Simulation Study of Local Multipoint Distribution Service (LMDS)

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Computer Science

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July 20, 2000
Blacksburg, Virginia

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(ABSTRACT)

This thesis describes simulation models for Local Multipoint Distribution Service (LMDS) systems, and uses simulation to examine the performance of two different multiple access schemes and two different duplexing schemes. LMDS is a broadband wireless point-to-multipoint access network that aims to improve network access capacity for end-users by solving the "last mile" problem. This study involves building a parameterized simulation model for symmetric LMDS systems and comparing performance of the systems for different multiple access and duplexing schemes.

The report describes the LMDS system and briefly discusses other broadband access networks. Objectives of this study are discussed and methodology is chosen. The simulation model design is explained. Further, the experimental design is discussed. The simulation results are presented and discussed, and conclusions are drawn.

The multiple access schemes under study are Time Division Multiple Access (TDMA), and Frequency Division Multiple Access (FDMA). The duplexing schemes under study are Time Division Duplexing (TDD), and Frequency Division Duplexing (FDD).

For the system under study, it was observed that TDMA results in lower end-to-end (ETE) delay per packet, but higher jitter, than FDMA. In addition, TDD results in lower ETE delay per packet than FDD. Specifically, TDMA in conjunction with TDD was found to result in lowest ETE delay per packet among the configurations under study. In addition, FDMA in conjunction with FDD was found to result in lowest jitter among the configurations under study.

Acknowledgements

I would like to thank my advisor, Dr. Scott F. Midkiff, for his excellent guidance and help during this research work and for giving me useful comments during the writing of the thesis. I would like to thank my committee members, Dr. Marc Abrams and Dr. Srinidhi Varadarajan, for their time and cooperation in reviewing the thesis.

I would also like to thank my colleague, Nattavut Smavatkul, for helping me with OPNET problems and the ECPE Workstation Lab administrator, John Harris, for Unix and OPNET installation support.

For the use of computing facilities for this study, I would like to thank the Virginia Tech Information Systems Center and ECPE Workstation Lab.

Finally, I would like to thank my family and friends for their love, encouragement and support.

Table of Contents

Abstract

Acknowledgements

Table of Contents

1. Introduction.....1

1.1. Background.....1
1.2. Research Goals.....2
1.3. Organization of the Report.....3

2. Background.....4

2.1. Overview of LMDS.....4
2.1.1. Architecture.....4
2.1.2. Advantages.....5
2.1.3. Challenges.....6
2.1.4. LMDS Deployment at Virginia Tech.....6
2.2. Other Broadband Access Technologies.....7
2.2.1. Broadband Wireless Technologies.....7
2.2.2. Broadband Wireline Technologies.....7
2.3. Multiple Access and Duplexing Schemes.....8
2.3.1. Multiple Access Schemes.....8
2.3.2. Duplexing Schemes.....9
2.4. Summary.....10

3. Objectives and Methodology.....11

3.1. Problem Statement.....11
3.2. Selecting an Evaluation Technique.....12
3.3. System Boundaries.....12
3.4. System Services.....13
3.5. Performance Metrics.....14
3.6. List of Parameters.....14

3.6.1. System Parameters 14
3.6.2. Channel Parameters 14
3.6.3. Traffic Model 16
3.7. Summary 17

4. Simulation Model 19
4.1. OPNET Modeler 19
4.2. TDMA/TDD Model 19
4.2.1. Network Level Design 20
4.2.2. Node Level Design 21
4.2.2.1. Central_Hub 21
4.2.2.2. Remote_Host 23
4.2.2.3. End_Host 23
4.2.3. Process Level Design 24
4.2.3.1. Central_Trans 24
4.2.3.2. Remote_Trans 26
4.2.3.3. Remote_Recv 27
4.2.3.4. Central_Recv 27
4.3. TDMA/FDD Model 28
4.3.1. Network Level Design 28
4.3.2. Node Level Design 29
4.3.3. Process Level Design 29
4.3.3.1. Central_Trans 29
4.3.3.2. Remote_Trans 30
4.3.3.3. Remote_Recv 31
4.3.3.4. Central_Recv 31
4.4. FDMA/TDD Model 32
4.4.1. Network Level Design 32
4.4.2. Node Level Design 32
4.4.2.1. Central_Hub 32
4.4.2.2. Remote_Host 34
4.4.3. Process Level Design 35
4.4.3.1. Central_Trans 35
4.4.3.2. Remote_Trans 36

4.4.3.3. Remote_Recv 36
4.4.3.4. Central_Recv 37
4.5. FDMA/FDD Model 38
4.5.1. Network Level Design 38
4.5.2. Node Level Design 38
4.5.2.1. Central_Hub 38
4.5.2.2. Remote_Host 39
4.5.3. Process Level Design 39
4.5.3.1. Remote_Trans 39
4.5.3.2. Remote_Recv 39
4.5.3.3. Central_Recv 40
4.6. Summary 40

5. Simulation Experiments and Results 41
5.1. Simulation Parameters 41
5.2. Simulation Parameter Values 42
5.2.1. Experimental Factors 42
5.2.1.1. Multiple Access Scheme 42
5.2.1.2. Duplexing Scheme 42
5.2.1.3. Size of Network 42
5.2.1.4. Traffic Types 43
5.2.1.5. Traffic Loads 43
5.2.2. Simulation Parameters 43
5.2.2.1. Data Rate of the Wireless Channel 44
5.2.2.2. Length of Time Slice for TDMA and TDD Schemes 44
5.2.2.3. Switching Overhead 44
5.2.2.4. Order of Access 44
5.2.2.5. Mean Packet Length 45
5. 3. Length of Simulation Experiments 45
5.4. Validation of Simulation Models 46
5.4.1. FDMA/FDD Model 48
5.4.1.1. Low Load 48
5.4.1.2. Moderate Load 49
5.4.2. FDMA/TDD Model 49

5.4.2.1. Low Load 49
5.4.2.2. Moderate Load 50
5.4.3. TDMA/FDD Model 50
5.4.3.1. Low Load 51
5.4.3.2. Moderate Load 51
5.4.4. TDMA/TDD Model 51
5.4.4.1. Low Load 52
5.4.4.2. Moderate Load 52
5.5. Simulation Results 52
5.5.1. TDMA/TDD Model 53
5.5.2. TDMA/FDD Model 54
5.5.3. FDMA/TDD Model 55
5.5.4. FDMA/FDD Model 56
5.6. Analysis of Results 57
5.7. Summary 61

6. Conclusions 62
6.1. Summary 62
6.2. Conclusions 63
6.3. Suggestions for Future Work 64

References 65
Appendix A – Comparison of ETE delay Results 67
Appendix B – Comparison of Jitter Results 71
Vita

List of Figures

2.1. Typical LMDS architecture 4
2.2. Conceptual operation of TDMA 9
2.3. Conceptual operation of FDMA 9
2.4. Conceptual operation of TDD 10
2.5. Conceptual operation of FDD 10
3.1. Configurations of LMDS system under study 12
4.1. Network level design of the TDMA/TDD model 20
4.2. Node level design of the Central_Hub node in the TDMA/TDD model 22
4.3. Node level design of Remote_Host node in the TDMA/TDD model 23
4.4. Node level design of End_Host node in the TDMA/TDD model 24
4.5. Process level design of the Central_Trans process model in the TDMA/TDD model 25
4.6. Process level design of Remote_Trans process model in the TDMA/TDD model 26
4.7. Process level design of Remote_Recv process model in the TDMA/TDD model 27
4.8. Process level design of Central_Recv process model in the TDMA/TDD model 28
4.9. Process level design of the Central_Trans process model in the TDMA/FDD model 29
4.10. Process level design of Remote_Trans process model in the TDMA/FDD model 30
4.11. Process level design of Remote_Recv process model in the TDMA/FDD model 31
4.12. Process level design of Central_Recv process model in the TDMA/FDD model 32
4.13. Node level design of Central_Hub node in the FDMA/TDD model 33
4.14. Node level design of Remote_Host node in the FDMA/TDD model 34
4.15. Process level design of the Central_Trans process model in the FDMA/TDD model 35
4.16. Process level design of Remote_Trans process model in the FDMA/TDD model 36
4.17. Process level design of Remote_Recv process model in the TDMA/FDD model 37
4.18. Process level design of Central_Recv process model in the FDMA/TDD model 37
4.19. Node level design of Central_Hub node in the FDMA/FDD model 38
4.20. Process level design of Remote_Trans process model in the FDMA/TDD model 39
4.21. Process level design of Remote_Recv process model in the FDMA/FDD model 40
5.1. Time average plot of ETE delay for a non-bursty TDMA/TDD model 45
5.2. Time average plot of ETE delay for a bursty TDMA/TDD model 45
A.1. Time average plot of the ETE delay statistic for the four simulation models under low load, small network size and non-bursty traffic 65

A.2. Time average plot of the ETE delay statistic for the four simulation models under low load, small network size and bursty traffic 65
A.3. Time average plot of the ETE delay statistic for the four simulation models under low load, large network size and non-bursty traffic 66
A.4. Time average plot of the ETE delay statistic for the four simulation models under low load, large network size and bursty traffic 66
A.5. Time average plot of the ETE delay statistic for the four simulation models under moderate load, small network size and non-bursty traffic 67
A.6. Time average plot of the ETE delay statistic for the four simulation models under moderate load, small network size and bursty traffic 67
A.7. Time average plot of the ETE delay statistic for the four simulation models under moderate load, large network size and non-bursty traffic 68
A.8. Time average plot of the ETE delay statistic for the four simulation models under moderate load, large network size and bursty traffic 68
B.1. Time average plot of the jitter statistic for the four simulation models under low load, small network size and non-bursty traffic 69
B.2. Time average plot of the jitter statistic for the four simulation models under low load, small network size and bursty traffic 69
B.3. Time average plot of the jitter statistic for the four simulation models under low load, large network size and non-bursty traffic 70
B.4. Time average plot of the jitter statistic for the four simulation models under low load, large network size and bursty traffic 70
B.5. Time average plot of the jitter statistic for the four simulation models under moderate load, small network size and non-bursty traffic 71
B.6. Time average plot of the jitter statistic for the four simulation models under moderate load, small network size and bursty traffic 71
B.7. Time average plot of the jitter statistic for the four simulation models under moderate load, large network size and non-bursty traffic 72
B.8. Time average plot of the jitter statistic for the four simulation models under moderate load, large network size and bursty traffic 72

List of Tables

3.1. Parameters and Factors of the Simulation System 17
5.1. Simulation Values of Experimental Factors 43
5.2. Results of Simulation Experiments on the TDMA/TDD Model 54
5.3. Results of Simulation Experiments on the TDMA/FDD Model 55
5.4. Results of Simulation Experiments on the FDMA/TDD Model 55
5.5. Results of Simulation Experiments on the FDMA/FDD Model 57
5.6. Effect of Increase in Network size on ETE delay and Jitter 59
5.7. Effect of Increase in Network load on ETE delay and Jitter 60

Chapter 1. Introduction

Broadband Internet access to homes and small businesses has always suffered from the "last mile" problem, i.e., the bandwidth bottleneck arising due to the use of traditional copper telephone wires in the local loop. Several solutions, both wireless and wireline, have been proposed. These include Digital Subscriber Line (DSL), Hybrid Fiber Coax (HFC), and broadcast satellite. Local Multipoint Distribution Service (LMDS) is an alternative solution, which provides symmetric (or, optionally, asymmetric) broadband service using a point-to-multipoint (or, optionally, a point-to-point) configuration. Applications of LMDS include voice, video, and high-speed data communications [LMVT99].

This thesis reports performance evaluation studies of the effect of using different multiple access schemes in conjunction with different duplexing schemes in the LMDS system architecture. Specifically, we examine frequency and time division multiple access, and frequency and time division duplexing.

1.1. Background

LMDS represents several licensed microwave frequency bands in the 28-31 GHz range. It can offer similar bandwidths for upstream and downstream traffic. It can also potentially offer transmissions speeds of multiple Gigabits per second to support advanced networking applications [LMVT99].

LMDS offers an alternative to traditional means for providing broadband access to consumers. Wireless connections eliminate the need and cost of laying wires, reduce right-of-way conflicts, and are often quicker to deploy. LMDS can provide quality of service and support a variety of applications including telephony, videoconferencing, Internet, video-on-demand, multi-channel video, and other data services.

There are some challenges to deploying and using LMDS, though. The relatively high frequency and shorter wavelengths of the spectrum lead to the transmission being hindered or stopped by walls, buildings, vegetation, or heavy rain. LMDS, thus requires line-of-sight, i.e., an unobstructed view from the transmitting antenna to the receiving antenna. Wireless link distances

are restricted to 12 to15 kilometers. The equipment is currently expensive, but it is becoming more affordable.

The Federal Communications Commission (FCC) auctioned off licenses for the LMDS spectrum in 1998. The Virginia Tech Foundation, on behalf of Virginia Tech's research and public service missions, participated in the auction and won licenses for four Basic Trading Areas (BTAs) in southwest Virginia. These are the Roanoke, Bristol, Danville, and Martinsville BTAs [LMVT99]. Last year, Virginia Tech in partnership with Wavtrace, a Washington based company, successfully deployed a LMDS network in Blacksburg. The deployed system includes one central hub and three remote hosts located in off-campus locations. The system was successfully tested for simultaneous voice, video, and Internet traffic.

1.2. Research Goals

LMDS is typically deployed as a point-to-multipoint system. The central hub communicates with several remote hosts in a single transmission beam. Communication from the central hub to the remote hosts is point-to-multipoint, while communication from a remote host to the central hub is point-to-point. A multiple access scheme is required to enable each of the remote hosts to separately send and receive traffic from the central hub. Further, a duplexing scheme is required for the coordination of upstream and downstream traffic.

There are two main objectives for this research. The first objective is to construct a parameterized simulation model of an LMDS network using the OPNET Modeler tool [Mil396]. It is hoped that this model will have utility for others studying LMDS performance issues. The second objective is to use the model to compare performance of the LMDS system when using combinations of two multiple access schemes and two duplex schemes. The multiple access schemes being considered are Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA). The duplexing schemes being considered are Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD).

Four different configurations of the system need to be developed using combinations of the two multiple access and two duplexing schemes described. The simulation study involves comparing performance of these four configurations for two different traffic models. The traffic models are described in detail in Chapter 3. The performance metrics used for comparing performance during

this study and the reasons behind choosing these metrics are also discussed in Chapter 3. Details of the simulation experiments and results are described in Chapter 5.

Deliverables from this research are the simulation model, the results of the simulation experiments, the conclusions that can be drawn from the results and this thesis describing the entire simulation process.

1.3. Organization of the report

The report is divided into six chapters. Chapter 2 gives background information. In particular, it provides an overview of LMDS and presents several alternative solutions for broadband access including both wireless and wireline solutions. In addition, it briefly introduces the multiple access and duplexing schemes under study. Chapter 3 describes, in detail, the objective of this simulation study and the methodology that was followed to develop the simulation model. Chapter 4 describes the simulation models in detail including the design of the models using the OPNET Modeler tool. Chapter 5 describes the simulation experiments in detail, explains how the simulation models were validated, and presents the results which were obtained from the experiments. Chapter 6 presents conclusions that were drawn from the simulation results and describes opportunities for further research.

Chapter 2. Background

This chapter gives an overview of the Local Multipoint Distribution Service (LMDS) system, including its architecture, its advantages over other "local loop" networks, and its limitations. Further, the LMDS network deployment at Virginia Tech is briefly discussed. Lastly, some of the contemporary broadband networks are introduced.

2.1. Overview of LMDS

2.1.1. Architecture

Local Multipoint Distribution Service (LMDS) is a broadband wireless point-to-multipoint communication system operating above 20 GHz that can be used to provide digital two-way voice, data, Internet and video services. In the United States, LMDS operates at the 28 GHz frequency range, while in Europe it operates at the 40 GHz range [LMNO00].

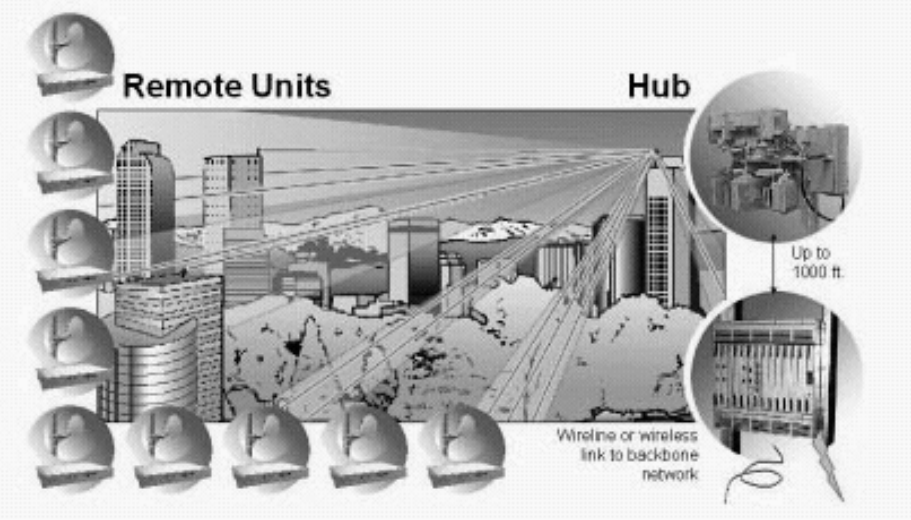

Figure 2.1. Typical LMDS architecture[1].

Figure 2.1 shows a typical configuration of the LMDS system. Each cell in the system has a base station or hub, which is henceforth referred to as the central hub. There are several remote units, henceforth referred to as remote hosts, which constitute the customer premise equipment. The central hub is connected to the backbone network through either a wireless or a wireline link. The

[1] Image obtained from www.wavtrace.com

remote hosts are located typically at customer premises, either residential subscribers or commercial small business subscribers [LMVT99].

In LMDS, there exists a wireless broadband point-to-multipoint wireless link between the central hub and all remote hosts. Each remote host communicates back to the central hub using a point-to-point wireless link. A multiple access scheme is required to regulate access to the channel by the remote hosts. Some of the typical schemes in use today are Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). The wireless channel is shared between the upstream and downstream traffic, thus requiring a duplexing scheme. The typical duplexing schemes used for this purpose are Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD).

The acronym LMDS is derived from the following [LMNO00].

L (local): Denotes that propagation characteristics of signals in this frequency range limit the potential coverage area of a single cell. Typically, cell sizes are in the range of 12 to 15 kilometers.

M (multipoint): Indicates that signals are transmitted in a point-to-multipoint method. The wireless return path, from subscriber to the base station, is a point-to-point transmission.

D (distribution): Refers to the distribution of signals, which may consist of simultaneous voice, data, Internet or video traffic.

S (service): Implies the "subscriber" nature of the relationship between the operator and the customer; the services offered through an LMDS network are entirely dependent on the operator's choice of business.

2.1.2. Advantages

LMDS can act as an effective "last mile" solution for service providers and it can be used by competitive service providers to deliver services directly to the end user. The benefits of using LMDS as a last mile solution can be summarized as follows.

a) Multi-gigabit capacity: The LMDS licensed spectrum in the US amounts to 1.3 GHz. This is more than double the bandwidth of AM/FM radio, VHF/UHF television, and cellular telephony combined. Over short distances, LMDS can carry broadband digital data in excess of one Gbps

[LMVT99]. Thus, LMDS systems can boast of simultaneously providing data, Internet access, voice, and video over the same link.

b) Ease and speed of deployment: Systems can be deployed rapidly with minimum disruption to community and environment [LMNO00].

c) Lower entry and deployment costs: Since a large part of the cost is not incurred until the customer premise equipment is installed, the service provider incurs expenditures only on acquiring new customers [LMNO00].

d) Demand-based buildout: Scalable architecture of LMDS guarantees that service as well as coverage area can be expanded as customer demand grows [LMNO00].

e) Integrated services: A combination of applications including data, Internet, voice and video can be supported [LMVT99].

2.1.3. Challenges

LMDS operates in the 28 GHz microwave range. This can introduce some challenges for the system to be deployed and used. These are summarized as follows.

a) Line of sight required: LMDS requires line of sight between the central hub and the remote hosts. This places constraints on network deployment [LMVT99].

b) Signal fading: Transmissions experience fading due to heavy rain. Vegetation can also attenuate and possibly stop the transmission [LMVT99].

c) Short antenna range: The high frequency of transmission limits the cell size to 10 to 12 kilometers [LMVT99].

d) Expensive equipment: Though, in some environments, LMDS works out to be far cheaper than fiber installation, the customer premises equipment is expensive compared to other technologies. On-going research and development is expected to bring down the costs and make LMDS more viable [LMNO00].

