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Performance Evaluation of an Integrated FDDI-ATM-FDDI Network

by

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

**Ottawa-Carleton Institute for Electrical Engineering
Faculty of Engineering
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Carleton University
Ottawa, Ontario, Canada**

March 30, 1992

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**"Performance Evaluation of an
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submitted by

**Yue Yang,
B. Eng.**

**in partial fulfillment of the requirements
for the degree of Master of Engineering**

Thesis Supervisor

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March 30, 1992**

Abstract

An integrated network is expected to support both conventional and broadband traffic. In this thesis, we focus on the performance evaluation of a FDDI-ATM-FDDI network in an integrated traffic environment. The study shows that the FDDI protocol and the ATM protocol, in their basic forms, are unable to divide the bandwidth evenly between different categories of traffic. The problem is correctable by adopting optimal mechanisms. In addition, we also analyze the buffer sizes required in the ATM network, as well as the traffic statistics in both ATM-FDDI and FDDI-ATM bridges.

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To My Husband

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Chapter 1

Introduction

1.1 Background

High speed local area networks (LAN) in the 50-150 megabit-per-second range are now becoming commercially available. These networks are based on the fiber-distributed data interface (FDDI) [1] and the distributed queue dual bus (DQDB) standards. As LANs proliferate, the need for interconnecting them into such larger entities as metropolitan-area networks and the even larger wide-area networks (MANs and WANs) becomes apparent [2]. Broadband ISDN will be the suitable backbone network to connect the local area networks. Asynchronous Transfer Mode (ATM) [3] is expected to be a target technology for the B-ISDN.

The integrated traffic environment presents a challenge for interconnected wide-area networks, due to the different traffic arrival pattern. One such configuration, involving the interconnection of 100 Mbps Fiber Distributed Data Interface (FDDI) high speed LAN, through a backbone B-ISDN network based on the ATM protocol, is analyzed in this thesis. Figure 1.1 shows the core principal topology of the Wide Area Network (WAN) environment. An integrated traffic arrival process, including both broadband traffic (graphics, high/low resolution images or any other kind of data) and conventional traffic (electronic mail, spread sheet, personal database query, etc.), is considered in the investigation.

1.2 Thesis Objective

In this thesis, a FDDI LAN is first chosen as the backbone for conventional traffic and three such FDDI LANs are interconnected by an ATM network. At this stage, the broadband stations (the stations which produce large quantity of data in short period of time) are connected directly to the FDDI LANs.

Figure 1.1 Wide Area Network

The objective of the thesis is to examine FDDI-ATM-FDDI networks in terms of traffic characteristics, end-to-end delay and buffer sizes, and to investigate the sensitivity of the network behavior to the choice of parameter settings within the FDDI protocol. Presentation of the distribution of end-to-end delays provides a measure of the environment that would be faced by end-to-end Transport Protocols in the attached stations. In order to provide satisfactory service, it is shown that certain improvement mechanisms, such as restricted token and priority, are beneficial, while adjustment of the FDDI Target Token Rotation Time is ineffective.

1.3 Methodology

The thesis objective is achieved by organizing the research according to the following four steps:

(1) A WAN of three FDDI rings, connected by an ATM network, is set up as a platform for the purpose of investigating the statistical behavior of the integrated network. Two categories of nodes, broadband station and attached conventional LANs, are included

in the model. The timed-token FDDI protocol is chosen and no priority scheme in the FDDI ring is considered in this model.

(2) The traffic arrival processes for both attached conventional LANs and broadband stations are assumed to be burst-idle process, and a two-state Markov model [4] is adopted for the traffic used in the investigation. The main difference between the conventional traffic and broadband traffic is the level of burstiness.

(3) A series of simulation experiments is conducted on the FDDI-ATM-FDDI network model. The study is focused on this network's ability to handle and balance the two categories of traffic (conventional traffic and broadband traffic). The simulation experiments are conducted to explore whether the current basic FDDI and ATM protocols are capable of balancing the system capacity between the two categories of traffic when the average load of the two types of traffic are equal. It is found that the current basic version of the FDDI protocol and the ATM protocol are not optimized for this purpose.

(4) After a thorough investigation of the basic FDDI-ATM-FDDI model, another group of simulation experiments is performed. These investigations are aimed at evaluating the effectiveness of utilizing some features of FDDI protocol and ATM protocol, such as:

- Using the restricted token option
- Granting priority to broadband traffic in the ATM multiplexer
- Tuning FDDI parameters

It has been shown that, by combining the restricted token mechanism and priority scheme in the ATM multiplexer, the system service quality can be improved significantly. It is also shown that tuning one of the FDDI parameters, such as Target Token Rotation Time (TTRT), a scheme which is useful in the conventional traffic case [5], is ineffective in the integrated environment.

The performance of the FDDI-ATM-FDDI integrated network is analyzed from the point of view of the end-to-end delay for both conventional traffic and broadband traffic under an intermediate range of network load, i.e. 50% of the FDDI system capacity. Other issues, such as maximum throughput and packet or cell recovery methods are beyond the scope of this thesis and are not discussed. The FDDI protocol and the ATM protocol

Figure 1.2 Scope of the Networks

considered here are defined for asynchronous types of traffic only. Further analysis and investigations of the FDDI-ATM-FDDI network are needed in order to evaluate the network behavior when dealing with synchronous traffic.

The FDDI-ATM-FDDI model employed in this thesis is restricted to the functions of the source FDDI MAC layer to the destination FDDI MAC layer, as shown in Figure 1.2. Higher layer protocol functions will not be considered. The architecture of the model is at the block level and not at the lower hardware level; it thus details only functional elements. The architecture of the model is scalable, which means that a similar effect will occur when the network size and number of stations are changed. Although the investigation is based on a particular FDDI-ATM-FDDI network model, the analysis and results can be generalized to serve as a reference for other network topologies and to accomplish possible solutions to other similar types of networks.

1.4 Literature Review

Recent developments in the area of high-speed fast packet switching technologies are expected to support multimedia applications [6]. Multimedia communications are distinguished by different resource requirements, traffic characteristics, and performance objectives for each medium. Novel fast packet switching technologies are being developed for broadband-integrated-services-digital-networks (B-ISDN), capable of providing

a wide range of services — from conventional voice and low-speed data transfer to high-speed image transfer and video in the wide area environment. Broadband ISDN access can be tailored on a single optical fiber, to meet the needs of individual clients. Large scale production of highly integrated system components of a unique B-ISDN will lead to a cost-effective solution [7][8]. Asynchronous Transfer Mode (ATM) is expected to be a target technology for the B-ISDN [9][10][11][12]. In the ATM-based transport network, all the information, including voice, data, and video, are conveyed using a fixed-size cell. An ATM network is a high-speed-multimedia network which handles various classes of traffic with different bit-rates and with different quality of service requirements. To achieve a high-speed-multimedia network, the ATM network adopts a simplified transport mechanism based on hardware cell switching without any flow control and without retransmission inside a network [3]. The necessary number of cells is allocated on demand and bursty information is statistically multiplexed.

In the LAN case, FDDI employs an optical fiber medium which is one of the candidates of the future integrated local-area network. FDDI is being developed in Accredited Standards Committee (ASC) X3T9-chartered to develop computer input/output (I/O) interface standards in 1983 [13]. FDDI followed the packet data architecture concepts of IEEE P802 and chose the emerging 4 Mbit/s token ring protocol.

The priority mechanisms of IEEE 802.4 Token Bus, which have been selected for FDDI, have been studied by Watson [14]. A comparison study of MAC protocols of CSMA/CD Bus, Token Bus, Token Ring, and Slotted Ring for use with high-speed LAN as FDDI and 140 Mbps Backbone Wideband Network of the ESPRIT-project is given by Danthine [15]. Performance analysis of the FDDI 100 Mbps optical token ring was conducted by A. Schill [16], Th. Welzel [17], R. O. LaMaire [18], and P. Martini [19]. Schill investigated the behavior of the timed-token protocol with respect to its controlling timers and the ring topology. He also evaluated the effectiveness and sensitivity of the FDDI priority mechanism. All his studies were based on simulation. Welzel's [17] work emphasized the performance analysis for a token ring acting as a high-speed backbone network. He assumed all traffic in the token ring was accumulated from several conventional LANs such as Ethernet, and he defined two categories of traffic in the network: file transfer, which was bursty in nature, and interactive traffic, which were considered as continuing streams of traffic. After a thorough simulation study,

he presented the statistics of file delay and packet delay. LaMaire [18] discussed the importance of delay analysis in the FDDI network and he developed an approximation method for delay investigation. Martini [19] considered the case of file transfer in high-speed token ring network. He studied the suitability of multiple token access protocols and depicted the statistics of both file and packet delay.

The throughput performance of FDDI has been analyzed by Dykeman and Bux [20]. Simulation studies conducted by Pang and Tobagi [21] were the throughput performance of the timed-token bus (802.4) which used a protocol similar to that of FDDI. Another study with respect to the traffic characteristics was done by N. Wainwright and A. Myles [22]. They studied different network sizes under different traffic conditions and compared the delay characteristics of FDDI and IEEE 802.6 metropolitan area networks (MAN) network-access mechanisms. The authors concluded that the maximum throughput of both the networks is adversely affected by the presence of a high proportion of short packets in the traffic, and that this effect is greater in IEEE 802.6 network. The actual measurements and experiments of a FDDI-installation was done by P. Davids, Th. Measer, and O. Spaniol in Aachen University of Technology [23]. They commented that while most research contributions focused on high load in FDDI or DQDB and on fairness problems under very high load, realistic situations call for more attention to the lower and intermediate load ranges.

R. Jain [5] studied the effect of parameters of the FDDI network's performance. The metrics used in [5] as measurements are: productivity and responsiveness. Productivity for FDDI is measured by its throughput while responsiveness is measured by the response time and access delay. Jain assumed a "burst Poisson" arrival pattern for his simulation model. From his experiments he concluded that the TTRT is the key network parameter available to the manager for optimizing the performance of the FDDI ring. He also indicated that the value of TTRT shouldn't be too small since a small TTRT gave poor efficiency. On the other hand, a very large TTRT is also undesirable since it yields long access delay. He concluded that a TTRT value equal to 8 ms is the most desirable since it gives 80% or more efficiency on all configurations and results in a less than one second maximum access delay on big rings.

Despite the many research papers that have been published for the analysis of separate FDDI and ATM cases, few results have been developed for FDDI rings connected by

an ATM network. To the best knowledge of this author, the only analytic results on the LAN-WAN-LAN networks are those of M. el. Zarki, and Ness Shroff [24]. They provided an approximate analysis for determining the mean end-to-end delay for different packet loss recovery schemes over heterogeneous interconnected LAN-WAN-LAN type networks. They also demonstrated the trade-off between the different recovery schemes as a function of WAN link capacity and nodal buffer sizes for different throughput values.

1.5 Thesis Outline

This thesis will present a detailed study of an integrated wide-area network consisting of three FDDI collector rings connected by an ATM backbone network. The study will focus on this wide-area network's ability to support the requirements of different categories of traffic and more important, will attempt to evaluate the system ability of balancing the allocation of bandwidth between all active stations on the network. Two major areas are investigated by the study:

- The efficiency and fairness of the FDDI-ATM-FDDI network in supporting both conventional traffic and broadband traffic.
- The abilities of several mechanisms to improve the FDDI-ATM-FDDI network's behavior in the integrated traffic environment.

In order to evaluate the performance of such a WAN to support the integrated traffic, simulation models have been developed using the Simscript-II.5 [25] which is a general-purpose simulation programming language. Simscript is a powerful, free-form, English-like language, which supports the applications of software engineering principles such as structured programming and modularity. This thesis uses Simscript as a discrete-event simulator for conducting the performance evaluation.

The remainder of the thesis is composed of five chapters. Chapter Two describes the aspects of the FDDI standard and the ATM standard related to the thesis. The difference between the FDDI protocol and the 802.5 protocol is discussed, as is the network architecture and timing requirements. A minimum functionality bridge protocol proposed in [26] is briefly described.

Chapter Three presents the development of the detail simulation model of three FDDI rings connected by an ATM network. The model's development is divided into two stages. The first stage is devoted to the construction of an FDDI model. This model is verified by comparing it with another FDDI model evaluated by a block oriented network simulator called Bones [27]. The second stage develops an ATM network model, and connects the verified FDDI model with the ATM model, thus setting up a completed wide-area network model. This final model is verified by testing each processing step. A two-state Markov process model is defined as the traffic model to support the investigation.

Chapter Four presents a detailed study of the FDDI-ATM-FDDI network's ability to provide fair services in the integrated traffic environment based on the current protocol. Particular emphasis is placed on the network's ability to guarantee reasonable end-to-end delay for different categories of traffic. It is observed that with the current version of the FDDI and the ATM protocols' standards, broadband traffic suffers a much longer delay than conventional traffic, which implies poor services for broadband users. The conclusion is that it is necessary to employ improvement mechanisms in such integrated networks. For the purpose of providing necessary information for future researchers, traffic statistics were collected at two critical points in the integrated network:

- the FDDI-ATM bridge, and
- the ATM-FDDI bridge

Chapter Five extends the study performed in Chapter Four by tuning the Target Token Rotation Time (TTRT) parameter, as well as employing new improvement mechanisms into the model. The chapter presents a thorough picture of the effectiveness of three different improvement mechanisms and the influence of the TTRT. Then, by employing several effective improvement mechanisms, the optimized system performance is evaluated, and the results are discussed.

Finally, Chapter six summarizes the major conclusions and provides some suggestions for future work.

1.6 Thesis Contribution

The contributions of this thesis are summarized in the following:

- The determination that the FDDI standards and the ATM standards in their current basic forms cannot fairly divide bandwidth between conventional and broadband stations. It is also shown that this problem is extreme when only a small percentage of broadband traffic exists in the network.
- The unfairness is found to stem from the way the FDDI standard allocates system capacity.
- The unfairness problem is correctable by adopting restricted token mechanism in the FDDI ring and priority scheme in the ATM network. Adjusting TTRT is not an effective way to improve the unfairness. Combining restricted token and priority methods allows the network manager to efficiently control the network.

