MULTI-CHANNEL OPTICAL NETWORK ARCHITECTURES WITH CHANNEL CONTROLLER BASED MEDIA ACCESS PROTOCOLS

By
MARK W. JANOSKA , P.Eng, B.Eng

A Thesis
Submitted to the School of Gaduate Studies
in Partial Fulfillment of the Requirements
for the Degree of
Doctor of Philosophy

McMaster University

OPTICAL NETWORKS WITH CHANNEL CONTROLLERS

Doctor of Philosophy (1995)
(Electrical Engineering)

McMaster University
Hamilton, Ontario

TITLE: Multi-Channel Optical Network Architectures with Channel Controller based Media Access Protocols

AUTHOR: Mark Janoska, B.Eng (McMaster University)

SUPERVISOR: Dr. Terrence D. Todd

NUMBER OF PAGES: xvii,189

Abstract

Future photonic data communication networks may be based on emerging wavelength division multiplexing (WDM) technology. In such networks, stations communicate using some combination of wavelength agile transmission or reception. Unfortunately, the multiple channel environment tends to increase station optical hardware requirements, and complicate the station media access protocols.

In this thesis, a number of new network architectures are presented which use either a fully broadcast and select topology, or a partial broadcast and select topology with wavelength routing. The design objective is the creation of multichannel networks and multichannel single hop packet switched media access protocols, which require a minimal amount of station optical hardware, and minimal media access protocol complexity. This is accomplished through the use of channel controllers which assist in the operation of the network. Channel controllers are able to reduce the volume of network state information that a station is required to track and process, assist stations with their media access protocol, and provide synchronization information.

The fully broadcast and select single passive star network, and one of the partial broadcast and select networks require a station to have a single fast discrete tunable transmitter and a single fixed or slow tunable receiver, while two other partially broadcast and select networks require a station to be configured with an additional fixed or slow tunable receiver.

Acknowledgments

Many people have provided input and support during the development of this thesis, and I would like to take this opportunity to thank them.

First, I would like to thank my fellow graduate students in the Optical Networks Group, Adrian Grah, Nima Ahmadvand and Sabu Joseph, with whom I have shared an office for the past four years, and discussed data communication networks at great length.

On the personal side, I wish to mention the *Voiders*, Paul, Kyle, Nick, Rob, Saleh, Aldo, Keith, Uwe, Dave, Mike and Wayne, friends and fellow grad students with whom I have spent many a night discussing our other friends, Mr. J. Beam and Mr. T. Horton.

Last, but not least, I would like to thank my supervisor, Dr. Terry Todd. Who has guided me through this thesis, and treated me more as a colleague, rather than a graduate student.

I would also like to thank NSERC and TRIO for the funding which has made this project possible.

Dedicated to my grandparents
Bill and Doris Melnyk

Contents

List of Tables

List of Figures

List of Acronyms

APU	Allocation Processing Unit
ASIC	Application Specific Integrated Circuit
ATM	Asynchronous Transfer Mode
CCWC	Common Control with Wavelength Converter
CSMA	Carrier Sense Multiple Access
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
DBR	Distributed Bragg Reflector laser source
DCCN	Distributed Channel Controller Network
DCWC	Distributed Control channel with Wavelength Converter
DFB	Distributed FeedBack laser source
EDCCN	Extended Distributed Channel Controller Network
FCCN	Flat Channel Controller Network
FCS	Fiber Channel Standard
GBPS	GigaBits Per Second
GHZ	Giga HertZ
HIPPI	HIgh speed Parallel Peripheral Interface
HOL	Head Of Line
ICBA	Inter-Channel Bandwidth Allocation algorithm
IEEE	Institute of Electrical and Electronics Engineers
I-SA	Interleaved Slotted ALOHA
I-TDMA	Interleaved Time Division Multiple Access
KBPS	KiloBits Per Second

KHZ	Kilo HertZ
LAN	Local Area Network
LHOME	Local HOME channel
LOC	Local Optical Cluster
LON	Local Optical Network
MAN	Metropolitan Area Network
MBPS	MegaBits Per Second
MHZ	Mega Hertz
RCA	Reciever Collision Avoidance protocol
RHOME	Remote HOME channel
RON	Remote Optical Network
RPU	Request subframe Processing Unit
SONET	Synchronous Optical NETwork
SPU	Status subframe Processing Unit
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
WAN	Wide Area Network
WDIN	Wavelength Division INterconnect
WDM	Wavelength Division Multiplexing

Chapter 1

Introduction

1.1 Overview

Over the past few decades optical fiber has become the transmission medium of choice for long distance high bandwidth communication [Ram93]. Long distance copper networks are being upgraded with fiber optical cable, the driving forces behind this replacement being the vast bandwidth, low signal attenuation and low bit error rate of the fiber optic medium. Today, single mode optical fiber, along with advances in transmitter and receiver design, provides the communication engineer with a medium that has capabilities which far exceed the transmit and receive performance of the fastest electronic computers. Currently, an electronic station is only able to transmit and receive a bit stream operating at 1 or 2 Gigabits per second [GYZ94] [LK92] [SGK91], while the optical transmission medium is capable of supporting terabits per second of transmission capacity, creating what has been termed the ***electronic bottleneck***. The most promising solution to this problem is Wavelength Division Multiplexing, or WDM. With WDM the total optical spectrum is divided into a number of lower bit rate wavelength channels. Advances in optical device technology, particularly Wavelength Division Multiplexing devices, have spurred interest in the design of multichannel communication networks for the local and metropolitan area environment. Using multiple channels over a single fiber in the point-to-point long distance network provides a large increase in transmission capability without the added expense of installing additional fibers. Researchers have also realized that WDM has network applications in addition to its ability simply to increase the bandwidth-distance product of a point-to-point communication link [Sen92]. Designers are concerned with creation of dynamic networks for connecting hundreds or thousands of computers, and the ability to provide them with high bandwidth communication facilities on demand. In such networks a station has the ability to transmit and receive over multiple wavelength channels using one or more fixed or tunable transmitters and receivers.

The need for high bandwidth data communication networks is evident from several indicators. Interest in the Internet is growing at an exponential rate, office buildings and laboratories are acquiring larger and faster computers and networking them together, and there is a requirement to connect computers to high speed peripherals and memory systems as is evident from the standardization of High Speed Parallel Peripheral Interface (HIPPI) and the Fiber Channel Standard (FCS) interface. In addition, applications such as medical imaging, which require transmission of large uncompressed image files and supercomputer visualization [Ram93] are demanding high bandwidth dynamic communication facilities.

A number of questions have been raised in the literature regarding the design of multichannel communication networks. Specifically in the areas of network topology, station transmitter and receiver configuration, type of optical components and the effect of optical component performance limitations on network performance. Considering the network topology, what is the best configuration in a multichannel environment? Should the topology be based on a multihop design, as in a traditional packet switched network where data packets travel from station to station until the final destination is reached, or should a single hop design as used in Ethernet be adapted? How does topological design effect the performance of the network? With regard to station configuration, what is the optimal number or fixed or tunable transmitters and fixed or tunable receivers at a station, and how is network performance affected by these choices? How does the performance and availability of components produced by optical device manufacturers affect the ability to create networks? Is it feasible to create a wavelength converter, or a tunable transmitter with a tunability range of fifty channels and microsecond tuning speed? And can these devices be produced economically? How is the performance of a network designed on the assumption of nanosecond transmitter tunability limited by transmitters capable of only microsecond tunability? Similarly, if a network is proposed using the assumption that hundreds of wavelength channels are available, what performance limitations are imposed if only a few channels are available?

Although multichannel optical device technology is in an early stage of development, research and thought into the problems and design issues associated with multichannel networks is a precursor to the time when WDM networks can be practically and economically constructed.

1.2 Scope of Thesis

The work presented in this thesis falls within the area of multichannel data communication network and multichannel medium access protocol design. Specifically, it deals with network design using the optical fiber medium and capabilities of optical devices as determined from the current research literature.

Research in optical network and protocol design is a vast area with many subdivisions and regions of specialty. These can be classified using the criteria of link configuration, network span and mode of data exchange. Link configuration refers to the number of transmitters and receivers which can be assigned to a single communication link. The networks presented in this thesis are based on a broadcast and select topology in which a large number of transmitters and receivers are assigned to both transmit and receive from a single channel. Networks are considered which use both a fully broadcast and select architecture, and a partial broadcast and select architecture. In the first case all stations can transmit onto any channel, and all are potentially able to receive a transmission from any other station in the network, while in the second case stations can only transmit to and receive from a subset of the total channels. Considering network span or size the thesis concentrates on networks for the local or metropolitan area environment, rather than for the wide area long haul environment. Further, the work presented considers a single hop packet switched mode of data exchange as opposed to a multihop packet mode or a circuit switched mode of operation. Stations communicate with each other without prior set up, and data packets traverse the network from source to destination in a single hop without intervening optical-electronic-optical conversion or interpretation at intermediate nodes.

1.3 Contributions

The objectives of this thesis are to make advancements in the area of single hop, multichannel network design based on optical device capability, and multichannel multiaccess protocol design with stations capable of transmitter and receiver tunability. The major contribution of the research is the introduction of channel controllers as a means to reduce station complexity and medium access control difficulties in the multichannel broadcast and select environment.

Specific accomplishments are the development of the Distributed Channel Controller single star network along with centralized and decentralized collision free reservation multichannel medium access protocols. The number of stations supported in the network is greater than the number of available wavelength channels, and the protocols provide shared demand access to channel capacity. Use of channel controllers allows the optical transmitter and receiver hardware at a station to be reduced to a minimum of a single tunable transmitter and a single fixed receiver. In addition, the channel controllers allow the volume of state information tracked by a station to be reduced, and hence the protocol processing load to be reduced also. A detailed network simulator was designed as a means to experiment with the dynamics of the network under many configurations. Mathematical capacity and delay-throughput models were developed and used to verify the operation of the network simulator.

Further contributions are extensions of the channel controller concept to a network with hierarchical wavelength reuse as a solution to limited wavelength channel availability. A two level local and remote multichannel packet switched medium access protocol is proposed, with five specific remote protocols investigated and compared.

The extension of the network is accomplished with the addition of only a single fixed receiver per station over the single star network. A remote channel network simulator was developed as a mechanism to experiment with the dynamics of the network, and mathematical capacity and delay-throughput models were developed as a validation of simulator operation.

The final contributions are accomplished through the development of a non-hierarchical wavelength reuse network and a number of multichannel medium access protocols. The network utilized channel controllers and introduced the use of wavelength converters operating on static tuning schedules to reduce station receiver requirements. Two network variations are presented, the first requires each station to have a single fixed receiver and a single tunable transmitter, while the second requires an additional fixed receiver per station. A number of collision free reservation medium access protocols are developed, and one proposes the use of channel controller sharing to reduce control channel overhead and channel controller processing loads. A network simulator was developed as a mechanism for investigation of network behavior, and validated through the development of mathematical models for capacity and delay-throughput.

1.4 Outline

Chapter 2 provides a brief background discussion of the fiber medium and optical device technology which has been a prime motivation for research into multichannel optical networks and medium access protocols, including the work carried out by this thesis. This also provides insight into the issues related to network and medium access protocol design. The chapter merely touches on the key points, but provides references so that the interested reader can locate additional material.

A survey of the existing research literature is provided in chapter 3. Emphasis is placed on architectural and medium access protocol issues encountered in the development of multichannel optical networks. A number of specific optical networks and medium access protocols are presented in detail. Using this review, the advantages and complexities involved with multichannel network design are emphasized and discussed.

The original content of the thesis begins with chapter 4, which presents the Distributed Channel Controller Network. This is a multichannel, packet switched, fully broadcast and select, single hop network which proposes the use of distributed channel controllers to simplify station design and solve some of the complexities encountered in multichannel network design. The chapter provides an in depth description of the network, a quantitative analysis, and comparison with other networks of similar design which have been proposed in the literature. A discussion of the ability of channel controllers to overcome design complexity, along with limitations of the Distributed Channel Controller Network are presented.

Chapter 5 expands on the Distributed Channel Controller Network by introducing hierarchical spatial wavelength reuse as a mechanism to overcome limitations caused by reduced wavelength channel availability. The extended network divides stations into local optical networks connected by a remote optical network. The work proposes the use of both a local and remote medium access protocol based on the channel controller concept. Specifically, a number of remote medium access protocols and channel controller configurations are proposed and analyzed.

The final section of the research, presented in chapter 6 describes and analyses a multichannel packet switched network with a non-hierarchical spatial wavelength reuse architecture. This network along with a number of channel controller based medium access protocols is proposed as a solution to limited channel availability.

Finally chapter 7 summarizes the research undertaken in this thesis. Emphasis is placed on describing the architectural advancements made, the benefits and disadvantages of channel controllers and the interesting results revealed by the study. Lastly, a discussion of future work describing areas in which the author feels additional research is required within the scope of multichannel network design.

Chapter 2

Background

A number of topics and terminology fundamental to communication network and medium access protocol design are discussed in this chapter. In particular, issues related to network design based on optical device technology and the fiber medium are addressed. No attempt is made to provide exhaustive explanations of these topics since they are already well described in published text books, research journals and conference proceedings. Rather, brief highlights are presented along with references as preparation for the discussions in later chapters.

2.1 Networks

A communication network is a system used to connect a set of stations or nodes together and provide them with a mechanism to exchange data. In this section a number of topics related to network architecture and medium access protocol design are discussed. A more thorough treatment of this material can be found in references [Sta87] [Tan89] [Sun89] [Hui90] and [Spr91].

2.1.1 Network Classification

A network can be classified in many ways, including link configuration, network span, and the mode of communication between stations.

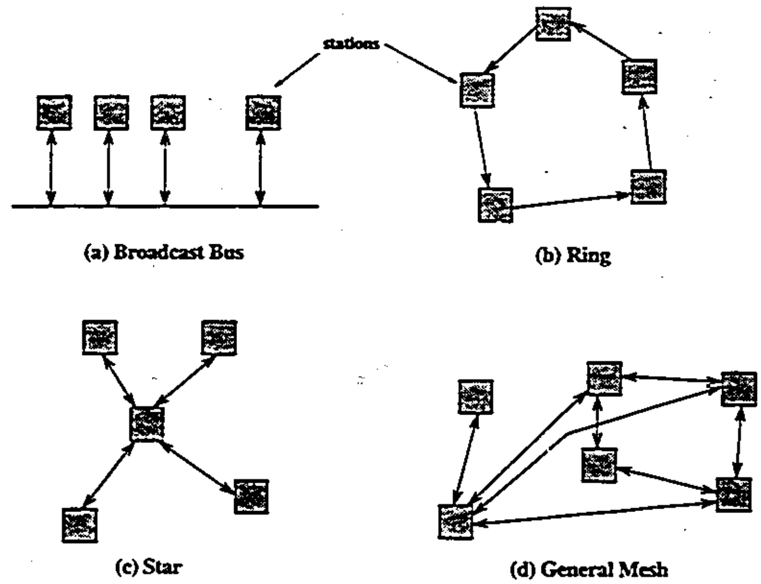

Figure 2.1: Network link configuration. (a) Broadcast and select. (b) Ring. (c) Star. (d) General mesh.

A number of common network link configurations, or connection topologies are illustrated by figure 2.1. Figure 2.1a shows a network with a broadcast and select bus configuration. Each station has a transmitter and receiver connected to a shared medium over which it both transmits and receives data. A station is able to receive the transmissions of all other stations. Data travel from source station to destination station in a single hop without buffering or routing by intermediate stations. Multiple transmitters can access the same transmission medium simultaneously, therefore a set of rules, or medium access protocol is required to coordinate the flow of data. A station must examine all data packets and keep only those addressed to itself. The configuration of 2.1b is a physical ring network. A single dedicated unidirectional link connects each station into a physical ring. Each communication link has only a single transmitter and a single receiver, and as a result conflicts do not arise with data packet transmission as they did with the broadcast bus network. Ambiguity does not exist as to whether or not a station should accept data, it must receive and process all data packets. Data travel around the ring in a multihop manner from the source station until it reaches the destination station. A star connection pattern is illustrated by figure 2.1c. In this network a special node with multiple transmitters and receivers acts as a hub station. Communication between stations must pass through the central hub. As with the physical ring network each link has a single transmitter and single receiver, eliminating the requirement for a medium access protocol. Finally, figure 2.1d illustrates a general mesh connected network. Each station has a number of transmitters and receivers connecting it with adjacent stations in a pattern dependent on the data traffic flow between stations. Data travel from source to destination station in a multihop manner similar to that of the ring network. However, as a result of the general connection pattern a data packet routing function is required at intermediate stations to pass data packets to the destination station.

Three common classifications are in use with regard to network span or size. Networks spanning distances of a few kilometers are classified as Local Area Networks, or LANs. These are typically used to connect stations within a single room or building, have very high data transmission rates and use protocols which are able to adapt to changing traffic patterns. Metropolitan Area Networks, or MANs span distances of tens of kilometers. These are typical of the distances used to connect stations within a city or university campus and have similar characteristics of local area networks. Finally, Wide Area Networks, or WANs span entire countries or continents. These have diameters of hundreds or thousands of kilometers, use static allocation of transmission bandwidth and have stable long term traffic patterns.

Considering the mode of communication between stations, two main classifications exist, circuit switched communication and packet switched communication. A network using circuit switching requires a source station to establish a path through intermediate nodes and links to the destination station before communication commences; this is referred to as the circuit set up phase. Once a circuit has been established the stations can exchange data. Upon completion of data exchange the circuit is released. An excellent example of a circuit switched network is the public telephone system. The advantages of this mode of communication are a guaranteed bandwidth allocation after circuit set up, protection from unstable traffic requirements of other stations and low transmission delay variance. Disadvantages are the inability to utilize idle bandwidth on a circuit and overhead due to circuit set up and release. Both of these problems prevent circuit switching from being an attractive mode of communication for high speed networks with bursty dynamic traffic characteristics. Packet switching is based on sending data from source to destination in self contained units called data packets. Large messages are broken up into multiple packets and each is sent through the network independently. This mode of communication does not require a circuit to be set up prior to communication since a data packet contains the address of the source and destination stations. The source station sends each packet into the network, where in a multihop manner it is routed to its final destination through intermediate nodes. The advantage of packet switching is an increase in channel utilization, since unused bandwidth can be used by any station, and circuit set up and release overhead are not incurred. A number of problems arise in packet switched networks. Increase in station complexity due to a packet routing protocol, unstable congestion due to bursty traffic sent into the network, lost or disordered packets, and large variance in packet transmission delay.

The work presented in this thesis is based on local and metropolitan area networks using a broadcast star topology and packet switched communication.

2.1.2 Medium Access Protocols

A medium access protocol is a procedure executed by a station to facilitate the coordination of transmitted and received data on a shared communication channel. Complexity arises since the channel must be shared by a number of stations, and the situation becomes more complex when consideration is given to the multichannel environment where each station is capable of transmitting and receiving on a number of channels.

Examples of three well known single channel packet switched medium access protocols are Ethernet, based on the IEEE 802.3 standard [Sta87] [otICS85a] [HL93] [SM85], Token Bus, based on the IEEE 802.4 standard [Sta87] [otICS85b] and Token Ring, based on the IEEE 802.5 standard [Sta87] [otICS85c] [Nil90] [Hel94]. Ethernet and Token Bus use the fully broadcast and select bus network illustrated by figure 2.1a, while Token Ring uses the point-point physical ring network of figure 2.1b.

Ethernet uses a random medium access protocol to coordinate station transmissions. A station waits for the channel to become idle, transmits a data packet and then listens for a collision with another transmitter. If a collision occurs both stations stop transmitting and re-execute the protocol at a later random time. Token Bus uses a collision free medium access protocol. A logical ring is overlaid onto the physical broadcast and select architecture and a special data packet called a token is passed around the ring from station to station. A station can only transmit data packets when it has possession of the token, when it is finished it passes the token to the next station in the logical ring. Token Ring is similar to Token Bus except that a token and data packets are passed around the physical ring.

2.2 Optical Networks Historical Perspective

Since this thesis deals specifically with optical network design it is beneficial to provide a brief discussion of the characteristics and limitations of the optical devices used as building blocks.

The use of the optical medium for communication, as discussed by [Sen92] [Gre93] was initiated by the development of optical sources and receivers at the $0.8\mu m$ wavelength, and by the development of fiber optic cable with a low enough attenuation to make it a feasible replacement for copper wire. Further advancements in optical source and detector technology enabled transmission at optical wavelengths of $1.3\mu m$ and $1.5\mu m$, which allowed exploitation of the low attenuation and dispersion of silica based fiber in these regions. Improvements in fiber construction techniques provided core diameters small enough for single mode transmission at wavelengths of $1.3\mu m$ and $1.5\mu m$. This increased the usable bandwidth and inter-repeater spacing distance (also refered to as the distance-bandwidth product) of point-to-point links by reducing modal dispersion. Most recently, device research has proceeded into the area of wavelength tunable sources, wavelength tunable detectors and optical amplifiers, spawning research in the area of multichannel network architectures and multichannel medium access protocols.

Optical communication network architectures, as stated in [Gre93] can be considered as either first generation, second generation or third generation network architectures. First generation systems were communication networks developed before the use of the optical medium was considered, all developments were based on copper and free space medium. The networks were characterized by low bandwidth point-to-point communication links, with emphasis placed on increasing the transmission speed and repeater spacing for long haul networks. In smaller local area networks, medium access protocols such as Ethernet and Token Ring were developed to allow many stations to share the transmission capacity of a single communication channel. Second generation networks were based on the same network architectures as first generation systems except the copper medium was replaced by the fiber optic medium. In these systems the potential benefits of the fiber medium were not fully exploited since their single channel nature was maintained and stations were not capable of communicating at the full bandwidth of the fiber medium. These networks had the same design objectives as first generation, increase the distance-bandwidth product of the point-point link and for the local area, allow a number of stations to share the bandwidth of a single channel. This work is still continuing today, as evident from research into fluoride based fibers with very low attenuation and soliton pulse transmission to allow very long distance unrepeated transmission [Sen92]. Third generation networks are at the forefront of network architectural research. The research literature indicates that a shift in network design objectives has occurred. Rather than attempt to increase the distance-bandwidth product of a single point-point communication link, emphasis has shifted to the entire network architecture, station to station connectivity and dynamic bandwidth utilization. The new objective is to increase the capability of the communication network to support many diverse traffic patterns and move the availability of bandwidth closer to the stations. Third generation optical networks are characterized by simple physical network structure and have minimal interpretation and processing of transmitted information within the network. They attempt to exploit the properties of the optical fiber medium and the capabilities of optical device technology, especially that of wavelength division multiplexing.

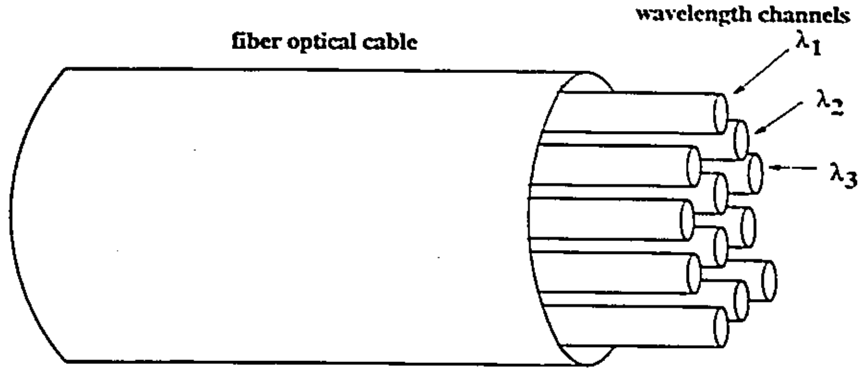

Figure 2.2: Wavelength Division Multiplexing Concept

2.3 Wavelength Division Multiplexing

The optical fiber medium contains a vast amount of bandwidth, approximately 25THz in the low attenuation wavelength windows at $1.3\mu m$ and $1.5\mu m$ [Sen92]. Utilization of this bandwidth is far beyond the capability of the fastest and simplest electronic devices [GYZ94] [JM93a] [LK92] [SGK91] [LA95] [Bra90]. Among researchers of optical networks the most favored solution to this problem is wavelength division multiplexing, or WDM. As illustrated by figure 2.2, wavelength division multiplexing is based on the division of the optical bandwidth of a single fiber into a number of lower bandwidth wavelength channels referred to as λ_1 through λ_C, where C is the total number of available channels. Each channel has a bandwidth or capacity equal to the maximum transmission rate of an electronic station, a few hundred MHz to a few GHz of bandwidth. The use of WDM creates a multichannel network architecture, using stations equipped with one or more fixed or tunable optical transmitters and one or more fixed or tunable optical receivers. A dividing line among proposed multichannel WDM networks is the assumption regarding the number of available wavelength channels. Networks which assume the availability of hundreds or even thousands of channels are referred to as dense WDM networks, while those which assume the availability of only a moderate number of channels, in the range of ten to fifty are referred to as course WDM networks [Bra90] [CSR90] [Ram93]. This simple concept has lead to a great deal of research in the area of multichannel network architecture

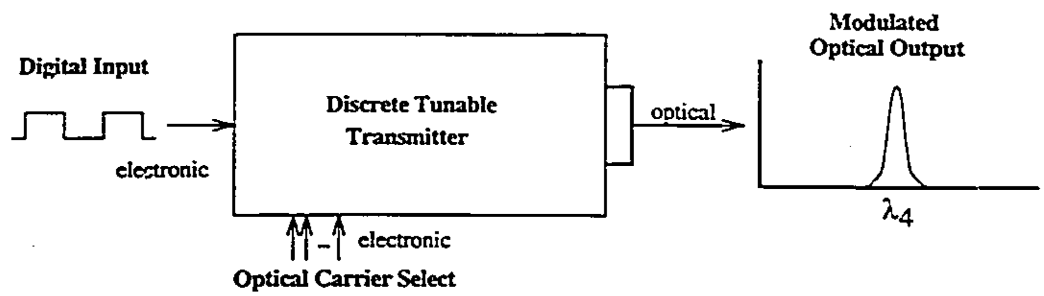

Figure 2.3: Ideal Discrete Tunable Transmitter

and multichannel multiaccess protocol design.

2.4 Optical Network Components

Many fundamental components or building blocks are used in the design of optical networks. Presently a majority of these devices are not commercially available, but have either been proposed in the device research literature or experimentally demonstrated in research labs. The functionality and primary characteristics of each device are discussed as a foundation for later chapters.

2.4.1 Discrete Tunable Transmitter

A discrete tunable optical transmitter is a device capable of modulating a digital information signal onto one of multiple optical carrier wavelength channels. An ideal "black box" representation of such a device is illustrated by figure 2.3. Inputs are an electrical serial digital bit stream of information and an electrical parallel digital word for carrier wavelength selection. The output is an optical signal at the selected optical carrier wavelength modulated by the digital input signal. Optical spectral characteristics of a discrete tunable transmitter are illustrated by figure 2.4. This shows a set of wavelength channels λ_1 through λ_N occupying a region within either the $1.3\mu m$ or $1.5\mu m$ waveband. Only a single wavelength channel is output from the device at any time. Parameters of primary importance are the number of resolvable channels and the inter-channel tuning speed; these are dependent on the method of

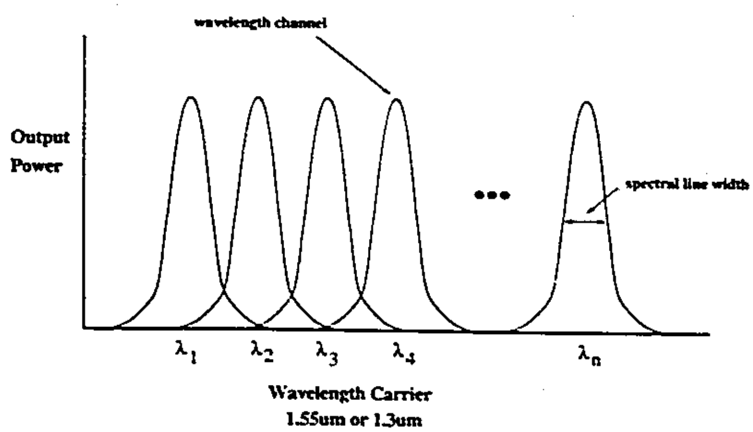

Figure 2.4: Discrete Tunable Transmitter Output Spectrum

device construction. Considering the number of resolvable channels, the optimal case is a minimal linewidth and tunability over the entire 200nm low loss transmission window within either the $1.3\mu m$ or $1.5\mu m$ waveband. A discrete tunable source can be constructed with laser arrays, with spectral slicing or by changing the center frequency of a single laser. Laser arrays [Gre93] [Mid93] are created by integrating a number of single frequency lasers into a one or two dimensional array on a single substrate and coupling the outputs of all lasers to a single output fiber. Only a single laser is enabled at any one time; from an external point of view the device is a discrete tunable optical source. A tunable source constructed using this technique is advantageous since tuning speeds can be very high, laser wavelengths can be stabilized and the device can output across the entire 200nm low loss region. A disadvantage is the problem of efficiently coupling a large number of sources to a single output fiber. Spectral slicing as a means to create a discrete tunable source has also been proposed in [Gre93]. This technique uses a wideband source followed by a tunable filter to transmit selectively on the desired wavelength channel. In this case the speed of tunability is a function of the tunability of the optical filter. A problem with this technique is that a large portion of optical energy is attenuated since only a small fraction of the spectrum is allowed to pass through the filter. Continuously tunable lasers can also be used as the basis for creating discrete tunable sources. Continuous tunability is achieved by using thermal effects, mechanical effects, acousto-optic effects

Technique	Tunability Range	Tuning Speed
Thermal	1-2nm	millisecond
Mechanical	100nm	millisecond
Acousto-optical	100nm	microseconds
Electro-optical	10nm	nanoseconds

Table 2.1: Laser Tuning Range and Speed Comparison

or electro-optic effects [Bra90]. Table 2.1 provides a comparison of tuning range and maximum tuning speed achievable using these techniques. Thermal tuning of distributed Bragg reflector (DBR) lasers provides a very small tuning range and slow tuning time, mechanically tuning using an external cavity has a very wide tuning range but retains the slow millisecond tuning time. These techniques are suitable for circuit switched networks which do not require fast packet-by-packet switching times. Acousto-optic tuning relies on a change in the index of refraction of the material used to construct a DBR laser as a function of an applied acoustic wave. These devices have large tuning ranges, however tuning speed is limited to the microsecond range due to the velocity of acoustic waves. Electro-optic tuning relies on a change in the index of refraction as a function of an applied electric field. Since the electro-optic effect is weak in most materials [Gre93] the index change and hence the tunability range is small, however devices have been reported with very fast nanosecond tuning times. Devices with microsecond and nanosecond tuning speed are required for the creation of multichannel packet switched networks which rely on the ability to re-tune their transmitters on a packet by packet basis.

The discrete tunable transmitter along with its counterpart the discrete tunable receiver are the primary driving force behind the design of third generation optical networks.