2.1.4. LMDS Deployment at Virginia Tech

In 1998, the Federal Communications Commission (FCC) auctioned off licenses for LMDS spectrum nationwide. Virginia Tech participated in this auction and successfully bid for licenses for four Basic Trading Areas (BTAs), Roanoke, Danville, Martinsville, and Bristol. This covers 40 percent of the Commonwealth of Virginia and some parts of Tennessee and North Carolina. In 1999, Virginia Tech in partnership with WavTrace, a Redmond, Washington-based company, successfully deployed an LMDS network in Blacksburg. At present, two sectors (or beams) and three remote hosts are operational. The equipment currently provides capacity, equivalent to

seven DS1 channels (about 11 Mbps) to each sector. Each remote has a 10BaseT interface while the central hub has one OC3 as well as one 10BaseT interface [LMVT99].

2.2. Other Broadband Access Technologies

In this section, we briefly introduce some alternative broadband technologies using both wireless and wireline transmission.

2.2.1. Broadband Wireless Technologies

Satellite Broadband [Macy96]**:** Satellite systems can provide "anytime anywhere" service even in the most rural and remote parts of the world. Satellite systems fall into two general categories, Geosynchronous (GEO) and Low Earth Orbit (LEO). Of the currently available GEO systems, Direct Broadcast Satellite (DBS) provides multi-megabit per second transmission though latencies are high (more than 500 ms for the downlink itself). However, DBS is highly asymmetric and uses wireline networks like Public Switched Telephone Network (PSTN) for upstream traffic. DBS is more suitable for broadcast types of applications.

Multi-channel Multipoint Distribution Service (MMDS) [Net00]**:** This carrier service was initially intended for television broadcast and it is popularly known as "wireless cable". In the United States, MMDS service is available at 2.5 GHz. Typically, MMDS provides analog one-way communication with a range of 30 miles (50 km). It is currently deployed in the US, Latin America, and parts of Europe and Asia. Some service providers have introduced Internet access by using a hybrid system with the PSTN forming the return path. The hybrid system limits the range to about 6 miles (10 km).

2.2.2. Broadband Wireline Technologies

Digital Subscriber Line (xDSL) [Jain99]**:** A Digital Subscriber Line makes use of the existing telephone copper infrastructure to provide broadband service. It uses two modems, one at the phone company end and the other at the customer premise. The Plain Old Telephone Service (POTS) uses only the lower 4 kHz of the total 1 MHz bandwidth of copper wires and, thus, can carry data, modulated to an analog form, at only 56 kbps. On the other hand, DSL uses advanced digital signal processing techniques to use the upper frequencies for data services. DSL comes in different flavors, hence the term xDSL. One of the most promising of the xDSL technologies is Asymmetric DSL (ADSL), which provides a substantially higher downstream bandwidth as compared to the upstream bandwidth. Typical data rates for ADSL are of the order of 1.5 to 6

Mbps downstream and 16 to 640 kbps upstream. One of the current impediments to the growth of the DSL services, currently, is the high cost of the modems. Also, limited number of copper lines with sufficient integrity to support high data rates, currently exist.

Cable Modems [Jain99]**:** Growth of the Internet has led to cable companies using their Hybrid Fiber Coax (HFC) Cable TV (CATV) network, for providing broadband services to residential customers. Depending on the network design, cable modems can provide bandwidth from 96 kbps to 10 Mbps. The overwhelming advantage in favor of cable modems in the US is the fact that nearly 40 percent of households are connected to the cable network. However, cable modems provide asymmetric service and the service is found to deteriorate quickly as more subscribers use the network. The downstream data rates are of the order of 45 Mbps and upstream data rates are of the order of 1.5 Mbps. In some systems, the cable system provides one-way data and POTS is used for the upstream link.

2.3. Multiple Access and Duplexing Schemes

This research considers the performance of LMDS using different combinations of multiple access schemes and duplexing schemes. This section introduces the two multiple access schemes and two duplexing schemes that are examined. Note that CDMA is not considered because very few very high data rate fixed wireless systems use CDMA.

2.3.1. Multiple Access Schemes

Multiple access schemes provide a technique for two or more data streams to access the same frequency channel. The multiple access schemes introduced in this section are the Time Division Multiple Access (TDMA) scheme and the Frequency Division Multiple Access (FDMA) scheme.

Time Division Multiple Access (TDMA): In TDMA, each of the competing data streams is given access to the entire channel for a fixed length of time. Figure 2.2 shows the conceptual operation of a TDMA scheme.

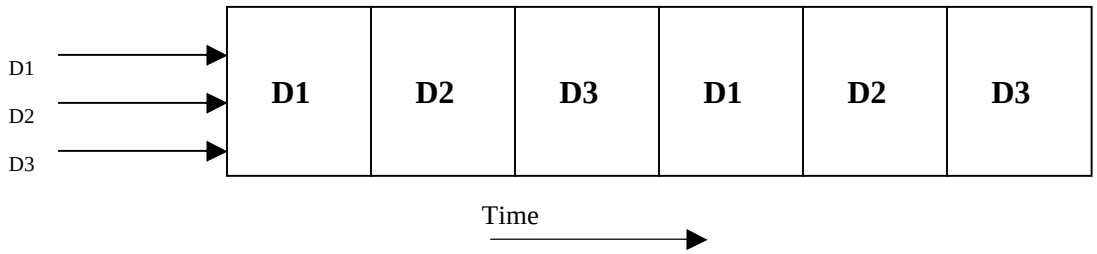

Figure 2.2. Conceptual operation of TDMA.

Frequency Division Multiple Access (FDMA): In FDMA, each of the competing data streams is given access to a segment of the entire channel. The data streams get to access their part of the channel without any interruptions. Figure 2.3 shows the conceptual operation of an FDMA scheme.

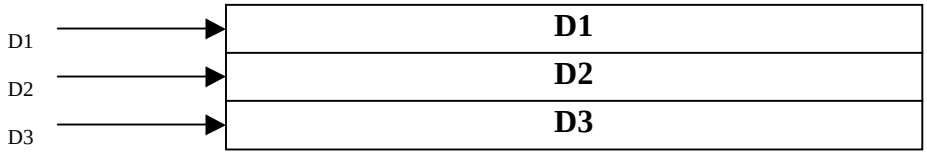

Figure 2.3. Conceptual operation of FDMA.

2.3.2. Duplexing Schemes

Duplexing schemes provide a technique whereby data flowing in both directions can be carried over the same frequency channel. The duplexing schemes considered here are the Time Division Duplexing (TDD) scheme and the Frequency Division Duplexing (FDD) scheme.

Time Division Duplexing (TDD): In this technique, both the upstream and downstream data is given access to the entire channel for a fixed slot of time. Figure 2.4 shows the conceptual operation of a TDD scheme.

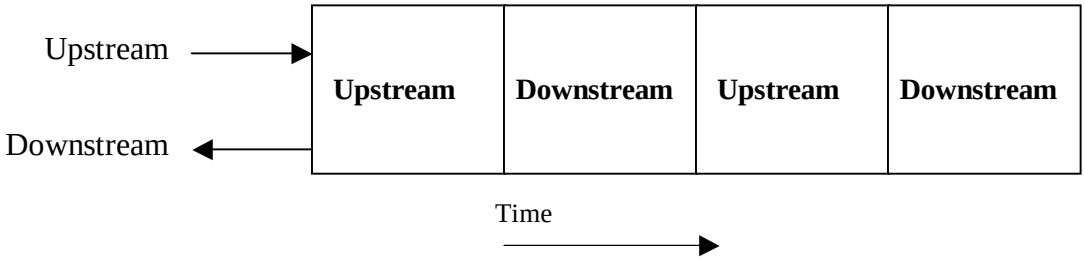

Figure 2.4. Conceptual operation of TDD.

Frequency Division Duplexing (FDD): In this technique, the upstream and downstream traffic are carried on separate parts of the entire channel. The bandwidth of each channel and, hence, capacity, is less as compared to the TDD scheme, but the data streams can access their channels without interruption. Figure 2.5 shows the conceptual operation of a FDD scheme.

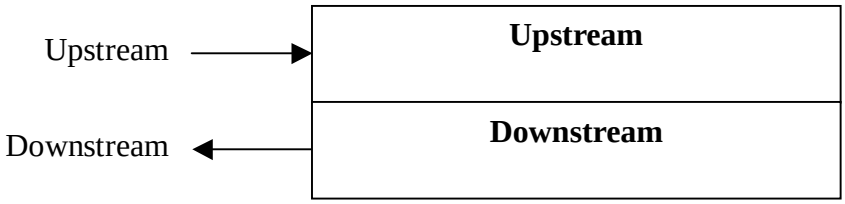

Figure 2.5. Conceptual operation of FDD.

2.4. Summary

This chapter presented an overview of the LMDS system. The advantages of the LMDS system over other contemporary broadband technologies were discussed and some challenges in deploying LMDS networks were presented. A brief introduction to the LMDS system deployment at Virginia Tech was provided. Other broadband technologies currently in use, both wireless and wireline, were briefly introduced. Lastly, the two multiple access schemes and two duplexing schemes of interest in this study were introduced.

Chapter 3. Objectives and Methodology

This chapter describes in detail the objectives of this study and the methodology adopted. The problem is defined first. The performance evaluation technique used is described. The system boundaries and the parameters of the model are also discussed.

3.1. Problem Statement

There are two main objectives of this research. The first objective is to construct a parameterized model of an LMDS network using the OPNET Modeler tool [Mil3]. It is hoped that this model will be useful for others studying LMDS performance issues. The second objective is to use the model to compare performance of the LMDS system when using combinations of two different multiple access schemes and two different duplex schemes. The multiple access schemes considered are Time Division Multiple Access and Frequency Division Multiple Access. The duplex schemes being considered are Time Division Duplexing and Frequency Division Duplexing.

The simulation model of the LMDS network should be useful for performance evaluation, both for this study as well as for subsequent related research efforts. The main concern while building the model is to parameterize the factors that affect the model's performance so that different configurations of the LMDS system can be modeled without excessive changes to the structure of the model itself. The factors that have been parameterized are explained later in this chapter.

The second part of this study involves comparing the performance of the LMDS network for four different configurations. One of these configurations uses TDMA as the multiple access scheme for communications between the central hub and the remote hosts and TDD as the duplexing scheme for sending the upstream and downstream traffic on the same wireless link. We call this scheme the TDMA/TDD scheme. The other configurations studied are the TDMA/FDD, FDMA/TDD and the FDMA/FDD schemes, where TDMA/FDD indicates TDMA as the multiple access scheme and FDD as the duplexing scheme, and so on. Figure 3.1 illustrates the different configurations of the LMDS system that are studied.

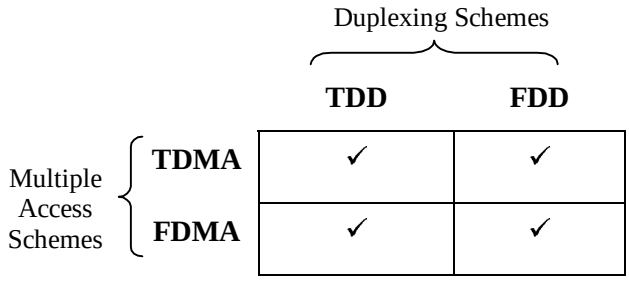

Figure 3.1. Configurations of LMDS network under study.

3.2. Selecting an Evaluation Technique

The three most common techniques used for performance evaluation are analytical modeling, simulation, and measurement [Jain91]. In this study, the simulation technique is chosen for the reasons explained below.

To make a reasonably accurate model of the LMDS system, we need to take into consideration a number of factors that influence the performance of the system. These factors are explained later in this chapter. Constructing an analytical model that could be expected to be reasonably accurate is, therefore, not a simple or even feasible task given the time frame of this project. Simulation allows creation of a model that is accurate enough for performance evaluation. Another argument in favor of simulation is that, in this case, it is possible to validate the model using real data. As stated earlier, Virginia Tech has already deployed an LMDS network on its campus. Real data about a variety of metrics is being collected on this deployed network. This data can be utilized to validate the model, thus further improving its reliability. Note, however, that data was not available to validate the model in this way. The cost involved in performing measurements for comparing the different configurations of the LMDS system would be prohibitive. Thus simulation was chosen as the most viable approach.

3.3. System Boundaries

The system considered as part of this study consists of an LMDS network set up in the following configuration. There is one central hub and an arbitrary number of remote hosts. The central hub communicates with all remote hosts using a point-to-multipoint scheme. The remote hosts communicate back to the central hub using point-to-point wireless links. The central hub is connected to the outside world using a wired link.

We define system boundaries as factors that delineate the system under study. The system boundaries for our model can be stated as follows.

Physical Layer Parameters: The physical layer in this system is a wireless link. There are several parameters involved that can affect the system performance. These include the channel bit rate, the bit error rate (BER) and associated error model used, the radio frequency at which data is being transmitted, the power of the transmitting signal, the antenna pattern, and the height of the antenna above the ground. Though these parameters affect the performance of the system, they are not the focus of our study. Hence, all of these parameters are kept constant for different configurations of the system.

Higher Layer Parameters: In this study, we evaluate performance of the system for different values of data link layer parameters. Parameters involved with higher layers in the Open Systems Interconnection (OSI) architecture might affect performance. For example, a World Wide Web (WWW) browser application can be expected to produce bursty traffic, which might affect the mean delay per packet. We incorporate these issues as part of the workload parameters, as discussed later in this chapter.

Data Link Layer Functionality: Some of the data link layer functionality is not important for this performance study. This includes framing, error detection and error correction. Parameters related to this functionality are not expected to directly affect the performance of one configuration of the system as compared to another. Hence, the model does not incorporate these parameters.

3.4. System Services

The single service provided by the system is data communications, specifically, transmission of data over a wireless link. The service is a best effort service, at least for the system boundaries of interest. No guarantees are made with respect to time delays nor with respect to allocated bandwidth. As explained earlier in this chapter, the system could be configured in four different ways. These configurations will be transparent as far as the end user is concerned, except, perhaps, for performance.

3.5. Performance Metrics

The performance metrics that are studied are listed below.

Throughput: Throughput is defined as the rate (requests per unit time) at which the requests can be serviced by the system. For this study, we measure throughput in terms of received packets per second. This metric is calculated both for individual receivers and for the overall system.

End-to-End Delay (ETE delay): ETE delay is defined as the time difference between the instance a packet is ready to be sent and the instance the packet reaches its final destination. Mean ETE delay is calculated both for individual channels in the system and for the overall system.

Jitter: Jitter is defined as the variation in End-to-End Delay. This metric is important while evaluating the performance of the system for certain types of applications like video, and voice.

3.6. List of Parameters

For any performance evaluation study, it is important to identify all the parameters that affect the performance of the system. We divide the list of parameters into three broad sub-groups, each of which lists and describes related parameters. Included are sub-groups for parameters related to the overall simulation system, the wireless channel medium, and the traffic model. These are presented as below.

3.6.1. System Parameters

The parameter that affects performance on a system-wide basis is explained below.

Number of Remote Hosts: The number of remote hosts is a factor that can influence the system performance dramatically. In the case of a TDMA scheme, a larger number of remote hosts implies either shorter time-slices for each remote host, or more delay between successive time-slices for a particular host, or both. In the case of FDMA, a larger number of remote hosts directly reduces the amount of bandwidth for each remote host.

3.6.2. Channel Parameters

Modeling the channel involves several parameters. These are discussed below.

Maximum Data Rate of the Wireless Channel: This is the total capacity of the wireless channel measured in bits per second. In the case of TDMA, each transmitting station has access to this capacity during its time slice. In the case of FDMA, this capacity is divided among all the transmitting stations. In the case of TDD, both the upstream and the downstream traffic have access to this capacity, but only during the appropriate time slice. In the case of FDD, this capacity is divided between the upstream and downstream traffic.

Propagation Delay: According to the LMDS system configuration, the distance between the central hub and the remote hosts is in the range of two to five kilometers. This introduces some amount of propagation delay in the data transmission. For the purpose of this study, the propagation delay is very small compared to the transmission delay and switching overhead. Moreover, propagation delay does directly affect the performance of one configuration of the system as compared to another. Hence, propagation delay is assumed to be zero with respect to the transmission delay and switching overhead.

Multiple Access Scheme: Since the LMDS system is a point-to-multipoint network, we need a multiple access scheme for different remote hosts to communicate with the central hub over a single wireless channel. Two schemes are investigated as part of this study. They are the Time Division Multiple Access (TDMA) scheme and the Frequency Division Multiple Access (FDMA) scheme.

Duplexing Scheme: The LMDS system uses the same wireless channel to transmit data upstream as well as downstream. To make this possible, we need a duplexing scheme to multiplex both the upstream and downstream traffic on the same channel. In this study, two schemes are investigated for this purpose. They are the Time Division Duplexing (TDD) scheme and the Frequency Division Duplexing (FDD) scheme.

Length of Time Slice for the TDMA Scheme: The length of each time slice is an important factor that can affect the performance of a TDMA-based system. This parameter specifies the time interval for which each host in the systems gets to access the wireless channel at a time.

Length of Time Slice for the TDD scheme: This parameter is important in case of the FDMA/TDD configuration. It specifies the time interval for which either of the upstream and downstream traffic gets access to the wireless channel. For the TDMA/TDD configuration, this

parameter value is directly derived from the length of time slice for the TDMA scheme and the number of remote hosts.

Switching Overhead: We introduce a factor called *switching overhead* that specifies the sum of all overhead associated with the multiple access and duplexing scheme being used. One of the factors involved is the delay between the time the central hub (or remote host) is ready to receive data and the time the receiving antenna has homed onto the transmitting antenna. Other factors are specific to the particular multiple access scheme. For example, in the TDMA scheme, there is overhead decreasing the transmission capacity since control signals for synchronization and, perhaps, other purposes, need to be exchanged between the central hub and the remote hosts at regular intervals.

Order of Access: When using a TDMA/TDD configuration, the same channel is being used for upstream traffic for some of the time slices and for downstream traffic for the remaining time slices. Thus, the order in which the time slices for the upstream traffic and those for downstream traffic are inter-mixed might be important for some applications.

3.6.3. Traffic Model

The choice of a reasonable traffic model is important for any performance evaluation study. The LMDS system, as discussed in Chapter 2, offers integrated service for transmitting voice, data, and video over the same channel. Thus, considering the varying traffic flowing over the LMDS network, we consider two classes of traffic in this study. These are bursty traffic and non-bursty traffic. Bursty traffic involves data being transmitted in bursts with idle periods of arbitrary durations in between data transmissions. This is characteristic of web and other types of traditional data traffic. Non-bursty traffic involves data being sent at a fixed rate with no bursts. This traffic types is representative of video or voice traffic.

The idea here is to characterize traffic using these broad definitions rather than concentrating on, say, a particular kind of video traffic like an Moving Picture Experts Group (MPEG) stream. The assumption is that by considering both the bursty and non-bursty traffic when designing the simulation experiments, we will take into account the important features of most classes of traffic that would normally flow on a real LMDS network.

The following parameters define the traffic model.

Packet Inter-arrival PDF: World Wide Web (WWW) traffic is best modeled by a self-similar process [Crov96][PaFl95]. Therefore, in the simulation model, bursty traffic is modeled as a packet generator generating packets according to a self-similar process. Non-bursty traffic consists of data packets being sent at a constant rate. This is typically true of the scenario where video traffic is being considered. This is modeled quite simply as a constant rate packet generator. Henceforth, this parameter is referred to as traffic type.

Packet Size: We define packet size as the size of data frames sent on the data link layer in our system. Since we are studying two categories of traffic over the LMDS network, we differentiate between the packet sizes for the two traffic models. For non-bursty traffic, we use packets of fixed length to introduce predictability in the system performance. This simplifies the study of other parameters. For bursty traffic, we use packets with sizes varying according to a normal distribution.

3.7. Summary

This chapter presented the objectives of this research and the methods used to attain those objectives.

Table 3.1. Parameters and Factors of the Simulation System

Parameters	Factors
Switching overhead	Multiple access scheme
Maximum channel data rate	Duplexing scheme
Propagation delay	Traffic type
Length of time slice	Number of remote hosts
Order of access	
Packet size	

In Section 3.1, we described the problem. Section 3.2 explained the reasons behind choosing the simulation technique to solve the problem. In Section 3.3 and Section 3.4, we focused on the system under study and discussed that the system would offer best effort service. In Section 3.5, we identified ETE delay, Jitter and Throughput as metrics used for performance evaluation of the system. And finally, in Section 3.6, we discussed the parameters associated with the system. In

conclusion, we present Table 3.1. This table lists the parameters of the system and those parameters that also act as factors. Factors are those parameters of the system that are varied in the simulation experiments, as described in Chapter 5.