Chapter 2

Network Standards and Protocols Used in This Thesis

2.1 Overview

In the near future, local-area networks based on the FDDI protocol are expected to be linked across a city, or a country. One means of interconnection is the 150 Mbps Asynchronous Transfer Mode (ATM) [3] recommended by CCITT. Bridges can interconnect LANs into a wide-area network (WAN). The bridges interconnecting the FDDI and the ATM networks relay packets and cells between the LAN and the WAN by fast packet switching and perform the necessary protocol conversion on reformatted packets or cells.

To provide background for the rest of the thesis, this chapter reviews certain aspects of the three protocols — FDDI, ATM, and the Bridge Interface protocol (BI) and briefly explains the underlying operational concepts of the FDDI network and ATM network.

2.2 FDDI Standard and Protocol

2.2.1 FDDI Standard

The FDDI [1] standard encompasses both the MAC layer and the physical layer. Figure 2.1 depicts the architecture of the FDDI standard. The standard assumes the use of the IEEE 802.2 standard, LLC. The standard is in four parts:

- Medium access control
- Physical protocol
- Physical medium dependant
- Layer management

Figure 2.1 FDDI Architecture

The MAC protocol is the heart of the FDDI standard. The specification defines the packet structure and the interactions that take place between MAC entities. For the detailed functions of physical protocol (PHY), physical medium dependant protocol (PMD), and layer management protocol (LMT), which are not considered in this thesis, please refer to [1].

2.2.2 FDDI MAC Protocol

FDDI [1] is a 100 Mbps token ring with a maximum configuration of 100 kilometers and 500 stations. The MAC protocol provides fair and deterministic access to the medium, address recognition, and generation and verification of packet check sequence. Its primary function is the delivery of packets, including packet insertion, repetition and removals.

Basic function of MAC protocol and MAC Algorithm

As with IEEE 802.5, the FDDI MAC protocol [1] is a token ring. The basic operation

of the token ring is very similar for both 802.5 and FDDI. The FDDI token ring technique is based on the use of a small token packet that circulates around the ring when all stations are idle. A station wishing to transmit must wait until it detects a token passing by. It then seizes the token by absorbing the token transmission as soon as the usable token is recognized. After the captured token is completely received, the station may begin transmitting packets. The station may continue to transmit until it has no more data to transmit or until a token-holding timer (THT) expires.

There is now no token on the ring, so other stations wishing to transmit must wait. They listen to the ring and repeat passing packets. Each station introduces into the ring approximately a 60-bit delay as the time to examine, copy, or change a bit as necessary. The packet on the ring will make a round trip and be purged by the transmission station. The transmitting station inserts a new token on the ring when it has completed transmission of its packets.

The bandwidth allocation scheme used in the FDDI network is quite different from the one used in the 802.5 network. For the purpose of supporting both a mixture of stream and bursty traffic, and multipacket dialogue, FDDI defines two types of traffic:

- Synchronous
- Asynchronous

The scheme works as follows. A target token rotation time (TTRT) is defined; each station stores the same value for TTRT. Some or all stations may have a synchronous allocation (SA), which may vary among stations. The allocation must be set such that:

$$\sum SA_i + D(Max) + P(Max) + Token.Time \leq TTRT \quad (2.1)$$

where

SA_i = asynchronous allocation for station i

$D(Max)$ = propagation time for one complete circuit of the ring

$P(Max)$ = time required to transmit a maximum length packet (4500 octets)

$Token.Time$ = Time required to transmit a token

Since we did not include the studies of synchronous traffic in this thesis, "SAi" here is assumed to be zero.

When a station receives the token it measures the time since it last received a token, which is counted in a token rotation timer (TRT). This value is saved in the token-holding timer (THT). TRT is reset to zero and begins running again. The station can then transmit according to the following rules:

- It may transmit synchronous packets for a time SA.
- After transmitting synchronous packets, or if there were no synchronous packets to transmit, THT is enabled and begins to run from its set value. The station may transmit asynchronous data only so long as $THT < TTRT$.

The intent is to ensure that the time between successive sighting of a token is on the order of TTRT or less.

In addition, FDDI provides a mechanism that satisfies the requirement for dedicated multipacket traffic. When a station wishes to enter an extended dialogue (which is the case of the broadband traffic transmission we are going to study in later chapters), it may gain control of all the unallocated bandwidth by using a restricted token. The station captures a nonrestricted token, transmits the first packet of the dialogue to the destination station, and then issues a restricted token. Only the station that received the last asynchronous packet may transmit asynchronous packets using the restricted token. The two stations may then exchange data packets and restricted tokens for an extended period, during which no other stations may transmit asynchronous packets. The standard specifies that restricted transmission must not violate the TTRT limitation, and it does not require the use of THT during this mode.

Figure 2.2 depicts the complete capacity allocation scheme, and Figure 2.3 summarizes the relationship among the various types of traffic.

Packet Format

The MAC packet format is shown in Figure 2.4, and its various fields are briefly described below.

Figure 2.2 FDDI Capacity Allocation Scheme

Figure 2.3 FDDI Capacity Allocation

SPS = Start of Packet Sequence

PA= Preamble

SD= Starting Delimiter

PC= Packet Control

DA= Destination Address

SA = Source Address

INFO = Information

PCS = Packet Check Sequence

EPS = End of Packet Sequence

ED = Ending Delimiter

PS = Packet Status

Figure 2.4 Packet Format

- **Packet Control (PC)** field is an 8 bit field which carries information on packet type and class, and on the address length.

- **Destination Address(DA)** and **Source Address (SA)** are two separate fields which can be either 16 or 48 bits in length.
- **Information (INFO)** field contains user data and can be of any length from 0 to 45000 octets.
- **Packet Check Sequence (PCS)** is used to detect erroneous data bits within the packet as well as erroneous addition or detection of bits to the packet.

2.2.3 FDDI Operations

An FDDI network uses a double counter-rotating ring topology [28] [29], or a "dual ring of trees" (Figure 2.5) with stations characterized by their attachment types and number of Media Access Controllers (MACs). A Dual Attachment Station (DAS) has two physical attachments, one to each ring of the dual trunk ring, and one or two MACs (single or dual MAC). Higher end stations, servers and routers will generally be DAS stations. Stations that have only one physical attachment (Single Attachment Station: SAS) are connected to one of the dual rings by stations called concentrators. Lower end desktop workstations and personal computers are likely to be FDDI SAS stations. Distributed applications that are candidates for FDDI can be classified by their bandwidth and response requirements and by their computation model. High end graphics, image processing, or computer-intensive applications that distribute the computation to high-speed devices and communicate large blocks of data for display are at one end of this spectrum. Desktop applications that access print, file, or database servers are at the other end. The matching FDDI spectrum has dual-MAC attached stations at the high end and single-MAC single attached stations at the lower end.

As described in previous sections, access to the ring is controlled by the rotation of a special type of packet called the token. The transmission of a packet waiting in the output buffer of a station is conditioned by the arrival of the token to the special station, and by some additional conditions based on timers' expiration which should maintain equal opportunities to transmit for all stations. The timers governing the transmission rights are negotiable between stations at start-up time by using the claim token process (the initiation process is not considered in this thesis). It is the responsibility of the sending station to strip the packet from the ring when it recognizes its own source address.

Figure 2.5 FDDI Network Station Types

All the processes, including management, are completely distributed, and each station participates in them.

There are two possible ways to use FDDI:

- For back-end applications, where computers directly connected to FDDI networks take advantage of the high throughput offered by FDDI in order to transfer data at high-speed over the network. These applications are expected to be heavily used in the next one or two years [29].
- For back-bone applications, where computers connected to low-speed LANs such as Ethernet and Token Ring communicate using the existing well-known LAN interfaces over an "Extended LAN". FDDI is used as the backbone of the "Extended LAN" [29].

Up to now, FDDI networks have been used almost only as backbones. The following are some examples:

- Inria, France [29], is one of the world's most active and advanced institutes in the fields of computer science and automation. The Inria's Recquencourt site is one of

France's best equipped computer installations . By the end of 1988, Inria operated a system of about 20 Ethernet networks, linking its complex computer facilities. Facing major congestion in their network, Inria's staff decided to build an extended LAN based on FDDI. After a trial pilot of two months, Inria's FDDI installation became operational in February, 1989.

- Aachen University, Germany [29], is situated in several locations around the city of Aachen. The requirement for a high-speed LAN for the University was presented by Prof. Spaniol in several symposiums on this matter. The network implemented contains 21 FDDI nodes which are connected by optical fibers supplied by the German PTT. Covering the city area, this implementation is a typical implementation of FDDI as a Metropolitan Area Network.

2.3 ATM Protocol

2.3.1 ATM Protocol

ATM is a high-bandwidth, low-delay, packet-like switching and multiplexing technique. Figure 2.6 depicts the hierarchical relationship of some of the functional layers required for information transfer access BISDN. In the ATM-based transport network, all the information, including voice, data and video, are conveyed using a fixed-size "cell". An ATM network is a high-speed-multimedia network which handles various classes of traffic with different bit-rates and different quality of service requirements. To achieve a high-speed-multimedia network, the ATM network adopts a simplified transport protocol based on two approaches — shift the semantic transparency as well as the time transparency to the boundary of the network. The ATM concept results from the merging of two well-known concepts:

1. Packet Switching

- No error or flow control on the links inside the ATM network.
- Connection-oriented at the lowest level. All information is transferred in a virtual circuit assigned for the complete duration of the connection.

- **Packets have a fixed and small length.** Instead of allowing variable length packets to be switched, only fixed small packets (called cells) are accepted by the network. This choice allows the use of very high speed switching nodes and puts no constraints on services, since large information entities will be chopped into cells.
- **Limited functionality in the header of the cells.** The sole functionality supported by the header of the ATM cells is the identification and characterizations of the virtual circuits. In addition, some error detection and correction on the virtual circuit identifiers is provided.

Figure 2.6 BISDN functional layers

2. TDM In the ATM network

The ATM protocol model recommended by CCITT is shown in Figure 2.7. The size of a time slot is set to 48 bytes, the header being 5 bytes long, thus the total length of a cell is 53 bytes.

A layered architecture is used for the ATM model, and there are three major components in the model:

- **ATM Adaptation Layer (AAL)**
- **ATM layer**
- **Physical Medium Dependent (PMD) layer**

Figure 2.7 BISDN ATM Protocol Reference Model

The ATM and AAL layers provide the transfer functions for both connection-oriented and connectionless types of services. For the ATM to FDDI bridge [26], a connection-oriented mode is used. One of the main functions of the ATM layer is cell multiplexing and demultiplexing. It multiplexes cells coming from individual VC/VPs into a noncontinuous composite flow of cells, and provides buffering to outgoing cells for contention resolution.

2.3.2 ATM Cell Structure and Description of Fields

The cell structure has been standardized to have 5 bytes of header and 48 bytes of payload. It is shown in Figure 2.8.

The meanings of each field are explained below:

- **Generic Flow Control (GFC)** field is used for flow-control at the user-network interface.

ATM Cell Structure

GFC: Generic Flow Control

VCI/VPI: Virtual Channel/Virtual
Path Identifier

PT: Payload Type

Res.: Reserved for future

HEC: Header Error Check

ATM Header Structure

Figure 2.8 ATM Cell and Header Structure

- **Virtual Channel/Virtual Path Identifier (VCI/VPI)** identifies a source-destination pair on an ATM virtual circuit. The VCI/VPI is also used to route a cell from a source to a destination on the ATM network.
- **Payload Type (PT).**
- **Reserve (Res.)** field is reserved for future use.
- **Header Error Check (HEC)** contains error checking information for the header.

2.4 Bridge Interface Protocol

When two systems are to be connected, they are connected through an intermediary, known in International Standard Organization terminology as a “relay”. There can be one or more relays resident in different layers of the ISO-defined reference model between the two systems. A bridge implemented in the data link layer is the intermediary chosen in my simulation model. In this section, a brief description of the BI protocol (bridge interface) designed by S. Agrawal [26] used in this thesis will be presented.

The functionality of a bridge varies according to the types of services supported by it. The bridge considered here supports only asynchronous services which are not time critical but bursty in nature. The core functions of this bridge are segmentation and reassembly.

The BI protocol is intended to interface a standard implementation of FDDI MAC layer on one side, and ATM Adaptation layer (AAL) on the other side by using the architecture shown in Figure 2.9. The essential data transfer functions of the bridge interface are to:

- Segment the FDDI packets into ATM cells for transmission
- Sort and reassemble incoming ATM cells into FDDI packets

Figure 2.9 Functional Architecture of the Bridge

The sender bridge makes 47-byte segments of a MAC packet in order to create ATM payloads. These packet segments are appended with a one-byte BI protocol header to form a 48-byte ATM payload as depicted in Figure 2.10. The structure of the BI protocol data unit (BI-PDU), which constitutes the full payload of an ATM cell, is shown in Figure 2.11.

The BI header provides the identification of the packet segments; it uses a 2-bit Cell-Type field to identify start-of-packet (SOP), end-of-packet (EOP), and continuity-of-packet (COP). The individual consecutive intermediate cells are not distinguished from

Figure 2.10 The segmentation of a MAC packet into ATM cells

Figure 2.11 BI Protocol Data Unit

each other as it is assumed that all the packet segments are delivered in order. The format of the BI header for different types of cells is also shown in Figure 2.12. The remaining 6 bits of the BI header are utilized to carry different information for different types of cells which are not considered in this thesis. The segmentation-and-reassembly (SAR) policy for the BI protocol involves less functionality than that carried by the standard AAL.

2.5 Conclusion

In this chapter we have briefly reviewed the necessary portions of FDDI protocol, ATM protocol and one of the bridge protocols which will be employed in this thesis.

Figure 2.12 BI Header Format for Different Cells

The related functions of those protocols are discussed. For more detailed information concerning these protocols, please refer to the references listed in this chapter.

