). The movement from analogue to digital television is now changing how spectrum is managed, and creating vacant VHF and UHF bands. This opens up the possibility of using these vacant bands for broadband regional communications (5) (36) (8).

This leads to the unique design challenges for long range regional networks. Communication networks, particularly radio communication systems, incorporate capacity sharing amongst different users, and a multiple access technique is used to achieve this. A multiple access technique provides a method of dividing network capacity for simultaneous use by multiple users.

This thesis explores various multiple access methods for a long range fixed wireless access network. We begin this chapter by providing further background on the status of broadband communications in Australia. The protocols involved in network communications are then reviewed. Background information on communication mechanisms and different medium access control (MAC) protocols is then outlined. We consider different MAC systems in greater detail in subsequent chapters.

1.1 Broadband Access in Regional Australia

The telecommunications market in Australia is as diverse as the continent itself. The provision of telecommunications services began with the formation of Telecom Australia in the 1975 Telecommunications Act (47). Over time this legislation has been updated to reflect changes in technology and society. In 1991 the Act made significant movements towards deregulating the industry, by promoting competition amongst various service providers.

A key part of the Act has been the Universal Service Obligation (USO). The motivation of the USO was to "ensure that the standard telephone service is reasonably accessible to all people in Australia on an equitable basis, wherever they reside or carry on business" , as taken from the 1991 Act (22). This was designed to provide services to those parts of the country that were uneconomic to service, specifically the rural and regional areas. This was done by means of subsidy, firstly to Telecom, then Telstra, and after 1997, the entire telecommunications industry (60).

The failure of the USO and the deregulated market to deliver the high speed data and Internet services available in the city to those living in the bush has been a regular point of analysis and debate, particularly in the political arena. Indeed, the issue of 'last-mile' communications for the bush has been the thorn in the federal Government's attempts to privatise Telstra. Despite over $11 billion in total regional telecommunications funding between 1997-2005, including the Estens regional inquiry, the Besley service inquiry, and a House of Representatives Standing Committee report, there has been very little tangible achievement (49). A case in point is the service in Carroboblin Station in central NSW, where many district users currently work at 28 kbps or less. A 2004 Senate report to provide minimum data speeds of 40 kbps over the next two years is hardly sufficient, and would require "a lot of line improvements" (54).

The fundamental problem of last-mile services to the bush lies in the large distances, low population density, and lack of infrastructure. This means the conventional communication methods used in urban areas are not practical. The infrastructure requirements of wireline methods such as broadband cable are prohibitively expensive. A national fibre optic network has been estimated to cost up to $30 billion, while digital subscriber line (DSL) technology on copper wires is limited to a maximum of four kilometres from a telephone exchange (60).

Furthermore, current wireless technologies are also unsuitable. Metropolitan area networks such as LMDS and Wifi operate in microwave frequencies with short wavelengths that require line of sight communications over small distances. Satellites have been considered as a potential option, but remain very expensive and consequently not in mainstream use. Chapter 2 considers these wireless technologies in further detail.

However, recent developments on spectrum regulation and management, both internationally and within Australia, are leading towards wireless technologies more suitable for bush communications. Specifically, the introduction of digital television broadcasting is creating free spectrum in old analogue VHF and UHF TV bands (5). This has led to regulators such as the FCC to propose that it would be "desirable to allow unlicensed devices to access the largest practicable number of television channels" (8).

VHF and UHF spectrum are ideally suited to the needs of bush communications, as their long wavelengths can provide non line of sight transmissions over large distances. Moreover, the hardware required for VHF/UHF communications is relatively inexpensive. Existing TV equipment such as antennas, transmitters and receivers could be recycled and modified for digital data communications. Cognitive radio technology can be used to identify which bands are available in a given area, and determine the most suitable transmission parameters (51).

The potential application of TV bands for long range network communications is an exciting prospect, and has led to the formation of the IEEE 802.22 Working Group on Wireless Regional Area Networks (WRANs) (12), and the BushLAN Project at the Australian National University (18). Further details on WRANs and BushLAN are provided in Chapter 2. This thesis studies MAC protocols and analyses their suitability for long range broadband networks, with particular focus on BushLAN.

1.2 The OSI Model

The Open Systems Interconnection (OSI) model defines a hierarchy of seven protocol layers for networking (1). Figure 1.1 illustrates this framework.

The uppermost layer, the application layer, supports end user processes. This layer provides application services for network software such as e-mail, file transfers and web browsing. Layer 6 formats data to be sent across a network, providing freedom from compatibility problems, and is sometimes called the syntax layer. The session layer establishes, manages and terminates connections between applications.

The transport layer provides transparent transfer of data between end users, and is responsible for end-to-end error recovery and flow control, ensuring complete data transfer. Common examples of transport layer protocols include Transmission Control Protocol (TCP) and User Datagram Protocol (UDP).

The network layer provides switching and routing technologies, creating the logical paths, or virtual circuits for transmitting data between nodes. Addressing, internetworking, congestion control and packet sequencing are function of this layer. The Internet Protocol (IP) belongs to the network layer.

At the data link layer, the data packets are encoded and decoded into bits. The data link layer contains two sublayers, the Medium Access Control (MAC) and the Logical Link Control (LLC) layer. The MAC controls how a computer gains access to transmit and receive data over a network. The LLC controls frame synchronisation, flow control and error checking.

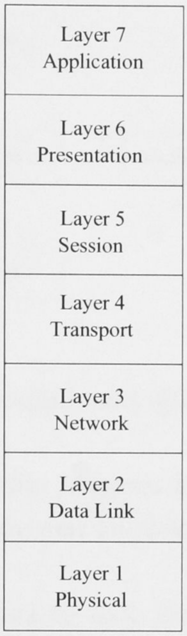


Figure 1.1: The 7 Layers of the OSI Model.

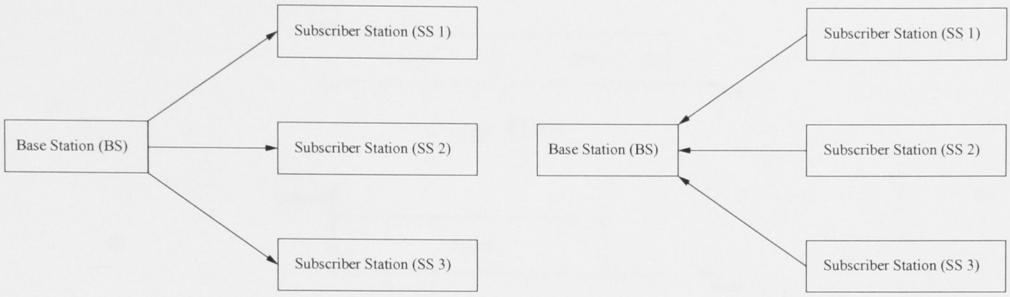
The lowest layer, the physical (PHY) layer converts between bit streams and electrical impulses, light or radio signals through the network. It is the final hardware means of sending and receiving data over a channel, where the channel may be a cable or wireless. Ethernet and Wifi are protocols with data link and physical layers.

Any data communications between two end users travels down the OSI stack of the transmitting node and up the OSI stack of the receiving node.

1.3 Duplexing

A multiuser wireless network means the same channel must be shared between multiple users. In this thesis, we consider a point to multipoint setup with a base station (BS) serving multiple fixed (immobile) subscriber stations (SS). The fixed positions of the stations is commonly referred to as a fixed wireless access network.

There are two types of multiuser channels, the uplink channel and the downlink channel, as illustrated in Figure 1.2. This defines a bi-directional system for two way communications.



(a) Downlink (b) Uplink

Figure 1.2: Downlink and uplink data flows.

Duplexing defines the relationship between the uplink and downlink channels. A network may use either Time Division Duplexing (TDD), or Frequency Division Duplexing (FDD).

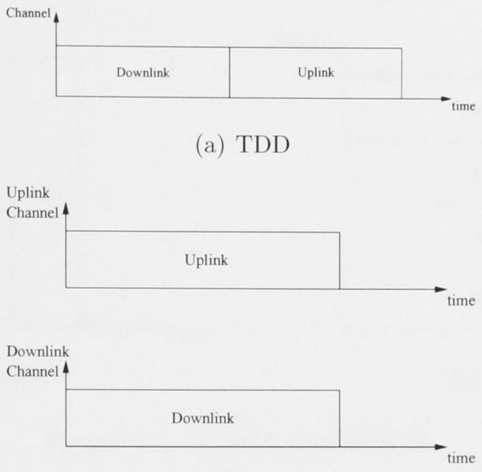
TDD assigns orthogonal timeslots for each user to transmit and receive between a BS. FDD assigns separate frequency bands for transmission and reception. TDD and FDD are illustrated in Figure 1.3.

A MAC protocol must be applied to both the uplink and downlink channels. MACs may be either half duplex, where a station may only transmit or receive at anyone time, or full duplex, where a station can transmit and receive simultaneously.

1.4 Medium Access Control

Medium access control (MAC) is the mechanism that allows multiple stations to transmit and receive over the same medium, which in this study is the wireless channel. MAC protocols are divided into two broad categories, contention based or contention free.

Contention based, or random access protocols, provide each station with the authority to access the channel at any time they deem appropriate. This decentralised method can be efficient, as stations only access the medium when the need to communicate arises. However, it is possible that multiple users may choose the same time to transmit, resulting in a collision of data signals at the receiver.



(a) TDD

(b) FDD

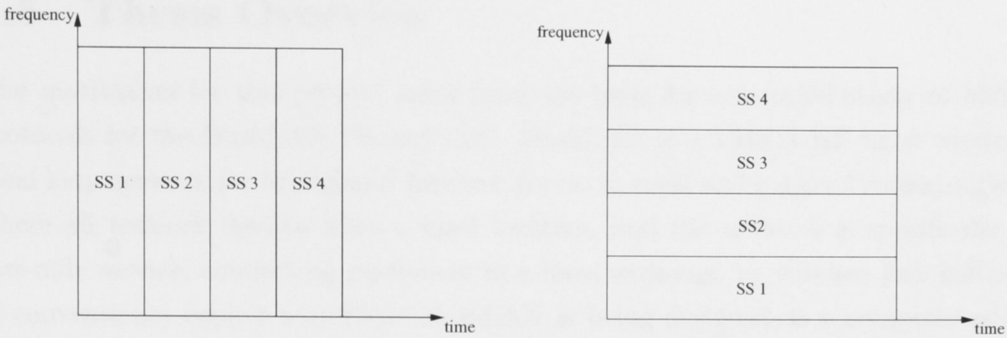
Figure 1.3: TDD and FDD.

Generally speaking, a collision means multiple signals have combined at the receiver, making it impossible to accurately decipher. These protocols require a collision resolution function to minimise these occurrences, for if collisions are high, channel capacity is underutilised. Random access protocols are considered in detail in Chapter 3.

Contention free protocols ensure that a collision can never occur. Typically these networks have a base station managing the medium to prevent collisions. Two main forms of fixed access protocols are frequency division multiple access (FDMA), and time division multiple access (TDMA).

In FDMA, the total channel bandwidth in a network is divided between all users. In TDMA, the total channel bandwidth is cyclically allocated to each station in the network. FDMA and TDMA are illustrated in Figure 1.4. In TDMA, each individual allocation is referred to as a TDMA slot. It is also common for MAC protocols other than TDMA to measure time in discrete units known as slots. The length of the slot time varies according to the MAC protocol, and may be the length of the transmission time of a data packet, or the length of the propagation delay.

One cycle of slots in TDMA is referred to as a TDMA frame, and the frame is cyclically repeated over time. MAC frames encapsulate higher layer data packets from all users into a format suitable for transmission and reception by the MAC



(a) TDMA (b) FDMA

Figure 1.4: TDMA and FDMA.

layer.

Unlike random access where users must contend for channel capacity, TDMA and FDMA are classed as fixed assignment strategies, where capacity is guaranteed to users without any form of request. With developments in hardware and software technology that can be used in networks, and the growing diversity of applications that networks must be able to support, it is increasingly common for MAC schemes to employ a combination of random access and fixed assignment to allocate capacity amongst users, such as in demand assignment strategies (52). Random access can be useful for variable bit rate (bursty) applications such as web traffic, while fixed assignment is ideal for constant bit rate (stream) traffic such as voice. It is possible for users to request channel capacity using a random access scheme, and then be allocated either a segment of spectrum in FDMA, or slots in TDMA.

Code division multiple access (CDMA), which uses spread spectrum signalling for multiple users to simultaneously transmit on the same channel, was not considered in this thesis. Collisions are not as immediately disastrous in CDMA networks as in the random or fixed access networks described above, but do require large amounts of bandwidth. However, further studies into long range broadband wireless networks may analyse the feasibility of CDMA for BushLAN.

1.5 Thesis Overview

The motivation for this project arose from the need for a detailed study of MAC protocols for the BushLAN Project (20). BushLAN is a VHF/UHF fixed wireless local loop network for broadband Internet access to rural and regional communities, where all network devices have a fixed location, and the network is specifically a last-mile service, connecting customers to a local exchange by wireless link instead of conventional copper wire (36). BushLAN is being designed as a comprehensive network system, considering all aspects of the OSI model for communications.

The objective of this thesis is to examine the suitability of various MACs for long range wireless communications, such as in BushLAN. Firstly we review wireless networks in Chapter 2. Chapter 3 considers random access protocols and their potential functionality in a long range setting. Chapter 4 analyses two fixed access protocols, TDMA/FDMA - a TDMA downlink with an FDMA uplink; and TDMA/FDD TDMA up and down links that occur on separate frequency bands. Chapter 5 investigates the influence of different traffic types on TDMA/FDMA. Finally Chapter 6 concludes by summarising the main results and discussing possible further work.

Chapter 2

Overview of Wireless Networks

This chapter discusses broadband wireless access networks currently available in commercial deployments as well as research trends, with particular focus on their MAC techniques. Background information on BushLAN is also provided that is relevant to design and analysis of a MAC protocol suitable for this long range system.

2.1 Current Wireless Technology

There is a wide array of wireless communications technology available in the market today. Since the introduction of the mobile phone, and more recently with the explosion of Wifi, consumers have enjoyed the convenience of wireless networks. This section presents an overview of a selection of the major forms of currently available commercial wireless data networks. Specifically, we consider Wifi, LMDS, satellites and HIPERLAN/2. We also touch briefly on some proprietary networks, both in Australia and overseas.

The motivation is to understand the nature of these networks and the MAC protocols they employ, to make an informed analysis of MACs suitable for BushLAN. Note that as BushLAN is a fixed wireless data network, mobile phone standards such as 3G are not considered, which predominantly service voice and other media applications, usually under conditions of user mobility.

2.1.1 Wifi

Wifi technology, as defined by the Institute of Electrical and Electronic Engineers (IEEE) is the 802.11 standard for microwave network distribution, operating in unlicensed spectrum around 2.4 GHz and 5.8 GHz [3]. This local area network (LAN) is able to support DSL services to users without adequate wireline infrastructure. These deployments have been popular in offices, cafes, campus environments and in residential locations. Wifi is able to provide high broadband speeds, ranging from 1 Mbps to 100 Mbps, and allows user mobility within the localised network range.

There are two specific reasons for the popularity of Wifi, beyond the intrinsic convenience of wireless communications. Firstly, its operation in the industrial, science and medical (ISM) bands means it is a licence-free communications system without spectrum costs. Secondly, the common standard allows interoperability between devices. This allows products from different manufacturers to coexist in the same network, meaning suppliers work in a complimentary manner to build the market.

Its popularity has extended beyond private LANs, as many cities worldwide move towards providing blanket Wifi coverage, particularly in central commercial districts (3). However, the microwave frequency range in Wifi limits the networks to line of sight (LOS) connections with a maximum range of a few hundred metres. While this is acceptable for urban scenarios, it would not be sufficient for sparsely populated remote communities.

Nevertheless, there has been research into the potential for Wifi in regional areas (50) (61) (68) (25) (48). These studies recognise the pitfalls of Wifi, and attempt to increase range by adjusting parameters in link power budgets. However, once low population density numbers are factored, the net present value of the projects generally make them unfeasible (68), and can have installation costs as expensive as $A2000 per link (61), as they require a high concentration of base stations.

By contrast, the large wavelengths in UHF spectrum are more suited to the needs of long range communications, and can operate without line of sight. Moreover, installation costs need not be high, as the same equipment used in TV broadcasts can be reused, such as TV antennas.

The IEEE 802.11 standard specifies a random access MAC from the carrier sense multiple access (CSMA) family, with collision avoidance (CA). Chapter 3 analyses the CSMA/CA protocol.

2.1.2 LMDS

Local Multipoint Distribution Service (LMDS) is a fixed wireless system in the 25 GHz and higher spectrum range(27). It can be used for point-to-multipoint communications, as illustrated in Figure 1.2, with a base station servicing a number of subscriber stations. LMDS can provide voice and data services, pay TV, high-speed Internet access and wireless telephony, thus providing an opportunity for converged service providers (36).

Much like Wifi, the high frequencies used in LMDS require LOS, and have limited coverage area "5 kms). However, provided a LOS link exists with carefully set up external antennas and high power, data rates up to 600 Mbps over 3 kms can be obtained, similar to fibre optic links (36). This is due to the large amount of bandwidth available in the LMDS frequency range. Thus LMDS could provide an effective wireless backbone linking together nearby rural townships. However the LOS requirements make it unfeasible for remote last mile connections.

Moreover, LMDS equipment can be costly, with base stations up to \$US100,000, and customer premise equipment (CPE) as much as \$USlO,OOO (62). Consequently, deployments have been limited, and generally used for backhaul applications. In Australia, AAPT has LMDS facilities in various locations around regional Victoria, offering 2 Mbps to business and government users (36).

Currently, most LMDS system designs are built around the TDMA and FDMA approaches (32) (39) (31). In the downlink direction from the base station to clients, most companies supply TDMA. For the uplink, either TDMA and/or FDMA access methodologies are used. The choice between these two access links is related to the system operator business case, service strategy, and target market. Chapter 4 explores the possibility of TDMA and FDMA uplinks for BushLAN.