Chapter 4. Simulation Model

This chapter describes the simulation model. First, the OPNET Modeler tool is briefly explained. This tool was used to construct the model and run the experiments. Four different models were built for the four different configurations: TDMA/TDD, TDMA/FDD, FDMA/TDD, and FDMA/FDD. The configurations were explained in detail in Chapter 3.

4.1. OPNET Modeler

The OPNET Modeler tool [Mil3] was chosen to build the simulation model. OPNET Modeler is an excellent tool to model the physical layer and data link layer functionality of any network. While other modeling tools exist, few, if any, can match the flexibility that OPNET Modeler provides for modeling the lower two layers in the network hierarchy. OPNET Modeler includes good and easy-to-use, built-in models and library functions, many of which have been utilized in building the simulation models for this study. New models can be built more easily, quickly and accurately using the built-in components than developing entirely new models using custom code. In addition, OPNET Modeler includes good tools for presentation and analysis of the results. Moreover, OPNET Modeler is currently a popular network simulation tool used in both academia and industry. The simulation model developed during this study is expected to be of value to later studies of LMDS at Virginia Tech.

Design of any model in the OPNET Modeler consists of three levels of design. These are called *network* level design, *node* level design and *process* level design. The network level and node level designs are developed using visual editors. The process level design is in the form of a finite state machine and is developed using the process model visual editor. Program code is integrated into the finite state machine to define the *action* of the process model in response to the occurrence of user-defined *events*.

4.2. TDMA/TDD Model

This section explains the simulation model for the TDMA/TDD configuration of the LMDS system. As we have seen, the TDMA/TDD configuration uses TDMA as the multiple access scheme for point-to-multipoint communication and TDD as the duplexing scheme. The four models share some design features among them, which will be highlighted.

As explained in Section 4.1, each model in OPNET consists of a network level design view. Each node in the network model is designed using a node editor and each process model in the node design is designed using the process editor. Each level of the design is explained below.

4.2.1. Network Level Design

Figure 4.1 shows the network design for the TDMA/TDD model in OPNET. The LMDS system consists of two types of nodes, *Central_Hub* and *Remote_Host*. Each of these nodes is connected to one *End_Host* node using a point-to-point link. The *End_Host* connected to a *Remote_Host* models the client network at the remote site. The *End_Host* connected to the *Central_Hub* models the Internet connection provided by the Internet Service Provider. The *Central_Hub* is separated from the *Remote_Host* nodes by a distance of 2 to 3 km. The screen shot in Figure 4.1 shows a configuration with five *Remote_Host* nodes. The model can be configured to include up to a maximum of fourteen *Remote_Host* nodes. Although the model has been developed to be as parameterized as possible, certain parts of the model cannot be parameterized. This necessitates the maximum number of *Remote_Host* nodes to be fixed prior to the simulation run. Fourteen is a good figure for the current set of experiments since it covers all the experimental scenarios, as discussed in Section 5.2.

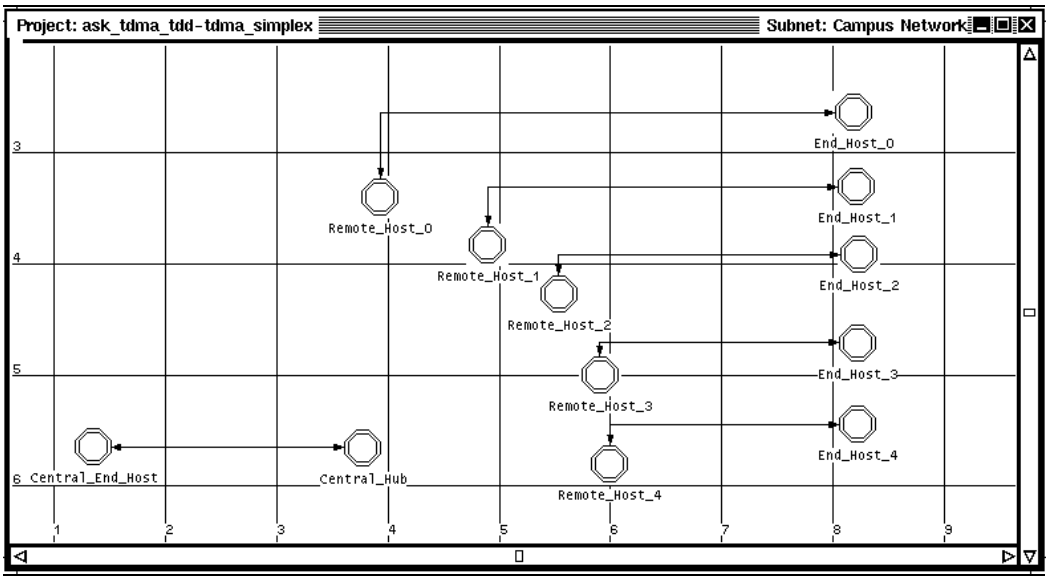

Figure 4.1. Network level design of the TDMA/TDD model.

We briefly discuss the function of each of the nodes in the above design. The *End_Host* nodes can either generate packets according to a self-similar process to model bursty traffic [Brag99]

[Schu96], or use the built-in packet generator model in OPNET to model non-bursty or constant rate traffic. They also act as a sink for incoming packets. Before the packets are destroyed, statistics on the packet, like end-to-end delay, are collected. The *Central_Hub* contains logic for the transmitter portion of the point-to-multipoint transmission. It also includes logic for the receiver portion of the point-to-point upstream traffic. The *Remote_Host* node contains logic for the receiver portion of the point-to-multipoint link and the transmitter portion of the upstream traffic. In addition, the *Central_Hub* and the *Remote_Host* nodes implement logic for the multiple access scheme and the duplex scheme being used. All communication between the *Central_Hub* node and the *Remote_Host* nodes is carried over the wireless medium. The wireless channel is not explicitly visible in the design, but is implicitly modeled by the parameters of the radio transmitters and receivers.

It should be noted that the network level design for all the models is essentially the same, although different parameters might assume different values.

4.2.2. Node Level Design

Described below is the node level design of three nodes, *Central_Hub*, *Remote_Host* and *End_Host*. The *Central_Hub* and the *Remote_Host* nodes implement the multiple access and duplexing logic at the base station site and the remote site, respectively. The design of these two nodes varies between the different configurations of the LMDS model. The *End_Host* node has essentially the same design for all four models.

4.2.2.1. Central_Hub

The node level design of the *Central_Hub* node in the TDMA/TDD model is shown in Figure 4.2. There are two basic functions of this node, transmitting data from the *Central_End_Host* node to the *Remote_Host* nodes and transmitting data from the *Remote_Host* nodes to the *Central_End_Host* node.

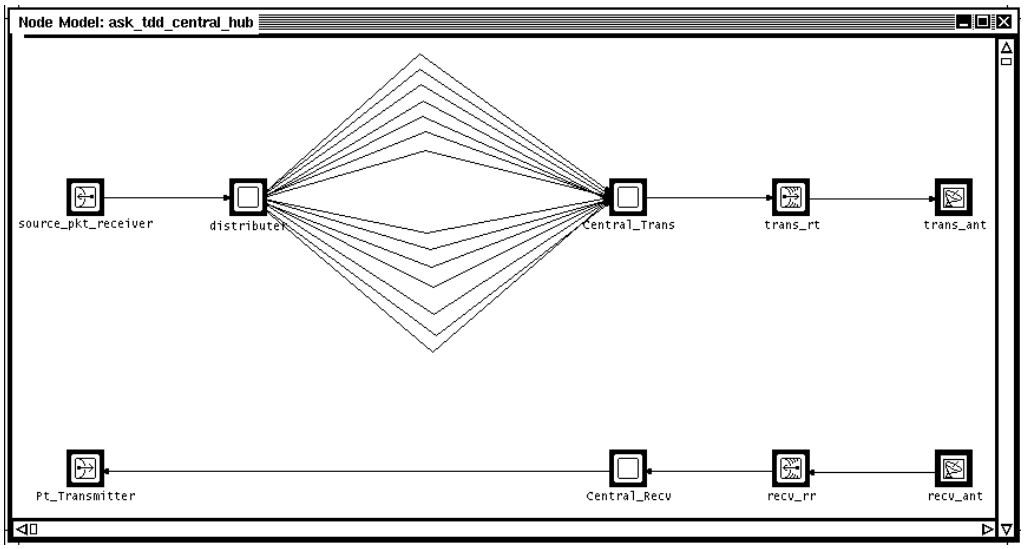

Figure 4.2. Node level design of the Central_Hub node in the TDMA/TDD model.

The *Central_Hub* node has a point-to-point receiver, called *source_pkt_receiver*, and a point-to-point transmitter, called *Pt_Transmitter*, both connected to the *Central_End_Host* node. The packets received by the *source_pkt_receiver* are sent to a process model called *distributer*. The *distributer* model distributes the incoming packets onto one of the output streams using a uniform distribution. The *distributer* model is in essence assigning a destination address to each of the packets. There are fourteen output streams connected to the *distributer* model corresponding to a maximum of fourteen *Remote_Host* nodes. The *Central_Trans* process model implements the TDMA and TDD transmitter logic. One slot is statically assigned for each *Remote_Host* node. The *Central_Trans* model segments the packets into slot-sized segments. The *Central_Trans* model sends the packets to transmitting antenna, *trans_ant*, through a radio transmitter model, *trans_rt*.

The receiving antenna, *recv_ant*, is connected to a radio receiver model, *recv_rr*. The packets received over the wireless channel are forwarded to the *Central_Recv* process model. The *Central_Recv* process model reassembles the original packets and forwards them to the point-to-point transmitter to be sent to the *Central_End_Host* node. It should be noted that the point-to-point transmitter and receiver, the radio transmitter and receiver, and the transmitting and receiving antennas are part of the standard OPNET library.

4.2.2.2. Remote_Host

The node level design of the *Remote_Host* node in the TDMA/TDD model is shown in Figure 4.3. The *rx_point* process model uses the coordinates of the transmitting antenna and orients the receiving antenna in the correct direction and altitude. The receiver antenna, *recv_ant*, and radio receiver model, *remote_rr*, forward the incoming packets to the *Remote_Recv* process model. This process model destroys all packets received during a time slot different from the *Remote_Host* node's receiver time slot. The packets that are received in the *Remote_Host* node's receiver time slot are reassembled into the original packets, which are forwarded to the *End_Host* node through the point-to-point transmitter model, *trans_pt*.

The packets received by the point-to-point receiver model, *recv_pt*, are forwarded to the *Remote_Trans* process model. This model segments the packets into segments, which would fit one time slot. At the proper time slot, the segments are sent over the wireless channel through the radio transmitter model, *remote_rt*, and the transmitting antenna, *trans_ant*.

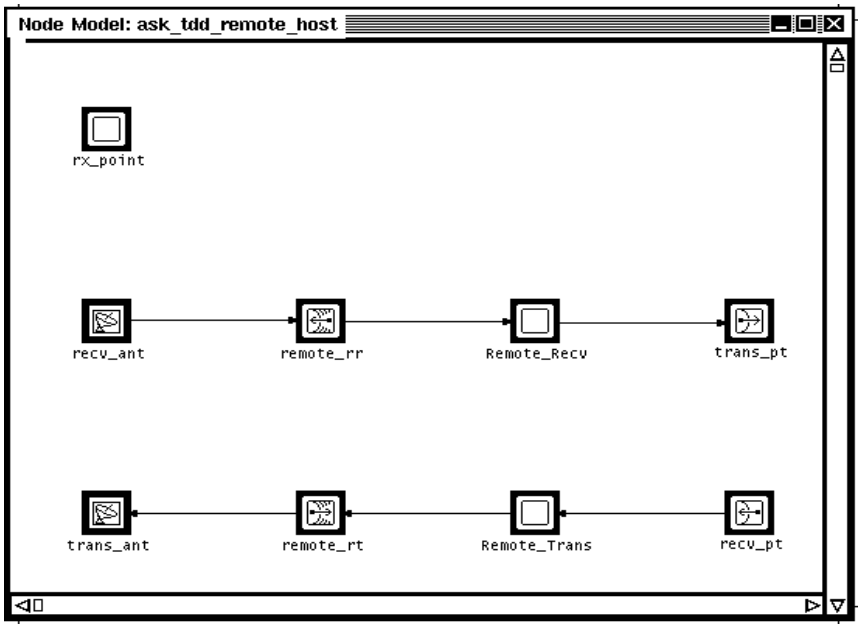

Figure 4.3. Node level design of Remote_Host node in the TDMA/TDD model.

4.2.2.3. End_Host

The node level design of the *End_Host* node in the TDMA/TDD model is shown in Figure 4.4. The function of the *End_Host* node is to generate packets and to collect statistics on incoming packets before destroying them.

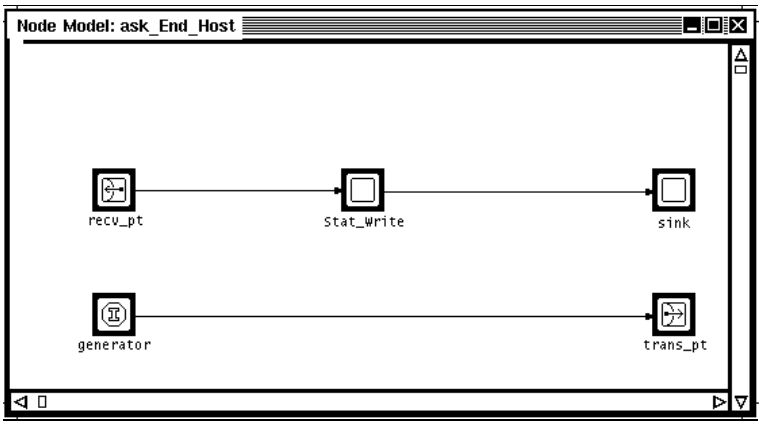

Figure 4.4. Node level design of End_Host node in the TDMA/TDD model.

The *generator* process model generates variable-length packets with either self-similar inter-arrival time-interval or constant time-intervals according to the process model used for the particular configuration of the system. The mean inter-arrival rate and the mean packet size are parameterized. The generated packets are sent to the *Remote_Host* nodes through the point-to-point transmitter model, *trans_pt*. The packets received by the point-to-point receiver model, *recv_pt*, are forwarded to the *stat_write* process model. The *stat_write* process model calculates the End-to-End Delay statistic for the incoming packet and then forwards the packet to the *sink* model where it is destroyed. The *sink* model is part of the standard OPNET library. It should be noted that the *Central_End_Host* node connected to the *Central_Hub* node has exactly the same design as the *End_Host* node.

4.2.3. Process Level Design

This section explains the process level design of four process models. These are the *Central_Trans*, *Central_Recv*, *Remote_Trans*, and *Remote_Recv*. Section 4.2.2 had referred to these models in the node level design of the *Central_Hub* and the *Remote_Host* nodes.

4.2.3.1. Central_Trans

The process level design of the *Central_Trans* process model in the TDMA/TDD model is shown in Figure 4.5. In OPNET, a process model is designed as a finite state machine.

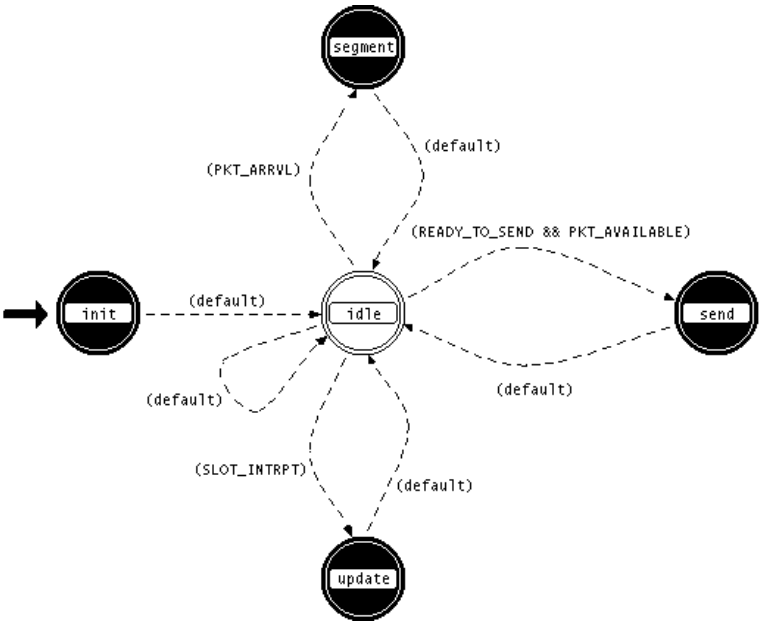

Figure 4.5. Process level design of the Central_Trans process model in the TDMA/TDD model.

In the process model shown in Figure 4.5, the model remains in the *idle* state by default. All the initializations for the process model are done in the *init* state, which is also the start state of the model. Whenever a packet arrives, the model jumps to the *segment* state and then returns to the *idle* state. In the *segment* state, the incoming packet is inserted into the appropriate segmentation buffer. There is a segmentation buffer for each of the incoming streams to the *Central_Trans* process model. Recall that each of these streams corresponds to the packets destined for a particular *Remote_Host* node. Before the process model gets to the *idle* state, it schedules an interrupt for itself, called *Slot_Interrupt*, to go off at the next transmission time slot. When the process model gets a *Slot_Interrupt*, it jumps to the *update* state and returns to the *idle* state. In the *update* state, the process model updates its current slot information and schedules another *Slot_Interrupt* for itself. Note that after the *Central_Hub* node gets a chance to send data to each of the *Remote_Host* nodes, it has to wait a time slot each for every *Remote_Host* node to get a chance to send data to the *Central_Hub* node. The *Slot_Interrupt* is scheduled accordingly.

When the model returns from the *update* state, it checks to see if there are any outstanding data segments on the incoming stream that corresponds to the current slot. If there is data available to be sent, the process jumps to the *send* state, where the data is sent, and returns to the *idle* state.

4.2.3.2. Remote_Trans

The process level design of the *Remote_Trans* process model in the TDMA/TDD model is as shown in Figure 4.6. The *Remote_Trans* process model is responsible for implementing the transmitter logic of the *Remote_Host* node according to the TDMA and TDD schemes.

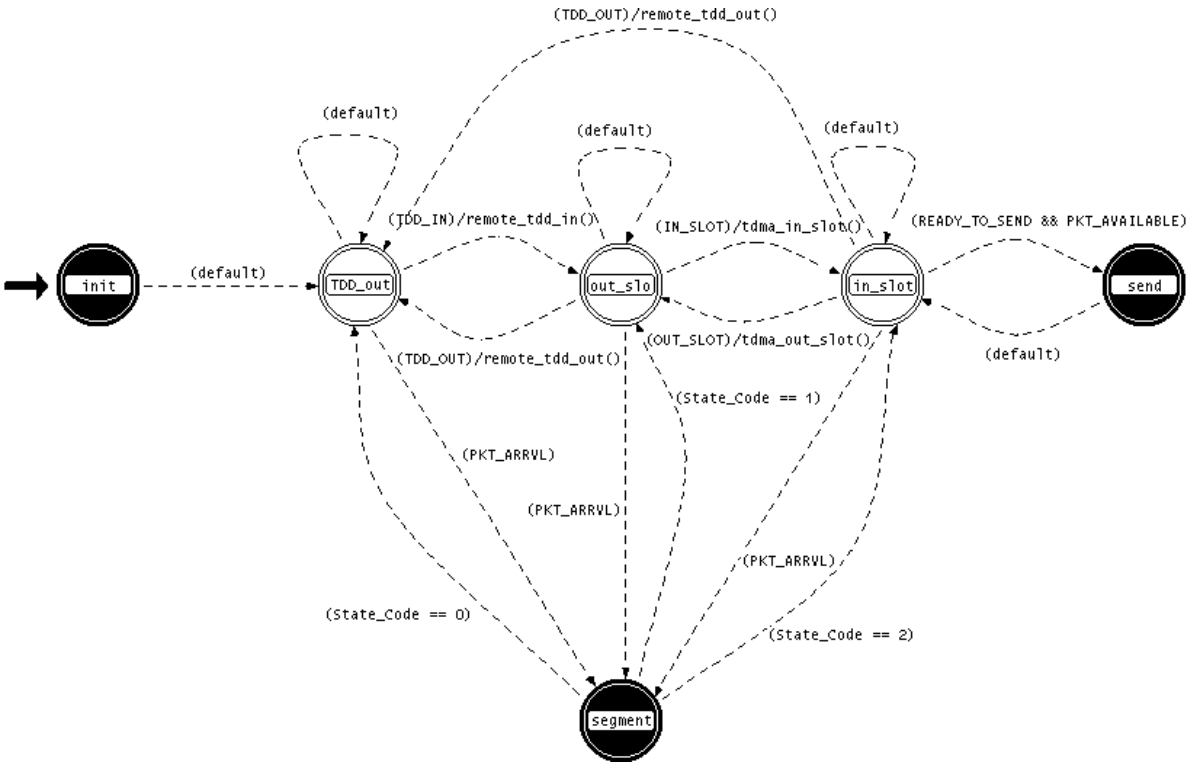

Figure 4.6. Process level design of Remote_Trans process model in the TDMA/TDD model.