Chapter 3

FDDI-ATM-FDDI Simulation Model and Model's Verification

In this chapter, a simulation model of three FDDI LANs connected by an ATM WAN will be built up and verified. Section 1 sets up an exhaustive-service FDDI LAN model and the model's verification is discussed. Section 2 extends the basic FDDI model into the final model – three FDDI LANs with timed-token protocol connected by an ATM WAN. A reasonable traffic model will be presented and the final verification of the FDDI-ATM-FDDI model will be discussed. Section 3 will give a brief conclusion. We will use this FDDI-ATM-FDDI model for our simulation experiments.

3.1 FDDI Simulation Model and Model's Verification

One way to verify a model is to build up two models of the same network using two entirely different simulation tools and compare the results. For the FDDI model of this section, Simscript [25] and Bones [27] are chosen.

3.1.1 Building up FDDI Simulation Model by Simscript

A six-node exhaustive-service FDDI ring is modeled by using a discrete-simulation language: Simscript. The model is shown in Figure 3.1.

A packet life-time behavior process could be depicted in Figure 3.2. First, a packet is generated by a sending station on the FDDI ring, it is then filed into the sending station's transmission queue and possible queueing delay is introduced. Then it is removed from the queue for transmission; the transmission delay is based on the packet size and ring

Figure 3.1 FDDI Model

Figure 3.2 FDDI Packet Lifetime Behavior Process

capacity (here, the FDDI's capacity is assumed to be 100Mbps). After a certain period of propagation delay, the packet arrives at its destination station.

Simulation experiments are conducted on the FDDI model by using the parameters below:

- mean packet length: 10,000 bits, exponentially distributed
- number of stations: 6
- link capacity: 100 Mbps
- propagation delay: $5\mu\text{s/km}$
- ring length: 100km
- delay introduced by each station when it passes the coming packets: 60bit
- load: 0.05, 0.2, 0.35, 0.5, 0.65, 0.8, 0.95

In order to get accurate results, a large number of packets were simulated. For low load to media load range (from load = 0.05 to 0.65), 535,000 packets were generated, while for heavy load cases (load = 0.8 to 0.95), 5,000,000 packets were simulated, based

on the 95% confidence level and the $\pm 10\%$ confidence interval. The results of packet queueing time and packet transmission time are presented in Table 3.1 (throughout the thesis actual simulation results are quoted, but in fact their accuracy is $\pm 10\%$).

Table 3.1 The Results from Simpscript Model

Load	No.of packets simulated	Delay(μs)	Queueing-time(μs)
0.05	535,000	616.0	266.1
0.2	535,000	676.7	326.8
0.35	535,000	766.0	416.0
0.5	535,000	907.7	557.7
0.65	535,000	1172.4	822.5
0.8	5,000,000	1835.2	1485.1
0.95	5,000,000	6462.9	6112.8

From the way the FDDI ring works, we know the queueing delay of a packet (for example, a packet in station 1's queue) before it is transmitted is composed of three time elements:

- The transmission time required for all packets which arrive earlier than this particular packet in the same queue (tx.1).
- The transmission time for all packets in the queues whose servers could seize token before queue-1's server (tx.2).
- The propagation time the token has to spend before it arrives at station 1 (prop.t).

So the queueing time felt by a packet (q.t.p) could be expressed as follows:

$$q.t.p = tx.1 + tx.2 + prop.t \quad (3.1)$$

At lower load the ring is frequently idle; the mean queueing time and the mean propagation delay are each half of the ring latency. Having 6 stations with an average delay of 0.6μ s per station, this ring latency is 503.6μ s (due to the 100km ring length).

The packet transmission time is $100 \mu\text{s}$. Thus, the calculated mean queueing delay is approximately:

$$q.t.p = 0 + 0 + 503.6/2 = 251.8 \mu\text{s} \quad (3.2)$$

The mean packet transmission delay is the sum of the packet transmission time, the mean queueing time, and the actual packet propagation delay:

$$100 + 251.8 + 503.6/2 = 603.6 \mu\text{s} \quad (3.3)$$

The queueing time and the delay calculated above are within 5% of the simulation results listed in Table 3.1 (row 1, column 3 and 4).

When load increases, channel utilization increases and queueing time rises. However, due to the transmission of multiple packets per token, the mean packet transmission delay increases slowly at lower and intermediate load range and rises faster rather later when reaching throughput saturation.

3.1.2 Building up FDDI Simulation Model by Bones

According to the same assumptions and token scheme as described in 3.1.1, another copy of the FDDI model is built up by using Bones. Unlike the Simscript model, which simulates a realistic situation, the Bones model uses a virtual token technique for the purpose of saving CPU time [27]. The virtual token technique was implemented using a global memory which keeps track of two things: the state of the channel (free/busy), and how many packets are waiting to be transmitted when a station is currently holding the token.

There is a "want token" register in the system. When a station wants to transmit (i.e. it has a packet intended for another node), it first declares that it wants to transmit by incrementing the "want token" register. The station then checks if the channel is currently busy or not. If it is, it waits until a token appears. However, if it is not busy, it grabs the token by declaring the channel to be busy and waiting a random amount of time before transmitting (to model the time the token would have taken to go around

the ring and reach this station). When a station gets a token (either by waiting for it or grabbing it), it transmits its packets. It then decrements the “want token” register for each packet sent. The station then checks if other stations are still waiting to transmit. If so, it sends a token out on the ring. Otherwise, the station sets the channel state to free. The next time another station wants to transmit, it will grab the token using the technique described above. Therefore, the waiting time felt by a packet is composed by the same three elements as in Simscript case.

By adopting the same parameters as used in the Simscript model, seven experiments were conducted and the results are shown in Table 3.2.

Table 3.2 The Results from the Bones Model

Load	No.of packets simulated	Delay(μs)	Queueing-time(μs)
0.05	535,000	623.9	274.9
0.2	535,000	690.1	340.3
0.35	535,000	770.8	424.5
0.5	535,000	910.4	563.6
0.65	535,000	1172.4	823.1
0.8	5,000,000	1826.9	1485.2
0.95	5,000,000	6412.0	6092.8

3.1.3 Results Discussion and Model's Verification

In 3.1.1 and 3.1.2, two FDDI models with the same assumptions and parameters were built up by using Simscript and Bones respectively. Seven simulation experiments were performed and results were derived. In this subsection, we are going to verify the models by comparing the two sets of results.

For the purpose of comparison, the Simscript results and Bones results will be listed

in the same table (Table 3.3, Table 3.4), and the derivation of the two group of results will be calculated.

Table 3.3 Queueing time comparison

Load	Queueing-time(μ s)		Deviation
	Simscrip model	Bones model	
0.05	266.1	274.9	3.3%
0.2	326.8	340.3	3.9%
0.35	416.0	424.5	2.0
0.5	557.7	563.5	1.05%
0.65	822.5	823.1	0.007%
0.8	1485.1	1485.2	-0.006%
0.95	6112.8	6101.8	-0.18%

Table 3.4 Delay comparison

Load	Delay(μ s)		Deviation
	Simscrip model	Bones model	
0.05	616.0	623.9	1.28%
0.2	676.7	690.1	1.98%
0.35	766.0	770.8	0.62%
0.5	907.7	910.4	0.03%
0.65	1172.4	1172.4	0.0%
0.8	1835.7	1826.9	-0.45%
0.95	6462.9	6432.0	-0.48%

From Table 3.3 and Table 3.4, we can see that the results of queueing-time and delay from the Simscript model and Bones model are close enough to verify the FDDI model. However, we also observed a very interesting phenomenon: for the light load range (0.05, 0.2 and 0.35), there is, approximately, a 3% deviation between the two groups of queueing time results (Table 3.3) from the two models. However, when the load increases, the deviation decreases and eventually approaches zero. In order to gain more confidence for the FDDI model and explain this interesting phenomenon, let us take a closer look at the two models. We will start with the Simscript model first. As explained in 3.1.1, packet transmission delay is composed of $tx.t1$, $tx.t2$ and token propagation delay (as in equation 3.1); since the six stations are equally distributed around the ring, let ' τ ' represent the propagation time between two neighbor stations, so that the possible values for token propagation delay are six discrete numbers, such as:

"0" : as token is now in queue-1.

"1*(propagation delay between two neighbor stations) = τ ".

"2*(propagation delay between two neighbor stations) = 2τ ".

"3*(propagation delay between two neighbor stations) = 3τ ".

"4*(propagation delay between two neighbor stations) = 4τ ".

"5*(propagation delay between two neighbor stations) = 5τ ".

Using "prop.d" to symbolize the propagation delay, the mean token propagation time for this case is:

$$E(prop.t) = (0 + 5 * \tau) / 2 = 2.5 * \tau \quad (3.4)$$

Next, let us look at the Bones model. As described in 3.1.2, instead of simulating a realistic situation, a virtual token technique was employed in Bones model. With the virtual token technique, when a station wants to transmit, and the communication channel is not currently busy, the station just grabs the token by setting the channel as busy and waiting a random amount of time before transmitting. This random amount of time was used to simulate the propagation time the token had to spend before it could reach the station. It was assumed in the model, that this propagating time was uniformly distributed from "0" to " $6*\tau$ ". Obviously, the possible values for token propagation delay in the Bones model are continuing values ranged from "0" to " $6*t$ ". The mean propagation delay for this case is:

$$E(prop.t) = (0 + 6 * \tau) / 2 = 3 * \tau \quad (3.5)$$

Therefore, the delay derived from the Bones model should be a little larger than the delays derived from the Simscript model for the light load case. However, for a heavy load case there are almost always packets waiting on other queues for transmission when any of the servers are busy. Therefore, when a server completes transmission, it just passes the token to another station; no station need grab it.

Thus, the two models become almost identical in heavy load situations. This is the reason why the results from the Simscript model are smaller than the results from the Bones model in lighter load ranges, and the deviations approach zero when load increases.

In conclusion, the FDDI model is validated by the above simulation experiments and analysis. The Simscript FDDI model will be used as a critical part in later FDDI-ATM-FDDI model for future investigation.

3.2 FDDI-ATM-FDDI Simulation Model and Model's Verification

In this section, the verified FDDI model will be extended into a FDDI-ATM-FDDI model. The situation is different in this more complicated case, where some of the packets are generated in one FDDI LAN (referred to as "source" FDDI LAN in this thesis), sent to the FDDI-ATM bridge and segmented there into cells. Those cells then travel across the ATM network. The ATM network is modeled as an ATM multiplexer connected by an ATM link. The cells segmented by the FDDI-ATM bridges are first filed in the ATM multiplexer input buffer, then the ATM multiplexer multiplexes the cells and feeds the cells to the link towards the destination ring. The cells are reassembled at the ATM-FDDI bridge, and are eventually terminated at another FDDI LAN (referred to as "destination" LAN in this thesis).

For the purpose of setting up the FDDI-ATM-FDDI model correctly, we will first examine the realistic situation in the FDDI-ATM-FDDI network, clarify the segmentation and reassembly processes, then set up a FDDI-ATM-FDDI model based on the verified

FDDI model, define a reasonable traffic model, and finally validate the FDDI-ATM-FDDI model.

3.2.1 The Realistic Traffic Situation in FDDI-ATM-FDDI Networks

Three FDDI rings connected by an ATM network are shown in Figure 3.3.

Figure 3.3 Three FDDI Rings Connected by an ATM WAN

For convenience, it is assumed that only one-direction traffic exists in this network. Two completely different characteristic traffics — conventional traffic and broadband traffic — will appear in the network. A certain percentage of traffic is local and others are internet (the internet traffic is defined as the traffic which is generated in a source FDDI ring and transmitted through the ATM network towards the destination LAN). Packet segmentation (FDDI packet → ATM cell) is performed at the FDDI-ATM bridge: a certain processing delay is introduced here and an ATM header is added to each cell. The ATM network is assumed to be lossless. At the ATM-FDDI bridge, reassembly is

Figure 3.4 FDDI Local Traffic Process

processed, and delay is also added there. The detailed processing steps of the local traffic process and the internet traffic process are presented below.

1. FDDI Local Traffic Process

In the FDDI and ATM interconnected network environment, the FDDI local traffic is the traffic generated and terminated in the same LAN. The lifetime behavior of those traffic is exactly the same as the traffic in a single FDDI ring. Figure 3.4 depicts the FDDI local traffic process.

2. Internetworking Traffic Process

The process of internetwork traffic is much more complicated than the simple FDDI local traffic. There are three main steps for such a network:

Step 1: source FDDI network

Step 2: ATM network (includes FDDI-ATM bridge, ATM link, ATM-FDDI bridge)

Step 3: destination FDDI network

The outline of the whole process is presented in Figure 3.5. The detailed steps of the process are explained in Figure 3.6

3.2.2 Segmentation and Reassembly Process

In the FDDI ring, the information unit is the packet. The packet size could be variable according to some distribution. However, in the ATM network, only fixed-size cells (53 bytes) are allowed to enter. Thus, packet segmentation and cell reassembly have to be performed in two places:

- FDDI-ATM bridge (segmentation).

Figure 3.5 Outline of Internetworking Traffic Process

Figure 3.6 Detailed Steps for Internetwork-Traffic Process

Figure 3.7 FDDI Packet Segmentation

- ATM-FDDI bridge (reassembly).

1. Segmentation

Segmentation is performed at the FDDI-ATM bridge. The sender bridge makes 47-byte segments of a FDDI packet in order to create ATM payloads. These packet segments are appended with a one-byte BI protocol header to form a 48-byte ATM payload. This is shown in Figure 3.7 [26]. The throughput of the bridge is 100 Mbps. The total delay across the bridge per 32-bit word is 640ns after optimization [26].

The BI header provides the identification of the packet segments: it uses a 2-bit Cell-Type field to identify start-of-packet (SOP), end-of-packet (EOP), continuity-of-packet (COP). The individual consecutive intermediate cells are not distinguished from each other as it is assumed that all the packet segments are delivered in order.