2.4.2 Discrete Tunable Receiver

A discrete tunable optical receiver is a device capable of demodulating an information signal from one of many optical wavelength carrier signals. Figure 2.5 is an ideal

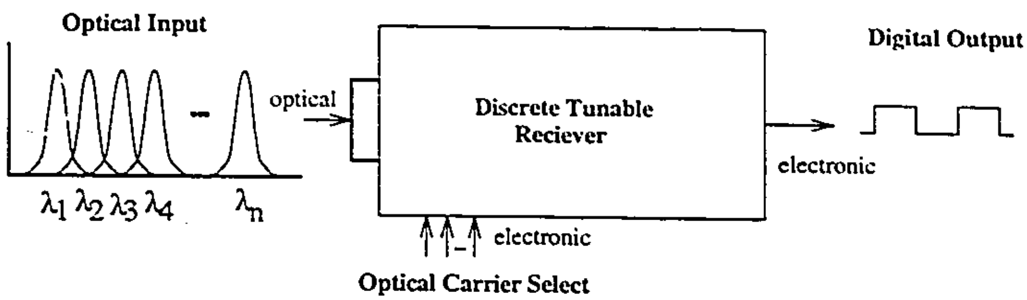

Figure 2.5: Ideal Discrete Tunable Receiver

Technique	Channels Resolved	Tuning Speed
Passive filters	100-1000	millisecond
Acousto-optical filters	100	microseconds
Electro-optical filters	10	nanoseconds
Laser amplifier	< 10	nanosecond

Table 2.2: Receiver Channel Resolution and Speed Comparison

"black box" representation of such a device. Inputs are a single fiber with modulated information on multiple wavelength channels and electronic parallel digital word for wavelength selection. The output is an electronic serial bit stream of information demodulated from the selected wavelength channel. As with the transmitter the parameters of interest are the number of resolvable wavelength channels and the speed with which the device is able to switch between wavelength channels.

A discrete wavelength receiver can be constructed with either passive or active techniques [Bra90]. With passive techniques, a mechanical feature of the detector structure is varied, this includes Fabry-Perot etalons, tunable Fabry-Perot filters and tunable Mach-Zehnder filters. Both techniques rely on phase shifting and interference to pass optical energy of a desired wavelength only. Active filters use either acousto-optical or electro-optical effects to change the refractive index of a filter structure. A distributed feedback (DFB) or distributed Bragg reflector (DBR) laser operating below threshold can also be used to selectively amplify and pass wavelengths. Table 2.2 provides a comparison of tunability range and tuning speed of these devices. Similar

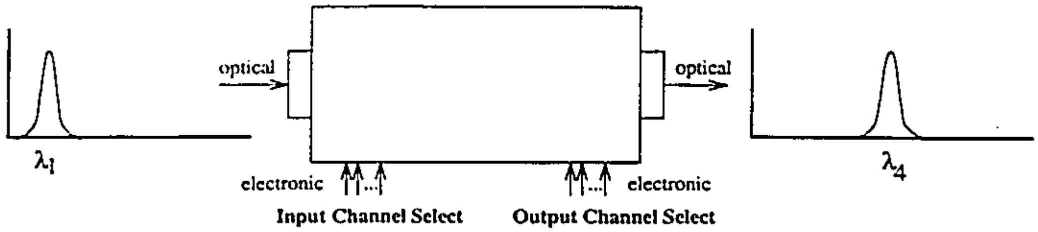

Figure 2.6: Wavelength Converter

to tunable transmitters a tradeoff in tunability range for tuning speed is observed, as the number of resolvable channels increases the inter-channel tuning speed decreases.

2.4.3 Wavelength Converter

The wavelength converter is a device which accepts an information signal modulated on an input wavelength carrier λ_{in} and outputs the same information signal on a different wavelength carrier λ_{out} without interpretation or modification of the information signal [Mid93]. This device has received much less attention than either the tunable transmitter or tunable receiver in the device research literature, however a number of networks have proposed its use [LL93] [TWB95] [AT95]. Figure 2.6 provides a "black box" representation of an ideal wavelength converter. Inputs are multiple wavelength carrier signals on a single fiber and two electronic parallel digital selection inputs. The first digital input selects the input wavelength carrier while the second selects the output wavelength carrier. The output is a single fiber with one wavelength carrier signal. Parameters of interest are the number of resolvable channels and the reconfiguration time. The device can be created in either the optical or electronic domain. In the optical domain wavelength converters can be constructed with four wave mixing in optical amplifiers, bistable laser operation and gain saturation in semiconductor optical amplifiers [YIYO95] [YIT+94] [DPM+93] [TKY+94] [SPE+93] [ZPD+94] [KKYW92] [GWK+92]. Devices have been reported which are able to convert wavelengths over a 90nm range with tuning speeds as fast as 5ns [GWK+92]. In the electronic domain a wavelength converter can be created with a discrete tunable receiver and a discrete tunable transmitter with their analog output and analog input tied together. In this case the number of resolvable channels and reconfiguration time

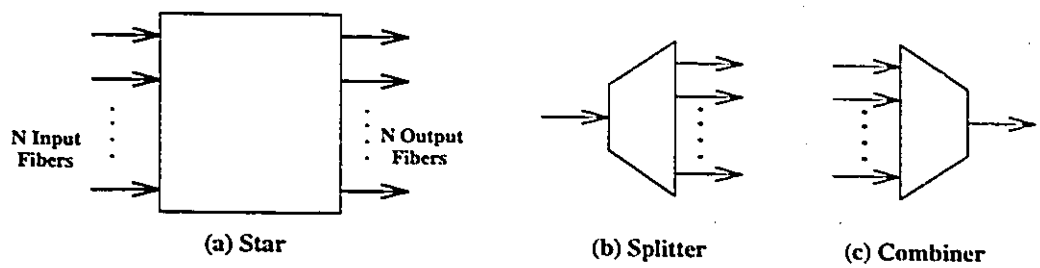

Figure 2.7: Passive Couplers and Splitters

are determined by the characteristics of the tunable transmitter and tunable receiver.

2.4.4 Passive Couplers and Splitters

Passive couplers and splitters are often used to connect network components. The most common devices found in the network literature are star couplers, combiners and splitters as illustrated by figure 2.7. Figure 2.7a shows an $N \times N$ star coupler. In the ideal case this device divides optical energy on all wavelength channels from each input fiber equally to each output fiber, however in a practical situation some of the optical energy is wasted due to insertion loss and some variation in output power across the output ports is expected. The most common construction technique uses multiple stages of 2×2 couplers to construct an $N \times N$ star coupler. This requires a total of $\frac{N}{2}$ couplers. Other techniques based on integrated optics promise inexpensive passive star couplers of size 100×100 [Bra90]. Figure 2.7b illustrates an N port splitter which equally divides optical energy from a single input fiber to N output fibers, independent of wavelength channel. Finally figure 2.7c shows an N port combiner which couples optical energy on all wavelength channels from N input fibers to a single output fiber. These combiners and splitters also exhibit some degree of insertion loss and nonuniform power coupling.

2.4.5 Wavelength Routers

A wavelength router, also referred to as a WDM crossconnect is an advanced coupler or splitter [Mid93]. The device provides a selective method of broadcasting from one or more input ports to one or more output ports based on wavelength discrimination.

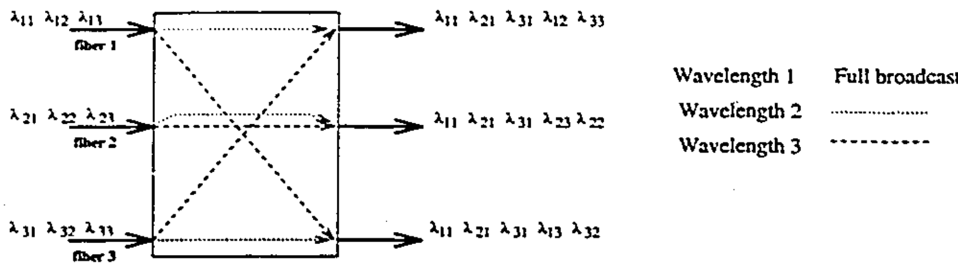

Figure 2.8: Wavelength Router

Figure 2.8 illustrates an example of a 3×3 port wavelength router using three wavelength channels. Wavelength channel j on input fiber i is referred to as λ_{ij}. In the example λ_1 has been designated as a fully broadcast channel and is routed from all input fibers to all output fibers, while wavelength channels λ_2 and λ_3 are selectively routed based on the source input fiber. The parameters of interest for such devices are the number of input and output ports available, wavelength channel resolution and speed of reconfigurability. Wavelength routers are a key component in networks which incorporate some form of spatial wavelength reuse.

2.5 Discussion

This chapter has introduced a number of issues and topics related to the design of packet switched communication networks and medium access protocols. The optical components which are essential for the construction of third generation optical networks have been described along with brief discussions of their performance characteristics and limitations. Optical device technology is still in its infancy and in the next few years it is expected that device performance will improve beyond what has been described.

In the next chapter a review of the optical network research literature provides a discussion of many proposed optical networks and multichannel medium access protocols which are based on these concepts and optical devices.

Chapter 3

Review of Multichannel Optical Networks

A great deal of research has been undertaken in the development and analysis of single hop multichannel network architectures and medium access protocols. As a first step towards discussing the material presented in this thesis, and as an aid to understanding the issues involved with such network development, a number of networks which have been proposed in the research literature are presented. The review begins with an examination of single star networks, then proceeds to more complex networks which incorporate wavelength routing and spatial wavelength reuse. Finally, as a result of the literature review a summary of complexities arising in the design of single hop multichannel packet switched networks is presented.

3.1 Single Star Optical Networks

Examination of the research literature indicates the single star network to be a popular physical topology for the local and metropolitan area network environment. The architecture in its most basic and general form consists of a single $N \times N$ port passive star coupler and a set of N stations. Each station is connected to the star coupler with an uplink fiber and a downlink fiber pair as illustrated by figure 3.1. Using WDM, the optical bandwidth is divided into a set of lower bit rate wavelength channels. A

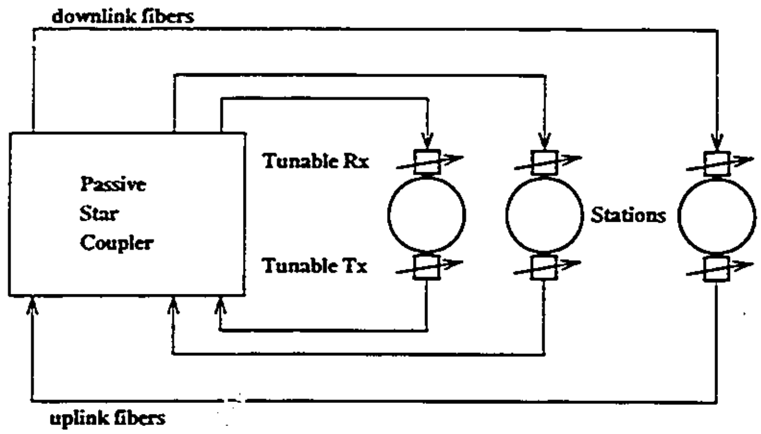

Figure 3.1: General Single Star Network Architecture

transmission from a station is broadcast to all stations in the network by the star coupler regardless of the wavelength channel of the transmission. Each station is equipped with one or more fixed tuned or discrete tunable transmitters and one or more fixed tuned or discrete tunable receivers. A station can use either transmitter tunability, receiver tunability or the tunability of both the receiver and transmitter to communicate with other stations in the network.

From a high level, design of single hop packet switched networks can be divided into two classes, networks with random medium access protocols and networks with collisionless medium access protocols. Each class of network is described along with representative examples and discussions. Using this approach the advantages as well as the complexities encountered in the development of multiaccess protocols for multichannel single star networks are highlighted.

3.1.1 Random Media Access Protocols

Random medium access protocols coordinate their packet transmissions using collisions, and if necessary data retransmission. In such networks data channel throughput is characterized as low and unstable, as is the case for the single channel slotted aloha protocol [Tan89]. Using the slotted aloha protocol a single channel is divided into equal time slots, a station with a packet to transmit waits until the beginning of a slot and commences transmission. If no other stations have a packet to send then the transmission is successful, however if another station is ready to transmit then a collision occurs on the channel and both packets are lost. If many stations are generating packets under a Poisson arrival rate, the channel throughput can be described as in [Tan89]

$$S_{aloha} = Ge^{-G} \tag{3.1}$$

where G is the total offered packet load due to new and retransmitted packets from all stations in units of packet arrivals per slot. From the throughput equation S_{aloha} has a maximum of 36% of channel capacity occuring at an offered load of $G = 1$ packet per data slot. Consequently, if the channel rate is $1Mbps$ then only $360Kbps$ is available for useful data transmission. In addition, the channel is unstable, if the offered load exceeds the optimal value of one packet per slot then data channel throughput begins to rapidly degrade due to increased packet collisions and retransmissions.

In the multichannel environment two subclasses of random access network are prevalent, those which use one or more control channels to coordinate activity, [LK92] [SK91] [HKS87] [JM93b] [SGK91] [JM93a] [Meh89] [Dow91] [SKG91] [LA95], and those which do not use control channels, [MR83] [GK91] [SBD93] [Dow91]. A control channel is a dedicated wavelength channel used to exchange signaling information among stations, it is not used for transport of data packets. Typically, these networks have adapted traditional single channel random multiaccess protocols such as slotted aloha for either the control channel, the data channels or both.

A typical network using a random access protocol without a control channel is characterized by [GK91]. The physical network topology is the fully broadcast and select passive star with a set of N stations, which can be greater than the number of wavelength channels C. Each station is configured with a single discrete tunable transmitter capable of tuning to a limited subset of the wavelength channels, and a set of fixed tuned receivers. T_i is defined as the set of channels that station i can transmit onto and R_i as the set of channels from which station i can simultaneously receive packets. The set of wavelengths that stations can transmit onto and receive from must be such that single hop communication can take place between any two stations in the network. This is formally stated as

$$T_i \cap R_j \neq 0, \forall i, j, i \neq j. \quad (3.2)$$

Each data channel is overlaid by a repetitive time multiplexed frame structure consisting of a single data slot. Transmission is accomplished with the slotted aloha protocol. A station i with a packet to transmit to station j must select a data channel at random from the set of channels $T_i \cap R_j$, tune its transmitter to the channel and make a packet transmission. The transmission is only successful if no other stations selected the same data slot on the same channel. An immediate problem is evident with this protocol, due to limited receiver hardware a station can not determine the state of all channels in the system. If station i transmits on a channel for which it has no receiver it is unable to determine the loading state of the channel, this is important for the stability of the aloha protocol. The theoretical capacity of a data channel is very high, almost 100% since no signaling or overhead is present on the channel. However, the throughput is limited due to the lack of state information available to a station and the random nature of the medium access protocol. Assuming that a large number of stations are generating data packets, the throughput on channel k can be expressed as

$$S_k = G_k e^{-G_k}, \quad (3.3)$$

where G_k is the offered load by all stations on channel k from new and retransmitted packets in units of packets per slot. This has a maximum throughput of $S_k = 36\%$ for an offered load of 1 packet per slot.

A similar network using the slotted aloha protocol is proposed in [Dow91] [SBD93] and is referred to as the Interleaved Slotted Aloha protocol, or I-SA. The network requires a station to have only a single fixed receiver, however the discrete tunable transmitter is capable of tuning to all wavelength channels. An earlier multichannel network proposed by [MR83] proposed the use of carrier sense multiple access (CSMA) and carrier sense multiple access with collision detection (CSMA/CD) as the medium access protocols in the multichannel environment. This requires that a station be configured with an additional discrete tunable receiver so that it can receive from the channel it is transmitting onto as well as receive data from a fixed channel.

A single wavelength channel dedicated as a control channel has been proposed as a technique to improve the performance of multichannel random access protocols. A disadvantage of such an arrangement is that one channel cannot participate in useful data transmission. If the total number of available wavelengths is small then this can lead to a significant degradation in network throughput. A typical random access network using a control channel is characterized by [SGK91]. The physical network architecture is the fully broadcast and select passive star with a set of N stations and C wavelength channels. The number of stations can be greater than the number of data channels. Each station is configured with a single discrete tunable transmitter and a single discrete tunable receiver. Wavelength channel λ_0 is designated as a common control channel, while channels λ_1 through λ_{C-1} are data channels. The control channel is used by all stations to coordinate transmission and reception of data packets. Stations do not fix tune either their transmitter or receiver to a dedicated channel. Idle stations with no packets to transmit tune their receivers to the control channel. If station i has a data packet to send to station j then it selects a data channel r and transmits a message over the control channel indicating the intended destination station and the data channel it is using. Immediately afterwards station i transmits the data packet over data channel r. If station j is also idle and tuned to the control channel it receives the control message, tunes to the specified data channel and waits for reception of the data packet. Other networks have modified this approach by using an additional receiver [SKG91], or an additional receiver and transmitter [LK92] fixed tuned to the control channel to allow a station to continuously receive and/or transmit control information.

Since the number of stations is much greater than the number of channels the proposed network discusses a number of random access methods to coördinate transmission on both the control and data channels. The remainder of the discussion concentrates on a specific protocol referred to as Slotted Aloha Case 4, which uses the slotted aloha protocol on both the control and data channels. Each of the control and data channels is overlaid by a repetitive time multiplexed frame structure as illustrated by figure 3.2. The control channel consists of X control minislots, each with a relative duration of 1 time unit and some wasted capacity. The data channels consist

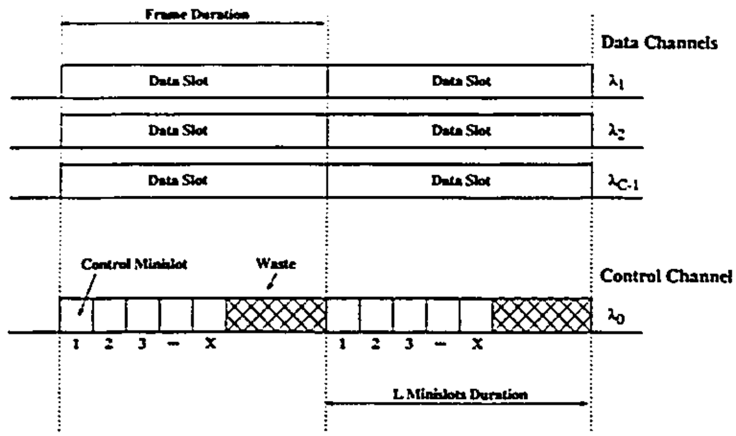

Figure 3.2: Control and Data Channel Formats for a random medium access protocol

of a single fixed sized data slot of duration L time units. The total duration of the control frame can not exceed the duration of the data frame, $L \geq X$. A station i with a packet to transmit must randomly select a data channel r, randomly select a control minislot, transmit a control message addressed to the intended destination station indicating which data channel it has selected, and transmit a data packet into the data slot of the next frame on channel r. The transmitting station i must then determine if the transmission was successful by receiving from the control and data channels, and taking action based on the state of the channels. Two cases arise, the first has the control message of station i corrupted by collision from another station. In this situation the destination station could not have received the control information and is unable to receive the data packet. Station i can deduce this by listening for its own transmission on the control channel. A retransmission of the control message and data packet must occur to correct this situation. The second case occurs if station i made a successful control message transmission and determined that other control minislots suffered collisions. In this situation station i is unable to resolve which data channel the colliding stations made data packet transmissions onto. The possibility exists that one or more of the colliding stations transmitted a data packet onto the same data channel r as station i. This case can be resolved in one of two ways. If station i assumes that a data channel collision also occured it must retransmit its control and data messages. Alternatively, station i can examine the data channel for a successful data slot transmission and only if the data slot is corrupted would it have to retransmit the control and data messages.

The theoretical data channel capacity of this network is very high since almost no overhead exists on the data channels and only one channel is dedicated as a signaling channel. The actual throughput on a data channel however, can be very low due to the random nature of the medium access protocol. If station i selected channel 1 then a successful transmission only occurs if no other control minislot selected channel 1 and no other active station selected the same control minislot as station i. Data channel throughput can be expressed as

$$S_{case4} = \frac{GX}{N} e^{-(1+\frac{(X-1)}{N})G}, \tag{3.4}$$

where G is the offered packet load per data slot from all N stations as a result of new and retransmitted packets. This does not take into account overhead from the control channel which can not be used for data packet transmission.

An improvement to the protocol is proposed in the same paper, and by [Meh89] and [Dow91], which prevents a data channel transmission from occuring unless a successful control channel transmission occurs. This improves throughput performance by preventing packet collisions on the data channel at the expense of increasing access delay by requiring a station to wait a least one full station-star-station propagation delay between control minislot transmission and data slot transmission.

In addition to the aloha protocols on control and data channels, other protocols have been proposed such as reservation aloha [SGK91] and Carrier Sense Multiple Access (CSMA) [HKS87] [SK91]. The reservation aloha scheme favors stations with messages larger than one data slot in duration by reserving a control minislot or data slot until the entire message has been transmitted. The CSMA protocol requires stations to locate an idle channel before making data slot transmissions. This attempts to increase channel capacity by reducing the number of data channel packet collisions.

A single control channel poses limitations to network throughput. Under the random access protocols only successful control minislot transmissions can potentially lead to successful data channel transmissions, thus as the offered load to the control channel exceeds the optimal value, the number of successful transmissions on the control channel degrades causing a degradation in data channel throughput. The network of [SKG91] introduced the concept of multiple control channels and grouping of stations as a solution to control channel congestion problem.

This network also emphasizes another problem with networks that use receiver tunability and limited receiver hardware. If a station makes a successful control minislot and data slot transmission, but the intended destination station has its receiver tuned to a different data channel then the destination station is unable to receive either the control minislot or the data packet. This problem is referred to as *receiver collision*. A network described in [JM93b] proposes a solution to this problem by using a more complex medium access protocol and a great deal of network state information tracking.

3.1.2 Collisionless Media Access Protocols

The second class of medium access protocol proposed for single star networks are collisionless. These use either fixed pre-assignment of transmission resources to individual stations or a reservation mechanism. Networks which rely on pre-assignment typically have very simple medium access protocols, and as a result suffer from fixed bandwidth allocations and do not adapt well to changing traffic load conditions. Networks using reservation protocols tend to be complex, but can assign bandwidth to stations on demand. Similar to the random access protocols, concepts have been adapted from traditional single channel multiaccess networks, an example being static Time Division Multiple Access or TDMA. Using single channel TDMA the channel is divided into a number of fixed sized data slots, and each station in the network is preassigned a single data slot. A station with a packet to transmit waits for its data slot and makes its transmission. If a station has no data to transmit the data slot remains idle, even if other stations are backlogged with data packets. The capacity of a TDMA channel is close to 100% since no signaling and little overhead are required. If there are N stations in the network then each receives at most $\frac{1}{N}$ of the channel capacity. Channel throughput can be much greater than that achieved with random access protocols since collisions do not occur.

As with the random access protocols two subclasses of network are prevalent, those which use a control channel to coordinate medium access [CY91] [CSR90] [CF92] [KFG94a] [GYZ94] [CF91] [CDR90] [CY92] [TMS94] [CZA93] [BCD92] [CZA92], and those which do not use a control channel [SGK92] [SBD93] [GG92].

A representative network using a collisionless multichannel multiaccess protocol without a control channel is described by [SBD93]. The network consists of a single fully broadcast passive star with N stations and C wavelength channels. Each station is configured with a single fast discrete tunable transmitter capable of tuning to all wavelength channels and a single fixed tuned receiver. A station has its receiver fix tuned to a preassigned *home* channel, and many stations can have the same home channel assignment. Each channel is divided into a repetitive time multiplexed frame structure consisting of a fixed number of fixed sized data slots, with the number of data slots per frame equal to the total number of stations in the network. Each station is preassigned dedicated use of a single data slot on each data channel. Frames are aligned across all channels so that a station can synchronize transmission onto any channel by receiving frame synchronization information from only its home channel. The frame format for a five channel and eight station network is illustrated by figure 3.3. Slot assignments are interleaved across the channels such that assignments for a particular station do not overlap in time. If station i has a data packet to transmit to station j it must determine which channel station j's receiver is tuned to and then transmit the data packet into its dedicated data slot on the proper channel. Since very little overhead and no signaling information exists on the data channels, the theoretical channel capacity is very high, almost 100%. However, due to the pre-assignment of data slots to stations, dynamic use of bandwidth is not possible. Actual throughput on a data channel is dependent in a non-trivial manner on the queue configuration of the station, the queue servicing policy and the arrival rate of data packets for each destination channel. If a station can not make use of its preassigned slots due to lack of data packets, or possibly due to head of line blocking in one of its packet queues then capacity is wasted. As described by [SBD93], channel throughput becomes degraded as the station-to-channel ratio decreases due to each channel having a data slot preallocated to each station in the network. As the number of channels increases the probability of a station being able to use all

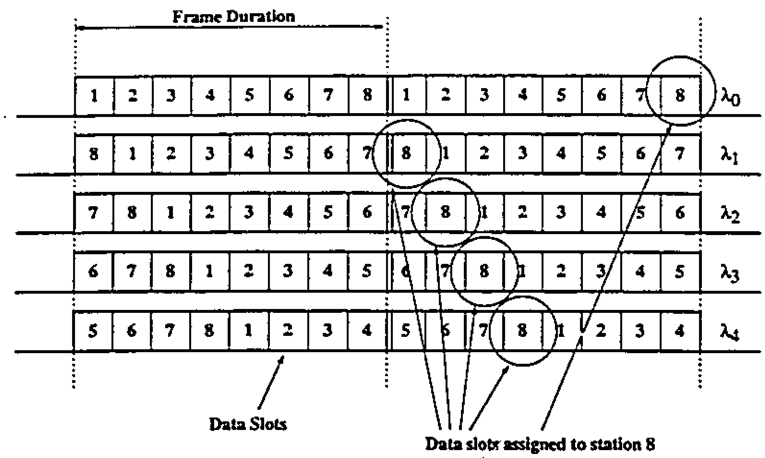

Figure 3.3: Data channel frame format for a collisionless medium access protocol without a control channel

of its slots on all of the channels decreases dramatically. An extreme limit occurs when only a single station is assigned to receive from each data channel, and every station has a preassigned data slot on each channel. This network is typical of other collisionless multichannel multiaccess networks without a control channel. All are characterized by a limited number of transmitters and receivers per station and no mechanism for exchanging signaling information. Channel throughput is traded off for a simple medium access protocol.

The network proposed by [GG92] introduces dynamic bandwidth allocation by using a system controller. Rather than use static time slots assignments for a station, the controller periodically determines and distributes optimal time-wavelength assignments for the stations based on station-to-station traffic patterns. Using the schedules, each station transmits packets on the specified destination channel at the specified time. The network proposed by [SGK92] did not use a dedicated wavelength channel as a control channel, however it did use control and status information time multiplexed onto each data channel to exchange signaling information among the stations. Using these multiple time multiplexed control channels a dynamic reservation medium access protocol is implemented. As a consequence, the network is able to reduce the number of optical devices to the minimum of a single discrete tunable transmitter and a single fixed tuned receiver per station.

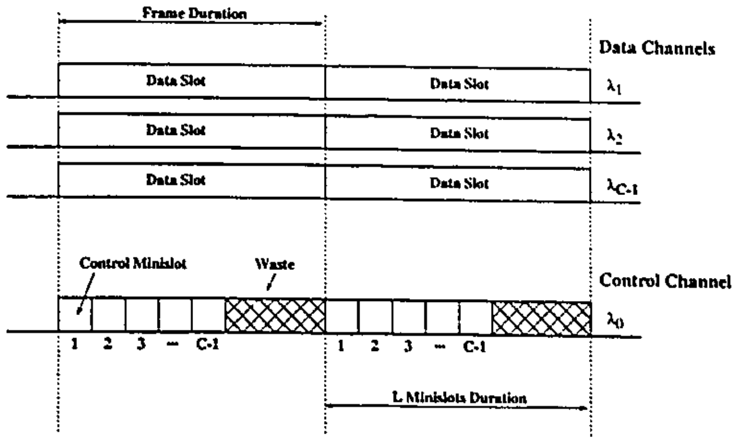

Figure 3.4: Control and Data Channel Formats for a collisionless medium access protocol

Almost all networks with a dynamic collisionless medium access protocol incorporate a dedicated control channel to exchange signaling information and coordinate data slot transmission. A representative collisionless multichannel network is described by [CZA92]. The network consists of a single fully broadcast passive star with N stations and C wavelength channels. One channel λ_0 is designated as the control channel while λ_1 through λ_{C-1} are the data channels. The network is constrained to have number of stations equal to the number of data channels, $N = C - 1$. Each station is configured with a single fast discrete tunable receiver, tunable over the full range of channels and a single fixed tuned transmitter, tuned to is own dedicated data channel. In addition, each station has a second fixed transmitter and a second fixed receiver for use on the control channel. A station is configured with a separate packet queue for each channel. The data channels are overlaid by a time multiplexed frame structure consisting of a single data slot per frame, while the control channel has a time multiplexed frame structure consisting of a number of control minislots, each station is preassigned the use of a dedicated control minislot. This is illustrated by figure 3.4. The duration of a control frame is constrained not to exceed the duration of a data slot. The proposed medium access protocol is referred to as the Dynamic Allocation Scheme, or DAS. Using this protocol a station selects which queue to transmit from and where to tune its receiver for each frame with a scheduling algorithm executed simultaneously at each station. Algorithm execution requires that each station know the state of the N packet queues of all other stations in the network, for a total of N^2 queues, by using status information from the control minislots. The algorithm, as executed simultaneously and identically by each station is summarized as follows. A station i is selected at random in the range $1 \leq i \leq N$. From the non-empty queues at station i a queue r is selected at random. The queue r is used as the source for transmission by station i in the next slot on its dedicated channel. Since all stations execute the identical algorithm using the same random number generator seed station r also tunes its receiver to the transmit channel used by station i. The algorithm is then repeated. A station j is randomly selected from among the remaining stations in the range $1 \leq j \leq N$ such that $j \neq i$. From the non-empty queues at station j a queue s is chosen such that $s \neq r$, since a station only has a single tunable receiver. This process is repeated until all receivers are allocated. Data channel capacity is expected to be high since a single control channel is used and very little overhead exists on the data channels. Due to the dynamic behavior of the medium access protocol it is also expected that a large percentage of the capacity can be used under many traffic loading conditions.

This protocol highlights three problems with multichannel reservation protocols. Large volumes of state information, heavy processing loads for each frame and control channel congestion. The heavy processing load experienced per frame is a result of a single data slot per frame and the decentralized nature of the protocol. The SP2 protocol of [SGK92] used multiple data slots per frame to relax processing constraints, while another [CY92] introduced a level of centralized control in the form of a scheduler to offload station reservation processing. Control channel congestion is also a result of a single data slot per frame. This places a limit on minimum data slot size for a given number of channels. As an example, assume that 16 bits are required to report the state of each queue at a station and 100 bits of guard time plus preamble are required between control minislots and between data slots. Control frame duration in bits can be calculated as

$$t_f = (16 \times (C-1) + 100) \times (C-1). \tag{3.5}$$

This results in a minimum data frame duration of t_f = 2196 bits for a ten channel network, t_f = 7676 bits for a twenty channel network and t_f = 166716 bits for a one hundred channel network. If the network is used to transport 53 byte (424 bit) ATM cells then control channel congestion occurs, and either data channel capacity is wasted or multiple ATM cells from the same source must be transported per data slot.