2.1.3 Satellites

Satellite systems have a number of features that are not common in terrestrial wireless systems, but which are relevant to BushLAN. Similar constraints on the MAC protocol design include the long signal propagation delay, signal power, capacity, and minimising the complexity in hardware and software.

A detailed analysis of satellite MAC protocols is presented in (52). Early access schemes used simple capacity assignment strategies, predominantly designed for applications such as telephony or broadcast television. However, with the growing trend towards variable bit rate applications such as data traffic over the Internet, it is common now for satellites to employ a hybrid MAC scheme that combines several capacity assignment strategies (46). Satellite MACs are commonly either a modification of existing terrestrial schemes, or are unique to the purposes of the satellite communications.

In one case, the Transmit Before Assignment Using Collision Requests (TBACR) scheme (21), a user wanting to send a data packet must first transmit a reservation request packet on a slotted Aloha request channel (the Aloha protocol is analysed in Chapter 3). If the request is successful, the scheduler assigns a slot in a future TDMA frame to the user for data communications. If the user is not assigned a slot before an appropriate timeout period, it repeats the request process after a randomised rescheduling delay. The scheduler may be on the satellite, or it may be a terrestrial node that relays slot allocations between ground stations and the satellite. In the case where there are more requests than slots for a particular frame, the requests are randomly honoured. The other requests are dropped, as the scheduler does not maintain a request queue.

Demand Assignment Multiple Access (DAMA) schemes are popular in satellite systems, where capacity (either in the form of TDMA or FDMA) is allocated to users in response to random user requests. This form of MAC is also used in terrestrial wireless LANs such as HIPERLAN /2 and WiMAX, which are discussed later.

2.1.4 HIPERLAN/2

The Broadband Radio Access Networks (BRAN) project of the European Telecommunications Standards Institute (ETSI) works on different kinds of wireless broad-

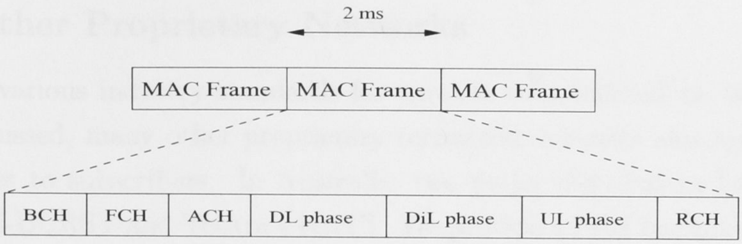


Figure 2.1: The HIPERLAN/2 MAC Frame.

band access networks in a similar way to the IEEE organisation (37). One ETSI BRAN project, called High Performance Radio Local-Area Network, type 2 (HIPERLAN/2), provides high-speed communications to broadband core networks and moving terminals in the 5 GHz band, typically for short ranges up to 150 m (40).

HIPERLAN/2 has been compared with IEEE 802.11a, as they both operate in the same spectrum and provide similar data rates, around 54 Mbps, due to their similar PHY layers (29). However the higher cost of HIPERLAN/2 and limited availability outside Europe has resulted in the IEEE 802.11 standards becoming the predominant global wireless LAN standard.

The key difference between 802.11 and HIPERLAN/2 is in the MAC protocol. HIPERLAN/2 uses a TDMA/TDD MAC as illustrated in Figure 2.1.

Before a new MAC frame commences, during the random access channel (RCH), stations send their request for capacity to the BS in order to send data in the next frame. The broadcast channel (BCH) at the start of the new frame contains information on the control of radio resources, and the frame channel (FCH) contains an exact description of the allocation of resources for the current MAC frame. The access feedback channel (ACH) informs stations about previous request attempts during the last RCH. The down link (DL) and uplink (UL) phases allow transmission of information between SSs and the BS. The direct link phase (DiL) is an optional space for SSs to communicate directly with one another without intervention from the BS.

This form of random access TDMA/TDD, or DAMA, allows rapid changes to capacity allocation from frame to frame depending on the requirements of users, which can be very efficient. However, it also requires a large amount of bandwidth to minimise the delay that is created from the MAC overhead in each frame.

2.1.5 Other Proprietary Networks

Aside from various industry standards for wireless communications, such as those already discussed, many other proprietary terrestrial networks also provide broadband services to subscribers. In Australia, two major distributors have been ArrayComm's i-BURST and Telstra's lxRTT. We provide a brief background on these wireless networks to illustrate the nature of products available to consumers.

ArrayComm has developed its own network, i-BURST, a trademarked mobile broad band access system, that claims to be a complete end-to-end wireless IP solution, akin to "mobile DSL" (9). ArrayComm acquired 3G spectrum in the 2.1 GHz band for its i-BURST network, and uses a TDMA/TDD MAC layer offering maximum speeds of 1061 kbps on the downlink and 346 kbps on the uplink (a 3:1 downlink/uplink throughput asymmetry). Power consumption from CPE units are around 5 W, meaning its network is fundamentally "coverage-limited". The business model for i-BURST rollouts requires high population density areas to achieve sufficient subscriber penetration. In Australia, i-BURST is currently offered in metropolitan areas such as Sydney, Brisbane and Melbourne.

Telstra proposed a national rollout of lxRTT (Single Carrier Radio Transmission Technology), which is part of the CDMA2000 standard for the international 3G data services. lxRTT is phase one in the evolution of next generation wireless networks and devices (23). It provides a maximum speed of 144 kbps, and will use Telstra's existing CDMA sites as base stations. As such, it is only available wherever there is good CDMA coverage, or about one-fifth of the Australian landmass. Telstra promoted the importance of lxRTT as a wireless local loop to rural areas where customers currently access dial-up internet speeds off approximately 14.4 kbps, and their only alternative for faster internet speeds has been satellite technology. Ultimately though, this service is still confined to areas with CDMA coverage, and its limited network capacity can be highly variable.

These network systems are predominantly tailored towards providing broadband services with the freedom of mobility to more urban populations. The underlying technology of deployments such as i-BURST mean their application to rural and regional areas is limited, as the economics does not provide return to investment in wide sparsely populated areas. Moreover, the expectation of a feasible solution from

Telstra and the Federal Government seems less and less likely (60). However, further research into developing new long range wireless systems is gaining momentum, and may lead to a potential solution.

2.2 Wireless Networks Research

The penetration of wireless technology as an efficient and productive networking system, particularly Wifi, has led the IEEE to expand its scope to further potential applications for wireless networks. Two broadband standards currently being developed are WiMAX (IEEE 802.16), and WRAN (IEEE 802.22).

2.2.1 WiMAX

WiMAX is a wireless metropolitan area network (MAN) governed by the IEEE 802.16 standard. It is a fixed wireless broadband system, and intends to complement last mile cable modem and xDSL connections by providing Internet services where there is no wired infrastructure. The PHY layer operates between 10-66 GHz (IEEE 802.16) and 211 GHz (IEEE 802.16a), with data rates in the range of 32-130 Mbps.

At this frequency range, coverage area is an issue. The high data rate also requires considerable power. Despite claims of connectivity up to 50 kms, preliminary studies suggest a 3 km cell radius with a BS transmit power of 50 W is more realistic (34). In a business case model for WiMAX, rural deployments have a net present value (NPV) of $US1m after five years, assuming nearly 2,000 subscribers for one base station in a 2 km radius (7). For residential and commercial districts in metropolitan areas, a WiMAX broad band cellular access network could have a net present value upwards of $US 10m after five years. This assumes a cell radius of less than 1km, with an average of 423 subscribers per base station, and 63 base stations for a population of over 1 million, where the cheapest CPE types are assumed to be around $US250.

These values are similar to LMDS, and while suitable for high density access or backhaul operations, it is not ideal for last mile services to rural areas. As yet the final standard has not been certified, but pre- WiMAX networks are currently being implemented in major cities in the USA and elsewhere (4).

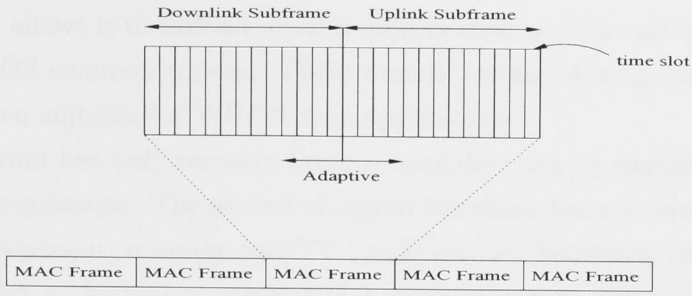


Figure 2.2: The WiMAX (IEEE 802.16) MAC Frame.

The current WiMAX standard is based on a DAMA TDMA/TDD MAC similar to HIPERLAN/2. The WiMAX MAC frame is illustrated in Figure 2.2.

In each MAC frame, time slots are allocated according to priority based on traffic class to meet deadlines for different applications, thus providing a guaranteed level of quality of service (QoS). For the uplink, the BS broadcasts an uplink map message (UL-MAP) at the beginning of each frame, informing all SSs which slots are available for their uplinks. Each SS will transmit its up link data during the slots allocated to it as indicated in the UL-MAP. The UL-MAP is determined by BW-requests sent from SSs to the BS. The BW-request mechanism exists in either a contention mode or a contention-free mode. In the contention mode, SSs send their BW-requests during a contention period, much like HIPERLAN/2 with its RCH. In the contention-free mode, the BS polls each SS, which replies with its BW-request.

Again, the rapid flexibility of these MACs allows efficient capacity allocation. However it is a scheme that requires high bandwidth to overcome the MAC overheads, such as with the bandwidth requests, and for the transmission of numerous data packets in a single MAC frame. Thus this MAC scheme is popular in high bandwidth networks such as WiMAX, HIPERLAN /2 and satellites.

2.2.2 WRAN

The IEEE Working Group on Wireless Regional Area Networks (WRAN), or IEEE 802.22, is the newest group of the IEEE 802 LAN/MAN standards committee, formed in 2004. It is also a fixed wireless system, but critically it focuses on VHF/UHF TV bands between 54 and 862 MHz (12). This frequency range is ideal for long range networks, as its long wavelength requires less power to travel further distances, and allows it to diffract around objects such as hills and vegetation, permitting non-LOS communications. These reasons are the driving motivation for it being considered suitable for WRAN type applications.

This spectrum has only recently become available, due to changes in television broadcasting regulations. The advent of digital television has resulted in changes to spectrum management, meaning free TV bands are now becoming available (5). Of course, a WRAN is the perfect application for this spectrum, hence the stimulus for research into optimal designs for this new network type. Aside from industry bodies such as IEEE, regulators such as the FCC are also supporting the potential of this new technology (8).

Current research into WRANs is principally on designing a cognitive radio system. The cognitive radio aspect of WRANs would allow the networks to determine what spectrum resources are free. Specifically, this could entail a base station using a GPS to send its location coordinates to a centralised server (in the USA this would be managed by the FCC), which would then respond with information about free TV channels in its area. Another proposal would be to allow the base station to scan the spectrum range locally and decide by itself which channels are available for network communications (2).

As yet no PHY nor MAC layers have been specified for IEEE 802.22. However, as TV channels are only 6-7 MHz, this is a very narrow bandwidth compared to microwave frequency networks such as LMDS and WiMAX. Thus PHY and MAC considerations are of critical importance in being able to provide adequate broadband connections to rural communities.

2.3 BushLAN

The BushLAN Project at the Australian National University is the development of a cognitive radio transceiver in the VHF/UHF TV bands, with the motivation of supplying low cost broadband services to rural and regional communities. This radio is expected to conform to the future WRAN standards, and is a collaboration with industry and government partners. It is being designed specifically for remote areas removed from wireline facilities by distances in the order of 10-30 kms, with a relatively low subscriber density, typically around 10-20 users per base station.

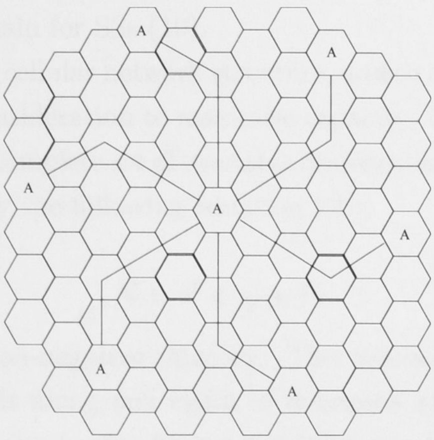


Figure 2.3: Co-channel cell location in a cellular system, where $N = 19$, $i = 3$, $j = 2$, from Equation 2.1.

The BushLAN base station would be placed in a central, well elevated position, with access to backbone infrastructure such as satellite or cable. This would allow it to provide good capacity and coverage for last mile connections to remote subscribers. The subscribers would be equipped with a low cost radio modem, an antenna and power supply.

The PHY and MAC layer processing is done by Field Programmable Gate Arrays (FPGAs) in the modem. This extends onto an RF front end, that converts between digital and analogue signals, and contains amplifiers and the antenna. The particular construction details of the transceiver is currently classified as commercially sensitive, but we will mention a few key parameters relevant to the MAC analysis of the thesis. The confidential information pertains largely to the FPGA and RF front end development for VHF/UHF radio communications, rather than the MAC layer. The MAC layer analysis for a long range wireless local loop presented in this thesis has been published (64).

To minimise the cost of subscriber terminals, an output power of 10 W would be optimal, as power amplifiers are a particularly expensive component of wireless transceivers. At the base station, an output power around 50 W would be acceptable.

As BushLAN is a fixed wireless system, the SS antennas would be directional towards the BS, whereas the BS antenna would need to be omnidirectional, for maximum coverage area. The current specifications are for a 9 dBi antenna gain at the base, and a 15 dBi gain for SSs (19).

BushLAN will have a cellular network structure, and so cluster size and frequency reuse is an important consideration to maximise capacity. Given N cells in a cluster that collectively use the complete set of available frequencies, then under a hexagonal geometry, N must satisfy the following equation (57),

$$N = i^2 + ij + j^2 \tag{2.1}$$

where i and j are non-negative integers. The nearest co-channel neighbor of a particular cell is i cells along any chain of hexagons and then turn 60 degrees counter-clockwise and move j cells. Figure 2-3 illustrates this for $i = 3$ and $j = 2$.

In Australia, TV bands are divided in 7 MHz channels, whereas in the US they are 6 MHz channels. Given the relatively small about of available bandwidth in TV channels, and the large cell sizes to be deployed in BushLAN networks, the smallest value of N is optimal. Thus, for $i = 1$, $j = 1$, $N = 3$. Dividing by total TV channel bandwidth gives 2 MHz of bandwidth per cell, and we shall assume a modulation scheme with a spectral efficiency of 1 bps/Hz. This gives a total channel capacity of 2 Mbps.

2.4 Summary

This chapter presented a brief outline of various different wireless network technologies. The IEEE 802.11, LMDS, HIPERLAN/2 standards were discussed, as well as satellites, and commercial systems such as i-BURST and 1xRTT. Research into large scale networks such as WiMAX and WRANs were also summarised. The MAC schemes used in these systems were mentioned for their possible examination for a long range UHF wireless network being developed at the ANU, called BushLAN.

Early proposals for a BushLAN MAC were to simply use the IEEE 802.11 standard. This would mean the only challenge in the BushLAN system would be to scale the carrier frequency and channel bandwidth for UHF. In Chapter 3 we analyse random access protocols and test the suitability of the IEEE 802.11 MAC for a BushLAN type setting. In Chapter 4 we explore the MAC concepts used in LMDS, TDMA/TDD and TDMA/FDMA.

Chapter 3

Random Access Protocols

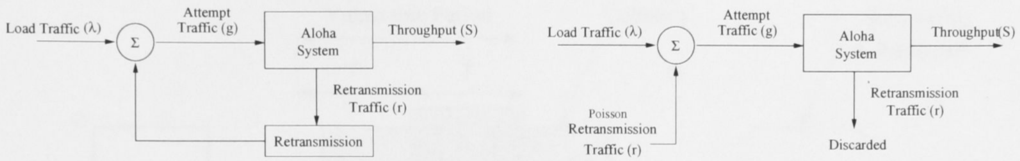
3.1 Introduction

This chapter reviews random access protocols and considers their suitability to long range networks. These protocols operate in a decentralised manner, where network stations are able to transmit their data over the channel once the packets have been generated. These protocols are popular in packet radio networks, where the motivation is to maximise efficiency by allocating bandwidth to stations on a needs basis.

Given the individual nature of operation, any transmission from a station is not guaranteed to be successful, as multiple transmissions may commence at the same time. This results in a collision of transmissions, and the receiver is unable to correctly read any useful information.

In the event of a collision, all unsuccessful stations must retransmit until they are successful. To avoid further collisions, the protocol must execute a retransmission algorithm that schedules the unsuccessful transmission to a random time in the future. By arranging a transmission involved in a collision to be retransmitted at a random time, the algorithm aims to minimise the chance of further collisions.

In the following sections, we review the early random access protocols of Aloha and slotted Aloha. We then consider Carrier Sense Multiple Access (CSMA), and the IEEE 802.11 DCF protocol, which uses a Binary Exponential Backoff (BEB) retransmission algorithm. Finally we investigate the potential application of random access protocols to long range networks.



(a) The accurate model (b) The simplifed model

Figure 3.1: The Aloha models for performance analysis.

3.2 Aloha

The first random access protocol was named Aloha (14), and was intended for wireless communications between several stations. The motivation was to connect the island nodes in the University of Hawaii computer network. Its simple operation was to allow any station to immediately transmit any data frame once it arrived at the link layer. As all stations share the same radio channel, a collision occurs whenever two or more stations transmit at the same time.

No retransmission algorithm is specified in Aloha, meaning a station does nothing if its transmission suffered a collision. Aloha assumes an upper layer of the protocol stack is providing the reliable communication service, so after a collision there will be a timeout at an upper layer from lack of response, causing it to retransmit.