All the initializations for the process model are done in the *init* state, which is also the start state of the model. The process stays in the *TDD_OUT* state by default. When time slots for upstream traffic start, the process model jumps to the *out_slot* state. When the time slot for the particular *Remote_Host* node for upstream traffic starts, the process model jumps to the *in_slot* state. When it enters the *in_slot* state, the model determines if there are any outstanding data segments waiting to be sent. If so, the model jumps to the *send* state, sends the data, and then returns to the *in_slot* state. The process model jumps back to the *out_slot* and the *TDD_OUT* state after the corresponding time slot durations expire. If a packet arrives, at any given time, the model jumps to the *segment* state, where the packet is inserted into the segmentation buffer, and then returns back to its original state.

4.2.3.3. Remote_Recv

The process level design of the *Remote_Recv* process model in the TDMA/TDD model is as shown in Figure 4.7. The *Remote_Recv* process model is responsible for implementing the receiver logic for the *Remote_Host* node according to the TDMA and TDD schemes.

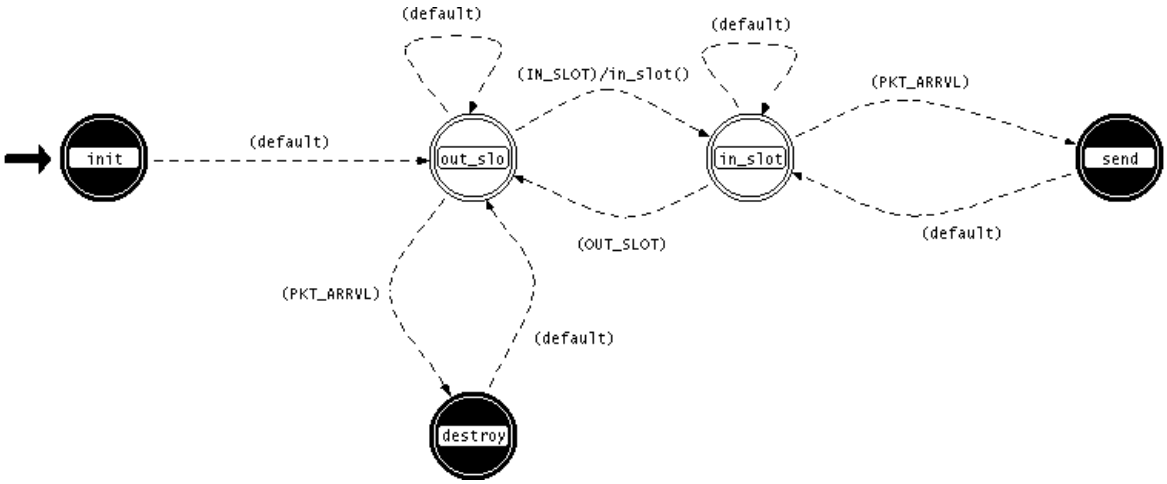

Figure 4.7. Process level design of Remote_Recv process model in the TDMA/TDD model.

All the initializations for the process model are done in the *init* state, which is also the start state of the model. The process model stays in the *out_slot* state by default. When the particular *Remote_Host* is scheduled to receive packets, the model jumps to the *in_slot* state. If packets arrive during the *out_slot* state, the model jumps to the *destroy* state where the packets are destroyed. If packets arrive during the *in_slot* state, the model jumps to the *send* state, where the packets are re-assembled into the original packets and then forwarded to the output stream.

4.2.3.4. Central_Recv

The process level design for the *Central_Recv* process model in the TDMA/TDD model is shown in Figure 4.8. The *Central_Recv* model is responsible for implementing the receiver logic of the *Central_Hub* node according to the TDMA and TDD schemes.

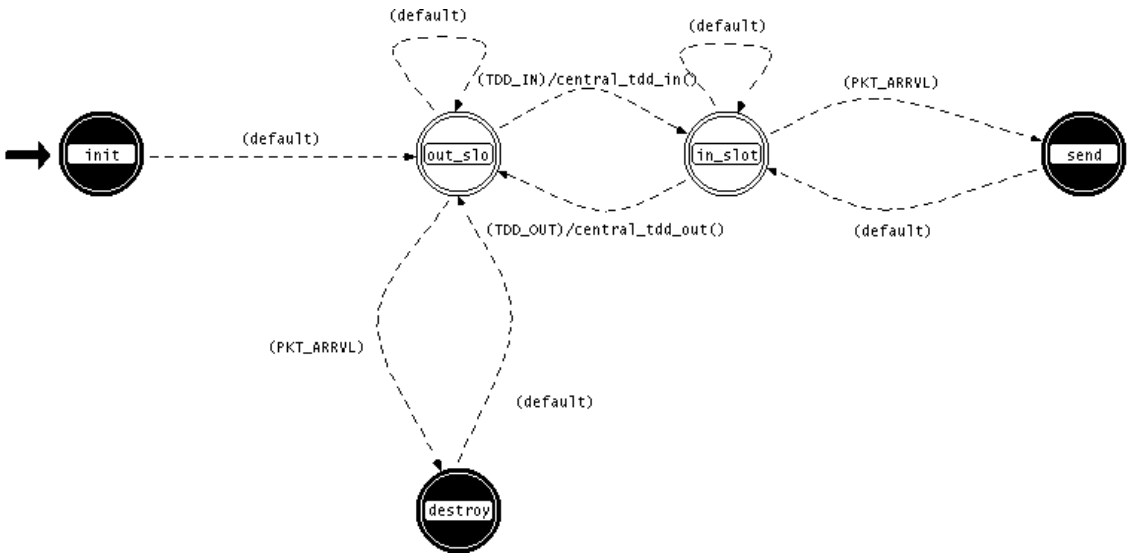

Figure 4.8. Process level design of Central_Recv process model in the TDMA/TDD model.

It is similar to the design of the *Remote_Recv* process model discussed earlier in Section 4.2.3.3. All the initializations for the process model are done in the *init* state, which is also the start state of the model. The model jumps to the *in_slot* state from the *out_slot* state when the time slots for the upstream traffic start and jumps back to the *out_slot* state when the time slots for the downstream traffic start. If packets arrive when the model is in the *out_slot* state, then the packets are destroyed. Otherwise, the packets are reassembled into original packets before being sent on the output stream.

4.3. TDMA/FDD Model

This section explains the simulation model for the TDMA/FDD configuration of the LMDS system. The TDMA/FDD configuration uses TDMA as the multiple access scheme for point-to-multipoint communication and FDD as the duplexing scheme. The three levels of the design are explained below.

4.3.1. Network Level Design

The network level design of the TDMA/FDD model is same as that for the TDMA/TDD model, which was explained in Section 4.2.1. Parameter values in the network design may be different.

4.3.2. Node Level Design

There are three nodes present in the network design for the TDMA/FDD model. These are the *Central_Hub*, *Remote_Host*, and *End_Host* nodes. The design of these three nodes is the same as the design of the *Central_Hub*, *Remote_Host*, and *End_Host* nodes for the TDMA/TDD system as explained above in Section 4.2.1. However, the process models used in the node models are different from those for the TDMA/TDD system, explained in the Section 4.2.3.

4.3.3. Process Level Design

This section describes the process level design of the four process models in the TDMA/FDD model, *Central_Trans*, *Central_Recv*, *Remote_Trans*, and *Remote_Recv*.

4.3.3.1. Central_Trans

The process level design of the *Central_Trans* process model in the TDMA/FDD model is shown in Figure 4.9.

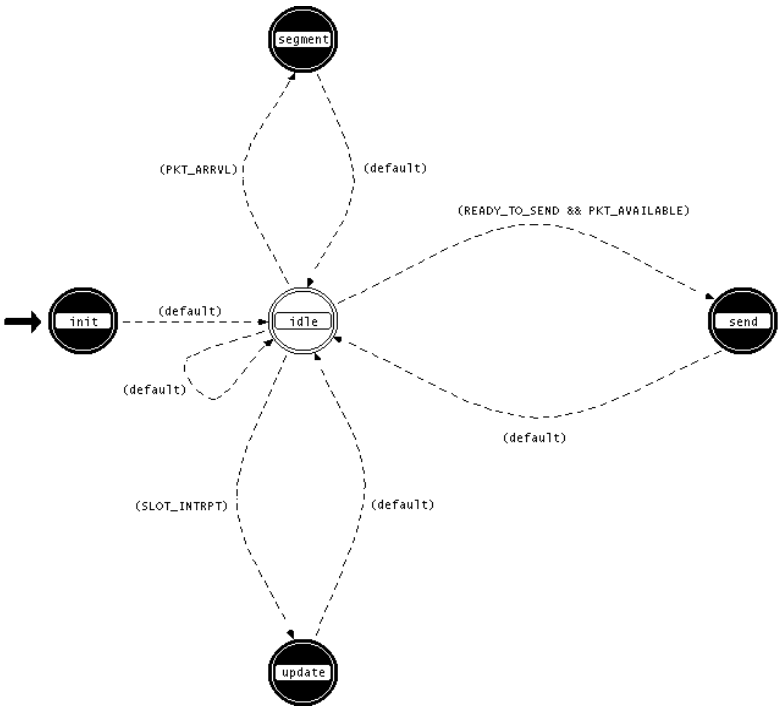

Figure 4.9. Process level design of the Central_Trans process model in the TDMA/FDD model.

The design and operation of the model is similar to the *Central_Trans* process model of the TDMA/TDD model, which is explained in Section 4.2.3.1. The only difference between the two models is that, here, the *Central_Trans* process model always schedules the *Self_Interrupt* for a

duration of one time slot. This is because in the TDMA/FDD model the downstream traffic is carried on a different channel than the upstream traffic, so, the *Central_Hub* node can transmit data continuously. Recall that in the TDMA/TDD model, the *Central_Hub* transmits data and then has to wait to receive data from each of the *Remote_Host* nodes before getting a chance to transmit again.

4.3.3.2. Remote_Trans

The process level design of the *Remote_Trans* process model is shown in Figure 4.10. The *Remote_Trans* process model is responsible for implementing the transmitter logic of the *Remote_Host* node according to the TDMA and FDD schemes.

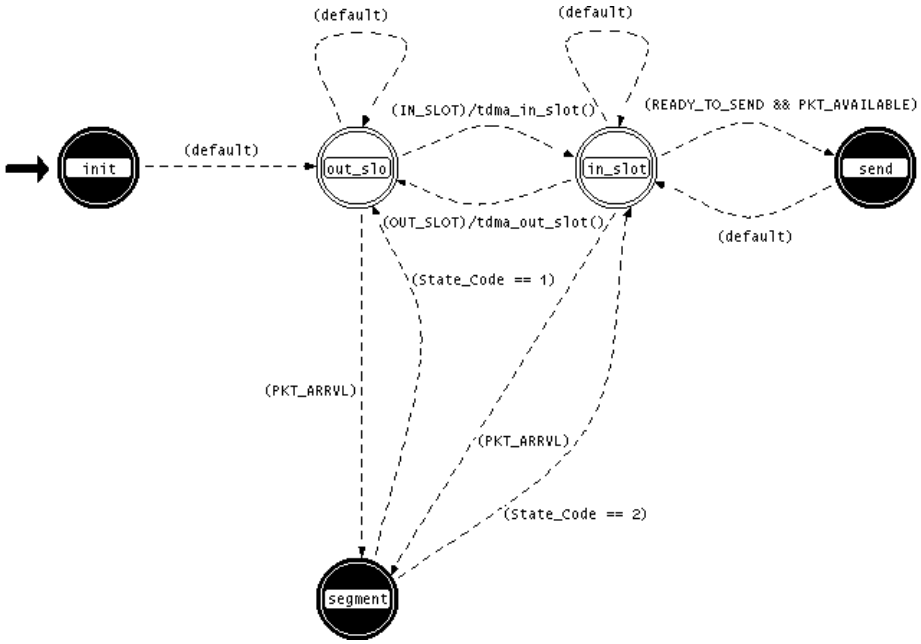

Figure 4.10. Process level design of Remote_Trans process model in the TDMA/FDD model.

All the initializations for the process model are done in the *init* state, which is also the start state of the model. The process stays in the *out_slot* state by default. When the time slot for the particular *Remote_Host* node for upstream traffic starts, the process model jumps to the *in_slot* state. When it enters the *in_slot* state, the model determines if there are any outstanding data segments waiting to be sent. If so, the model jumps to the *send* state, sends the data, and then returns to the *in_slot* state. The process model jumps back to the *out_slot* after the time slot duration expires. At any given time, if a packet arrives, the model jumps to the *segment* state, where the packet is inserted into the segmentation buffer, and returns back to its original state.

4.3.3.3. Remote_Recv

The process level design of the *Remote_Recv* process model in the TDMA/FDD model is shown in Figure 4.11. The *Remote_Recv* process model is responsible for implementing the receiver logic for the *Remote_Host* node according to the TDMA and FDD schemes.

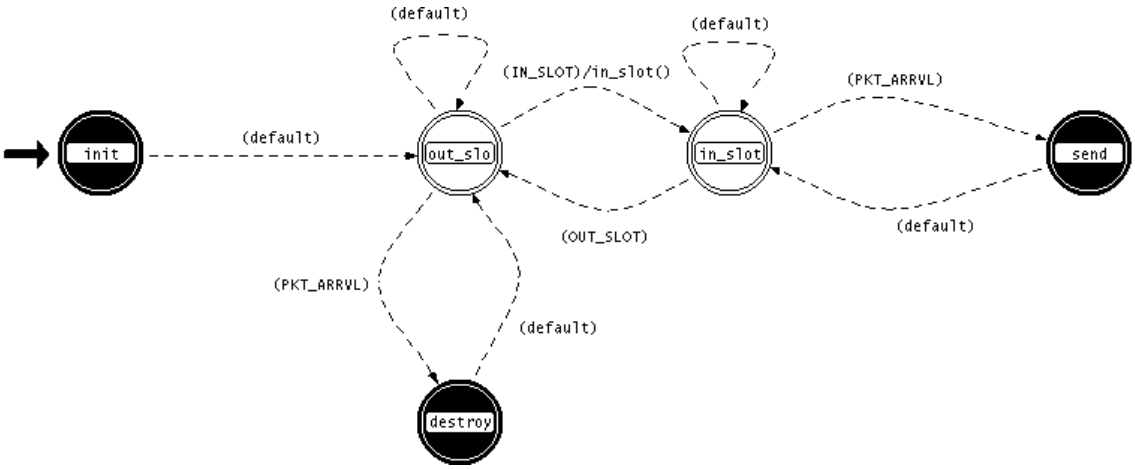

Figure 4.11. Process level design of Remote_Recv process model in the TDMA/FDD model.

All the initializations for the process model are done in the *init* state, which is also the start state of the model. The process model stays in the *out_slot* state by default. When the particular *Remote_Host* is scheduled to receive packets, the model jumps to the *in_slot* state. If packets arrive during the *out_slot* state, the model jumps to the *destroy* state where the packets are destroyed. If packets arrive during the *in_slot* state, the model jumps to the *send* state, where the packets are re-assembled into the original packets and then forwarded to the output stream.

4.3.3.4. Central_Recv

The process level design for the *Central_Recv* process model is shown in Figure 4.12. The *Central_Recv* model is responsible for implementing the receiver logic of the Central_Host node according to the TDMA and FDD schemes. The design is simple. All the initializations for the process model are done in the *init* state, which is also the start state of the model. Packets are forwarded to the *Central_End_Host* through the point-to-point link.

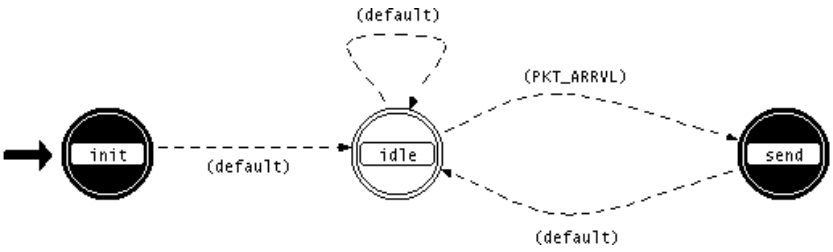

Figure 4.12. Process level design of Central_Recv process model in the TDMA/FDD model.

The process remains in the *idle* state by default. On packet arrival, it jumps to the *send* state and then returns to the *idle* state. In the *send* state, the arriving packet segment is inserted into the reassembly buffer and reassembled packets, if any, are forwarded to the *Central_End_Host*.

4.4. FDMA/TDD Model

This section explains the simulation model for the FDMA/TDD configuration of the LMDS system. As we have seen, the FDMA/TDD configuration uses FDMA as the multiple access scheme for point-to-multipoint communication and TDD as the duplex scheme. The three levels of the design are explained below.

4.4.1. Network Level Design

The network level design of the FDMA/TDD model is same as that for the TDMA/TDD model, which was explained in Section 4.2.1. Parameter values in the network design may be different.

4.4.2. Node Level Design

There are three nodes present in the network design for the FDMA/TDD model, *Central_Hub*, *Remote_Host,* and *End_Host*. The design of the *End_Host* node is the same as the design of the *End_Host* node in the TDMA/TDD model, which was explained earlier, in Section 4.2.1.3. The design of the *Central_Hub* node and the *Remote_Host* node for the FDMA/TDD model is explained below.

4.4.2.1. Central_Hub

The node level design of the *Central_Hub* node in the FDMA/TDD model is shown in Figure 4.13. There are two basic functions of this node, transmitting data from the *Central_End_Host* node to the *Remote_Host* nodes and transmitting data from the *Remote_Host* nodes to the *Central_End_Host* node.

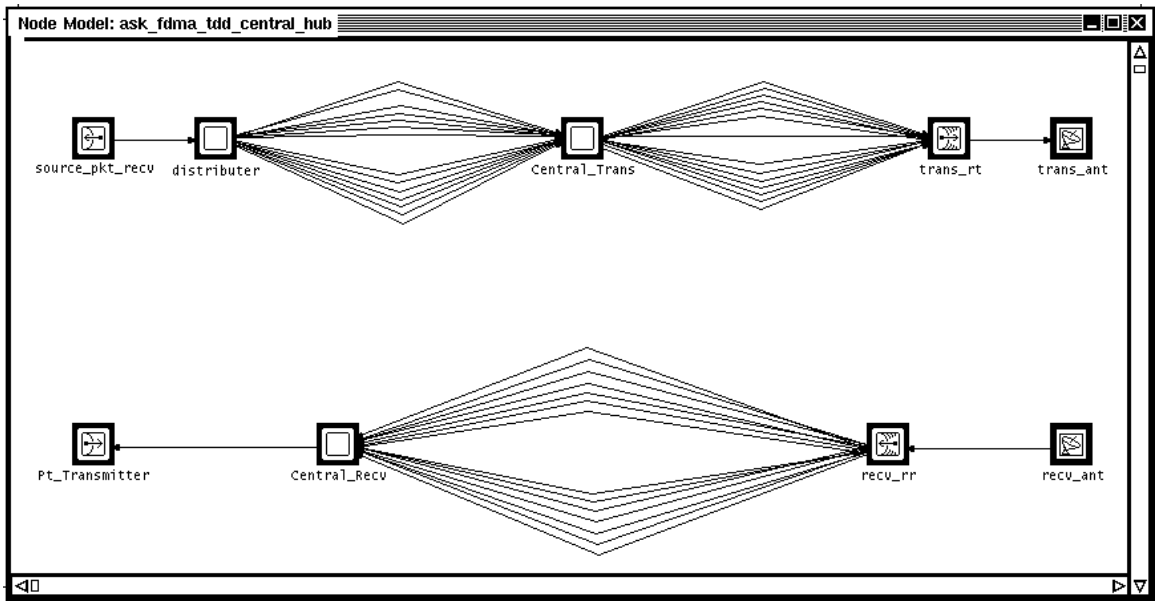

Figure 4.13. Node level design of Central_Hub node in the FDMA/TDD model.

The functions of the *source_pkt_receiver*, *Pt_Transmitter* and *distributer* models are the same as that of the corresponding nodes in the *Central_Hub* node in the TDMA/TDD model, which is explained in Section 4.2.1.1.