The large volume of state information is a result of medium access protocol dependence on every station tracking the state of the entire network. In [KFG94a] the problem of control information volume is addressed, and a modification made to the DAS protocol which allows only a subset of stations to transmit queue backlog information in each control frame. The different subsets of stations time share access to the control channel minislots.

3.2 Networks with Spatial Wavelength Reuse

Spatial wavelength reuse networks incorporate static wavelength routing to multiplex and demultiplex wavelength channels selectively. A majority of these networks use a multihop topology with data packets traveling from source to destination by passing through one or more intermediate stations incurring numerous optical-electronic and electronic-optical conversions. Recently, a number researchers have begun to investigate the possibility of incorporating spatial wavelength reuse into multichannel single hop networks since the number of available wavelength channels may not be as vast as first envisioned. Rather than broadcast all wavelength channels from each station in the network to all stations in the network, a partial broadcast and select topology is formed. A subset of stations receive data transmissions dependent on the location of the transmitting station and the wavelength channel used. In such a network, the total capacity is no longer a function of the number of channels, but rather a function of the number of channels and how many times each wavelength channel can be spatially reused.

Within the literature two classes are discussed, networks with hierarchical wavelength reuse [HWM94] [GL93] [DS94] [KFG94b] and those using non-hierarchical or

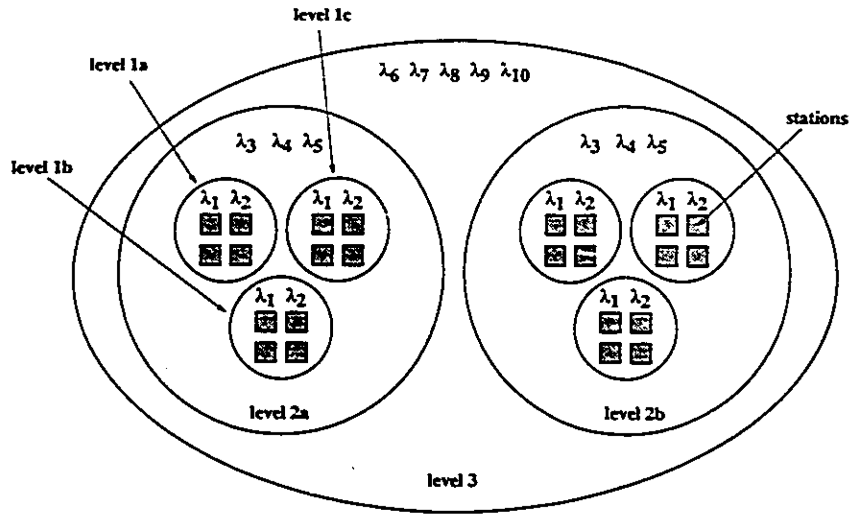

Figure 3.5: Hierarchical Spatial Wavelength Reuse using 10 channels and 3 levels

flat wavelength reuse [Mat93].

3.2.1 Hierarchical Wavelength Reuse

The general structure of networks with hierarchical wavelength reuse is created by dividing stations into L levels of clusters of stations. The total number of clusters in level i is N_i, and each is assigned Λ_i wavelength channels. This is illustrated by figure 3.5 for an $L = 3$ level network with $\Lambda_1 = 2$, $\Lambda_2 = 3$, $\Lambda_3 = 5$, $N_1 = 6$, $N_2 = 2$ and $N_3 = 1$. Stations within a cluster at level 1 communicate among themselves using wavelength channels λ_1 and λ_2, stations within level 2 communicate with any other station in the same level 2 using wavelength channels λ_3, λ_4 or λ_5 and any station in the network can communicate with any other station using wavelength channels λ_6 through λ_{10}. In this example with $C = 10$ wavelength channels, the total number of wavelength-spatial channels is

$$\begin{aligned} C_{total} &= \sum_{i=1}^{L} N_i \cdot \Lambda_i \\ &= 6 \cdot 2 + 2 \cdot 3 + 1 \cdot 5 = 23. \end{aligned} \tag{3.6}$$

The fully broadcast and select network is a special case when $L = 1$. Single hop connectivity is maintained provided that a station is configured with either three

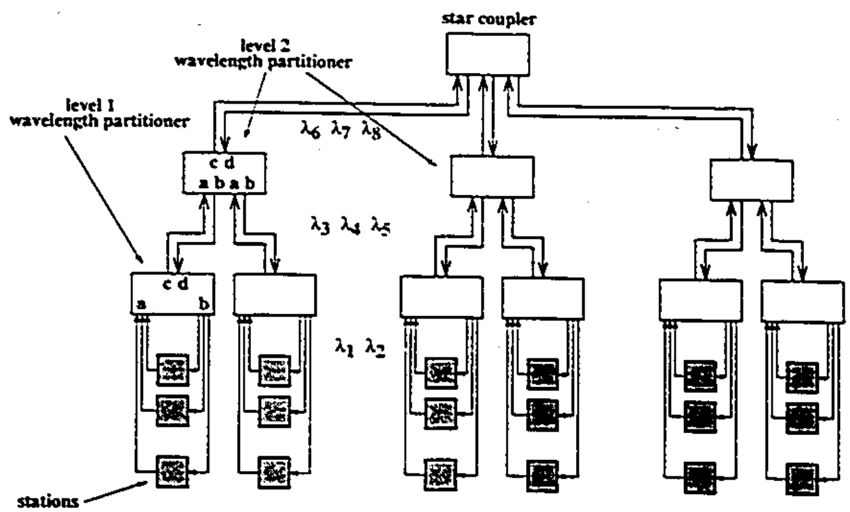

Figure 3.6: Hierarchical Network with 3 Levels

fixed receivers, one for each level or at least one tunable receiver.

A representative hierarchical wavelength reuse network, extendible to any number of levels is described by [DS94]. The physical layout of a three level network is constructed using static wavelength selective couplers, called wavelength partitioners, at each level. This is illustrated by figure 3.6. A wavelength partitioner routes wavelengths used within its level from input ports labeled *a* to the output ports labeled *b*, while wavelengths not used within the level are routed to a higher level through output port *c*. In addition, wavelengths from higher levels received on input port *d* are routed to output port *b*. The highest level wavelength partitioner, in this case level 3, is a passive star coupler. Each station is configured with three fixed receivers, one for reception of data packets from one wavelength in each of the three levels, and a single fast tunable transmitter. In the example, eight wavelengths are used with two assigned for level 1 communication, three assigned for level 2 communication and three for level 3 communication. The protocol uses a multichannel extension of static time division multiple access referred to as interleaved TDMA, or ITDMA. Each station in the network is preassigned a dedicated data slot on each wavelength channel. Channel capacity is expected to be close to 100% since no signaling information and very little overhead is required. Channel throughput is

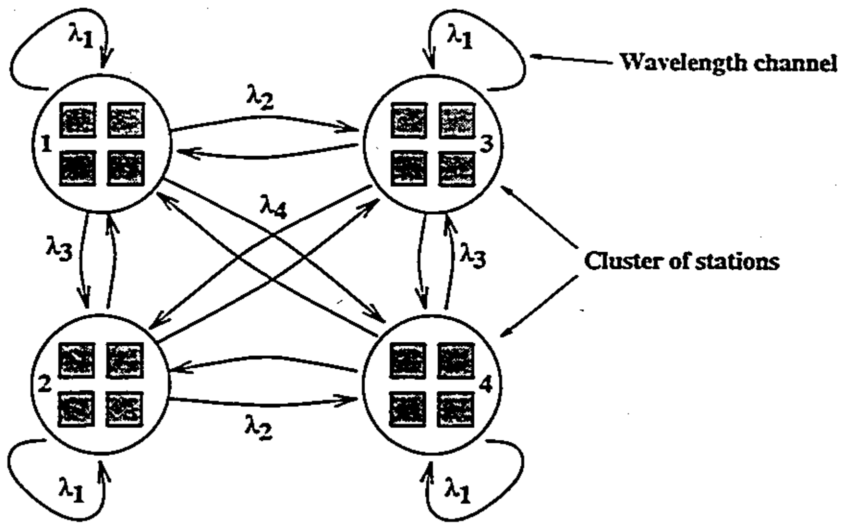

Figure 3.7: Flat Network with 4 Clusters and 4 Wavelength Channels

dependent on the packet queue configuration of a station, queue servicing algorithms and data packet generation rate at a station. The medium access protocol is simple, however it does not have the ability to dynamically allocate data slots. This may not be a very serious limitation on the level 1 channels since the number of stations is small, however on the level three channels the amount of bandwidth allocated to a station can be very small. As an example, assume ten stations in each level 1 cluster, four level 1 clusters in each level 2 group, and four level 2 groups in level 3. As a result there are forty stations per level 2 group and one hundred and sixty stations in the network. On a level 1 channel a station is allocated $\frac{1}{10}$ of the channel capacity, but only $\frac{1}{160}$ of the capacity on a level 3 channel.

3.2.2 Flat Wavelength Reuse

A network can provide wavelength spatial reuse with a non-hierarchical, or flat network topology. The general structure of this type of network is illustrated by figure 3.7. The figure shows a network with four clusters of stations using four wavelength channels, for a total of sixteen spatial-wavelength channels. Stations spatially reuse wavelength channel λ_1 for intra-cluster communication, while cluster 1 and cluster 2 communicate using wavelength λ_3 as do cluster 3 and cluster 4. A number of

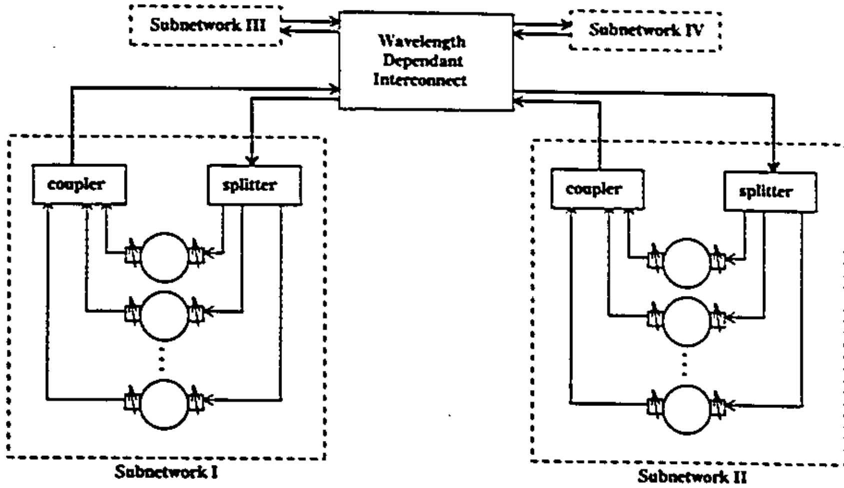

Figure 3.8: MANDALA Physical Network Architecture

features are evident from this figure. The destination cluster is uniquely selected by the wavelength and the source cluster of the transmission. A station in cluster 4 receives data packets from cluster 2 using wavelength λ_2. In the general case, multiple wavelength channels can be routed between source and destination cluster. Each station must have a fixed receiver for each wavelength channel, or a tunable receiver to maintain single hop connectivity.

A representative flat wavelength routed network, referred to as MANDALA is described by [Mat93]. The physical network topology is illustrated by figure 3.8. The network consists of C wavelength channels and N stations divided into subnetworks. One wavelength channel, λ_0 is dedicated as a global control channel. Each station is configured with a single tunable transmitter and a single tunable receiver. Within a subnetwork the data packets transmitted from all stations over all wavelength channels are passively combined and forwarded to a wavelength dependent interconnect, or WDIN. Packets received from the WDIN are passively split and sent to each station of each subnetwork. Internal structure for a five channel WDIN used to connect four subnetworks is illustrated by figure 3.9. Four wavelength channels, λ_1 through λ_4 are used for data packet transmission, while λ_0 is used as a global control channel. Stations in subnetwork I transmit exclusively to subnetwork I using λ_4, transmit to subnetworks I and II using wavelength λ_1, transmit to subnetworks III and I using

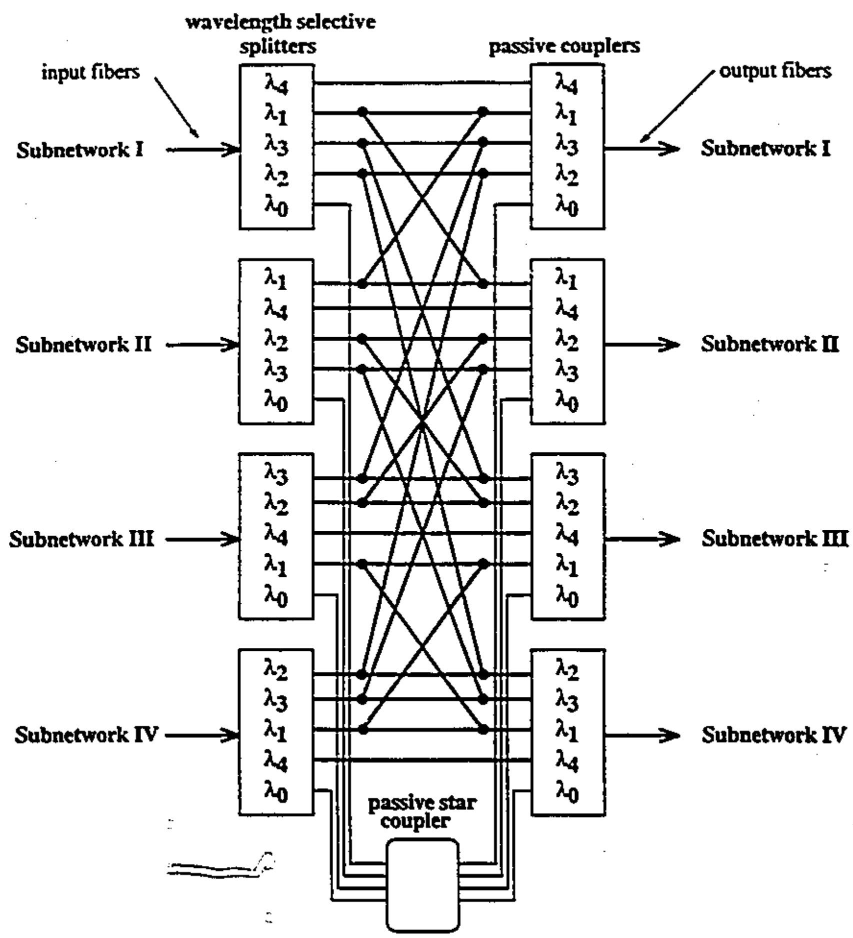

Figure 3.9: MANDALA Wavelength Dependent Interconnect

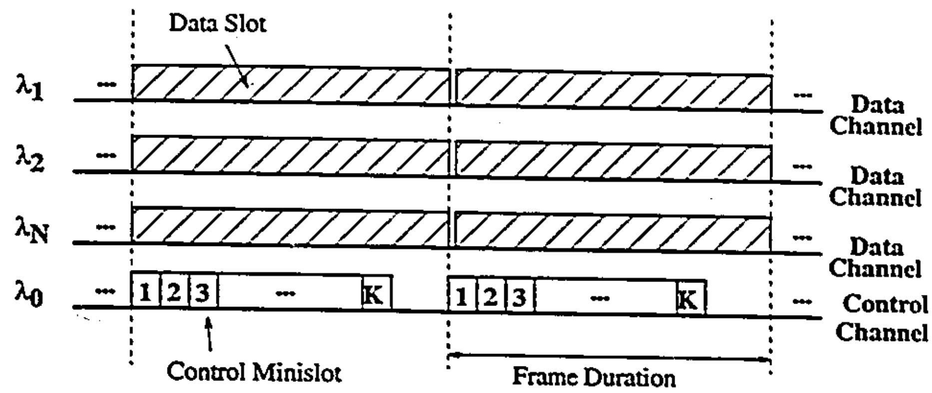

Figure 3.10: MANDALA Data and Control Channel Frame Formats

wavelength λ_3 and transmit to subnetworks IV and I using wavelength λ_2. Using this cross connect configuration, the total number of spatial-wavelength channels K created from C wavelength channels can be calculated as

$$K = \frac{(C-1)C}{2}. \tag{3.7}$$

A dynamic random access packet switched medium access protocol based on the aloha protocol is implemented. A repetitive and aligned time division multiplexed frame structure is imposed on the data and control channels, as illustrated by figure 3.10. A data channel frame consists of a single fixed sized data slot, while a control frame consists of K control minislots, one for each spatial-wavelength channel in the network. If a station i has a data packet to transmit to station j, it determines which cluster, and hence the spatial-wavelength channel k from which station j can receive data. Next, station i tunes its transmitter to the control channel and transmits control information, consisting of station j's address, into the control minislot for spatial-wavelength channel k using the aloha protocol. Finally, station i transmits the data packet onto spatial-wavelength channel k in the next frame. If two or more stations had a packet to send on channel k then a collision occurs in control minislot k and on the data channel, causing corruption of the packet and requiring a retransmission. To facilitate packet reception, idle stations tune their receivers to the control channel and monitor control minislots for an indication of packets addressed to themselves. When this occurs the station tunes its receiver to the intended channel and waits for packet reception.

Total network capacity is theoretically very high since no signaling information is placed onto data channels, spatial wavelength reuse occurs and only a single control channel is present. However, due to the random nature of the slotted aloha medium access protocol throughput is a fraction of total capacity. Assuming that a large number of stations have data to transmit to all spatial wavelength channels, the throughput on a channel is the same as that calculated for a single channel slotted aloha network by equation 3.1.

Limited receiver hardware causes two problems in this network. First, to ensure that the aloha protocol is not operated beyond the optimal point of 1 packet arrival per frame per channel a station must be able to sense the loading state of all data channels. Since a station only has a single receiver it can not continuously monitor the control channel. Second, receiver collision is a problem since a station can only receive a data packet from one channel, and hence one cluster at a time. As a result, successful packet transmission does not guarantee successful packet reception.

3.3 Discussion

A number of specific single star and wavelength routed networks using multichannel multiaccess protocols found in the research literature have been described. The advantages of these multichannel networks are two fold. They allow a greater portion of the optical bandwidth to be exploited than is possible using single channel techniques, and they allow a large number of stations a high degree of dynamic connectivity as a result of transmitter and receiver tunability. However, complexities arise as a result of the multichannel multiaccess protocols used to control dynamic access by a large number of stations.

With regard to the number of optical transmitters and receivers at a station, two limiting cases occur. The first case provides each station with the maximum amount of optical hardware, each has C separate transmitters and C receivers, one for each wavelength channel, which allows simultaneous operation. However, this may not be practical due to device cost, space limitations and station processing requirements.

The second case provides each station with a minimal amount of optical hardware, each has either a single tunable transmitter and fixed receiver, or a single fixed transmitter and tunable receiver. As observed from the literature review, a reduction in the number of transmitters and receivers can require a complex medium access protocol and algorithms to track multichannel state information. As the number of transmitters and receivers per station are varied between these two limits tradeoffs in protocol complexity, capacity performance, access delay performance and ability to dynamically share bandwidth occur. The network described by [SGK91]consisted of stations with a single tunable receiver, a single fixed transmitter, and used a common control channel. A station was required to use the same receiver to monitor the control channel, monitor the success or failure of transmissions and receive data from other stations. With such limited receiver hardware, complex interactions and transmission blocking occurs between the transmission protocol and the reception protocol. If a station has data to transmit then it is blocked from receiving data, similarly, if a station is receiving data it is blocked from transmitting data. The use of a complex medium access protocol is required to supplement limited transmitter and receiver capability at the station. The collisionless network described by [SBD93]reduced station optical hardware to a minimum of a single tunable transmitter and a single fixed receiver. The tradeoff, however was an inability to have dynamic bandwidth utilization, the protocol operated using static time division multiple access. The collisionless network of [CZA92]adapted a control channel, required each station to have a single tunable transmitter and fixed receiver for data communication, along with an additional fixed transmitter and fixed receiver for control channel communication. Using the additional optical hardware and a more complex medium access protocol this network achieved dynamic bandwidth utilization, and demonstrated that a small increase in station hardware added a great deal of flexibility to the network. Using a network architecture proposed in chapter 4, a similar level of dynamic medium access protocol performance is captured while eliminating the additional control channel receiver and transmitter hardware.

Transmitter collision is a problem with single channel shared medium networks, and the multichannel environment serves to aggravate the situation. Transmitter collision occurs when two or more stations attempt to transmit onto the same wavelength channel during the same time interval, causing corruption of all information on the channel and rendering it unusable. In multichannel networks transmitter collision potentially occurs in systems using tunable transmitters, or in networks using multiple fixed transmitters with overlapping transmitter channel assignments. The medium access protocol must either avoid collisions, or retransmit packets after collision detection. As observed from the description of [SGK91]and [GK91], the ability of a station to detect collisions in a network using a multichannel random access protocol is severely limited by a reduced number of receivers, or limited receiver tunability. For example, if a station has a single fixed receiver and a single tunable transmitter then it is not possible to detect the occurrence of collisions on any channel except the channel to which its receiver is tuned.

Receiver collision is a problem unique to multichannel networks which rely on receiver tunability. If a station contains only a single tunable receiver, and two or more stations successfully transmit packets on different channels at the same time to the same destination station, then the receiving station can only receive one of the packets, the others are lost. If the protocol also relies on the single tunable receiver to receive coordination information from a control channel then the problem becomes more complex, since the receiving station can not be aware that a potential receiver collision exists and can not notify the transmitter. A number of multichannel networks are proposed as solutions to this problem [JM93b] [JM93a], however these rely on a great deal of state information tracking and processing by stations to resolve potential receiver collision modes. Networks with fixed receivers and tunable transmitters do not suffer from the problem of receiver collision.

In a multichannel network, tracking channel state information can cause difficulties. The amount of state information increases as the number of channels increases, and a station with limited receiver hardware may not be able to track the state of all channels.

Many proposed networks use a single shared control channel to coordinate packet transmission over a set of data channels. Networks with random access protocols have data channel throughput which is tightly coupled with control channel throughput, every station in the network must compete for control channel access causing it to become a bottleneck for data channel performance. Networks with collisionless reservation protocols require each station to be assigned control channel resources which can place a limit on the number of stations in the network, and degrade scalability [Mat93] [SGK91]. In the general case, the throughput of a network using a control channel is the minimum of the throughput achievable on the data channels and the control channel, this can be expressed as

$$S_T = \min(S_C, S_D), \tag{3.8}$$

where S_C is the throughput on the control channel, S_D is the aggregate throughput on the data channels and S_T is the network throughput. As an example, consider a network with a slotted aloha random access control channel using R control minislots per frame, D data slots per frame, C channels, and a large number of stations generating data packets uniformly to all data channels. The throughput of the network can be expressed as

$$S_T = \min(\frac{R}{e}, (C-1)\cdot D). \tag{3.9}$$

Where e is the base of the natural log. This indicates that the control channel is a bottleneck to data channel performance whenever

$$R < e\cdot(C-1)\cdot D. \tag{3.10}$$

Similarly, consider a network with a collision free reservation protocol, using R request minislots per frame, D data slots per frame, the ability to request up to N_{max} data slots per request, and stations generating data packets uniformly to all channels. Network throughput can be expressed as

$$S_T = \min(R\cdot N_{max}, (C-1)\cdot D). \tag{3.11}$$

This indicates that the control channel is only a bottleneck to data channel performance whenever

$$N_{max} < \frac{(C-1)\cdot D}{R}. \tag{3.12}$$

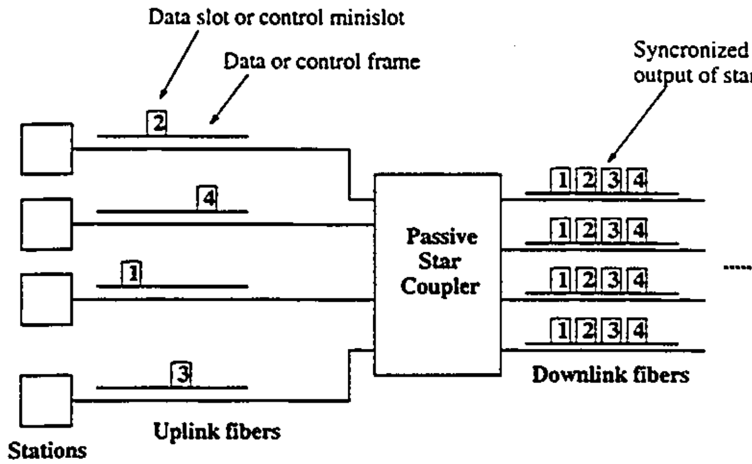

Figure 3.11: Data Slot Synchronization

A multichannel single star network using some form of time division multiplexing requires that stations have a mechanism to synchronize their control minislot and data slot transmissions. This is illustrated by figure 3.11 which shows an example of four stations transmitting on the same wavelength channel. Transmissions must be time synchronized such that interference does not occur at the passive star output. As a consequence stations must know their distance from the passive star and have a common global synchronization marker generated by a common reference clock. Further, synchronization must be maintained across all wavelength channels simultaneously. Procedures for achieving this level of synchronization are not clearly discussed by many network proposals. Some issues dealing with synchronization of slotted packet transmission in a multiwavelength network are discussed in [SH93].

In this chapter single star and wavelength routed optical network architectures from the research literature which are relevant to the material of this thesis have been discussed. As a result of this investigation the complexities associated with the design of multichannel single hop packet switched networks has been emphasized. In the next chapter a single star multichannel packet switched network with multiple time multiplexed control channels and a collision free reservation medium access protocol is presented. The network uses a set of channel controllers, one assigned to each wavelength channel as a solution to multichannel network design complexities. The channel controllers provide stations with synchronization information, assist with tracking channel state and assist stations with their multichannel medium access protocol. In later chapters the channel controller concept and reservation medium access protocols are applied to more complex wavelength routed networks incorporating both hierarchical and non-hierarchical wavelength spatial reuse.

Chapter 4

Distributed Channel Controller Network

An optical network architecture based on the fully broadcast and select single passive star topology is described and analyzed. The network, referred to as the Distributed Channel Controller Network, or DCCN is a collision free, single hop, packet switched network with a reservation multichannel multiaccess protocol. This work has previously been presented in the IEEE Journal of Lightwave Technology [JT94a] and in a number of IEEE conference proceedings [JT93b] and [JT93a].

The contributions of this work are the introduction of channel controllers and a reservation multichannel medium access protocol. By using channel controllers the complexities involved with multichannel multiaccess network design, as outlined in the literature review chapter are addressed and their effects limited.

The chapter is organized as follows. First, the physical and logical network architecture are described, then two variations of the reservation medium access protocol are presented. Next, a performance analysis of the network under various operating conditions is undertaken. Finally, a discussion of the benefits derived through the use of channel controllers is provided.

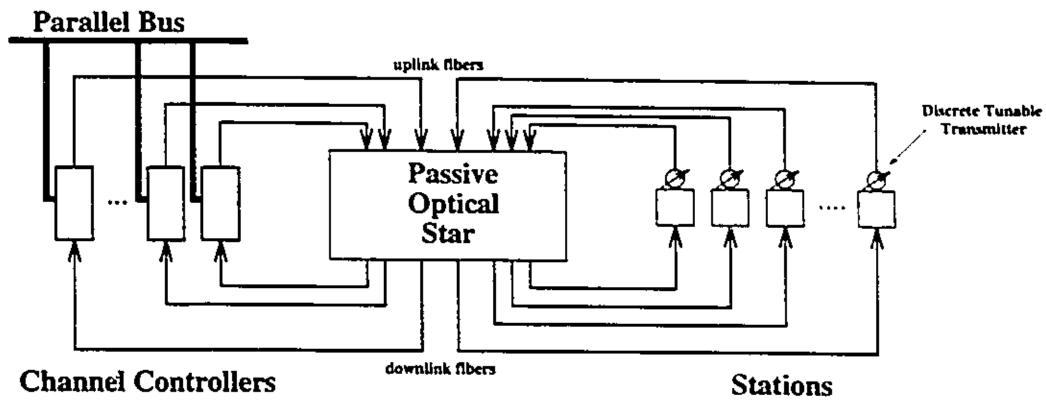

Figure 4.1: DCCN Physical Architecture

4.1 DCCN Network Architecture

The physical network architecture is based on the multichannel broadcast and select passive optical star topology. In such a network, N stations are connected to a central passive star coupler using a pair of optical fibers, an input or uplink fiber and an output or downlink fiber. Wavelength division multiplexing is used to provide C distinct wavelength channels, effectively creating C parallel fully broadcast and select networks each operating using its own wavelength channel. Since it is expected that WDM technology will provide only a modest number of wavelength channels, the case of the number of stations much greater than the number of wavelength channels is considered. In addition to the set of stations the DCCN uses a set of channel controllers, each connected to the central passive star coupler using an uplink and downlink fiber pair.

The basic DCCN architecture is illustrated by figure 4.1, each station contains a single fast discrete tunable transmitter, capable of tuning to all wavelength channels and a fixed or slow discrete tunable receiver. A discrete tunable device is one which is tunable to a set of specific wavelength channels, in contrast to a continuously tunable device which is able to transmit or receive on any wavelength carrier within its tunability range. Each station is preassigned a "home" channel to which it fix tunes its receiver. Once tuned to its assigned channel a station *never* re-tunes its receiver. A station uses its home channel to receive data from all other stations in the network, receive synchronization information from its home channel controller and to coordinate transmission to all stations on all wavelength channels.

Referring again to figure 4.1, each channel controller contains a single fixed or slow discrete tunable transmitter and a single fixed or slow discrete tunable receiver. One channel controller is assigned to control each wavelength channel in the network, to which it tunes its transmitter and receiver. Channel controllers are electronic processing units which provide synchronization information to their associated stations and assist stations with their medium access protocol. The set of channel controllers is physically co-located at a wiring hub location, and interconnected by a parallel backplane bus. It is important to note that the channel controllers do not use the backplane bus to switch data traffic, as may be the case in an electronic switch design, instead this bus is used to exchange configuration, clocking and status information. At this point it is beneficial to clarify some terminology. The channel controller assigned to a station's home channel is the "home channel controller" of the station and stations on a home channel are "associated" with the channel controller assigned to control their home channel. This terminology is used frequently throughout the remainder of the chapter.

The use of wavelength division multiplexing to divide the bandwidth of a physical fiber into a number of parallel channels prevents the physical network architecture from conveying the salient multichannel features of the network. In this case a virtual network topology, or logical architecture provides a better illustration. The DCCN logical architecture is illustrated by figure 4.2. This shows a number of parallel broadcast channels, a set of C channel controllers each communicating on their assigned channel, a set of N stations with receivers fixed tuned to their assigned home channel and station transmitters able to tune to any wavelength channel.