Aloha is implemented as a half-duplex system, so that any station may only operate its transmitter or receiver at one time. The analysis presented here on the Aloha protocol was originally described in (41) (42) (45).

3.2.1 Pure Aloha

The Aloha model is shown in Figure 3.1(a). The load traffic from all stations is λ data frames per second, and is merged with the retransmission traffic of arrival rate r. The total traffic entering the Aloha network is then $g = \lambda + r$.

Two key assumptions are made for a mathematically tractable analysis of Aloha. Firstly, we assume all stations generate data frames according to a Poisson process. Secondly, we assume there is a large retransmission time, such that collided frames are retransmitted at a very distant future time. A long retransmission delay reduces the correlation between the load and retransmission traffic.

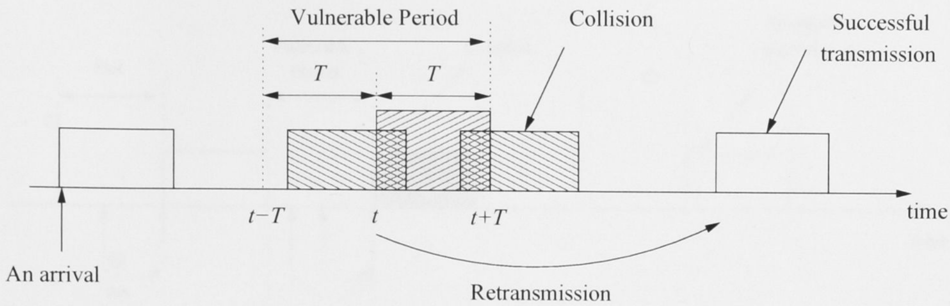


Figure 3.2: A snapshot of the Aloha channel.

Figure 3.1(b) uses these assumptions to simplify the model, where the load traffic is a Poisson arrival process, and the retransmission traffic is also Poisson traffic that is independent of the load traffic. Thus the attempt traffic is also a Poisson process with mean g arrivals per second.

The size of all data frames are taken to be fixed with transmission time of T units of time, where a transmission can be a new data frame or a retransmission. A frame arriving on the channel at time t will not suffer a collision if no other data frames are transmitted within the vulnerable period. The vulnerable period is the interval of time where two transmissions may overlap, causing a collision. Figure 3.2 illustrates a snapshot of the Aloha channel, and shows that for an arrival at time t, it will suffer a collision if at least one other transmission occurs between $t - T$ and $t + T$. Hence the vulnerable period is $2T$.

For a Poisson process with mean arrival rate μ, the probability that the number of packet arrivals $X(t)$ in a time period $[0, t]$ is equal to some integer k is given by (35)

$$P(X(t) = k) = \frac{(\mu t)^k}{k!} e^{-\mu t} \tag{3.1}$$

For a transmission to be successful, no other station must commence their transmission during the vulnerable period. Therefore the probability of a successful transmission, P_s, is

$$P_s = P(X(2T) = 0) = \frac{(g \cdot T)^0}{0!} e^{-2T \cdot g} = e^{-2gT} \tag{3.2}$$

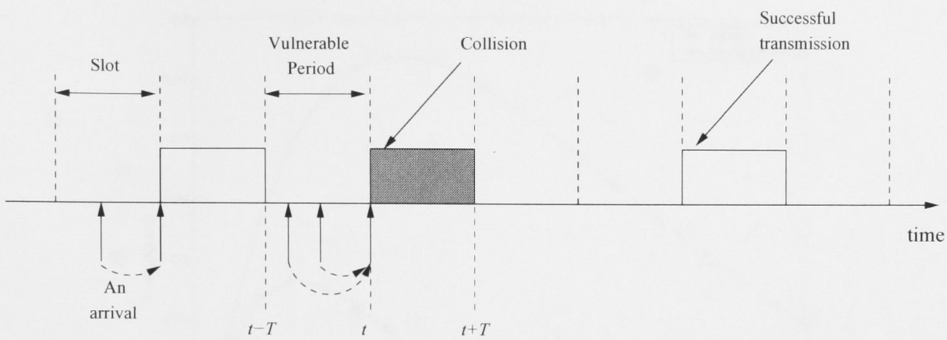


Figure 3.3: A snapshot of the Slotted Aloha channel.

The throughput, S, is defined to be the proportion of time that the channel carries successful data transmissions, and is also referred to as the channel utilisation. Given the arrival rate is g, the rate of successful transmissions is $g \cdot P_s$, and so the throughput is

$$S = g \cdot P_s \cdot T = gTe^{-2gT} \tag{3.3}$$

The attempt rate g can be normalised to the transmission time T by defining $G = gT$. This gives a normalised throughput expression,

$$S = Ge^{-2G} \tag{3.4}$$

3.2.2 Slotted Aloha

As an improvement to Aloha, a system was proposed where time was divided into discrete intervals called slots (58). All stations are synchronised and can only commence their transmissions at the beginning of a slot, where the slot time is equal to the transmission time of a frame. This is known as slotted Aloha.

Under slotted Aloha, if a frame arrives between some time $t - T$ and t, it will be transmitted at t. A collision will occur if at least one additional frame arrives between $t - T$ and t, as it will also begin transmission at t. If any frame arrives between t and $t + T$, it will be scheduled for transmission at the beginning of the next slot. As a result, the vulnerable period is now T, half of the Aloha value. This is illustrated in Figure 3.3.

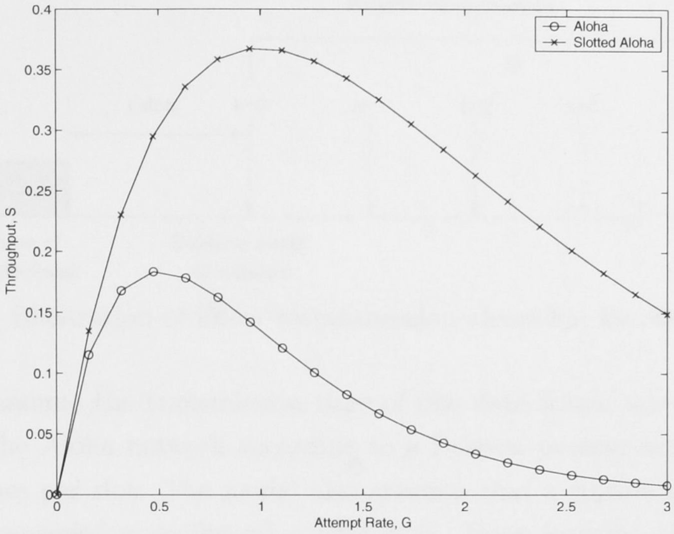


Figure 3.4: Throughput, S, versus attempt rate, G, for Aloha (Equation 3.4), and Slotted Aloha (Equation 3.5).

Repeating the previous calculation with the new vulnerable period, the throughput of slotted Aloha is

$$S = Ge^{-G} \tag{3.5}$$

From Equation (3.4) we note that the peak throughput of Aloha is $S = 1/2e \approx 0.18$ when $G = 0.5$. By comparison, slotted Aloha achieves a maximum throughput of $S = 1/e \approx 0.36$ when $G = 1$. Figure 3.4 plots the throughput as a function of arrival rate for the Aloha systems.

We observe that by synchronising users to align all transmissions in time, slotted Aloha avoids the partial overlap of packets. However, even with this improvement, the effective data rate is still less than 40% of the raw transmission rate, which is still wasteful of limited wireless bandwidth.

3.2.3 Slotted Aloha with Linear Retransmission

The Aloha model so far has assumed the retransmission traffic is a Poisson process that is independent of the load traffic. Using the analysis in (45), we now consider the influence of a linear retransmission algorithm in slotted Aloha.

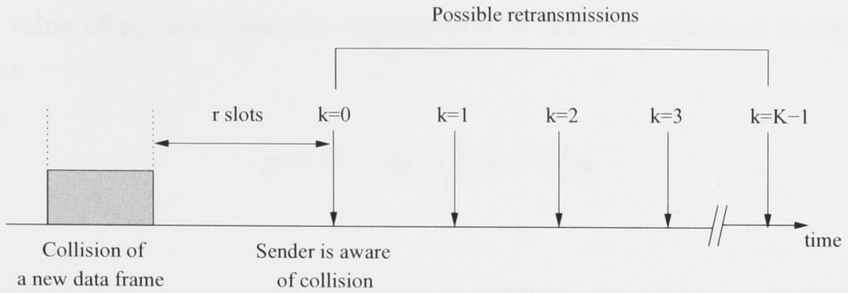


Figure 3.5: Illustration of linear retransmission algorithm for slotted Aloha.

Again we assume the transmission time of one data frame takes one slot, and traffic enters the Aloha network according to a Poisson process with mean arrival rate of G frames per slot. The model also assumes that a station learns about an unsuccessful transmission (collision) r slots later. Upon learning about the transmission failure, the station will schedule a retransmission after some random integer of slots, k, which is uniformly chosen between 0 and $K-1$. The k value represents the delay in slots for the retransmission attempt. If zero is chosen, the station will retransmit as soon as it discovers its transmission was unsuccessful.

Figure 3.5 illustrates the retransmission algorithm. The throughput, S, requires the following quantities:

q_n - the probability that a new data frame will be transmitted successfully.

q_t - the probability that a collided data frame will be transmitted successfully.

p_i - the probability that a collided data frame is successfully transmitted after i retransmission attempts, where $i \geq 1$.

H - the average number of retransmissions required to successfully transmit a data frame, so $H = E[p_i]$.

In (45), q_n and q_t were derived to be

$$q_n = \left[e^{-G/K} + \frac{G}{K} e^{-G} \right]^K \cdot e^{-G} \tag{3.6}$$

and

$$q_t = \left[\frac{e^{-G/K} - e^{-G}}{1 - e^{-G}} \right] \cdot \left[e^{-G/K} + \frac{G}{K} e^{-G} \right]^{K-1} \cdot e^{-G} \tag{3.7}$$

The value of p_i, and hence its expectation H, can be expressed in terms of q_t and q_n as

$$p_i = (1 - q_n)(1 - q_t)^{i-1} \cdot q_t \tag{3.8}$$

and

$$H = E[p_i] = \frac{1 - q_n}{q_t} \tag{3.9}$$

The system throughput, S, can now be determined by the aggregate attempt rate, G, and the average number of retransmissions, H. As H is the average number of retransmissions, the average number of transmission attempts for a successful transmission is $H + 1$. The probability of a transmission being successful, P_{succ}, is then $\frac{1}{H+1}$. The throughput can now be expressed as

$$S = G \cdot P_s = G \cdot \frac{1}{H+1} = G \cdot \left[\frac{q_t}{1 - q_n - q_t}\right] \tag{3.10}$$

When the limit $K \to \infty$ is taken, both q_n and q_t become e^{-G}, and the throughput S becomes

$$\lim_{K\to\infty} S = G \cdot \left[\frac{e^{-G}}{1 - e^{-G} + e^{-G}}\right] = Ge^{-G} \tag{3.11}$$

As shown in (45), this is identical to the throughput result of Equation (3.5) using the assumption of Poisson retransmission traffic. This indicates that if the delay under the linear retransmission algorithm is large, we can consider the retransmission traffic to be Poisson traffic that is independent of the load traffic.

3.3 Carrier Sense Multiple Access

We observed that in Aloha access modes a significant fraction of the channel capacity is not utilised. Using Carrier Sense Multiple Access (CSMA), we are able to recover a large portion of this loss.

In a radio channel, the propagation delay is typically very small compared to the packet transmission time. This suggests a new approach for using the channel, where the station attempts to avoid collisions by first listening for ("sensing") the carrier of other transmissions. As the delay in sensing another stations transmission is the propagation delay, carrier sensing reduces the vulnerable period from the transmission time to the propagation time. This in turn reduces the length of the slot time to be equal to the propagation delay. Of course, the practical problems of slot synchronisation in Aloha are still applicable to CSMA.

Once a station has sensed for the presence of a carrier, one of various actions may be taken depending on the state of the channel (41); (i) nonpersistent CSMA, (ii) 1-persistent CSMA, and (iii) p-persistent CSMA.

In nonpersistent CSMA, if the channel has been sensed idle, a station is free to transmit its packet. If the channel is sensed busy, the station waits for some amount of time before re-sensing the channel. The amount of waiting time is specified by a retransmission delay distribution.

In the 1-persistent CSMA protocol, a station wanting to transmit senses the channel until it is idle, at which point it transmits its packet with probability one. This was devised in order to never let the channel go idle if a ready terminal is available. Of course, whenever two or more stations become ready, they all transmit with probability one, and so a collision will occur. This differs from nonpersistent CSMA in that here the station continues sensing the channel, instead of waiting and re-checking the channel.

To reduce the potential level of interference and improve throughput, one solution is to randomise the starting time of transmissions. This scheme would use an additional parameter p, to denote the probability of transmitting in the next available slot (and $1 - p$ would be the probability of delaying transmission by another slot). The parameter p must be chosen to minimise interference while keeping idle periods to a minimum. This scheme is known as p-persistent CSMA. Note that 1-persistent CSMA is a special case of p-persistent CSMA, where $p = 1$.

The throughput of these CSMA systems has been analysed by (41). In the ideal case, $p = 1/n$, where n stations have a packet to send. This means in an idle channel, the expected number of stations that will attempt to transmit is $np = 1$. If $np > 1$, then a collision would be expected.

CSMA is widely implemented in link layer protocols. The IEEE 802.3 (Ethernet) standard uses CSMA with collision detection (CSMA/CD). As Ethernet is a cable network, a station is able to continuously read any signals on the wireline, including during its own transmission. Therefore it can determine whether there has been any interference to its transmission ("collision detection").

In a wireless network, it is not possible to detect collisions. The nature of wireless communications means the transmitter power can be very large relative to the receiver sensitivity. Thus when a station is transmitting, it is difficult for its receiver to detect any other signals present in the medium, as it is being swamped by its own transmission. Therefore wireless networks use collision avoidance (CSMA/CA).

We now consider the throughput analysis of the CSMA/CA protocol implemented in IEEE 802.11 (Wifi), which uses a binary exponential backoff as its retransmission algorithm for collisions.

3.4 The IEEE 802.11 Distributed Coordination Function

The IEEE 802.11 protocol has been widely deployed for wireless networks in local area communications, and continues to grow in popularity. In this protocol the fundamental mechanism to access the medium is called the distributed coordination function (DCF), a random access scheme based on CSMA/CA (53).

3.4.1 The Protocol

The DCF scheme describes two techniques for packet transmission. The default method is a two-way handshake technique called basic access (BA). Under this method, once a successful data transmission has been received, a positive acknowledgement (ACK) is returned. An explicit acknowledgement is required since in a wireless medium a station is unable to determine the success of its transmission. If no return ACK is received, the sender assumes its transmission has collided.

A station will wait for a short interframe space (SIFS) period for the return ACK, after which it will timeout assuming its transmission failed, and prepare for retransmission. The SIFS must provide sufficient time to allow the receiver to process the incoming data and transmit an ACK frame if required.

To avoid interference from other stations during the ACK phase, a station must first sense an idle channel for at least a distributed interframe space (DIFS) before

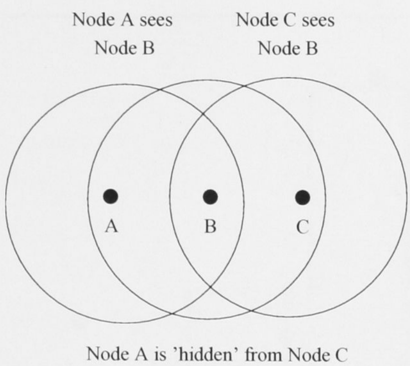


Figure 3.6: Illustration of the hidden node case.

commencing its own transmission, where the DIFS is greater than the SIFS. This prevents other stations from gaining channel access during the quiet SIFS period before an ACK can be returned.

In addition to the basic access method, there is an optional four way handshaking technique, known as request-to-send/clear-to-send (RTS/CTS). In this mode, a station must first "reserve" the channel by sending a short Request-to-Send (RTS) frame. If the destination station replies with a Clear-to-Send (CTS) frame, the normal packet transmission and ACK response occurs. Otherwise, if there is a lack of CTS response, the sender assumes its RTS was not correctly received.

The motivation for RTS/CTS is to remove the potential of collision in any hidden terminal scenarios (42). In a hidden terminal network, not all stations are capable of sensing each other's transmissions. Consider the case in Figure 3.6, where node B can hear node A and node C (and vice versa), but node A and C cannot hear each other. As nodes A and C cannot hear each other, it possible for both stations to transmit simultaneously to node B in a carrier sensing system. Node B would then receive corrupted data from the superposition of both signals.

Under the RTS/CTS mechanism, nodes A and C would first request the channel from B using an RTS frame. If the RTS is successful, node B will broadcast a CTS frame informing both nodes who has the right to transmit data. Although the other station did not receive the RTS, it will receive the CTS and remain quiet, even though it does not sense any physical carrier in the channel during the data transmission. The RTS/CTS sequence mitigates the hidden terminal problem by

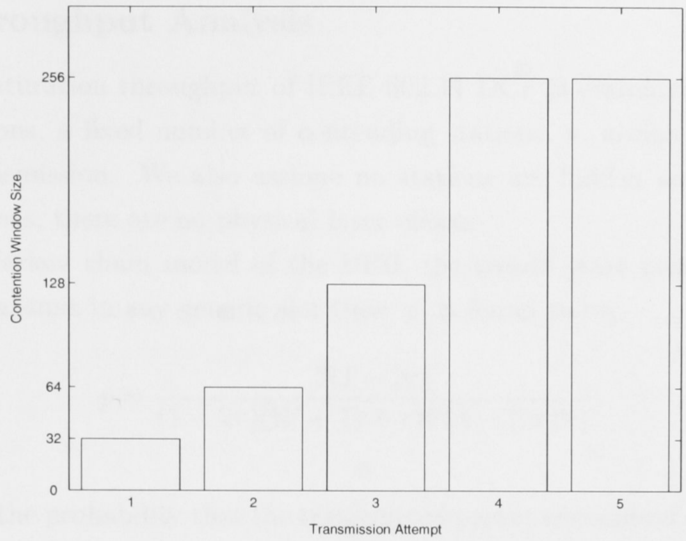


Figure 3.7: Contention window backoff size versus transmission attempt, where $CW_{max} = 2^m CW_{min}$ and $m = 3$, $CW_{min} = 32$.

reducing the length of collision time, as collisions occur between short RTS frames instead of large data frames.

