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OPTICAL INTERFACE ADAPTERS
FOR DRONET AND DQDB

by

Bo Wang
B.S.E.E. Tsinghua University, Beijing, China, 1987
M.S.E.E. Tsinghua University, Beijing, China, 1989

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE

in the School
of
Engineering Science

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December 1991

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Optical Interface Adapters for DRONET and DQDB

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ABSTRACT

High capacity multiple access communication systems, using optical media, are an active area of research. As transmission rates in multiaccess fiber-optic networks increase, routing optical signals using conventional opto-electronic switches, which have to convert optical signals to electrical signals, will become increasingly difficult. This limitation can be overcome by performing the required processing optically.

In order to eliminate the electronic bottleneck raised by opto-electronic interface adapters in optical networks, this thesis describes the design of optical interface adapters for DRONET and DQDB incorporating photonic switching and logic. DRONET is proposed in this thesis as a dual ring optical network, with the second ring being used as an additional data path, instead of providing redundancy as in FDDI. This second ring is used to transmit synchronous traffic only, with statistical code-division multiplexing for good bandwidth efficiency. The performance of DRONET with optical interface adapter is evaluated and compared to FDDI. The performance of DQDB with optical interface adapter is also evaluated.

In this thesis, the implementation of photonic switching in optical interface adapters is proposed, and a bridge for the interconnection of DRONET through DQDB is also proposed. The performance of DRONET and DQDB with optical interface adapters shows that the throughput can be enhanced and the message transfer delay can be decreased.
To all my friends

in Tsinghua University
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I sincerely thank my senior supervisors Dr. Steve Hardy and Dr. Jamal Deen for their supervision and management of my thesis. They have provided valuable advice and guidance throughout this project. I also would like to thank Dr. John Jones, Dr. Shawn Stapleton, and Mr. Peter McConnell for their advice and help. I am grateful to Dr. Geng Wu for his help when I encountered problems in telecommunications, and for his useful suggestions. I thank Mrs. Brigitte Rabold for her help when I needed information. Finally, I would like to thank all my friends in the School of Engineering Science who certainly contributed to the work I have done in SFU.
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<th>Description</th>
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<tbody>
<tr>
<td>ACF</td>
<td>Access Control Field</td>
</tr>
<tr>
<td>ASC</td>
<td>Accredited Standards Committee</td>
</tr>
<tr>
<td>BAP</td>
<td>Broadband Access Point</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>BIDS</td>
<td>Broadband Integrated Distributed-Star Network</td>
</tr>
<tr>
<td>BISDN</td>
<td>Broadband Integrated Service Data Network</td>
</tr>
<tr>
<td>BOC(x)</td>
<td>Beginning of a Carrier Signal on Channel x</td>
</tr>
<tr>
<td>BOM</td>
<td>Beginning of Message</td>
</tr>
<tr>
<td>BSY</td>
<td>Busy bit (in DQDB)</td>
</tr>
<tr>
<td>BT</td>
<td>British Telecom</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code-Division Multiplexing Access</td>
</tr>
<tr>
<td>COM</td>
<td>Continuous of Message</td>
</tr>
<tr>
<td>CR</td>
<td>Cambridge Ring</td>
</tr>
<tr>
<td>CSMA/CD</td>
<td>Carrier Sense Media Access/Collision Detection</td>
</tr>
<tr>
<td>DA</td>
<td>Destination Address</td>
</tr>
<tr>
<td>DMPDU</td>
<td>Derived MAC Protocol Data Unit</td>
</tr>
<tr>
<td>DQDB</td>
<td>Distributed Queue Dual Bus</td>
</tr>
<tr>
<td>DQP</td>
<td>Distributed Queuing Protocol</td>
</tr>
<tr>
<td>DRONET</td>
<td>Dual Ring Optical Network</td>
</tr>
<tr>
<td>EDF</td>
<td>Erbium-Doped Fiber</td>
</tr>
<tr>
<td>E/O</td>
<td>Electronic-to-Optical Conversion</td>
</tr>
<tr>
<td>EOC(x)</td>
<td>End of a Carrier Signal on Channel x</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>EOM</td>
<td>End of Message</td>
</tr>
<tr>
<td>EOT(x)</td>
<td>End of a Train of Packets (or a Series) on Channel x</td>
</tr>
<tr>
<td>FDDI</td>
<td>Fiber Distributed Data Interface</td>
</tr>
<tr>
<td>FDM</td>
<td>Frequency Division Multiplexing</td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency Division Multiplexing Access</td>
</tr>
<tr>
<td>FOLAN</td>
<td>Fiber Optic Local Area Network</td>
</tr>
<tr>
<td>FSK</td>
<td>Frequency Shift Keying</td>
</tr>
<tr>
<td>HCS</td>
<td>Header Check Sequence</td>
</tr>
<tr>
<td>HDTV</td>
<td>High-Definition TV</td>
</tr>
<tr>
<td>HSLAN</td>
<td>High Speed Local Area Network</td>
</tr>
<tr>
<td>ICR</td>
<td>Integrated Cambridge Ring</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronic Engineers</td>
</tr>
<tr>
<td>IMPDU</td>
<td>Initial MAC Protocol Data Unit</td>
</tr>
<tr>
<td>ISDN</td>
<td>Integrated Service Data Network</td>
</tr>
<tr>
<td>kHz</td>
<td>kiloHertz</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>LLC</td>
<td>Logical Link Control</td>
</tr>
<tr>
<td>L-R Bus</td>
<td>Left-to-Right Bus</td>
</tr>
<tr>
<td>MAC</td>
<td>Media Access Control</td>
</tr>
<tr>
<td>MAN</td>
<td>Metropolitan Area Network</td>
</tr>
<tr>
<td>MID</td>
<td>Message Identifier</td>
</tr>
<tr>
<td>MPDU</td>
<td>MAC Protocol Data Unit</td>
</tr>
<tr>
<td>O/E</td>
<td>Optical-to-Electronic Conversion</td>
</tr>
<tr>
<td>OSI</td>
<td>Open System Interconnection</td>
</tr>
<tr>
<td>PA</td>
<td>Pre-Arbitrated (in DQDB)</td>
</tr>
<tr>
<td>PDU</td>
<td>Protocol Data Unit</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical Layer Protocol</td>
</tr>
<tr>
<td>PMD</td>
<td>Physical Layer Medium Dependent</td>
</tr>
<tr>
<td>PSR</td>
<td>Previous Slot Received (in DQDB)</td>
</tr>
<tr>
<td>QA</td>
<td>Queued Arbitrated (in DQDB)</td>
</tr>
<tr>
<td>QPSX</td>
<td>Queue Packet and Synchronous Exchange</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>RC</td>
<td>Request-bit Counter</td>
</tr>
<tr>
<td>REQ</td>
<td>Request bits (in DQDB)</td>
</tr>
<tr>
<td>RSVD</td>
<td>Reserved bit (in DQDB)</td>
</tr>
<tr>
<td>R-L Bus</td>
<td>Right-to-Left Bus</td>
</tr>
<tr>
<td>RQ</td>
<td>Request Counter</td>
</tr>
<tr>
<td>SEG_HDR</td>
<td>Segment header</td>
</tr>
<tr>
<td>SMF</td>
<td>Single Mode Fiber</td>
</tr>
<tr>
<td>SMT</td>
<td>Station Management</td>
</tr>
<tr>
<td>SR</td>
<td>Source Routing</td>
</tr>
<tr>
<td>SSM</td>
<td>Single Segment Message</td>
</tr>
<tr>
<td>ST</td>
<td>Spanning Tree</td>
</tr>
<tr>
<td>TAG</td>
<td>Technical Advisory Group</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time-Division Multiplexing Access</td>
</tr>
<tr>
<td>THT</td>
<td>Token Holding Time</td>
</tr>
<tr>
<td>TRT</td>
<td>Token Rotation Time</td>
</tr>
<tr>
<td>TTRT</td>
<td>Target Token Rotation Time</td>
</tr>
<tr>
<td>VCI</td>
<td>Virtual Circuit Identifier</td>
</tr>
<tr>
<td>WAN</td>
<td>Wide Area Network</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength-Division Multiplexing</td>
</tr>
<tr>
<td>WDMA</td>
<td>Wavelength-Division Multiplexing Access</td>
</tr>
</tbody>
</table>
VARIABLES AND FUNCTIONS

\( a \) Normalized channel propagation delay
\( \text{Late}_Ct \) Token arrival late counter
\( N \) Total number of stations on the network
\( T_{1A} \) Optical delay line time
\( T_{2A} \) Optical switch element time
\( T_{3A} \) Optical correlator and discriminator time
\( T_{1B} \) Opto-electronic and serial-to-parallel conversion time
\( T_{2B} \) Decode circuit to media access circuit transfer time
\( T_{3B} \) Media access address recognition time
\( T_{Opr} \) Shortest requested time
\( U \) Channel utilization
\( \gamma \) Transmission velocity of optical signal in optical fiber
\( \tau \) Pulse width
CHAPTER 1

INTRODUCTION

With the development of communication systems comes the need for an interconnection facility for the communication system. Networks provide interconnections among various equipments, such as computers and peripheral devices, and allow sharing of information and expensive resources. Local Area Networks (LANs), Metropolitan Area Networks (MANs), and Wide Area Networks (WANs) provide such capabilities within a limited geographical area.

A LAN is a communication network that provides interconnection of a variety of data communicating devices such as computers, workstations, terminals, and peripheral devices within a limited geographical area, enabling the user to share efficiently local processing and computing resources [STAL84].

Some of the key characteristics of LANs are:
1. High data rate — LANs usually use much higher data rates than WANs, typically 1 - 100 Mbps,

2. Short distances — LANs are usually used within a building or a campus and only span from several kilometers to 50 kilometers,

3. Low bit error rate (BER) — typical BERs are in the range of $10^{-8} - 10^{-10}$,

4. Ownership by a single organization — because of the limitation of area, it is usually owned by a single organization.

LANs are often characterized in terms of their topologies, three of which are common: star, ring, and bus or tree (actually the bus is a special case of the tree with only one trunk and no branches, usually the term bus/tree is used when the distinction is unimportant).

The bus/tree topology is characterized by the use of a multiple-access, broadcast medium. Because all devices share a common communications medium, only one device can transmit at a time. Transmission employs a packet containing source and destination address fields and data. Each station monitors the medium and copies packets addressed to itself.

In the star topology, a central switching element is used to connect all the nodes in the network. A station wishing to transmit data sends a request to the central switch for a connection to some destination stations, and the central element uses circuit switching to establish a dedicated path between the two stations. Once the circuit is set up, data are exchanged between the two stations as if they were connected by a dedicated point-to-point link.
The ring topology consists of a closed loop, with each node attached to a repeating element. Data circulate around the ring on a series of point-to-point data links between repeaters. A station wishing to transmit waits for its next turn and then sends the data out onto the ring in the form of a packet, which contains, as with the bus/tree, both the source and the destination address fields as well as data. As the packet circulates, the destination node copies the data into a local buffer. The packet continues to circulate until it returns to the source node, providing a form of acknowledgement.

Ethernet is a bus-topology network with IEEE 802.3 protocol, which is based on Carrier Sense Multiple Access with Collision Detection (CSMA/CD) protocol. It is a contention protocol with no provisions for priorities or capacity allocation. This random access, contention-based protocol allows a station to initiate transmission when the bus network is apparently quiet. If a station detects a collision with a frame originating from another station before its own message has been successfully transmitted, it begins transmitting a jamming signal so that all stations recognize that a collision has occurred. It then waits for a time interval before beginning a retransmission.

Both IEEE 802.5 token ring and ASC X3T9.5 are ring-topology networks, their protocols are based on coordinated token capture [HANS90]. With token passing, a station must possess the token before it is permitted to transmit. Several techniques may be added to the basic token-passing mechanism to regulate access. The simplest, which is used on all three token-passing LAN standards, is to limit the amount of time that a station may hold the token. If each station is given the same time limit, then fair access is provided. Alternatively, a higher-priority station (such as the network
monitor center or a gateway to a long-haul network) can be given a greater time limit. All three token-passing protocol standards specify the optional use of these time limits but not how they are to be assigned. The assignment of time-limit values is a network management function.

The use of time limits provides a simple but static means of giving preference to some stations over others. For greater control, each of the token-passing LAN protocol standards provides techniques for capacity allocation that can be used to augment or replace the simple time-limit technique. In IEEE 802.5 token passing ring, all stations are not peers since one station is elected to be the Active Monitor. It supplies the ring clock source, inserts an elastic buffer into the ring to accommodate accumulated jitter, and inserts a fixed delay. The maximum network length is not explicitly specified, however, the trade-off between the number of ring stations and total link length is bounded by the allowed accumulated clock jitter. In 1982, ASC X3T9.5 started developing the FDDI standard [ROSS86] [ROSS89] [ROSS90]. FDDI utilizes a dual-ring topology, and its MAC is based on coordinated, timed token capture. In order to reduce latency, FDDI supports early token release after a station completes transmission of its frame, rather than waiting for the return of the leading edge of the frame from around the ring. Because of its higher data rate and distance requirements, FDDI is the first LAN standard that started out based on fiber optic technology.

WANs imply long-haul trunking between channel-concentration points, telephone central offices or tandems, and switching centers or channel drop and insert points. They interconnect facilities in different parts of the country or are used as a public utility [HOSS90] [STAL87].
The networks which share some of the characteristics of both LANs and WANs have emerged recently, they are MANs. A MAN can be viewed as a very large LAN using access protocols less sensitive to network size than those used in LANs. They are used to provide similar services as LANs along with intercommunications capabilities among more widely distributed user resources. They also serve as backbone networks to interconnect distributed user LANs. Thus, they typically use very high bit rates, cover larger distances, and are capable of supporting data, voice and video communication services.