Thus far the channel configuration of the network has been discussed, attention is now focused on the data streams present on individual channels. Each wavelength channel has a repeating time division multiplexed (TDM) frame structure imposed on it consisting of overhead information and a fixed number of fixed sized data slots as illustrated by figure 4.3. The frame structure across all wavelength channels is required to maintain time alignment with reference to the output side of the passive

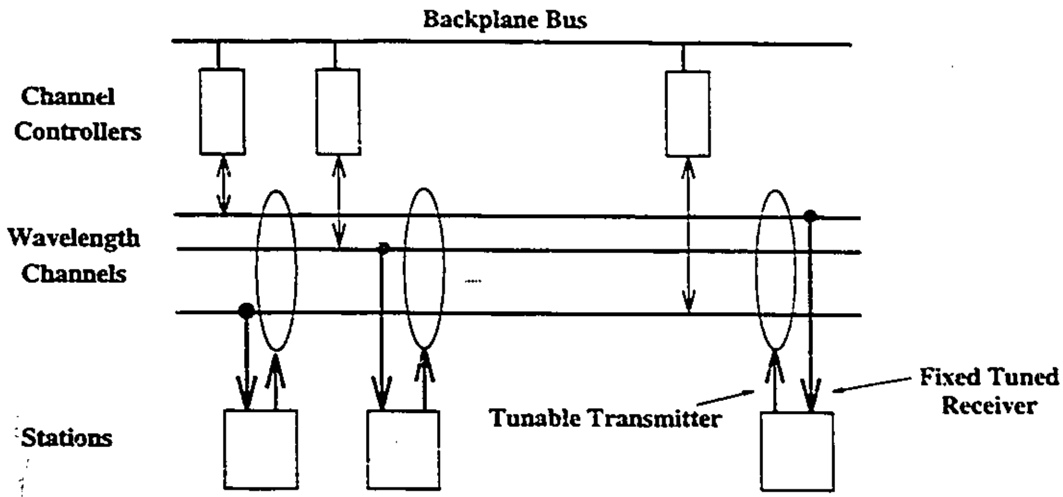

Figure 4.2: DCCN Logical Architecture

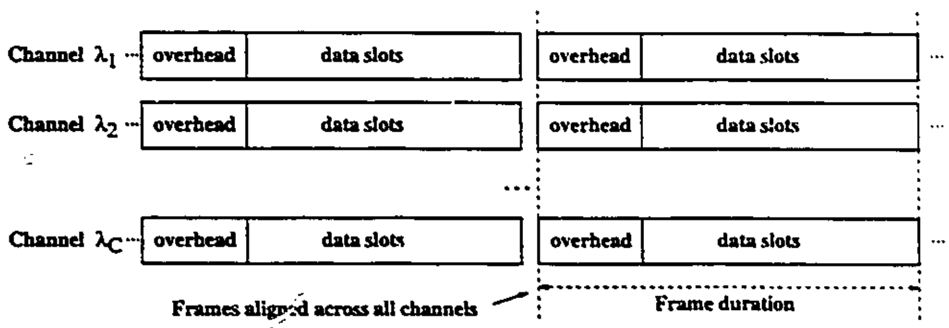

Figure 4.3: DCCN Frame Format

star, this constraint is necessary since a station synchronizes its data slot transmissions to any one of the wavelength channels by receiving synchronization information from only its home channel. The contents of the frame overhead are protocol dependent and discussed in a later section.

4.2 Network Operation

Network operation includes a description of the multichannel medium access protocol used by a station to transmit data onto an arbitrary data channel as well as a description of the channel controller functionality. A two level collision free reservation medium access protocol is used with the DCCN. The first level is referred to as the Inter-Channel Bandwidth Allocation (ICBA) protocol and provides course bandwidth assignment among the channel controllers using a movable boundary TDMA scheme. The second level provides a reservation medium access protocol which allows a station to gain access to individual data slots on any of the C channels. Two variations of the station medium access protocol are presented. A centralized version which places a majority of the protocol processing load on the channel controllers, and a decentralized version which places more protocol processing in the stations.

4.2.1 Inter-Channel Bandwidth Allocation Protocol

As previously described each channel has a repetitive and aligned frame structure with overhead and a fixed number of data slots. Each channel controller has domain over a single channel and allocates to each other channel controller in the network, including itself a contiguous block of data slots within each frame. These blocks of data slots are referred to as a slot block, and each channel controller is assigned a slot block on every channel in the network. Data slots within a particular channel controller's set of slot blocks are used exclusively by stations associated with that particular channel controller.

Slot block allocations can be either static or dynamic. With static allocation, block sizes are pre-configured and do not change, while with dynamic allocation block sizes can be updated as frequently as desired based on the detection of changing channel to channel traffic conditions. Investigation of mechanisms to determine optimal slot block assignments based on traffic flows was not a major part of this research and is not discussed any further.

An example of slot blocking on the data channels for a four channel network is provided by figure 4.4. Considering channel 3, the first block of slots is assigned to stations on home channel 1 that have data packets to transmit to stations on home channel 3. This is referred to as slot block B_{13}. Similarly the second slot block, B_{23} is allocated for access by stations on channel 2 with packets to transmit to stations on channel 3. It is important to note that station access to individual slots in blocks $B_{ik}, k \in \{1,\ldots,C\}$ is done independently using activity occuring solely

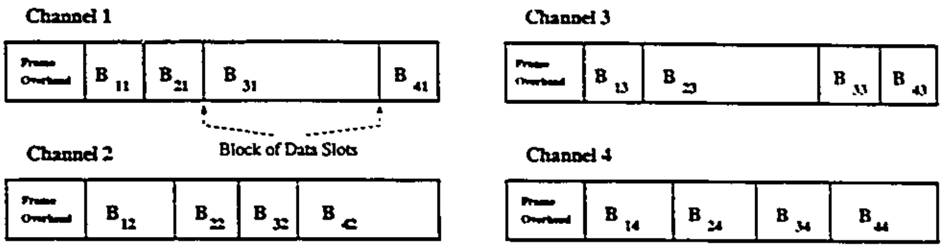

Figure 4.4: Example Inter-channel Block Allocation

on home channel i. The advantage of this arrangement is that contention for slots on a destination channel is restricted to those stations on the same source channel whose block allocation contains those slots, and the source channel controller is able to oversee all aspects of the station medium access protocol.

4.2.2 Station Medium Access Protocol

This level of the multichannel medium access protocol allows stations to communicate using fixed length packets referred to as data slots. Transmission occurs without pre-coordination or prior circuit setup between the source station and intended destination station. Transmission resources are assigned to stations on a demand basis, potentially increasing data channel throughput by preventing bandwidth waste from stations with bursty traffic characteristics. If a station is idle then other stations can utilize the channel bandwidth. Two variations of the protocol are presented: A centralized version which places a majority of the protocol processing load on the channel controllers and a decentralized version which places more protocol processing in the stations.

Using the centralized medium access protocol a station transmits slot requests to its home channel controller, waits for an allocation and then transmits one or more data slots based on the allocation received from the home channel controller. Before describing the interactions between a station and its home channel controller or the medium access protocol, detail of the frame structure, particularly the overhead portion is required. This is illustrated by figure 4.5. Each frame consists of

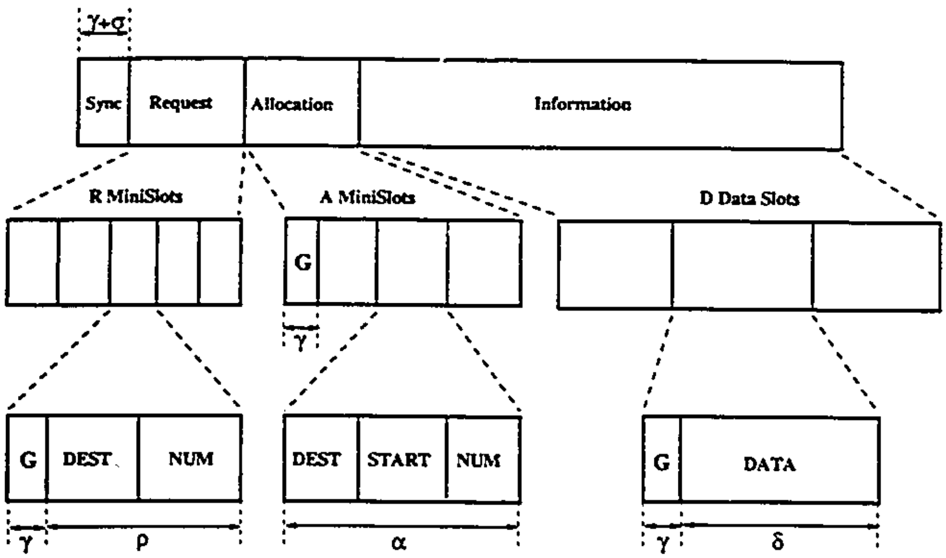

Figure 4.5: Centralized Frame Format

a synchronization subframe, a request subframe, an allocation subframe and an information subframe. The synchronization subframe is generated by each channel controller simultaneously at the start of a frame and is of duration σ time units. This is used by a station to acquire frame and slot timing for all channels directly from its home channel. Since channel controllers are co-located and interconnected via a bus this level of channel controller synchronization is realizable. Total synchronization subframe duration can be calculated as

$$t_{sync} = \gamma + \sigma. \tag{4.1}$$

The request subframe consists of R request minislots of duration ρ time units, one for each station assigned to the home channel. Request minislots are generated by stations and contain two fields. The DEST field indicates the destination channel for which a station wants to make data slot allocations and the NUM field indicates the number of data slots requested. Since a minislot is generated by a different station, each must be preceded by a guard time and preamble time, of duration γ time units to absorb timing errors and provide receiver bit synchronization. Total request subframe duration can be calculated as

$$t_{req} = R(\gamma + \rho). \tag{4.2}$$

The allocation subframe is generated by the channel controller associated with the channel and consists of A allocation minislots of duration α time units, one preassigned to each station associated with the channel. Since a station has its receiver fixed tuned to its home channel it is able to continuously monitor its assigned allocation minislot. Each contains three fields. The DEST field indicates the channel a station can transmit over in the next frame, the START field indicates into which data slot to begin transmission and the NUM field indicates how many contiguous data slots can be transmitted. The channel controller must precede the allocation subframe with a guard time plus preamble. Total allocation subframe duration can be calculated as

$$t_{alc} = \gamma + A\alpha. \tag{4.3}$$

Finally, the information subframe on each channel consists of D data slots of fixed size δ time units. Each data slot is preceded by a guard time plus preamble. Total information subframe duration can be calculated as

$$t_{info} = D(\gamma + \delta). \tag{4.4}$$

Time durations for all frame and subframe components are expressed in general time units; actual time duration can be calculated by choosing a bit rate for the channel and determining the number of bits required in a particular component. As an example consider a channel with a 1 Gigabit per second bitrate, 100 bits of guard time, 1000 bits of synchronization, 100 bits per request minislot, 100 bits per allocation minislot, 1000 bits per data slot, 50 request and allocation minislots per frame and 100 data slots per frame. The subframe component durations can be calculated as $\gamma = 0.1\mu s$, $\sigma = 1.0\mu s$, $\rho = 0.1\mu s$, $\alpha = 0.1\mu s$, and $\delta = 1.0\mu s$. Subframe durations can be calculated as $t_{sync} = 0.2\mu s$, $t_{req} = 10\mu s$, $t_{alc} = 5.1\mu s$, $t_{info} = 110\mu s$ for a total frame duration $t_f = 125.3\mu s$.

The centralized protocol is described by considering the transmit and receive sides separately. The receive protocol allows a station to receive data slots from any other station in the network. A station simply monitors all data slots on its home channel for those addressed to itself and copies them into its local receive buffer. In addition, once per frame a station monitors its preassigned allocation minislot and copies valid allocations into an allocation register. This is used by the transmit protocol and is required only to balance timing differences between the arrival of an allocation and transmission of data slots into the next frame. Reception protocol simplicity derives from the fact that a station operating in the DCCN does not use receiver tunability and a station is only required to track the state information within its own dedicated allocation minislot.

The inter-channel bandwidth allocation protocol ensures that stations on different home channels do not interfere with each other while transmitting data packets, the station level transmit protocol is responsible for transmitting data over an arbitrary channel without interfering with other stations on the same home channel. A station accomplishes this by tuning the transmitter to its home channel once per frame and then transmitting data slot requests into its preassigned request minislot. The station then examines the contents of the allocation register. If a valid entry exists then the station tunes its transmitter to the specified channel and transmits the specified number of data slots starting at the specified slot location within the frame. It is important to note that a minimum of a station-star-station propagation delay occurs between request transmission and allocation reception, however a station does not have to wait for matching allocations before transmitting additional requests.

From the above description it is evident that a station must re-tune its agile transmitter twice per frame, once to transmit requests and once to transmit data. When tuning to the home channel to make slot requests the worst case occurs if the station has been transmitting into the last data slot of a frame and has been assigned the first request minislot in the frame, this is illustrated by figure 4.6a. In this case the period of time available for re-tuning to the home channel is equal to the duration of the synchronization subframe t_{sync}. In situations where the minimum tune time of the transmitter is longer than this the duration of t_{sync} can be increased to absorb the timing difference. When tuning to a data channel the worst case occurs when the station with the last request minislot assignment is allocated the first data slot on the channel, this is illustrated by figure 4.6b. In this case the period of time for re-tuning is equal to the allocation subframe duration t_{alc}. Again, if this duration is too short then idle time can be added between the end of the allocation subframe and the start

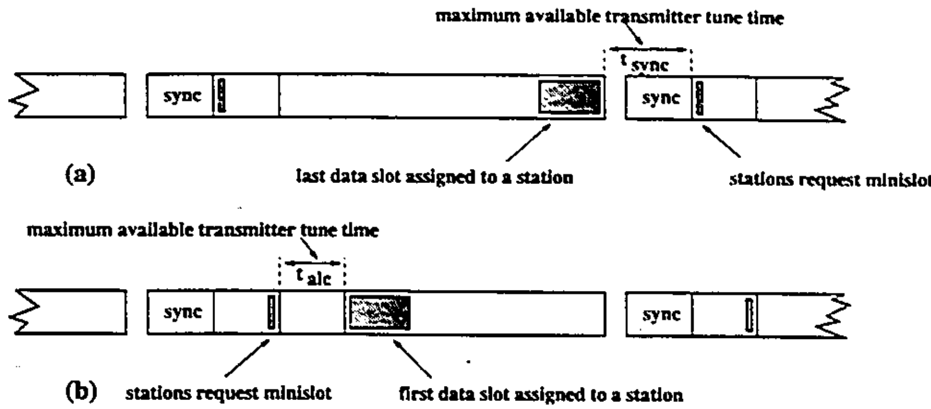

Figure 4.6: Worst case tuning scenarios for centralized DCCN

of the data subframe. This incurs only a single waste of tuning overhead per frame rather than a possible per slot waste if the transmitter is required to re-tune once per data slot.

Using the centralized station medium access protocol the simplicity of station operation is traded off at the expense of channel controller complexity. A channel controller must be able to accept requests continuously, and generate allocations for all stations on its channel once per frame. As validation that this is possible at high data rates, a high level channel controller design is provided which could be implemented using custom hardware. Figure 4.7 illustrates a block diagram of this request/allocation processing hardware. It consists of a request counter for each destination channel for each station. This is a total of $C \cdot N_C$ request counters per channel controller, where N_C is the maximum number of stations assigned to a home channel. A channel controller requires a single request processing unit, or RPU and one allocation processing unit, or APU for each destination channel. The RPU is responsible for receiving and processing incoming request minislots, this is achieved using the sequence of operations described by figure 4.8 after each request minislot has been received. In step 1 the RPU locates the proper request counter based on the relative location of the request minislot within the request subframe and the DEST field of the request minislot. In step 2 the RPU increments the request counter by the value specified by the NUM field of the request minislot. Even though a station

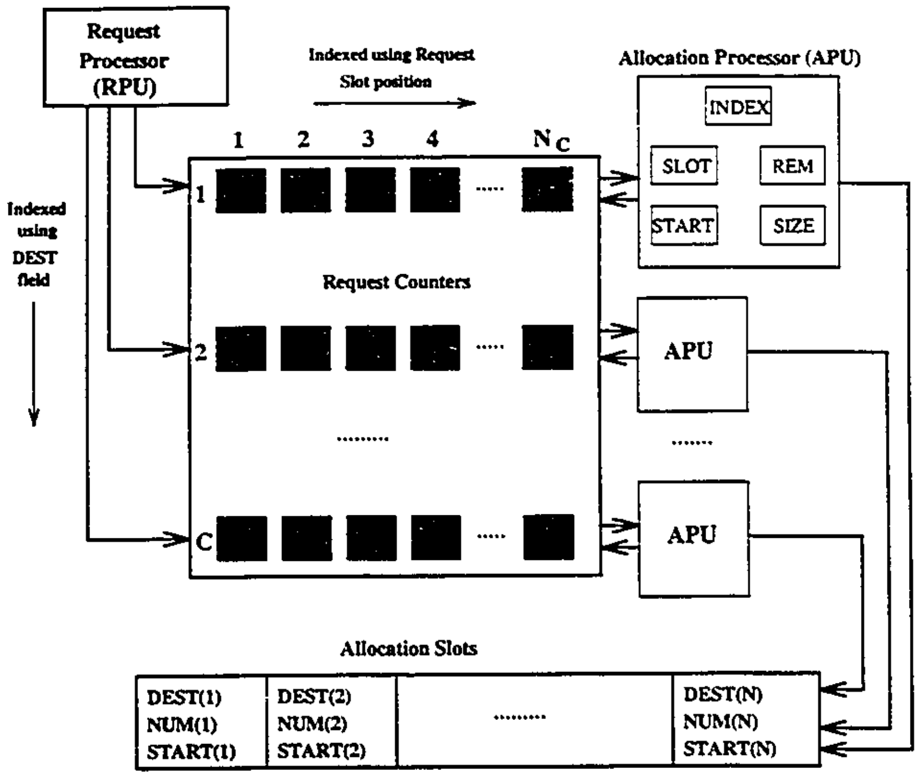

Figure 4.7: Centralized Channel Controller Block Diagram

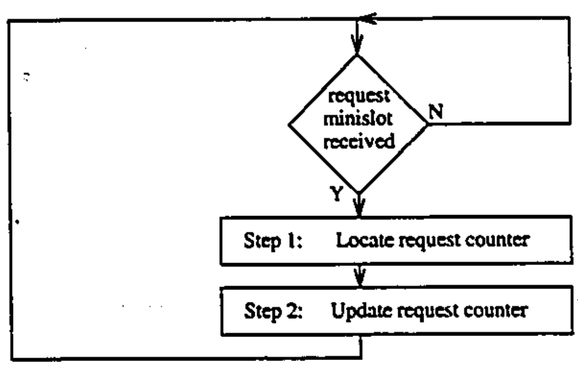

Figure 4.8: RPU Processing Steps

can have requests outstanding to any number of destination channels it can be active only on one channel at a time. The active channel is determined as the last channel to which a station made a slot request.

Once per frame the channel controller must generate and transmit an allocation subframe containing slot allocations. The allocations are based on the station request counters and the APU's. A single APU is dedicated to processing requests for one destination channel. Referring to figure 4.7, the operation of the APU is explained by considering it as a set of five registers and counters. The INDEX register indicates which request counter and allocation minislot to access. The START and SIZE registers indicate the start position and size, respectively of the data slot block on the destination channel for which the APU will generate allocations. As a side note, these are the two registers which are set/updated by the previously discussed Inter-Channel Block Allocation protocol. The REM counter indicates how many data slots remain to be allocated within the slot block for the current frame and the SLOT counter is used to hold the position of the next free data slot within the slot block. REM and SLOT are loaded with the contents of SIZE and START, respectively at the beginning of the allocation process for each frame. All APU's operate in parallel using the sequence of operations illustrated by figure 4.9. The variable VAL is a temporary variable required for the description of the allocation process. Step 1 occurs at the beginning of each frame and initializes variables used for the allocation process. The value of INDEX carries over from frame to frame and is initialized only once at channel controller power up time. After step 1 the APU checks to see if it has completed the allocation process. This occurs either when there are no data slots remaining for allocation ($REM = 0$) or if the total slots requested from all of the request counters from active stations associated with the APU are zero. Step 2 determines the number of slots which can be allocated to the current station, referenced by INDEX. The number of slots allocated to the station is the minimum of the number of slots remaining for allocation and the number of slots a station has accumulated in its request counter. If slots are required then step 3 updates the NUM, START and DEST fields of the current station. The APU also updates its own REM and SLOT counters to reflect the data slot allocations. Step 4 increments INDEX to the next

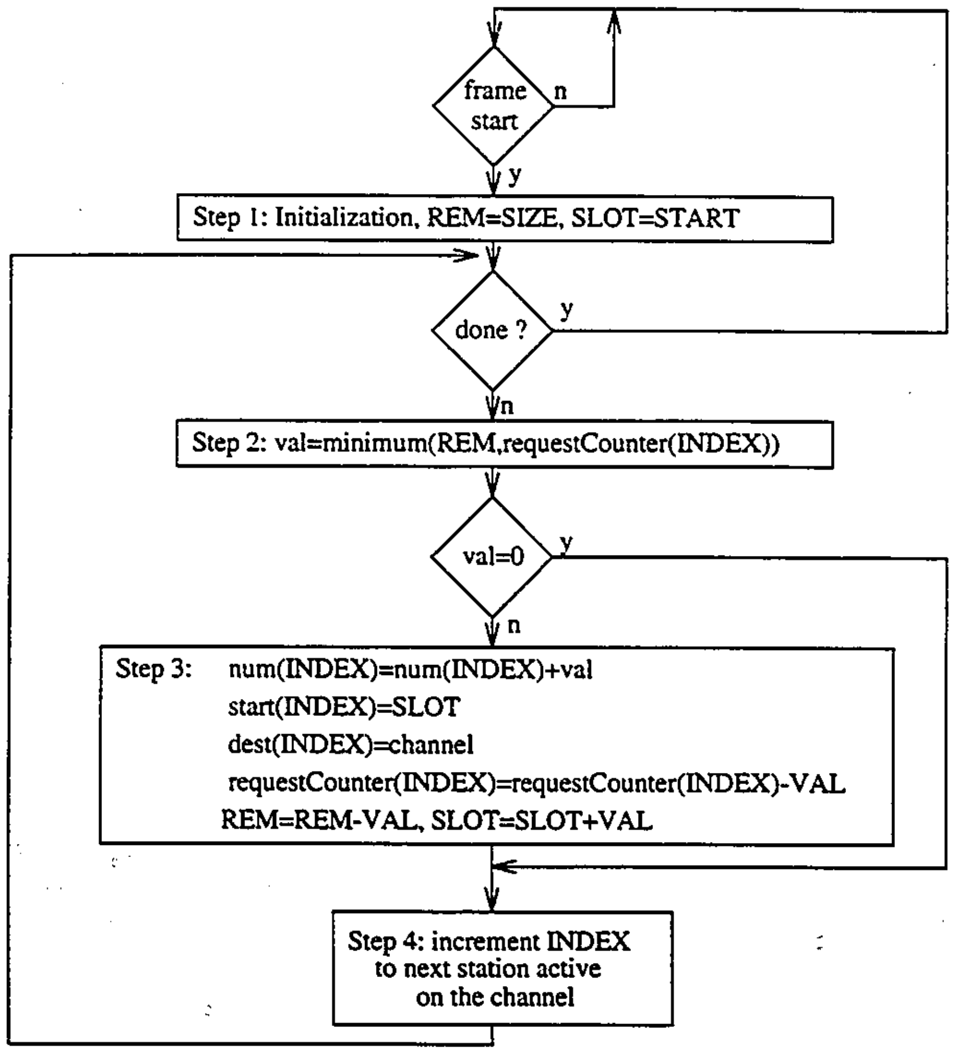

Figure 4.9: APU Processing Steps

station which is active on the channel with wrap around back to the first station if required. Although the preceding description for an APU is linear, a number of the operations can be performed in parallel.

In the design described above a delay is imposed between request generation and allocation reception at a station. Requests made in a particular frame are granted by the channel controller in the allocation subframe of a future frame. This is necessary to absorb large propagation delays between the station and channel controller relative to frame transmission times. A positive effect of this pipelining is that it drastically reduces the processing requirements for performing the scheduling computations at the channel controller. Under worst case conditions a channel controller must complete its slot allocations within a single frame period. Thus the actual rate of electronic processing at a channel controller may be quite low. As an example, assume a network diameter of 5km, a transmission rate of 1Gb/s, $C = 20$ channels, $D = 150$ data slots per frame, slots of 1000 bits in length including guard and preamble, allocation and request minislots of 100 bits in duration including guard and preamble and $N_C = 50$ stations per home channel. Frame duration can be calculated as

$$\begin{aligned} t_f &\approx \frac{(100N_C + 100N_C + 1000D)}{10^9} \\ &= 160\mu s. \end{aligned} \tag{4.5}$$

Referring again to figure 4.9 and remembering that much of the arithmetic can be performed in parallel an estimate of $N_{op} = 10$ operations is required to complete each loop of the APU allocation cycle which generates data slot allocations for a single station. If it is further assumed that all operations occur at a speed of $t_{op} = 100ns$ then APU computation time for $N_C = 50$ stations assigned to the channel controller can be calculated as

$$\begin{aligned} t_{apu} &= N_C \cdot N_{op} \cdot t_{op} \\ &= 50\mu s. \end{aligned} \tag{4.6}$$

Thus a duration of only $50\mu s$ is required for the allocation calculations. This value is far less than the maximum time requirement of a full frame period of $160\mu s$.

Next, consider a fully dynamic inter-channel bandwidth allocation mode of operation where channel controllers perform a complete reconfiguration of their slot block allocation each N_{update} frames. Slot block reconfiguration requires each channel controller to transmit its desired data slot requirements for each destination channel on the backplane bus for a total of C^2 transfers, perform the inter-channel block assignment algorithm and then transmit the slot block configuration for each channel controller over the backplane bus, another C^2 transfers. The total transfer rate over the back plane bus can be calculated as

$$t_{backplane} = \frac{2C^2}{t_f \cdot N_{update}}. \tag{4.7}$$

Thus, a network with a frame period of $t_f = 160\mu s$, $C = 20$ channels and an inter-channel bandwidth allocation reconfiguration interval of $N_{update} = 1$ frame requires a backplane transfer rate of

$$t_{backplane} = 5 \times 10^6 \tag{4.8}$$

transfers per second. Since only slowly varying inter-channel block allocation updates are envisioned, a much lower backplane transfer rate merely restricts the minimum updating interval to $N_{update} > 1$.

Using this design there is clearly no data slot switching at the channel controllers, each independently generates allocations for the stations on its home channel. This is very different from an electronic shared backplane switch where the backplane is a concentration point which must support the entire throughput of the switch. Also, the proposed design is much simpler in that shared data paths need not be provided in the hardware for switching purposes. It is also clear that constraining a station to be active on a single destination channel in a particular frame results in a very simple channel controller implementation.

A possibility not investigated is the ability of a channel controller to make allocations to multiple channels for the same station in the same frame, assuming that the station transmitters are capable of multiple transmitter tunings per frame. In this case the slot allocation process is no longer independent for each APU, a channel controller must ensure that a new allocation does not overlap in time with any previous allocations made to the same station. This coupling could result in a dramatic

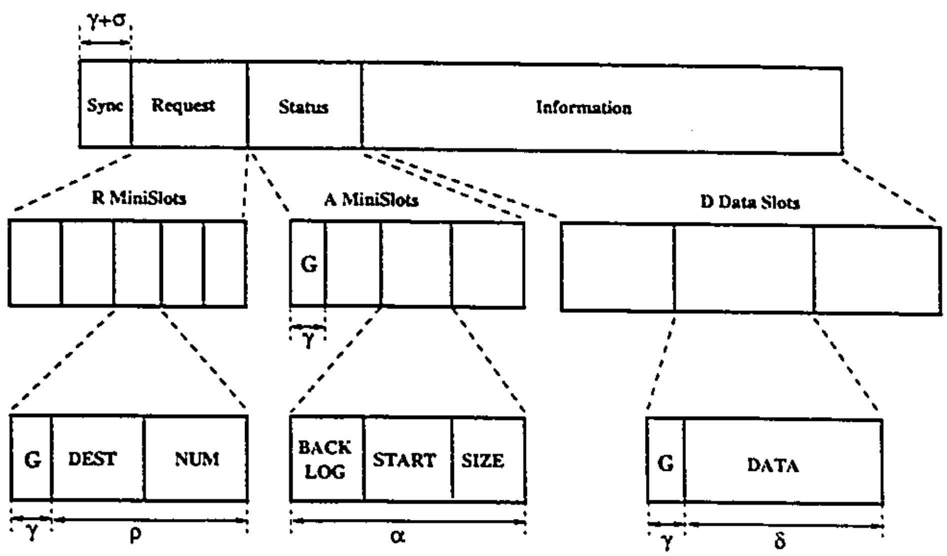

Figure 4.10: Decentralized Frame Format

increase in computation at the channel controller if an efficient allocation is desired with minimal slot wastage at a station due to overlapping allocations.

With the decentralized version of the station medium access protocol channel controllers only provide synchronization and channel status information to their associated stations. As with the centralized protocol the frame structure is presented and then station and channel controller functionality are described. Figure 4.10 illustrates the decentralized frame format. The synchronization, request and information subframes are identical to that previously described, while the allocation subframe is replaced by a status subframe. This is generated by the channel controller and consists of C status minislots of duration α time units. One status minislot is dedicated for each channel in the network. Each status minislot consists of three fields. The START and SIZE fields indicate the start and size, respectively of the slot block on the channel associated with the status minislot. The size and start of the slot block are determined by the Inter-Channel Bandwidth Allocation protocol. The BACKLOG field indicates the current total outstanding requests on the channel from all stations associated with the channel controller at the time the status minislot was generated by the channel controller.

The receive and transmit protocols are similar to those described for the centralized protocol and based on a multichannel extension of the distributed satellite packet access protocol proposed in[Rob73]. The primary difference between the centralized and decentralized protocols is that a station must determine its own slot allocations using the requests of other stations and the status minislot of the desired destination channel. To accomplish this a station builds a distributed queue consisting of time ordered entries indicating how many slots to let pass and how many slots to use for itself on the desired destination channel. The following protocol description assumes that a station is designed to communicate over a single destination channel in a given frame and is referred to as the active destination channel.

Three distinct phases of operation occur, the idle phase, the initialization phase and the utilization phase. During the idle phase a station has no data to transmit and does not participate in the medium access protocol. During the initialization phase a station selects a destination channel and initializes its distributed queue by waiting for the next status subframe and extracting the appropriate status minislot. The station then uses the START, SIZE and BACKLOG fields to initialize its distributed queue and allocation registers. A station is not able to make slot requests or transmit data onto the channel until it passes the initialization phase. During the utilization phase a station makes requests, generates its own allocations and transmits data.