The retransmission algorithm in IEEE 802.11 is based on a binary exponential backoff (BEB). Before transmitting, a station must first wait, or "backoff", a random amount of quiet channel time, by uniformly selecting a value in the range $[0, W_i - 1]$.

The parameter W is the contention window, and depends on the number of previous failed transmission attempts. At the first transmission attempt, $i = 1$, it is set to the minimum contention window, CW_{min}. For convenience, we define $W_1 = CW_{min}$.

After each unsuccessful transmission, the window is doubled, up to a maximum value $CW_{max} = 2^m W$, where m refers to the maximum backoff stage. The values m, CW_{min} and CW_{max} are defined in the protocol standard [3], and are specific to the type of physical layer used. Figure 3.7 graphs the contention window as a function of transmission attempts. Once a stations successfully transmits its data frame, its backoff window resets to $[0, CW_{min}]$.

We now use the analysis in (16) to present the throughput results of the BEB and packet exchange procedures in BA and RTS.

3.4.2 Throughput Analysis

In (16), the saturation throughput of IEEE 802.11 DCF is evaluated. Under saturation conditions, a fixed number of contending stations, n, always have a packet ready for transmission. We also assume no stations are hidden and, as with the previous analysis, there are no physical layer effects.

Using a Markov chain model of the BEB, the steady state probability that a station will transmit in any generic slot time, p, is found to be,

$$p = \frac{2(1-2\tau)}{(1-2\tau)(W+1)+\tau W(1-(2\tau)^m)} \tag{3.12}$$

where τ is the probability that the transmitted packet encounters a collision, and W is the minimum contention windows size. As τ requires at least one of the other $n-1$ remaining stations to also transmit, this yields

$$\tau = 1-(1-p)^{n-1} \tag{3.13}$$

Equations (3.14) and (3.15) represent a nonlinear system for two unknowns, τ and p, which can be solved numerically to give a unique solution. Note that this result is independent of the whether BA or RTS/CTS used. In the second part of the analysis we consider the events of each access mechanism to express throughput as a function of p.

We define P_{tr} to be the probability that there is at least one transmission in a slot time. Given there are n stations each with a transmission probability p,

$$P_{tr} = 1-(1-p)^{n-1} \tag{3.14}$$

The probability that a transmission on the channel is successful, P_s, is given by the probability that only one station transmits, conditioned on the fact that at least one station transmits,

$$P_s = \frac{np(1-p)^{n-1}}{P_{tr}} = \frac{np(1-p)^{n-1}}{1-(1-p)^n} \tag{3.15}$$

The system throughput, S, defined as the fraction of time the channel is used to successfully transmit payload packet bits, can then be expressed simply as the ratio of the average amount of information transmitted in a unit time over the average length of a unit time,

$$S = \frac{E[\text{payload information transmitted in a unit time}]}{E[\text{length of unit time}]} \tag{3.16}$$

The average length of a unit time is obtained by considering that, with probability $1 - P_{tr}$, there is an empty contention window slot; with probability $P_{tr}P_s$ there is a successful transmission, and with probability $P_{tr}(1 - P_s)$ there is a collision. Hence, Equation (3.18) becomes

$$S = \frac{P_s P_{tr} E[P]}{(1 - P_{tr})\sigma + P_{tr}P_s T_s + P_{tr}(1 - P_s T_c)} \tag{3.17}$$

Here, $E[P]$ is the average length of the packet size (measured in time). In the case where all packets are equal length, $E[P] = P$. T_s is the average time the channel is busy due to a successful transmission, T_c is the time consumed by a collision, and σ is the duration of an empty slot.

In the throughput expression, the values of T_s and T_c are dependent on the access mechanism used. As shown in Figure 3.9, for BA

$$T_s^{bas} = H + P + SIFS + \delta + ACK + DIFS + \delta \tag{3.18}$$

and,

$$T_c^{bas} = H + P^* + DIFS + \delta \tag{3.19}$$

where δ is the propagation delay, H contains PHY and MAC header information, and P^* is the length of the longest packet involved in a collision. In the case where all packets are equal length, $P^* = P$.

Similarly for RTS/CTS,

$$\begin{aligned} T_s^{rts} = {} & RTS + SIFS + \delta + CTS + SIFS + \delta + H + \\ & + P + SIFS + \delta + ACK + DIFS + \delta \end{aligned} \tag{3.20}$$

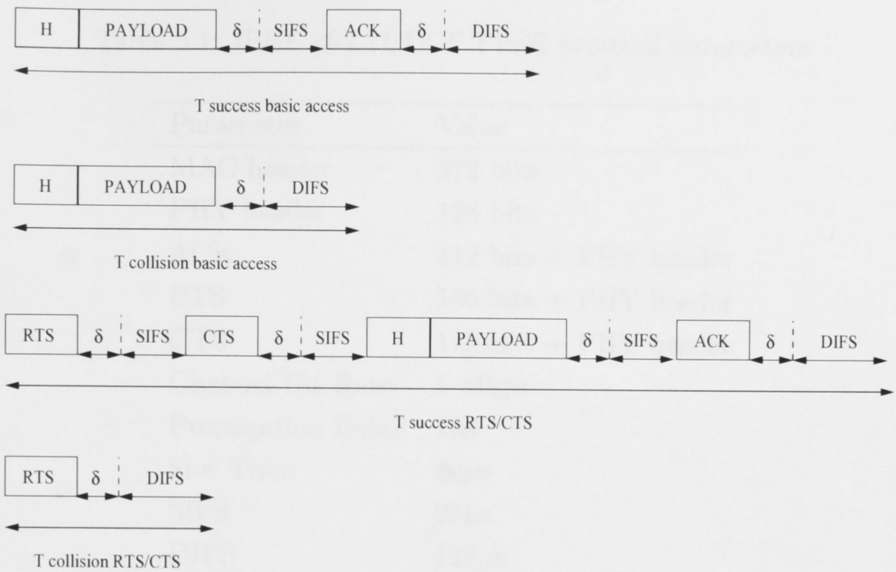


Figure 3.8: The time taken for a successful transmission, T_s, and the taken during a collision, T_c, for basic access and RTS/CTS mechanisms.

and,

$$T_c^{rts} = RTS + DIFS + \delta \tag{3.21}$$

Numerical results for the 802.11 DCF can be obtained using the parameters in Table 3.1, taken from the protocol specifications for the frequency hopping spread spectrum (FHSS) physical layer (53). Figure 3.10 shows the saturation throughput versus the number of stations. While channel utilisation remains constant for RTS/CTS, with BA throughput steadily declines.

Equation (3.19) can be used to determine the maximum achievable saturation throughput. Rearranging it gives

$$S = \frac{P}{T_s - T_c + \frac{\sigma(1-P_{tr})/P_{tr}+T_c}{P_s}} \tag{3.22}$$

As T_s, T_c, P and σ are constants, throughput is maximised when the following quantity is maximised:

$$\frac{P_s}{(1-P_{tr})/P_{tr} + T_c/\sigma} = \frac{n\tau(1-\tau)^{n-1}}{T_c^* - (1-\tau)^n(T_c^* - 1)} \tag{3.23}$$

Table 3.1: IEEE 802.11 DCF FHSS protocol parameters

Parameter	Value
MAC header	272 bits
PHY header	128 bits
ACK	112 bits + PHY header
RTS	160 bits + PHY header
CTS	112 bits + PHY header
Channel Bit Rate	1 Mbps
Propagation Delay	$1\mu s$
Slot Time	$50\mu s$
SIFS	$28\mu s$
DIFS	$128\mu s$

where $T_c^* = T_c/\sigma$, is the length of a collision measured in slot time units. Taking the derivative of Equation (3.25), setting it equal to zero, and solving for τ gives the following solution for maximum throughput in a p-persistent CSMA/CA network (assuming $\tau \ll 1$):

$$\tau = \frac{\sqrt{[n + 2(n-1)(T_c^* - 1)]/n} - 1}{(n-1)(T_c^* - 1)} \tag{3.24}$$

Equation (3.26) provides an explicit solution for the optimal transmission probability that each station should use to achieve maximum saturation throughput. When using this result with the system parameters from Table 3.1,both BA and RTS/CTS provide similar maximum throughputs, independent of n (16).

Note however that as the optimal transmission probability is a function of T_c, it is not constant across the BA and RTS/CTS mechanisms.

3.5 Influence of Propagation Delay

In a long range network the key considerations at the MAC are the hidden node problem and propagation delay. We now consider the suitability of the IEEE 802.11 DCF protocol under these conditions.

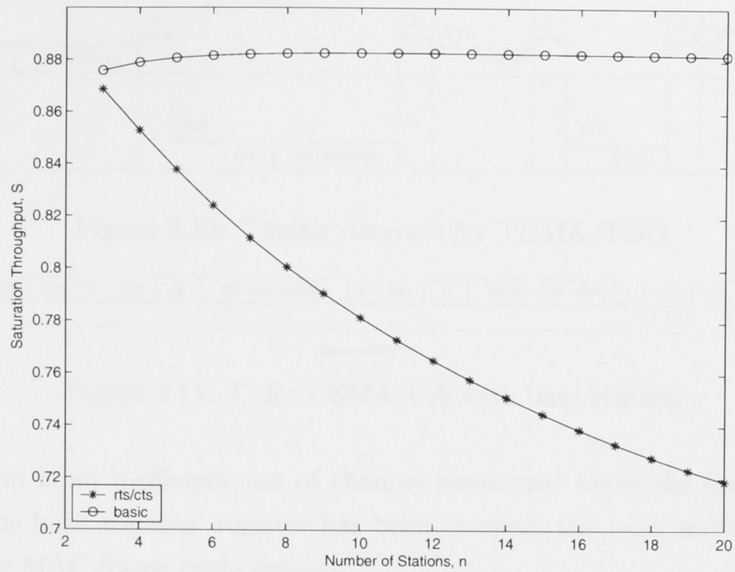


Figure 3.9: Saturation throughput for IEEE 802.11 DCF FHSS (Equation 3.19), where $m = 5$, $W = 32$, and $P = 1500$ bytes.

In a wide area outdoor setting where stations are separated by large distances, carrier sensing for medium access is not sufficient to avoid collisions, particularly from the hidden terminals. The previous analysis has shown that irrespective of hidden nodes, RTS is more efficient than BA by reducing the time wasted in collisions. Therefore any long range CSMA/CA system would deploy the four-way handshake.

If the network radius is large, propagation delay can have a significant influence on channel throughput. The influence of propagation delay on saturation throughput in a CSMA/CA system is now presented relative to a TDMA/TDD system.

In a TDMA/TDD network, the BS polls each SS in a round-robin fashion, first sending down link information before allowing the SS to uplink its information. This process is illustrated in Figure 3.11, and is similar to that used in WiMAX and HIPERLAN/2, where the uplink and downlink phases are separated in time. The BS sends a downlink MAC frame to SS 1, and SS 1 responds with an uplink MAC frame. The header, H, contains the polling and acknowledgement information.

In this example, SS 2 has no uplink nor downlink data. Of course, polling an

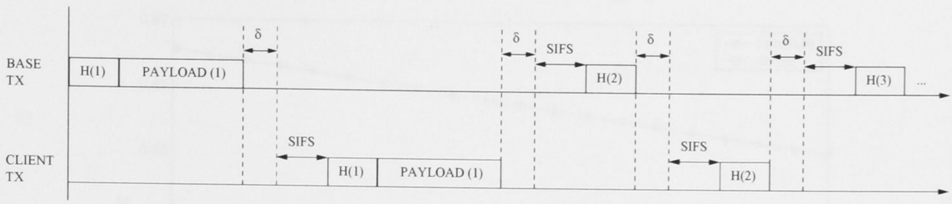


Figure 3.10: Timing diagram for TDMA/TDD.

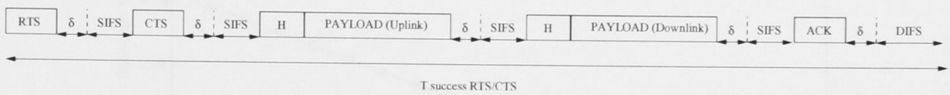


Figure 3.11: T_s for CSMA/CA with base station.

empty station is an inefficient use of channel resources. Once the final subscriber station in the base stations' register has been reached, the base station returns to SS 1 and the MAC frame cycle repeats.

Unlike random access protocols, TDMA is a deterministic system which yields a simple throughput expression. Using the timing diagram in Figure 3.11, the channel utilisation for TDMA/TDD is

$$S = \frac{n \cdot P}{n \cdot P + N(SIFS + H + \delta)} \tag{3.25}$$

Where n is the number of active stations and N is the number of total stations. Under saturation conditions, $n = N$.

In order to compare CSMA/CA with TDMA/TDD, an adjustment to the CSMA/CA model is required. The analysis in Section 3.4.2 does not specify the intended receiver of any transmission, as it assumes an adhoc network. That is, a network without an explicit BS and SSs.

Now we define a base station which all other stations are attempting to communicate with. Furthermore, once a station has successfully delivered an uplink to the base, the base replies with the acknowledgement and a downlink information frame. Figure 3.12 illustrates the new time consumed for a successful transmission, such that now

$$\begin{aligned} T_s = RTS + SIFS + \delta + CTS + SIFS + \delta + H + \\ + P + SIFS + \delta + H + P + DIFS + \delta \end{aligned} \tag{3.26}$$

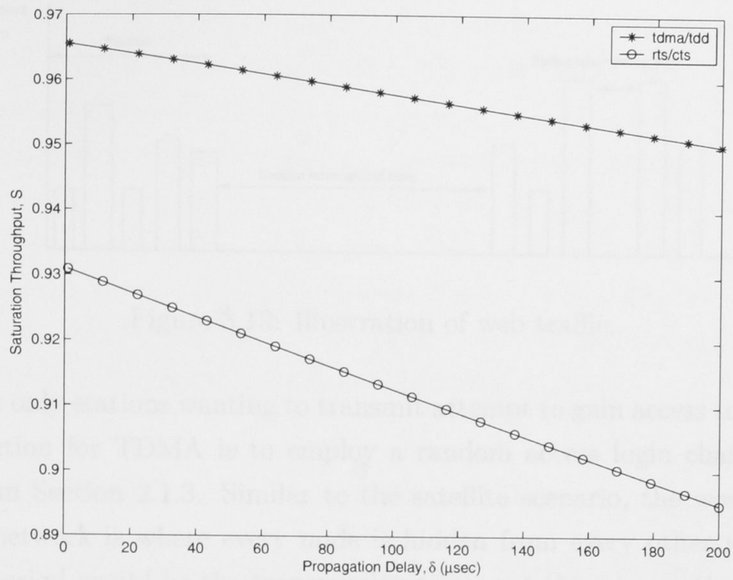


Figure 3.12: TDMA/TDD (Equation 3.27) and CSMA/CA (Equations 3.19 and 3.28) saturation throughput, where $n = 10$ and $P = 1500$ bytes.

With the new T_s value for CSMA/CA, it will have higher throughput efficiency than the standard IEEE 802.11 because we are effectively doubling the throughput for the same level of contention, by granting the BS a contention free downlink.

Figure 3.13 compares channel utilisation as a function of propagation delay for CSMA/CA and TDMA/TDD. These results use the optimal transmission probability for CSMA/CA given in Equation (3.26) with the same overhead parameters for both MACs taken from Table 3.1.

The difference in throughput is seen to be significant. At $100\mu s$, there is over 5% difference in channel utilisation. Given a constant probability of collision, as propagation delay increases, the time wasted in collisions and contention backoffs also increases.

We expect a contention free system to outperform a random access system under saturation conditions, due to the time saved from collisions. We also observe propagation delay has a stronger negative influence on random access throughput.

While TDMA provides higher saturation throughput, it can be inefficient by allocating channel time to stations with no information to transmit. This is avoided

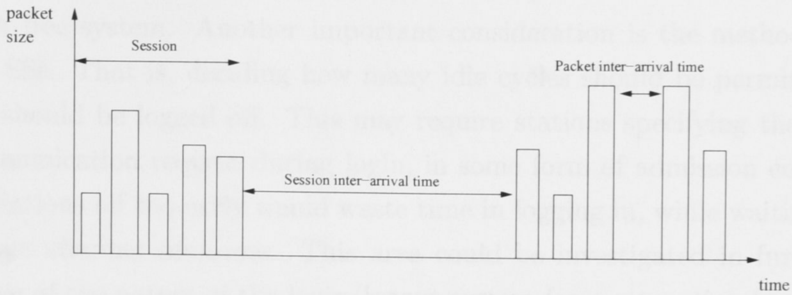


Figure 3.13: Illustration of web traffic.

in CSMA, as only stations wanting to transmit attempt to gain access to the channel.

One solution for TDMA is to employ a random access login channel, as with TBACR from Section 2.1.3. Similar to the satellite scenario, the worst case for a long range network is where every node is hidden from every other node and the vulnerable period would be the transmission time, not the propagation delay. This means an Aloha system is the most appropriate model for a login channel.

Furthermore, studies have found that the inter-arrival times of web sessions over the Internet can be modelled as an exponential distribution, which makes the number of sessions that arrive in a specific time interval a Poisson distribution (67) (24) (17). This process is illustrated in Figure 3.14. Therefore the results from Section 3.2 can be applied to an Aloha login channel, and we could expect a maximum login rate of approximately 0.36 requests per slot time, which is determined by the login packet length.