2. Reassembly

Reassembly is processed at the ATM-FDDI bridge. Since a receiver bridge may be receiving more than one packet at a time in the form of interleaved cells from different sources, a packet-identification is needed to separate the incoming packet segments in order to get them reassembled. According to the ATM protocol, a 24-bit field in each ATM header acts as Virtual channel/Virtual path identifier (VCI/VPI). The VCI/VPI field is used to identify the LAN bridge from which the cell has come. Since each bridge can

only be transmitting one FDDI packet at a time, the VCI/VPI field also identifies the correct packet to which the cell should be reassembled at the receiving bridge.

The basic functions of the ATM-FDDI bridge are:

- Read the VCI/VPI field to find the header-cell of a packet.
- Read the VCI/VPI field to distinguish the cells coming from different rings.
- Separate the cells from two rings into two groups of buffers.
- When all cells belonging to one packet have arrived, reassemble those cells into a packet.

The throughput of the FDDI-ATM bridge is assumed to be 150 Mbps. The total delay across the ATM-FDDI bridge per 32-bit word is 520ns (not including the FDDI physical layer reception time which is 320ns) [26].

3.2.3 Building up the Simulation Model

Based on the discussion in the previous two sections, a simulation model was set up using a discrete simulation language: Simscript. The outline of the model is shown in Figure 3.8. In this model, the two source FDDI rings are statistically identical. There are altogether ten stations in each of the source FDDI rings. Some of them are broadband stations which produce very large files and images, others are conventional stations whose traffic comes from some small local area networks such as Ethernet. In the destination FDDI ring, only conventional sources exist. The traffic produced by conventional stations is typically a combination of e-mail, database query, small file transfer, and interactive communications.

The traffic produced by both conventional stations and broadband stations is modelled as burst-idle processes. The broadband traffic is much more bursty than the conventional traffic. In the destination FDDI ring, only conventional traffic exists.

In both source and destination FDDI networks, a nonexhaustive service token strategy is assumed. The target token rotation time (TTRT) is chosen as 8 milliseconds, as suggested in Jain's paper [5]. Residual service is allowed, which means that if a packet is being transmitted when the THT expires (for the calculation of THT, please refer to

Figure 3.8 Simulation Model Outline

"2.2.2"), the station is allowed to finish the transmission of this packet before it has to release the token. If an empty-queue station gets a token, it just lets the token go to the next down-stream neighbor. Certain propagation delay and station latency are added when the token travels across the FDDI ring and passes stations.

It is assumed that 50% of traffic is local and 50% is internet. The internet packets are segmented in the FDDI-ATM bridge and are reassembled in the ATM-FDDI bridge. The packets waiting for segmentation are segmented in a FIFO manner. Two intermediate queues, pre.seg1 and pre.seg2, are used in the simulation model for the purpose of intermediate processing. After the packets' segmentation, the corresponding cells are filed into two queues: min.q1 for FDDI ring1 packets and min.q2 for FDDI ring2 packets. The ATM multiplexer checks the min.q1 and min.q2 every 5 microseconds to remove all cells in the min.q1 and min.q2 in turn to the multiplexer queue, if there are cells waiting to be removed. Cells wait in the multiplexer queue until they are transmitted by

the ATM server. The cell propagation delay along the ATM link is simulated by filing the cell into a queue "intnt_list", where every cell which has been transmitted by the ATM server has to wait for 500 microseconds (it is assumed that the length of the ATM link is 100 km) before they can be filed into the reassembly queue. The cells are put into the reassembly queue after they finish the ATM trip. At the reassembler, a packet is reconstructed whenever all cells belonging to one packet have arrived. Then, the newly-constructed packets wait in the destination FDDI entrance queue: "d.brdg.q". The packets will be removed after a certain period of queueing if there are already packets queueing and when the entrance station gets a usable token.

In the simulation model, there are eighteen subprograms and routines in the two source FDDI network parts, four subprograms and routines for source FDDI ring1 segmentation and source FDDI ring2 segmentation, two subprograms for the ATM multiplexer, two subprograms for the reassembly process, and nine subprograms and routines for the destination FDDI ring.

3.2.4 Traffic Modelling

1. FDDI Application and Workstation Types

The applications that are candidates for FDDI can be classified by their bandwidth and response requirements and by their computation models. High-resolution graphics, image processing or computer-intensive applications that distribute the computation to high-speed devices and communicate large blocks of data for display are considered as one group: broadband application. Desktop applications that access print, file, or electronic mail are the other group: conventional applications. Table 3.5 illustrates the classification of FDDI applications.

To choose the most suitable workstation types for different applications, we should consider service requirements of the applications. First, let us examine the applications with different requirements.

1. Broadband Applications [29]:

Table 3.5 FDDI Applications

Conventional traffic	Electrical mail; Spread sheet; Personal database query
Broadband application	Computer graphics; Application data; Simulation program

Figure 3.9 FDDI Topology for Broadband Applications

From Table 3.5, we know the characteristics for broadband applications are:

- High throughput requirements
- Small workgroups
- Delay-sensitive for image-transmission

With a small workgroup that performs compositionally-intensive applications requiring high bandwidth, it is reasonable to connect stations directly to the FDDI ring (FDDI now acts as a back-end network). Figure 3.9 shows one FDDI topology for broadband applications.

2. Conventional Applications [29]:

The characteristics for conventional applications (see Table 3.5) are:

- Low throughput requirements
- Large workgroups
- Delay-critical (except e-mail application)

Figure 3.10 FDDI Topology for Conventional Applications

Figure 3.11 Model of Conventional-traffic Station

Figure 3.10 presents a FDDI topology that matches these requirements.

As shown in Figure 3.10, low-speed desktop workstations are first connected by Ethernet or other LANs (using FDDI as a backbone), through the LAN's router (or bridge) or the concentrator, to the FDDI network. However, in my simulation experiments, I assume that all conventional traffic comes from Ethernet, for the purpose of simplicity. Thus, the model for conventional-traffic stations is illustrated in Figure 3.11.

Therefore, traffic in the FDDI network can be roughly divided into two groups:

Figure 3.12 Traffic Model

Table 3.6 Types of Conventional Traffic

Application	Mean number of packets in a burst	Percentage of total traffic
interactive	2	10 %
E-mail	4	20 %
file-transfer	50	60 %
database query	20	10 %

broadband traffic, which comes directly from workstations to the FDDI, and conventional traffic, which is first collected in Ethernet then routed to the FDDI network.

Measurement on networks [5] has shown that when a station wants to transmit, it generally transmits not one packet, but a burst of packets. Therefore, a two-state Markov model (Figure 3.12) [4] is employed in the simulation for both conventional and broadband traffics.

During a burst period, a station continuously transmits fixed-length packets for an exponentially distributed period, then it stays in an idle state for another exponentially distributed period. Since the characteristics of conventional traffic and broadband traffic are quite different, the packet length, mean burst period, and mean idle period for both traffics will be decided separately:

1. Conventional Traffic

Conventional traffic packet size is chosen as 517 bytes. The average number of packets

Table 3.7 Types of Broadband Traffic

Application	Mean size of the information block transmitted once	Mean number of packets in a burst	Percentage of total traffic
color-high-resolution image transmission	$1024 \times 680 \times (8+8) = 11,141,120 \text{ bits} = 1,392,640 \text{ bytes}$	2786	10 %
color-low-resolution image transmission	$1024 \times 680 \times (4+8) = 8,355,840 \text{ bits} = 1,044,480 \text{ bytes}$	2089	10 %
black/white-high-resolution image transmission	$1024 \times 680 \times 8 = 5,570,560 \text{ bits} = 696,320 \text{ bytes}$	1393	10 %
black/white-low-resolution image transmission	$1024 \times 680 \times 4 = 2,785,280 \text{ bits} = 348,160 \text{ bytes}$	693	10 %
magnification of particular part of an image	64 kbytes (Ref. 3)	128	20 %
broadband file transfer	1024 kbytes	2048	40 %

in a burst, based on the assumptions listed in Table 3.6 is 33 packets.

When load = 0.05, the average idle time is 13600 microseconds.

2. Broadband Traffic

The broadband traffic we discuss here consists of: broadband file-transfer, and high and low resolution graphic transmission. All of the applications have the same characteristic: large amounts of data have been transmitted during a short period. The packet size for broadband traffic is assumed to be the same as that of conventional traffic: 517 bytes. The average number of packets in a burst, based on Table 3.7, is 1542 packets. The mean burst length is 63,777 μs .

When load = 0.05, the interburst time is: 1,211,765.28 microseconds.

3.2.5 Network Parameters for the Simulation Model

1. FDDI LAN Parameters

The FDDI model is based on the typical cases in Jain's paper [5], with a little modification. All the parameters are listed below:

- FDDI ring length: 4 Km
- Number of stations on the two source FDDI ring: 10 stations which are equally spread on each ring.
- Number of stations in the destination FDDI ring: 5 stations which are equally distributed on the ring.
- Average load to each station: 5 Mbps
- For each source FDDI ring station, 50 % of the traffic is local, 50 % is internet.
- Packet size: 517 bytes for both conventional traffic and broadband traffic.
- Target token rotation time (TTRT): 8000 μ s.
- Propagation delay: 5 μ s/km.
- Station latency: 60 bits
- FDDI ring capacity: 100 Mbps
-

2. ATM WAN Parameters

- ATM link length: 100Km
- ATM capacity: 150 Mbps
- Propagation delay: 5 μ s/km
- Multiplexer buffer size: infinite
- Reassembler buffer size: infinite

3. Bridges' Parameters [26]

- Throughput (segmentation speed): 100 Mbps
- Throughput (Reassembly speed): 150 Mbps

Figure 3.13 Critical Points of FDDI-ATM-FDDI Networks

3.2.6 Verification of the Model

It is not feasible to set up a mathematical model for such a large, complicated and realistic-situationed FDDI-ATM-FDDI system. Even using two different simulation tools to build up two copies of the model for comparison is also very time consuming. Thus, we have to find a way to verify the model.

The model is mainly composed of two kind of networks: FDDI LAN and ATM WAN. The critical points of the entire system are (Figure 3.13):

- Source FDDI LANs (A)
- FDDI-ATM-bridge (packet segmentation is performed here) (B)
- ATM multiplexer (C)
- ATM-FDDI bridge (cell reassembly is performed here) (D)
- Destination FDDI LAN (E)

If we can show that at each critical point (A, B, C, D, E), the system works correctly, then we will be confident that the entire system is implemented correctly.

1. The FDDI LAN Verification

The FDDI model was validated by comparing it with the results derived from the Bones model, as discussed in 3.1.

2. FDDI-ATM Bridge Verification

The throughput of the FDDI-ATM bridge is 100 Mbps. When there are packets ready for segmentation, this bridge segments the packets at a speed of 24,180 packets ($10^8/517 * 8 = 24,180$ packets/s), while it stays idle when no packets arrive. Thus, the FDDI-ATM bridge works in a two-state mode (Figure 3.14). Therefore, to verify the FDDI-ATM

Figure 3.14 FDDI-ATM Bridge Transition State

Table 3.8 Burst-State of FDDI-ATM Bridge

Start Time(μ s)		End Time(μ s)		Cell Sent		Throughput (Mbps)	
Ring1	Ring2	Ring1	Ring2	Ring1	Ring2	Ring1	Ring2
975.72	561.99	1017.1	603.35	11	11	100	100
5993.8	1389.5	6035.2	1430.8	11	11	100	100

bridge, we need to verify the two-state process first.

(1) Verify the idle-state:

In the simulation model, when the FDDI-ATM bridge is in an idle state, the corresponding process is turned off and no packets are segmented.

(2) Verify the burst-state:

The time of entering the burst-state, the time of exiting the burst-state, and the number of packets segmented during this period are shown in Table 3.8 (two samples are chosen arbitrarily from either source FDDI ring1 and source FDDI ring2).

Table 3.8 shows that during the period that the FDDI-ATM process stays in the burst-state, the throughput is 100 Mbps. Thus, the implementation of the two-state model is verified.

3. ATM Multiplexer Verification

Based on the assumption of the simulation model, the throughput of the ATM multiplexer is 150Mbps. Like the FDDI-ATM bridge, the ATM multiplexer works in a two-state mode: when there are cells ready for transmission, it multiplexes the cells at a speed of 353,773.5 cells per second ($150 \times 10^6 / 53 \times 8 = 353,773.5$ cells/s); however, when there are no cells waiting, the ATM multiplexer stays idle. The method we use to verify the ATM multiplexer is the same as the FDDI-ATM bridge case.

(1) Verify the idle-state:

In the model, when there are no cells waiting, the ATM-multiplexer process is turned off and no cells are multiplexed.

Table 3.9 Burst-State of ATM Multiplexer

Start Time (μs)	End Time (μs)	Cells Multiplexed	Throughput (Mbps)
570.0	572.83	1	150
575.0	583.49	3	150
5630.0	5632.83	1	150
6000.0	6056.6	20	150

(2) Verify the burst-state:

Table 3.9 (samples are chosen arbitrarily) lists the time the multiplexer enters the burst-state, the time it gets out off the burst-state, and the number of cells multiplexed during this period.

Table 3.9 shows that during the burst-state, the throughput of the ATM multiplexer is 150 Mbps. Therefore, the ATM multiplexer implementation is verified.

4. ATM-FDDI Bridge Verification

One of the main tasks the ATM-FDDI bridge performs is to reassemble the ATM cells into the original FDDI packets. It is assumed in the simulation model that the reassembly

speed is 150 Mbps. The ATM-FDDI bridge works in a similar way as the FDDI-ATM bridge: whenever cells arrive, it enters the burst-state, otherwise it stays idle. By adopting the same method as used in the previous cases, we are going to verify the two states of the ATM-FDDI bridge model.

(1) Verify the idle-state:

In the model, if there are no cells waiting, the reassembly process is turned off, no cell is reassembled.

Table 3.10 Burst-State of ATM-FDDI Bridge

Start Time (μ s)	End Time (μ s)	Cell Multiplexed	Throughput (Mbps)
1072.83	1075.34	1	150
5687.83	5690.34	1	150
9008.49	9010.99	1	150
10012.83	10015.34	1	150

(2) Verify the burst-state:

Table 3.10 presents four samples (chosen arbitrarily) of the time a burst-state starts, the time a burst-state ends, and the cells reassembled in the corresponding burst-period. Table 3.10 depicts that in the burst-state, the ATM-FDDI bridge reassembly speed is 150 Mbps. Consequently, the ATM-FDDI bridge model is verified.