As with the centralized protocol the transmitter and receiver parts are considered separately. For reception a station monitors its home channel for data slots addressed to itself, those addressed to the station are placed into a reception buffer. In addition all request minislots on the stations home channel are monitored for slot requests to its active destination channel. Using the request minislots the station accumulates three counts per frame, a count of the number of slot requests before its own request minislot, a count of the number of slots in its own request and a count of the total number of slots after its own request minislot. The values of these three counters are placed into the distributed queue and used by the transmitter to coordinate transmission.

For transmission a station must tune its transmitter twice per frame. First, the station tunes the transmitter to its home channel and transmit slot requests into its

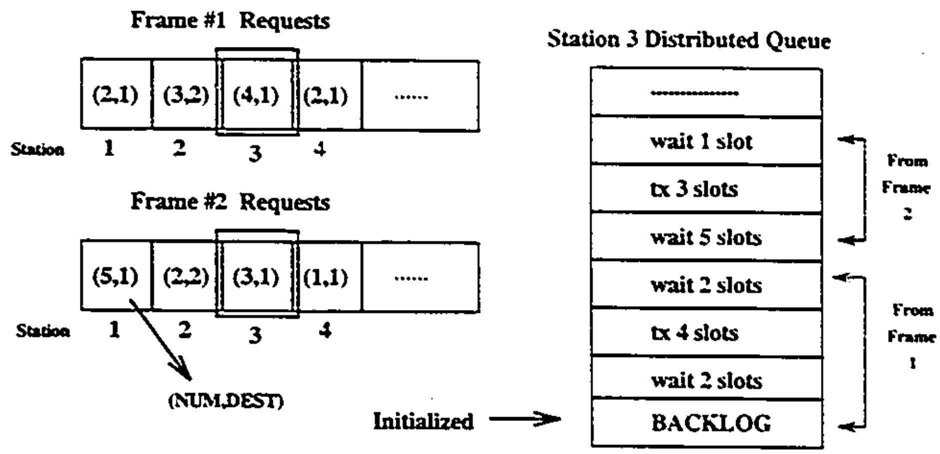

Figure 4.11: Decentralized Distributed Queue Example

dedicated request minislot. Second, the station tunes to its active destination channel and makes slot transmissions according to the entries in its distributed queue, allowing the proper number of slots to pass and transmitting into the slots assigned to itself. The same constrains on tuning times discussed for the centralized protocol apply to the decentralized protocol.

The mechanics of distributed queue management are demonstrated by figure 4.11. In the example, two channels are used and four stations are assigned to the home channel under observation, with detail for station 3 being provided. Station 3 decides that it wants to make channel 1 its active destination channel, therefore it initializes its distributed queue with the BACKLOG field for channel 1 as supplied by its home channel controller. The station then transmits its own slot requests for channel 1 and monitors request slots from all other stations for requests to channel 1. The first frame received by station 3 has station 1 requesting 2 slots on channel 1, this is entered into the queue of station 3. Station 3 next receives its own request for slots on channel 1 and enters this into its queue. Finally it receives the request from station 4 for 2 slots on channel 1 and this is entered into its queue. The same procedure is followed for the second frame, stations 1, 3 and 4 again make requests for slots on channel 1 which are entered into the queue of station 3. Not shown in the example is the removal of entries from the distributed queue. The maximum number of entries removed per frame is simply the number of data slots in the slot block of channel 1.

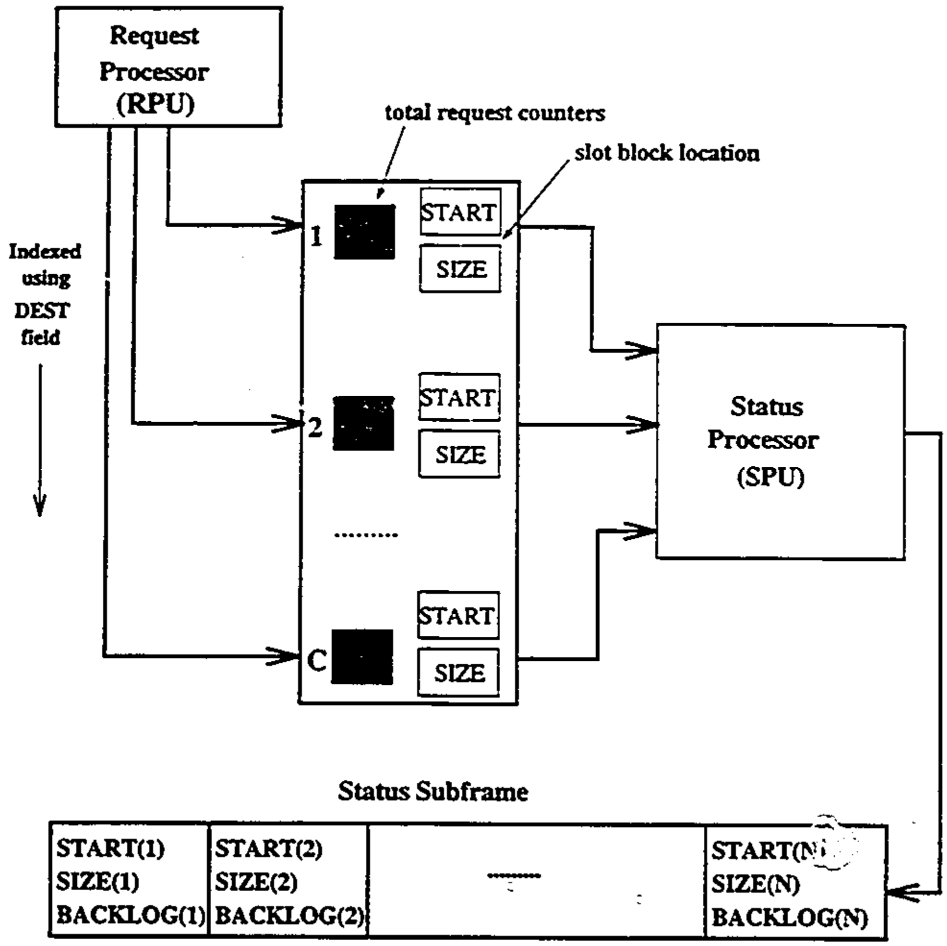

Figure 4.12: Decentralized Channel Controller Block Diagram

Data slots are allowed to go idle if fewer entries are in the queue.

The functionality of the channel controllers is illustrated by the block diagram of figure 4.12. Each channel controller consists of a single request processing unit, or RPU, a single status processing unit, or SPU and a backlog counter, a slot block start register and a slot block size register for each destination channel. The RPU differs from that of the centralized channel controller, it need only update a backlog counter for each destination channel rather than a request counter specific to each station and destination channel. The SPU is required to generate the status subframe once per frame period, it copies the contents of the backlog, start and size register for each destination channel and then decrements the backlog counter by the size of the slot block. The processing requirements of the channel controllers are greatly reduced at the expense of added station complexity.

4.3 Performance Analysis

The performance of the DCCN architecture using the centralized reservation medium access protocol is investigated, and where possible compared with other networks of similar hardware configuration. The performance measures of interest are capacity and delay-throughput under various network and traffic loading configurations. Table 4.1 provides a summary of symbols used in the quantitative analysis of performance.

σ	synchronization subframe duration
γ	guard time + preamble duration
α	allocation and status minislot duration
ρ	request minislot duration
δ	data slot duration
D	number of data slots per frame
C	number of wavelength channels
R	number of request minislots per frame
A	number of allocation minislots per frame
N_C	number of stations per home channel
N_T	total number of stations in the network
N_A	number of active stations on a home channel
L	ratio of data slot size to request minislot size
P	station-star propagation delay

Table 4.1: Symbols used for Performance Analysis

4.3.1 Capacity

The optimal situation in a communication network is the utilization of all available bandwidth for *useful* data transmission. However, due to the practical requirements for channel synchronization, guard times, preambles, error check sequences and signaling overhead a portion of the bandwidth is lost. Investigation as to how the number of channels, number of stations per channel and sizes of the various frame components affect channel capacity is performed. Channel capacity is defined as the ratio of bandwidth available for useful data transmission to the bandwidth of a full channel. Considering the repetitive frame format used in DCCN, the capacity of a data channel is calculated as the ratio of total data slot duration to total frame duration. For the centralized and decentralized medium access protocols this is calculated as

$$C_{DCCN_C} = \frac{\delta D}{\sigma + \gamma + (\rho + \gamma)R + \gamma + \alpha A + (\delta + \gamma)D} \tag{4.9}$$

$$C_{DCCN_D} = \frac{\delta D}{\sigma + \gamma + (\rho + \gamma)R + \gamma + \alpha C + (\delta + \gamma)D}. \tag{4.10}$$

These equations are exact, however the salient features are better observed if a number of assumptions are made. First, all parameters are normalized to the duration of a request minislot, therefore $\rho = 1$. Allocation minislots and status minislots are the same duration as a request minislot, therefore $\alpha = 1$. Assume that guard time plus preamble are taken into account by the request minislot duration, therefore $\gamma = 0$. Assume the duration of the synchronization subframe is negligible. The number of stations assigned to each home channel is identical and equal to $N_C = \lceil \frac{N_T}{C} \rceil$, as a result $A = R = N_C$ for centralized DCCN and $R = N_C$ for decentralized DCCN. Finally, define the ratio of data slot size to minislot size as $L = \frac{\delta}{\rho}$. The DCCN capacity equations can be re-written as

$$C_{DCCN_C} = \frac{LD}{2N_C + LD} \tag{4.11}$$

$$C_{DCCN_D} = \frac{LD}{N_C + C + LD}. \tag{4.12}$$

The capacity results are compared to several other networks with similar hardware requirements. This includes a network which uses a collision free reservation protocol, referred to as NET1 and two networks which use random access protocols, referred to as NET2 and NET3.

NET1 is a modified version of the SP2 protocol as described by [SGK92]. The protocol uses a single passive star coupler and each station requires a single fixed receiver and a single fast discrete tunable transmitter. As with DCCN, each wavelength channel is overlaid by a repetitive TDMA frame structure consisting of a control subframe with N_T minislots, one for each station in the network, an information subframe with $D \cdot C$ minislots and a data subframe consisting of D fixed sized data slots. Each station tunes its receiver to a fixed reception channel. To transmit a packet a station tunes to the desired channel and transmits a request into its dedicated request minislot. The station acquires transmit authority by examining the contents of the D information minislots on its own reception channel associated with the selected destination channel. When transmit authority is received the station transmits a data slot into the specified data slot on the destination channel. Data slot reception is achieved by examining the address of each data slot and copying those addressed to itself into a receive buffer. The original network allows only a single station to be assigned to each wavelength channel, however for comparison purposes with DCCN the SP2 protocol was modified to allow multiple stations per channel. This is achieved by allowing multiple stations to receive from the same channel and designating one station per channel to make the data slot reservations. Assuming a control and information minislot size of 1 time unit including guard time plus preamble, a relative data slot size of L time units and negligible synchronization duration, the capacity of a channel can be expressed as

$$C_{NET1} = \frac{DL}{N_T + DC + DL}. \tag{4.13}$$

NET2 is the random access RCA protocol as described by [JM93b]. The network consists of C channels and uses a dedicated random access control channel for signaling purposes. Each station is equipped with a single discrete tunable transmitter and a single discrete tunable receiver. Idle stations tune their receivers to the control channel and listen for transmit requests to themselves, when this occurs they tune to the desired channel and wait for packet reception. To transmit a packet, a station makes a transmission onto the control channel, determines if the transmission suffered a collision and then transmits onto the selected data channel. The capacity of a data channel is expressed as

$$C_{NET2} = (C-1)\left(1-\frac{1}{N_T}\right)^{N_T-1}\left(\frac{1}{C}\right)\frac{1}{1+r/N_T(1-1/N_T)^{N_T-1}} \quad (4.14)$$

$$r = C-1+\frac{T(C-1)}{L}, \quad (4.15)$$

where T is the receiver tuning time expressed relative to that of a control minislot. This equation is modified from the original to include overhead from the dedicated control channel in the capacity of each data channel.

NET3 is the improved case 4 protocol described by [SGK91]. This network and protocol were discussed in the literature review chapter as a random access network which used a control channel. The capacity of a data channel is expressed as

$$C_{NET3} = \left(\frac{GX}{C-1}e^{-G}\right)\left(\frac{(C-1)}{C}\right)\left(1-\frac{G}{C-1}e^{-G}\right)^{X-1}\left(\frac{L}{X}\right), \; X > L \quad (4.16)$$

$$= \left(\frac{GX}{C-1}e^{-G}\right)\left(\frac{(C-1)}{C}\right)\left(1-\frac{G}{C-1}e^{-G}\right)^{X-1}, \; X \leq L, \quad (4.17)$$

where X is the number of control minislots on the control channel. A numerical technique was used to determine the offered load G which produced the maximum throughput, and this value is used as the capacity in comparison with DCCN. This equation is also modified from the original to include overhead due to a dedicated control channel.

Figures 4.13 through 4.18 illustrate the channel capacity limit of the centralized DCCN network plotted against the total number of stations in the network for various network configurations. Capacity results were generated under the following conditions. For the random access protocols of NET2 and NET3 it was assumed that a large number of stations were competing for access to each channel and that loading conditions were maintained such that maximum utilization was made of the data slots. Networks which used a dedicated control channel, NET2 and NET3 had the overhead due to the control channel folded into the channel capacity value.

Figure 4.13 is plotted for the case of 10 channels, figure 4.14 for 20 channels and figure 4.15 for 40 channels. In all cases the relative data slot size was fixed at $L = 20$. A set of curves was plotted for $D = 100$ and $D = 25$ data slots per frame for the

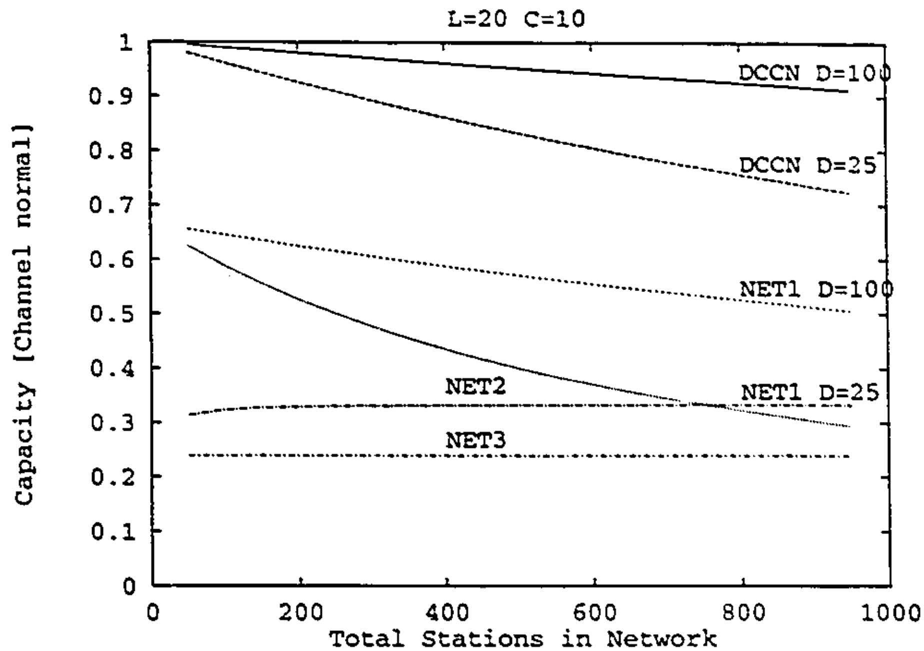

Figure 4.13: Capacity comparisons of DCCN, NET1, NET2 and NET3 for $C = 10$ channels and a relative data slots size of $L = 20$

frame based protocols of DCCN and NET1. As expected, the networks which used random medium access protocols had generally lower per channel capacity than those networks which used collision free reservation protocols. However, the capacity of the request protocols degrades as the number of stations in the network increases due to their requirement for request signaling resources, while the random protocols reach a limit which is invariant with the number of stations per channel. In addition, the effect of increasing the number of channels in the network is observed from these plots. The capacity of centralized DCCN increases due to a reduction in per channel overhead as a consequence of the stations being spread across more home channels. The exact opposite effect is observed with the NET1 reservation protocol since a substantial decrease in per channel throughput occurs as a result of each channel requiring overhead on every channel for signaling. An extreme limit is demonstrated for the case of $C = 40$ channels, where NET1 capacity falls below that of the NET2 random access protocol.

The effect of changing the relative data slot size is illustrated by figures 4.16

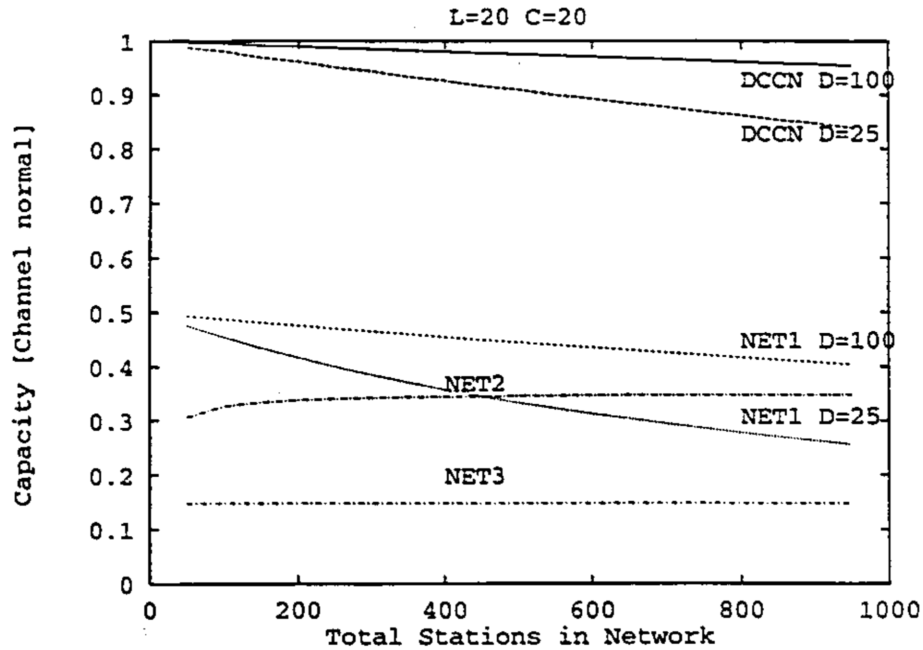

Figure 4.14: Capacity comparisons of DCCN, NET1, NET2 and NET3 for $C = 20$ channels and a relative data slots size of $L = 20$

through 4.18. As the data slot size increases, reservation protocols which include signaling information on the data channels show an increase in capacity due to a relative decrease in signaling overhead. Figure 4.18 illustrates an extreme case of a very small data slot size relative to a request signaling minislot. The capacity of the two reservation protocols degrades rapidly as the number of stations in the network increases. Again, the capacity of reservation protocol NET1 falls below that of both random access protocols for $D = 25$ data slots per frame.

4.3.2 Delay-Throughput

The second performance metric of interest is the average delay experienced between the time of packet generation at a station and the time the data packet begins transmission. Results were generated primarily through the use of a custom designed network simulator since construction of an actual experimental optical network was impossible. Network simulation is an appealing choice since a digital computer is

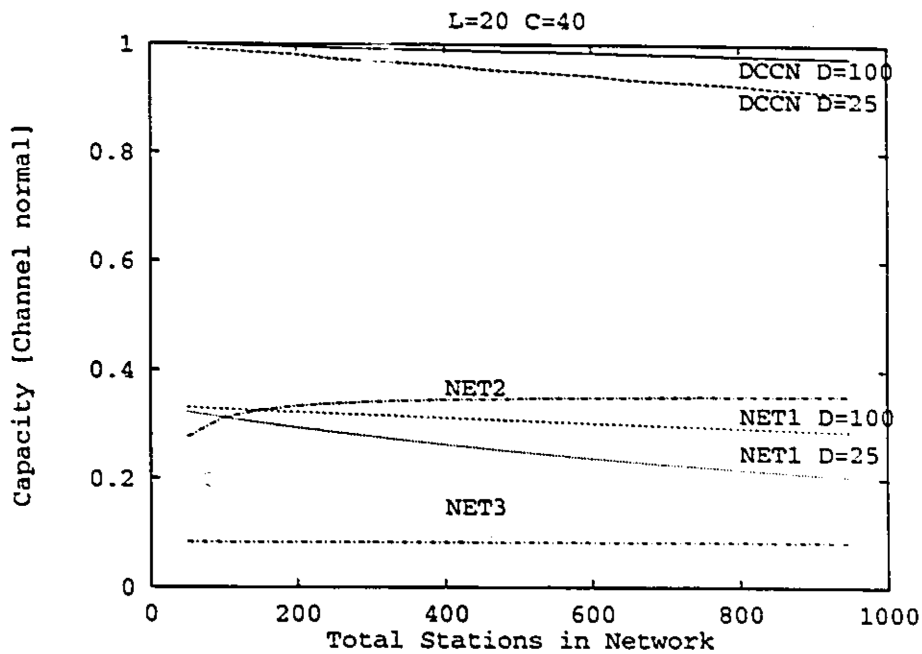

Figure 4.15: Capacity comparisons of DCCN, NET1, NET2 and NET3 for $C = 40$ channels and a relative data slots size of $L = 20$

easily capable of simulating the dynamics of a digital communication network under almost any configuration. For details of continuous time discrete event simulation see [Abu88]. Queuing theoretic models were also used as a source of mean delay results, however due to the mathematical complexity and limited scope of application of these models the queue theory results were used only as a validation for the network simulator.

Performance evaluation of a full DCCN system under arbitrary traffic loading and network configuration is a reasonably complex undertaking, therefore a subset of a full network was used for delay-throughput experiments. Figure 4.19 illustrates graphically the subset of DCCN under analysis. The activity of a single home channel i and the interaction between the stations associated with this channel and the channel controller are considered. Among the N_C stations associated with channel i a subset N_A actively generate data packets to the C wavelength channels, the remaining $N_C - N_A$ stations are idle.

Experiments were performed with two packet generation scenarios. In the first

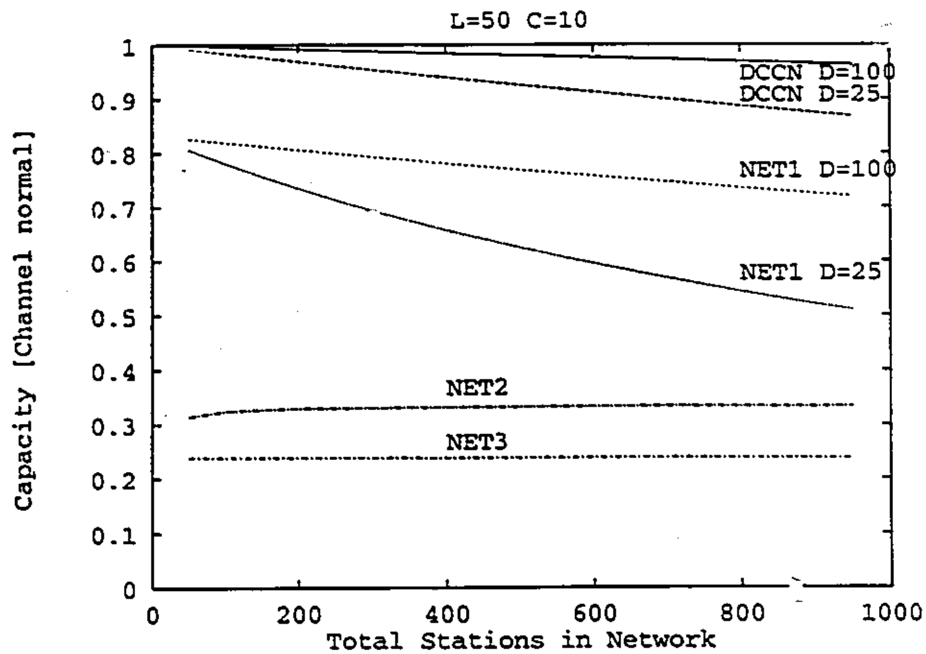

Figure 4.16: Capacity comparisons of DCCN, NET1, NET2 and NET3 for $C = 10$ channels and a relative data slots size of $L = 50$

case the set of active stations generate packets destined for a single destination channel k. This allows the dynamics of the medium access protocol and station to channel controller interaction to be investigated without making assumptions regarding the station model. In the second case a more general packet generation scenario was considered, the set of active stations generated packets to a subset of the available channels. This required the specification of a station model and allowed the dynamics of communication over multiple channels to be investigated. Each station is equipped with C transmit queues, one for packets to each destination channel. A station transmits packets from a single queue either until it is empty or until the queue has been serviced for some preset maximum number of frames. A round robin technique is used to select the next non-empty queue as the source of packets. For all experiments of both scenarios it is assumed that the Inter-Channel Bandwidth Allocations remain fixed, therefore the slot block allocation on channel j for stations on channel i, B_{ij}, for $j = \{1 \ldots C\}$ remain constant.

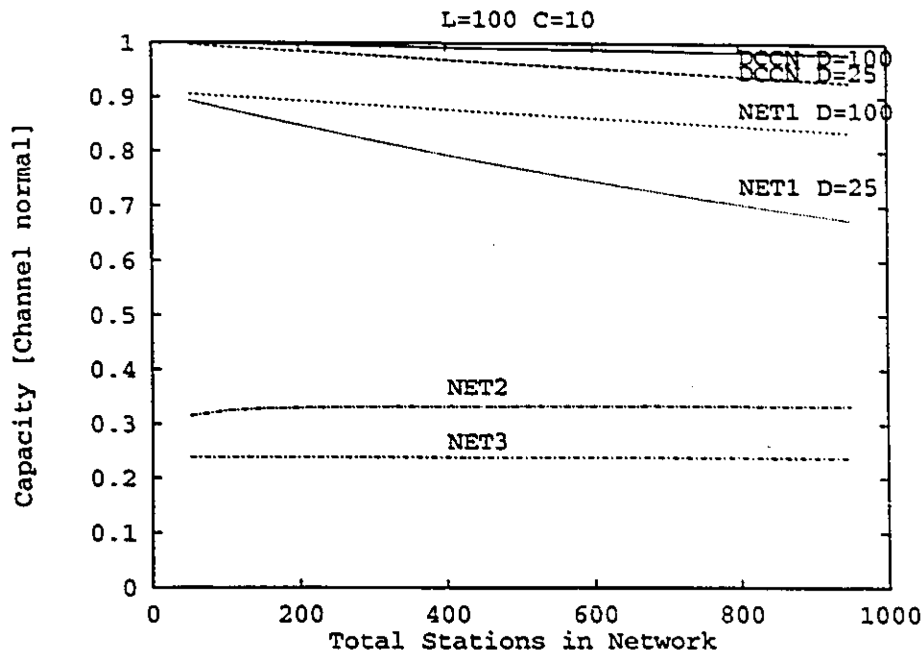

Figure 4.17: Capacity comparisons of DCCN, NET1, NET2 and NET3 for $C = 10$ channels and a relative data slots size of $L = 100$

The queuing theory model was developed only for packets generated to a single destination channel using the following assumptions. All stations have identical packet generation rates based on a Poisson distribution, with packet length equal to one data slot. The total traffic is modeled as generated by a single station with an aggregate traffic generation rate equal to the sum of the individual station packet arrival rates. All traffic is modeled as passing through a single queue located at the passive star. Due to the request nature of the protocol and the contiguous block of data slots allocated on the destination channel, packet departures are modeled as arising from a single server. The server removes a block of data slots from the queue at deterministic periodic intervals of a frame duration. Complete theoretical delay equations for this model are derived in appendix A, with the average packet access delay result expressed as

$$\overline{d} = 2P + 2t_f - (2P) \bmod t_f + \overline{m}t_f, \tag{4.18}$$

where $\overline{m}$ is the average number of frames a stations request remains queued at its

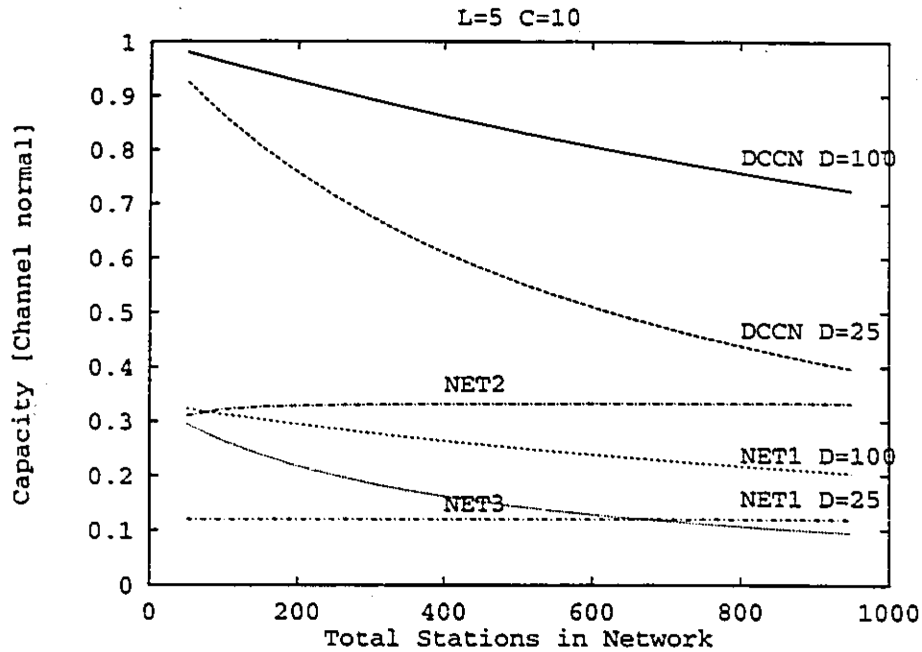

Figure 4.18: Capacity comparisons of DCCN, NET1, NET2 and NET3 for $C = 10$ channels and a relative data slots size of $L = 5$

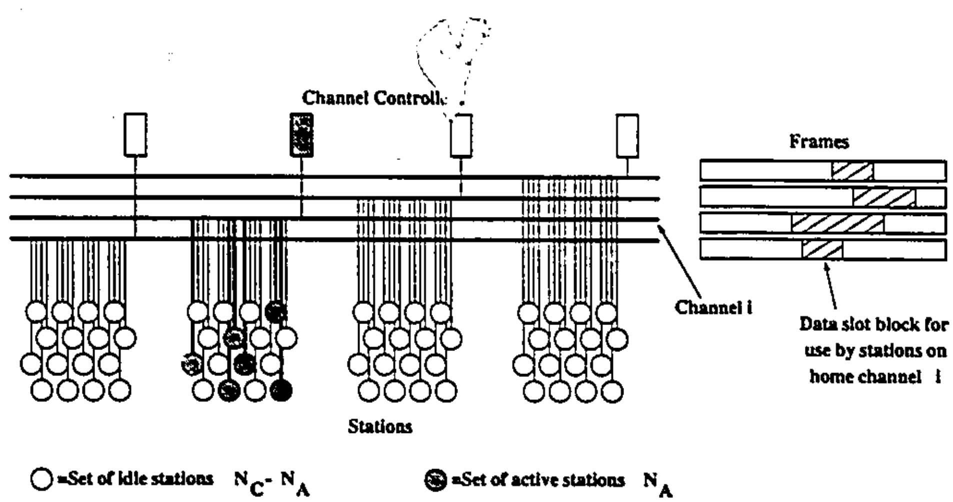

Figure 4.19: DCCN Experimental Model

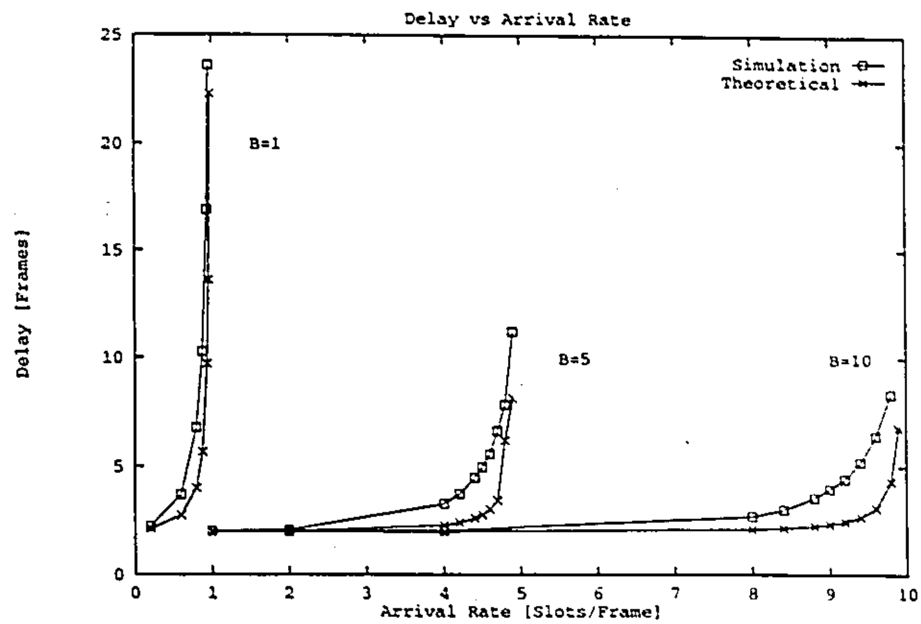

Figure 4.20: Simulation Validation for Low Propagation Delay

home channel controller before an allocation is granted.