The login packets would be small, needing only to transmit simple information such as user identification (e.g. a MAC address, 6 bytes), an authentication method (e.g. password), packet security (e.g. encryption) and possibly QoS requirements. Once MAC and PHY headers are included, a login frame size could be in the order of 20 bytes. If 10 kHz of bandwidth is allocated to a login channel using a modulation scheme with spectral efficiency of 1 bps/Hz, a login request would take 16 ms to transmit, and another 16 ms to receive confirmation from the base, assuming negligble processing time for small login packets. This translates to a maximum load of roughly ten successful login requests per second, using only a very small fraction of channel bandwidth.

Of course, a login function is a simple proposition to maximise efficiency in a contention free system. Another important consideration is the method for a BS to log off SSs. That is, deciding how many idle cycles should be permitted before a station should be logged off. This may require stations specifying the nature of their communication request during login, in some form of admission control (66). Logging stations off too early would waste time in logging in, while waiting too late would waste channel resources. This area could be investigated in further work. Irrespective of the nature of the login/logout system for a contention free MAC, we expect it would still be superior to the performance of random access, given the large disparity in throughputs, as observed in Figure 3.13.

3.6 Summary

This chapter presented various random access protocols. Early models of the Aloha system were analysed, followed by the CSMA/CA protocols. A throughput model for the IEEE 802.11 DCF protocol was described and analysed in reference to a long range network. It is shown that with large propagation delay, the time consumed in contention backoffs and collisions greatly reduces its efficiency. In comparison with a TDMA/TDD system, we observe that 10 users at $100\mu s$ delay, there is over 5% difference in channel utilisation.

Therefore we conclude that contention based MACs are not suitable for long range networks such as BushLAN. To alleviate wasted channel time in a contention free MAC, a simple Aloha login channel was proposed, which should be able to handle the expected load from a BushLAN network. Further analysis on admission control would be required to maximise the efficiency of the contention free MACs by eliminating empty TDMA slots. The next chapter examines contention free MACs in further detail.

Chapter 4

Contention Free Protocols

4.1 Introduction

The previous analysis showed contention free multiple access can provide higher channel utilisation than contention based techniques by reducing idle channel time and time wasted in collisions. We now consider two contention free methods with separate uplink and downlink channels (FDD). Note that we now require two TV bands, but if the frequency reuse of three is maintained, we assume every cell has equal uplink and downlink bandwidths of 2 MHz each.

This would require a full duplex base station, to transmit and receive simultaneously on both channels. However, the MACs should be designed to keep client stations as half duplex, to minimise complexity and hence cost.

A broadcast TDMA system is used on the downlink channel for both MACs. The motivation for a TDMA downlink is simple, it has the efficiency of contention free access, but is better able to dynamically allocate the channel than FDMA. For instance, it is simpler to reallocate TDMA slots per MAC frame cycle than it is to reallocate downlink spectrum for all users, as this would require a separate control channel for stations to continuously monitor in order to determine where to receive their downlinks.

On the uplink, one MAC also uses TDMA, while the other uses FDMA. While numerous MAC systems (such as WiMAX, HIPERLAN/2, i-BURST) use TDMA uplinks, we believe an FDMA uplink would be better suited to the needs of Bush-LAN. The FDMA uplink could be managed by the TDMA downlink controlling the frequency allocations, by sending broadcast frames to all users updating the FDMA assignments as required. Using FDMA to divide the spectrum may require less transmission power for each individual client, making it more economical.

In this chapter we compare the TDMA/FDD and TDMA/FDMA MACs. These MACs have been discussed for LMDS, which has a similar network structure to BushLAN. We construct timing diagrams for the MAC frames specific to BushLAN operation, and compare throughput calculations.

4.2 TDMA/FDD

Here we define a MAC that uses two different channels for the up and downlinks (FDD), and where each channel uses TDMA for communication between the BS and SS. TDMA/FDD has also been deployed in second generation cellular networks such as GSM (57).

The sequence of events, illustrated in Figure 4.1, is as follows. The BS uses the downlink channel to continuously send MAC frames containing downlink information for each SS. The TDMA cycle length is defined as the period of time taken for all n stations to receive one downlink, for an equitable distribution.

The BS is full duplex and it simultaneously monitors the uplink channel for uplink frames from SSs. As client stations are half duplex, the time frame allocated for their uplinks immediately follows the time frame in which they received their downlink. This means that no SS can be allocated two adjacent downlink frames. In this way, the uplink channel allocation is a delayed version of the downlink channel allocations.

As the broadcast downlink controls frame lengths, this constrains uplink length. However in each new frame, the client wanting to uplink is not aware of the length of the downlink. To ensure frame synchronisation, the downlink frame length must be fixed, P_d. The uplink packet size, P_u, can then be vary in the range $0 \leq P_u \leq P_d$, where we assume the up and downlink channels have equal capacity.

Thus the frame length is

$$T_f = H + P_d + \delta + IFS \tag{4.1}$$

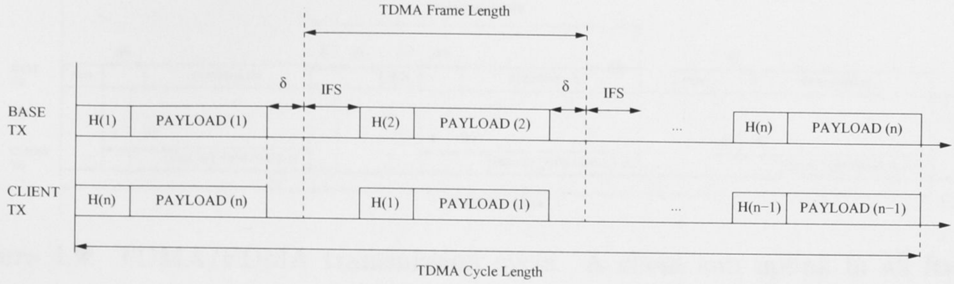


Figure 4.1: TDMA/FDD transmission cycle. A client's uplink frame follows its downlink frame.

where we have a header, H, containing MAC and PHY information. The downlink packet length, P_d, which determines the frame length, is set to have a maximum size of 1500 bytes, a standard maximum transmission unit (MTU) for IP networks. Propagation delay is accounted for with δ, and IFS allows for processing time at the receiver. The cycle length, T_c, is the time taken for the base to cycle through all stations in the network, and is

$$T_c = nT_f \tag{4.2}$$

Equations (4.1) and (4.2) are used to determine channel utilisation and throughput efficiency of TDMA/FDD.

4.3 TDMA/FDMA

In this MAC we propose a TDMA downlink with an FDMA uplink, with a full duplex base station and half duplex clients. In order for client stations to be half duplex with their uplinks, they must be synchronised with the base. To do this we propose that at the start of a new TDMA frame, the BS broadcasts a header that informs all SSs who the current downlink is addressed to. After waiting an IFS to allow clients to process the header, it then transmits the data packet. Of course only the intended receiver needs to listen to the downlink, leaving the remaining $(n-1)$ stations free to send any uplink information in the time remaining for that frame on their FDMA uplink allocations. This process is illustrated in Figure 4.2.

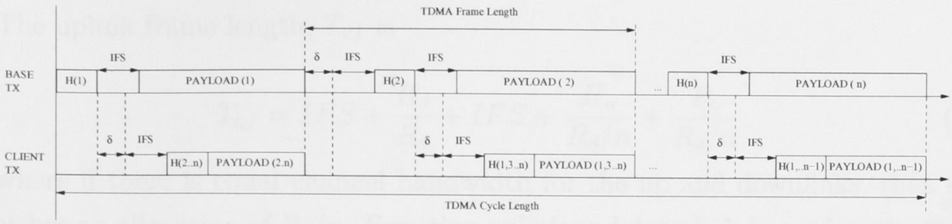


Figure 4.2: TDMA/FDMA transmission cycle. A client can uplink in all frames except for it's downlink frame.

To facilitate multiple simultaneous uplinks, FDMA divides the total uplink spectrum and allocates each client its share. In an equitable division, each client would be allocated $1/n^{\text{th}}$ of the total uplink bandwidth, but it could be possible to construct different frequency division schemes based on the individual traffic demands. As the number of users changes through login and logouts, the base could dynamically re-allocate the uplink spectrum using the broadcast header. As with TDMA/FDD, each client would have to wait until its downlink slot to receive acknowledgement for its uplinks.

In each frame first there is the header informing which SS should be ready to receive the downlink. Once this header arrives and is processed by the clients, all remaining clients are free to send their uplinks. The key difference between this MAC and TDMA/FDD can now be defined. In TDMA/FDD, the entire uplink bandwidth is allocated to each SS for one frame per cycle. In TDMA/FDMA, each SS is allocated a $1/n$ share of the uplink bandwidth for $n-1$ frames per cycle.

By broadcasting the payload size in the first segment of each TDMA/FDMA frame, it is possible to vary downlink, and hence uplink packet sizes. This flexibility is a result of broadcasting the MAC header prior to the large data frame, and somewhat mimics the RTS method of transmission, where all users are informed about the duration of the subsequent data transmission.

The uplink payload size is set to make the TDMA uplink and downlink frame lengths equal. From Figure 4.2, the downlink frame length, T_{df}, is,

$$T_{df} = IFS + \frac{H_d}{R_d} + IFS + \frac{P_d}{R_d} + \delta \tag{4.3}$$

where R_d is the downlink link channel rate.

The uplink frame length, T_{uf} is

$$T_{uf} = IFS + \frac{H_d}{R_d} + IFS + \frac{H_u}{R_d/n} + \frac{P_u}{R_d/n} \tag{4.4}$$

where if there is equal channel bandwidth for the up and downlinks, then each client has an allocation of R_d/n. Equating uplink and downlink frame lengths ($T_{df} = T_{uf}$) gives

$$P_u = \frac{P_d}{n} - H_u - \delta\frac{R_d}{n} \tag{4.5}$$

Note that if $P_d \leq nH_u + \delta R_d$, then it is not possible to send any uplink information. That is, this minimum condition must hold on the length of the downlink packet in order for clients to send their uplinks. Assuming each client receives one downlink per cycle, it is free to uplink on $n-1$ frames, so the total uplink per cycle is

$$P_{uc} = (n-1)P_u \tag{4.6}$$

From the above two equations, we can see that the total amount of uplink in a cycle will always be less than the amount of downlink, as

$$P_{uc} = (n-1)P_u = \frac{n-1}{n}(P_d - \delta R_d) - (n-1)H_u < P_d \tag{4.7}$$

so $P_{uc} < P_d$. Uplink throughput is considered further in the next section.

On the downlink, there is only a negligible difference between TDMA/FDD and TDMA/FDMA. From Equations (4.1) and (4.3), TDMA/FDMA has an extra IFS period per frame to account for the additional processing required for the separate header download. As the MACs are contention free, there are no probabilistic outcomes, such as of backoff times or collisions, so throughput is simply the proportion of payload delivered in a given time period,

$$S_x = \frac{P_x}{T_c} = \frac{P_x}{nT_f} \tag{4.8}$$

where for downlink throughput, $x = d$, and for uplink throughput, $x = u$.

Figure 4.3 plots SS downlink throughput in a 2 Mbps channel with 100 μs propagation delay, using the header and IFS from Table 3.1. Firstly, there is a negligible

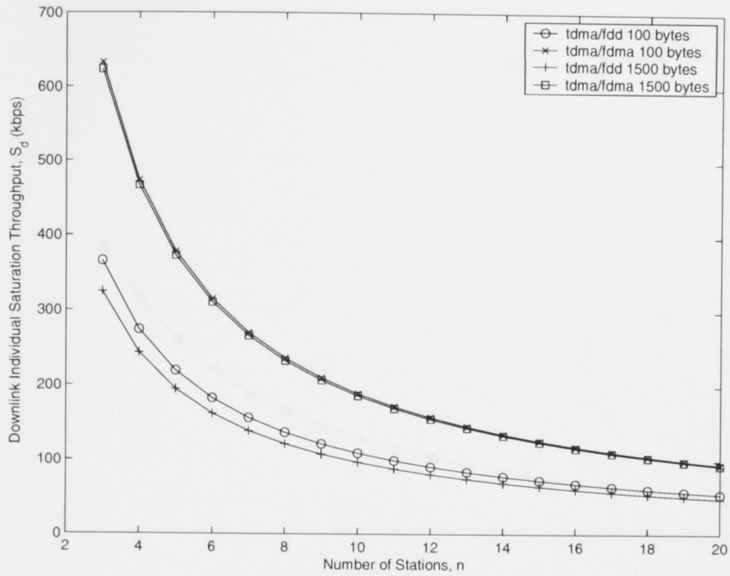


Figure 4.3: Individual downlink throughput under TDMA (Equation 4.8) for different packet sizes and numbers of users in a 2 Mbps channel, $\delta = 100$ μs, $H = 400$ bits, and IFS $= 28$ μs.

difference on the downlink throughput for the MACs. Secondly, the MAC overhead for both systems is not significant, as the per user throughput is approximately equal to the whole channel bandwidth divided. Only as payload size decreases does it occupy a proportionately less amount of channel time, so with the diminished efficiency and we notice more separation between the MACs. This contrasts with random access protocols, where the MAC overhead of backoffs and collisions consumed a large fraction of the available channel.

4.4 Uplink Capacity

As the base station requirements are identical for TDMA/FDD and TDMA/FDMA, the fundamental difference lies in the uplink structure at the client. The uplink capacity for each MAC with respect to number of users, channel bit error rate (BER) and signal to noise ratio (SNR) is now analysed.

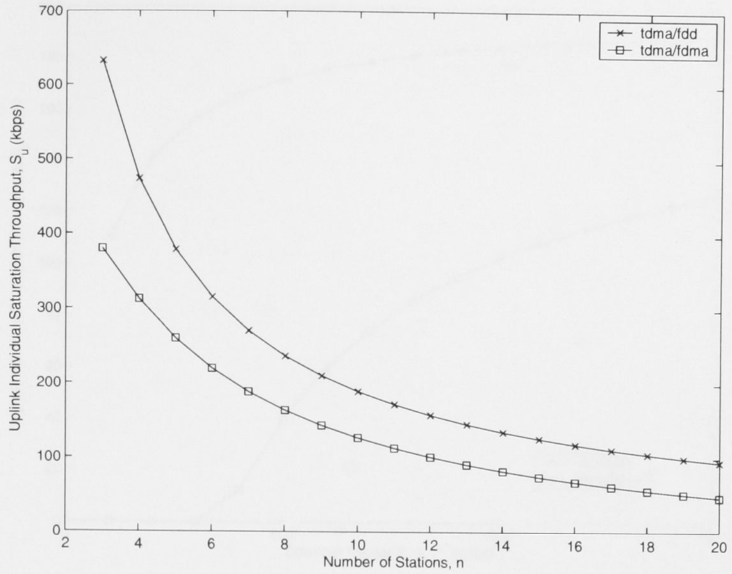


Figure 4.4: Individual uplink throughput based on number of users, n, when $P_d =$ 1500 bytes (Equation 4.8).

4.4.1 Ideal Channel Conditions

We first assume ideal channel conditions to analyse how the MAC timing structure delivers throughput. As TDMA/FDD has a symmetrical downlink and uplink, its uplink is identical to the results in Figure 4.3. For TDMA/FDMA, the uplink payload is determined by (4.5) and (4.6), and throughput by (4.8). As previously mentioned, in both MACs the uplink per frame is constrained by the size of the downlink, for TDMA synchronisation.

Figures 4.4 and 4.5 illustrate uplink throughput as a function of number of users and downlink packet size. The difference in throughput between MACs is significant. There are two effects that create this result. Firstly, under FDMA, in each frame a client must wait to process the header and confirm it is not the intended receiver of the downlink. This is a large amount of overhead, and is unlike the FDD case, where a client knows that it has a whole TDMA frame for uplink in the frame succeeding its downlink.

Secondly, as the total uplink bandwidth is divided between clients in FDMA, the uplink throughput per frame is again reduced relative to FDD. Increasing the

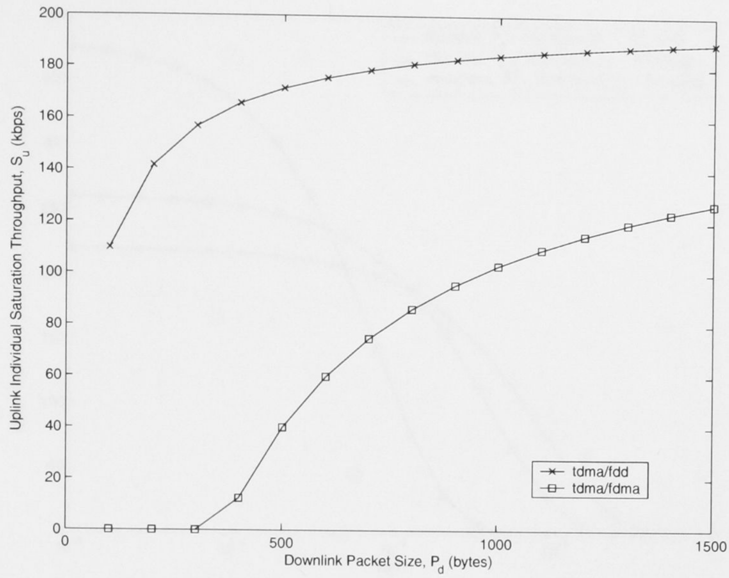


Figure 4.5: Individual uplink throughput as a function of downlink packet size, P_d, when $n = 10$ (Equation 4.8).

number of active client stations increases the number of frames available for uplink, but it also decreases the individual bandwidth allocation. The final result we observe is that the FDD system is able to deliver much higher up link throughput.

Although it is possible to have variable frame sizes in TDMA/FDMA by using the separate broadcast header at the start of each TDMA frame to inform clients of the next downlink payload size, if the downlink size is too small, no uplink is possible. Only as downlink packet size increases does the FDMA uplink approach FDD, but still does not offer comparable throughput.

We now remove the assumption of ideal channel conditions to examine how the MACs perform with an erroneous channel.