Broadly speaking, a MAN is a network capable of providing high speed (greater than 1 Mbps) switched connectivity across distance from a few to several hundred kilometers, i.e., within a metropolitan area. In addition, more demanding requirements, for example, voice, video, data, etc, are carried simultaneously.

MANs have assumed such growing importance that the IEEE (Institute of Electrical and Electronic Engineers) has already begun standardizing them under Project 802.6. The 802.6 working group has determined that the MAN standard will provide for the two-way interchange of digital bit streams using a shared medium between nodes located within an area up to 50 km in diameter, supporting services that require guaranteed bandwidth rates ranging from 1 Mbps up to the appropriate limits for the media used [MOLL88] [KLES86]. The detailed information about IEEE 802.6 is described in Chapter 4.

IEEE 802.6 dual bus MAN employing the QPSX (Queued Packet and Switch Exchange) [NEWM86] [BUDR86] [NEWM88] access protocol is the ideal networking technology for a MAN operating in the public network. Its performance is more reliable and efficient than other protocols that were proposed. This is because its
multilevel priority structure, synchronization, and signaling are unaffected by congestion [HULL88].

The need to make the MAN compatible with the public network environment was brought into sharp focus by those working on it. The following goals are adopted for a MAN standard:

1. It should accommodate fast and robust signaling schemes for MAN
2. It should guarantee security and privacy and permit establishment of virtual private networks within MANs
3. It must ensure high network reliability, availability, and maintainability
4. It should promote efficient performance for MANs regardless of their size.

Today's networks have been designed to optimally handle either voice traffic, using circuit-switched technology, or data traffic, using packet-switched technology. Future communication networks, on the other hand, are expected to handle in a unified manner an unpredictable mix of services with different types of traffic, such as voice, data, image, and even video communications. Applications, ranging from very low-speed transmission to wideband full-motion video, are anticipated. The design of these future networks must be flexible not only to accommodate the characteristics and traffic requirements of each service, but also to respond to new service demands. Thus, comes the need for optical networks.

The explosive advance of lightwave technology over the past decade has been in long distance communication. There has been an increasing tendency to use optical fibers in LANs, replacing the conventional metallic media such as twisted pair and
CHAPTER 1. INTRODUCTION

coaxial cables. The most exciting possibility is the use of photonic technology to push LANs beyond basic data transport into the realm of integrated total communications services for a total entity such as a building or campus [HENC88].

Optical fibers have several desirable characteristics including

1. very high bandwidth
2. protection against electromagnetic interference
3. lower signal attenuation characteristics compared to coaxial cables
4. small size, light weight, and absence of corrosion problems
5. more elastic than conventional metallic cables

Some representative LANs and applications according to [HENC88] are shown in Table 1.1, along with approximate values of network transmission rates.

Table 1.1: Local Area Networks and Application

<table>
<thead>
<tr>
<th>Transmission Rate</th>
<th>LANs</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Mbps</td>
<td>Starlan</td>
<td>PC</td>
</tr>
<tr>
<td>10 Mbps</td>
<td>Ethernet</td>
<td>Workstation</td>
</tr>
<tr>
<td></td>
<td>Starlan10</td>
<td></td>
</tr>
<tr>
<td>100 Mbps</td>
<td>FDDI</td>
<td>Supercomputer</td>
</tr>
<tr>
<td>1 Gbps</td>
<td>UltraNet</td>
<td>Ultragraphics</td>
</tr>
<tr>
<td></td>
<td>VectorNet</td>
<td></td>
</tr>
<tr>
<td>&gt; 1 Gbps</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>
A subcommittee of IEEE has been working on recommending optical fiber technology into IEEE based networks [GIBS90] [STAL87]. The purpose of the IEEE 802.8 subcommittee — Fiber Optic Technical Advisory Group (TAG), is to provide technical guidance to the other subcommittees on optical fiber technology. It is investigating the use of optical fiber as an alternative transmission medium for 802.3, 802.4, 802.5, and 802.6 standards. It is also considering installation recommendations and a tutorial of fiber optic standards and related information, for example, the multi- and single-mode optical duplex connectors recommended by IEEE 802.8.

In this thesis, a new architecture of optical network — dual ring optical network (DRONET) — is proposed. The optical interface adapters for DRONET and DQDB are designed. In addition, an implementation of photonic switching in an optical interface adapter is also proposed.
CHAPTER 2

OVERVIEW OF OPTICAL NETWORKS

In this chapter, the current optical fiber communication networks and the corresponding topologies and the protocols will be reviewed.

2.1 Overview of Optical Network

2.1.1 Bus Networks

In bus networks, all stations are connected to a single transmission path that spans the whole length of the network. The medium is usually passive. If the bus is broken or disconnected between network nodes, the network will function as two buses. Thus many installations require a backup cable installed to prevent failure of the system.
if a cable is damaged. A disadvantage of bus networks is that baseband signals will suffer more attenuation and distortion compared to the shorter point-to-point links of ring, star, tree, or mesh networks. Therefore, especially in the case of fiber-optic bus networks, only a few stations can usually be supported. Optical amplifiers, which are made with doped optical fiber may be used to increase the number of stations supported, but this would increase the overall cost of the network.

2.1.1.1 Expressnet

Expressnet was first proposed in 1983 by Tobagi, et al [TOBA83a] [TOBA83b]. It is a unidirectional bus structure, shown in Figure 2.1. The unidirectional medium provides a linear ordering among the stations. One channel, which is called inbound channel, is used exclusively for reading the transmitted data, and the other, the outbound channel is used for transmitting data. All signals transmitted on the outbound channel are duplicated on the inbound channel thus achieving broadcast communication among
CHAPTER 2. OVERVIEW OF OPTICAL NETWORKS

A station that has a message to transmit in Expressnet is said to be backlogged. Otherwise, it is said to be idle. An idle station does not contend for the channel. When a backlogged station has a message to transmit, it will proceed as follows:

1. The station waits for the next end of carrier on the outbound channel, i.e., EOC(outbound) — outbound channel becomes idle.

2. When outbound channel becomes idle, the station starts to transmit the packet.

3. At the same time, the station detects the activity of upstream stations. If there is no interruption from upstream stations, the transmission will be completed.

A train of packets will be formed in a transmission cycle. This train is generated on the outbound channel and entirely seen on the inbound channel by all stations. The end of a train on the inbound channel (EOT(inbound)) is detected whenever the idle time exceeds the gap between two consecutive packets in the same round. This EOT(inbound) is used by all stations to start a new cycle of transmission, as the synchronizing event, just as EOC(outbound) was used within a round.

To avoid losing the synchronizing event EOT(inbound), if all stations are idle for a long period of time, all the stations will transmit an unmodulated carrier whenever it is detected on the inbound channel (EOT(inbound) is detected). The station starts a new round by transmitting its packet after detecting the end of a train of unmodulated carriers.

According to the algorithm described above, it is clear that Expressnet can maintain high efficiency under extreme conditions where short packets, high loads, and
CHAPTER 2. OVERVIEW OF OPTICAL NETWORKS

high data rates are used. It appears to be an attractive candidate for high-speed fiber-optic local area networks (FOLAN).

The fiber-optic configuration for Expressnet with a transmission rate of 10 \textit{Mbps} is reported in [MARH86]. And its performance was evaluated in [TOBA83a]. Under heavy load, the channel utilization $U$ of Expressnet is

$$U = \frac{1}{1 + \frac{a}{N}}$$

where $N$ is the total number of stations on the network, and $a$ is the normalized channel propagation delay, defined as the ratio of the end-to-end channel propagation delay to the packet transmission time.

A disadvantage in Expressnet is the complexity of the access protocol, which may result in high implementation costs.

2.1.1.2 X-Net

X-Net architecture is based on the dual, unidirectional bus topology [KAMA89]. Stations are connected to two optical fiber buses with active taps in the interface adapters, as shown in Figure 2.2. With the use of active switches, a station may either allow the optical signal received from the upstream side of a bus to flow towards the downstream section, or discontinue the signal propagation.

In X-Net, a station can be in one of three modes: Random mode, Transient mode, and Controlled mode. A station will be in the random mode when the loads are light and the station is idle. The station in the random mode will enter the transient mode if one of the following events occurs:
CHAPTER 2. OVERVIEW OF OPTICAL NETWORKS

Figure 2.2: Dual-Unidirectional Bus Architecture of X-Net

1. station \( i \) becomes ready and starts its transmission immediately, or

2. station \( i \) detects BOC(\( x \)) (beginning of a carrier signal on channel \( x, x = \text{Bus A}, \text{or Bus B} \)) on any bus.

When stations switch to the transient mode, they also assume either an R-L cycle or an L-R cycle of transmission. If the R-L(L-R) is assumed, ready stations transmit when the R-L(L-R) becomes idle.

After the transmission or detection of a Dummy packet, which is used to establish the next cycle of transmissions, a station will switch from the transient to the control mode. Under heavy load, when all or most of the stations are continuously backlogged, a station will continuously be in the controlled mode, alternating between R-L and L-R cycles of transmission.

Under heavy load, the channel utilization of X-Net can be expressed by

\[
U = \frac{1}{1 + \frac{\alpha}{N}}
\]
where $N$ is the total number of stations on the network, $a$ is the normalized channel propagation delay as in Expressnet.

The channel utilization of X-Net is higher than that of Expressnet described previously. Because of its high channel utilization over a wider range of "a" values, X-Net is a potential candidate for operation as an HSLAN. The disadvantages are the possible higher implementation costs because of the use of active switches on both buses, and reduced performance due to non-zero switching times.

2.1.2 Star Networks

2.1.2.1 Multiwavelength Optical Network

The multiwavelength optical network architecture is based on the $LAMBDANET^{TM}$ network of Bellcore [GOOD87]. The network architecture has a unique optical wavelength associated with each node in a cluster of nodes.

The $LAMBDANET^{TM}$ architecture is composed of a cluster of $N$ communication nodes connected by single mode fibers to a hub location, as shown in Figure 2.3. The essential feature is that each node within a cluster transmits its information on a unique wavelength using single frequency laser diodes. The optical fibers are passively coupled at the hub location using an $N \times N$ transmissive star coupler. Each output fiber from the star coupler carries all of the wavelength channels to its corresponding node. The incoming optical signal with a different wavelength is demultiplexed with a diffraction grating, which is followed by as many as $N$ optical receivers.
CHAPTER 2. OVERVIEW OF OPTICAL NETWORKS

The LAMBDANET™ architecture allows the implementation of a virtual private network for large business customers. In this application, the virtual network is defined as a set of customer points; each point has a number of directly connected T1 lines or their equivalent via fiber to the nearest LAMBDANET™ cluster. The LAMBDANET™ has also some other potential system applications for point-to-point traffic and video distribution.

Figure 2.3: Star Architecture of LAMBDANET™

2.1.2.2 BIDS Network

In 1979, plans were laid for the first British Telecom (BT) distributed-star fiber system. This led in 1982 to the Fibervision trial, a small network servicing 18 customers, which remained operational for two years [FOX90]. It utilized the familiar structure of the distributed-star (switched-star) network. Primary links from the load-end delivered the video channels to a remote switch point, and the customer-selected channels were then fed out on the dedicated star connection to each customer.
In addition to considering a new, more advanced cable TV design, attention was also focussed on a multiservice network using the distributed-star architecture. This has become known as BIDS (Broadband Integrated Distributed Star) and integrates together the concepts of a switched cable TV network and a remote telecommunications multiplexer, in order to provide the full range of services to a customer.

The network configuration used in BIDS is the distributed-star with a central cable head-end and modern digital telephone exchange, remote hub-sites, and street-located broadband access points (BAP), as shown in Figure 2.4. Primary links connect the head-end to hub-sites, and then on down to the BAPs. Secondary fiber links connect the BAPs to the customer units in the home or business. All the fiber links use single-mode fiber at 1300 nm.

Multiservice networks, as in BIDS, require different types of communication links according to the service to be carried, for example, TV, FM radio, telephone, and data. The modulation format for the primary video links in BIDS was chosen to be FM because of its performance advantages, both at low carrier-to-noise ratios and in the presence of interference and cross-talk. Telephone and data service on the network is provided entirely by digital means. Each fiber carries 16 FM TV carriers and one digital phase-modulated FM radio carrier. Wavelength division multiplexing (WDM) was evaluated in the application in BIDS. However, the economics still favored an additional fiber rather than an extra wavelength. It is a technique that has been waiting in the wings for a number of years but has, so far, been preempted by the improvements in electrical multiplexing. For a distributed-star network, the customer link is undemanding on bandwidth and hardly warrants WDM. The exception here might be the use of one wavelength for telecommunications services (perhaps cheap 850 nm
Cable TV Head-end

**-prim-

Links

Hub-site

To Other Hub-sites

Primary Links

Broadband Access Point

To Other BAPs

Secondary Links

Customer Term. Unit

To Other Customers

16 channel video per fiber + audio sub-carrier links

140 Mbps primary telephony and data links

Figure 2.4: BIDS Network Configuration
devices operating "multimode" over the fiber) and a different one for broadband. Full high definition TV (HDTV) service might also require an extra wavelength.

It was expected that the BIDS network would be supplying service to real customers in 1990 or later.

2.1.3 Ring Networks

2.1.3.1 Integrated Cambridge Ring

Cambridge Ring (CR) is based on the empty slot principle and data are transmitted using minipackets. Integrated Cambridge Ring (ICR) provides the ability to transmit simultaneously short control minipackets and long data packets [HOPP83].

An ICR consists of a set of repeaters connected by a communication medium, such as optical fiber cables, and a monitor station which has the responsibility for synchronizing and maintaining the network. To transmit, a station must wait until an empty slot arrives, then having filled it with a minipacket, it waits until the slot returns and marks it empty. When the slot has returned, two response bits, which are located after the data bytes, are inspected to see whether the minipacket was accepted, rejected, or marked busy by the destination station. Each station is provided with a unique address as well as information about the number of slots in the system so that it can mark empty slots it has used without increasing repeater delay.