With this queue model, theoretical results were generated and compared to the results of the network simulator under the same simplified traffic conditions. Figures 4.20 and 4.21 illustrate average delay curves comparing the queue theory and simulator results. The throughput on the destination channel is measured in aggregate data slot arrivals per frame period, while the access delay is normalized to frames. Figure 4.20 provides comparisons for a small station to star propagation delay of less than one frame in duration, a relative data slot size of $L = 20$ minislots, $D = 100$ data slots per frame and a slot block size of $B_{ik} = 1, 5$ and 10 slots. Figure 4.21 is similar, except that the propagation delay was increased to approximately five times the station to star propagation delay. The two sets of results show close agreement between the simulator and the queue model, based on these comparisons the simulator was determined to be operating correctly. Additional experimental results were generated with the network simulator under various network and packet loading conditions.

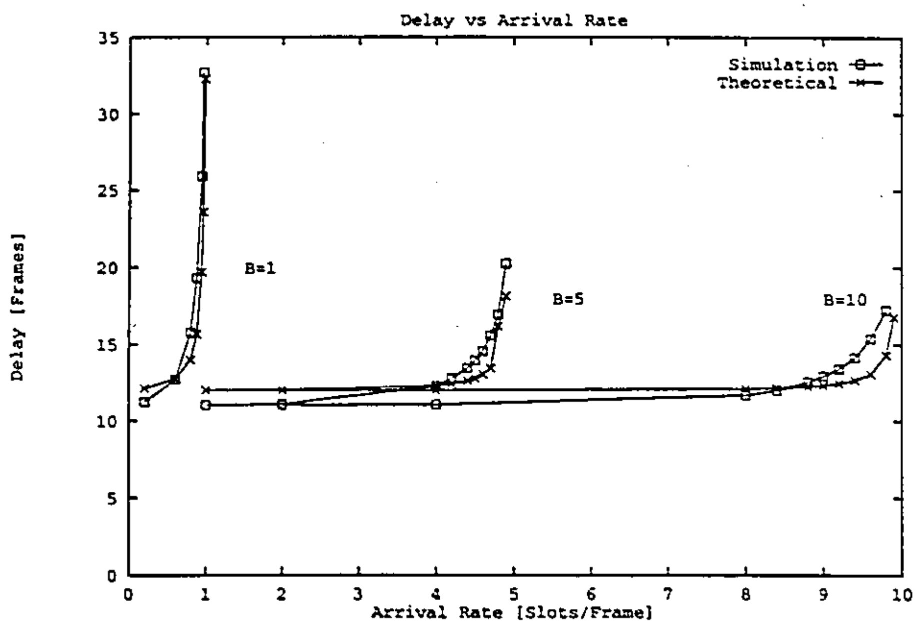

Figure 4.21: Simulation Validation for High Propagation Delay

4.3.3 Single Destination Channel

Single destination channel experimental results were generated using the network configured with $C = 10$ channels, $N_T = 1000$ stations in the network, $N_A = 10$ stations on the home channel actively generating data, $D = 100$ data slots per frame, the slot block of interest on channel k beginning at slot 25 of size $B_{ik} = 50$ slots, a relative allocation minislot duration of $\alpha = 0.5$ and a relative data slot duration of $\delta = 5.0$. This results in a request subframe duration of $t_{req} = 100$ minislots, an allocation subframe duration of $t_{alc} = 50$ minislots, an information subframe duration of $t_{info} = 500$ minislots and a total frame duration of $t_f = 650$ minislots. All experimental data points were generated from the average results of 10 simulator runs with 10^5 frames per run to increase the confidence of the experimental data points.

The first set of experiments involved generation of packets of length equal to one data slot. Each station was configured with the same packet generation rate and allowed to compete for a single destination channel using the centralized DCCN

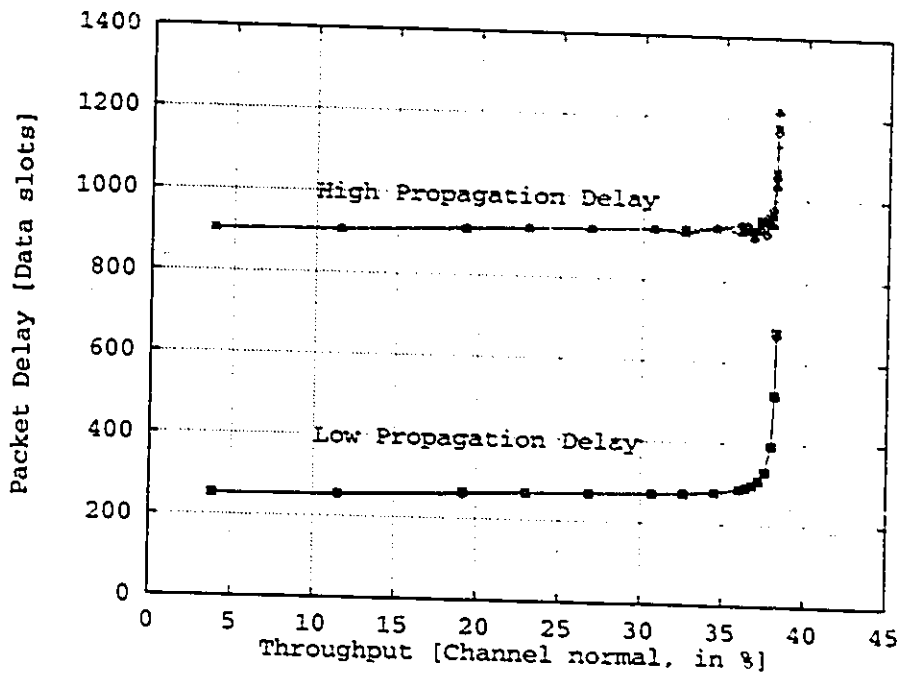

Figure 4.22: Single destination channel, Uniform station station loading, Packet size of one data slot

medium access protocol. Two cases were examined, the first with a low station-star propagation delay of 150 minislots in duration and the second using a larger propagation delay of 2000 minislots in duration. Figure 4.22 illustrates a plot of average delay vs. aggregate throughput on the channel. The access delay is that experienced by one of the active stations , expressed in units of data slots, and since stations are uniformly loaded they all experience a similar packet delay. Throughput is normalized to the capacity of a single data channel, expressed as a percentage. A number of features are evident from this plot. Taking into account a slot block-size of 50 out of a possible 100 data slots and signaling overheads, theoretical maximum throughput on the channel is calculated as approximately 38% which agrees with the experimental results. Low load access delay is approximately two times the frame duration for the low propagation delay case and approximately two times the station to star propagation delay for the high propagation delay case. This is expected due to the nature of the request and allocation protocol, since a station has to make a request and then wait for an allocation before each packet transmission.

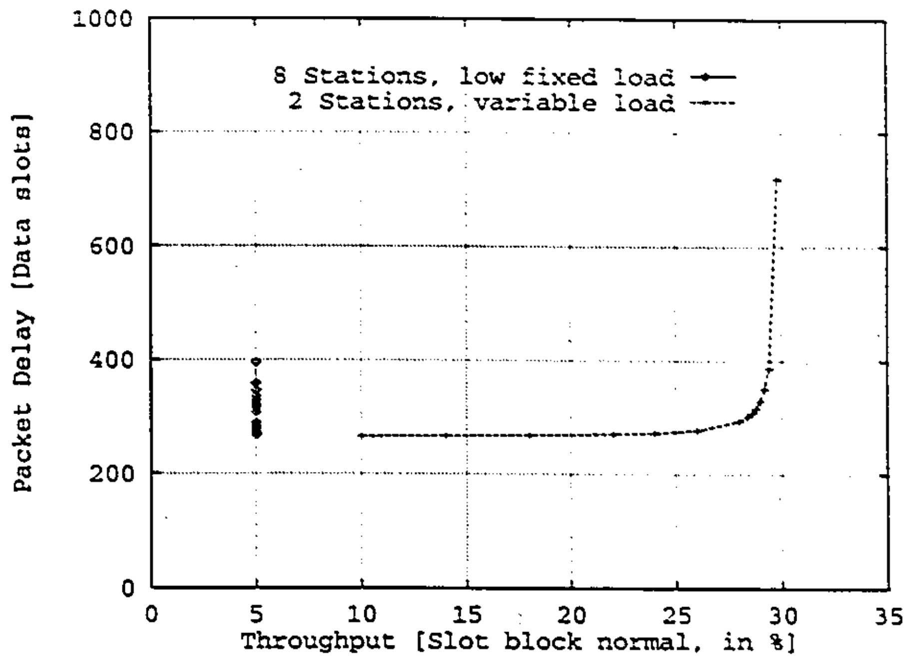

Figure 4.23: Single destination channel, Skewed station loading, Packet size of one data slot

The second set of experiments involves unequal station packet loading conditions. Eight of ten stations were configured with a low constant packet generation rate, while the remaining two stations were configured with a variable packet generation rate. The objective of these experiments was to investigate the ability of the DCCN centralized medium access protocol to divide unused capacity among heavily loaded stations and observe delay coupling effects transfered to the fixed loaded stations. A station to star propagation delay of $P = 150$ minislots was used. Figure 4.23 illustrates the delay-throughput experienced by one of the low loaded stations and one of the variable loaded stations. Throughput is normalized to the capacity of the slot block on the destination channel, rather than the capacity of a full channel, thus a throughput of 20% indicates that ten of the possible fifty data slots on the destination channel are utilized by a particular station. Delay is expressed in units of data slots. Each heavily loaded station uses a maximum of 30% of the slot block while each low loaded station uses 5%, thus the total throughput achieves a maximum of $8 \cdot 5\% + 2 \cdot 30\% = 100\%$. This is expected since the medium access protocol makes data slot assignments on a demand basis, unused capacity from the low loaded stations is used by stations with a larger packet load. This is not the case for static medium access protocols such as TDMA, under which the low loaded stations leave unused data slots idle and the heavily loaded stations lose packets.

Examining the delay-throughput of a low loaded station, an increase in access delay is experienced as the packet load generated by other stations increases. This delay coupling is also a consequence of the dynamic protocol and does not occur in static TMDA networks. The negative effects of delay coupling are limited by the DCCN reservation protocol, as the heavily loaded stations generate enough data packet traffic to overload themselves and the channel, the access delay experienced by the low loaded stations is capped. This is a result of the channel controller limiting the number of data slots allocated to each station before moving to the next station. If ten stations are active on the destination channel then fairness dictates each should receive $\frac{1}{10}$ of the slot block capacity. Provided that an active station is using less than its fair share of a destination slot block, the effect of delay coupling by heavily loaded stations is limited.

The third and final set of single destination channel experiments considered uniform generation of packets greater than one data slot in duration. Each of ten active stations is given an identical packet generation rate, however in this case a packet arrival at a station causes multiple data slots to be placed into the stations transmit queue. The objective is to examine the ability of a station to make multiple data slot reservations, transmit multiple data slots per frame and analyze delay-throughput performance as a function of packet size. The station to star propagation delay is set at $P = 150$ minislots in duration with a slot block size of 50 data slots, for each value of packet size the delay for a single active station is plotted against total throughput on the destination channel. Throughput is normalized to channel capacity. Delay is the difference in time between packet arrival at a station and the start of transmission of the final data slot in the packet. Results are illustrated by figure 4.24, showing that both the average access delay and rate of change in access delay increase as the number of slots per packet increases. The three lowest delay curves of figure 4.24 use packet sizes of 1, 10 and 40 data slots respectively, all less than the slot block size,

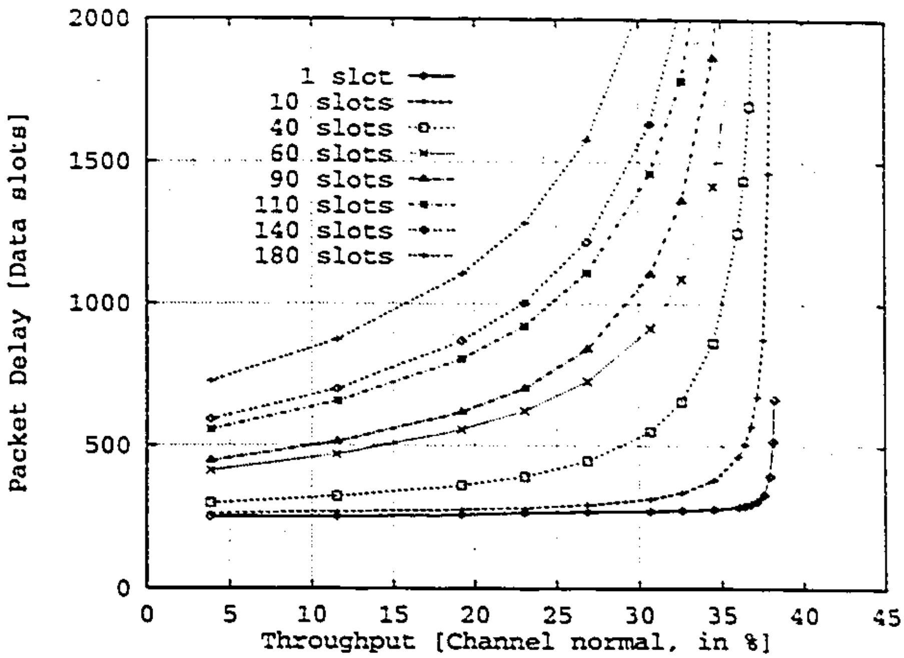

Figure 4.24: Single destination channel, Uniform station loading, Packet size greater than one data slot

while the next curve increases packet size to 60 data slots, greater than the slot block size. An increase in packet size from 1 to 40 data slots shows only a small increase in access delay, while a further increase of only 20 data slots incurs a much larger increase in access delay. This is a result of the packet transmission spanning multiple frames. The same pattern is observed as the number of data slots increases beyond two and three times the data slot block size. The dynamic nature of the reservation protocol benefits cases when packet size is greater than one data slot. Consider a static TDMA medium access protocol with a frame size of 100 data slots with each station assigned a single slot. The access delay for a packet of 60 data slots in length requires approximately 60 frames, or 6000 data slots to complete transmission. This is in sharp contrast to the reservation protocol which requires approximately 550 data slots to transmit the same packet, assuming an aggregate channel load of 20% on figure 4.24.

4.3.4 Multiple Destination Channel

Multiple destination channel experimental results were generated with the network configured with $C = 10$ channels, $N_T = 500$ stations in the network. $N_A = 100$ stations on the home channel actively generating data packets. $D = 100$ data slots per frame, all slot blocks beginning at slot 40 of size of $B_{ij} = 20$ slots, $j = \{1 \ldots C\}$, an allocation minislot duration of $\alpha = 0.5$, a data slot duration of $\delta = 5.0$, a station-star propagation delay of 150 minislots and a fixed packet size of 10 slots. This results in a request subframe duration of $t_{req} = 51$ minislots, an allocation subframe duration of $t_{alc} = 26$ minislots, an information subframe duration of $t_{info} = 500$ minislots and a total frame duration of $t_f = 577$ minislots. Figures 4.25 through 4.28 illustrate delay-throughput curves under various multichannel loading conditions.

The first part of the multichannel performance investigation had all active stations generate an identical packet load to one of the destination channels, then to two channels, five channels and finally to ten of the ten available destination channels. Total data slot utilization and average packet access delay on each channel was monitored, with the results presented by figure 4.25. As the number of destination channels increases the full slot block capacity is utilized, however a small increase in delay occurs. The increase in delay is a result of switching from one destination channel to the next. Full utilization of all data slots on the destination channels is expected since the number of active stations, $N_A = 100$ was much greater than the number of channels, $C = 10$. If the number of active stations is not much greater than the number of channels then it is possible that channel throughput may not reach capacity since a disproportionate number of stations can be active on a particular destination channel during any particular frame, leaving some destination channels with no active stations even though data slot requests are pending. This is a consequence of the round robin queue servicing algorithm used by stations, and could be improved by using a more complex transmit queue selection algorithm at the stations and/or channel controllers. Further investigation of this phenomenon was not pursued in this thesis.

The second part of multichannel analysis involves investigation of non-uniform channel loading. The aggregate load to each destination channel is set independently,

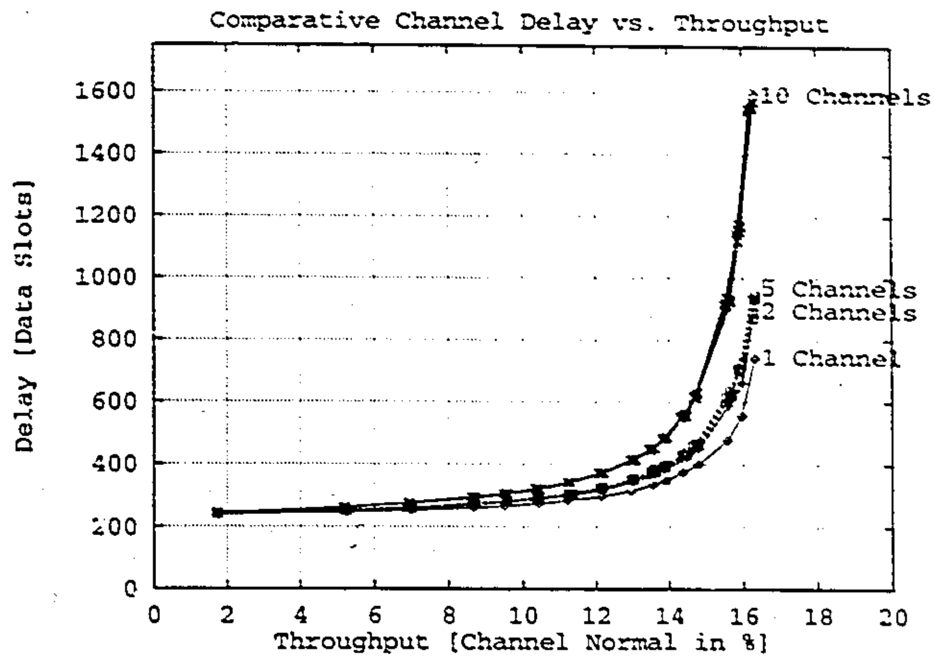

Figure 4.25: Multiple destination channels, Uniform channel loading Packet size of ten data slots

while the active stations each generated the same packet load to a particular destination channel. Three specific cases are examined. In the first case one channel is configured with a low fixed packet load resulting in a throughput of approximately 5% of slot block capacity, and a second channel has a packet load swept from a throughput of 5% up to 85% of slot block capacity. Figure 4.26 illustrates the resulting aggregate delay-throughput curves for the two channels. As expected the delay experienced on channel 2 increases with increasing load, however an increase in access delay also occurs on channel 1 even though the packet generation rate to this channel is fixed. This is expected since a station is configured with a single transmitter which must be shared between data transmissions on the two channels. The packet access delay of the fixed loaded channel does not increase indefinitely, even as channel 2 becomes overloaded. This is a result of the station's multiple queue servicing algorithm which limits the maximum period of time a particular packet queue is serviced before moving to the next queue.

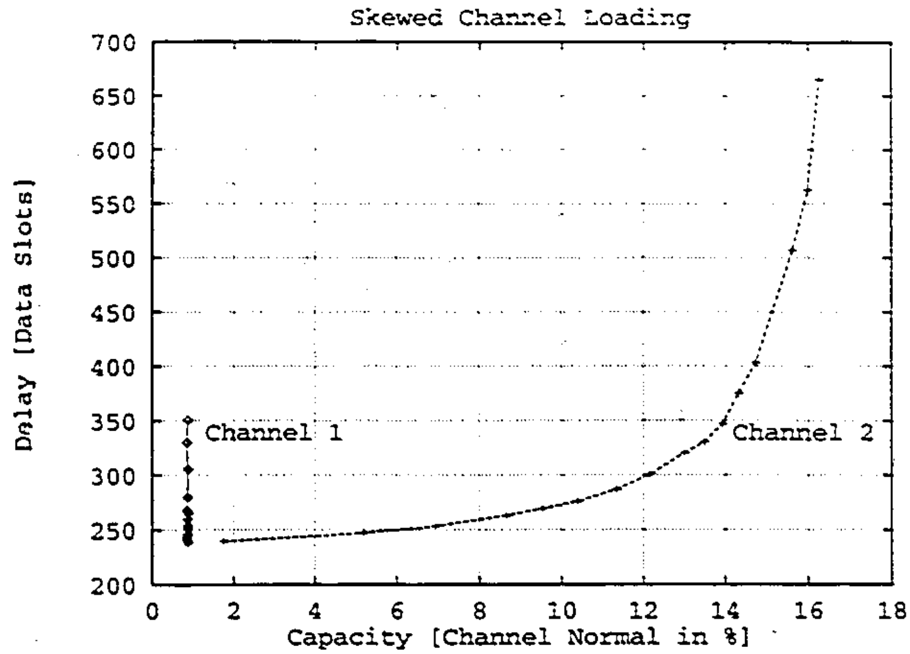

Figure 4.26: Multiple destination channels, Skewed channel loading, Packet size of ten data slots

The second multiple channel loading case is identical to the first except that stations generated an additional low fixed packet load, identical to the load on channel 1, to a third channel. Results are presented by figure 4.27. The performance of channels 1 and 2 is identical to the previous case. In addition, the delay-throughput of channel 3 is the same as channel 1. Packets generated for a third channel did not effect the performance of channels 1 and 2.

The final multiple channel case is similar to the previous two cases, except that the fixed load on channel 1 was increased to 50% of the slot block capacity. Results are presented by figure 4.28. As long as channel 2 throughput remains below approximately 14% of the channel capacity, little difference is observed between this and the previous case. However, as the throughput on channel 2 approaches capacity, packet delay coupling effects observed on channel 1 and channel 3 are greater than the previous loading case.

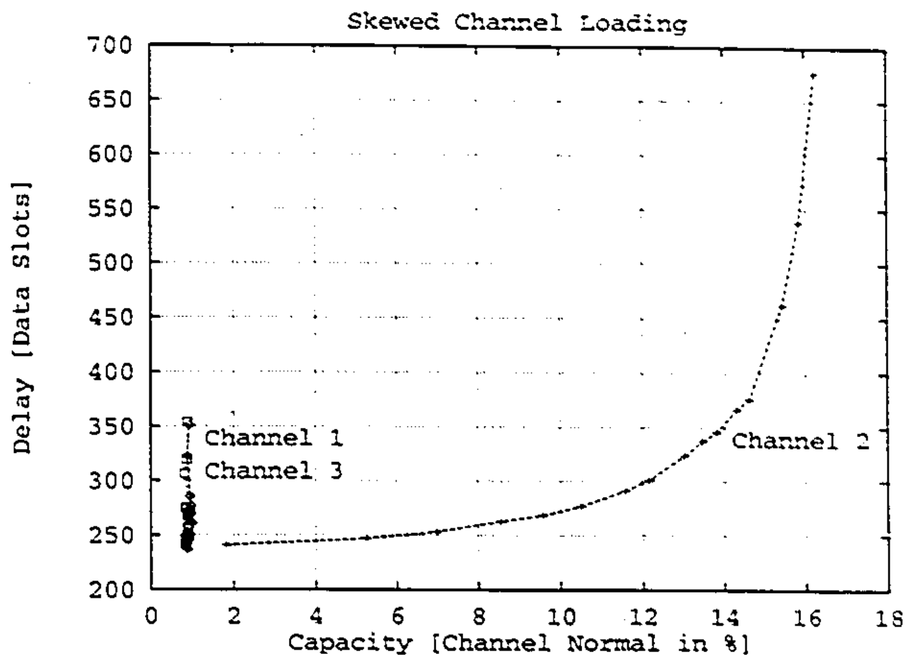

Figure 4.27: Multiple destination channels, Skewed channel loading, Packet size of ten data slots

4.4 Discussion

4.4.1 Multiple Destination Channel Communication

The station model provides an added complexity for a multichannel multiaccess protocol. Unlike single channel networks, where a station has a single transmit queue, two configurations exist for a multichannel network station. The first uses a single transmit queue for packets destined to all channels, while the second uses multiple packet queues, one for each subset of channels. The multiple queue case has many variations, two extremes are a single queue for each destination channel, or one queue for all channels. Consider a station with a single queue, the packet at the front of the queue can be destined for channel λ_1 which is heavily loaded, while the next packet can be destined for channel λ_2 which is lightly loaded. The station is unable to process the packet for λ_2 until the first packet is transmitted, this is referred to as Head of Line Blocking, or HOL. A station with multiple queues does not suffer from HOL

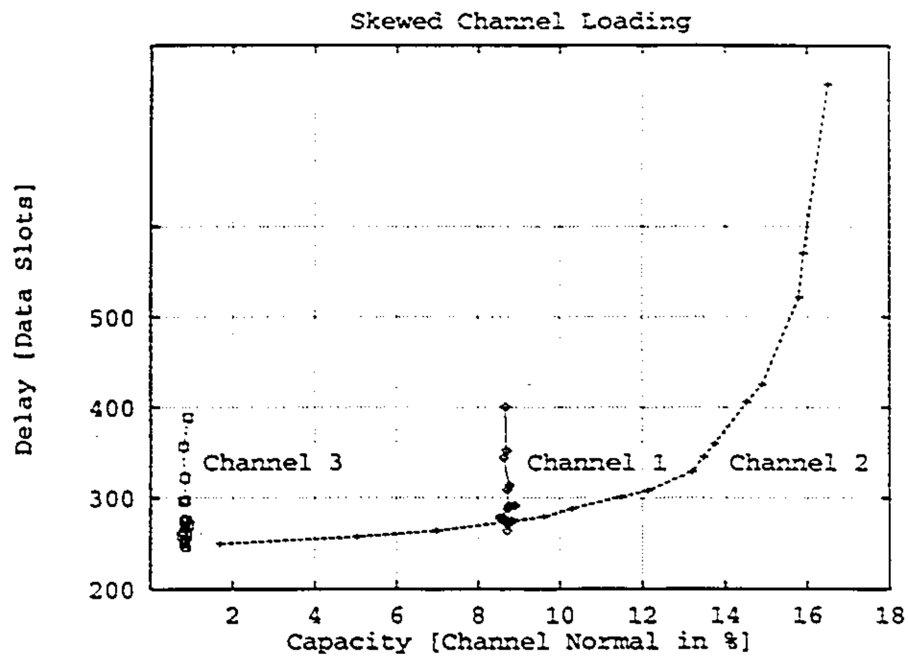

Figure 4.28: Multiple destination channels, Skewed channel loading, Packet size of ten data slots

blocking, however the problem of deciding how to service the set of queues complicates the multichannel medium access protocol. Stations in the DCCN use an exhaustive round robin queue servicing policy, with upper limit on the number of frames a particular queue gets service. Other techniques are possible, perhaps based on adaptive feedback of destination channel packet throughput. The DCCN centralized medium access protocol was shown to handle communication to multiple destination channels under uniform channel throughput conditions with minor degradation in throughput and packet access delay performance over that achieved for single destination channel communication. It should be noted that the DCCN architecture is robust enough to allow "special stations" such as file servers to be extended so that they can make slot requests to multiple channels simultaneously, and transmit simultaneously onto multiple destination channels using a set of tunable transmitters rather than a single tunable transmitter. This extension does not require the channel controller to prevent overlapping data slot allocations across multiple destination channels and is therefore transparent to the proposed channel controller model.

4.4.2 Channel Controllers

Channel controllers create a hybrid network design which exploits the relative strengths of both electronics and photonics. Request and allocation processing is performed electronically, while data transmission and switching occur using the wavelength tunability of station transmitters. This is in contrast to a conventional switch, where all switching and control operations must take place using electronic data paths. Only the information required to control transmissions is exchanged and processed through electronics. Clearly, the quantity of control information is orders of magnitude less than that of the data to be transmitted. As a result, a simple hardware based channel controller design is able to perform the required allocations.

In the literature review of chapter 3 a number of design complexities due to the multichannel nature of WDM optical networks was discussed, also it was stated that the use of a set of channel controllers could potentially reduce or eliminate these complexities. Each area of concern is revisited in the context of DCCN to show that this has been accomplished.

Considering the number of receivers and transmitters, the DCCN architecture reduced station transmitter and receiver requirements to the minimum for a single hop network: Specifically, a single fixed receiver and a single tunable transmitter per station. However, it should be noted that DCCN was not able to provide a network wide minimum number of optical devices, since an additional C fixed transmitters and C fixed receivers were required for the channel controllers. Unlike many other networks with similar receiver and transmitter hardware, the DCCN is able to provide a dynamic medium access protocol and have the number of stations greater than the number of wavelength channels.