4.4.2 Influence of Channel BER

The influence of a channel bit error rate (BER) on uplink throughput is now considered. For a given BER, P_e, the probability that an uplink is correctly received, P_s, is the probability that no bits were erroneously received,

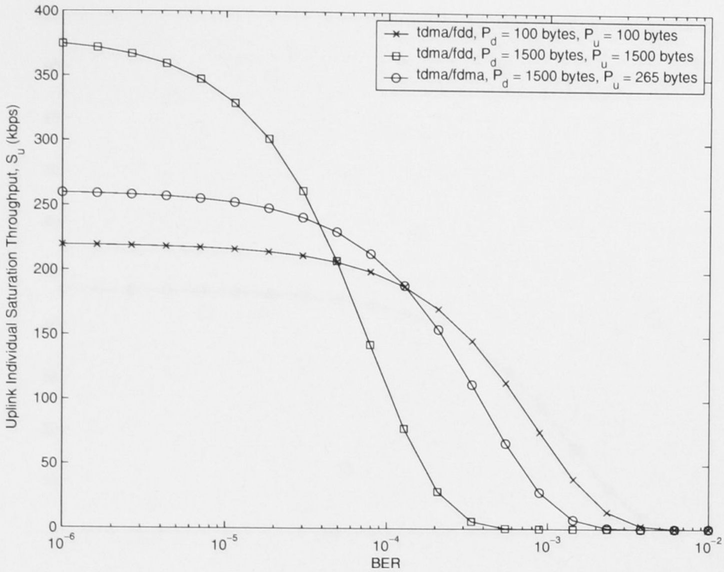


Figure 4.6: Individual uplink throughput in an erroneous channel with $n = 5$ for TDMA/FDMA (Equation 4.13) and TDMA/FDD (Equation 4.14).

$$P_s = Pr[\text{frame success}] = (1 - P_e)^{P_u + H} \tag{4.9}$$

The probability of a successful transmission on the i^{th} attempt is simply a geometric distribution,

$$P(X = i) = (1 - P_s)^{i-1} P_s \tag{4.10}$$

The expected number of transmissions, $E[X]$, before success is

$$E[X] = \frac{1}{P_s} \tag{4.11}$$

As a client has to wait until the next cycle to learn which uplink frame(s) were successfully received, the average delay, $E[D]$, for a successful upload is the expected number of attempts for a successful transmission multiplied by the time taken for a TDMA cycle. That is,

$$E[D] = T_c \cdot E[X] = \frac{nT_f}{P_s} \tag{4.12}$$

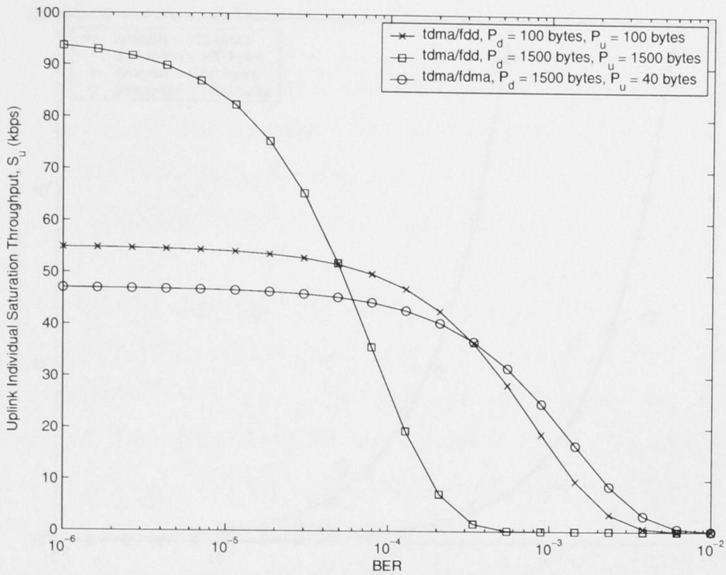


Figure 4.7: Individual uplink throughput in an erroneous channel with $n = 20$ for TDMA/FDMA (Equation 4.13) and TDMA/FDD (Equation 4.14).

In each TDMA/FDMA cycle there can be $n - 1$ packets of P_u bytes, whereas TDMA/FDD has a single upload frame per cycle, so that in saturation, $P_d = P_u$.

The uplink throughput for TDMA/FDMA is then

$$S_u = (n-1) \cdot \frac{P_u}{E[D]} = \frac{n-1}{n} \cdot \frac{P_s P_u}{T_f} \tag{4.13}$$

and for TDMA/FDD

$$S_u = \frac{P}{E[D]} = \frac{P_u}{nT_f} \tag{4.14}$$

Of course for any period of time, given equal bandwidths, each MAC will have different frame lengths and uplink payload sizes (P_u), so we can expect BER to affect each MAC's uplink throughput differently.

Figures 4.6 and 4.7 show the influence of BER on MAC uplink throughput. In good channel conditions, TDMA/FDD can significantly outperform TDMA/FDMA. As BER increases, shorter frames are better able to use the channel. Thus the additional overhead from fragmenting uplink data into small frames becomes beneficial in adverse channel conditions.

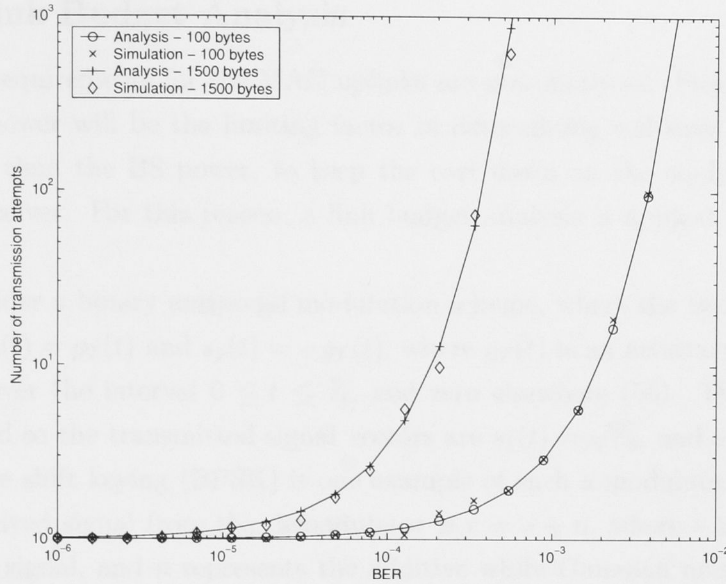


Figure 4.8: The number of retries as a function of channel BER, where the channel is modelled as a Bernoulli random variable (Equation 4.10).

However, these results are not necessarily in support of TDMA/FDMA. As the number of users increases, the throughput in TDMA/FDMA decreases by a larger proportion than in the case of TDMA/FDD. Indeed, in a very erroneous channel, reducing the payload size in TDMA/FDD to 100 bytes provides higher throughput than TDMA/FDMA at maximum capacity. This is because reducing the payload size in TDMA/FDD reduces the frame length, and hence increases the number of cycles per period. Note that this would require TDMA/FDD to have the flexibility to vary frame sizes, which would require some form of regular broadcast slot be inserted in the TDMA cycle, to update all SSs on the new frame size. This would reduce efficiency by creating additional overhead, and may not be useful if channel BER changes rapidly.

To show the influence of frame size on channel efficiency with BER, Figure 4.8 plots the number of retries required for a given frame size. The simulation results using a Bernoulli random variable to represent BER closely match those from the analysis using the geometric distribution for the probability of frame success.

4.4.3 Link Budget Analysis

The power requirements for the MAC uplinks are now analysed. From Section 2.3, SS output power will be the limiting factor in determining cell sizes, as it will be much lower than the BS power, to keep the cost down on the equipment for the client transceiver. For this reason, a link budget analysis is applied to the uplink channels.

We consider a binary antipodal modulation scheme, where the two signal waveforms are $s_1(t) = g_T(t)$ and $s_2(t) = -g_T(t)$, where $g_T(t)$ is an arbitrary pulse which is nonzero over the interval $0 \leq t \leq T_b$, and zero elsewhere (56). The energy per bit is $\mathcal{E}_b$, and so the transmitted signal vectors are $s_1(t) = \sqrt{\mathcal{E}_b}$, and $s_2(t) = -\sqrt{\mathcal{E}_b}$. Binary phase shift keying (BPSK) is one example of such a modulation scheme.

The received signal from the demodulator is $r = s + n$, where s is the original transmitted signal, and n represents the additive white Gaussian noise component with zero mean and variance $\sigma_n^2 = N_0/2$.

The probability of bit error is now a function of the signal to noise ratio (SNR $= \mathcal{E}_b/N_0$) (56),

$$P_e = Q\left(\sqrt{\frac{2\mathcal{E}_b}{N_0}}\right) \tag{4.15}$$

where

$$\frac{\mathcal{E}_b}{N_0} = \frac{1}{R_b} \cdot \frac{P_r}{N_0} \tag{4.16}$$

with R_b as the bit rate, P_r is the received signal power, and N_0 is the noise floor at the BS receiver. Therefore for a given received signal power, we can use SNR to determine BER and hence evaluate throughput for each MAC.

Note that (4.15) and (4.16) are also applicable to QPSK and MSK modulations. The spectral efficiency, which is assumed to be 1 bps/Hz, can be achieved under these modulation schemes by appropriate pulse shaping of the waveforms (28).

Figure 4.9 shows uplink throughput in an AWGN channel as a function of received signal power. TDMA/FDMA reaches its maximum throughput with a much lower received power, as it divides the bandwidth between users and provides multiple uplink frames.

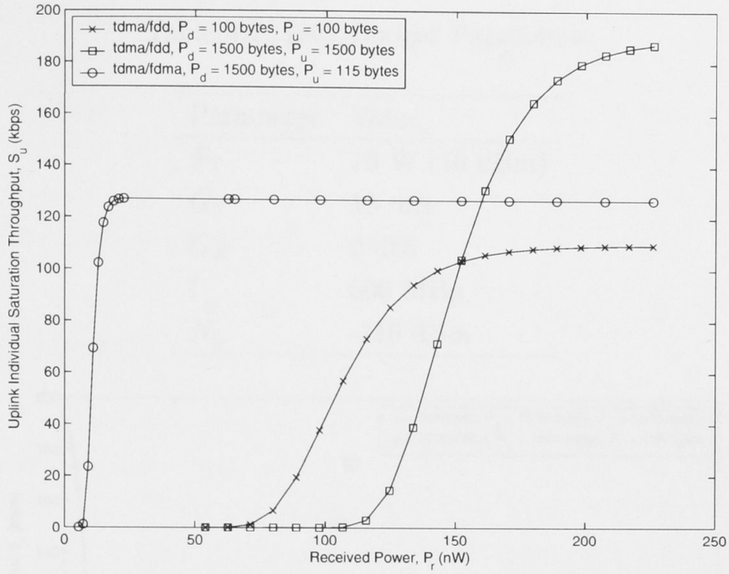


Figure 4.9: Uplink throughput in AWGN channel with with $n = 10$ and $P_d = 1500$ bytes. The noise floor, N_0, is -110 dBm.

TDMA/FDD uplink requires 10 dB greater received power than TDMA/FDMA for equal throughput. This is significant when considering the cost of power amplifiers for long range terrestrial wireless communications.

However, TDMA/FDD is has greater throughput with higher received power. Thus we have a trade off between a low power MAC, TDMA/FDMA, and a higher power, higher throughput MAC, TDMA/FDD.

Note also that with TDMA/FDD, if smaller uplink packet sizes are used, then for a given received power, there is more energy per bit, meaning higher SNR, lower BER, and higher throughput at lower received power levels.

Finally, the received power levels can be translated into distances to determine the potential coverage area by a base station (56),

$$P_{R|dB} = P_{T|dB} + G_{T|dB} + G_{R|dB} - \mathfrak{L}_{S|dB} \tag{4.17}$$

P_R is the received power, P_T is the transmitted power, G_T and G_R are the transmit and receive antenna gains respectively, $\mathfrak{L}_S$ is the path loss, and all parameters are defined in decibels.

Table 4.1: Link Budget Parameters

Parameter	Value
P_T	10 W (40 dBm)
G_T	15 dBi
G_R	9 dBi
f	500 MHz
N_0	-110 dBm

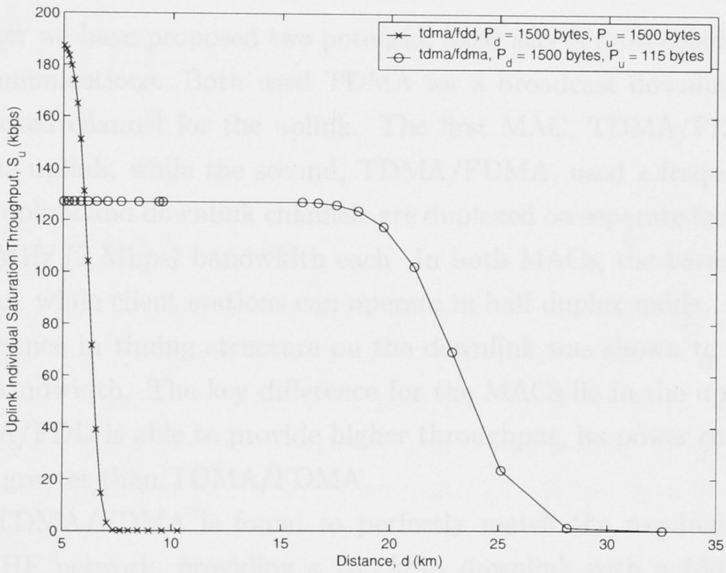


Figure 4.10: Individual uplink throughput based on the distance away from the base station, with $n = 10$ and $P_d = 1500$ bytes. The link budget parameters from Table 4.1 are used.

The free space path loss, $\mathcal{L}_S$, is given by (57),

$$\mathcal{L}_{S|dB} = 20 \log_{10} \left(\frac{4\pi d}{\lambda} \right) \tag{4.18}$$

where d is the transmitter-receiver separation distance, and λ is the carrier wavelength.

Figure 4.10 uses the link budget parameters in Table 4.1 (11) to show the effect of distance on throughput, as greater separation pushes down SNR, increasing BER.

It shows that in cells smaller than 5 kms, TDMA/FDD provides higher uplink throughput.

However, TDMA/FDMA offers a larger coverage area; a low power client transceiver (10 W) can be up to 20 kms away from a BS and receive up to 130/200 kbps uplink/downlink speed in a cell with ten users, which is ideal for BushLAN. Note that these results are without error correction, which could increase the range (56).

4.5 Summary

In this chapter we have proposed two potential fixed access protocols for long range wireless communications. Both used TDMA for a broadcast downlink with a frequency duplexed channel for the uplink. The first MAC, TDMA/FDD, also used TDMA on its uplink, while the second, TDMA/FDMA, used a frequency division uplink. The uplink and downlink channels are duplexed on separate frequency channels with 2 MHz (2 Mbps) bandwidth each. In both MACs, the base station must be full duplex, while client stations can operate in half duplex mode.

The difference in timing structure on the downlink was shown to be negligible for a given bandwidth. The key difference for the MACs lie in the uplink method. While TDMA/FDD is able to provide higher throughput, its power consumption is significantly greater than TDMA/FDMA.

Indeed, TDMA/FDMA is found to perfectly match the requirements for the BushLAN UHF network, providing a 200 kbps downlink with a 130 kbps uplink for 10 users in a 20 km cell radius, with 10 W of output power at the client. In contrast, an equivalent TDMA/FDD system could not cover a range much greater than 5 kms.

We now examine the TDMA/FDMA MAC further, by considering its ability to support the traffic generated in typical broadband applications.

Chapter 5

Traffic Support under TDMA/FDMA

5.1 Introduction

The previous analysis assumed saturated clients. However, not all applications saturate the MAC layer. In this chapter we explore how TDMA/FDMA supports application specific traffic models. We investigate perceived client throughput for broad band applications. In particular, we analyse MAC layer performance under Voice over IP (VoIP), a typical HTTP web browsing session, and a typical SMTP email send application.

These three traffic types represent a fair spread of application specific demands on MAC capacity. VoIP requires a support for constant bit rate (CBR), as its packets are sent at a constant rate. Web browsing is one of the most dominant applications used in broadband networks, and so we consider how it is supported under TDMA/FDMA. Sending email is another popular application. HTTP and SMTP are both asymmetric traffic flows. In HTTP, the majority of the data flow is on the downlink channel, whereas in SMTP, the data flow is mostly on the uplink.

5.2 VoIP Support

Voice over Internet Protocol (VoIP) is one of the fastest growing Internet applications, contributing to the rapid rate of convergence of services available over broadband networks (10). The ability to provide telephony should have significant importance in the design of a rural and regional wireless data network, as these areas are fundamentally constrained by poor wireline communications infrastructure.

In this section we study how many VoIP connections can be supported under TDMA/FDMA. For VoIP, the voice signals are encoded and compressed into a low rate packet stream by a codec. Commonly used VoIP codecs include G.711, G.726 and G.729. The attributes of a codec are the bit rate, framing interval, payload size, and number of packets per second (65). These VoIP codecs are CBR applications, meaning packets are generated with a periodicity defined by the packets per second.

For this study, we use G.729, which is a common industry standard, and has comparatively low bandwidth requirements. The G.729 codec transmits 50 packets per second, with a payload of 10 bytes and framing interval of 10 ms. Unlike other codecs where the framing interval is the reciprocal of the packets per second, for G.729, two frames are combined into one packet, meaning a packet is transmitted every two framing intervals, which is 20 ms. G.729 requires a bandwidth of 8 kbps. By comparison, the GSM 6.10 standard for 2G mobile phones requires 13.2 kbps.

However, transmitting the VoIP packet over the Internet requires additional headers from lower OSI layers. Firstly, a 12 byte real time protocol (RTP) header is added to the voice payload. The transport layer then adds an 8 byte UDP (User Datagram Protocol) header, and finally the network layer adds a 20 byte IP header (6). Consequently, the MAC layer receives a 60 byte VoIP frame, which equates to 24 kbps.