The *Central_Trans* process model implements the FDMA and TDD transmitter logic. The radio transmitter model, *trans_rt*, has a separate frequency channel for each of the *Remote_Host* nodes. The *Central_Trans* process model keeps track of two time slots corresponding to the upstream traffic and downstream traffic according to the TDD scheme. In the correct slot, the transmitter model forwards any outstanding packets on its input channels to the correct output stream channel. There is a one-to-one correspondence between the input streams to the *trans_rt* model and the frequency channels provided by the *trans_rt* model. The *trans_rt* model thus forwards the packets arriving on its input streams to the corresponding frequency channel in the wireless spectrum through the transmitting antenna model, *trans_ant*.

The receiving antenna, *recv_ant*, is connected to a radio receiver model, *recv_rr*. The *recv_rr* model has a separate incoming channel for each of the *Remote_Host* nodes. The *recv_rr* model forwards the packets received over the wireless channels to the *Central_Recv* process model along the corresponding stream. The *Central_Recv* process model reassembles packets from the segments arriving on the different input streams and forwards them to the point-to-point transmitter, *Pt_Transmitter*, to be sent to the *Central_End_Host* node.

It should be noted that the point-to-point transmitter and receiver, the radio transmitter and receiver, and the transmitting and receiving antennas are part of the standard OPNET library.

4.4.2.2. Remote_Host

The node level design of the *Remote_Host* node in the FDMA/TDD model is shown in Figure 4.14. The process model *rx_point*, uses the coordinates of the transmitting antenna and orients the receiving antenna in the correct direction and altitude. The radio transmitter and the radio receiver models are *remote_rt* and *remote_rr*, respectively. Each of these models has one frequency channel for each of the *Remote_Host* nodes. The *remote_rr* model forwards the packets arriving on the different wireless channels to the *Remote_Recv* process model along the corresponding stream. The *remote_rt* model transmits the packet arriving on its input streams on the corresponding frequency channel through the antenna model, *trans_ant*. The *Remote_Recv* model keeps track of the upstream and downstream time slots according to the TDD scheme. Packet segments received in the correct slot are reassembled into original packets and forwarded to the *End_Host* nodes through the point-to-point transmitter model, *trans_pt*. Packet segments arriving in the incorrect slot are destroyed. The *Remote_Trans* process model also keeps track of the upstream and downstream time slots. It segments the incoming packets. In the correct time slot, it forwards the packet segments to the correct output stream depending on the *Remote_Host* node to which it belongs.

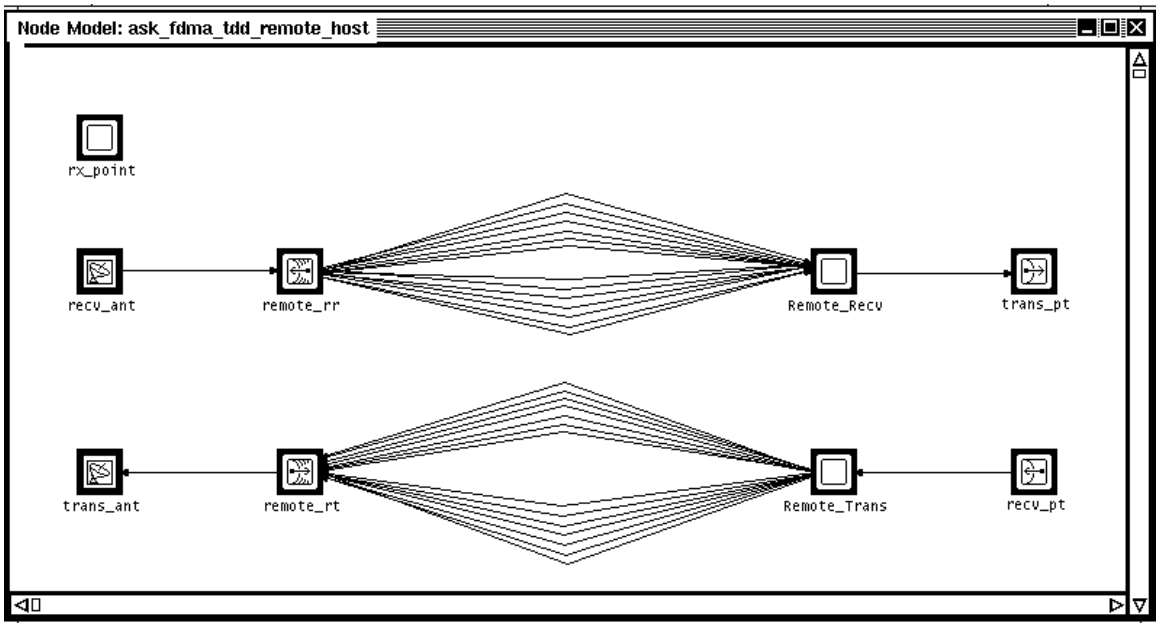

Figure 4.14. Node level design of Remote_Host node in the FDMA/TDD model.

4.4.3. Process Level Design

This section describes process level design of the process models in the FDMA/TDD model. Four process models are explained, *Central_Trans*, *Central_Recv*, *Remote_Trans*, and *Remote_Recv*.

4.4.3.1. Central_Trans

The process level design of the *Central_Trans* process model in the FDMA/TDD model is shown in Figure 4.15.

All the initializations for the process model are done in the *init* state, which is also the start state of the model. The process stays in the *out_slot* state by default. The process model maintains one segmentation buffer for each *Remote_Host* node. At any given time, if a packet arrives, the model jumps to the *segment* state, where the packet is inserted into the corresponding segmentation buffer, and returns back to its original state. When the time slot for downstream traffic starts, the process model jumps to the *in_slot* state. When it enters the *in_slot* state, the model determines if there are any outstanding data segments waiting to be sent. If so, the model jumps to the *send* state, sends the data, and then returns to the *in_slot* state. The process model jumps back to the *out_slot* after the time slot duration expires.

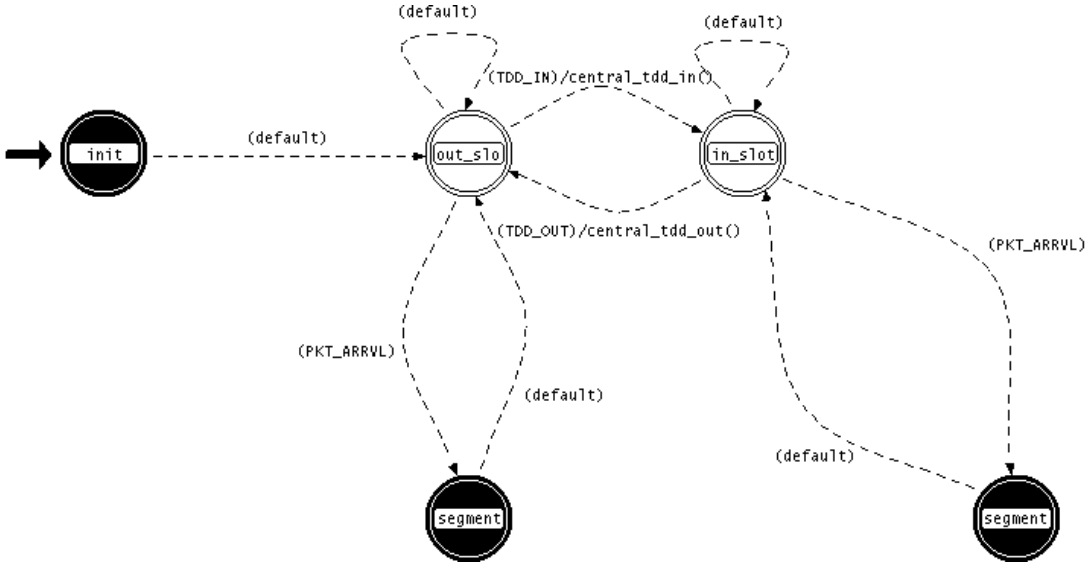

Figure 4.15. Process level design of the Central_Trans process model in the FDMA/TDD model.

4.4.3.2. Remote_Trans

The process level design of the *Remote_Trans* process model in the FDMA/TDD model is as shown in Figure 4.16. The function of the *Remote_Trans* process model is to keep track of the upstream and downstream time slots and transmit data from the *Remote_Host* node to the *Central_Hub* node. The design is exactly same as the design for the *Central_Trans* process model discussed earlier in this section.

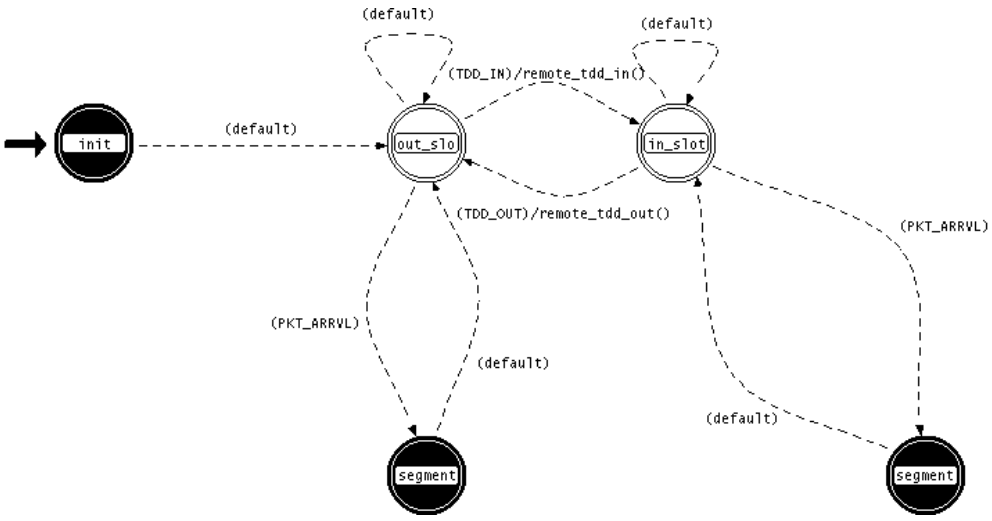

Figure 4.16. Process level design of Remote_Trans process model in the FDMA/TDD model.

4.4.3.3. Remote_Recv

The process level design of the *Remote_Recv* process model in the FDMA/TDD model is shown in Figure 4.17. The *Remote_Recv* process model is responsible for implementing the receiver logic for the *Remote_Host* node according to the FDMA and TDD schemes.

All the initializations for the process model are done in the *init* state, which is also the start state of the model. The process stays in the *idle* state by default. As we have seen in the node level design of the *Remote_Host* node in Section 4.4.2.2, the *Remote_Recv* process model has multiple incoming data streams. Each of these streams corresponds to one of the *Remote_Host* nodes. If a packet segment arrives on the correct stream, the process jumps to the *send* state and then returns back to the *idle* state. In the send state, the packet segment is inserted into the reassembly buffer and the reassembled packets, if any, are forwarded to the corresponding *End_Host* node. If the packet segment arrives on an incorrect stream, then the process jumps to the *discard* state where the segment is destroyed and the process returns to the *idle* state.

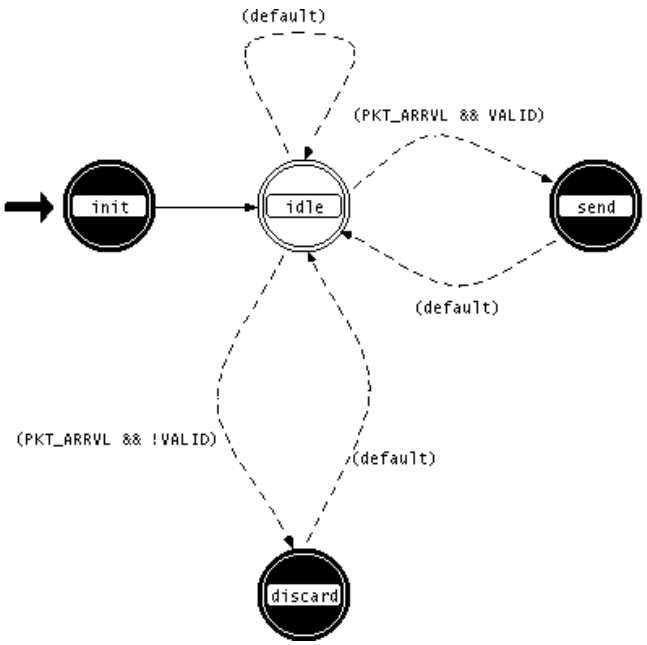

Figure 4.17. Process level design of Remote_Recv process model in the TDMA/FDD model.

4.4.3.4. Central_Recv

The process level design for the *Central_Recv* process model is shown in Figure 4.12.

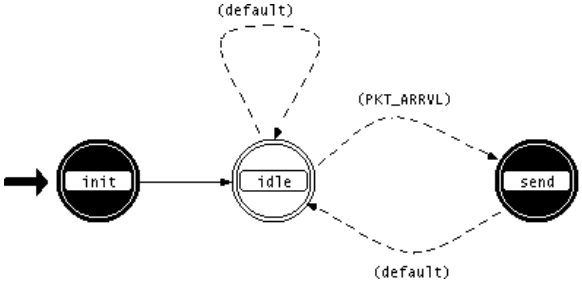

Figure 4.18. Process level design of Central_Recv process model in the FDMA/TDD model.

The design is simple. All the initializations for the process model are done in the *init* state, which is also the start state of the model. Packets are forwarded to the *Central_End_Host* through the point-to-point link. The process remains in the *idle* state by default. On packet arrival, it jumps to the *send* state and then returns to the *idle* state. In the *send* state, the arriving packet segment is inserted into the reassembly buffer and reassembled packets, if any, are forwarded to the *Central_End_Host*.

4.5. FDMA/FDD Model

This section explains the simulation model for the FDMA/FDD configuration of the LMDS system. As we have seen, the FDMA/FTDD configuration uses FDMA as the multiple access scheme for point-to-multipoint communication and FDD as the duplexing scheme. The three levels of the design are explained below.

4.5.1. Network Level Design

The network level design of the FDMA/FDD model is same as that for the TDMA/TDD model, as explained in Section 4.2.1. Parameter values in the network design may be different.

4.5.2. Node Level Design

There are three nodes present in the network design for the FDMA/TDD model, *Central_Hub*, *Remote_Host,* and *End_Host*. The design of the *End_Host* node is the same as the design of the *End_Host* node in the TDMA/TDD model, which was explained in Section 4.2.1.3. The design of the *Central_Hub* node and the *Remote_Host* node for the FDMA/TDD model is explained below.

4.5.2.1. Central_Hub

The node level design of the *Central_Hub* node in the FDMA/FDD model is shown in Figure 4.19. There are two basic functions for this node, transmitting data from the *Central_End_Host* node to the *Remote_Host* nodes and transmitting data from the *Remote_Host* nodes to the *Central_End_Host* node.

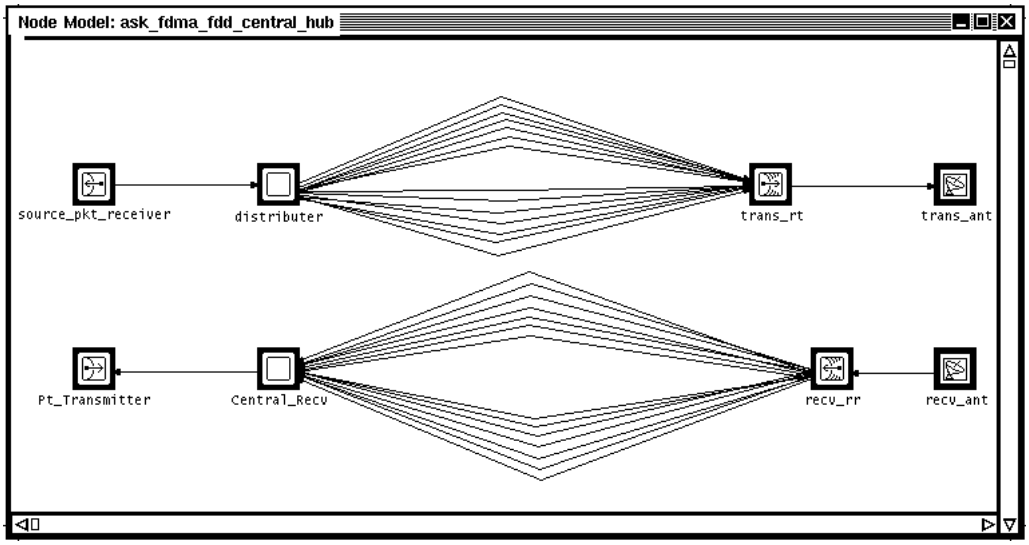

Figure 4.19. Node level design of Central_Hub node in the FDMA/FDD model.

The design of the *Central_Hub* node shown in Figure 4.19 is almost exactly the same as the design of the *Central_Hub* node in the FDMA/TDD model, which was explained in Section 4.4.2.1. The only difference is that the *Central_Trans* process model is not required. The output streams from the *distributer* process model act as input streams for the radio transmitter model, *trans_rt*. In the FDMA/FDD model, there are no time slots as required in the previous model and so, the necessity of a process model to manage the transmission logic is not required.

4.5.2.2. Remote_Host

The node level design of the *Remote_Host* node in the FDMA/FDD model is same as the design of the *Remote_Host* node in the FDMA/TDD model, which was explained in Section 4.4.2

4.5.3. Process Level Design

This section describes process level design of three process models in the FDMA/TDD model, *Central_Recv*, *Remote_Trans*, and *Remote_Recv*.

4.5.3.1. Remote_Trans

The process level design of the *Remote_Trans* process model in the FDMA/TDD model is as shown in Figure 4.20. The design is simple. Since the FDMA/FDD model does not have to handle any time slots, the incoming packets are simply forwarded onto the radio transmitter model.

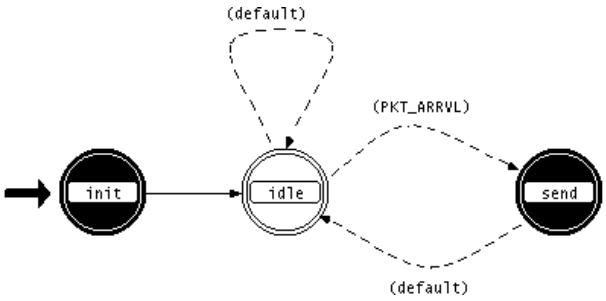

Figure 4.20. Process level design of Remote_Trans process model in the FDMA/FDD model.

4.5.3.2. Remote_Recv

The process level design of the *Remote_Recv* process model in the FDMA/FDD model is shown in Figure 4.17.

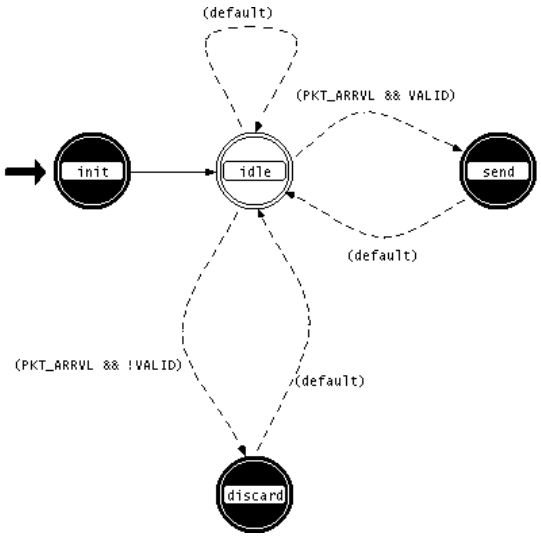

Figure 4.21. Process level design of Remote_Recv process model in the FDMA/FDD model.

The design is almost exactly the same as the design for the *Remote_Recv* process model in the FDMA/TDD model, which was explained in Section 4.4.3.3. The difference between the two models lies in the fact that the *Remote_Recv* model in the FDMA/FDD model does not need to reassemble packets. Since there are no time slots involved in the FDMA or FDD schemes, the packets do not need to be segmented before transmitting. So, in the design of Figure 4.21, the incoming packets are forwarded to the corresponding *End_Host* node without change.

4.5.3.3. Central_Recv

The process level design for the *Central_Recv* process model for the FDMA/FDD model is the same as the design for the *Central_Recv* process model in the FDMA/TDD model, which was explained in Section 4.4.3.4. There is no reassembly process involved and the packets are forwarded to the *Central_End_Host* without change.

4.6. Summary

This chapter explained the design of the four simulation models of the LMDS system. For each model, the network level, node level and the process level designs were explained. OPNET Modeler was introduced and the reasons behind choosing the tool for this simulation study were outlined. When the actual simulations are run, proper values need to be assigned for various parameters in the design. The next chapter explains the choice of parameter values for the simulation models and presents the results of the experiments.

Chapter 5. Simulation Experiments and Results

This chapter discusses the experiments that were carried out as part of this study and presents the results. The design of the experiments is explained, and the values assumed by different parameters in the experiments are stated and justified. Further, the simulation model itself is validated by comparing simulation results with analytical results. Lastly, the results of the experiments are presented and discussed.