Transmitter collision was eliminated through a reservation medium access protocol. This allowed a high percentage of channel capacity to be utilized without waste due to collisions. The dynamic nature of the protocol also allowed a high degree of channel capacity to be utilized under non-uniform packet loading conditions, where one station had more data packets destined to a particular channel than the rest of the stations on its home channel. Receiver collision was also eliminated since each station used only a single receiver fixed tuned to its home channel.

The distributed channel controllers, along with the two level medium access protocol allowed a reduction in the volume of state information that a station was required to track and process. This was achieved by dividing the network into a number of independently operating networks tied together by inter-channel slot block allocations. The channel controllers further reduced the volume of state information by acting as central points for signaling information gathering, reservation processing and allocation or status information distribution.

A mechanism for frame and slot level synchronization was provided through co-location of channel controllers and parallel bus connection. Each channel controller simultaneously generated a synchronization subframe which was received by all stations associated with its channel. Since all data channel frames were of identical duration and maintained alignment, a station was able to synchronize itself with any channel by listening only to its home channel.

Finally, control channel congestion was eliminated by assigning stations request and allocation minislots only on their home channel, rather than on all channels.

4.4.3 Fully Broadcast Single Star Limitations

The Distributed Channel Controller Network is based on a single fully broadcast passive star coupler. Although simple from an architectural point of view, the total network capacity is limited to the capacity of a single channel $C_{channel}$ multiplied by the number of available wavelength channels C.

$$C_{network} = C_{channel} \cdot C. \tag{4.19}$$

This is true since no form of wavelength routing or spatial wavelength reuse is utilized. This capacity limitation is a potential problem if either WDM optical device technology does not provide a large number of wavelength channels, or a large number of stations need to be connected into the same network. Considering equation 3.6 of the review chapter, networks which utilize spatial wavelength reuse can have a total capacity which far exceeds the capacity of a single fully broadcast star.

$$C_{network} = C_{channel} \cdot \sum_{i=1}^{L} N_i \cdot \Lambda_i, \tag{4.20}$$

where L is the number of levels, N_i is the number of clusters of stations and Λ_i is the number of wavelength channels assigned for use in level i. Even for a small number of channels a large increase in network capacity can be realized.

In the next chapters, two multichannel networks using hierarchical and non-hierarchical wavelength reuse schemes are presented as solutions to these problems. Both networks build on the concepts of the DCCN and channel controllers.

Chapter 5

Hierarchical Wavelength Reuse

In the last chapter, a fully broadcast and select single star network using a single hop packet switched medium access protocol was described and analyzed. With such a simple network architecture, an upper limit on capacity is imposed by the number of wavelength channels which can be resolved by the optical transmitters and receivers.

In this chapter, a network based on two level hierarchical wavelength spatial reuse and channel controllers is proposed as a solution to the problem of limited wavelength availability, this work has been presented by [JT94b] and [JT95]. The network incurs a minimal increase in station transmitter and receiver hardware over that proposed for DCCN while maintaining the single hop packet switched medium access protocol. The basic network architecture is similar to that proposed by [DS94] [HWM94] and [GL93], and uses static wavelength routing devices to create a two level hierarchical network. The motivation for such a reuse scheme is derived from a possible high degree of locality among sets of related stations in a LAN or large MAN. As an example, consider the computers within a university campus, those belonging to a particular department often form a strong community of interest from a packet flow perspective.

Network operation is motivated by the single star DCCN architecture and is referred to as the Extended Distributed Channel Controller Network, or EDCCN. The network consists of a set of Local Optical Networks, or LONs which are interconnected optically by a single remote network using static wavelength-routing devices.

Wavelength reuse is achieved by dividing the total available wavelength channels into local and remote channel sets. The local channels are spatially reused within each local network, while the remote channels are shared for internetwork communication. A multichannel medium access protocol permits single-hop dynamic sharing of the channels using a single fast discrete tunable optical transmitter and two fixed or slow discrete tunable optical receivers per station. Since *all* stations dynamically share the single set of remote wavelengths, it is important that these channels are used efficiently, and several remote channel protocols are proposed for this purpose. It is shown that the most efficient remote access protocols involve a coupling of local and remote network operation.

5.1 Network Architecture

The physical architecture of EDCCN is based on a wavelength routed, partial broadcast and select topology as illustrated by figure 5.1. The network is divided into a two level hierarchy consisting of A local optical networks and a single remote optical network, or RON. At the lower level, LONs operate independently and concurrently, while at the higher level the remote optical network provides connectivity between the LONs. In the figure, two LONs are shown connected to the RON at the top of the diagram, with additional details shown in the LON on the left of the figure. Stations within the same geographic location are connected to the same LON with an uplink and downlink fiber pair. The number of stations in LON i is denoted by $N(i)$, while the total number of station in the network is $N_S = \sum_{i=1}^{A} N(i)$. The number of stations per LON is not restricted in any manner by the number of wavelength channels.

Using wavelength division multiplexing the optical spectrum is divided into two contiguous sets of wavelength channels, referred to as the local waveband Λ_L with C_L channels, and the remote waveband Λ_R with C_R channels. Local channels are used for intra-LON communication and are spatially reused in each LON, while remote channels are used for inter-LON communication and are globally shared among all stations in the network. In addition to these data communication pathways, local wavelength channels are reused over the RON for signaling purposes, use of this is

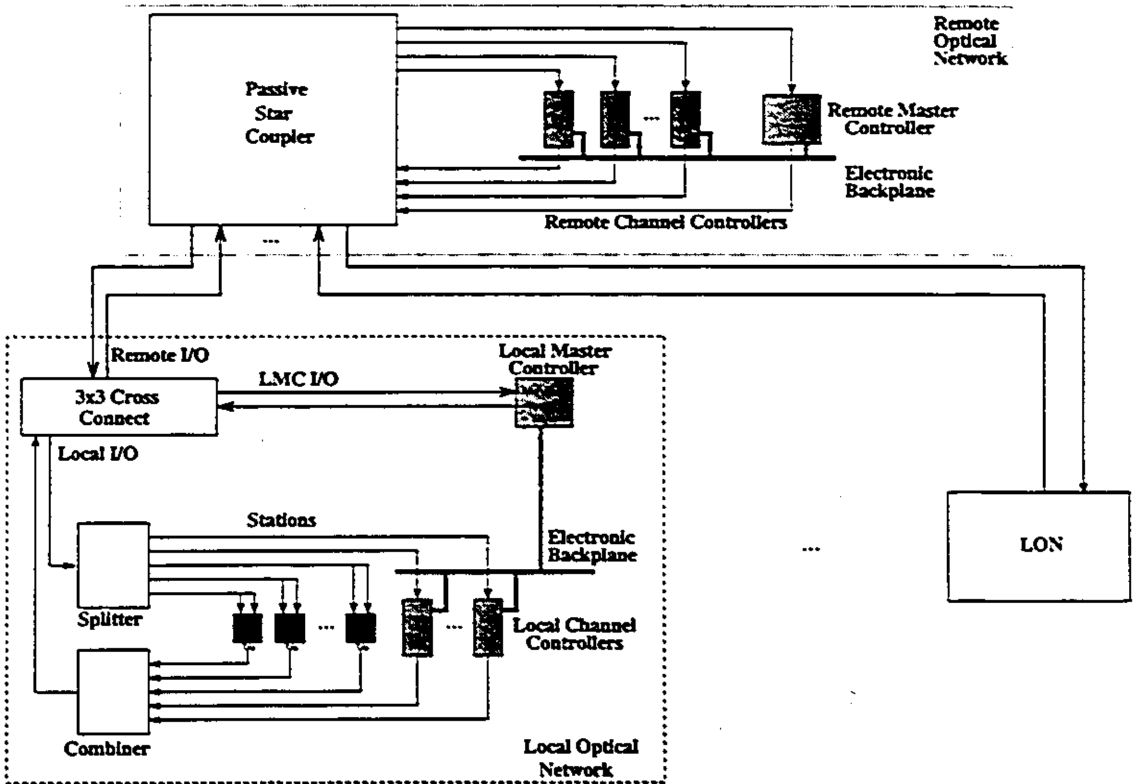

Figure 5.1: EDCCN Physical Network Architecture

protocol specific and discussed later.

Each LON is connected to the RON with an uplink and downlink fiber pair, and a 3×3 WDM cross-connect. as illustrated by figure 5.2. This performs three wavelength routing functions. First, it routes the local waveband from the local input fiber to the local output fiber, creating a fully broadcast and select topology within the LON. The second function is to route the remote waveband from the local input fiber to the remote output fiber and the remote waveband from the remote input fiber to the local output fiber. Since all remote cross-connect ports terminate at the remote star coupler, all remote wavelengths are shared across all LONs. The final function is to create the remote signaling function by routing the local waveband from the Local Master Controller input fiber to the remote output fiber and the local waveband from the remote input fiber to the Local Master Controller output fiber. The WDM cross connect is not required to resolve individual wavelength channels, only the two

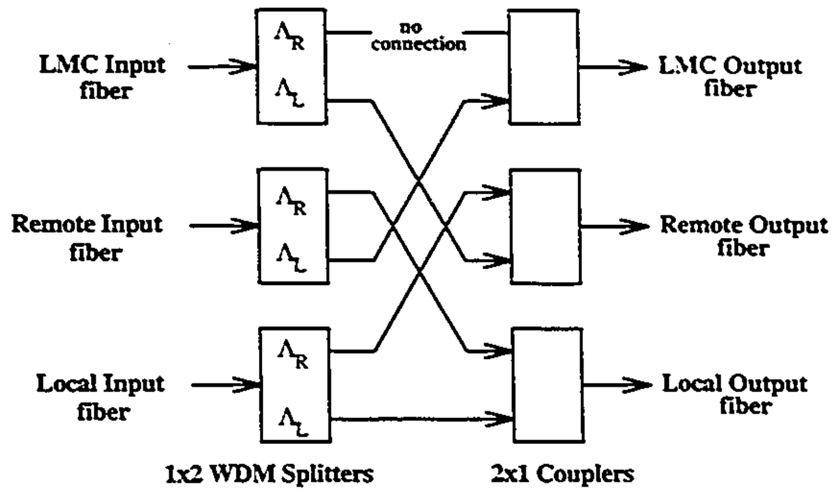

Figure 5.2: 3×3 Wavelength Cross Connect

wavebands.

Each station is configured with two fixed tuned or slow discrete tunable receivers and a single fast discrete tunable transmitter, all capable of tuning across all wavelength channels. Each is also pre-assigned a "Local HOME" channel, or LHOME channel within the local waveband to which it fix tunes one of its receivers, and pre-assigned a "Remote HOME" channel, or RHOME channel within the remote waveband to which it fix tunes its other receiver. Once the LHOME and RHOME channel assignments are made, station receivers are not re-tuned. Although not a strict requirement, it is assumed that all stations with the same LHOME channel assignment on the same LON have the same RHOME channel assignment, and stations on different LONs can share the same RHOME channel assignment. A station uses its LHOME channel to receive data packets from stations within its own LON to establish LON synchronization, coordinate packet transmissions on its own LON, and gain access to the RON. A station uses its RHOME channel to receive data packets from stations outside its own LON, establish RON synchronization and coordinate packet transmissions on the RON.

Channel controllers are incorporated into the network design as a mechanism to reduce station hardware and multichannel medium access protocol complexity. Two types of channel controllers are used, local channel controllers and remote channel controllers. Referring to figure 5.1, a local channel controller is assigned to each locally reused wavelength channel of each LON, while a remote channel controller is assigned to each remote wavelength channel. Each is equipped with a single fixed or slow discrete tunable transmitter and receiver pair which are tuned to the channel controllers assigned channel. Each set of local channel controllers and the set of remote channel controllers are co-located and connected by a parallel backblane bus. Local channel controllers assist their associated stations with local channel medium access, and provide LON synchronization and local status information, while remote channel controllers assist their associated stations with remote channel medium access, and provide RON synchronization and remote status information.

Each LON is also assigned a Local Master Controller and the RON is assigned a Remote Master Controller, which distribute synchronization and status information to their associated channel controllers. The local master controllers and the remote master controller can communicate among themselves using the remote signaling pathways created via reused local wavelengths in the RON.

Due to the multichannel nature of the network, the physical architecture is insufficient to convey the salient network features, a better description is provided by the logical network architecture of figure 5.3. This illustrates an example network consisting of $C_L = 4$ local wavelength channels, $C_R = 3$ remote wavelength channels and $A = 2$ LONs with $N(1) = N(2) = 2$ stations per LON. Each station has both a fixed local home channel connection and remote home channel connection, and each has transmitter capability across four local channels and three remote channels. Since two LONs are used, two sets of reused local wavelengths are available, providing a total of $C_{Total} = A \cdot C_L + C_R = 11$ spatial wavelength channels.

Each local wavelength channel within each LON has a repetitive time multiplexed frame structure imposed on it consisting of signaling overhead and a fixed number of fixed sized data slots. The frames on all local channels within the same LON are of identical length and time synchronized. In the general case, frame duration and alignment need only be maintained on the local channels within a LON and not on local channels across the LONs, or with the remote channels of the RON. Figure 5.4 illustrates the relationships between local frame durations and alignments for two LONs.

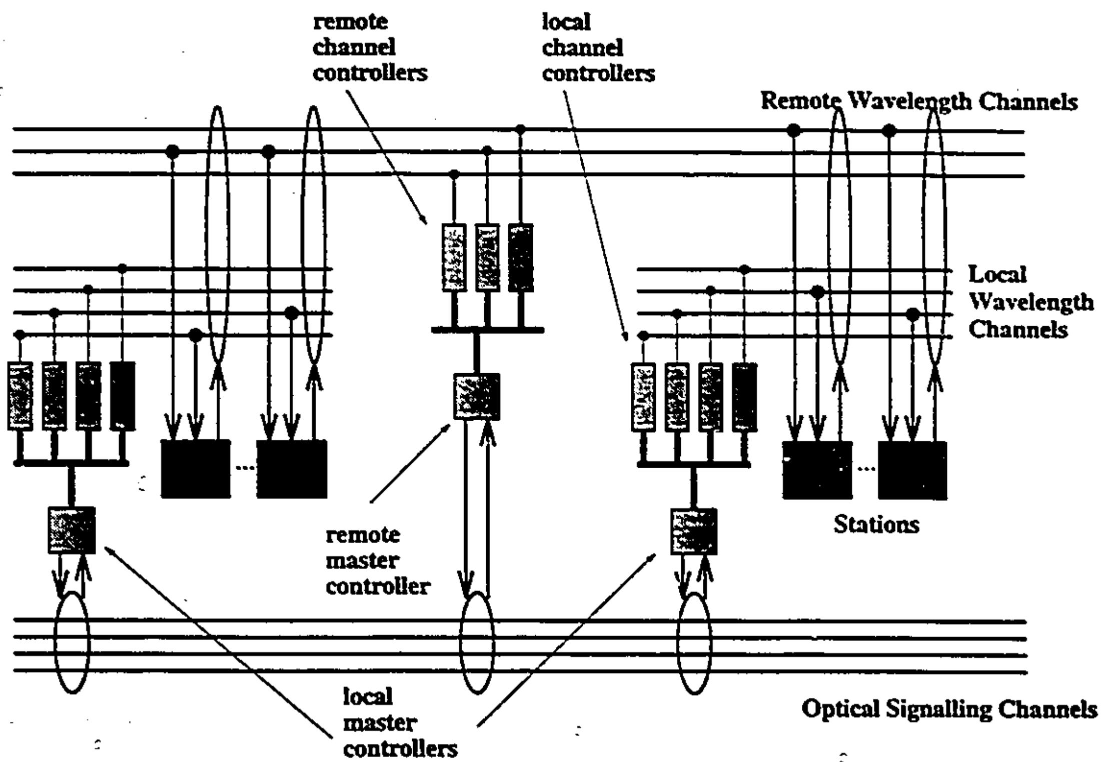

Figure 5.3: EDCCN Logical Network Architecture

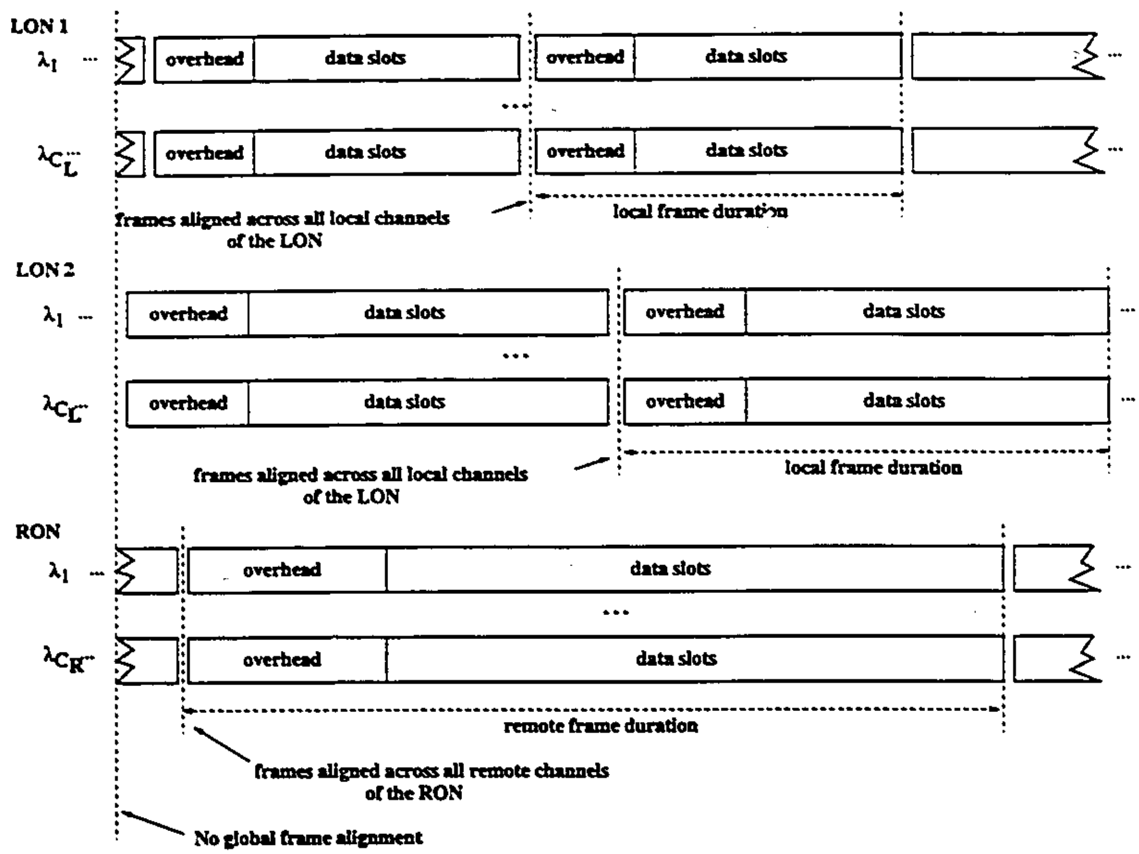

Figure 5.4: Frame duration and alignment relationships between local wavelength channels on different local networks and remote wavelength channels on the remote network

This shows frames on channels λ_1 through λ_{C_L} of LON 1 all with the same duration and time aligned. Similarly, the channels within LON 2 have the same duration and aligned, but have different duration and alignment with respect to the channels of LON 1. This relaxes global network synchronization requirements and allows frame duration to be independently optimized within each LON. A similar repetitive time multiplexed frame structure is implemented on each remote channel, with identical remote frame duration and frame alignment being maintained on the set of remote channels. Figure 5.4 illustrates the frame duration and alignment relationship of remote channels with the local channels of two LONs.

5.2 Network Operation

The medium access protocols proposed for EDCCN permit single-hop packet switched communication between any two stations in the network. Since the network is divided into local and remote networks, two medium access protocols are required. A local medium access protocol is executed by a station if it is performing intra-LON communication, while a remote medium access protocol is executed for inter-LON communication.

The local packet switched medium access protocol is identical to that of DCCN, using the tunable transmitter and LHOME channel receiver. The dynamics of the local medium access protocol are identical to DCCN and are not analyzed.

The remote channels and remote channel controllers are a shared resource among all stations in the network, therefore consideration must be given to designing bandwidth efficient remote medium access protocols which minimize remote channel controller processing loads. Five remote packet switched medium access protocols using reservation techniques and various degrees of coupling with the local medium access protocol are described and analyzed, with a summary and comparison provided by table 5.1. A station uses its tunable transmitter and RHOME channel receiver for remote communication.

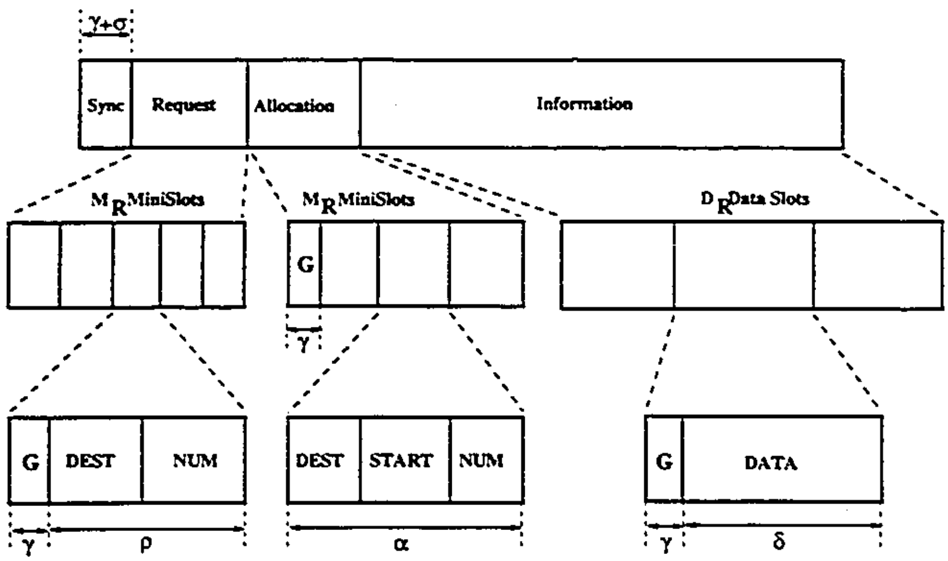

Figure 5.5: Remote protocol 1 frame format. Identical to the local frame format.

5.2.1 Remote Protocol 1

Protocol 1 is a straight forward extension, functionality is duplicated directly from the local network. The same two level medium access protocol and frame format are maintained, as illustrated by figure 5.5. The synchronization subframe, request subframe, allocation subframe and information subframe are the same as those described for DCCN, with the request and allocation subframes containing M_R minislots and the information subframe containing D_R fixed sized data slots. Subframe durations and total frame duration can be calculated as

$$t_{sync} = \gamma + \sigma, \tag{5.1}$$

$$t_{alc} = \gamma + M_R \cdot \alpha, \tag{5.2}$$

$$t_{req} = M_R \cdot (\gamma + \rho), \tag{5.3}$$

$$t_{info} = D_R \cdot (\gamma + \delta), \tag{5.4}$$

$$t_{rf} = t_{sync} + t_{alc} + t_{req} + t_{info}. \tag{5.5}$$

If it is assumed that station RHOME channel assignments are equally distributed among the remote channels then

$$M_R = \lceil \frac{N_S}{C_R} \rceil. \quad (5.6)$$

At the higher protocol level, each remote channel controller allocates a contiguous block of data slots within the frame to each other remote channel controller including itself, for a total of C_R slot blocks. At the lower protocol level, each station is pre-assigned a dedicated remote request and allocation minislot on its RHOME channel. Remote channel controller functionality is identical to the local channel controllers, each must process remote requests and generate remote slot allocations for all stations associated with its remote channel. Protocol 1 completely decouples the operation of the local and remote medium access protocols, and although simple from a protocol perspective, two potential problems exist. First, due to the large number of stations assigned to each RHOME channel remote capacity is expected to degrade due to large volumes of request and allocation signaling overhead. Second, remote channel controller processing loads can become excessive due to the large number of stations.

5.2.2 Remote Protocol 2

Protocol 2 reduces remote channel request and allocation signaling by completely eliminating it, and tightly coupling the remote medium access protocol with the local medium access protocol. This is achieved by moving remote signaling from the remote channels to the local channels and imposing strict global channel synchronization. Referring again to figure 5.4, local frames across all LONs and remote frames are constrained to have the same duration and global time alignment. The remote frame contains D_R fixed sized data slots and some wasted capacity of duration equal to the frame overhead on the local channels, as illustrated by figure 5.6. Subframe durations and total frame duration can be calculated as

$$t_{sync} = \gamma + \sigma, \quad (5.7)$$

$$t_{waste} = t_{lalc} + t_{lreq}, \quad (5.8)$$

$$t_{info} = D_R \cdot (\gamma + \delta), \quad (5.9)$$

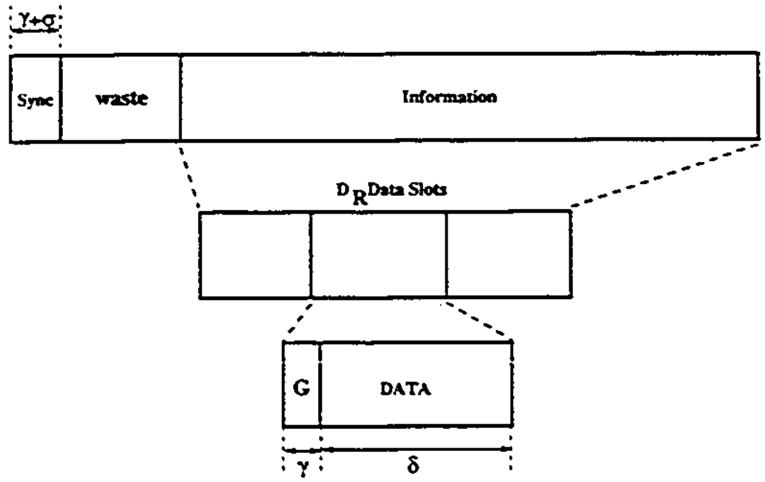

Figure 5.6: Remote protocol 2 frame format

$$t_{rf} = t_{sync} + t_{waste} + t_{info}, \tag{5.10}$$

where t_{lalc} and t_{lreq} are the duration of the allocation subframe and request subframe on a local channel.

The same two level medium access protocol hierarchy is maintained. At the higher level each remote channel controller allocates a contiguous block of data slots to each local channel controller of each LON in the network, for a total of $A \cdot C_L$ slot blocks. At the lower level each station views a remote channel as simply another "local" channel and makes remote channel data slot requests using its dedicated local request minislot. Similarly, a station receives remote channel data slot allocations in its dedicated local allocation minislot from its local channel controller. Remote channel controller functionality is significantly reduced for Protocol 2 since they are only required to calculate channel slot block allocations, and do not assist stations with remote medium access. However, as a tradeoff local channel controller functionality increases since each must take over processing of slot allocations for an additional C_R channels.

5.2.3 Remote Protocol 3

Protocol 3 reduces remote channel signaling by sharing request and allocation minislots among stations with the same LHOME channel assignment on the same LON. The same frame format and two level medium access hierarchy described for Protocol 1 are maintained. However, rather than assigning each station a dedicated remote request and allocation minislot pair on its RHOME channel, each local channel controller is assigned a set of remote request and allocation minislots on the RHOME channel associated with its stations. The number of remote request and allocation minislots per frame is a configurable network parameter which can be set in the range

$$\frac{A \cdot C_L}{C_R} \geq M_R > \lceil \frac{N_S}{C_R} \rceil. \tag{5.11}$$

The minimum value of M_R assigns one remote minislot pair to be shared by all stations assigned to the same LHOME channel of the same LON, while the maximum value assigns each station in the network its own remote minislot pair, this case makes protocol 3 identical to protocol 1. A station must gain permission to use a remote minislot pair, using a remote minislot arbitration protocol with its local channel controller, before it can participate in the remote channel medium access protocol. Although many remote minislot arbitration protocol possibilities are available, a token-passing scheme with early token release, is used. A station signals whether or not it requires remote transmit capability via bits within its dedicated local request minislot, notifying its the local channel controller that it wants to become part of the logical ring. If the local channel controller is holding unused remote minislot pairs then it assigns them to waiting stations in the logical ring. Notification of remote minislot assignment is achieved with bits in a station's dedicated local allocation minislot. A station can use a remote minislot pair for a pre-configured maximum number of remote frames, or until it no longer requires the remote request minislot. A station releases the remote minislot via bits within its dedicated local request minislot. Remote channel controller functionality is identical to Protocol 1, except that processing loads are reduced as a result of a reduction in the number of remote minislots. As a tradeoff, local channel controllers must provide the remote minislot arbitration protocol, as well as process local request and allocation minislots.

5.2.4 Remote Protocol 4

Protocol 4 reduces remote channel signaling by sharing request and allocation minislots using a similar technique as protocol 3, the difference being the arbitration protocol used by the local channel controller. Rather than deterministic token scheduling, a random procedure is used, a local channel controller chooses the stations which receive remote minislots at random from the set of waiting stations. In all other respects and functionality Protocol 4 is identical to protocol 3.

5.2.5 Remote Protocol 5

Protocol 5 is a hybrid between protocols 1 and 2. Remote network capacity is increased by moving part of the remote channel signaling to the spatially reused local wavelengths on the RON, which previous protocols have left idle. A similar two level medium access protocol as described for Protocol 1 is maintained. Each remote channel is divided into C_R slot blocks, however at the lower level each station is pre-assigned only a dedicated allocation minislot on its RHOME channel, as illustrated by figure 5.7. Subframe and total frame durations can be calculated as

$$t_{sync} = \gamma + \sigma, \quad (5.12)$$

$$t_{alc} = \gamma + M_R \cdot \alpha, \quad (5.13)$$

$$t_{info} = D_R \cdot (\gamma + \delta), \quad (5.14)$$

$$t_{rf} = t_{sync} + t_{alc} + t_{info}, \quad (5.15)$$

where M_R is calculated in a similar manner to protocol 1. Stations make remote channel slot requests via their dedicated local request minislot, and the local channel controller passes remote channel requests to the appropriate remote channel controller using the signaling network between the local master controllers and the remote master controller. Remote channel controller functionality is similar to Protocol 1, however they receive remote requests via the electronic backplane from the remote master controller rather than directly from stations. Local channel controllers have the added processing load of sorting remote channel requests from local channel requests and passing them to the local master controller.