5. Long-Term Behavior Verification

The next step we are going to do is to observe whether the long-term behavior of the FDDI-ATM bridge, the ATM multiplexer, and the ATM-FDDI bridge are correct or not.

(1) FDDI-ATM Bridge:

As we discussed in 3.2.5, the average load on the source FDDI rings is 50 Mbps, of which half is to cross the bridge towards the destination ring. As a result, the long-term

Table 3.11 FDDI-ATM Long-Term Behavior

Start Time (μs)	End Time (μs)	Cells Produced	Average Throughput (Mbps)
975.72	100,000,000	6,866,468	25.8

Start Time (μs)	End Time (μs)	Cells Produced	Average Throughput (Mbps)
561.99	100,000,000	6,258,439	23.5

average throughput of the FDDI-ATM bridge for this case should be approximately 25 Mbps.

We run the simulation for a considerably long period; we collect the first time the FDDI-ATM bridge enters the burst-state, the simulation stop time and the total number of cells produced during this sample period. The data is listed in Table 3.11.

As we can see, the average throughput is approximately 25 Mbps.

(2) ATM Multiplexer:

Since the ATM multiplexer multiplexes cells from both ring1 and ring2, the long-term average throughput of the ATM multiplexer should be around 50 Mbps. Table 3.12 lists the sample data. The average throughput is about 50 Mbps.

(3) ATM-FDDI Bridge:

Similar to the ATM multiplexer, the long-term average throughput of the ATM-FDDI bridge should be about 50 Mbps. Table 3.13 presents the results. The average throughput is approximately 50 Mbps.

In conclusion, based on the above discussion, the FDDI-ATM-FDDI model is verified.

Table 3.12 ATM Multiplexer Long-term Behavior

Start Time (μs)	End Time (μs)	Cells Multiplexed	Average Throughput (Mbps)
1022.83	100,000,000	13,124,870	49.35

Table 3.13 ATM-FDDI Bridge Long-term Behavior

Start Time (μs)	End Time (μs)	Packets Reassembled	Average Throughput (Mbps)
1072.83	100,000,000	1,193,170	49.35

3.3 Conclusion

This chapter provided a detailed discussion of a FDDI-ATM-FDDI simulation model and model's verification. Two copies of the FDDI model were first developed by using Simscript and Bones. This model's verification was completed by comparing the results derived from the two models and analyzing the difference.

Based on the verified FDDI model, a more complicated FDDI-ATM-FDDI model was set up. An integrated traffic environment was assumed, and two proper traffic models (one for conventional traffic and one for broadband traffic) were assumed. The FDDI-ATM-FDDI model was verified by testing each of the critical points of the model separately. This verified model will be used as a platform for investigation in later chapters.

Chapter 4

The Impact of Broadband Traffic on a Basic FDDI-ATM-FDDI Network

This chapter presents results to demonstrate the effect of introducing broadband traffic into a FDDI-ATM-FDDI WAN. The parameters of the WAN have been set for conventional traffic as suggested by [5]. This WAN is referred to as the "Basic FDDI-ATM-FDDI network". Section 4.1 illustrates the effects of introducing broadband traffic on:

- End-to-end delay for both conventional traffic and broadband traffic, and
- Queueing behavior of the ATM multiplexer buffer, and the destination ring entrance server buffer.

Approximate analytic results are used to verify the simulation results in certain cases where it is seemed feasible. Section 4.2 presents the delay distributions of conventional packet, broadband packet, and broadband files. Section 4.3 presents and discusses the traffic statistics in both the FDDI-ATM bridge and the ATM-FDDI bridge.

4.1 The Impact of Broadband Traffic on Network Behavior

In this section, a performance study of the basic-form FDDI-ATM-FDDI network is discussed. This initial study will be used as a basic platform for more complicated studies presented in Chapter Five. The study focuses on the mean end-to-end delay for both conventional traffic and broadband traffic under the same average total load. The study also analyzes the queueing behaviors in the ATM multiplexer and the destination FDDI entrance server queue. In order to get a clear view of the influence of the broadband traffic, a series of simulation experiments are conducted with the percentage of broadband traffic in both source FDDI rings and the destination FDDI ring as the independent variable. The Target Token Rotation Time (TTRT) in this series of experiments is chosen as 8000

microseconds, which is the value chosen by Jain [5] to be optimal for conventional traffic, all other network parameters being the same as the parameters listed in the network model (as in 3.2.5). The confidence level for all experiments is 95%. The confidence interval is limited within $\pm 10\%$ of the value to be collected. It is collected for each batch of the simulation run and the run is continued until the limitation is met. The impact of the source FDDI rings' broadband traffic on the end-to-end traffic delay behavior is studied first.

4.1.1 The Impact of the Source Ring's Broadband Traffic

The number of broadband stations in both source FDDI rings is chosen as "0", "4", and "8" respectively, which means the percentage of broadband traffic generated by the source rings is "0%", "40%", and "80%" respectively.

Figure 4.1 and Figure 4.2 give an indication of the end-to-end delay experienced by the conventional packets and the broadband packets vs. the percentage of the broadband traffic in the source rings respectively (please notice that the straight lines between the points are used to indicate the trend of the results, they are not part of the simulation results). Under the condition of the same average total load (≈ 50 Mbps), when the percentage of broadband traffic in the source FDDI rings increases from "0" to "40%" then to "80%", the average end-to-end conventional packet delay increases from 882 microseconds to 37,351 microseconds, then to 86,355 microseconds; the average end-to-end broadband packet delay increases from "0" to 128,924 microseconds, then to 185,016 microseconds.

The increased portion of the packet end-to-end delay has two parts:

- The increased access delay in the source FDDI rings (see Figure 4.3 Figure 4.4).
- The increased queueing delays in the ATM multiplexer queue and the destination FDDI entrance queue (which are implied by the rapidly increased queue sizes as presented in Figure 4.5 and Figure 4.6).

1. Mean Conventional Packet End-to-End Delay and Buffer Sizes Consideration

(1) Delay in Source FDDI Ring

Figure 4.1 Mean end-to-end conventional packet delay vs. the percentage of broadband traffic in source FDDI ring

Figure 4.2 Mean broadband packet end-to-end delay

Figure 4.3 Mean broadband packet delay (μ s) in source FDDI ring

Figure 4.4 Mean conventional packet delay in source FDDI ring

Figure 4.5 Mean ATM multiplexer queue size

Figure 4.6 Mean destination ring entrance server queue size

Figure 4.7 An approximated model

As mentioned previously the first part of the increased delay is in the source ring. When there is no broadband traffic in the source rings, on average the conventional packets do not need to wait long to access the ring since the total load is not high (50%), the arrival process is not very bursty, and the TTRT ($=8000\mu s$) is reasonably large. More particularly, based on the model we can approximate the non-broadband traffic case as in Figure 4.7: a 4 Km ring with 5 stations evenly distributed on the ring, each station producing packets at a constant rate of 10 Mbps, the packet size having a fixed value of 517 bytes, the service scheme being exhaustive service, and the delay introduced by each station when passing a packet being 120-bit time.

The reason for the approximation is listed below:

- The ratio of the burst-period and the idle-period of conventional traffic is $13,235.2\mu s / 13,600\mu s = 0.97 \approx 1$, which implies that on average, about half of the time, the conventional stations are active. Thus, we can approximate two stations as one station which is always active.
- The TTRT chosen in the model is 8000 microseconds, which is quite large for the total load of the 50 Mbps case; for this value of TTRT, a maximum of 193 packets are allowed to be sent for each token rotation. The system maximum utilization for such a TTRT is 99.78%, which can be safely assumed as exhaustive service.
- In the simulation model, we have assumed each station introduces a 60-bit time delay when it passes a packet. However, in the approximation we combine two stations into one, therefore, the time introduced by one station becomes 120-bit time.

By adopting the formula introduced by [30], the transfer delay “ t_f ” (including access delay) for such an approximated case is:

$$\begin{aligned}
 t_f &= \frac{L(1 - \rho/N)}{2(1 - \rho)} + \frac{\lambda}{2} * \frac{m^2}{(1 - \rho)} + m + \frac{L}{2} \\
 &= \frac{26 * (1 - 0.5/5)}{2 * (1 - 0.5)} + \frac{1}{2} * 0 + 41.36 + \frac{26}{2} \\
 &= 77.76\mu s
 \end{aligned} \tag{4.1}$$

The simulation experiments gives the value of transfer delay “ t_f ” as “93.3 μ s.

The larger number produced by simulation is due to:

- The traffic fluctuation due to overlapping bursts makes the approximation optimal.
- The service is not exhaustive.

However, when broadband traffic exists in the source rings, the conventional packets arriving during a broadband burst will suffer a much longer access delay. Since during this broadband burst, there are always very large quantities of packets waiting in the broadband stations’ queues, the broadband stations will send as many packets as possible to the ring until they exhaust their THT. As a consequence, during broadband burst, conventional stations have to wait a considerably longer period before they can get a usable token. As the number of broadband stations increases (which means the percentage of broadband traffic increases), the probability of conventional packets coinciding with the broadband burst becomes larger, thus more conventional packets have to wait longer before they can access the ring. As a result, the mean conventional packet access delay increases when the number of broadband stations increases.

(2) Queueing Delay in ATM Network and Mean Buffer Size Consideration

The second part is the increased queueing delay in the ATM multiplexer and in the destination FDDI ring entrance server queue. We can see in Figure 4.5 and Figure 4.6 that both the mean multiplexer and the mean destination FDDI ring entrance server queue lengths increase as the number of broadband stations increases. The reason is very clear:

in the model the maximum FDDI transmission rate is 100Mbps; however, the maximum ATM multiplexer transmission rate is 150Mbps. Thus if two bursts from the two source FDDI rings arrive at the same time to the ATM multiplexer, the total arrival rate during this period is 200 Mbps, which surpasses the ATM multiplexer's transmission speed (Figure 4.8). As a result, the redundant packets are accumulated and form a queue. The longer the burst length, the longer the queue is; the more often the bursts arrive, the more often the queue appears.

Figure 4.8 ATM multiplexer

The reasons for the ATM-FDDI bridge queue are quite similar to the reasons for the multiplexer queue. The transmission speed of the ATM network is 150 Mbps, while the FDDI's maximum speed is 100 Mbps (Figure 4.9). Therefore, whenever there is traffic arrival, there is a queue, the queue size being based on the length of each burst duration as well as on the situation of the destination FDDI ring. If the destination ring is heavily loaded, the probability that the ATM-FDDI bridge will get a usable token becomes smaller and the waiting queue becomes longer. The traffic statistics in the destination FDDI ring also have an effect on the queue length, which will be discussed in 4.1.2.

Based on the simulation results of the mean ATM multiplexer queue size and the mean destination ring entrance server queue size, the mean queueing delay in the ATM multiplexer input buffer ($E(T1)$, $E(T2)$ and $E(T3)$ for the percentage of broadband traffic as 0%, 40% and 80% cases respectively), and the mean queueing delay in the destination

Figure 4.9 The destination ring entrance server

ring's entrance server queue ($E(T4)$, $E(T5)$ and $E(T6)$ for the percentage of broadband traffic as 0%, 40% and 80% cases respectively) could be calculated by Little's formula as follows:

$$\begin{aligned}
 E(T1) &= E(N1)/\lambda1 = 0.57/0.118 = 4.83\mu s \\
 E(T2) &= E(N2)/\lambda1 = 150/0.118 = 1.525.42\mu s \\
 E(T3) &= E(N3)/\lambda1 = 761/0.118 = 6.449.15\mu s \\
 E(T4) &= E(N4)/\lambda2 = 1.17/0.0121 = 96.69\mu s \\
 E(T5) &= E(N5)/\lambda2 = 619.25/0.0121 = 51.177.69\mu s \\
 E(T6) &= E(N6)/\lambda2 = 1431.83/0.0121 = 118.333.05\mu s
 \end{aligned} \tag{4.2}$$

Where:

$$\begin{aligned}
 \lambda1 &= 50/53 * 8 = 0.118cell/\mu s \\
 \lambda2 &= 50/517 * 8 = 0.0121packet/\mu s
 \end{aligned} \tag{4.3}$$

The simulation results and the calculated results are listed in Table 4.1

The results in Table 4.1 show that when the percentage of broadband traffic in the source rings increases, the queue sizes and delays rise sharply. When the percentage of broadband traffic reaches 80%, the mean queueing times in the ATM multiplexer input buffer and the destination ring entrance server queue are about 6.45 milliseconds and 118.3 milliseconds respectively, which is impractical. Thus, the percentage of broadband traffic should be tightly controlled, or the burst rate of broadband traffic should be

reduced by using some kind of compressing methods. The mean queue sizes for the ATM multiplexer and the destination FDDI ring entrance queue are 761 cells and 1,432 packets, equivalent to 323,664 bits and 5,922,049 bits. Buffer size requirement based on cell-loss probability are estimated in Chapter5.

Table 4.1 Delay comparison

% of broadband traffic in source rings	Mean ATM multiplexer queue size(cell)	Mean destination ring entrance queue size(packet)	Mean queue-time in ATM multiplexer (μs)	Mean queue-time in destination ring entrance queue(μs)
0	0.57	1.17	4.83	96.69
40	180	619	1,527	51,178
80	761	1,432	6,455	118,333

2. Mean Broadband Packet End-to-End Delay

Next, let us consider the mean broadband packet end-to-end delay. As shown in Figure 4.2, when the percentage of broadband traffic is “40%”, the broadband packet end-to-end delay is “128,924 μ s”, while when the percentage of broadband traffic reaches “80%”, the delay is increased to 185,016 μ s. The increased rate is not very significant compared with the conventional packet delay case.