The number of data bytes in a minipacket in ICR is extended to 8 bytes whereas in the minipacket of CR there are only 2 bytes of data. The data format is shown in Figure 2.5.
The two extra control bits in the minipacket format of ICR is the main change that makes the ICR incompatible with CR. These two user control bits are available to the user who can load them and read them as required. They are treated with the hardware as an extension of the data field and not changed in any way. Another way of using the control bits is to allow hardware to interpret them in a specific way.

Statistical results show that most of the data transmitted on ICR consists of large data packets, which mainly consist of data transfers to and from the file storage devices on the ring and high portion of these are the maximum length — 2048 bytes, whereas the largest number of packets transmitted are short packets. The short packets are used to transmit mainly protocol control information. With the traffic consisting predominately of very short packets, the overall performance of the network would be severely degraded as the number of stations waiting to transmit increased. Thus, a hybrid ring, which supports both ICR channel mode and short slot compared to channel mode, is proposed. This ensures that the bandwidth available to channel users would be still high while there are a lot of short slots to be transmitted. Figure 2.6 shows the hybrid ring slot train format.
With two kinds of slots, different types of traffic such as voice, facsimile, and data can be allocated bandwidth in accordance with their traffic patterns. In advanced systems, the configuration of slots can be changed dynamically with needs. With the availability of high-quality fiber-optic transmission cables, the ring could operate at a very high data rate. The system would support traffic ranging from inter-processor communications, high-quality video, and fast file transfer to protocol control information and voice traffic.

2.2 Main Problems and Proposed Solutions

Although there have been numerous demonstrations of optical LANs, most have operated at relatively modest bit rates ($\leq 100\,Mbps$) [GERL91], thus failing to take advantage of the multigigabit transmission capacity of optical fibers already achieved in long-distance transmission systems [JONE88] [KEIS83]. The basic problem is that a LAN is much more complicated than the point-to-point links used in long-distance transmission systems, and gigabit data rates have been much more difficult to achieve.
The most important point to emphasize at the outset is that fiber cannot simply be substituted for other transmission media to upgrade the capacity of a wire-based LAN; the differences between photonic and electronic communications techniques are too great [HENR85]. Compared to electronic networks, fiber-based networks are characterized by:

1. severely limited signal power, and
2. abundant transmission bandwidth.

To use the enormous bandwidth, however, two basic problems arising from these characteristics must be solved [HENR88]: first, the achievable data transfer rates are limited by the output power of the optical transmitter, the dispersion of optical fiber, coupler loss and insertion loss of optical devices, and the minimum energy level required at the optical receiver for reliable detection of signals; and second, the limitation of the speed of electronic interfaces used. The terms power bottleneck and electronic bottleneck have been used to describe these two problems. The power bottleneck makes it difficult to translate many high capacity networking concepts into practical photonic implementations. The electronic bottleneck limits the bandwidth to far less than the capability of optical fiber.

To date, much work has been done to solve the first problem — power bottleneck. One solution is the use of lumped amplifiers [MOLLE91]. For wavelength-division multiplexing, which is an attractive feature of the "all-optical" approach to ultra-long distance transmission, it is well known that solitons of different velocities (different wavelengths) are transparent to each other. Such transparency is also maintained in a system using lumped amplifiers, as long as the length of the collision (the distance
the solitons travels down the fiber while passing through each other), is long enough, e.g. two or more times the amplifier spacing. The result demonstrates the potential for multichannel WDM at Gbps rates over transoceanic distance.

Another promising approach is Erbium-doped fiber (EDF) amplifiers [NAKA90] [CONR91] [GILE91]. Present optical fiber communications systems are composed of regenerative repeaters, which are inserted into the line in order to compensate for signal attenuation created by long fiber transmission distances. In a conventional regenerative repeater, the optical signal is first converted to an electrical signal. If the optical signal can be directly amplified with low noise, the repeater can be smaller and cheaper than existing repeaters. In addition, the electronic bottleneck raised by electronic repeater can also be eliminated.

Erbium-doped single-mode fibers were first demonstrated in 1987, and their use as a novel traveling-wave-type optical amplifier in optical fiber communications systems in 1989 [GILE91]. Now these active fibers in optical amplifiers, lasers, switches, and a variety EDF amplifiers have many merits, such as high gain, low noise, wide bandwidth, optical pumping, and gain controllability. With the use of EDF amplifiers, many advantages can be achieved, for example, elimination or reduction of electronic circuits, potential use of high speed wideband optical signal processing, simultaneous signal amplification, etc. A simultaneous amplification of 16-channel coherent FSK (Frequency Shift Keying) transmission at 622 Mbps using EDF amplifiers over 2223 km, and soliton propagation using EDF amplifiers over 10,000 km have been reported [CONR91]. This shows that the EDF amplifier is a powerful component not only for long-haul transmission but also for multichannel distribution networks.
In this thesis, the second issue — electronic bottleneck, which is mainly associated with opto-electronic interface in optical networks, is researched and possible solutions described.

In order to satisfy all the needs and requirements of users, optical fibers have become the preferred transmission medium in communication systems in the last decade. At the same time, present switching systems, however, still consist of conventional electronic switches and cannot directly exchange optical signals. In these architectures, electronic switches are connected by optical links. High throughput can be achieved in electronic switching architectures through high dimensionality, since the transmission bandwidth on an individual channel is limited to a few GHz. However, the relatively low-transmission bandwidth of the electronic switches, the associated optoelectronic interfaces, and the processing electronics for routing control, present an obstacle to fully utilizing the large bandwidth-distance product of the optical fiber. This obstacle could be overcome if signals remained in optical form during the switching and signal processing operations.

The first step in completing the optical transmission path is to replace electronic switches with photonic switches[LEA88a]. A photonic switching system, which would leave the information in optical form during switching, would have several advantages over electronic switching systems. Photonic switches have a large transmission bandwidth (in excess of 1 THz) and faster switching time (subpicosecond) than electronic switches. The use of photonic switches would also eliminate the need for optoelectronic conversion which will result in a decrease of the hardware complexity and failure rate of the switch. In contrast to electronic switches, the potential bottleneck at the optoelectronic interface that will result from the discrepancy in the optical
transmission rate and the electronic processing speed would be eliminated, since pho-
tonic switches have a faster response time than their electronic counterparts, and can
therefore accommodate a high optical transmission data rate, and a large throughput
can be achieved in photonic switching architectures through very high-transmission
bandwidth, rather than large dimensionality.
CHAPTER 3

DUAL RING OPTICAL NETWORK

In this chapter, ASC 3T9.5 MAC will be briefly described. And then the architecture of DRONET will be discussed. The performance of DRONET with optical interface adapter, which is designed in Section 3.4, is evaluated with the comparison to FDDI.

3.1 Introduction

The Fiber Distributed Data Interface (FDDI) is a local Area Network (LAN) with a transmission rate of 100 Mbit/s. Using optical fiber as the medium, the FDDI protocol is based on a token passing ring access method. It was originally proposed as a packet switching network with two primary areas of applications: first, as a high performance interconnection among mainframes, and among mainframes and their
CHAPTER 3. DUAL RING OPTICAL NETWORK

associated mass storage subsystems and other peripheral equipments; and second, as a backbone network for use with lower speed LANs such as IEEE 802.3, 802.4, and 802.5. FDDI grew from the original proposals to satisfy the need of many applications, including the back-end interface and front-end high performance LAN applications. One enhancement, FDDI-II, will offer significantly increased services by integrating circuit-switched data traffic capabilities into what originally had been strictly a packet switching LAN, expanding the field of application of FDDI to include those requiring the incorporation of voice, video, and control signals.

The widespread acceptance of FDDI has been due to a number of factors. With the many other advantages that the use of optical fiber offers — high data bandwidth, security, safety, immunity to electromagnetic interference, and reduced weight and size — the concept of an all fiber LAN was most attractive. Because the FDDI design has been optimized to the use of optical fiber since its inception, FDDI now in a leadership role in the development of optical fiber LAN technology.

The ring topology can be shown to offer superior reliability, availability, and serviceability, even in the face of physical damage to the network. Ring topologies of FDDI allow for the isolation of attachments through several mechanisms. Counter-rotating rings, as shown in Figure 3.1, are basic to the FDDI structure. The counterrotating ring concept uses two rings connected to each station or concentrator— one clockwise and the other counterclockwise. When a failure in a link occurs, the stations on either side reconfigure internally as shown in the middle diagram. The functional stations adjacent to the break make use of the connection in the reverse direction to close the ring, thus eliminating the bad link. In this figure, the dark squares
CHAPTER 3. DUAL RING OPTICAL NETWORK

Figure 3.1: Reconfiguration of Counterrotating Rings

represent the logical (MAC) attachment within the stations. Should a station itself fail, as shown in the bottom diagram of this figure, the stations on either side reconfigure to eliminate the failed station and both of the links to it. The use of this two ring topology allows FDDI networks to be configured to tolerate a variety of station or link failures and physical network configurations without catastrophic consequences [ROSS86] [ROSS89].

In FDDI, one of the two rings acts to provide redundancy. Only in periods of failure of the main ring or station is the second ring required to act independently. Although FDDI provides for an overall bit rate of 200 megabits per second, with each ring operating at 100 Mbits/s, only half of the bandwidth can be used at a given time. In this work, we propose a dual ring optical network (DRONET) with the second ring being in continuous use as an additional data path. This second ring is
used to transmit synchronous traffic only, using a code division technique, combined with statistical multiplexing, for good bandwidth efficiency.

3.2 Description of ASC X3T9.5 FDDI Standard

The initial version of FDDI uses optical fiber with light-emitting diodes (LED's) transmitting at a normal wavelength of 1325 nm over multimode fiber. Connections between stations are made with a dual fiber cable employing a polarized duplex connector. A single-mode fiber (SMF) version of Physical Layer Medium Dependent (PMD) uses laser diode transmitters, with two power levels categories specified, the lower of which retains the same receivers as the basic PMD.

The data transmission rate is 100 Mb/s. The effective sustained data rate at the data link layer will be well over 95 percent of this peak rate. The four out of five code used on the optical fiber medium, requires a 125 megabaud transmission rate. The nature of the clocking limits frames to 4500 octets maximum. Multiframes may however be transmitted on the same access opportunity.

A circuit-switched mode of operation, referred to as FDDI-II, has been specified which allocates the bandwidth of the FDDI to circuit-switched data in increments of 6.144 Mb/s isochronous channels. Up to 16 isochronous channels may be assigned using a maximum of 98.304 Mb/s of bandwidth. Each of these isochronous channels offers a full duplex data highway which may in turn be relocated into three 2.048, or four 1.536 Mb/s data highways; meeting the requirements of the European and North American telephone systems, respectively. A residual token channel of 1 Mb/s capacity remains even when all 16 isochronous channels are assigned and reassigned
on a real-time basis with the bandwidth of any not assigned available to the token channel.

FDDI-II is initialized identically to the basic FDDI and is fully interoperable with it prior to the assignment of any isochronous channels. The presence of any non FDDI-II capable stations in a ring prevents the assignment of any isochronous channels and thus the activation of the FDDI-II mode of operation [ROSS86].

3.2.1 FDDI Token Ring MAC

FDDI is most easily described in terms of its component standards. There are seven standards in all. These are being developed in accordance with the OSI reference model and the OSI management framework and layer management guidelines. The basic FDDI, when completed, will consist of the following standards: a Station Management (SMT) standard, which specifies the FDDI station configurations, ring configurations, and the control required for proper operation of stations in an FDDI ring; a Media Access Control (MAC) standard, which specifies access to the medium, addressing, data checking, and frame generation/reception; a Physical Layer Protocol (PHY) standard, which specifies the encode/decode, clocking, and data framing; and a Physical Layer Medium Dependent (PMD) standard, which specifies the optical fiber link and related optical components. There are two versions of the PMD standard: the basic PMD as described above and SMF-PMD (Single-Mode Fiber version of the PMD standard), which provides an alternate to the basic PMD, allowing the use of single-mode optical fiber and increasing the permissible fiber links from 2 to 60 km in length. Figure 3.2 shows the component entities necessary for an FDDI station.
In this section, we will analyze the performance of the FDDI MAC protocol. Since we are studying the error-free operation of the protocol, we concentrate on the network-access control and priority mechanism, and omit details of network initialization, error recovery, and other functions unrelated to frame transmission.

All traffic in FDDI is classified as either synchronous or asynchronous. In FDDI terminology, traffic that is assigned guaranteed bandwidth is called synchronous traffic, and they have critical delivery time constraints. Synchronous frames are those which must be transmitted on time; and the waiting time must be less than the value determined. Voice, control signals, etc, are examples of synchronous frames. All other traffic is called asynchronous traffic. Asynchronous traffic is sent only if the load on the ring is light enough to support it. Its priority class is divided into multiple levels.
During ring operation, station timers interact to provide each station guaranteed access to the channel to satisfy its synchronous transmission requirements; asynchronous transmission is allowed only to the extent that it will not infringe upon these synchronous guarantees.

As part of the ring initialization process, the stations negotiate a value for the Target Token Rotation Time (TTRT), a parameter which specifies the expected token rotation time. Each station requests a value that is fast enough to support its synchronous traffic needs. The long term average token rotation time cannot exceed the TTRT. The protocol also guarantees that the maximum token rotation time will not exceed $2 \times TTRT$ [JOHN87] [SEVC87], so stations with strict transmission delay requirements must request a TTRT equal to one half of the maximum acceptable delay. The shortest requested time is assigned to $T_{Opr}$, a parameter which specifies the operational TTRT. $T_{Opr}$ is used to limit token rotation time, and thus is an important ring parameter.