5.1. Simulation Parameters

In Section 3.6, we identified the parameters that could affect the performance of the LMDS system. Further, in Section 3.7, we identified those parameters that are to be varied as part of this study and denoted them as experimental factors. In this section, the parameters involved are listed again for reference.

The factors that are going to be studied are as follows.

a) Choice of multiple access scheme
b) Choice of duplexing scheme
c) Size of the network
d) Traffic type
e) Traffic load

The other parameters, which were identified in Section 3.6, are as follows.

a) Data rate of wireless channel
b) Length of time slice for TDMA and TDD schemes
c) Switching overhead
d) Order of access
e) Propagation delay
f) Mean packet length

Refer to Table 3.1, for a tabulated form of the parameters and experimental factors. Note that the traffic model parameter, which is listed as a factor, also includes packet length and packet inter-arrival PDF parameters.

5.2. Simulation Parameter Values

In the previous section, parameters that are likely to affect the performance of the LMDS system were listed. This section discusses the values that are assigned to the parameters, including the experimental factors, for the simulation experiments. First, the set of values for each of the experimental factors is discussed. Then, fixed values for the other parameters are discussed.

5.2.1. Experimental Factors

Discussed below are the set of values for each of the experimental factors and the rationale behind the choice of the set of values.

5.2.1.1. Multiple Access Scheme

Two multiple access schemes are considered, Time Division Multiple Access and the Frequency Division Multiple Access. The TDMA scheme gives each of the contending data channels access to the wireless channel for a fixed time period called a time slot. The FDMA scheme divides the entire frequency spectrum of the LMDS channel equally among the contending data channels.

5.2.1.2. Duplexing Scheme

Two duplexing schemes are considered, Time Division Duplexing (TDD) and the Frequency Division Duplexing (FDD) schemes. The TDD scheme alternates access to the single LMDS channel between the upstream and the downstream traffic, providing traffic in each direction access to the channel for a fixed time period called a time slot. The FDD scheme divides the frequency spectrum equally among the upstream and downstream traffic, creating two separate logical channels.

5.2.1.3. Size of the Network

The simulation model of the LMDS network consists of a single central hub and multiple remote hosts. The size of the network is, thus, directly dependent on the number of remote hosts in the system. For the experiments, two network sizes are considered. The first consists of one central hub and five remote hosts and is referred to as the small network. The second consists of one central hub and ten remote hosts and is referred to as the large network. This number is consistent with current actual deployments of the LMDS network. For example, the LMDS network deployment in Virginia Tech consists of one central hub and four remote hosts.

5.2.1.4. Traffic Types

Two traffic types are considered, referred to as bursty traffic and non-bursty traffic. The bursty traffic source generates variable-sized packets with self-similar inter-arrival times. The length of the packets is varied according to a normal distribution. The non-bursty traffic source generates packets of fixed length with constant inter-arrival times. Section 3.6.3 explains the traffic models being considered more clearly.

5.2.1.5. Traffic Loads

There are two traffic loads considered for each of the traffic sources. These loads are named as low load and moderate load. In the low load case, the system as a whole is subjected to a loading factor of 0.2. In other words, on average, the utilization of the wireless channel is 20%. In the moderate load case, the system is subjected to a loading factor of 0.5. It is expected that these two loads would be representative of actual loads on a typical LMDS system. A larger number of load levels would have enabled better understanding of the results, but due to time constraints only two load levels were considered. The discussion in Section 5.2.1 is summarized in tabular form in Table 5.1.

Table 5.1. Simulation Values of Experimental Factors

Experimental Factors	Set of Values
Multiple Access Scheme	TDMA, FDMA
Duplexing Scheme	TDD, FDD
Size of Network	Small (5 Remote Hosts), Large (10 Remote Hosts)
Traffic Types	Non-bursty, Bursty
Traffic Load	Low (20% utilization), Moderate (50% utilization)

5.2.2. Simulation Parameters

Discussed below are the fixed values of the simulation parameters for the experiments and the rationale behind the choice of the values.

5.2.2.1. Data Rate of the Wireless Channel

A data rate of 10 Mbps is considered for the wireless channel in the simulation experiments. This value as been chosen considering the fact that the current LMDS network deployment in Virginia Tech has a similar data rate. Choosing the same value for the experiments would allow comparisons between the simulation results and actual values, although this study does not undertake any such comparison. It is believed that the results obtained from the set of experiments in this study are likely to scale proportionately for higher values of the wireless channel data rate.

5.2.2.2. Length of Time Slice for TDMA and TDD Schemes

In TDMA scheme, each of the remote hosts accesses the channel for a fixed period of time called time slot or time slice. The length of this time slot affects the end-to-end delay as well as the jitter. In pilot runs of the simulation model, it was observed that lowest values of end-to-end delay and jitter are obtained when the time slot is made equal to the time required to transmit an average packet over the wireless channel. Hence, for the simulation experiments involving TDMA, the time slot has been made equal to the transmission time of an average-length packet. This value works out different for different configurations of the simulation model. For the FDMA/TDD model, which involves FDMA as the multiple access scheme and TDD as the duplexing scheme, the above observation still held true during pilot simulation runs. Hence, the time slot for the FDMA/TDD configuration has also been made equal to the transmission time of an average-length packet.

5.2.2.3. Switching Overhead

To model overhead for exchanging control information etc., an inter-frame delay of 12 ms has been used. Refer to Section 3.6, for a more complete discussion of this parameter.

5.2.2.4. Order of Access

In the case of the TDMA/TDD configuration, the order in which upstream and downstream packets are intermixed might be important for certain application. In this study, the simulation models schedule time slots for all downstream channels followed by time slots for all upstream channels and so on. This order ensures that the time interval between two consecutive time slots for each data stream is the same.

5.2.2.5. Mean Packet Length

Previous studies have found that Ethernet frame lengths are concentrated around values of 64, 160-170 and 1090-1518 bytes [KcCy98]. Since the end networks for the LMDS model are most likely to be local area networks like Ethernet, a typical Ethernet frame length can be used at the mean packet size of the simulation experiments. Hence, we consider a mean packet length of 1000 bytes, or 8000 bits, for the simulation experiments. It should be noted that the LMDS system does not do any framing on its own.

5.3. Length of Simulation Experiments

The length of the simulation experiments is an important consideration. If not set correctly, conclusions can be incorrect or biased. In pilot runs of the simulation models, it was observed that the results for all models stabilized to within 5% of the final values within 15 minutes of simulated time.

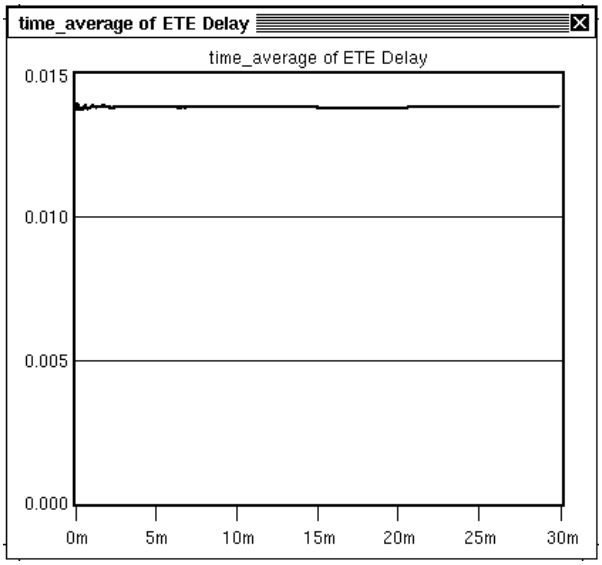

Figure 5.1. Time average plot of ETE delay for a non-bursty TDMA/TDD model.

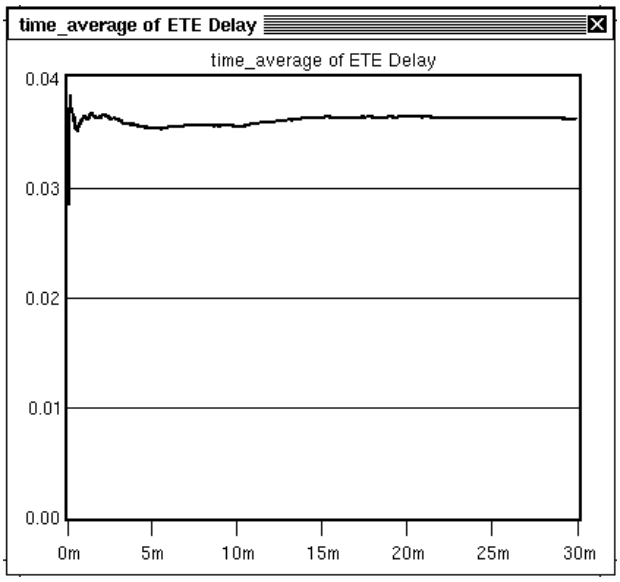

Figure 5.2. Time average plot of ETE delay for a bursty TDMA/TDD model.

Figure 5.1 and Figure 5.2 are graphs of the end-to-end delay statistic for two configurations of the TDMA/TDD model. The first configuration uses bursty traffic sources and the second configuration uses non-bursty traffic sources. Both the configurations use a large network with moderate load.

As seen in Figure 5.1 and Figure 5.2, the curves stabilize within 15 minutes of simulation time. Its should be noted that the configuration chosen for Figure 5.2 is likely to be the one of the worst case scenarios among all the simulation runs in this study with respect to stabilization of results. Other similar pilot runs were performed on each of the TDMA/FDD, FDMA/TDD, and FDMA/FDD models. For each model, the curves were found to stabilize within 15 minutes of simulated time. Considering these results, a simulation time of 30 minutes was fixed for all experiments. It is believed that this length of simulated time is sufficient for the simulation runs in this study.

5.4. Validation of the Simulation Models

Results obtained from pilot runs of each configuration were compared with expected results obtained from analytical calculations. The calculations for each of the FDMA/FDD, FDMA/TDD, TDMA/FDDD and TDMA/TDD models are described below. The calculations are based on an example analysis of Time Division Multiplexed (TDM) and Frequency Division Multiplexed (FDM) systems using M/D/1 queues with vacations found in [Bert97]. The example

provides equations for average queuing delay per packet for FDM and TDM systems. For all the models, the observed results from the simulation experiments matched to within 2% of the calculated values. Thus, we can conclude with a high degree of confidence that the models correctly simulate the configurations of the LMDS system.

The average queuing delay per packet for FDM systems, W_{FDM}, is given as

$$W_{FDM} = \frac{\lambda \times m}{2(1-\lambda)} \qquad \textbf{(5.1)}$$

where we have m incoming streams of equal length packets arriving according to a Poisson process with rate λ/m for each stream. The traffic streams are frequency-division multiplexed on m sub-channels of the available channel and the transmission time of each packet is m time units. Note that the transmission time is normalized to 1 if the full capacity of the channel is available to a given packet. Each sub-channel can be represented by an M/D/1 queuing system.

The average queuing delay per packet for TDM systems, W_{TDM}, is given as

$$W_{TDM} = \frac{m}{2(1-\lambda)} \qquad \textbf{(5.2)}$$

where the *m* traffic streams are time-division multiplexed such that the time axis is divided in *m*-slot frames with one slot dedicated to each traffic stream. Each slot is one time unit long and can carry a single packet. Detailed explanations of Equation 5.1 and Equation 5.2 are provided in [Bert97].

Based on the above equations, we present the values calculated for each configuration of the simulation model. The simulation parameters have been chosen to match the requirements of the above equations. Particularly, Poisson sources have been used. After each calculation, the calculated values are compared with results of the simulation experiment for the particular configuration of the model.

Since the simulation model collects the end-to-end delay statistic, we need to calculate the delay per packet beyond just the queuing delay. We denote this additional delay as the "Common Factor" since this additional delay is common to all configurations of the model.

Common Factor = Transmission delay over the wireless links in the network + Propagation delay over the wireless channel

Common Factor = 0.0016 s + 0.00007 s = 0.001607 s **(5.3)**

We consider only downstream traffic for the calculations below. The data rate of the wireless channel is 10 Mbps. Fixed-sized packets of 8,000 bits are considered. For each model, two loads are considered.

1. Low Load: 1 Mbps downstream, where $\lambda = \frac{1}{5} = 0.2$
2. Moderate Load: 2.5 Mbps downstream, where $\lambda = \frac{2.5}{5} = 0.5$

We define the following.

W = Queuing delay

d = Transmission delay

α = Common Factor (from Equation 5.3) = 0.001607 **(5.4)**

D = ETE delay = $W + d + \alpha$ **(5.5)**

τ = Length of unit time (time to transmit one packet)

Calculations for each model are presented below.

5.4.1. FDMA/FDD Model

Each data stream in the FDMA/FDD model is independent. Therefore, we can consider just 1 stream for the calculations. Thus,

$m = 1$ **(5.6)**

Since the transmission time is normalized,

τ = 8000 / 1000000 = 0.008 s **(5.7)**

$d = \tau = 0.008$ s **(5.8)**

5.4.1.1. Low Load

For low load, $\lambda = 0.2$. From Equation 5.1 and Equation 5.6,

$W_{FDMA/FDD} = \frac{\lambda \times m}{2(1-\lambda)} = \frac{0.2 \times 1}{2(1-0.2)} = 0.125$ time units **(5.81)**

Substituting the value of τ from Equation 5.7, we have,

$W_{FDMA/FDD}$ = 0.125 × 0.008 = 0.001 s **(5.82)**

Using Equations 5.5, 5.4, and 5.8,

$D = W + d + \alpha$ = 0.001 + 0.008 + 0.001607 = 0.010607 s **(5.83)**

The ETE delay result using simulation is D = 0.0106 s. The simulation result deviates from the calculated value by 0.07 percent.

5.4.1.2. Moderate Load

For moderate load, λ = 0.5. From Equation 5.1 and Equation 5.6,

$$W_{FDMA/FDD} = \frac{\lambda \times m}{2(1-\lambda)} = \frac{0.5 \times 1}{2(1-0.5)} = 0.5 \text{ time units} \quad \textbf{(5.84)}$$

Substituting the value of τ from Equation 5.7, we have,

$W_{FDMA/FDD}$ = 0.5 × 0.008 = 0.004 s **(5.85)**

Using Equations 5.5, 5.4, and 5.8,

$D = W + d + \alpha$ = 0.004 + 0.008 + 0.001607 = 0.013607 s **(5.86)**

The ETE delay result using simulation is D = 0.0136 s. The simulation result deviates from the calculated value by 0.05 percent.

5.4.2. FDMA/TDD Model

For FDMA/TDD, there are two time slots corresponding to upstream and downstream traffic, and five logical channels. Thus,

m = 2 **(5.9)**

Since the transmission time is normalized,

τ = 8000 / 200000 = 0.004 s **(5.10)**

$d = \tau$ = 0.004 s **(5.11)**

5.4.2.1. Low Load

For low load, λ = 0.2. From Equation 5.2 and Equation 5.9,

$$W_{FDMA/FDD} = \frac{m}{2(1-\lambda)} = \frac{2}{2(1-0.2)} = 1.25 \text{ time units} \quad \textbf{(5.111)}$$

Substituting the value of τ from Equation 5.10, we have,

$$W_{FDMA/FDD} = 1.25 \times 0.004 = 0.005 \text{ s} \quad \textbf{(5.112)}$$

Using Equations 5.5, 5.4, and 5.11,

$$D = W + d + \alpha = 0.005 + 0.004 + 0.001607 = 0.010607 \text{ s} \quad \textbf{(5.113)}$$

The ETE delay result using simulation is D = 0.0106 s. The simulation result deviates from the calculated value by 0.07 percent.

5.4.2.2. Moderate Load

For moderate load, $\lambda = 0.5$. From Equation 5.1 and Equation 5.9,

$$W_{FDMA/FDD} = \frac{m}{2(1-\lambda)} = \frac{2}{2(1-0.5)} = 2 \text{ time units} \quad \textbf{(5.114)}$$

Substituting the value of τ from Equation 5.10, we have,

$$W_{FDMA/FDD} = 2 \times 0.004 = 0.008 \text{ s} \quad \textbf{(5.115)}$$

Using Equations 5.5, 5.4, and 5.11,

$$D = W + d + \alpha = 0.008 + 0.004 + 0.001607 = 0.013607 \text{ s} \quad \textbf{(5.116)}$$

The ETE delay result using simulation is D = 0.0137 s. The simulation result deviates from the calculated value by 0.7 percent.

5.4.3. TDMA/FDD Model

For TDMA/FDD, there are five time slots corresponding to upstream and downstream traffic and 2 logical channels. Thus,

$$m = 2 \quad \textbf{(5.12)}$$

Since the transmission time is normalized,

$$\tau = 8000 / 5000000 = 0.0016 \text{ s} \quad \textbf{(5.13)}$$

$$d = \tau = 0.0016 \text{ s} \quad \textbf{(5.14)}$$

5.4.3.1. Low Load

For low load, $\lambda = 0.2$. From Equation 5.2 and Equation 5.12,

$$W_{FDMA/FDD} = \frac{m}{2(1-\lambda)} = \frac{5}{2(1-0.2)} = 3.125 \text{ time units} \quad \textbf{(5.141)}$$

Substituting the value of τ from Equation 5.13, we have,

$$W_{FDMA/FDD} = 3.125 \times 0.0016 = 0.005 \text{ s} \quad \textbf{(5.142)}$$

Using Equations 5.5, 5.4, and 5.14,

$$D = W + d + \alpha = 0.005 + 0.0016 + 0.001607 = 0.008207 \text{ s} \quad \textbf{(5.143)}$$

The ETE delay result using simulation is D = 0.00827 s. The simulation result deviates from the calculated value by 0.8 percent.

5.4.3.2. Moderate Load

For moderate load, $\lambda = 0.5$. From Equation 5.1 and Equation 5.12,

$$W_{FDMA/FDD} = \frac{m}{2(1-\lambda)} = \frac{5}{2(1-0.5)} = 5 \text{ time units} \quad \textbf{(5.144)}$$

Substituting the value of τ from Equation 5.13, we have,

$$W_{FDMA/FDD} = 5 \times 0.0016 = 0.008 \text{ s} \quad \textbf{(5.145)}$$

Using Equations 5.5, 5.4, and 5.14,

$$D = W + d + \alpha = 0.008 + 0.0016 + 0.001607 = 0.011207 \text{ s} \quad \textbf{(5.146)}$$

The ETE delay result using simulation is D = 0.0113 s. The simulation result deviates from the calculated value by 0.8 percent.

5.4.4. TDMA/TDD Model

For TDMA/TDD, there are ten time slots corresponding to upstream and downstream traffic and 1 logical channel. Thus,

$$m = 10 \quad \textbf{(5.15)}$$

Since the transmission time is normalized,

$$\tau = 8000 / 10000000 = 0.0008 \text{ s} \quad \textbf{(5.16)}$$

$$d = \tau = 0.0008 \text{ s} \quad \textbf{(5.17)}$$

5.4.4.1. Low Load

For low load, $\lambda = 0.2$. From Equation 5.2 and Equation 5.15,

$$W_{FDMA/FDD} = \frac{m}{2(1-\lambda)} = \frac{10}{2(1-0.2)} = 6.25 \text{ time units} \quad \textbf{(5.171)}$$

Substituting the value of τ from Equation 5.16, we have,

$$W_{FDMA/FDD} = 6.25 \times 0.0008 = 0.005 \text{ s} \quad \textbf{(5.172)}$$

Using Equations 5.5, 5.4, and 5.17,

$$D = W + d + \alpha = 0.005 + 0.0008 + 0.001607 = 0.007407 \text{ s} \quad \textbf{(5.173)}$$

The ETE delay result using simulation is D = 0.00745 s. The simulation result deviates from the calculated value by 0.6 percent.

5.4.4.2. Moderate Load

For moderate load, $\lambda = 0.5$. From Equation 5.1 and Equation 5.15,

$$W_{FDMA/FDD} = \frac{m}{2(1-\lambda)} = \frac{10}{2(1-0.5)} = 10 \text{ time units} \quad \textbf{(5.174)}$$

Substituting the value of τ from Equation 5.16, we have,

$$W_{FDMA/FDD} = 10 \times 0.0008 = 0.008\text{s} \quad \textbf{(5.175)}$$

Using Equations 5.5, 5.4, and 5.17,

$$D = W + d + \alpha = 0.008 + 0.0008 + 0.001607 = 0.010407 \text{ s} \quad \textbf{(5.176)}$$

The ETE delay result using simulation is D = 0.0106 s. The simulation result deviates from the calculated value by 1.85 percent.

5.5. Simulation Results

In this section, results of the simulation experiments are presented. Each of the five simulation factors presented in Section 5.2.1 can assume two possible values. This creates a total of 32 different combinations of the factors. Each experimental setup was repeated three times with different seeds for random number generators to ensure that the results are not sensitive to seed values. The results presented in this section are the average of values from these three

experimental runs for each of the 32 combinations of factors. Given the stability of results, as discussed in Section 5.3, reported results are the time average from the beginning of simulation (time 0) until the end of the simulation run.