(1) Delay in Source FDDI Ring

Similar to the conventional traffic case, the broadband packet delay is combined by access delay in the source rings and queueing delays in the ATM network, plus propagation delay. The delay in the source FDDI ring is almost insensitive to the change in the number of broadband stations, as shown in Figure 4.3. There are two reasons for this phenomenon:

- The way FDDI protocol works is trying to divide the system capacity equally among the active stations. The results depicted by Figure 4.10 and Figure 4.11 shows this: the mean number of broadband packets sent during each THT is almost the same, and the mean utilized THT of the broadband station is almost insensitive to the change

Figure 4.10 Mean number of broadband packets sent each THT

Figure 4.11 Mean utilized THT of the broadband station

in the percentage of broadband traffic in the source FDDI rings when the broadband station is in the bursty period. According to the FDDI protocol [1], the THT for each station is decided dynamically each time the station seizes the token; even though the broadband stations have a large number of packets waiting for transmission during their bursty period, they are not allowed to utilize the total amount of TTRT time, under the condition that other stations may have packets for transmission. Thus, in the steady state, the THT utilized by the broadband stations is around $3,100\mu s$.

- The ratio of the mean burst period to the mean idle-period is small for broadband traffic ($63736\mu s/1211765\mu s = 0.05$), which means that the probability of more than one broadband burst arriving during the same time period is small. Thus, usually only one broadband station is active and it is this particular active station that shares the bandwidth with other conventional stations.

Therefore, increasing the number of broadband stations does not have much impact on the broadband packet access delay in the source FDDI ring.

(2) Queueing Delay in ATM Network

From the results of the experiments (Figure 4.5, Figure 4.6), we observed that the increased delay of broadband packets when the percentage of broadband traffic in source rings increases, is mainly introduced in the ATM network as the necessary queueing time in the ATM multiplexer queue and the destination FDDI ring entrance server queue. Figure 4.5, Figure 4.6 and Table 4.2 show that the queue size and the queueing delay increases rapidly as the number of broadband stations increases. Consequently, the queueing delay in the ATM multiplexer is increased from $1,527\mu s$ to $6,457\mu s$ and the queueing delay in the destination ring entrance server queue is increased from $51,178\mu s$ to $118,333\mu s$. However, compared to the almost constant value of the delays in the source rings (Table 4.2, column 2), the delay increase in the ATM multiplexer queue ($4927.9\mu s$) is not significant. Thus, the increased broadband packet end-to-end delay is mainly due to the increased delay in the destination ring entrance queue ($67,155\mu s$). The delays and queue sizes in the ATM network which we have discussed are the mean packet delays, including both conventional packet and broadband packet delays. The actual broadband packet delay is much longer than the numbers in Table 4.2, but the tendency is the same.

Table 4.2 Broadband packet delay elements

% of Broadband traffic	Mean broadband packet source ring delay(μs)	Mean broadband packet destination ring local delay (μs)	Mean multiplexer input buffer queueing delay (μs)	Mean destination ring entrance server queueing delay (μs)	Mean broadband packet end-to-end delay (μs)
40	53,043	54.60	1,527	51,178	128,924
80	56,402	56.21	6,457	118,333	185,016

The reason for this phenomenon is clear: the ATM multiplexer queue length increases rapidly as the number of broadband stations increases, and the large amount of broadband packets dominating the queues when broadband bursts arrive will be transmitted in large quantities during a short period, considering the rapid ATM network transmission speed. However, the situation for the destination ring entrance queue is different. The maximum capacity of the FDDI ring is 100 Mbps, and this capacity is shared by all stations connected to the ring. When the broadband traffic arrives at a speed of 150 Mbps, it is only allowed to consume part of the destination ring's capacity. As a result, the delay introduced here is much longer.

4.1.2 The Impact of the Destination FDDI Ring's Broadband Traffic

We have studied the influence of the source FDDI ring's broadband traffic on the network end-to-end delay performance. What happens in a case when there is broadband traffic in the destination FDDI ring? In this section, the studies concentrate on this area.

First, we assume there are no broadband stations in the source FDDI ring, and the number of broadband stations in the destination FDDI ring is chosen as "0", "2", and a "4" for three experimental cases. Since the total number of stations in the destination ring is "5", and each station on average contributes the same amount of load to the ring, the corresponding percentage of broadband traffic for each case is "0%", "40%", and "80%"

of the total local load of the destination ring.

The mean conventional packet end-to-end delay vs. the percentage of broadband traffic in the destination FDDI ring is depicted in Figure 4.12. When there is no broadband traffic in the destination FDDI ring, the mean end-to-end conventional packet delay is a rather small number ($882.39 \mu s$). However, when the percentage of broadband traffic in the destination ring is increased to "40%", the delay goes up sharply to $15,649 \mu s$, and is further increased to $26,575 \mu s$ when the percentage of the broadband traffic reaches "80%". Obviously, the very long delay is due to the existence of broadband traffic in the destination ring. Now, let us take a closer look at this phenomenon. The values of the mean packet delays in the source FDDI rings, the mean internet packet delays in the destination ring (including access delay in the entrance server queue), the mean destination ring entrance server queue lengths, and the mean packet end-to-end delays are listed in Table 4.3.

The results in Table 4.3 show:

- The mean packet delays in the source FDDI rings for the three cases are almost the same.
- When the percentage of broadband traffic in the destination ring increases, the mean internet packet access delay in the destination ring increases sharply (as in Figure 4.13), the mean destination ring entrance server queue size increases tremendously, and the mean packet end-to-end delay increases sharply.

The reasons for the first conclusion above is very simple: the change in the percentage of broadband traffic in the destination ring has no reverse impact on the source rings. The explanation for the second conclusion is also quite straight forward: in the period when the broadband stations in the destination FDDI ring produce long bursts, those stations consume as much of their THT as possible, so the actual token rotation time becomes longer. Consequently, the time between the ATM-FDDI bridge getting a usable token becomes longer too.

Figure 4.12 Mean conventional packet end-to-end delay

Table 4.3 Delays and queue-sizes vs. the percentage of broadband traffic in the destination ring

% of broadband traffic in the destination ring	Mean packet delay in source ring (μs)	Mean internet packet delay in destination ring(μs)	Mean destination ring entrance server queue length (packet)	Mean packet end-to-end delay (μs)
0	93.16	153	1.17	882
40	93.76	14,916	179	15,649
80	94.90	25,866	310	26,575

4.1.3 The Impact of Broadband Traffic When It Exists in Both the Source FDDI Rings and the Destination FDDI Ring

In realistic communication networks, it is possible that broadband traffic exists in both the source ring and the destination ring. As expected, both conventional and broadband traffic end-to-end delays rise significantly when the percentage of broadband traffic is increased in either the source rings or the destination rings (Figure 4.14, 4.15 and 4.16). The reasons for the increased delay are the same as those discussed in 4.1.1 and 4.1.2. Thus, no further discussion is given here.

One thing should be noticed is that the mean broadband packet end-to-end delay is always about 100,000 μ s larger than the mean conventional packet end-to-end delay, as presented in Table 4.4. This is also due to the fact that a large number of broadband packets is generated during the broadband traffic burst-period. As we discussed before, the ratio of the bursty period and idle period for broadband traffic is "0.05", that is to say, for a broadband station, it is active only 5% of the time. However, the ratio of the burst-period to the idle-period for conventional traffic is " $13,235.2\mu$ s/ $13,699\mu$ s = 0.97", which means that the conventional stations transfer from burst-state to idle-state or from idle-state to burst-state quite frequently. During most of the time, there is only conventional traffic in the network, the traffic is not very bursty (during the burst-period, the arrival rate for each conventional station is 10 Mbps) and the average load is not high (30 Mbps in the case of 6 conventional stations in the source FDDI ring). The conventional packets are removed for transmission upon their arrival or after only a short period of queueing. Thus, the network works peacefully and smoothly and the average conventional packet

Figure 4.13 Mean conventional packet access delay in the destination FDDI ring

end-to-end delay during this period is low. However, when broadband stations enter the burst-state, they produce packets at a speed of 100 Mbps for each broadband station (according to the assumption of the traffic model), and the temporary load during this period goes up, exceeding the system's capacity. But the timed-token protocol prevents the broadband stations from sending all the packets generated at a single, continuous time period. As a result, large amount of broadband packets are accumulated in the broadband station's queue, which leads to longer broadband packet end-to-end delay.

4.2 The Delay Distribution

Up to now, what we have studied are the mean end-to-end delays for conventional traffic and broadband traffic. In order to have a deeper understanding of the integrated network statistical behavior, the delay distribution will be analyzed next.

In the case of 4 broadband stations in each source FDDI ring, no broadband station in the destination FDDI ring is considered in the experiments to collect the delay distribution. 5,907,864 packets were simulated (among them 3,600,157 were conventional packets, 2,307,707 were broadband packets) to get the distribution curves. 1,526 broadband files were simulated in the experiment. Due to the very large size of the broadband file and very long time required to run the simulation, it is very hard to collect more file-delay samples. Thus, the file-delay distribution only shows a rough tendency. The maximum conventional packet delay is 860,981 μ s, the maximum broadband packet delay is 1,331,426 μ s, and the maximum broadband file delay is 499,804,288 μ s. The distribution curves are depicted in Figure 4.17, 4.18 and 4.19.

From Figure 4.17 , Figure 4.18 and Figure 4.19, we notice that:

1. Even though the mean conventional packet delay is quite long, over 50% of the packets have much shorter delays, as indicated in the distribution curve.
2. The broadband packets delay is distributed in a very wide range. The tail of the distribution curve is very long. The long tail-shaped distribution curve leads to a serious problem for the broadband traffic: since the information unit for broadband

Figure 4.14 Comparison of conventional packet end-to-end delay

Figure 4.15 Comparison of broadband packet end-to-end delay

Figure 4.16 Comparison of broadband file end-to-end delay

Table 4.4 Comparison of broadband packet delay and conventional packet delay

percentage of broadband traffic in destination ring	40% broadband traffic in source ring			80% broadband traffic in source ring		
	0%	40%	80%	0%	40%	80%
mean conventional packet end-to-end delay	37,352 μ s	53,837 μ s	76,673 μ s	86,355 μ s	97,895 μ s	118,791 μ s
mean broadband packet end-to-end delay	128,924 μ s	146,400 μ s	180,500 μ s	185,016 μ s	191,098 μ s	220,892 μ s
the delay difference	91,572 μ s	92,563 μ s	103,827 μ s	98,662 μ s	93,203 μ s	102,101 μ s

traffic is a file, a file's transmission is not considered as finished until the last packet belonging to a file has arrived, thus the file's delay is determined by the *last packet's delay*. Obviously, the long-tailed distribution curve means the file delay will be very large.

3. The broadband file delay distribution curve shows that a large percentage of files have very long delays which matches the inference in "2".

4.3 Traffic Statistics in the Two Bridges

4.3.1 Packet Interarrival Time Distribution in the FDDI-ATM Bridge

As presented in Figure 4.20, about 34% of packet interarrival times are less than 50 microseconds. The other 66% of packet interarrival times are distributed from 50

Figure 4.17 Conventional packet end-to-end delay probability

Figure 4.18 Broadband packet end-to-end delay probability

Figure 4.19 Broadband file end-to-end delay probability

Figure 4.20 Packet interarrival time probability in the FDDI-ATM bridge

Figure 4.21 Packet interarrival time probability in the ATM-FDDI bridge

microseconds to 7,800 microseconds. The distribution curve drops rapidly from 50 microseconds to 500 microseconds.

4.3.2 Packet Interarrival Time Distribution in the ATM-FDDI Bridge

Figure 4.21 depicts the packet interarrival time distribution in the destination ring's entrance. The result shows that for about 50% of the packets, the inter-packet time is less than 60 microseconds. In other words, the interarrival time for half of the internet packets are from 2.507 microseconds (the time needed to transmit a cell at the assembler) to 60 microseconds. The interarrival time for the remaining 50% of the packets are distributed over a wide range. The greater fluctuation of the packet interarrival time is because: cells reassembled here come from two source rings and most of them are mixed together when they reach the entrance of the destination ring; thus, the reassembler has to wait for all the cells belonging to one packet to arrive before it can reassemble them. The mean packet interarrival time is 83.39 microseconds (the arrival rate based on this value is 49.6 Mbps; again this number verifies the ATM-FDDI bridge of the simulation model), and the maximum inter-packet time is 8,496 microseconds.

4.4 Summary and Conclusion

In this chapter, we have studied the performance of a basic form FDDI-ATM-FDDI network. The criteria of the performance evaluation is the traffic end-to-end delay and the queueing behavior in the ATM network.

It has been found that the conventional packet end-to-end delay increases sharply as the percentage of broadband traffic in either the source rings or the destination ring increases. However, the increase in the percentage of the broadband traffic has not as significant an effect on the broadband packet end-to-end delay as on the conventional packet case. On the other hand, it has been noticed that the broadband packet end-to-end delay is always longer than that of the conventional packet. The buffer sizes needed for such a network with the assumed integrated traffic arrival processes are very large; thus, we suggest that the link capacity should be increased or data compression mechanisms should be adopted

2 OF 2

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to reduce the peak rate of the broadband traffic.

In 4.2, the delay distributions of conventional packet end-to-end delay, broadband packet end-to-end delay, and the broadband file end-to-end delay are presented. The curves show that more than 50% of the conventional packet's end-to-end delay is very short. However, the broadband packet's end-to-end delay is distributed on a very wide range which leads to a serious problem for the broadband file transmission: very long file end-to-end delay. Thus, we should take serious care of the longer-broadband traffic delay and implement improvement methods to this integrated network.

4.3 collected the traffic statistics in both bridges.