A Token Rotation Timer (TRT) is used in each station to measure the time between successive arrivals of the token at the station. The TRT is reset each time the token has been received in order to time the next token rotation. The TRT will expire if it counts up to $T_{Opr}$ before the token has arrived back at the station. When the TRT expires, Late.Ct, a count which is initially zero, is incremented and the TRT is reset to zero and continues timing. When the token arrives late at a station (Late.Ct=1) the TRT is not reset, then it is allowed to continue timing, thus accumulating the lateness of the current token rotation time. The result of accumulating lateness is that following a token rotation that exceeds $T_{Opr}$ by time $A$, asynchronous transmission will be restricted until this lateness has been compensated.
for by token rotations less than T\_Opr by a total time of A. This ensures that the average token rotation time is at most T\_Opr. If Late\_Ct ever exceeds 1, then error recovery procedures are performed. Late\_Ct is reset to zero each time the token has been received.

A Token Holding Timer (THT) is used by each station to control the amount of time the token is held for transmitting asynchronous frames. The THT is loaded with the correct value of the TRT when the token is received on time (Late\_Ct=0) at a station. When the THT reaches the token-holding time threshold for a particular priority level, the token may no longer be used for transmitting frames of that level. Transmissions already in progress when the THT expires are completed. The transmission time following the expiration of the THT is called the residual frame transmission time. The maximum value is equal to the maximum frame transmission time.

A station’s specific actions in conventional an FDDI when it receives a token in FDDI ring are listed below. Each station has its own TRT and THT, and its own T\_Opr and Late\_Ct parameters \[JOHN87\] \[DYKE88\] \[SEVC87\].

1. If the token is on time, i.e., if Late\_Ct=0, then the current value of TRT is placed in THT, and TRT is reset to 0, its threshold is T\_Opr, both synchronous and asynchronous frames may be transmitted.

2. If the token is late, i.e. if Late\_Ct \neq 0, Late\_Ct is cleared, but the TRT is not reset. In this case the TRT accumulates its lateness, and only synchronous frames may be transmitted.
3. TRT is enabled during all ring operation, i.e. during both synchronous and asynchronous frames transmission. When a station’s TRT expires (TRT = T.Opr), or when its accumulation is otherwise interrupted, it is reset to zero and enabled again. THT is enabled only during transmission of asynchronous frames.

4. The length of time an individual station can transmit synchronous frames may not exceed its synchronous bandwidth allocation. A station may transmit asynchronous frame until its THT expires. Asynchronous overrun is allowed; this period has been called residual frame transmission time.

5. No frames of either class may be transmitted after expiration of the station’s TRT.

### 3.2.2 FDDI Protocol Data Unit

The standard expresses MAC data unit in terms of symbols exchanged between MAC entities. Each symbols corresponds to four bits. This assignment was chosen because, at physical layer, data are transmitted in four-bit chunks. Figure 3.3 depicts the formats of the frames generated by the FDDI protocol. The overall frame consists of the following fields:

- **SFS** = Start of Frame Sequence
- **PA** = Preamble (16 or more symbols)
- **SD** = Starting Delimiter (2 symbols)
- **FCS** = Frame Check Sequence
- **FC** = Frame Control (2 symbols)
3.3 Architecture of DRONET

3.3.1 Use of the Secondary Ring

From the previous section, we know that all traffic in FDDI is classified as either synchronous or asynchronous. In FDDI terminology, traffic that is assigned guaranteed bandwidth is called synchronous traffic, which has critical delivery time constraints. Voice, video, etc. are examples of synchronous traffic. All other traffic is called asynchronous traffic. Asynchronous traffic is sent only if the load on the ring is light enough to support it. Its priority class is divided into multiple levels.

As the synchronous traffic becomes heavy, the waiting time of asynchronous frame
will become longer and longer, approaching infinity when the throughput of synchronous traffic approaches 100 Mbps [BUX89] [DYKE88] [JAYA90]. In order to solve this problem and enhance both the synchronous and asynchronous traffic, it is proposed secondary ring be used for transmitting the synchronous traffic, while the primary ring remains to transmit asynchronous traffic only. As two rings can be used to transmit frames simultaneously, both synchronous and asynchronous bandwidth are guaranteed. In order to simplify the media access control of such a network, the MAC of FDDI is still used in the primary ring, but in the secondary ring, CDMA (Code-Division Multiplexing Access) is used, this will be discussed in Section 3.6. Because the synchronous frames can be generated in bursts with the superposition of optical orthogonal sequences, they can be transmitted concurrently. Using the optical self-routing interface adapter, which will be described in Section 3.4, we can obtain the architecture of the dual ring optical network (DRONET) on the basis of the architecture of FDDI. Figure 3.4 is the connection part of the station and transmission medium in DRONET. Interface adapter and physical medium dependent are the interface adapter with photonic switching and logic. Rings 1 and 2 are used to transmit synchronous and asynchronous traffic, respectively. This interface can bypass the failures of the station and of the interface adapter itself.

### 3.3.2 Media Access Protocol of DRONET

The asynchronous priority scheme used in FDDI will function in DRONET. Hence, the use of a reservation field is still effective. Furthermore, the DRONET protocol is intended to provide for greater control over the network than FDDI, to meet the requirements for a high speed local network which provides both synchronous and
asynchronous traffic. Figure 3.5 depicts the complete capacity allocation scheme.

3.4 Design of Optical Interface Adapter for Dual Ring Optical Network

This section will begin by discussing and comparing the three kinds of commonly used optical routing algorithms. Then, a design for an optical interface adapter design for DRONET incorporating photonic switching and logic is presented.

3.4.1 Routing Algorithm

The routing of incoming data streams at a switching node requires recognizing an address. This process can be easily carried out optically by correlation. Optical
Figure 3.5: DRONET Capacity Allocation Scheme
address recognition using spread spectrum and code-division encoding techniques was previously demonstrated in [PRUC87a] and [PRUC90a].

3.4.1.1 Optical Code-Division Routing Algorithm

Code-division multiple access, or CDMA, is based upon the assignment of orthogonal codes to the address of each user, which substantially increases the bandwidth occupied by the transmitted signal. A CDMA LAN therefore requires a wide bandwidth channel, such as an optical fiber. In addition, CDMA requires wide bandwidth signal processing at the receiver. Optical fiber delay-line signal processors using single-mode fiber have bandwidth-distance products in excess of 100 GHz.km, and losses less than 0.5dB/km.

In conventional CDMA sequences, each bit in a CDMA system is encoded into a waveform $s(t)$ that corresponds to a code sequence of $N$ chips representing the destination address of that bit. Each receiver correlates its own address $f(t)$ with the received signal $s(t)$. The receiver output $r(t)$ is

$$r(t) = \int_{-\infty}^{\infty} s(z) f(z - t) dz. \quad (3.1)$$

If the signal has arrived at the correct destination, then $s(t) = f(t)$, and Equation 3.1 represents an autocorrelation function. If the signal has arrived at an incorrect destination, then $s(t) \neq f(t)$, and Equation refeqn1 represents he cross-correlation function. At each receiver, to maximize the discrimination between the signal to be switched and all other signals at the controller, it is necessary to maximize the peak
of the autocorrelation function and minimize the standard deviation of the cross-correlation function. This is accomplished by selecting an appropriate set of orthogonal code sequences. Increasing the processing speed by using optical processing allows for a reduction in chip width and an increase in $N$. Increasing $N$ yields an increase in the number of orthogonal sequences and consequently, in the number of assignable addresses.

The set of code sequences that will yield adequate discrimination between the auto- and cross-correlation functions depends on the nature of the correlation process used. A fundamental difference exists between optical correlation and conventional electrical correlation. Conventional electrical correlation can be based on electrical delay-lines that coherently combine tapped signals. Though optical signals can also be processed coherently, this is not practical at the present time, owing to the high frequency of the optical carrier. A more feasible optical correlation technique employs fiber-optic delay lines that incoherently combine tapped signals. This results in a simple summation of optical power. Figure 3.6 shows a simple block diagram of the code-division optical routing architecture.

The orthogonal code sequences must be designed to satisfy two conditions, namely:

1. each sequence can be easily distinguished from a shifted version of itself; and

2. each sequence can be easily distinguished from (a possibly shifted version of) other sequences in the set.
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Figure 3.6: Code-Division Optical Routing Switching Architecture
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3.4.1.2 Optical Time-Division Routing Algorithm

Optical control of an optical switching element using a time-division encoding technique has been demonstrated [HINT89a] [HINT89b] [THOM87]. In one of these systems, each packet header is encoded with a sequence of length $N$, representing one of $N$ destination addresses. The address of a packet resides in the position of only one pulse within the packet header. For a given packet header length, time-division encoding can accommodate many more addresses than code-division encoding, in which the destination address of each packet is represented by a chip sequence of length $N^2$, thus resulting in a more efficient utilization of the channel bandwidth. Although the time-division encoding technique is more bandwidth efficient than the code-division encoding scheme, with its ability to differentiate superimposed orthogonal code sequences, code-division encoding scheme can allow asynchronous concentration of several input signals to the same switch output [PRUC90a] [PRUC90b] [PRUC90c].

The packet header of duration $T$, is divided into a frame of $N$ slots, each of duration $\tau$. The header slots are denoted $i = 1, 2, ..., N$. The packet destination address is encoded in the position of a single address bit within the header frame, and that bit will be referred to as the “address”. An optical clock (a train of narrow optical pulses of width $\tau$ and repetition rate $1/T$) is synchronously distributed to all switching nodes in the switching network. It is apparent that the width and repetition rate of the clock pulses determine the maximum number of addresses.

As shown in Figure 3.7, decoding of the destination address at the optical routing controller is performed by incoherently adding the optical clock, delay to the slots of the addresses to be switched, to the header frame. When delay $iT$ is connected to the
Figure 3.7: Time-Division Optical Routing Switching Architecture
summer, this delay shifts the optical clock pulse from the first slot to the \( i \)th slot. If the \( i \)th slot of the packet header is occupied by an address bit, the summer: incoherently adds the delayed clock pulse to the address bit in the \( i \)-th slot, resulting in a pulse of double amplitude. The discriminator threshold detects the double-amplitude pulse and generates a gating pulse of duration \( T_p \). The gating pulse sets the switching element in the cross state, and the entire packet present at the switch input is routed to the switch output.

An experiment on high-speed optical time-division switching has been reported. In this experiment [SUZU86], four color video signals from cameras are encoded into four 64 Mbit/s digital pulse streams and are combined into a 256 Mbit/s pulse stream by the multiplexer and then converted to an optical signal. This optical signal can control the bistable laser diode such that it either remains in the "off" state or changes to the "on" state in accordance with its intensity. The connection between optical signal and bistable laser diodes is accomplished by the time-division multiplexer and \( 1 \times 4 \) write optical switch matrix, which is composed of directional couplers. The \( 4 \times 1 \) read optical switch matrix connects the bistable laser diode outputs to the output in the specified read period and constructs an output time-division multiplexed optical signal.

### 3.4.1.3 Optical Spectral-Division Routing Algorithm

Frequency- and wavelength-division multiplexing in which different frequency or wavelength carriers are modulated with independent message channels is an old idea in widespread use in modern communication systems. These techniques can also be applied with advantage to optical communication systems. Generally, these techniques
can be divided into three categories.

1. Frequency-division multiplexing (FDM). In this type of system the multiplexing and demultiplexing functions are carried out in the electrical domain and the preassembled multiplex of carrier frequencies used is commensurate with the message channel bandwidth.

2. Wavelength-division multiplexing (WDM). In these systems the multiplexing and demultiplexing channel selections are carried out in the optical domain. The optical carrier spacing will be determined by factors other than the message channel bandwidth and in general will be much larger than the message bandwidths.

3. Coherent optical multiplexing. The multiplex may be assembled in either the electrical or optical domain, but at the receiver homodyne and heterodyne techniques are implemented by means of mixing the incoming optical multiplex with an optical local oscillator. In this system the carrier spacing will be of the order of the message channel bandwidth.

WDM will be considered to be the general case in optical routing algorithm, while coherent optical multiplexing is a new technique in optical routing. With an adequately designed system, wavelength carriers in the wavelength multiplex could carry FDM or coherent multiplexed systems.

The general architectural form that has been most commonly used in wavelength-division multiplexing networks is broadcast-and-select network, and it is illustrated in Figure 3.8. In broadcast-and-select network, all inputs are combined in a star
coupler and broadcast to all outputs. Several different possibilities exist, depending on whether the input lasers, output receivers, or both, are made tunable.

![Diagram of Broadcast Switching](image)

**Figure 3.8: Wavelength-Division Multiplexing Architectures**

It is clear that wavelength-division multiplexing and switching are desirable techniques for optical networks to enhance their overall throughput and eliminate the electronic bottleneck. Incorporating wavelength as an additional dimension in telecommunication networks are almost practical, and the feasibility of such networks has already been demonstrated. However, it is clear that there is much remaining work to be done, for instance, improvements of tunable lasers, filters and receivers, etc. At present time, nearly all the applications of wavelength-division multiple access and wavelength-division switching reported in the literature concern star topology networks and broadcast-type switches. These are far from the FDDI application.
3.4.2 Comparison of CDMA, TDMA and WDMA Multiplexing Routing Algorithms

For a code-division routing algorithm, each packet header of length $T$ is encoded with a waveform $s(t)$ that corresponds to the destination address of that packet. This orthogonal code sequence can represent $N$ destination addresses. For a given packet header rate, as $N$ becomes large, the generation of narrow pulses becomes increasingly difficult. Although the time-division encoding technique is more bandwidth efficient (this will be discussed in the next paragraph), the code-division encoding scheme, with its ability to differentiate superimposed orthogonal code sequences, can allow asynchronous concentration of several input signals to the same switch output port.

In a time-division routing algorithm, the packet header is encoded with a sequence of length $N$, representing one of $N$ destination addresses. The destination address of a packet resides in the position of any one pulse within the packet header. Given a packet header length, TDMA encoding can accommodate many more addresses than CDMA encoding and thus results in a more efficient utilization of the channel bandwidth. It is mostly used in broadcast systems.