As discussed in Chapter 4, four different models were built involving different combinations of two factors, the choice of multiple access scheme and the choice of duplexing scheme. These models are called TDMA/TDD, TDMA/FDD, FDMA/TDD, and FDMA/FDD. We present the results for each of these models separately. Values of four different statistics, end-to-end (ETE) delay, jitter, throughput measured at the end host connected to any of the remote hosts, and throughput measured at the central end host, are presented.

5.5.1. TDMA/TDD Model

The results of experiments for the TDMA/TDD model are presented in Table 5.2. The following observations are made.

1. For a given load and network size, the ETE delay and jitter values are the same for both bursty and non-bursty traffic. This is expected. In TDMA, almost all packets are queued before being transmitted. Thus, TDMA has an effect of smoothing out the bursts in traffic. So, in this case, results for the bursty and non-bursty traffic can be expected to be the same.
2. For a given load and traffic source, the ETE delay and jitter are greater for a large network than for a small network. This is expected and is justified in Section 5.6.
3. For a given network size and traffic source, the ETE delay and jitter statistics are greater for systems under moderate load than for systems under low load. This is expected and is justified in Section 5.6.
4. The value for throughput at the central host matches the sum of the mean generation rates of the remote hosts. The value for throughput at the end host matches the mean generation rate at the central host for a particular remote host. This is expected and is justified in Section 5.6.

Table 5.2. Results of Simulation Experiments for the TDMA/TDD Model

Load	Size of Network	Traffic Source	ETE delay (sec)	Jitter (sec)	Throughput at Central End Host (Mbps)	Throughput at End Host (Mbps)
low	small	non-bursty	0.0068	0.0024	1.0	0.20
low	small	bursty	0.0068	0.0026	1.0	0.20
low	large	non-bursty	0.0117	0.0044	1.0	0.10
low	large	bursty	0.0117	0.0056	1.0	0.10
moderate	small	non-bursty	0.0083	0.0030	2.5	0.50
moderate	small	bursty	0.0083	0.0034	2.5	0.50
moderate	large	non-bursty	0.0152	0.0055	2.5	0.25
moderate	large	bursty	0.0152	0.0070	2.5	0.25

5.5.2. TDMA/FDD Model

The results of experiments for the TDMA/FDD model are presented in Table 5.3. The following observations are made.

1. For a given load and network size, the ETE delay and jitter values are the same regardless of traffic type. This is expected. In TDMA, almost all the packets are queued before being transmitted. Thus, TDMA has an effect of smoothing out the bursts in traffic. So, in this case, results for the bursty and non-bursty traffic can be expected to be the same.
2. For a given load and traffic source, the ETE delay and jitter are greater for a large network than for a small network. This is expected and is justified in Section 5.6.
3. For a given network size and traffic source, the ETE delay and jitter statistics are greater for systems under moderate load than for systems under low load. This is expected and is justified in Section 5.6.
4. The value for throughput at the central host matches the sum of the mean generation rates of the remote hosts. The value for throughput at the end host matches the mean generation rate at the central host for a particular remote host. This is expected and is justified in Section 5.6.

Table 5.3. Results of Simulation Experiments for the TDMA/FDD Model

Load	Size of Network	Traffic Source	ETE delay (sec)	Jitter (sec)	Throughput at Central End Host (Mbps)	Throughput at End Host (Mbps)
low	small	non-bursty	0.0076	0.0027	1.0	0.20
low	small	bursty	0.0076	0.0026	1.0	0.20
low	large	non-bursty	0.0124	0.0047	1.0	0.10
low	large	bursty	0.0124	0.0058	1.0	0.10
moderate	small	non-bursty	0.0091	0.0033	2.5	0.50
moderate	small	bursty	0.0091	0.0034	2.5	0.50
moderate	large	non-bursty	0.0158	0.0059	2.5	0.25
moderate	large	bursty	0.0158	0.0070	2.5	0.25

5.5.3. FDMA/TDD Model

The results of experiments on the FDMA/TDD model are presented in Table 5.4.

Table 5.4. Results of Simulation Experiments for the FDMA/TDD Model

Load	Size of Network	Traffic Source	ETE delay (sec)	Jitter (sec)	Throughput at Central End Host (Mbps)	Throughput at End Host (Mbps)
low	small	non-bursty	0.0105	0.0016	1.0	0.20
low	small	bursty	0.0101	0.0021	1.0	0.20
low	large	non-bursty	0.0200	0.0042	1.0	0.10
low	large	bursty	0.0191	0.0046	1.0	0.10
moderate	small	non-bursty	0.0118	0.0027	2.5	0.50
moderate	small	bursty	0.0116	0.0032	2.5	0.50
moderate	large	non-bursty	0.0227	0.0045	2.5	0.25
moderate	large	bursty	0.0225	0.0063	2.5	0.25

For the results in Table 5.4, the following observations are made.

1. For a given load and network size, the ETE delay value seems to be marginally greater for non-bursty traffic than for bursty traffic. This is unusual but can be explained as follows. The FDMA/TDD model has one channel for each remote host. Upstream and downstream traffic is time-multiplexed onto these channels. For the upstream traffic, packets are queued until the next upstream time slot and then are transmitted to the central hub simultaneously. The central hub forwards these upstream packets to the central end host using the point-to-point link connected to it. Since these packets are sent simultaneously over the point-to-point link, there is some queuing delay involved at the point-to-point transmitter. This effect is more pronounced in case of non-bursty traffic than in the case of bursty traffic. Jitter values are greater for bursty traffic than for non-bursty traffic, for a given load and network size. The phenomenon discussed above does not affect jitter values for non-bursty traffic adversely in comparison to bursty traffic.
2. For a given load and traffic source, the ETE delay and jitter are greater for a large network than for a small network. This is expected and is justified in Section 5.6.
3. For a given network size and traffic source, the ETE delay and jitter statistics are greater for systems under moderate load than for systems under low load. This is expected and is justified in Section 5.6.
4. The value for throughput at the central host matches the sum of the mean generation rates of the remote hosts. The value for throughput at the end host matches the mean generation rate at the central host for a particular remote host. This is expected and is justified in Section 5.6.

5.5.4. FDMA/FDD Model

The results of experiments on the FDMA/FDD model are presented in Table 5.5. The following observations are made.

1. For a given load and network size, the ETE delay and jitter values are greater for bursty traffic sources than for non-bursty traffic sources. This is expected. In FDMA/FDD, there are no time slots and each data stream has its own logical channel. Bursty traffic, in this case, is expected to produce greater queuing delay and, hence, greater ETE delay.
2. For a given load and traffic source, the ETE delay and jitter are greater for a large network than for a small network. This is expected and is justified in Section 5.6.
3. For a given network size and traffic source, the ETE delay and jitter statistics are greater for systems under moderate load than for systems under low load. This is expected and is justified in Section 5.6.

4. The value for throughput at the central host matches the sum of the mean generation rates of the remote hosts. The value for throughput at the end host matches the mean generation rate at the central host for a particular remote host. This is expected and is justified in Section 5.6.

Table 5.5. Results of Simulation Experiments on the FDMA/FDD Model

Load	Size of Network	Traffic Source	ETE delay (sec)	Jitter (sec)	Throughput at Central End Host (Mbps)	Throughput at End Host (Mbps)
low	small	non-bursty	0.0097	0.0000	1.0	0.20
low	small	bursty	0.0099	0.0003	1.0	0.20
low	large	non-bursty	0.0184	0.0008	1.0	0.10
low	large	bursty	0.0189	0.0014	1.0	0.10
moderate	small	non-bursty	0.0110	0.0013	2.5	0.50
moderate	small	bursty	0.0112	0.0015	2.5	0.50
moderate	large	non-bursty	0.0212	0.0030	2.5	0.25
moderate	large	bursty	0.0217	0.0034	2.5	0.25

5.6. Analysis of Results

Results of the simulation experiments were presented in Section 5.5. Preliminary observations regarding the results of each simulation model were also presented in Section 5.5. This section attempts to further analyze results, primarily by comparing results from the four different simulation models. The conclusions that can be drawn from this analysis are presented in Section 6.2.

In Section 5.5, observations regarding the experimental results for each model were presented. The observations common to all models are as follows.

a) For a given load and traffic source, the ETE delay and jitter statistics are greater for a large network than for a small network. This result is expected since a large network implies more time slots for a TDMA network or more frequency channels for an FDMA network. More time slots in a TDMA network results in larger time intervals between successive time slots for a particular data stream, thus increasing delay per packet. More frequency channels in an FDMA network results in smaller bandwidth per frequency channel, thus increasing delay per

packet. The same reasons would contribute towards more variation in delay and, hence, greater values of jitter.

b) For a given network size and traffic type, the ETE delay and jitter statistics are greater for systems under moderate load than for systems under low load. This result is expected since a heavier load results in greater average queuing delay per packet, thus increasing delay per packet. Again, the same reasons would contribute towards more variation in delay and, hence, greater values of jitter.

c) The value for throughput at the central host matches the sum of the mean generation rates of the remote hosts. The value for throughput at the end host matches the mean generation rate at the central host for a particular remote host. This result is expected because as the ETE delay is stabilized, the throughput at the destination should match the mean generation rate at the source.

d) For all models, ETE delay was found to stabilize more quickly for non-bursty traffic than for bursty traffic. In addition, and as a result, throughput was also found to stabilize more quickly for non-bursty traffic than for bursty traffic. This result is expected because bursty traffic is expected to result in greater variation in delay and thus, ETE delay for models using bursty traffic is expected to stabilize more slowly.

Figures A.1 through A.8 in Appendix A show the comparison of results for the ETE delay statistic collected for the TDMA/TDD, TDMA/FDD, FDMA/TDD, and FDMA/FDD models. Figures B.1 to B.8 in Appendix B show the comparison of results for jitter statistic collected for the TDMA/TDD, TDMA/FDD, FDMA/TDD, and FDMA/FDD models.

Based on Figures A.1 to A.8 in Appendix A, the following observations are made.

a) The TDMA/TDD model has lowest values of ETE delay among the four simulation models for any given combination of load, network size, and traffic source. This is expected. In general, TDMA-based systems generate greater queuing delay per packet than FDMA-based models. However, the vastly lower transmission delay for the TDMA-based models than for the FDMA-based models causes the ETE delay to be lower for TDMA-based models. In the TDMA-based models, TDMA/TDD is expected to have slightly lower values of ETE delay than TDMA/FDD. This is due to a similar reasoning for TDD against FDD.

b) For all cases, the TDMA-based models, TDMA/TDD and TDMA/FDD, show lower ETE delay than the FDMA-based models, FDMA/TDD and FDMA/FDD. This is expected and justified in item a) above.

c) For all cases, the FDMA/TDD model shows the greatest ETE delay. This is expected because apart from the disadvantages of FDMA as opposed to TDMA explained in item a) above, FDMA/TDD also faces other problems as explained in item 1 in Section 5.5.3.

Based on Figures B.1 to B.8 in Appendix B, the following observations are made.

a) For all cases, the FDMA/FDD model shows the lowest values for jitter among all simulation models. Each data stream in FDMA/FDD has its own logical frequency channel. Thus, transmission delay forms a major part of ETE delay per packet. Thus, variance in ETE delay is low and jitter is extremely small.

b) A particular observation to be made is that in the case of a small network, non-bursty traffic, and a low traffic load, FDMA/FDD was found to show jitter values very close to zero. This is expected since for the given configuration, the likelihood of queuing delay and, hence, variation in delay is very small.

c) Jitter values for the TDMA-based models, TDMA/TDD and TDMA/FDD are broadly similar. TDMA/FDD is found to have same or marginally lower values of jitter than TDMA/TDD model. As explained in item a) above, FDD would be somewhat less likely to cause variance in ETE delay than TDD and, hence, jitter is relatively lower for FDD than for TDD.

Table 5.6. Effect of Increase in Network Size on ETE delay and Jitter

Model	Load	Traffic Source	% Increase in ETE delay	% Increase in jitter
TDMA/TDD	low	non-bursty	72	83
		bursty	72	115
	moderate	non-bursty	83	83
		bursty	83	105
TDMA/FDD	low	non-bursty	63	74
		bursty	63	123
	moderate	non-bursty	73	79
		bursty	73	105
FDMA/TDD	low	non-bursty	90	162
		bursty	89	119
	moderate	non-bursty	92	66
		bursty	94	97

FDMA/FDD	low	non-bursty	90	-
		bursty	91	366
	moderate	non-bursty	93	131
		bursty	94	127

From Table 5.6, we observe that the TDMA/TDD and TDMA/FDD models show less increase in ETE delay for an increase in network size than do the FDMA/FDD and FDMA/TDD models. This is expected and it further strengthens the belief that TDMA systems scale better in terms of network size than do FDMA systems.

Table 5.7. Effect of Increase in Network Load on ETE delay and Jitter

Model	Network Size	Traffic Source	% Increase in ETE delay	% Increase in Jitter
TDMA/TDD	small	non-bursty	22	25
		bursty	22	31
	large	non-bursty	30	25
		bursty	30	25
TDMA/FDD	small	non-bursty	20	22
		bursty	20	31
	large	non-bursty	27	26
		bursty	27	21
FDMA/TDD	small	non-bursty	12	69
		bursty	15	52
	large	non-bursty	14	7
		bursty	18	37
FDMA/FDD	small	non-bursty	13	-
		bursty	13	400
	large	non-bursty	15	275
		bursty	15	143

From Table 5.7, we can observe that the FDMA/TDD and FDMA/FDD models show less increase in ETE delay for an increase in network load than do the TDMA/FDD and TDMA/TDD

models. This result is expected. The TDMA systems show greater ETE delay if a packet is queued for more than one cycle of time slots. As the load increases, the queue length for a particular data stream in TDMA is likely to increase beyond one and, therefore, ETE delay increases. FDMA systems also face greater queuing delay as the load increases, but since there are no time slots for multiple access, the increase in ETE delay for FDMA systems is relatively small.

5.7. Summary

This chapter discussed the design of the simulation experiments and presented the results of the experiments. The simulation parameters and experimental factors were listed. Values for the simulation parameters as well as the factors were discussed and the rationale behind the selections was explained. The simulation models were validated by comparing the results of pilot simulation runs to analytical results.

Results of the simulation experiments were presented for the four different models and observations about the performance were drawn from the results. Comparison of the corresponding results for different models was made and observations were noted and justified. The next chapter summarizes the research, draws conclusions based on the comparisons, and outlines ideas for future work.

Chapter 6. Conclusions

This chapter summarizes this research and draws conclusions from the results. Further, issues deserving more study are indicated.

6.1. Summary

This thesis was aimed at developing a parameterized simulation model for the LMDS system and, further, to use the model to compare performance of the LMDS system when using different combinations of multiple access schemes and duplexing schemes.

As described in Chapter 4 and Chapter 5, a parameterized simulation model for LMDS network was developed. The model was developed using OPNET Modeler [Mil3]. Four different models were developed corresponding to the four configurations of the LMDS system. As discussed in Section 3.1, these configurations are TDMA/TDD, TDMA/FDD, FDMA/TDD, and FDMA/FDD. The design of the model is such that almost all attributes are parameterized. Particular component related attributes appear as node model attributes in the network level design view. These node model attributes can assume different values for different nodes in the network level design. Global attributes appear as simulation parameters. These parameters can be set at the start of each simulation run. Components common to the different models have been developed once and re-used in the remaining models. This not only speeds up the design and development process, but also reduces redundancy of code and, thus, reduces maintenance. The models have been validated by successfully comparing sample simulation results with analytical calculations for Poisson arrivals of fixed length packets. The validation effort is documented in Section 5.3. Lastly, the simulation models have been tested by successfully running the simulation experiments in addition to numerous pilot runs.

The simulation experiments were documented in Chapter 5. The experimental factors for the simulation experiments were discussed in Section 5.2.1. In addition, the set of values for parameters other than the experimental factors was also discussed in Section 5.2.2. The results of the simulation experiments and observations were presented in Section 5.5 and 5.6. In addition, conclusions based on the analysis are put forward in Section 6.2.

6.2. Conclusions

This section presents general conclusions that can be drawn from the results of the simulation experiments. One of the objectives of this research work was to use the simulation models to try and compare performance of four different configurations of the LMDS system, namely TDMA/TDD, TDMA/FDD, FDMA/TDD, and FDMA/FDD, under different load levels, network sizes, and traffic types. This objective is partly addressed by this section. It should be noted that the conclusions drawn in this section are based on the assumptions of parameter values as stated in Section 5.2.

In the case of LMDS and broadband wireless communications, in general, advantages and disadvantages of deploying TDMA systems as opposed to FDMA systems and TDD systems as opposed to FDD systems is debated. Considering the results of this study, we can say that TDMA systems show lower ETE delay per packet than FDMA systems. In addition, TDMA systems show less increase in ETE delay values when scaling from small network sizes to large network sizes than do FDMA systems. However, FDMA systems show lower jitter than TDMA systems. In addition, FDMA systems show less increase in ETE delay values when the load is scaled up than do TDMA systems. One fact, which needs to be noted here, is that the TDMA scheme implemented for the simulation models in this study, is a fixed TDMA scheme. In other words, the time slot durations are fixed for any particular simulation run. Adaptive TDMA schemes exist where the time from an empty time slot is utilized for making another slot longer and so on [CbMi92]. These adaptive schemes can be expected to show better performance than the current static scheme, although some extra overhead is incurred in exchanging more control information.

The choice between a TDMA and a FDMA system would, thus, depend on the application. For applications in which jitter needs to be kept as small as possible, FDMA would be preferable. Transfer of uncompressed audio and video are two such applications. For applications in which relatively higher values of jitter are an acceptable trade-off for lower ETE delay, TDMA would be preferable. Carrying World Wide Web (WWW) traffic is one such application.

For duplexing, TDMA/TDD shows better performance than TDMA/FDD in terms of both, ETE delay and jitter. In addition, a fixed TDD scheme is modeled as part of this study. Adaptive TDD schemes exist in which time slots reserved for traffic in one direction can be utilized for traffic in the other direction, if needed [Wave00]. Adaptive TDD schemes can be expected to give better performance, although there is an extra overhead for additional control signals. It should be

noted, however, that TDD with FDMA, as is used in the FDMA/TDD model, shows a unique problem. This problem, explained in Section 5.5.3, arises due to the point-to-multipoint architecture of LMDS systems and results in higher ETE delay values for upstream traffic. Thus, we can conclude that TDD is preferable to be used in conjunction with TDMA and FDD is preferable to be used in conjunction with FDMA.

6.3. Suggestions for Future Work

There are two areas for future work. First, suggestions regarding improvement of the models are provided. Second, suggestions are provided for further experiments using the developed simulation models.

The simulation models built as part of this work model the data link layer functionality of the LMDS network, particularly the multiple access and duplexing schemes. Physical layer characteristics are modeled using built-in modules in the OPNET Modeler. It is suggested that the physical layer functionality be developed for the current models to correctly model the known characteristics of LMDS wireless frequency channels. This would improve the accuracy of the models. In addition, it is suggested that other multiple access and duplexing schemes, such as adaptive TDMA and adaptive TDD schemes mentioned earlier, be modeled in an effort to study the performance of those schemes for LMDS networks.

Simulation experiments were designed by varying the experimental factors as discussed in Section 5.2.1. Two different values were assumed for each factor. For example, two network sizes were used. More values could not be used per factor because of time constraints. For conclusions to be drawn with greater generality and accuracy, more values should be considered for each factor. Secondly, experiments can be designed to study the effect of using the LMDS system on higher layer protocols such as TCP and IP. In addition, the possibility of providing bandwidth guarantees over LMDS links can be studied.

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Appendix A. Comparison of ETE delay Results

Comparison of end-to-end (ETE) delay statistic for the four different simulation models, TDMA/TDD, TDMA/FDD, FDMA/TDD, and FDMA/FDD, are presented in this appendix. The terminology used for load conditions, network size, and traffic models is defined in Section 5.2.1.