Chapter 5

Performance Evaluation of the Improved FDDI-ATM-FDDI Network

From the previous chapter, we have clearly observed that the basic WAN configuration has difficulty in providing satisfactory service in an integrated-traffic environment. It is unable to divide the bandwidth fairly between conventional and broadband stations. As a result, the broadband traffic has much longer delay than the conventional traffic. The longer broadband traffic delay is a serious problem since the information unit of broadband traffic is a large collection of data: a file. A file's delay is based on the latest packet arrival of the file. As a consequence, the file delay is very long (as in Figure 4.19) for the basic WAN. Thus, it is necessary to find a way to improve the network performance. In this chapter, four possible improvement methods will be evaluated. After a thorough evaluation of individual methods, three effective methods will be applied to the basic WAN and the improved network performance will be examined. Furthermore, the buffer sizes needed for such a traffic environment will be analyzed and the traffic statistics in the two bridges will be collected and discussed.

5.1 Four Possible Improvement Methods Evaluation

There are possibly four methods we can try to use to improve the network behavior:

- Adjusting the TTRT. Other researchers have carefully studied the impact of the TTRT [16] [31] [32] [17] [5], and they have indicated that the TTRT is an important parameter for the FDDI network's performance. By adjusting the TTRT the traffic delay and network maximum throughput can be adjusted. The value of the TTRT should not be too small since a small TTRT results in a smaller value of maximum throughput. However, the value of the TTRT should not be too large, because a large TTRT leads to longer delay in heavy load range. A typical value of $8000\mu s$ has been

recommended as the most suitable value of TTRT [5]. However, nobody has ever considered the impact of TTRT in a FDDI-ATM-FDDI network with an integrated traffic. We will study this in 5.1.1.

- Grant "restricted token" to broadband stations during a burst. From the analysis in the previous section, we know that the long broadband traffic's delay is due to the fact that on average, for 95% of the time, the broadband stations are in an idle-state. However, whenever they enter the burst-state, they produce great quantities of packets (at a rate of 100 Mbps during a short period) which cannot be sent out within their allowed Token Holding Time (THT). Thus, they have to wait for several token rotations to clear their queues. Therefore, a considerable percentage of broadband packets suffer longer delay, which in turn results in longer file delay. If we forbid the conventional stations from transmission during the broadband station's bursty period, the broadband stations will have more time for transmission and the delay of broadband traffic will be reduced. This is the idea of the "restricted token" method which is included in the FDDI protocol standard ([1]) as a means for the integrated-traffic case. The strict definition of the restricted token mechanism is: *when the broadband station is in burst period, all other stations on the same ring have to stop transmission, thus the broadband station can use the entire system bandwidth during this period under the condition that it does not violate the predefined TTRT limitation.* Section 5.1.2 will concentrate on the study of the impact of the restricted token mechanism.
- Grant high priority to broadband cells in the ATM multiplexer. The reason for adopting this method is quite straight forward. When broadband traffic bursts from the two source FDDI rings arrive at the ATM multiplexer simultaneously, the large quantity of cells waiting for multiplexing forms a long queue. At the same time, some of the conventional cells also arrive and are filed into the same queue. We separate the queue into a *high-priority queue* for the broadband cells, and a *low-priority queue* for conventional cells. The multiplexer sends the low-priority cells only if the high-priority queue is empty. This priority scheme will be evaluated in Section 5.1.3.
- Using the restricted token for internet traffic at the ATM-FDDI bridge. Section 5.1.4 will investigate.

5.1.1 The Effect of TTRT

In this series of experiments, the topology of the network model is the same as previously discussed in Chapter Four; it is further assumed that there are 9 conventional stations and 1 broadband station in each of the source FDDI rings, and 5 conventional stations in the destination ring. The TTRT of the source FDDI rings we chose is: $4,000\mu s$, $8,000\mu s$, $24,000\mu s$, $40,000\mu s$, $56,000\mu s$, $72,000\mu s$, and $80,000\mu s$ for each experiment respectively. The TTRT value for the destination ring is fixed as $8,000\mu s$ for all experiments. The aim of this series of experiments is to investigate the impact of the different values of the source FDDI rings' TTRT to the traffic end-to-end delay. The results are presented in Figure 5.1, and Figure 5.2.

Figure 5.1, and Figure 5.2 show that: by increasing the TTRT, the mean conventional packet end-to-end delay increases slightly; the mean broadband packet delay decreases slightly, and the ratio of the mean broadband station utilized THT (when the broadband station is in burst period) to the system TTRT is almost a constant (Figure 5.3).

With the increased TTRT, every station has more time to access the ring when it seizes the token, but on average every station has to wait longer before it can get next token. One of the main differences between the conventional traffic and the broadband traffic is the burstiness of the arrival process. This different characteristic implies that: the broadband station can utilize its THT entirely when it is in the burst-state, while the conventional station may only utilize part of its THT. Therefore, when the TTRT is increased, more broadband packets have a chance to access the ring earlier. However, the broadband packet delay is not decreased significantly, since the broadband station is only allowed to transmit packets within its THT bound. When the THT expires, it is forced to release the token; thus the rest of the broadband packets have to wait for the next turn of a usable token. Also, the more packets the broadband station sends during its THT, the more packets accumulate in the other station's queues. So when other stations seize the token, they will keep the token for a longer time, which in turn results in the broadband station getting the next usable token later.

From the experiments and the analysis of the results, we have concluded that adjusting the TTRT is not an effective way to solve the long broadband traffic delay problem.

Figure 5.1 Mean conventional packet end-to-end delay vs. TTRT

Figure 5.2 Mean broadband packet end-to-end delay vs. TTRT

Figure 5.3 The ratio of the mean broadband station utilized THT to the system TTRT

5.1.2 The Effect of Implementing Restricted Token In Source FDDI Rings

In this group of experiments, restricted token is granted to the broadband station in both source FDDI rings. The network model is the same as in 5.1.1. The TTRT value chosen for both the source FDDI rings and the destination FDDI ring is 8000 μ s. In the experiments, it is assumed that whenever the broadband station enters the burst-state, the first token it gets from the upstream neighbor station will be transferred into a restricted token by adding a restricted-token indicator into the token packet. From now on, only the broadband station is allowed to transmit. After the broadband station has utilized all its THT, it releases the token, but other stations cannot start transmission even though they see a token pass by since, during this period, the token is a restricted token. The token goes around the ring, and the broadband station then starts another batch of transmission. This process continues until the broadband station empties its waiting queue; then it removes the restricted-token indicator from the token packet, so that other stations can then start transmission.

The simulation results (Table 5.1) show the restricted token improves the broadband packet delay and broadband file delay significantly.

5.1.3 The Effect of Implementing Priority in the ATM Multiplexer

In order to minimize the broadband traffic end-to-end delay, we separate the multiplexer's input-queue into two queues: high-priority for the broadband cells and low-priority for conventional cells. They are transmitted with non-pre-emptive priority.

The comparison of the results of the multiplexer priority case and the multiplexer non-priority case are depicted in Table 5.1. The results show the priority method only reduces the broadband traffic delay slightly (Table 5.1, column 2 and column 5).

The priority scheme reduces the queueing delay in the ATM multiplexer and in turn reduces the queueing delay in the destination ring's entrance server queue. However, the

Table 5.1 The Effectiveness of the three improvement methods

	normal token	restricted-token in source FDDI	restricted-token in destination FDDI	multiplexer priority
mean end-to-end con.packet delay	7612 μ s	16,623 μ s	1860 μ s	7747 μ s
mean end-to-end BB packet delay	86,220 μ s	41,963 μ s	51,714 μ s	84,870 μ s
mean end-to-endBB file delay	158,463 μ s	114,938 μ s	123,772 μ s	157,216 μ s
mean BB station utilized THT	3085 μ s	7100 μ s	3085 μ s	3085 μ s
mean BB packets sent in each THT	74	172	74	74
mean source FDDI con.packet delay	435 μ s	7155 μ s	435 μ s	435 μ s
mean source FDDI BB packet delay	55,600 μ s	594.5 μ s	55,600 μ s	55,600 μ s

percentage of conventional cells during a broadband traffic burst is small, and delaying them does not improve the broadband traffic delay significantly. A priority scheme in the ATM multiplexer is not enough for the purpose of reducing the broadband traffic delay. The priority scheme should be used together with the restricted token mechanism, for better results.

5.1.4 The Effect of Implementing Restricted-Token in ATM-FDDI Bridge

A major element of the queueing delay occurs in the destination ring's entrance server queue, where a reassembled packet has to wait for the entrance server to get a usable token and for earlier packets to be transmitted. The opportunity for the server to get a usable token and the length of the THT for the server is based on the traffic situation of

the destination ring and the FDDI protocol. One solution is to assign restricted-token to the entrance server when there is internet traffic waiting for transmission. The results are presented in Table 5.1. As shown in Table 5.1, this method significantly improves both the internet broadband traffic delay and the internet conventional traffic delay. The trade-off is the much longer delay of the destination FDDI local traffic ($730\mu\text{s}$ for a normal token case, and $19,188\mu\text{s}$ after implementing the restricted token in the ATM-FDDI bridge).

5.2 Performance Evaluation of the Improved FDDI-ATM-FDDI Network

It has been shown that the three effective improvement methods are: granting restricted token to the broadband stations in the source FDDI rings, assigning priority to the broadband cells in the ATM multiplexer, and giving restricted token to the ATM-FDDI multiplexer. In this section we combine the three effective methods.

1. Mean Internet Packet End-to-End Delay

Figures 5.4, 5.5 and 5.6 indicate that the mean broadband packet end-to-end delay is reduced by about 60% for the three values (0%, 40%, and 80%). Consequently the broadband file end-to-end delay is reduced around 50% (Figures 5.7, 5.8 and 5.9). Figures 5.10, 5.11 and 5.12 show that the internet conventional packet's end-to-end delay is also reduced after implementing the improvement methods; this is because the restricted token in the destination entrance server also benefits the internet conventional packets. In general, the internet broadband packets' end-to-end delay is still larger than the internet conventional packets' end-to-end delay, but the difference has been reduced by about half (Figure 5.13, 5.14 and 5.15). The trade-off for the shorter internet traffic delay is the much longer local destination FDDI traffic delay, as depicted by Figure 5.16 (for no broadband station in the destination FDDI ring), Figure 5.17 (for 2 broadband stations in the destination FDDI ring), and Figure 5.18 (for 4 broadband stations in the destination FDDI ring).

2. Delay Distribution

Figure 5.4 Comparison of broadband packet end-to-end delay (no broadband traffic in destination ring)

Figure 5.5 Comparison of broadband packet end-to-end delay (40% broadband traffic in destination ring)

Figure 5.6 Comparison of broadband packet end-to-end delay (80% broadband traffic in the destination ring)

Figure 5.7 Comparison of broadband file end-to-end delay (no broadband traffic in destination ring)

Figure 5.8 Comparison of broadband file end-to-end delay (40% broadband traffic in the destination ring)

Figure 5.9 Comparison of broadband file end-to-end delay (80% broadband traffic in the destination ring)

Figure 5.10 Comparison of conventional packet end-to-end delay (no broadband traffic in destination ring)

Figure 5.11 Comparison of conventional packet end-to-end delay (40% broadband traffic in destination ring)

Figure 5.12 Comparison of conventional packet end-to-end delay (80% broadband traffic in the destination ring)

Figure 5.13 The difference between broadband packet delay and conventional packet delay (no broadband traffic in the destination ring)

Figure 5.14 The Difference between broadband packet delay and conventional packet delay (40% broadband traffic in the destination ring)

Figure 5.15 The Difference between broadband packet delay and conventional packet delay (80% broadband traffic in the destination ring)

Figure 5.16 Comparison of local destination FDDI ring packet delay (no broadband traffic in the destination ring)

Figure 5.17 Comparison of local destination FDDI ring packet delay (40% broadband traffic in the destination ring)

Figure 5.18 Comparison of local destination FDDI ring packet delay (80% broadband traffic in the destination ring)

The end-to-end delay distribution of conventional packet, broadband packet, and broadband file are collected by simulation. As in 4.1 (the case of 4 broadband stations in each source FDDI ring), no broadband station in the destination ring is considered in the experiments. 5,923,104 packets (among them 3,609,444 were conventional packets and 2,313,660 were broadband packets) and 1,526 files were simulated to get the distributions in the experiments. The maximum conventional packet delay is $458,100\mu s$, the maximum broadband packet delay is $887,110\mu s$, and the maximum file delay is $2,524,894.75\mu s$. The distributions are presented in Figures 5.19, 5.20, and 5.21. By comparing Figures 4.17, 4.18, and 4.19 in 4.2, we can see that the tails of the distribution curves, after implementing the optimal methods, are reduced significantly.

In conclusion, the long end-to-end delay of the internet broadband traffic can be adjusted by applying restricted token and priority scheme; the trade-off of the internet traffic delay improvement being the much longer delay of the local traffic. The delay of the internet traffic and the local traffic cannot be optimized simultaneously as they are competitors for the limited bandwidth. By carefully choosing and applying the improvement methods, the network designers and managers can tune their networks to meet customers' requirements.

5.3 Buffer Size Analytic Results

In this section we obtain some analytic approximations for the worst-case conditions which have been simulated. This provides further verification of the previous results.

In the simulation model, both broadband traffic and conventional traffic models are two-state Markov processes. Broadband stations in both source FDDI rings generate data at a speed of 100 Mbps when the broadband stations are in the burst-state; conventional stations produce traffic at a speed of 10 Mbps for the duration of the bursty period. From the point of view of the ATM Multiplexer, the type of arriving traffic could be roughly divided into three categories:

- Traffic from both source rings are generated by conventional stations.
- Traffic is a combination of one ring's conventional traffic and another ring's broadband traffic.

Figure 5.19 Conventional packet delay probability after implementing the improvement methods

Figure 5.20 Broadband packet delay probability after implementing the improvement methods

Figure 5.21 Broadband file delay probability after implementing the improvement methods

- Traffic from both source rings is generated by broadband stations.

Since the ATM link capacity is 150 Mbps, for the above first two cases the arrival rate is almost always less than 150 Mbps, so we can say, approximately, that there is no queueing in the ATM multiplexer for the first two cases. However, in the third case the temporary arrival rate reaches 200 Mbps, and queueing occurs. The queueing problem becomes worse when we adopt the restricted token scheme in the FDDI rings. Thus, for the consideration of the maximum necessary buffer sizes needed in the ATM multiplexer and the destination ring's entrance, we need only study the worst case. Therefore, the analysis in the following is focused on this worst-case situation.