Wavelength-division routing algorithm has many advantages. For instance, 1) it has very large potential bandwidth or wavelength channels. (The low loss region of a single-mode fiber extends over wavelengths from roughly 1.2 to 1.6 $\mu$m, which is an optical bandwidth of more than $30\ THz$); 2) switching and routing are possible within the wavelength domain, etc. Wavelength-division routing algorithm, as well as code-division routing algorithm can be used in both broadcasting and polling systems. But in WDM systems tunable transmitters and tunable receivers, which are beyond
application now, are needed.

3.4.3 Architecture of Optical Interface Adapter for DRONET

Because the DRONET system has two rings to be used to transmit information, two switches are used in the interface adapter. One of them is used for routing asynchronous information, the other one for synchronous information, as discussed previously in Section 3.3.

Figure 3.9 is block diagram description of the architecture of the optical routing switching system for a dual ring local area network. If there is a frame being routed on the first ring, then input 1 of a station, through which the routed frame is passing, receives the optical signal. This signal is divided into two parts by an optical fiber splitter. One part enters optical delay line to be temporarily stored. The other part goes to optical correlator. The result of the optical correlation will determine the state of optical switching element. If the destination address is recognized, the switching element is crossed, and the information goes to output 1. If the destination address can not be recognized, the switching element will bar the information, and it will go to output 1' of the switching element. Recalling that we still have a synchronous signal on the second ring to be transmitted, input 2 receives the signal, the signal is led into two paths, as in input 1. One is an optical delay line path and the other is the optical correlation path. If the destination address cannot be recognized, the switching element connected to output 2 is still unswitched, and the switching element attached to output 1 is unchanged. If the destination address is recognized, the discriminator turns the switching element to the “on” state, and at the same time, it will control the switching element in path 1 to the “off” state via optical logic, i.e., blocking the
asynchronous information. This is to ensure that the synchronous information has the highest priority. In the second ring, because superimposed orthogonal sequences can be differentiated, synchronous information is unblocked for transmission. This behavior of the interface is described in the chart shown in Figure 3.10.

According to the FDDI protocol, the services provided by the physical layer are defined in terms of primitives and parameters. These are:

- PH-DATA.request (PH-REQUEST(symbol)).
Figure 3.10: Flow Chart of Photonic Switching
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- PH-DATA.indication (PH-INDICATION(symbol)).
- PH-DATA.confirmation (transmission-status).
- PH-INVALID.indication (PH-INVALID).

PH-DATA.request defines the transfer of data from MAC (Medium Access Control) to PHY (Physical Layer Protocol). PH-DATA.indication defines the transfer of data from PHY to MAC. PH-DATA.confirmation provides appropriate response to the PH-DATA.request primitive signifying the acceptance of a symbol specified by PH-DATA.request and willingness to accept another symbol. PH-INVALID.indication is generated by PHY and asserted to MAC to indicate that the symbol stream has been detected as invalid.

Figure 3.11 shows the architecture of optical interface adapter with photonic switch and logic for DRONET. This interface offers the services provided by PHY. As shown in Figure 3.11, MAC sends PHY a PH-DATA.request every time the sublayer has information to output. Upon receipt of this request, the PHY entity shall encode and transmit the information to the transmission medium. When the PHY entity is ready to accept another request, it will return to MAC a PH-DATA.confirmation, which signifies the transmission completion status, in order to synchronize the MAC data output with the data rate of the medium. When there is data to be transferred from PHY to MAC, PHY will send a PH-DATA.indication to MAC. This will happen when there is data flow to route on the medium, and destination address is recognized. In FDDI, PH-DATA.indication is sent once every time there is information on the transmission medium, whether the destination address is recognized or not. In
Figure 3.11: Architecture of Optical Interface Adapter for DRONET
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DRONET, the information first of all enters the optical interface adapter to be recognized. According to the state of the optical switching element, the information will be processed in one of two ways: 1) if optical switch is crossed, information will be detected by photodetector, and received by the station; 2) if optical switch is barred, information will be sent to transmission medium again with an optical fiber coupler. Switching is removed before the receiver in this interface adapter, in order that before the information is received, its path can be determined.

3.5 Performance Evaluation of DRONET

3.5.1 Switching Time Calculation

We compare, to a first order approximation, the switching times of an optical interface adapter with those of an opto-electronic interface adapter. Figure 3.9 and 3.12 show the comparative architectures of both interfaces. In Figure 3.12, the incoming signal is received with the optical receiver, and converted to an electrical signal. The buffer is used to store the packet, while the address decoder is used to process the destination address (DA). The discriminator is used to control the state of the switching element. Output and Output' are the two possible output paths for a given packet, depending on the packet’s DA.

Table 3.1 gives a comparison between switching time delays, based on the following assumptions: DA filed of 2 bytes, and an optical fiber data rate of 100 Mbps. $T_{1A}$, $T_{2A}$, and $T_{3A}$ are obtained as follows:
Figure 3.12: Architecture of Opto-Electronic Routing Switch for DRONET

$T_{1A}$ optical delay line time,

$T_{2A}$ optical switch element. This time does not affect $T_{total,A}$ due to the use of an optical delay line. The delay line ensures that the DA is recognized and the switch state is changed, prior to data arriving at the switch input,

$T_{3A}$ optical correlator and discriminator. This time does not affect $T_{total,A}$ because it is less than $T_{1A}$, the delay line time.

$T_{1B}$, $T_{2B}$, and $T_{3B}$ are defined as the opto-electronic and serial-to-parallel conversion time, decode circuit to media access circuit transfer time, and media access address recognition time respectively. These values are obtained from the published data for a commercial FDDI chip set [SUPE89].

The results of Table 3.1 show that the switching time for the optical routing
controller is substantially less than that of the electronic controller. In addition, the total switching time, $T_{total,A}$, of the optical controller is dependent only on the delay line $T_{1A}$, due to the parallel nature of the optical routing switch architecture.

Table 3.1: Comparative Switching Times

<table>
<thead>
<tr>
<th></th>
<th>Optical Routing Switch</th>
<th>Opto-Electronic Routing Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{1A}$</td>
<td>164 ns</td>
<td>$T_{1B}$</td>
</tr>
<tr>
<td>$T_{2A}$</td>
<td>100 ps</td>
<td>$T_{2B}$</td>
</tr>
<tr>
<td>$T_{3A}$</td>
<td>163 ns</td>
<td>$T_{3B}$</td>
</tr>
<tr>
<td>$T_{total,A}$</td>
<td>164 ns</td>
<td>$T_{total,B}$</td>
</tr>
</tbody>
</table>

A key feature of this design is the ability to diminish the effects of the electronic bottleneck experienced in Figure 3.12. For example, in Figure 3.9, if the physical data rate is increased from 100 $Mbps$ to 1 $Gbps$, then the delay $T_{1A}$ can be scaled down by a factor of 10, commensurate with the reduction in the time of the address field. $T_{total,A}$ can be reduced accordingly. However, in Figure 3.12, an attempt to increase the data rate is fundamentally limited by the electronic switching speed of the interface processor and discriminator, which perform the address decoding function.

The application of optical switching, and the processing of the signal optically, without optical-to-electronic and electronic-to-optical conversion, significantly decreases the routing time and eliminates the electronic bottleneck of a conventional interface adapter. These improvements, including the change of interface adapter structure, and the use of code-division access for non-blocking real-time transmission, can accommodate the high transmission rate of optical networks, and all the operations can
be processed in real-time.

### 3.5.2 Performance of FDDI and DRONET

We have mentioned in Section 3.3, in DRONETs with enhanced traffic, that we use the second ring as an additional data transmission path rather than for redundancy. One of the two rings is used to transmit synchronous frames, the other one to transmit asynchronous frames. In order to simplify the media access control the token passing protocols are still used in the first ring, and in the second ring, CDMA (Code-Division Multiplexing Access) is used. Because the synchronous frames can be generated in bursts with the superposition of optical orthogonal sequences, they can be transmitted concurrently.

For the ring to transmit asynchronous frames, we can use the same method of analysis as in conventional FDDI. The throughput of FDDI without synchronous frames is the throughput of one ring in the DRONET with enhanced traffic. The throughput of the ring for transmission of asynchronous frames is discussed next.

Defining $m$ to be the number of asynchronous priority levels ($1 \leq m \leq 8$ in our discussion), and the number of actively transmitting stations to be

$$n = \sum_{i=low}^{m} n(i)$$

(3.2)

where $low$ is the lowest priority level with nonzero throughput, and $n(i)$ is the number of stations transmitting frames of priority $i$. According to the TA (Throughput Approximation) algorithm in [DYKE88], the throughput of priority-$i$, $t(i)$ is given
by

\[ t(i) = \frac{r(i)}{(n + 1) \cdot r \cdot I + \sum_{j=\text{low}}^{m} n(j)} V \] (3.3)

where

\[ r(i) = n(i) \cdot (n \cdot T_{\text{Pri}}(i) - T_{\text{Pri}}(\text{low})) + (n - n(\text{low})) \] (3.4)

\[ + \ T_{\text{Pri}}(\text{low}) - \text{sum}_pri + T_{\text{Pri}}(i) - r \cdot I \]

and

\[ \text{sum}_pri = \sum_{i=\text{low+1}}^{m} n(i) \cdot T_{\text{Pri}}(i) \] (3.5)

and \( V \) is the arrival rate of priority-\( i \). The overall throughput is given by the sum of the throughputs for each priority level.

In order to demonstrate the TA algorithm, the following definitions are introduced. The “peak throughput” for a priority level is the maximum amount of throughput that will be received by frames of that priority in a given configuration. If the arrival rate of frames is less than the peak throughput, then all frames of that priority level will be transmitted after a finite delay. As the arrival rate approaches the peak, the mean frame transmission delay increases rapidly. If the arrival rate of frames exceeds the peak throughput, then not all of the frames can be transmitted, and the transmission delays will become arbitrarily large. The “guaranteed throughput” for a priority level is the minimum amount of throughput that will be received by the frames of that priority. The guaranteed throughput is therefore the amount of throughput received when all active stations continuously have frames queued for transmission. If the traffic intensity is reduced, the throughput may exceed the guaranteed value. When the arrival rate is less than the guaranteed throughput, then the throughput equals the offered load.
In evaluating the performance of DRONET, we make the usual assumptions, and consider only the error-free operation of the network, concentrating on the network-access control and priority mechanism without any errors or failures of physical components, and other functions unrelated to frame transmission. In this thesis, in order to compare the throughput of FDDI and dual ring optical network, the throughput algorithm and an example in [DYKE88] are employed. In the example of FDDI ring in [DYKE88], there are eight stations, each station attempting to transmit frames at one of the eight asynchronous priority levels. The synchronous priority class is not used. The arrival rate of frames to be transmitted is identical at each station. The target token rotation time is 100 ms, and the eight token-holding time thresholds are, from highest priority to lowest priority, 100, 76.5, 56.2, 39, 25, 14, 6.2, and 1.5 ms, respectively. The ring latency is 1.0236 ms, and the total frame length, including MAC framing bits, is 1.6 kbytes.

The procedure for calculating throughput estimates for each asynchronous priority level in the example in [DYKE88] does not account for transmitting frames of the synchronous priority class. We now examine the ring configuration with synchronous traffic. Since this transmission class guarantees bandwidth, the throughput of such frames will equal the arrival rate up to the highest arrivals that can be reached. If both synchronous frames and asynchronous frames are to be transmitted, and both transmissions are to be guaranteed, then the bandwidth should be divided into two parts. Thus we assume the transmission rates for the two kinds of traffic are both 50 Mbps. Using the same algorithm, we obtain Figure 3.13 for an FDDI ring, where the guaranteed throughput for the synchronous priority class is 50 Mbps.

It is obvious that we can apply this method of analysis to the primary ring of dual
CHAPTER 3. DUAL RING OPTICAL NETWORK

Figure 3.13: Throughput Versus Arrival Rate for FDDI

ring optical network in our work. The throughput of FDDI without transmitting
synchronous frames should be equal to that of the primary ring of DRONET. As
we reserve the secondary ring to transmit synchronous frames with CDMA, with
which we can transmit the messages concurrently, the physical layer protocols and
media access control protocols are somewhat more complicated than that of FDDI.
For simplicity of analysis, we only study the simplest situation, i.e., there is only one
synchronous frame being transmitted at a given time, and there is no superposition
and concurrency of orthogonal sequences and frames. Thus, it is obvious that the
largest throughput for synchronous frames, on the basis of our assumption, is 100
Mbps.

Figure 3.14 is the throughput of synchronous class and eight-priority asynchronous
classes, and the overall throughput of dual ring optical network. Comparing it to
the example in [DYKE88], the throughput is much higher, and to Figure 3.13, the transmission rates of both synchronous and asynchronous bandwidth can reach 100 Mbps. The overall throughput of DRONET is at least doubled. It is obvious that by using dual rings to transmit both synchronous and asynchronous frames, we can obtain a very high throughput, especially when the load of the system is heavy, or the loads for synchronous and asynchronous traffic are not the same.

Figure 3.14: Throughput Versus Arrival Rate for DRONET
3.6 Implementation of Photonic Switching in Optical Interface

We will begin this section by discussing the design of photonic switching in optical interface using modern optics. We start from the encoding method of the information and its addresses, and then the implementation of optical routing controller, the last part will be the optical switching element implemented with optical devices.