The regularity of VoIP packets requires a reliable MAC layer than can guarantee a specific quality of service (QoS). The cyclic nature of TDMA based MACs can provide this guarantee, unlike random access protocols, which cannot necessarily always be allocated access to the channel when required (33).

The number of MAC frames required to uplink a VoIP packet from a SS to the BS is P_v/P_u, where P_v is the size of the VoIP frame (60 bytes), and P_u is the size of the uplink frame. Note also that the value of P_v/P_u must be rounded up to

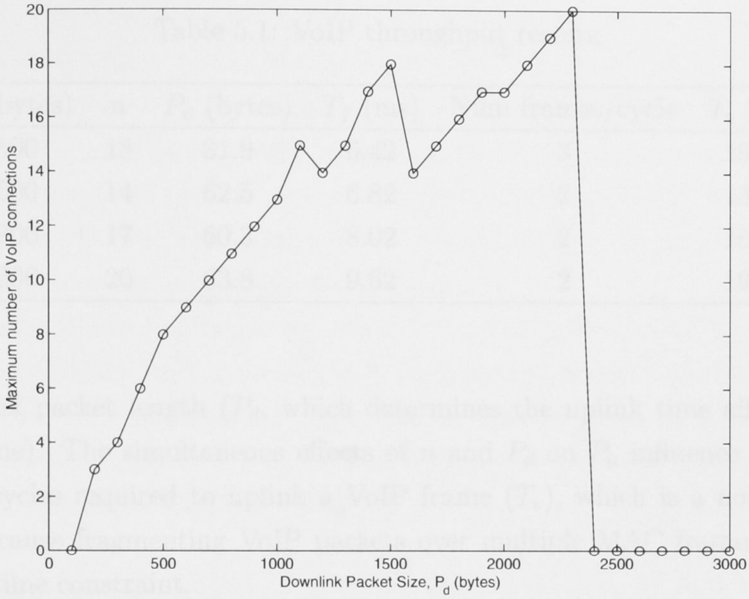


Figure 5.1: VoIP connections versus downlink payload size for TDMA/FDMA. The G.729 codec is used, where the time taken for an uplink/downlink VoIP packet sequence, T_v, is 20 ms.

the nearest integer, and that an additional frame is required for the downlink VoIP packet. Therefore, the time taken for one uplink and downlink VoIP sequence, T_v, is

$$T_v = \left(\mathrm{ceil}\left(\frac{P_v}{P_u}\right) + 1\right) \cdot T_f \tag{5.1}$$

where P_u is given by (4.5), and T_f is given by Equations (4.3) and (4.4). For G.729, the time taken for an uplink/downlink VoIP packet sequence, T_v, is 20 ms. Therefore, by solving $T_v \leq 20$ ms with (5.1), the maximum number of VoIP connections that can be supported as a function of the downlink packet size is determinable. Figure 5.1 plots the result.

The irregular shape is influenced by a number of factors specific to the nature of the TDMA/FDMA MAC as defined in Section 4.3. Firstly, the uplink packet length (P_u) is a function of both the number of users (n, which determines a client stations' FDMA bandwidth allocation and the number TDMA cycles available for uplinking)

Table 5.1: VoIP throughput results

P_d (bytes)	n	P_u (bytes)	T_f (ms)	Num frames/cycle	T_v (ms)
1500	18	31.9	6.42	3	19.26
1600	14	62.5	6.82	2	13.64
1900	17	60.3	8.02	2	16.04
2300	20	63.8	9.62	2	19.24

and downlink packet length (P_d, which determines the uplink time allocation per TDMA frame). The simultaneous effects of n and P_d on P_u influence the number of TDMA cycles required to uplink a VoIP frame (T_v), which is a noncontinuous function because fragmenting VoIP packets over multiple MAC frames would not satisfy the time constraint.

Table 5.1 highlights these effects. For each listed down link packet size P_d, the corresponding MAC parameters are listed, including the maximum number of VoIP connections. At 1500 bytes, clients must fragment their uplink VoIP packets into two uplink slots, whereas at the other listed values, clients are able to uplink their VoIP packet in one TDMA frame. At 1600 bytes, going beyond 14 connections would also mean clients require two uplink frames, as the reduction in individual bandwidth from supporting an additional caller would reduce P_u to below 60 bytes per uplink. However, unlike with the 1500 byte frames, three 1600 byte frames would exceed the 20 ms time limit for VoIP transmissions. Therefore beyond 1500 bytes, VoIP calls must operate under a two TDMA cycle.

Similar effects are observed at 1100-1200 and 1900-2000 download sizes in Figure 5.1, where the increase in frame time from larger downlink packets is offset by the number of frames required to send a single uplink packet. At a downlink size of 2400 bytes, the frame time T_f is greater than 10 ms, meaning no more VoIP calls can be supported. Note that the downlink packets are never saturated with VoIP calls, meaning the limiting factor is the uplink capacity. Moreover, uplink capacity is not necessarily maximised, as the number of uplink frames must be rounded up, which leaves uplink bandwidth for other applications. The value of the remaining capacity from VoIP calls under TDMA/FDMA could be considered for further work.

Of course, these results are dependent on definitions used for MAC overheads, such as from the values of the header length and IFS time. It is reasonable to expect that a BushLAN type WRAN would have a different header structure to IEEE 802.11, and processing time would be dependent on factors such as with the FPGA. Another note of caution is that the time taken for a VoIP frame to travel from the BS to the intended receiver, wherever that may be, is not considered. Consequently, these are only approximate figures.

Nevertheless, these results are broadly reflective of the nature of VoIP operation under TDMA/FDMA, and are sufficiently high that it is reasonable to expect adequate VoIP capacity in BushLAN deployments. Further work could consider how the MAC variables influence the number of VoIP connections that can be supported under the TDMA/FDMA MAC.

5.3 HTTP Traffic

Hyper Text Transfer Protocol (HTTP) is the method used to transfer information on the World Wide Web (WWW), and is the most common application on broadband networks, contributing more than 80% of the traffic over the Internet (38). It is a request/response protocol, where a client browser requests a file from a destination server, which stores the resources. Upon receiving the request, the server responds with the requested information. The most commonly used version today is HTTP/1.1 (30).

HTTP uses the transmission control protocol (TCP) at the transport layer to establish connections. In this section we describe the sequence of TCP and HTTP message exchange events involved in loading a typical web page, as outlined in (13). Results on perceived user throughput under the HTTP load with the TDMA/FDMA MAC are then presented.

5.3.1 HTTP Exchange Sequence

When a request for HTTP data is made using a URL (Uniform Resource Locator), the browser first translates the URL into an IP address. This is done using a Domain Name System (DNS), where the client sends a DNS_Query, which is a UDP message. The DNS Server replies with a DNS_Reply UDP message, which provides a translation for the URL to the IP address.

Once the IP address is known, the client attempts to establish a TCP connection with the HTTP server. This is a three way handshake, where the client first requests a TCP connection with a SYN packet, the server responds with a SYN-ACK, and the client completes the handshake with an ACK. The client then sends a HTTP_GET for the specific web page desired, and the web server responds with a HTTP _200_0K packet if the page is found. A TCP ACK for the GET is also piggybacked onto the OK packet, but it is also possible for the ACK to be sent separately to the OK. The web server then sends a second segment, HTTP_Continue, containing page data. After two HTTP segments, TCP on the client machine will typically send an ACK. The process of sending two HTTP_Continue segments in return for an ACK repeats itself until all the page data has been loaded. Note that this is an approximation of the TCP acknowledgement system, which actually uses a set of algorithms such as the slow start and the congestion window to determine how often to return ACKs for data packets (59).

It is possible for multiple simultaneous TCP connections (threads) to operate from a single URL request. This decision is made by the client browser if it decides there is a still a large amount of data to be loaded from the base page, and opening another HTTP thread could expedite the transfer process. Creating a new thread requires another three TCP handshake, and another HTTP_GET sequence. Usually new threads are created to download images on a webpage.

However, sharing bandwidth among multiple connections may increase the transfer time for individual objects. This is particularly true in wireless networks with limited bandwidth (38). Therefore, it is desirable to reduce certain object transfer times so that the web page viewer can read some partial information while the complete page contents are being downloaded. This would be done by down loading the objects sequentially instead of concurrently, and sending new GET requests when the previous object transfer is over, using the same TCP connection. This requires the HTTP client to set a low value for the maximum number of multiple parallel TCP connections.

Once the application has finished, such as if the user closes the browser, the browser releases the HTTP threads. This involves all threads sending FIN packets.

Table 5.2: HTTP Web browsing message exchanges

Packet Type	Uplink/Downlink	Packet Size (bytes)
1. HTTP Begin		
DNS_Query	U	512
DNS_Reply	D	512
2. New Thread Initialisation		
SYN	U	74
SYN_ACK	D	74
ACK	U	60
HTTP_GET	U	700
HTTP_200_OK	D	1500
HTTP_Continue	D	1500
ACK	U	60
3. Thread Body		
HTTP_Continue	D	1500
HTTP_Continue	D	1500
ACK	U	60
4. Close		
FIN, ACK	U	54
ACK	D	54

The server responds with ACK packets for each FIN received, finishing the thread. This HTTP process described here corresponds to one session in Figure 3.14.

Table 5.2 summarises the HTTP procedure, and lists packet sizes for each packet type. The DNS protocol specifies a maximum length of 512 bytes for DNS UDP packets (63). Packet sizes for TCP messages, such as SYN and ACK, are taken from empirical measurements recorded from a network trace using the Ethereal Network Protocol Analyzer (26). The message exchange sequence in Table 5.2, taken from (13), was also verified using Ethereal.

We observed the HTTP_GET packet had a range from 300-1500 bytes, however more than 70% of these packets were within 100 bytes of its mean of 700 bytes.

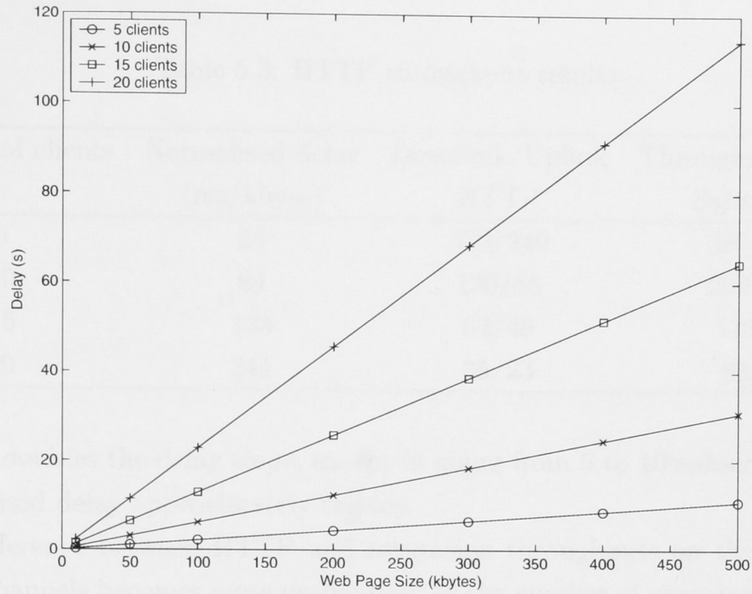


Figure 5.2: Evaluation of HTTP delay for TDMA/FDMA.

We assume the HTTP downloads are set to the MTU for IP networks at 1500 bytes. Ethereal observations for these packets were consistently close to this limit. However, it is also common for some networks to have MTUs around 500-600 bytes (44). Even with these smaller data sizes, it is possible for the MAC layer to join multiple packets in a single MAC frame, thus overcoming the inefficiency of small MTUs. The TCP ACK packets ranged between 54-74 bytes, with a mean of 60 bytes.

5.3.2 Throughput Results

The HTTP message exchange sequence defined in Table 5.2 was applied to the TDMA/FDMA MAC. We assume one TCP connection, a one-way Internet delay of 100 ms, and a fixed downlink payload size of 1500 bytes. The results are summarised in Figure 5.2 and Table 5.3.

Figure 5.2 shows a linear relationship between web page size and delay, for all levels of subscription. This indicates the HTTP download has a constant rate of delay, which is listed in Table 5.3 as normalised delay. We observe that an additional

Table 5.3: HTTP throughput results

Number of clients	Normalised delay (ms/kbyte)	Downlink/Uplink HTTP	Throughput (kbps) Saturation
5	24	370/240	380/260
10	64	130/85	200/127
15	134	62/40	118/69
20	241	35/23	93/44

five clients doubles the delay slope, except in going from 5 to 10 subscribers, where the normalised delay approximately trebles.

The difference between HTTP and saturation throughputs on the uplink and downlink channels becomes more pronounced as the number of users increases. This is because as the number of users increases, the longer cycle time combines with variability of the HTTP packet sizes to reduce the efficiency of the fixed timing structure we have defined for TDMA/FDMA. However, TDMA/FDMA need not have a fixed timing structure. Indeed, the broadcast MAC header on the TDMA downlink can facilitate variable payload sizes, which suggests there is potential for optimisation of the TDMA/FDMA system in web page downloads. Further work could consider how best to access the remaining bandwidth between HTTP and saturation, either by including more traffic, such as VoIP, or by incorporating variable frame sizes.

5.4 SMTP Traffic

The Send Mail Transfer Protocol (SMTP) is commonly used to transfer e-mail reliably and efficiently (43). SMTP can use TCP to send messages to one or more recipients, where the recipients are generally checked to exist. In this section we present a typical SMTP email sending message exchange sequence, and model it with the TDMA/FDMA MAC.

5.4.1 SMTP Exchange Sequence

When an SMTP client has a message to transmit, it establishes a TCP connection, as in the HTTP case. This is done by getting IP address of the SMTP server, using the DNS. A three-way TCP handshake is then established with the server, and is followed by a Sendmail reply from the server. The TCP layer at the SS acknowledges the Sendmail, and also returns an EHLO command, containing its name. The server responds with a TCP ACK, and if it accepts the EHLO request, also returns a 250 packet type confirmation.

The next SMTP packet, the MAIL FROM command, tells all SMTP receivers involved, including those relaying the message, that a new mail transaction is starting. the final receiver confirms this with a 250 Sender OK. The next step involves the client uplinking the list of message recipients using RCPT TO. If an address is verified, a 250 Recipient OK is returned, address failures will produce 550 Unknown user responses. The process of sending RCPT TO commands is repeated until all addresses have been uplinked and acknowledged.

The SMTP sender signals the start of message data by using the DATA command. The receiver then prompts for the start of the email with a 354 Enter mail reply. The email body is then uplinked in MTU sized segments, with the TCP layer using ACK confirmations for the data, providing reliability for the application layer.

Once all message information has been uplinked, the client signals the end of the email with a line containing just a dot (.). The SMTP receiver indicates the the email has been received with a 250 OK. The client then sends a QUIT command, and the receiver terminates the SMTP link. Finally, TCP closes the connection using the FIN handshake. Note that where in HTTP, the FIN procedure occurs once the application is closed, whereas in SMTP the application may remain open, but the TCP link is closed once the message sequence is complete.

Table 5.4 summarises this typical email sending exchange, which was referenced from (43) and (13). We verified this sequence, and measured packet sizes using empirical data from Ethereal recordings. The RCPT TO packet size was found to vary depending on the address length of each particular recipient, but is usually only a small packet.

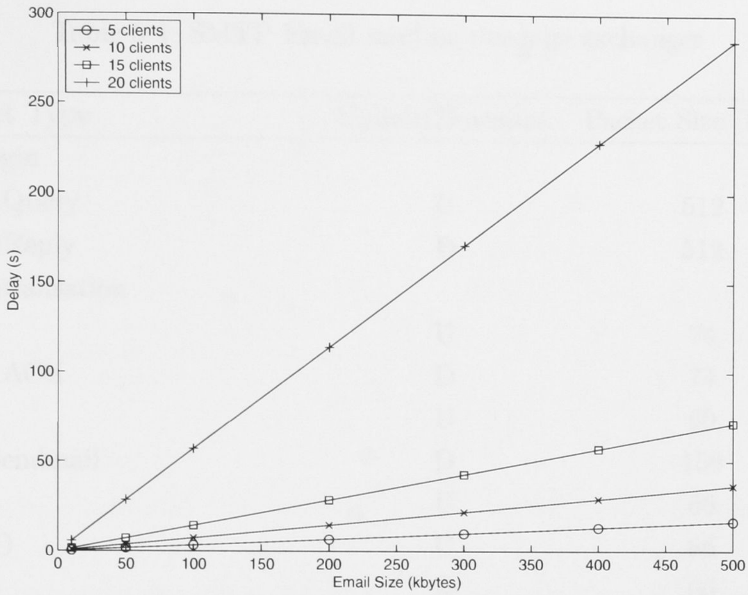


Figure 5.3: Evaluation of SMTP delay for TDMA/FDMA.

Note that while HTTP sends its web page data on the downlink channel from the server to the client, SMTP uplinks its message information from the client to the server. Moreover SMTP is not as time critical as HTTP, in that emails can be sent as a background operation, whereas HTTP requests should generally be satisfied with best effort, as the client is awaiting the webpage. Nevertheless, SMTP provides a useful system for analysing the level of throughput asymmetry on the FDMA uplink for the BushLAN network.

5.4.2 Throughput Results

The SMTP message exchange sequence defined in Table 5.5 was applied to the TDMA/FDMA MAC. As with the HTTP case, we assume a one-way Internet delay of 100 ms, and a fixed downlink payload size of 1500 bytes. The SMTP results are summarised in Figure 5.3 and Table 5.5.