In the worst case, if we ignore the token propagation time between two usable tokens, the traffic processes from the two rings can be approximated as two identical, independent Markov processes. Based on this understanding, the ATM multiplexer queue-size distribution can be derived from the probability distribution in the event of both Markov processes being in the burst-state. The excess arrival rate at the ATM multiplexer during the period when the two processes are all active is 50 Mbps (200 Mbps-150 Mbps), which implies that the queue size increases at a speed of 50 Mbps. Similarly, the maximum destination FDDI ring transmission speed is 100 Mbps and the traffic arriving from the ATM network in the worst case is 150 Mbps. Thus the redundant arrival rate at the entrance of the destination ring is also 50 Mbps. Consequently, the entrance server's queue size also increases at a rate of 50 Mbps. Therefore, the solution for the queue-size distributions could be found if we find the distribution of the time period when the two identical Markov processes stay in the burst-state.

As previously discussed, the two arrival processes are identical, independent Markov processes; if we let the two processes be named x and y . We have:

$$\begin{aligned}
 P\{x \geq t, y \geq t\} &= P(x \geq t)P(y \geq t) \\
 &= P(x \geq t)^2 \\
 &= e^{-2\lambda t}
 \end{aligned}
 \tag{5.1}$$

where:

$$\lambda = \frac{1}{E(x)} = \frac{1}{E(y)} \quad (5.2)$$

Next, let us choose three different burst-rate broadband traffic processes, and study the queue-size distributions for each individual case:

- Burst-rate is 100 Mbps
- Burst-rate is 80 Mbps
- Burst-rate is 60 Mbps

1. Burst-rate is 100 Mbps:

The formula used for the calculation in this case is:

$$\begin{aligned} E(x) &= 1542 * 41.36 = 63777.12 \mu s \\ P(x \geq t, x \geq t) &= e^{-0.031359t(ms)} \end{aligned} \quad (5.3)$$

(For the value of $E(x)$, please refer to p44.)

The results derived from the above formula are presented in Table 5.2.

The results show that for this kind of traffic situation, the ATM multiplexer buffer size and the ATM-FDDI buffer size should be 43,623 cells and 4,477 packets for a loss rate of 10^{-5} , and 60,719 cells and 6,232 packets in order to meet a loss rate of 10^{-7} .

The mean buffer sizes required for the ATM multiplexer and the destination ring entrance is 10,021 cells and 1,028 packets, when the broadband traffic burst rate is 100 Mbps from the analytical model. The simulation experiment for the same case yields 9241 cells and 940 packets respectively. The smaller numbers from the simulation are due to the way we collect samples in the experiment. The samples are collected starting from the instant the first cell of a burst (at the ATM multiplexer queue) or the first packet of a burst (at the destination ring's entrance) arrives, and ends when either the last cell belonging to the same burst or the last packet belonging to the same burst, arrives. This collection period which is slightly too long since, even after the broadband stations have

Table 5.2 Queue size distributions (100 Mbps case)

t (ms)	10	20	30	40	50	60
multiplexer queue (cells)	1179	2358	3537	4716	5895	7074
destination ring entrance queue (packets)	121	242	363	484	605	726
Probability distribution	0.7308	0.5341	0.3903	0.2853	0.2085	0.1524
t (ms)	70	80	90	100	200	300
multiplexer queue (cells)	8253	9432	10,611	11,790	23,580	35,370
destination ring entrance queue (packets)	847	968	1089	1210	2420	3630
Probability distribution	0.1113	0.0814	0.0595	0.0435	0.0013	8.2E-5
t(ms)	370	500	515	600	700	800
multiplexer queue (cells)	43,623	58,905	60,718.5	70,740	82,530	94,320
destination ring entrance queue (packets)	4,477	6050	6231.5	7260	8470	9680
Probability distribution	0.91E-5	1.55E-7	0.96E-7	6E-9	2.93E-10	1.27E-11

t: the duration that the two processes stay in the burst-state.

left the burst-state, the last packet they transmitted is still on its way and the samples are still collected.

2. Burst-rate is 80 Mbps:

The formula used for the calculation in this case is:

$$\begin{aligned} E(x) &= 1,195,872.7\mu s \\ P(x \geq t, x \geq t) &= e^{-0.025103t(ms)} \end{aligned} \tag{5.4}$$

The results derived from the above formula are depicted in Table 5.3.

The mean value of the buffer sizes derived from the analytical model are: 2782 cells for the ATM multiplexer queue and 1249 packets for the destination entrance server queue.

From the results in Table 5.3, we notice that as the burst rate decreases, the buffer size needed for the ATM multiplexer decreases to 10,856 cells (from 43,626 cells in the previous case), but the buffer size for the ATM-FDDI bridge increases to 5,566 packets (from 4,477 packets in the previous case) when the loss rate required is 10^{-5} . The reason for this phenomenon could be explained as such: when the burst rate decreases, the redundant arrival rate for the ATM multiplexer decreases too (e.g., in this particular situation, the redundant arrival rate decreased from 50 MB to 10 MB [160MB-150MB]); as a consequence, the number of cells accumulated in the ATM multiplexer input buffer becomes less. However, the arrival rate for the ATM-FDDI bridge is also 150 Mbps for this case. Therefore, the peak period of the arrival process for the ATM-FDDI bridge becomes longer, since reducing the broadband traffic burst rate means making the burst-period longer when the average arrival rate is unchanged. This means that the destination ring's entrance server has to stay in the busy-period for a longer time with the same redundant arrival rate (50 Mbps). Obviously, the number of cells waiting in the ATM-FDDI bridge input buffer increases significantly.

3. Burst-rate is 60 Mbps:

The formula used for the calculation in this case is:

Table 5.3 Queue size distributions (80 Mbps case)

t (ms)	10	20	30	40	50	60
multiplexer queue (cells)	236	472	708	944	1180	1416
destination ring entrance queue (packets)	121	242	363	484	605	726
Probability distribution	0.778	0.6053	0.471	0.366	0.285	0.22
t (ms)	70	80	90	100	200	300
multiplexer queue (cells)	1652	1888	2124	2360	4720	7080
destination ring entrance queue (packets)	847	968	1089	1210	2420	3630
Probability distribution	0.1725	0.134	0.104	0.08124	6.6E-3	5.36E-4
t(ms)	400	460	600	640	700	800
multiplexer queue (cells)	9440	10,856	14,160	15,104	16,520	18,880
destination ring entrance queue (packets)	4840	5,566	7260	7744	8470	9680
Probability distribution	4.36E-5	0.97E-5	2.87E-7	1.05E-7	2.3E-8	1E-9

$$\begin{aligned}
 E(x) &= 1,168.488.93\mu s \\
 P(x \geq t, x \geq t) &= e^{-0.018827t(ms)}
 \end{aligned}
 \tag{5.5}$$

The results derived from the above formula are listed in Table 5.4.

When the burst rate is decreased to 60 Mbps, there is no queueing at the ATM multiplexer, since the total arrival rate to the ATM multiplexer is 120 Mbps, which is less than the ATM link capacity (150 Mbps). The buffer size needed for the destination ring's entrance is 2974 packets when the required loss rate is around 10^{-5} . The mean buffer size required is "827" packets.

The analysis in this section shows that when the burst rate is 100 Mbps, very large buffers are needed to accommodate the rapidly incoming information units (cells or packets). In practice, it is very hard to implement such large-sized buffers. Thus, we would like to emphasize again the necessity of using compressing methods on the broadband traffic to reduce the burst peak rate before it enters the network.

5.4 Traffic Statistics

1. Packet Interarrival Time Distribution in the FDDI-ATM bridge

Figure 5.22 shows the packet interarrival time distribution after implementing the improvement methods. In comparing it with Figure 4.20, we find that there are two main differences between the two figures:

- More packet interarrival times (60%) in Figure 5.22 are less than 50 μs .
- The tail of the distribution curve in Figure 5.22 is much longer.

The reason for the first difference is because when restricted-token is implemented, large amounts of broadband packets are sent out sequentially during the broadband burst. The interarrival time between those sequentially-arrived packets is 41.36 μs . Thus, a considerable percentage of packet-interarrival-times are restricted within this range.

Table 5.4 Queue size distributions (60 Mbps case)

t (ms)	10	20	30	40	50	60
multiplexer queue (cell)s	0	0	0	0	0	0
destination ring entrance queue (packets)	49	97	145	194	245	290
Probability distribution	0.8284	0.6862	0.5683	0.471	0.39	0.323
t (ms)	70	80	90	100	200	300
multiplexer queue (cell)s	0	0	0	0	0	0
destination ring entrance queue (packets)	343	392	441	490	970	1450
Probability distribution	0.268	0.222	0.184	0.152	2.3E-2	3.5E-3
t(ms)	400	500	600	615	800	860
multiplexer queue (cells)	0	0	0	0	0	0
destination ring entrance queue (packets)	1940	2450	2900	2974	3920	4210
Probability distribution	5.36E-4	8.16E-5	1.24E-5	0.94E-5	2.8E-7	0.92E-7

Figure 5.22 Packet interarrival time probability (FDDI-ATM) after implementing the improvement methods

The reason for the second difference is also due to the effect of restricted-token. During broadband traffic burst, conventional stations are not allowed to transmit, so considerable amounts of packets are accumulated in the conventional stations' queues. As soon as the broadband traffic burst ends, the first conventional station (namely, conventional station no.1) getting the token will utilize the TTRT as much as possible to send its queueing packets, so that other conventional stations will have no chance to transmit in this token rotation. However, in the next token rotation, the sending station in the previous circle is not allowed to transmit (according to the FDDI MAC protocol). It is the next down-stream neighbor station's (conventional station no.2) turn to transmit. This station does the same thing as its upper-stream neighbor station. This process continues until all conventional stations finish transmitting the packets accumulated during the previous broadband traffic burst. Obviously, the packet interarrival time tends to be longer during this period.

2. Packet Interarrival Time Distribution in the ATM-FDDI Bridge

The packet interarrival time distribution of the improved network model is depicted in Figure 5.23. It is almost the same as the result derived from the basic model in Chapter Four.

The two figures show that adopting the improvement methods does not have much influence on the traffic statistics in the two bridges.

5.5 Conclusion

In this chapter we discussed and evaluated the performance of an optimized FDDI-ATM-FDDI model. The evaluation was conducted in two stages: first, we studied the four possible optimal methods individually in 5.1; the effectiveness of each method was presented by conducting simulation experiments, and the reasons for the degree of effectiveness were discussed. Then, we concentrated on the evaluation of an optimized network model (after adopting the three effective methods) in 5.2. The studies show that the mean broadband traffic end-to-end delay is reduced by about half. The delay distributions collected also show that the tail of the distribution curve are decreased to about 50%.

Figure 5.23 Packet interarrival time distribution (ATM-FDDI) after implementing the improvement methods

Then, in 5.3 the buffer sizes needed in such a network in the assumed integrated traffic environment were analyzed by an approximated two-state Markov model. It was observed that very large buffers are required if the broadband traffic peak rate is high. The implication is that the sum of possible peak rates in a WAN must be restricted to less than 100 Mbps, even though the probability of simultaneous peaks occurring is low, because the queue sizes build so rapidly during such peak. The analytic approximation we introduced is useful for assessing buffer sizes in worst-case conditions.

Chapter 6

Conclusion

6.1 Conclusion

The high-speed integrated network examined in this thesis represents a trend in future networks. When a variety of different traffic characteristics exist in one network, the network protocols are required to have the ability to divide the bandwidth fairly among the different categories of traffic. The performance study of a FDDI-ATM network provided in this thesis showed the inability of the current basic forms of FDDI and ATM protocols to divide the bandwidth evenly between conventional traffic and broadband traffic. Therefore, it is necessary to adopt improvement methods.

The basic conclusions of the research work and the results of this thesis are summarized as follows:

- The existence of broadband traffic has great influence on the network statistical behavior. As the percentage of broadband traffic is increased, the conventional traffic end-to-end delay rises sharply;
- Broadband traffic end-to-end delay is much longer than that of conventional traffic, even though the average load of broadband stations and that of conventional stations is the same. This longer delay problem is even worse if the size of a broadband file is large;
- The buffer size needed in the ATM network for such an integrated environment is very large, and for higher burst-rates or longer burst-lengths, much larger buffer sizes are needed to satisfy the required cell-loss rate;
- The FDDI-ATM-FDDI network can be tuned for integrated traffic by employing optimal mechanisms in the network. The mechanism involving granting of restricted-token to the broadband traffic in the source rings and to the internet traffic in the receiving bridge, and assigning higher priority to broadband traffic in the ATM multiplexer, has been shown to be very effective in solving the fairness problem

in current FDDI-ATM-FDDI networks. However, the method of adjusting the TTRT has little influence on the network end-to-end delay behavior; and

- The optimal mechanisms adopted in this thesis have almost no influence on the traffic statistics in the ATM-FDDI bridge.

6.2 Suggestions

Following are some suggestions for future research work:

- Isochronous traffic in the network: The analysis in this thesis has excluded the existence of isochronous traffic in the network. It is possible that in future applications both asynchronous traffic and isochronous traffic will co-exist in the network. Usually, isochronous traffic will have higher priority, based on the FDDI protocol. It will be of interest to study the impact of the higher-priority isochronous traffic on the integrated network behavior.
- FDDI priority scheme: In the thesis, we did not consider the FDDI priority scheme for asynchronous traffic. Actually, as the FDDI standard allows eight priorities for asynchronous traffic, the THT for the certain priority traffic could be decided dynamically. Future work may be needed to explore this area.
- Two-direction traffic: In this thesis, we assumed that only one-direction traffic exists in the network. For a more thorough investigation, two-direction traffic should be considered.
- IEEE 802.6-based analysis: The analysis done in this thesis could be further extended to a WAN environment, using the IEEE 802.6 metropolitan network (DQDB) standard instead of the FDDI LAN, or using the DQDB as a backbone to interconnect multiple FDDI.

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