An optical routing controller must perform the following functions: 1) recognize an address, 2) determine the outgoing link in broadcasting system, or determine whether the destination address matches the desired address and decide whether the outgoing link is a synchronous or an asynchronous one in polling system, and 3) generate a control signal, with photodetector if necessary, that will set the appropriate permutation of the photonic switching element. To route a packet in real-time, the controller must be able to accept a new destination address within a time $t$ that is less than or equal to the packet length, $T_p$, that is

$$t \leq T_p$$  \hspace{1cm} (3.6)

In FDDI, the length of a packet is less than 4500-octet, which is 4500×8 bits. At high bit rates, electronic processing would not be sufficiently fast to satisfy Equation 3.6, resulting in an electronic bottleneck in electrical routing controller at the input of station. With optical processing which does not need to convert an optical signal into an electrical one, time $t$ can be decreased substantially. In order to further reduce time $t$, parallel processing or pinelining can be used. By connecting a system of $k$-processors in parallel and sequentially allocating the input data to the individual processors, a $k$-fold increase in performance is obtained. In the optical routing controller, this method
can be implemented by changing optical signal from a serial one into a parallel one, or an array signal, and at the same time optical array devices can be used as parallel processor.

### 3.6.1 Encoding Strategy

The orthogonal code sequences need to be designed to satisfy two conditions, namely:

1. each sequence can be easily distinguished from a shifted version of itself and
2. each sequence can be easily distinguished from (a possibly shifted version of)
   other sequence in the set.

In order to avoid the interference of the two sequences of correlation, we choose a set of orthogonal code sequence with the same number of 1’s in the sequences and fewer coincidence of 1’s is needed for optical processing. It is prime codes of length \( N = P^2 \), which are derived from a prime sequence of length \( P \), where \( P \) is a prime number [SHAA83]. A \( P \times P \) matrix \( \tilde{S} \) can be set up, in which each element \( s_{ij} \) in the table is the product of the corresponding \( i \) and \( j \) modulo-\( P \). The prime sequences are then mapped into a binary code sequence \( C_i = (c_{i0}, c_{i1}, ..., c_{ij}, ..., c_{i(N-1)}) \), by assigning 1’s in positions \( n = s_{ij} + jP \) for \( j = 0, 1, ..., P - 1 \) and 0’s in all the other positions. i.e.

\[
C_{i,n} = \begin{cases} 
  1 & i = s_{ij} + jP \\
  0 & \text{otherwise}
\end{cases} \quad (3.7)
\]
3.6.2 Design of Optical Correlator in Optical Routing Controller

In photonic switching, the optical signal will pass a correlator whose output will determine the state of optical switching element in photonic switching.

Correlation is the integration operation that depends on two input functions $f_1(x, y)$ and $f_2(x, y)$ and is

$$f_1(x, y) \ast f_2(x, y) = \int \int f_1(x, y)f_2^*(x' - x, y' - y)dx dy$$

If we use Fourier transformation to both side of the Equation 3.8, we get:

$$F\{f_1(x, y) \ast f_2(x, y)\} = F_1(\frac{x}{\lambda f}, \frac{y}{\lambda f})F_2^*(\frac{x}{\lambda f}, \frac{y}{\lambda f})$$ (3.9)

where $F_1(\frac{x}{\lambda f}, \frac{y}{\lambda f})$ and $F_2^*(\frac{x}{\lambda f}, \frac{y}{\lambda f})$ are the Fourier transforms of $f_1(x, y)$ and $f_2(x, y)$, respectively. If $f_1(x, y) = f_2(x, y) = f(x, y)$, Equation 3.9 becomes:

$$F\{f(x, y) \ast f(x, y)\} = |F(\frac{x}{\lambda f}, \frac{y}{\lambda f})|^2$$ (3.10)

This is the theory we used for optical correlator.

Assuming there is a linear space-invariant filter with its impulse response $h(x, y)$ given by

$$h(x, y) = f_2^*(-x, -y)$$ (3.11)

Let us consider the input $f_i(x, y)$ excitation to this linear space-invariant system to be an additive mixture of signal $f_1(x, y)$ and a stationary random noise $n(x, y)$, i.e.

$$f_i(x, y) = f_1(x, y) + n(x, y)$$ (3.12)
where \( f_1(x, y) \) can be the output of optical delay line, \( n(x, y) \) is white noise with zero mean and unit variance, the output of the system is found to be

\[
f_o(x, y) = \int \int f_1(x', y') h(x - x', y - y') dx' dy'
\]

\[
= \int \int f_1(x', y') f_2^*(x - x', y - y') dx' dy' + \int \int n(x', y') f_2^*(x - x', y - y') dx' dy'
\]

\[
= f_1(x, y) * f_2^*(-x, -y) + n(x, y) * f_2^*(-x, -y)
\]

The first part of equation 3.13 is the cross-correlation of \( f_1(x, y) \) and \( f_2^*(-x, -y) \) and the second part of it is the cross-correlation of \( f_2^*(-x, -y) \) and white noise. Normally the cross-correlation of \( f_2^*(-x, -y) \) and white noise \( n(x, y) \) is a very small value, which can be ignored, thus the output \( f_o(x, y) \) is

\[
f_o(x, y) = f_1(x, y) * f_2^*(-x, -y)
\]

Using equation 3.9, we can get the multiplication of two functions, then auto- or cross-correlation can be obtained if the multiplication is transformed using Fourier transformation. For the convenience of discussion, we interpret this procedure into an optical system as shown in Figure 3.15.

The Fourier transform of the impulse response in Equation 3.15 shows that the required transfer function is

\[
H\left(\frac{x}{\lambda f}, \frac{y}{\lambda f}\right) = F_2^*\left(\frac{x}{\lambda f}, \frac{y}{\lambda f}\right)
\]

where \( H \) and \( F_2^* \) denote the Fourier transform of \( h \) and \( f_2^* \), respectively. Figure 3.15 shows a 4\( f \) system for optical correlation. The input plane is placed in the front focal plane of the first lens (and illuminated by a monochromatic plane wave or collimated
CHAPTER 3. DUAL RING OPTICAL NETWORK

Figure 3.15: Optical Implementation of Autocorrelation

if it is self-emitting object). In the back focal plane of the first lens, we obtain the Fourier transform of the input $F_i(x/f_i, y/f_i)$. The mask placed in this plane is given by $F_2(x/f_i, y/f_i)$. The multiplication of two functions is transformed by the second lens, and the correlation operation is produced in the output plane, i.e. the output is the cross-correlation of function $f_i(x, y)$ and $f_2(x, y)$, as in Equation 3.13, if white noise is omitted.

In the designed system, the output of optical delay line has been changed by the multiple-beam splitter from serial signal into array signals, and these signals are collimated and transformed. In the optical routing controller, these signals are the codes of the destination address, if the Fourier transform of these array signals is matched with the mask, the optical wave will be a plane wave, then at the back focal plane of the second lens will be a $\delta$-function. That is what we need for the destination address to be recognized.
The ability of lenses to perform Fourier transformation allows for very compact optical correlation systems. The procedure consists of the following steps (Figure 3.16):

1. Fourier transformation of the function $f_1(x, y)$.

2. Multiplication of $F_1(u, v)$ by the complex conjugate $F_2^*(u, v)$ of the Fourier transform of $f_2^*(x, y)$.

3. Inverse Fourier transformation of the product $F_1(u, v)F_2^*(u, v)$. If instead of an inverse Fourier transformation the forward Fourier transformation is used, only the sign of the output coordinates changes.
CHAPTER 4

DISTRIBUTED QUEUE DUAL BUS

4.1 Introduction

The Distributed Queue Dual Bus (DQDB) protocol has been specified by the IEEE 802.6 project team as their proposed standard. It is a promising candidate for upcoming metropolitan area network for interconnection of local area networks, computer mainframes and other devices. DQDB standard can integrate all communication services, thus, isochronous and non-isochronous services like voice and file transfer can be provided by a MAN. Up to now, the evolution of the Distributed Queue protocol passed several different versions. In Section 4.2, we will describe mainly the DQDB protocol and its evolution in Section 4.3.
In many networks incorporating optical fibers as transmission medium, the interface adapter is a main problem which is the electrical bottleneck of the system. The same problem exists in DQDB MAN. In Section 4.4, we design an optical interface adapter, and then in Section 4.5, we evaluate the network with this optical interface adapter.

4.2 Description of IEEE 802.6 Protocol

A distributed queue dual bus protocol is the access protocol specified in the IEEE 802.6 MAN standard which is based on a slotted bus topology. The first proposal with this topology was submitted by Telecom Australia and its originally called Queue Packet and Synchronous Exchange (QPSX) [NEWM88]. DQDB is a distributed network that will fulfill the requirements of a public MAN. The architecture of DQDB is based on two contra-directional buses as shown in Figure 4.1.

Every node is able to handle full duplex communications with each other node by
CHAPTER 4. DISTRIBUTED QUEUE DUAL BUS

sending information on one bus and receiving on the opposite bus. Nodes are attached to both buses via a logical OR-writing tap and a reading tap which is logically placed ahead of the write tap. The head station is also a frame generator to generate a frame every 125 μs which is subdivided into equal-sized slots. The end station called slave frame generator terminates the forward bus, remove all incoming slots and generates the same slot at the same transmission rate on the opposite bus.

Two buses, called Bus A and Bus B respectively, operate independently of each other. Since both buses are operational at all times, the effective capacity of the DQDB subnet is twice the capacity of a single bus.

DQDB can also operate in the looped dual bus topology. It is the extension of the open dual bus architecture. The only change in this topology from the original architecture is that the end points of the buses are co-located. But the data do not flow through the head (or end) point of the loop. The reason for looping the DQDB bus architecture is that it provides higher reliability than open dual bus architecture. Figure 4.2 shows the looped bus architecture.

4.2.1 IEEE 802.6 DQDB Media Access Control

As described earlier, DQDB networks must support a variety of services. Applications requiring isochronous service are time-sensitive, i.e., the application requires access to the medium on a regular basis and a guaranteed bandwidth of 64 kbps. Time slot for isochronous service uses the Pre-Arbitrated (PA) access method, which reserves time on the medium for various time-sensitive applications.
Figure 4.2: DQDB Looped Bus Architecture
CHAPTER 4. DISTRIBUTED QUEUE DUAL BUS

Non-time-sensitive applications do not require medium access on a regular, periodic basis. This includes both the connectionless MAC and connection-oriented data services supported by DQDB. These applications need to have access to the medium only when they have data to send. Therefore, time on the medium is not reserved for specific applications but granted on a as-needed basis. The Queued-Arbitrated (QA) access method is used for these services.

4.2.2 IEEE 802.6 Protocol Data Units

The fundamental DQDB MAC protocol data unit is the slot, which is composed of a set of octets. The slots are independently generated for each unidirectional bus by the frame generator at the head of that bus. The slot is transferred downstream along that bus, being available for access as it passes each node.

![Slot Format for DQDB](image)

Figure 4.3: Slot Format for DQDB

In accordance with the IEEE 802.6 standard, every slot contains 1 byte Access
Control Field (ACF) and 52 byte segment header, and payload segments for both isochronous and non-isochronous traffic.

The ACF is used to control the reading of a segment from a slot and the writing of segment into a slot. The first bit of the ACF is BSY bit, it indicates whether the slot is available (BSY=0) or not (BSY=1). SLOT-TYPE indicates two types of slots, SLOT-TYPE=0 for QA slot and SLOT-TYPE=1 for PA slot, respectively. PSR is the Previous-Slot-Received bit. The PSR bit makes it possible to upgrade the DQDB network capacity by re-using slots. When a slot is received, the receiver sets the PSR bit at next cycle to indicate that the previous slot can be reused. RSVD bit means that this bit is reserved for possible expansion in the future. The remaining four bits are request-bits, one for each of the four priority levels.

The segment header includes a 20 bit label which is used as the Virtual Circuit Identifier (VCI) field. The isochronous slot can be identified by an all-ones label value of the VCI. And it contains circuit type and priority information to be used in Integrated Service Data Network (ISDN) as well. The remaining 8 bits are Header Check Sequence (HCS).

### 4.2.3 IEEE 802.6 Access Protocol

The DQDB subnetwork is a distributed multiaccess network that supports integrated communications via connectionless and connection-oriented data transfer as well as isochronous communications.

Variable-length user data is segmented into 48 octet segments, which are carried in fixed-length (53 octets) slots as described in last section. User information is
communicated between nodes via these slots. Each slot provides fair and efficient information to allow a DQDB node to support a protocol that provides fair and efficient access to the subnetwork and allow each segment to reach its destination. One octet of Access Control Field provides the medium access control mechanism.

The QA access method supports services that are usually bursty in nature; i.e., the bulk of the data transfer occurs in a relatively short time. The unit of transmission is called a QA-slot. Recall that the DQDB network comprises two unidirectional buses. The term “upstream” and “downstream” indicate the relative positions of two nodes on the bus. Node $i$ is upstream of Node $j$ if a slot arrives at Node $i$ before it arrives at Node $j$; Node $j$, then is downstream of Node $i$.

A node wishing to transmit a slot makes a request and enters the distributed queue. The mechanism would then, in effect, force this node to perceive a waiting line for service. This node would know exactly when to be served without directly being able to watch the other nodes in line ahead of it. A node’s position in this queue is determined in a distributed manner by watching the information contained in the header of the slots passing the node on both attached buses. (This is the Distributed Queue component of the protocol.) A station access bus (for instance, Bus A), according to QA Access method has to follow three main procedures,

1. broadcasting request to upstream stations,

2. keeping track of access requests generated by downstream stations, and

3. accessing bus when all requests prior to its own are satisfied.

Without loss of generality only one class of priority is considered, and only Bus A
is used to transmit information and Bus B to request, to simplify the explanation of the protocol.

If a station, for instance node \( i \), wants to transmit a non-isochronous segment to the downstream stations of Bus A, then Node \( i \) sends a request bit of given priority to the next available slot on Bus B to notify the request to all nodes upstream. In this way all the nodes downstream of Node \( i \) on Bus B will see the request and appropriately increment a counter — Request Counter (RQ). Meanwhile Node \( i \) invokes another counter called CountDown (CD) counter. The value of RQ counter is transferred to CD counter, the RQ is reset to zero itself. The RQ counter now counts the number of new requests downstream, and the CD counter tracks the nodes position in the queue, i.e., as empty slots pass each node, their counters are decremented. When the value of the CD counter is zero, the node is allowed to transmit its QA segment in the next empty slot.