The linear behaviour is similar to HTTP, which can be attributed to the cyclic nature of the MAC protocol. However, the critical difference is on the performance difference between the downlink heavy application (HTTP) relative to the uplink

Table 5.4: SMTP Email sending message exchanges

Packet Type	Uplink/Downlink	Packet Size (bytes)
1. Begin		
DNS_Query	U	512
DNS_Reply	D	512
2. Initialisation		
SYN	U	74
SYN_ACK	D	74
ACK	U	60
220 Sendmail	D	159
ACK	U	66
EHLO	U	86
ACK	D	66
250 Hello	D	290
ACK	U	66
MAIL FROM	U	100
ACK	D	66
250 Sender OK	D	120
3. Email Address Verification		
RCPT TO	U	120
250 Recipient OK	D	120
4. Body		
DATA	U	72
354 Enter mail	D	116
Email body	U	1500
ACK	D	66
.\r\n	U	60
250 OK	D	120
QUIT	U	73
221 Closing Connection	D	120
5. Close		
FIN, ACK	U	66
ACK	D	66

Table 5.5: SMTP throughput results

Number of clients	Normalised delay (ms/kbyte)	Downlink/Uplink SMTP	Throughput (kbps) Saturation
5	34	17/245	380/260
10	74	8/110	200/127
15	145	4/56	118/69
20	582	1/14	93/44

heavy application (SMTP).

We see the normalised delay doubles for each additional five subscribers, except in going from 15 to 20 users. At 20 users, the performance degradation is significant, and there is a large difference between SMTP and saturation uplink throughput, which indicates a large portion of the available uplink bandwidth is not being utilised. This is a result of the SMTP exchange sequence, as a client may uplink a short SMTP command or a return ACK, which, takes less than five TDMA frames, under the assumed MAC parameters. This leaves each client with a remaining fourteen frames per cycle without a need to uplink.

The availability of uplink bandwidth from an uplink intensive application such as SMTP, combined with the almost unused downlink bandwidth, indicates it is possible for clients to use other applications in parallel with sending email. Further work could consider TDMA/FDMA performance with both HTTP and SMTP.

5.5 Summary

In this chapter we considered the TDMA/FDMA MAC under three traffic models; VoIP, HTTP and SMTP. Using the G.729 standard for Internet telephony, we find the MAC is able to support as many as 20 VoIP calls with a downlink payload size of 2300 bytes. By operating under a two frame cycle, the MAC is able to send half the users their downlink voice packets in one frame, while the other half uplinks their voice packets, and vice versa in the second frame.

The downlink and uplink throughput capacities of TDMA/FDMA were analysed using HTTP and SMTP loads respectively. We observe that an additional five users at least doubles the normalised delay. The difference between application throughput and saturation throughput also increases as a function of clients, but is consistently larger under SMTP.

Further work could consider methods of optimising the TDMA/FDMA protocol under application specific traffic models, by incorporating variability with the downlink frame sizes. MAC performance under multiple simultaneous traffic models could also be analysed.

Chapter 6

Conclusion

6.1 Summary

The objective of this thesis has been to investigate the techniques and issues associated with designing an effective Medium Access Control (MAC) protocol for long range wireless networks. This has been motivated by the need to develop a cost effective solution to the problem of telecommunication services in rural and regional communities.

In particular, we consider various MAC schemes for the BushLAN wireless regional area network. BushLAN uses vacant TV bands in UHF spectrum to provide broadband services to remote and isolated locations without adequate communications infrastructure. The network specifications are for a coverage range between 10-30 kms, with 10-20 subscribers per base station.

Firstly we analyse random access protocols, and show that the optimal form of p-persistent CSMA/CA, as derived from the IEEE 802.11 protocol, is not as efficient as a fixed access scheme, by comparing its throughput to TDMA/TDD under a large propagation delay. A simple implementation of the slotted Aloha protocol is shown to be a sufficient mechanism for handling random login requests under a TDMA type scheme, where contention free access is allocated as demanded (DAMA).

We explored two contention free MAC protocols, operating with a full duplex base station and half duplex subscriber stations. In the first MAC, TDMA/FDD, both the uplink and down link channels use TDMA, whereas in the second MAC, TDMA/FDMA, the downlink uses TDMA while the uplink uses FDMA. We devise timing diagrams and evaluate throughput for both MACs. We show that both MACs offer comparable downlink throughputs, but FDMA has greater uplink throughput as a function of SNR, and can provide significantly greater coverage area than TDMA. We conclude the most suitable MAC layer protocol for BushLAN is TDMA/FDMA. With ten clients and 2 MHz of bandwidth for each channel, each with 10 W of output power, users can attain maximum speeds of 200 kbps on the downlink and 130 kbps on the uplink in a 20 km cell radius without error correction.

Throughput results for TDMA/FDMA under VoIP, HTTP and SMTP traffic loads are also obtained. We show that TDMA/FDMA provides satisfactory capacity for each application without saturating the MAC layer.

6.2 Further Work

This thesis has identified the most suitable MAC protocol for a long range wireless network to provide last mile broadband Internet connections to rural and regional communities. That is, a MAC with a TDMA downlink and an FDMA up link on FDD channels. There is now significant potential to expand the role of the MAC layer in BushLAN.

Further analysis could include integration of the slotted Aloha login channel with the TDMA/FDMA data channel, by incorporating admission control. Tailoring the MAC and PHY headers to the needs of BushLAN also needs to be investigated, as this study has simply assumed the 802.11 parameters. Dynamic downlink packet sizes, and the ability to support multiple different traffic connections simultaneously could also be studied. Implementing the MAC layer onto the FPGA can also be considered.

References

[1] The 7 Layers of the OSI Model. http://www.webopedia.com/quick_ref/OSI_Layers.asp. Accessed January 2006. 4

[2] IEEE 802.22, wikipedia. http://en.wikipedia.org/wiki/IEEE_802.22. Accessed January 2006. 18

[3] Wi-Fi HotSpot Locations. http://www.wifi411.com. Accessed January 2006. 11

[4] WiMAX, Wikipedia. http://en.wikipedia.org/wiki/Wimax. Accessed January 2006. 16

[5] The ABA's General Approach to Digital Terrestrial Television Broadcasting Planning - As Varied April 2002. Technical report, Australian Broadcasting Authority, http://internet.aca.gov.au/webwr/aba/newspubs/radio_tv/broadcast_planning/documents/general_approach_to_digital_tv_planning.pdf, 2002. Accessed January 2006. 2, 3, 18

[6] Bandwidth Requirements for Voice over IP Transmission. White paper, Westbay Engineers Limited, http://www.businessmobileasia.com/whitepapers/0,3900956,39166588p-39001101q,00.htm, 2004. Accessed January 2006. 57

[7] Business Case Models for Fixed Broadband Wireless Access based on WiMAX Technology and the 802.16 Standard. Technical report, WiMAX Forum, http://www.wimaxforum.org/technology/downloads/, October 2004. Accessed January 2006. 16

[8] FCC Posts Details on TV Band Broadband. http://www.dailywireless.org/2004/05/26/fcc-posts-details-on-tv-band-broadband/, 2004. Accessed January 2006. 2, 3, 18

[9] The i-BURST Personal Broadband System overview. Technical report, ArrayComm, http://www.arraycomm.com/docs/iBurstOverview.pdf, 2004. Accessed January 2006. 15

[10] Including VoIP over WLAN in a Seamless Next-Generation Wireless Environment. Technical report, Texas Instruments, The International Engineering Consortium, http://www.iec.org/online/tutorials/, 2005. Accessed January 2006. 57

[11] RF manual 6th edition. Technical report, Philips Electronics, 2005. 54

[12] IEEE 802 LAN/MAN Standards Committee 802.22 WG on WRANs. http://grouper.ieee.org/groups/802/22, 2006. Accessed January 2006. 1, 4, 17

[13] TCP/IP Protocol Sequence Diagrams. http://www.eventhelix.com/eventstudio/tcp_ip_sequence_diagrams/, 2006. Accessed January 2006. 60, 62, 65

[14] N. Abramson. The Aloha System - Another Alternative for Computer Communications. In *Proceedings of Fall Joint Computer Conference, AFIPS Conference*, 1970. 22

[15] M. Anderson. Air Interface Design and Coverage Experiments for BushLAN. Engineering Honours Thesis, Australian National University, 2003. 1

[16] G. Bianchi. Performance Analysis of the IEEE 802.11 Distributed Coordination Function. *IEEE Journal on Selected Areas in Communications*, 18(3):535–547, March 2000. 31, 32, 35

[17] K. Blomquist. A study of Self-Similar Data Traffic and Development of a WWW Traffic Model. Master's thesis, Linkpings Universitet, 1997. 39

[18] G. Borg. BushLAN. http://www.bushlan.net. Accessed January 2006. 4

[19] G. Borg. Progress Report on the BushLAN UHF Transceiver Project for the Period July-Oct 2005. Commercial in Confidence Report, June 2005. Australian National University. 20

[20] G. Borg and L. May. BushLAN Concept Description. The Australian National University and Standard Communications, Commercial-in-Confidence, 2003. 9

[21] S. Bose and S. Rappaport. High Capacity: Low Delay Packet Broadcast Multiaccess. *IEEE Transactions on Aerospace and Electronic Systems*, AES-16(6):830–838, November 1980. 13

[22] M. Bourk. *Universal Service? Telecommunications Policy In Australia and People with Disabilities.* Authorhouse, 2001. 2

[23] N. Chandrasena. Telstra moves to connect rural Australia. CRN Australia, Haymarket Media Worldwide, January 2004. 15

[24] J. Charzinski. Internet Client Traffic Measurement and Characterisation Results. In *Proceedings of ISSLS*, Stockholm, June 2000. 39

[25] M. Cohen, D. Rouffet, L. Brignol, and M. Coupechoux. High speed Internet in sparsely populated areas. Technical Report 3rd Quarter, Alcatel Telecommunications Review, 2004. 11

[26] G. Combs. Ethereal - Network Protocol Analyzer. `http://www.ethereal.com`. Accessed January 2006. 62

[27] The International Engineering Consortium. Local Multipoint Distribution System. Technical report, `http://www.iec.org/online/tutorials/lmds/`, 2005. Accessed January 2006. 1, 12

[28] L. Couch. *Digital and Analog Communication Systems.* Prentice Hall, 2001. 52

[29] A. Doufexi, S. Armour, P. Karlsson, M. B. A. Nix, D. Bull, and J. McGeehan. A Comparison of the HIPERLAN/2 and IEEE 802.11a Wireless LAN Standards. *IEEE Communications Magazine*, 40(5):172–180, May 2002. 14

[30] R. Fielding, J. Gettys J. Mogul, H. Frystyk, L. Masinter, P. Leach, and T. Berners-Lee. Hypertext Transfer Protocol - HTTP/1.1, Request for Comments 2616. Technical report, Internet Engineering Task Force, 1999. 60

[31] B. Fong, N. Ansari, A. Fong, G. Hong, and P. Rapajic. On the Scalability of Fixed Broadband Wireless Access Network Deployment. *IEEE Communications Magazine*, 42(9):S12–S18, September 2004. 12

[32] R. Foster. The art of asymmetry. Technical report, Telephony Online, `http://telephonyonline.com/mag/telecom_art_asymmetry/`, October 1999. Accessed January 2006. 12

[33] S. Garg and M. Kappes. Can I add a VoIP Call? *International Conference on Communications*, 2:779–783, May 2003. 57

[34] A. Ghosh, D. Wolter, J. Andrews, and R. Chen. Broadband Wireless Access with WiMax/802.16: Current Performance Benchmarks and Future Potential. *IEEE Communications Magazine*, 43(2):129–136, February 2005. 16

[35] A. Goldsmith. *Wireless Communications.* Cambridge University Press, 2005. 23

[36] I.T. House of Representatives Standing Committee on Communications and the Arts. Connecting Australia! Wireless Broadband. Technical report, The Parliament of the Commonwealth of Australia, `http://www.aph.gov.au/house/committee/cita/Wbt/index.htm`, 2002. Accessed January 2006. 2, 9, 12

[37] M. Johnsson. HiperLAN/2 - The Broadband Radio Transmission Technology Operating in the 5 GHz Frequency Band. Technical report, HiperLAN/2 Global Forum, `http://easy.intranet.gr/paper_20.pdf`, 1999. Accessed January 2006. 14

[38] F. Khan, S. Kumar, K. Medepalli, and S. Nanda. *IEEE Multi-access, Mobility and Teletraffic for Wireless Communications*, chapter Performance of Data Applications over a CDMA Air Interface. Kluwer Academic Press, 2000. 60, 61

[39] A. Khobare. Simulation Study of Local Multipoint Distribution Service (LMDS). Master's thesis, Virginia Polytechnic Institute and State University, 2000. 12

[40] J. Khun-Jush, G. Malmgren, P. Schramm, and J. Torsner. HIPERLAN type 2 for broadband wireless communication. *Ericsson Review*, (2), 2000. 14

[41] L. Kleinrock and F. Tobagi. Packet Switching in Radio Channels: Part I - Carrier Sense Multiple-Access Modes and Their Throughput-Delay Characteristics. *IEEE Transactions on Communications*, 23(12):1400–1416, December 1975. 22, 28

[42] L. Kleinrock and F. Tobagi. Packet Switching in Radio Channels: Part II - The Hidden Terminal Problem in Carrier Sense Multiple-Access and the Busy-Tone Solution. *IEEE Transactions on Communications*, 23(12):1417–1433, December 1975. 22, 30

[43] J. Klensin. Simple Mail Transfer Protocol, Request for Comments 2821. Technical report, Internet Engineering Task Force, 2001. 64, 65

[44] A. Kos, M. Pustisek, and J. Bester. Characteristics of Real Packet Traffic Captured at Different Network Locations. *The IEEE Region 8 EUROCON, Computer as a Tool*, 1:164–168, Sept 2003. 63

[45] S. Lam. *Packet Switching in a Multi-Access Broadcast Channel with Application to Satellite Communication in a Computer Network*. PhD thesis, University of California at Los Angeles, 1974. 22, 25, 26, 27

[46] S. Lam. Satellite Packet Communication - Multiple Access Protocols and Performance. *IEEE Transactions on Communications*, 27(10):1456–1466, October 1979. 13

[47] F. Leite. Spectrum Management for a Converging World: Case Study on Australia. Technical report, International Telecommunications Union, `http://www.itu.int/osg/spu/ni/spectrum/aust-rsm.pdf`, 2004. Accessed January 2006. 2

[48] K. Leung, B. McNair, L. Cimini, and J. Winters. Outdoor IEEE 802.11 Cellular Networks: MAC Protocol Design and Performance. In *International Conference on Communications*, pages 595–599. IEEE, May 2002. 11

[49] K. Mackenzie. Bush broadband clinches T3. *The Australian IT*, 25 June 2003. 3

[50] N.P. Mailula. Low cost data access system for rural and under-served areas. In *The 7th AFRICON Conference in Africa*, pages 107–113. IEEE, 2004. 11

[51] M. Marcus. Unlicensed Cognitive Sharing of TV Spectrum: The Controversy at the Federal Communications Commission. *IEEE Communications Magazine*, 43(5):24–25, May 2005. 1, 4

[52] P. Mitchell. *Effective Medium Access Control for Geostationary Satellite Systems.* PhD thesis, University of York, 2003. 8, 13

[53] B. O'Hara and A. Petrick. IEEE 802.11 Handbook A Designer's Companion. Technical report, Standards Information Network, IEEE Press, IEEE, 1999. 1, 29, 34

[54] R. O'Niell. Back and beyond the bush telegraph, The Sydney Morning Herald. `http://www.smh.com.au/articles/2004/09/06/1094322703679.html?from=storyrhs`, 2004. Accessed January 2006. 3

[55] Inter Agency Policy, Department of Premier Project Unit, and Cabinet. Telecommunications In Tasmania 2004 Market Competitive Report. Technical report, Government Online Services - Telecommunications, `http://www.egovernment.tas.gov.au/__data/assets/pdf_file/13504/iappu-tele-open-market-2004.pdf`, 2004. Accessed January 2006. 1

[56] J. Proakis and M. Salehi. *Communication Systems Engineering.* Prentice Hall, 2002. 52, 53, 55

[57] T. Rappaport. *Wireless Communications Principles and Practice.* Prentice Hall, 2002. 20, 42, 54

[58] L. Roberts. Aloha Packet Systems with and without Slots and Capture. *Computer Communications Review*, April 1975. 24

[59] A. Rodriguez, J. Gatrell, J. Karas, and R. Peschke. *TCP/IP Tutorial and Technical Overview*. IBM Corporation, International Technical Support Organization, 7th edition, 2001. 61

[60] M. Sainsbury. Just a phone call away. *The Australian*, 10 August 2005. 1, 2, 3, 16

[61] A. Sale. Broadband Internet Access in Regional Australia. *Journal of Research and Practice in Information Technology*, 33(4):346–355, November 2001. 11

[62] D. Sweeney. The Reappearance of LMDS. *Broadband Wireless Business Magazine*, 4, November/December 2003. Shorecliff Communications. 12

[63] M. Tokarev. udns - stub DNS resolver libary. `http://www.corpit.ru/mjt/udns/dns.3.html`. Accessed January 2006. 62

[64] J. Vedi and G. Borg. MAC Performance Analysis in Long Range Wireless Local Loops. *IEEE and IFIP International Conference on Wireless and Optical Communications Networks*, April 2006. 19

[65] W. Wang, S. Liew, and V. Li. Solutions to performance problems in a VoIP Over a 802.11 wireless LAN. *IEEE Transactions on Vehicular Technology*, 54(1):366–384, January 2005. 57

[66] K. Wongthavarawat and A. Ganz. Packet scheduling for QoS support in IEEE 802.16 broadband wireless access systems. *International Journal of Communication Systems*, 16(1):81–96, 2003. 40

[67] M. Zaki. IEEE 802.11 Wireless LANs Carrying Integrated Traffic: Quality of Service and Performance Analysis. Master's thesis, The University of Western Ontario, 1999. 39

[68] M. Zhang and R. Wolff. Using Wi-fi for Cost-Effective Broadband Wireless Access in Rural and Remote Areas. In *Wireless Communications and Networking Conference*, volume 3, pages 1347–1352. IEEE, March 2004. 11