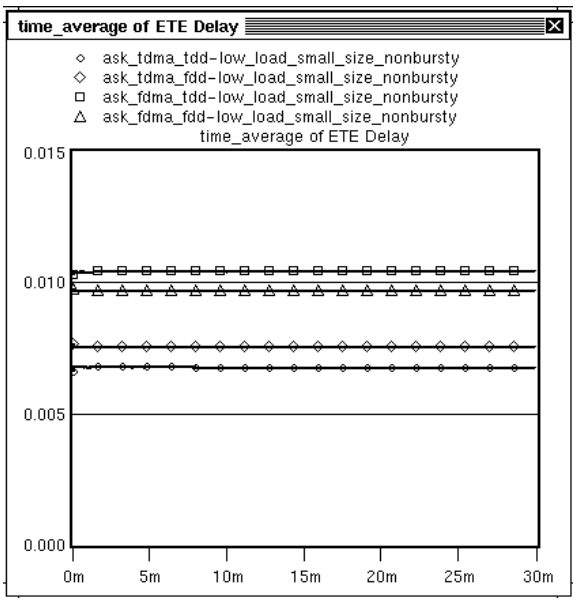

Figure A.1. Time average plot of the ETE delay statistic for the four simulation models under low load, small network size and non-bursty traffic.

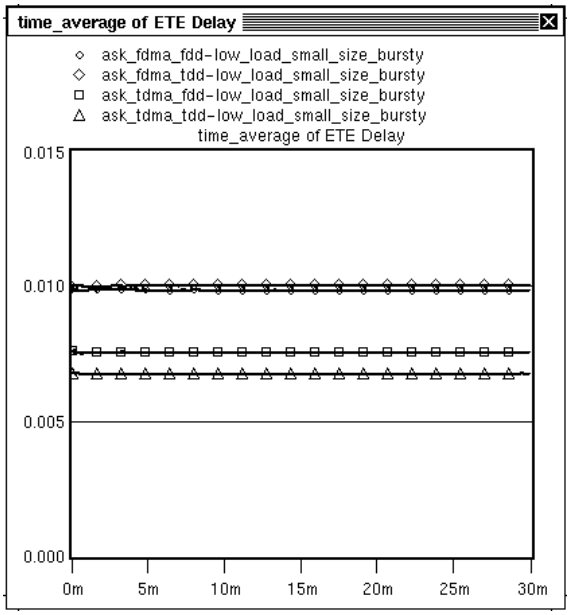

Figure A.2. Time average plot of the ETE delay statistic for the four simulation models under low load, small network size and bursty traffic.

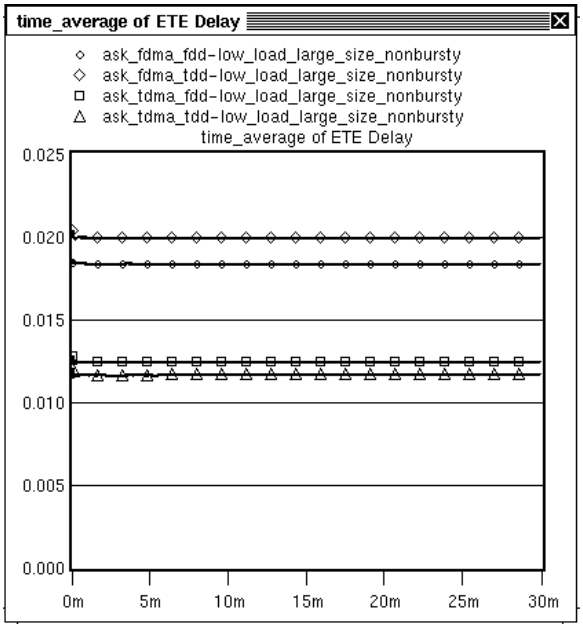

Figure A.3. Time average plot of the ETE delay statistic for the four simulation models under low load, large network size and non-bursty traffic.

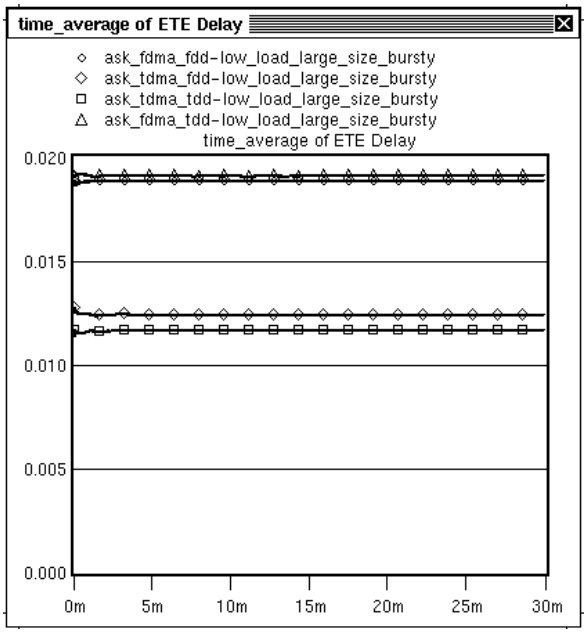

Figure A.4. Time average plot of the ETE delay statistic for the four simulation models under low load, large network size and bursty traffic.

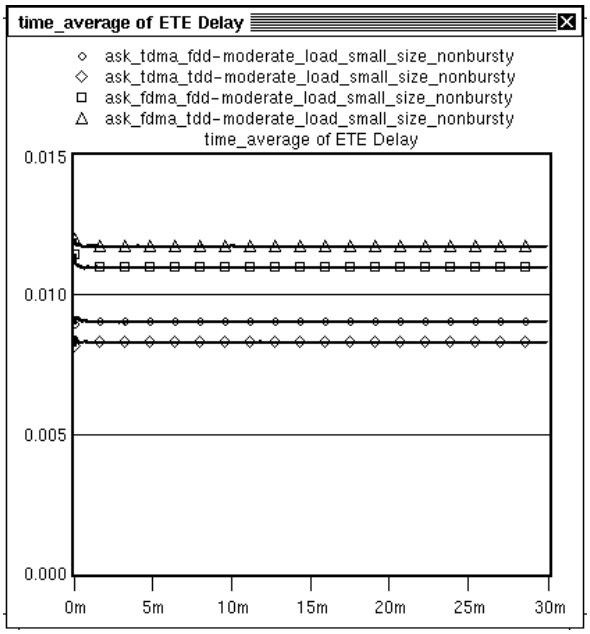

Figure A.5. Time average plot of the ETE delay statistic for the four simulation models under moderate load, small network size and non-bursty traffic.

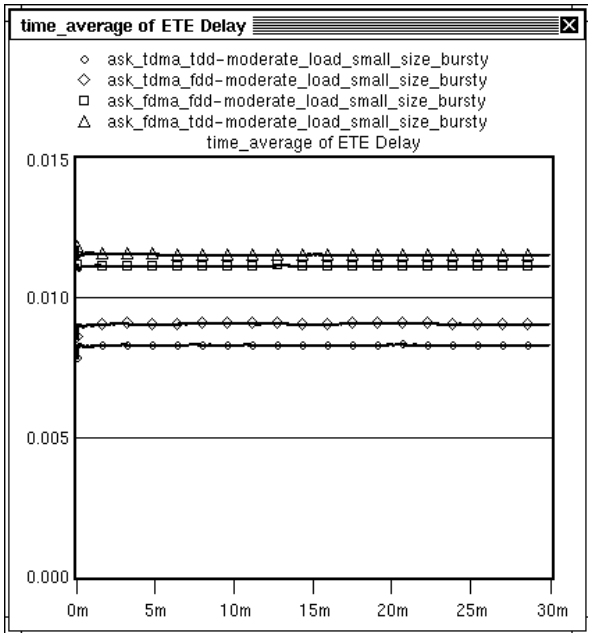

Figure A.6. Time average plot of the ETE delay statistic for the four simulation models under moderate load, small network size and bursty traffic.

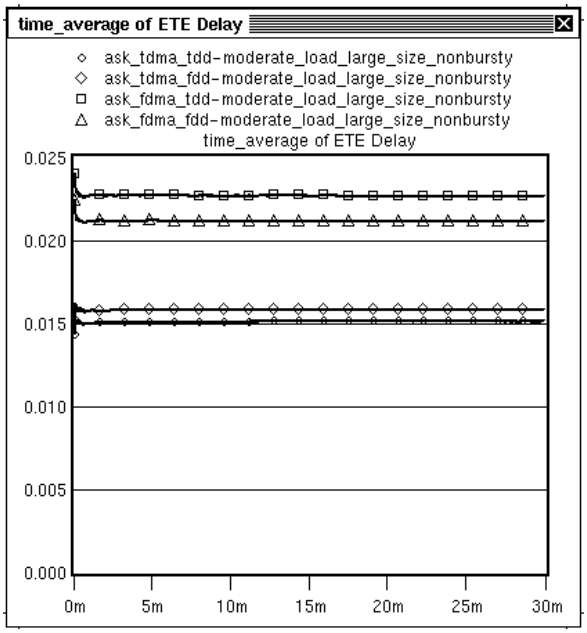

Figure A.7. Time average plot of the ETE delay statistic for the four simulation models under moderate load, large network size and non-bursty traffic.

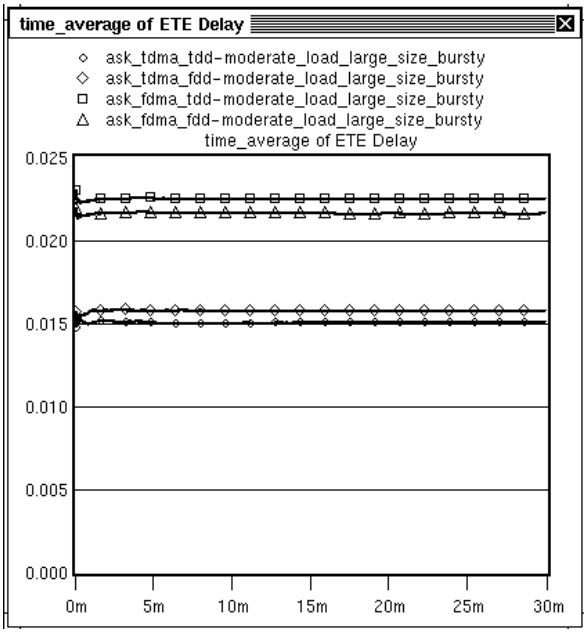

Figure A.8. Time average plot of the ETE delay statistic for the four simulation models under moderate load, large network size and bursty traffic.

Appendix B. Comparison of Jitter Results

Comparison of the jitter statistic for the four different simulation models, TDMA/TDD, TDMA/FDD, FDMA/TDD, and FDMA/FDD, are presented. The terminology used for load conditions, network size and traffic models is defined in Section 5.2.1.

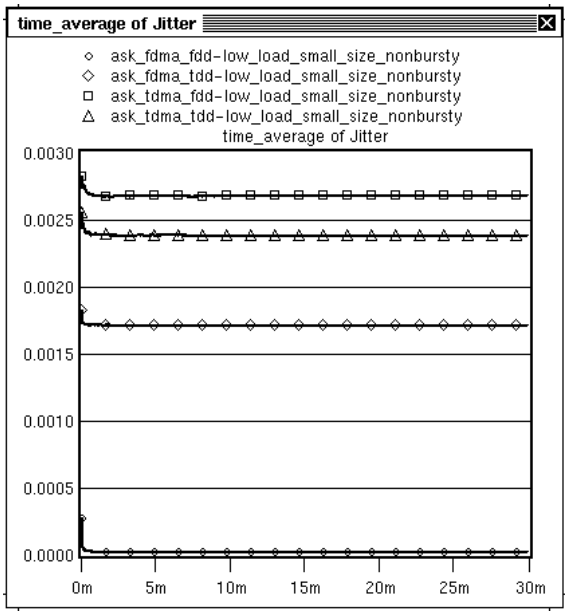

Figure B.1. Time average plot of the jitter statistic for the four simulation models under low load, small network size and non-bursty traffic.

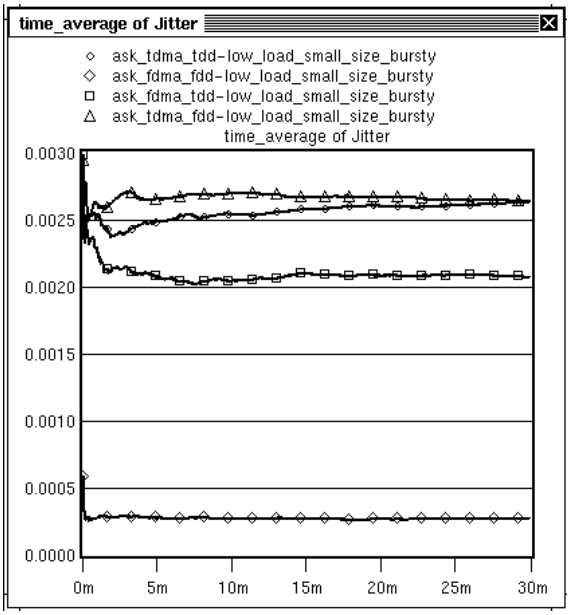

Figure B.2. Time average plot of the jitter statistic for the four simulation models under low load, small network size and bursty traffic.

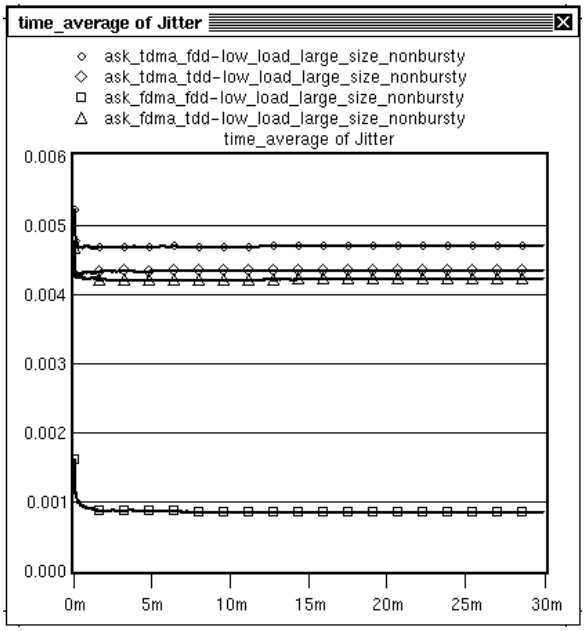

Figure B.3. Time average plot of the jitter statistic for the four simulation models under low load, large network size and non-bursty traffic.

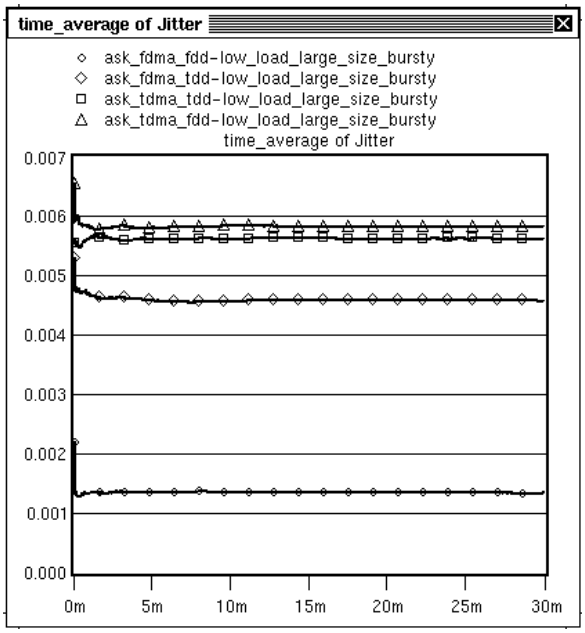

Figure B.4. Time average plot of the jitter statistic for the four si mulation models under low load, large network size and bursty traffic.

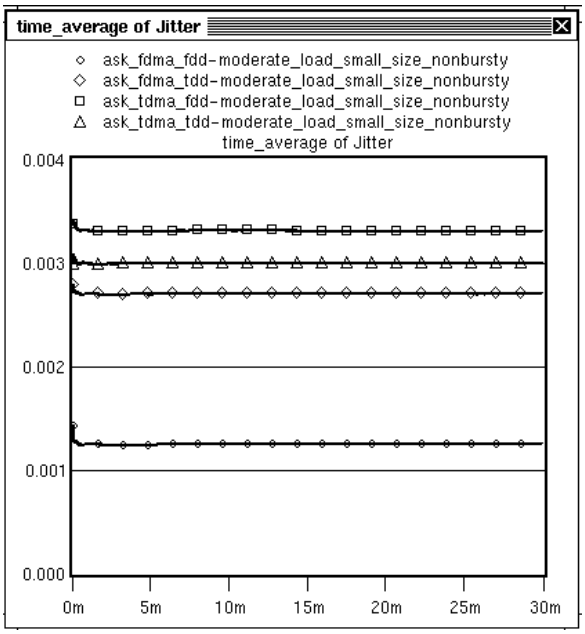

Figure B.5. Time average plot of the jitter statistic for the four simulation models under moderate load, small network size and non-bursty traffic.

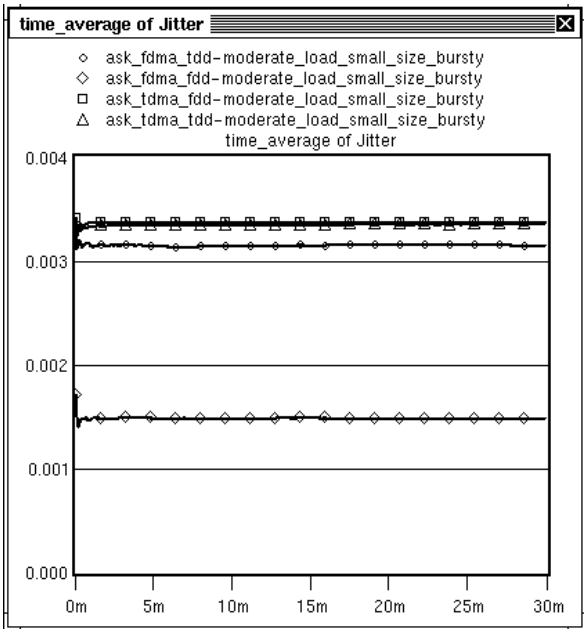

Figure B.6. Time average plot of the jitter statistic for the four simulation models under moderate load, small network size and bursty traffic.

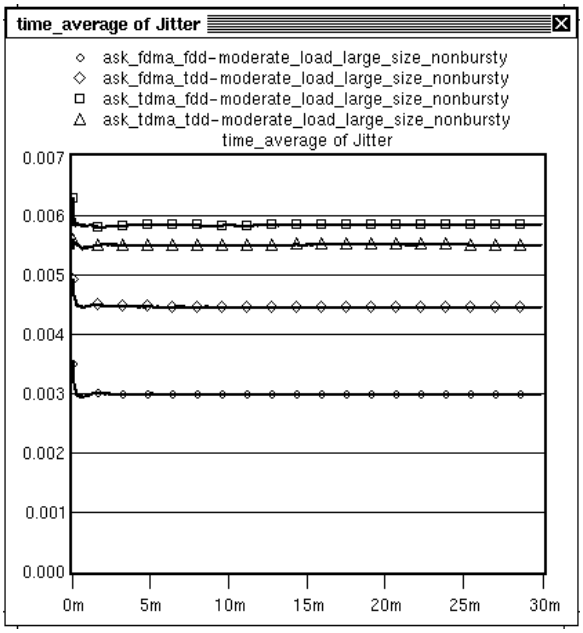

Figure B.7. Time average plot of the jitter statistic for the four simulation models under moderate load, large network size and non-bursty traffic.

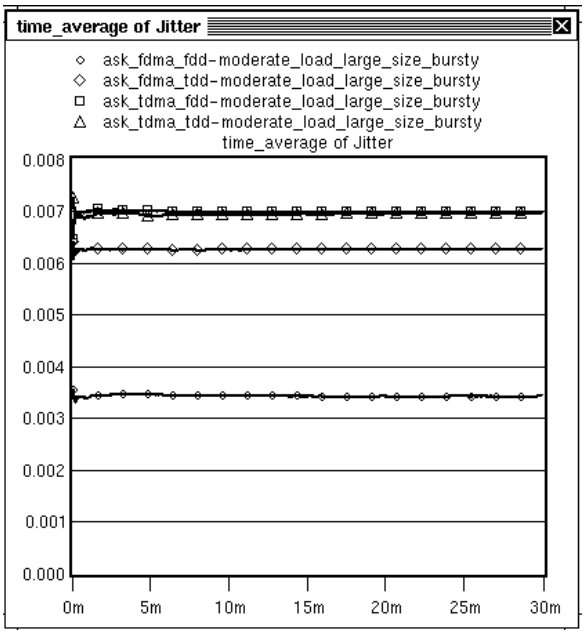

Figure B.8. Time average plot of the jitter statistic for the four simulation models under moderate load, large network size and bursty traffic.

Vita

Abhijit Khobare was born on November 4, 1976 in the city of Mumbai (earlier called Bombay), India. A chance enrollment in a BASIC programming language course while in high school introduced him to the fascinating field of computers. He graduated from the Karnataka Regional Engineering College, Surathkal, with a Bachelors degree in Computer Engineering in 1998. He then joined the graduate program in Computer Science at Virginia Tech. He will be graduating with a Master of Science degree in Computer Science in August 2000.