DQDB supports multiple QA priorities on each bus, thus separate RQ and CD counters and separate queues exist. The two buses are symmetrical.

The PA access scheme is designed for the transfer of isochronous service octets. Access to PA slots is very different with access to QA slots. A QA slot is wholly owned by a single node at a time, whereas, a PA slot may be used by different nodes.

The head of bus takes responsibility for sending a sufficient number of PA slots to ensure that all isochronous service users have adequate bandwidth available. When the head of the bus generates a PA slot, it places a VCI into a slot header. All nodes with an isochronous service examine the VCI value that the node must access, the node will maintain a table indicating which octet position(s) within slot that it
should use for reading and writing. Thus, the node will read from the appropriate octet positions within the slot and write to other octets. If the PA slot contains a VCI that is not used by this node, the entire slot is ignored. (Details of PA access are not relevant for the study presented in this report.)

4.3 Evolution of DQDB Protocol

Up to now, the evolution of the Distributed Queuing Protocol (DQP) passed several different versions. The state diagrams of three versions are shown in Figures 4.5 and 4.6. The first version is used for QPSX. As can be seen in Figure 4.5, there are five states: Countdown, Wait, Access, Idle and Standby. A node enters the Standby state if it has a segment to transmit and the Request-bit Counter (RC) is zero. Now the node attempts to access the next slot. If it is free, the segment is transmitted
CHAPTER 4. DISTRIBUTED QUEUE DUAL BUS

Figure 4.5: State Diagrams of the DQDB Packet MAC — 1
AQ(i): Number of segments queued for priority i
RC(i): REQUEST bit count for priority i
CD(i): Countdown count for priority i

Figure 4.6: State Diagrams of the DQDB Packet MAC — 2
without sending a Request. If the slot is busy, the node transmits a Request (REQ) on the opposite bus and then enters the Wait state, where it waits for the next free slot. The worth of the Standby state is to reduce the transmission of Request which may become out of date due to the propagation delay of the REQs along the bus.

Figure 4.6(a) shows the state transmission diagram of the next DQDB protocol version. Basically, there are two changes in the protocol. The first one comes from the introduction of four priority classes in the protocol. Therefore a node must send REQs to itself to ensure that the segments of higher priority levels are transmitted first. The second change is the queuing of REQs, i.e. a segment can be transmitted before the corresponding Request has been sent. Therefore bandwidth may be wasted because of state REQs which have been sent after transmitting the segment.

The newer version DQP still comprises of two states, as shown in Figure 4.6(b). The standby state has been removed because it causes a slight unfairness. Nodes at the head of the buses were able to transmit a segment out of the Standby state without sending a Request more often than the other nodes. These nodes had to wait for the demanded unused slot.

The newest issued version of DQDB protocol changed the format of ACF, the priority levels are reduced from four to three, and the reserved bits now become two [ABEY91].
4.4 Design of Optical Interface Adapter for IEEE 802.6 DQDB

In DQDB, data does not pass through each node since it is broadcast-type network. Nodes on the bus read the addresses of passing packets and copy data if there is an address match between the node and the destination address within the packet.

4.4.1 Architecture of Optical Interface

In the interface adapter for dual bus, the unidirectional reading and writing to each bus is implemented electronically using OR-gates and shift registers [HULL88], as shown in Figure 4.7. Writing is accomplished by transmitting a logical OR onto synchronized and formatted time structure generated by the frame generator at the head of each bus. Thus, the incoming optical signal must be converted into electrical signal and processed electrically.

As in the period of routing and erasing, the whole procedure is finished electronically, and since O/E and E/O conversion have to be finished before the data comes into and goes out of the node, then the bandwidth of transmission medium will be wasted, thus reducing the transmission rate. It is significant for the interface adapter to process all the procedures optically.

To implement an optical interface adapter in DQDB, the most important issues are

1. removing O/E and E/O conversions on the transmission medium in conventional
DQDB interface adapter;

2. routing ACF and VCI optically: routing ACF is for recognizing some bits in it in order to control the slot; routing VCI for recognizing the destination addresses;

3. writing information optically: the information includes the control bits in ACF and the whole message;

4. erasing the previous slot optically if PSR is 1; and

5. synchronizing all the system: an optical system clock will be needed in optical DQDB.

Generally, when a slot passes by a node, the node will read it in order that it can be split by a passive tap. As ACF and VCI (or SEG_HDR) contain different information and control different functions of the interface, these two parts will be
routed separately. Based on the assumption that when we describe the protocol of DQDB, there is only one bus — Bus A being used to transmit information, whereas Bus B is used to transmit the requests of the nodes. The following bits will be checked when ACF being routed:

1. PSR bit on Bus A in order to decide whether the previous slot will be erased;

2. request bits in order to decide whether the request can be put into the slot when there is a message to transmit; and

3. BSY bit: if BSY bit is one, the CD counter (when there is a message in queuing) or RQ counter will decrement.

The routing of VCI will decide whether the message will be received after recognizing the destination address.

According to all the requirements mentioned above, we can design a new optical interface adapter for DQDB to implement all the issues of DQDB protocol. Figure 4.8 is the diagram of the interface adapters.

In this interface adapter, we remove the O/E and E/O conversions in conventional interface adapters. The incoming signal is divided into two paths: one is still transmitted on the transmission media, but the other is sent to the interface adapter of DQDB node. This part of signal is split by an optical splitter into optical self-routing switching and ACF Routing respectively. The optical self-routing switching is easy to implement as we have discussed in [HARD91b]. Next, the routing ACF, writing control and optical erasing parts will be discussed in detail.

When a slot is transmitted on one of two buses, it is optically sent to the stations
passing by. The optical signal is divided into three parts to optical delay line, VCI routing and ACF routing, respectively. The signals enter to optical delay line and VCI routing will be recognized, like the operation of optical switching in [HARD91b], except for the routing result controlling the write-control component which will be discussed below. The operation of this part is described in [HARD91b].

![Diagram of the Optical Interface Adapter](image)

Figure 4.8: Diagram of the Optical Interface Adapter

The third part of the signal which enters the ACF routing component is for recognizing the bits in ACF in order to control the operations of components in photonic
interface. All the operations will satisfy the issues of DQDB access protocol.

In order to route ACF, at least three parts of ACF will be recognized: BSY bit, PSR bit and REQ bits. When the signal comes into the router which is used to route the ACF, the router will take the first eight bits automatically and omit other bits in the slot. These eight bits are arranged as shown in Figure 4.3. As described in Section 4.2.2, BSY bit indicates whether the slot is available or not. It has to be checked whether it is equal to zero or not (equal to one). i.e. the slot is available or not. If the BSY = 0, then CD = CD - 1 for the message queuing, the slot will be used by one of the downstream stations. When CD=0, the countdown counter will send out a control signal to Write-Control component which will be switched, and the message will be written onto the bus via optical OR-gate. If BSY = 1, CD will keep the original value. When PSR is read, it will decide whether to control the Write-Control component to erase the previous slot. When PSR = 1, it means the previous slot has been received, and the ERASE slot with all data bits and VCI bits being zeros and keeping only the REQ bits and other useful information will be AND-written onto the transmission media. Next step is the routing of REQ bits. Routing REQ is for increasing RC by 1 if REQ=1. And meanwhile, if the station has a message to transmit, it will enable the REQ to 1 if REQ was originally zero. There is another control bit enabled by the routing result of photonic self-routing switching. When the destination address in VCI can be recognized by the optical switching, the switching itself will emit a signal in order that PSR bit can be enabled to 1, this means that the previous bit is received.

In this part, the main problem is how to implement the component for routing ACF. As we have to check every bit in ACF, it is hard to be implemented for the
CHAPTER 4. DISTRIBUTED QUEUE DUAL BUS

conversion of time-domain to space-domain.

Now, we will discuss the implementation of every part of this optical interface adapter. As the information of every bit in ACF is needed, we have to route ACF bit by bit. It is hard to implement the conversion of time-domain to space-domain optically for this purpose, at least not as easy as in photonic self-routing switching discussed in [HARD91b]. The high-speed multiple quantum well photo-diode with switching time less than a nanosecond reported in [JEWE90] can be used for this purpose. The signal of ACF is fed into a high-speed electronic shift register which can divide the laser diode array. Both the shift register and laser array can operate at a rate of the order of Gbps, thus the conversion of time-domain to space-domain can also be in the range of Gbps. Every bit in ACF can then be easily checked. The Eras'ng node can be implemented with an optical AND-gate. But we must note that the same as OR-writing a message onto the transmission media, AND-writing must be synchronized with the previous slot by following the system clock.

4.5 Evaluation of the DQDB with Optical Interface Adapter

Based on the performance results in [WONG91], the performance of DQDB with optical interface adapter can be evaluated. First of all, we define some concepts with which we can discuss the performance conveniently.

1. Access Delay — the time a packet takes to access the channel from the time it moves to the head of the queue
2. Queuing Delay (or Waiting Time) — the time that elapses from the moment a message arrives at a station until its transmission begins

\[
\begin{align*}
T_{TD} &= \text{Total Delay} \\
T_{QD} &= \text{Queuing Delay} \\
T_{QT} &= \text{Queuing Time} \\
T_{RES} &= \text{Reservation Time} \\
T_{MTT} &= \text{Message Transfer Time} \\
T_{RITT} &= \text{Request Transfer Time} \\
T_{AD} &= \text{Access Delay} \\
T_{ARBS} &= \text{Access Delay After Reservation}
\end{align*}
\]

Figure 4.9: Delay Distribution in DQDB

3. Total Delay — the time that elapses from the moment a message arrives at a station until its transmission is completed

4. Message Transfer Time — the time that the message arrives at the destination station

5. Access Delay After Reservation — the time that elapses from the moment a station makes a reservation until the station is allowed to transmit.
The purpose of defining various delays is to point out clearly which components contribute to the delay. Note that in these various delays, Access Delay is equal to the sum of the Access Delay After Reservation and the time taken to make a reservation. Access Delay plus queuing time before moving to the head of the queue is equal to the Queuing Delay, or waiting time. The Message Transfer Time contains the time of message transmission on the medium and the time of O/E and E/O conversions if the message goes through the stations with opto-electronic interface adapter in conventional DQDB. According to these, the whole transmission time for a message from the original station to the destination station can be divided into two parts: the Total Delay, or Access Delay $T_{TD}$, and the Message Transfer Time $T_{MTT}$.

Considering the specific station, for instance station $i$, with a message to be transmitted to station $j$ ($j < i$), the message has to go through $(j - i - 1)$ stations. Assuming the distance between the station $i$ and station $i + 1$ is $r$, and the optical processing time when message enters the passive tap to OR-gate, with which the station can OR-write information in the current slot, is $t_o$ within the station. It is clear that $t_o$ depends on the routing time of ACF. Thus, $t_e$ is the routing time in the station with opto-electronic interface and $t_o$ in the one with optical interface adapter. Assuming that the propagation delay is at $5 \text{ ns/meter}$ [WONG91], the Message Transfer Time in DQDB with optical interface will be

$$T_{MTT-o(i)} = (j - i)(t_o + \frac{r}{\gamma})$$  \hspace{1cm} (4.1)

where $\gamma$ is the transmission speed in medium, and is in the range of $200 \times 10^6 \text{ m/s}$. Whereas the message transmission time in DQDB with opto-electronic interface is

$$T_{MTT-e(i)} = (j - i)(T_{o/e} + T_{e/o} + t_e + \frac{r}{\gamma})$$  \hspace{1cm} (4.2)
where $T_{o/e}$ and $T_{e/o}$ are O/E and E/O conversion time, respectively. Comparing the Equations 4.1 and 4.2, we know that the farther the destination stations, the longer the Message Transfer Time. And the difference of $T_{MTT}$ between two systems

$$\Delta T_{MTT(i)} = (j - i)(T_{o/e} + T_{e/o} + \Delta t) \quad (4.3)$$

is proportional to the distance between the original and destination stations, where $\Delta t = t_e - t_o$.

Now, we consider the message media access delay and message transfer delay of the specify station and then the system.

It is not easy to find a model which is suitable to DQDB, and it is much more difficult to mathematically analyze it. Thus, we can only give an approximate result of performance. As discussed in [WONG91], if we want to find a mathematical model for DQDB media access delay, we can look it roughly as a single-server queuing system in the case of a single-priority DQDB distributed queuing protocol. The server is a deterministic slotted server with an assumed service time of one unit. It is assumed that the packet generation process is Poisson distribution and all buffers are infinite. The average queuing time, $T_{QD}$, according to queuing theory [WONG91], is determined as follows:

$$T_{QD} = \frac{1}{2(1 - \rho)} \quad (4.4)$$

where $\rho = \text{input load into the network}$.

The total delay in Figure 4.9 is equal to:

$$T_{TD} = T_{QD} + T_{Slot} \quad (4.5)$$
where \( T_{\text{slot}} \) is the transmission time of DQDB slot. Thus,

\[
T_{QD} = \frac{1}{2(1 - \rho)} + 1
\]

\[
= \frac{3 - 2\rho}{2(1 - \rho)}
\]

The total delay of the message in the queue is dependent of protocol itself, and has nothing to do with the physical dependents in the physical layer, for instance, the interface adapter. Thus, we call total delay, \( T_{TD} \), the media access delay as well.

Transfer delay \( T_{\text{Trans}} \) can be defined as the time that elapses from the moment a message arrives at a station until the destination station receives this message. \( T_{\text{Trans}} \) is the sum of media access delay and the message transfer time \( (T_{MTT}) \), and is

\[
T_{\text{Trans}} = T_{TD} + T_{MTT}
\]

As defined in Eq. 4.2,

\[
T_{\text{Trans}..e(i)} = \frac{3 - 2\rho}{2(1 - \rho)} + (j - i)(T_{o/e} + T_{e/o} + t_{e} + \frac{r}{\gamma})
\]

for the DQDB network with opto-electronic interface adapter, whereas for the DQDB network with optical interface we design in the pervious section, the transfer delay is equal to

\[
T_{\text{Trans}..o(i)} = \frac{3 - 2\rho}{2(1 - \rho)} + (j - i)(t_{o} + \frac{r}{\gamma})
\]

\[
= T_{\text{Trans}..e(i)} \Delta T_{MTT}
\]

Thus, the overall message transfer time for Bus A is

\[
T_{\text{Trans}..o(total)} = \sum_{i=1}^{N-1} \left[ \frac{3 - 2\rho}{2(1 - \rho)} + (j - i)(t_{o} + \frac{r}{\gamma}) \right]
\]
Let us consider the average message transfer delay on Bus A in the case that every station has messages to transmit to every other downstream stations with uniform distribution. Thus, the average distance for the Station 1 to Station $N - 1$ can be expressed as $(N + 1)/4$. The message transfer delays for two systems with optical interface adapter and opto-electronic interface adapter are shown in Figure 4.10.

We have assumed that there are $N = 49$ stations, which are located on a dual bus system of length 96 km uniformly, and transmission capacity 150 $Mbps$ each bus. We can see that the message transfer delay with optical interface has been significantly reduced. When evaluating the performance of DQDB with optical interface adapters, we do not consider the Request Transfer Time which is comparable with the Message Transfer Time. As the request from station $i$ will go through all the stations upstream, the difference of request transfer time between DQDB with opto-electronic interface
adapter and with optical one will be $\Delta T_{RTT} = (i - 1)(T_{o/e} + T_{e/o})$. Evaluating the overall delay, which is the sum of request transfer time and message transfer delay, needs a complex mathematical model. But we could predict that the overall delay in DQDB with optical interface adapter will be significantly reduced compared to the one without optical interface adapter.
CHAPTER 5

INTERCONNECTION OF DRONET THROUGH DQDB

5.1 Introduction

One of the primary function of MANs will be LAN interconnection. Broadly speaking, a MAN is a network capable of providing high speed (greater than 1 Mb/s) switched connectivity across distances typical of those found within a metropolitan area. Furthermore, this connectivity is of such a nature as to allow different types of traffic (for example, voice, video, data) to be carried simultaneously [KLES86].

Source Routing (SR) and Spanning Tree schemes already successfully developed for LAN-LAN internet [BACK88] [DIXO88]. However, these schemes become extremely inefficient in a system with up to thousands of LANs. In particular, Source Routing would induce a very high discovery traffic overhead, while the Spanning Tree solution
would require the storage and maintenance of very large forwarding tables at the MAN Bridges, and would lead to suboptimal paths [ZHAN88] [SOHA88].

Bridges, which operate at the data link layer of the OSI model, interconnect LANs that have the same type of operating system. Therefore, the bridge does not have to perform protocol conversion. In this case, bridges simply look at the packet address to see where it is going. The bridge then forwards data packets destined for an address beyond the local network to other networks.

A router has more intelligence capabilities than a bridge because it can handle several levels of addresses. It keeps a map of the entire network, including all the devices operating at or below its own protocol level. It looks deeper than bridge. Referring to its internetwork map, it examines the status of the different paths to the destination and choose the best method of getting the packet to the addressee. Routers are protocol-dependent — that is, they can be used only to link LANs that have identical protocols.

A gateway operates at the highest levels of the OSI reference model. It interconnects networks or media with different architectures by processing protocols to allow a device on one type of LAN to communicate with a device on another type.

In our network, what we concentrate on is the interconnection of dual ring optical network through DQDB. Thus the bridges, both local ones and remote ones will be discussed. The former receives packets of data, scans only to the network (or station) address, and passes the packets to the appropriate network, where they are ultimately routed to the intended addresses. The latter, which can be logically considered as "normal" multiport bridges, is supposed to have the capability of searching for the
best routing path.

5.2 Proposed Interconnection Approach

One of the first services a broadband network will have to provide will be a connectionless data service. This is the direct consequence of the proliferation of private LANs operating at speeds of tens of Mbps, distributed over a metropolitan area and requiring interconnection.

5.2.1 Interconnection Approach

![Network Interconnection Architecture](image)

**Figure 5.1: Network Interconnection Architecture**
CHAPTER 5. INTERCONNECTION OF DRONET THROUGH DQDB

After Broadband ISDN (BISDN) technology reaches the advanced stage of development, certain services can be provided by using MAN technology in connecting LANs and MANs. A realistic scenario would be like the one shown in Figure 5.1, where a set of MAN subnets are connected by means of MAN Bridges, and a set of LANs are connected to the MANs by Subscriber Bridges, operating at the MAC level. Assuming that all the MAN subnets are DQDB networks. We consider in this section only a part of the of the connection scenario, which will contain only a backbone DQDB (subnet) and the possible facilities connected to it. The architecture is shown in Figure 5.2. In this figure, all the local networks are dual ring optical networks, LBs are local bridges, RBs are remote bridges.

5.2.2 Routing Strategy

We refer to the OSI standard reference model and DQDB MAC protocol in order to reduce the complexity of the connectivity problem. And we assume that dual ring optical network frames are encapsulated in DQDB frames in the entry LB1 before delivery to the destination DRONET. Within the DQDB connection, the segments (packets, or frames) are carried without encapsulating from LB to LB, or decapsulating from RB to RB.

As mentioned previously, both SR and ST will become extremely inefficient in a large system with thousands of LANs or so. Here in our system with all the subnets being DQDB, and LANs being dual ring optical networks, we propose a routing strategy which could be called Path Searching which can be used for efficient delivery frames (messages) from the source station to the destination station(s) which may belong to the other MANs or LANs, if the destination address has been “learned”.
Figure 5.2: Network Interconnection Architecture with DQDB Backbone
Alternatively, if the destination has not been "learned", or it is new to the system, the routing strategy should have the ability to forward the frame to the destination. Meanwhile, the destination address will be added in the forwarding table of addresses, which this station can reach.

We assume for this routing strategy that the address field consists of two sub-address fields — the bridge sub-address field which the frame will reach, and the destination sub-address field.

The aim of Path Searching routing is to deliver the frames efficiently, i.e. to reduce the high traffic overhead, and to transmit with a shortest path between stations in networks.

We assume, before discussing the routing strategy, that every station has a table, which consists of the possible addresses of bridges that destination stations belong to, we call it destination bridge (DB), and the addresses of bridges the frame will go through at the very first when being delivered on its way to the destination station. Every bridge has the function of decapsulating the field which is encapsulated by the source (or quasi-source) station.

The frame delivery is monitored by the following rules

1. In the forwarding table, which only contains the addresses of LANs instead of those of stations, of the source station, there is the address of DB to which the message will be forward, the frame will be encapsulated as shown in Figure 5.3.

2. If the address of DB has not been added in the forwarding table of source station, the frame will be sent to all the possible bridges it can reach broadcastly, the
CHAPTER 5. INTERCONNECTION OF DRONET THROUGH DQDB

Routing path is searched with this method until the shortest path is found. Those bridges that the message goes through along this shortest path will remain the DB address. This is the so-called 'self-learning' function of the bridge. At this circumstances, the frame will be encapsulated as shown in Figure 5.4.

<table>
<thead>
<tr>
<th>N_B</th>
<th>D_S</th>
<th>DATA</th>
</tr>
</thead>
</table>

N_B is the address of next bridge the message has to go through on its way to destination
D_S is the address of destination station

Figure 5.3: Address Field of Frames — 1

<table>
<thead>
<tr>
<th>B_B</th>
<th>D_S</th>
<th>N_HOP</th>
<th>DATA</th>
</tr>
</thead>
</table>

B_B is the broadcasting address of bridges which demonstrates that the message will be received by all the bridges it can reach.
D_S is the address of destination station
N_HOP records the number of hops while the message being transmitted from source to destination

Figure 5.4: Address Field of Frames — 2

For the first situation, when the frame is received by the bridge which it is supposed to go through, the N_B field will be decapsulated by the bridge, and the D_S field will
be checked. Then a new N.B field is encapsulated. This procedure is repeated until the frame reaches the destination bridge.

5.3 Bridge Architecture and Operation

To simplify the discussion, we consider DRONET as a non real-time and non-isochronous traffic distributed network. In the interconnection of DQDB and DRONET, there are two kinds of bridges to be discussed: one is DQDB-to-DQDB bridges, the other is DQDB-to-DRONET bridges, or more generally DQDB-to-LAN bridges.

DQDB-to-DQDB bridges are used to interconnect two or more DQDB subnetworks. And DQDB-to-LAN bridges are used to interconnect DQDB subnetworks and LANs based on IEEE 802 architectures.

In a public MAN environment, many different subnetworks are to be interconnected. We have assumed that in the MAN we discussed are a set of interconnected DQDB subnetworks.

5.3.1 Architecture of Bridges

5.3.1.1 DQDB-to-DQDB Bridges

The basic principle is to allow for segments (DMPDUs — Derived MAC Protocol Data Units) to flow all the way to their final destination without having to reconstruct IMPDUs (Initial MAC Protocol Data Units) at any intermedia point. This avoids the need for additional processing and larger storage capacity to store incomplete
IMPDU$s$, which would be the case in a bridge using MPDU-based relaying. Another principle is to associate an output port with every pair of source and destination addresses.

On the receiver side of the bridge, filtering should be done to extract DMPDU$s$, destined to nodes external to the DQDB subnetwork in which they flow. A Beginning of Message (BOM) segment is used to set up a virtual connection that will last until the corresponding End of Message (EOM) segment is handled. This connection will have to be on the virtual channel between the source and the destination MAC units designed by the corresponding fields in the IMPDU header, which is carried by the BOM segment.

On the sending side, only the DMPDU creation component is needed to construct the segments that will be transmitted. It should be note here that the VCI/MID values have to be changed as a segment is relayed from one DQDB subnetwork to another. Therefore, the bridge should be able to request MID pages on the output subnetwork and assign MIDs to the relayed IMPDU.

5.3.1.2 DQDB-to-DRONET Bridges

In these bridges, the relaying information should be done at the level of the MAC service.

The major techniques, namely, encapsulation and conversion, may be used in handling relayed MPDU$s$. Conversion means that the bridge has to extract from the received MAC frames all the control information and encode them again so that they can be used to construct new MAC frames according to the MAC protocol used in
CHAPTER 5. INTERCONNECTION OF DRONET THROUGH DQDB

Figure 5.5: Function Blocks of Bridges

the target subnetwork. In addition to that, information coding itself might need to be changed.

Conversion seems to be complex and may result in the loss of some information that do not have the corresponding fields in the target subnetwork. However, if this target subnetwork is the final destination, conversion is inevitable and should be done at the destination node, if it is not done at the bridge.

Encapsulation is useful in keeping the original MPDU intact until it is delivered to its final destination. This may be desired, especially when both the source and destination subnetworks used the same MAC protocol. Therefore, the preferred approach depends on the network topology and the source and destination subnetworks.

Figure 5.5 shows the common function blocks of DQDB-to-DQDB and DQDB-to-DRONET bridges.
5.3.2 Operation of Bridges

The DQDB uses small segments as its basic transmission unit, as described in Chapter 4. A MAC Service Data Unit (SDU) received from the LLC sublayer is first encapsulated in an MAC PDU (MPDU), which is called Initial MAC PDU (IMPDU) in IEEE 802.6 terminology by appending to it a header and a trailer. Then the IMPDU is segmented into 48 octet pieces and with various header and trailer fields, forming a Derived MAC PDU (DMPDU) as shown in Figure 5.6. The DMPDU header includes

1. a segment type field that can assume the values Beginning of Message (BOM), Continuation of Message (COM), and End of Message (EOM), or Single Segment Message (SSM);

2. a Message IDentifier (MID) field which assumes a single value for all the segments of an IMPDU. The segments belonging to the same IMPDU will normally be derived in sequency in order most protocols running at the LLC level or above to operate properly.
Figure 5.6: DRONET PDU Being Segmented
CHAPTER 6

CONCLUSION

In this thesis, the development of optical network is reviewed. As the increasing demands of various service in optical transmission systems, the electronic bottleneck existing in the current optical networks raised with the opto-electronic interface adapter, will limit the abundant transmission bandwidth in optical networks. Thus, a new architecture of dual ring optical network (DRONET) is proposed. In this network, one of the two rings is used to transmit the asynchronous frames, while the other one, which in FDDI is proposed to provide redundancy, is used to transmit the synchronous frames. The performance evaluation of DRONET shows that compared to the FDDI, DRONET can provide an overall throughput of 200 \( M\text{bps} \) which is the maximum throughput DRONET can provide. The potential throughput due to the use of CDMA in the secondary ring, can be much higher than this value.

In order to eliminate the electronic bottleneck, the optical interface adapters incorporating photonic switching and logic for both DRONET and DQDB are designed.
The switching time of optical interface adapter for DRONET is only 164 ns, which is much less than that in conventional opto-electronic interface adapter for FDDI. The performance of DQDB with optical interface adapter shows that the message delay time is significantly reduced.

The interconnection of DRONETs through DQDB is also proposed. In order to reduce the very high discovery traffic overhead in Source Routing and very large forwarding tables in Spanning Tree, we proposed the Path Searching method. In this routing method, only the addresses of next bridges and of destination addresses will be contained in the forwarding table. The architecture of bridges, both DQDB-to-DQDB and DQDB-to-DRONET, are proposed.

We can conclude now that with the use of optical interface adapters in optical networks, the performance of the networks will be highly enhanced, and the electronic bottleneck caused by opto-electronic interface adapters is eliminated.
REFERENCES


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