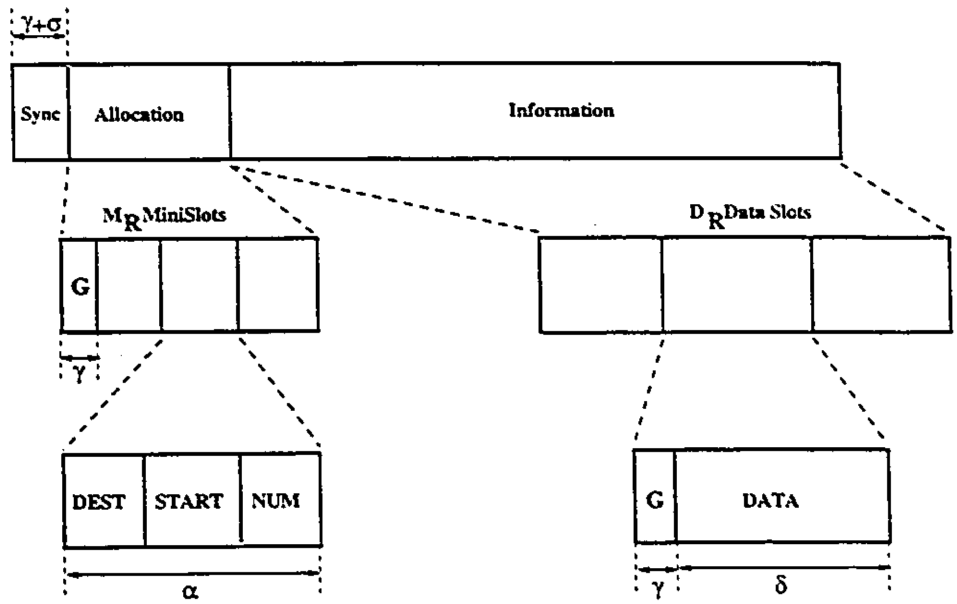

Figure 5.7: Remote protocol 5 frame format

Protocol	Local/Remote Frame Alignment	Remote Slot Blocks	Remote Channel Signaling	Coupled Local/Remote Medium Access
1	No	C_R	Dedicated	No
2	Yes	$A \cdot C_L$	None	Yes
3	No	C_R	Shared	Yes
4	No	C_R	Shared	Yes
5	No	C_R	Dedicated	Yes

Table 5.1: Remote Protocol Summary and Comparison

5.3 Capacity Analysis

Capacity analysis is performed for the five remote medium access protocols. Table 5.2 provides a summary of the parameters used in the calculations. A number of assumptions are made so that the salient capacity features of the remote protocols can be examined and compared. First, all parameters are normalized to the duration of a remote request minislot, therefore $\rho = 1$. Preamble and guard time are incorporated into the request minislot duration, therefore $\gamma = 0$. Allocation minislot duration is assumed to be normalized to the duration of a remote request duration. Synchronization duration is assumed to be negligible, therefore $\sigma = 0$. Also the number of stations assigned to each RHOME channel is uniformly distributed and equal to $\lceil \frac{N_S}{C_R} \rceil$, and the number of stations assigned to each LHOME channel of each LON is also uniformly distributed and equal to $N_L = \lceil \frac{N_S}{A \cdot C_L} \rceil$. Finally, define the ratio of remote data slot duration to remote request minislot duration as $L = \delta / \rho$.

α	remote allocation minislot duration
γ	guard time and preamble duration
ρ	remote request minislot duration
δ	data slot duration
σ	synchronization duration
C	total number of wavelength channels in the local and remote wavebands
C_L	number of local wavelength channels
C_R	number of remote wavelength channels
L	data slot size relative to remote request
A	number of LONs in the network
N_S	total number of stations in the network
N_L	number of stations per LHOME channel
D_R	data slots per remote channel
D_L	data slots per local channel
M_R	number of remote request and allocation minislots

Table 5.2: Summary of Network Parameters used in Capacity Analysis

Four capacity measures are developed as a means to compare the remote medium access protocols, remote channel capacity $C_R(i)$, uniform block capacity $C_{BU}(i)$, maximum block capacity $C_{BM}(i)$ and total system capacity $C_S(i)$, where i is the remote protocol identifier. Remote channel capacity is a measure of how efficiently a remote channel is used, and is defined as the fraction of time that the channel spends transporting data slots. For each remote protocol, this is expressed as

$$C_R(1) = \frac{L \cdot D_R}{(1+\alpha)\lceil\frac{N_S}{C_R}\rceil + L \cdot D_R}, \tag{5.16}$$

$$C_R(2) = \frac{L \cdot D_L}{(1+\alpha)\lceil\frac{N_S}{AC_L}\rceil + L \cdot D_L}, \tag{5.17}$$

$$C_R(3) = \frac{L \cdot D_R}{(1+\alpha)M_R + L \cdot D_R}, \quad \lceil\frac{A \cdot C_L}{C_R}\rceil \leq M_R < \lceil\frac{N_S}{C_R}\rceil, \tag{5.18}$$

$$C_R(4) = \frac{L \cdot D_R}{(1+\alpha)M_R + L \cdot D_R}, \quad \lceil\frac{A \cdot C_L}{C_R}\rceil \leq M_R < \lceil\frac{N_S}{C_R}\rceil, \tag{5.19}$$

$$C_R(5) = \frac{L \cdot D_R}{\alpha\lceil\frac{N_S}{C_R}\rceil + L \cdot D_R}. \tag{5.20}$$

Total system Capacity is a measure of maximum local data transfer capacity plus remote data transfer capacity. This takes account of channel reuse as well as individual remote channel capacity. For Protocol i this can be calculated as

$$C_S(i) = C_R \cdot C_R(i) + A \cdot C_L \cdot C_L(i), \tag{5.21}$$

$$C_L(i) = \frac{L \cdot D_L}{(1+\alpha)\lceil\frac{N_S}{A \cdot C_L}\rceil + L \cdot D_L}. \tag{5.22}$$

All of the remote medium access protocols rely on inter-channel slot block allocations. Maximum Block Capacity is used as a quantification of slot blocking, and is defined as the throughput with which a station on one source channel can communicate to a station on another destination channel. This occurs when all slot blocks, except one on the destination remote channel are set to a size of one, while the final slot block is configured with the remaining data slots. The maximum block capacities are expressed as

$$C_{BM}(1) = \frac{D_R - C_R + 1}{D_R} \cdot C_R(1), \tag{5.23}$$

$$C_{BM}(2) = \frac{D_L - AC_L + 1}{D_L} \cdot C_R(2), \tag{5.24}$$

$$C_{BM}(3) = \frac{D_R - C_R + 1}{D_R} \cdot C_R(3), \quad (5.25)$$

$$C_{BM}(4) = \frac{D_R - C_R + 1}{D_R} \cdot C_R(4), \quad (5.26)$$

$$C_{BM}(5) = \frac{D_R - C_R + 1}{D_R} \cdot C_R(5). \quad (5.27)$$

Uniform block capacity is similar to maximum block capacity, except it assumes all slot blocks on the destination remote channel are of equal size. This is a measure of the maximum bandwidth a station on a source channel can use to communicate with a station on a destination channel under uniform traffic loading conditions. These are given as

$$C_{BU}(1) = \frac{1}{C_R} \cdot C_R(1), \quad (5.28)$$

$$C_{BU}(2) = \frac{1}{AC_L} \cdot C_R(2), \quad (5.29)$$

$$C_{BU}(3) = \frac{1}{C_R} \cdot C_R(3), \quad (5.30)$$

$$C_{BU}(4) = \frac{1}{C_R} \cdot C_R(4), \quad (5.31)$$

$$C_{BU}(5) = \frac{1}{C_R} \cdot C_R(5). \quad (5.32)$$

Three sets of capacity results were generated and analyzed: The first set generated as a function of the number of remote wavelength channels, the second set generated as a function of the number of LONs in the network and the third set generated as a function of number of stations in the network. For all analysis the network parameters were set to the following values unless otherwise stated, $C_L = 15$ local channels, $C_R = 5$ remote channels, a relative data slot duration of $L = 5$, $A = 5$ LONs in the network, $N_S = 1000$ stations in the network, $D_R = 200$ data slots per remote frame and $D_L = 100$ data slots per local frame.

Results showing the effect that changing the division of local and remote channels has on capacity are provided by figures 5.8 through 5.11. The number of channels was fixed at $C = 20$, while the number of remote channels was varied in the range $C_R = \{1 \cdots 19\}$. For protocols 3 and 4, the number of remote request minislots per remote channel was set to the minimum value of $M_R = \lceil \frac{A \cdot C_L}{C_R} \rceil$. Figure 5.8

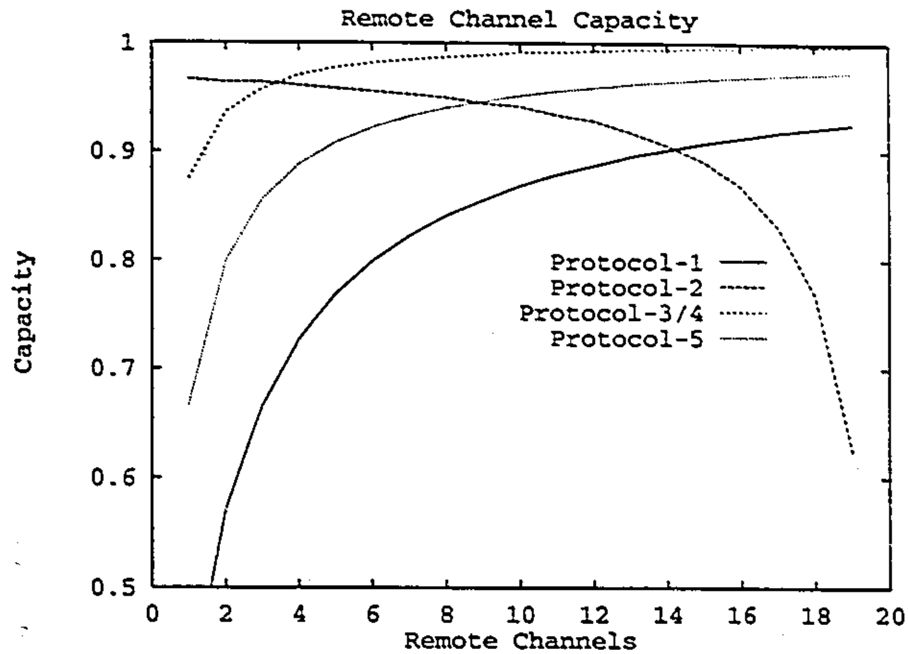

Figure 5.8: Channel Capacity vs. Number of Remote Channels

shows remote channel efficiency for protocols 1, 3, 4 and 5 increasing as C_R increases due to the number of stations per RHOME channel decreasing. Protocol 2 had a decreasing remote channel efficiency for increasing C_R since its remote channel structure is tied to the local channel structure. Increasing C_R decreases C_L, therefore decreasing both local and remote channel efficiency. Figure 5.9 shows the maximum block capacity of protocols 1, 3, 4 and 5 increasing rapidly with increasing C_R and then remaining relatively constant. This is due primarily to rapidly increasing remote channel efficiency with increasing C_R since stations are divided among more RHOME channels. All maximum block capacities are high due to the small number of slot blocks (C_R) per remote channel. Protocol 2 has poor maximum block capacity due to the high number of slots blocks (AC_L) per remote channel. This effect also decreases with increasing C_R due to decreasing C_L. Figure 5.10 shows uniform block capacity for protocols 1, 3, 4 and 5 decreasing rapidly as C_R increases due to an increased number of slot blocks per remote channel. Protocol 2 has extremely low uniform block capacity due to large remote channel slot blocking. Figure 5.11 shows system

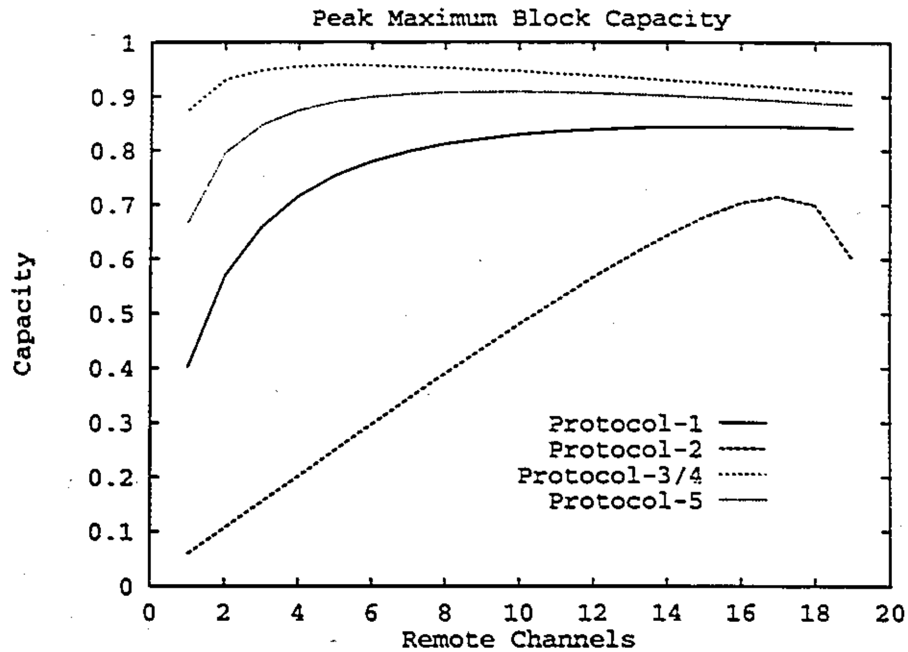

Figure 5.9: Maximum Block Capacity vs. Number of Remote Channels

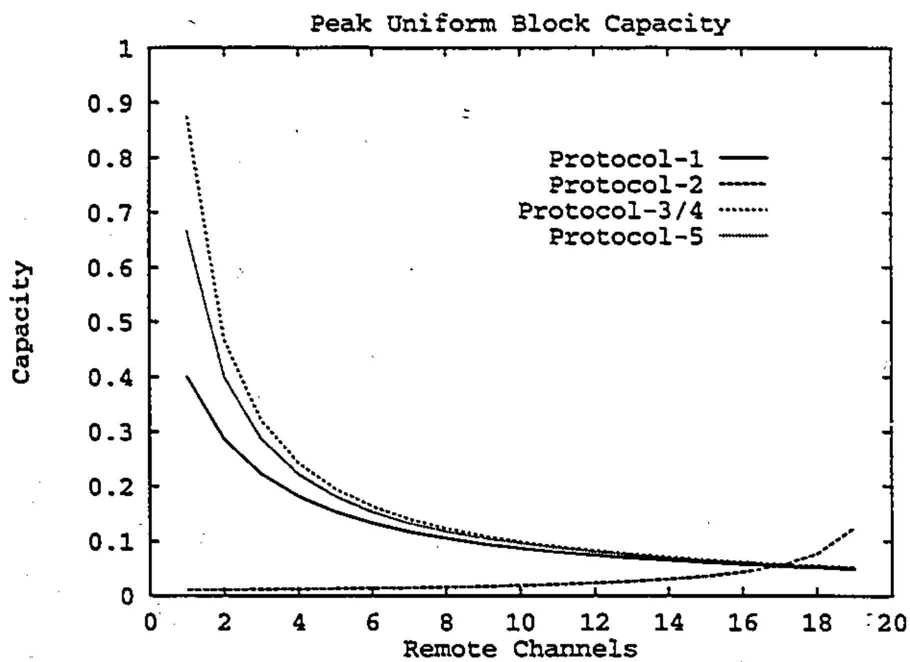

Figure 5.10: Uniform Block Capacity vs. Number of Remote Channels

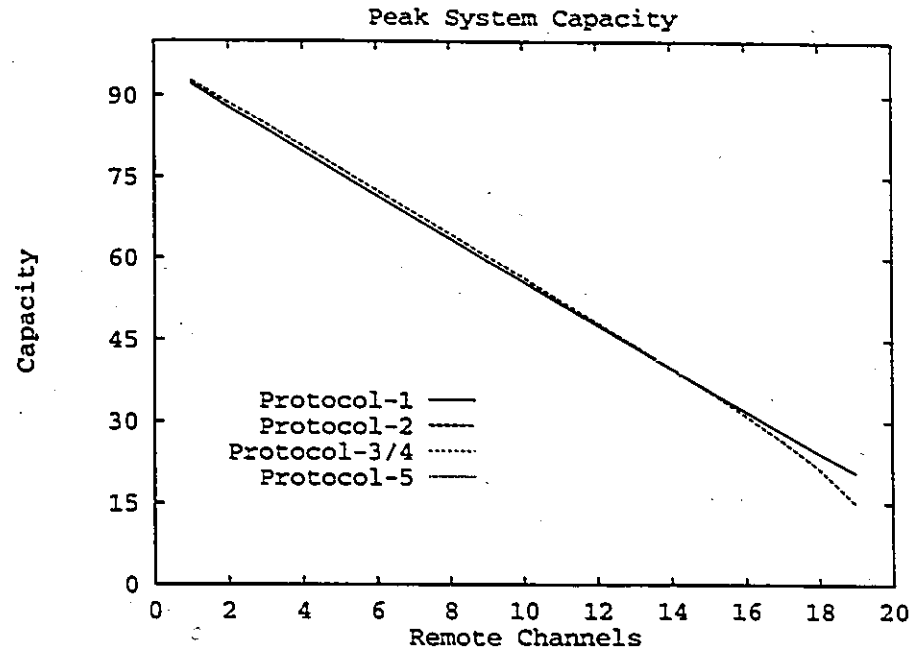

Figure 5.11: System Capacity vs. Number of Remote Channels

capacity for all protocols decreasing as C_R increases due to reduced channel spatial reuse.

Results showing the effect that changing the number of LOCs in the network has on capacity are provided by figures 5.12 through 5.15. The number of LONs was varied from one to ten, and again the number of remote request minislots per remote channel for protocols 3 and 4 was set to the minimum value of $M_R = \lceil \frac{AC_L}{C_R} \rceil$. Figure 5.12 shows that remote channel efficiency for protocols 1 and 5 is insensitive to the number of LONs since the total number of stations in the network does not change. Protocols 3 and 4 have slightly decreasing remote channel efficiencies as A increases. Protocol 2 has increasing efficiency as a result of stations spread across a larger number of local channels which decreases the local channel overhead, and consequently remote channel overhead. Figure 5.13 shows that the maximum block capacity of protocols 1, 3, 4 and 5 is insensitive to A. However, protocol 2 maximum block capacity dramatically decreases with increasing A, with an upper limit on the number of LONs occurring when the number of remote slot blocks exceeds the number of remote data slots,

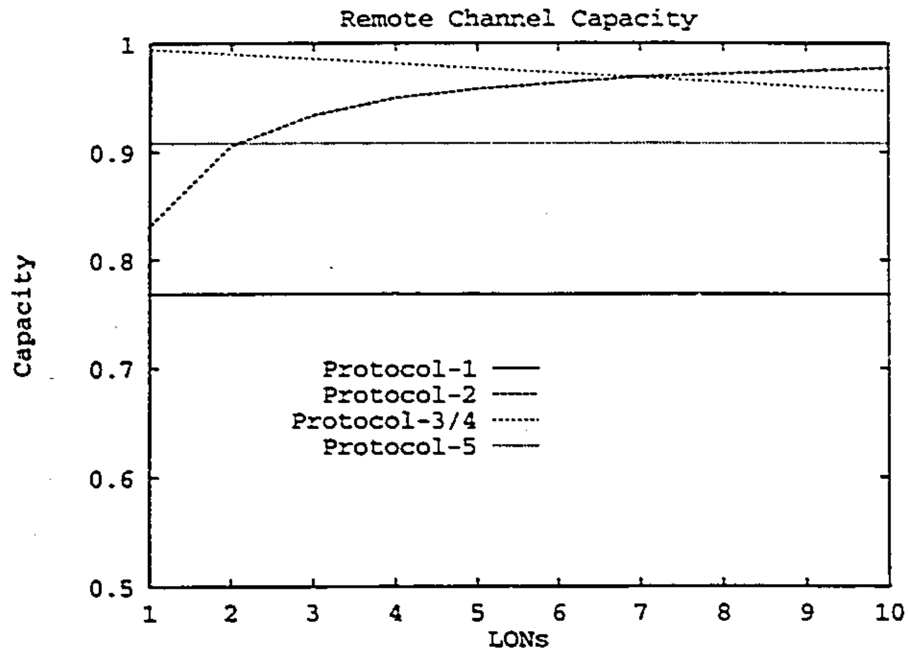

Figure 5.12: Channel Capacity vs. Number of LONs

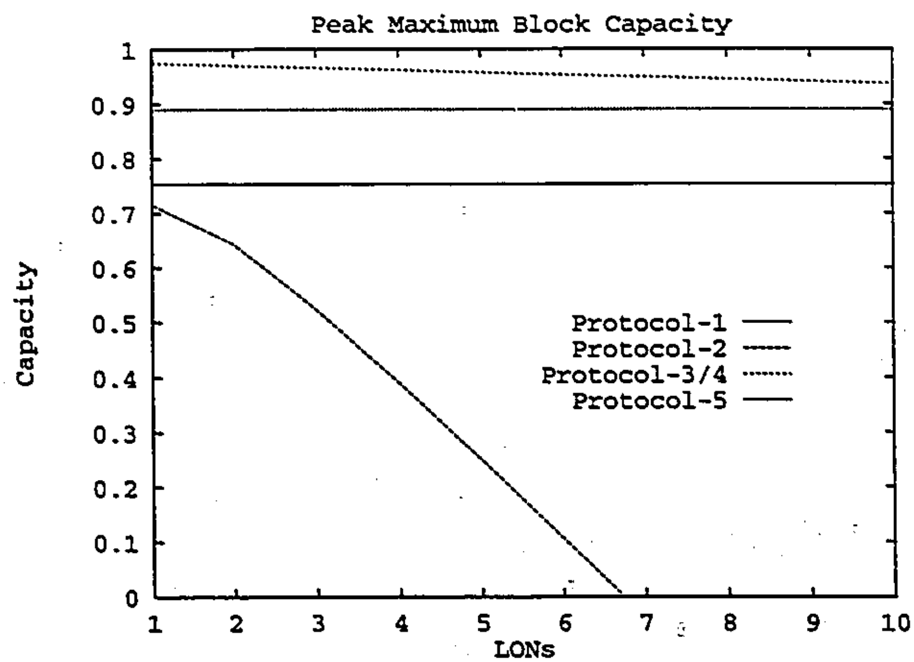

Figure 5.13: Maximum Block Capacity vs. Number of LONs

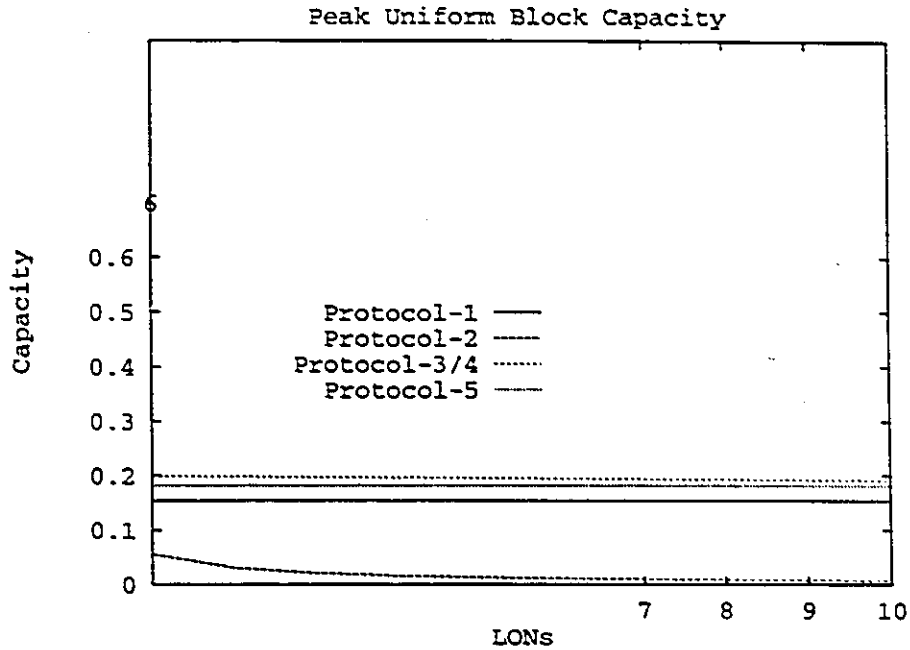

Figure 5.14: Uniform Block Capacity vs. Number of LONs

$A_{MAX} = \lfloor \frac{D_R}{C_L} \rfloor$. Figure 5.14 shows that the uniform block capacity for protocols 1, 3, 4 and 5 is insensitive to increasing A. Protocol 2 has extremely low uniform block capacity due to the large number of slot blocks. Figure 5.15 shows system capacity for all protocols increasing as A increases due to increased spatial wavelength reuse.

Results showing the effect that changing the number of stations has on capacity are provided by figures 5.16 through 5.19. The number of stations per local home channel was varied in the range $N_L = \{1 \cdots 50\}$, and the number of remote request minislots per remote channel for protocols 3 and 4 was set to the minimum value. Figure 5.16 shows remote channel efficiency for protocols 1, 2 and 5 decreasing as N_L increases due to increased overhead per remote and local channels. Protocols 3 and 4 are insensitive to increasing N_L since the existing remote request/allocation overhead on the remote channels is shared at the cost of increased access delay. Figure 5.17 shows that the maximum block capacity of protocols 1 and 5 decreases with increasing N_L due to a decrease in remote channel efficiency. Protocols 2, 3 and 4 remained essentially insensitive to increasing N_L. Figure 5.18 shows the uniform block capacity

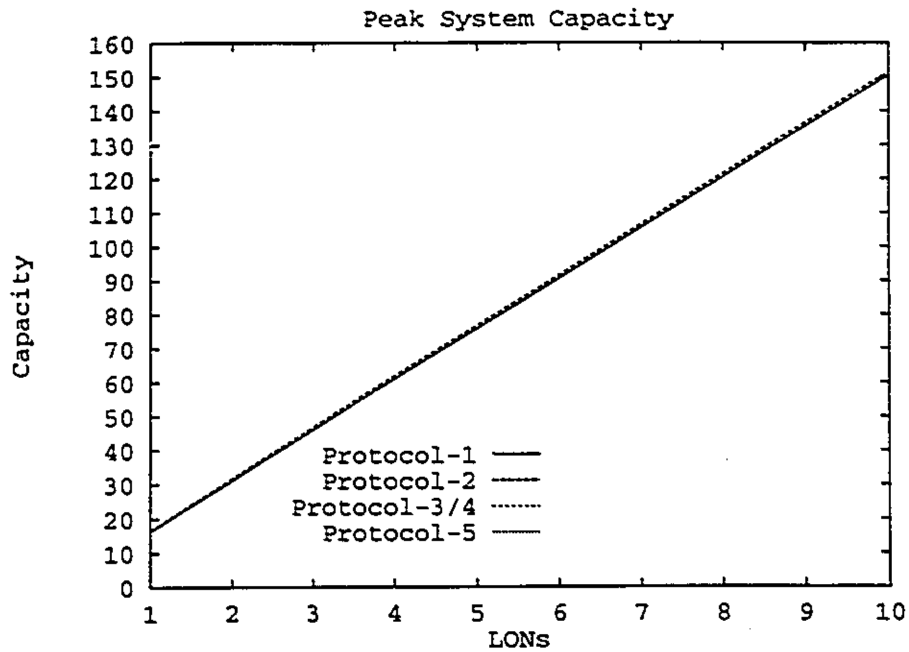

Figure 5.15: System Capacity vs. Number of LONs

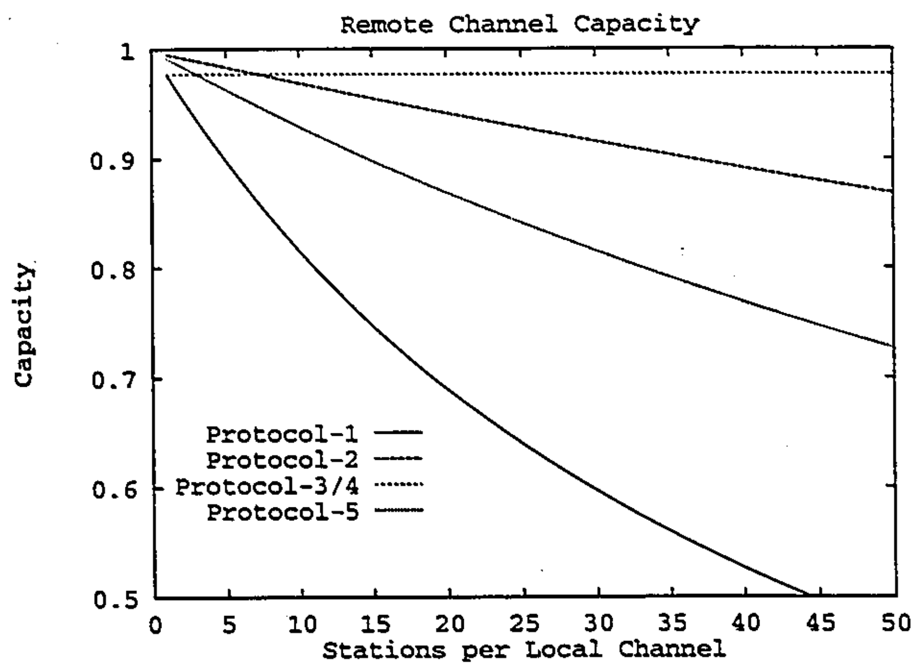

Figure 5.16: Channel Capacity vs. Stations

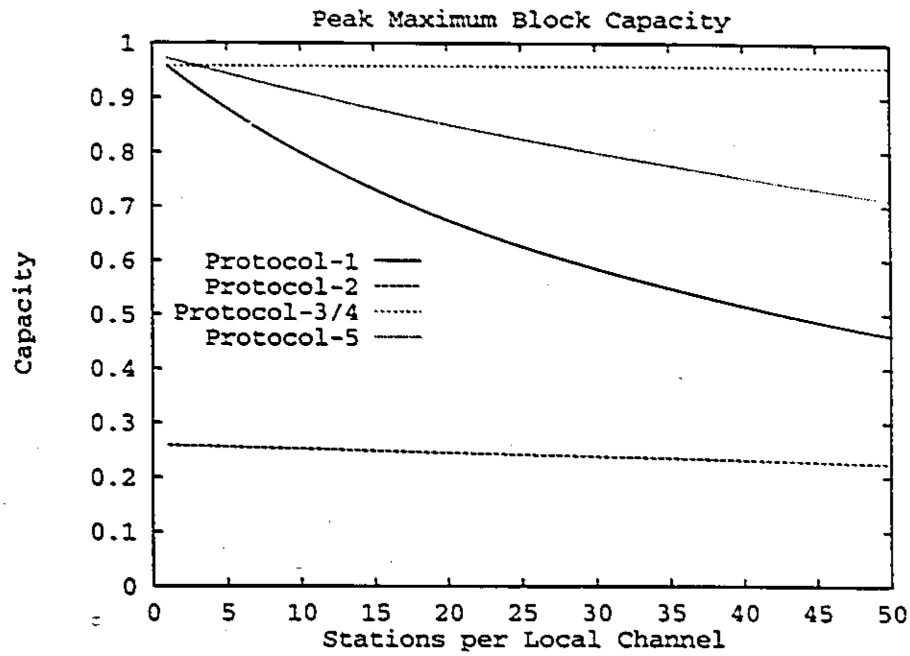

Figure 5.17: Maximum Block Capacity vs. Stations

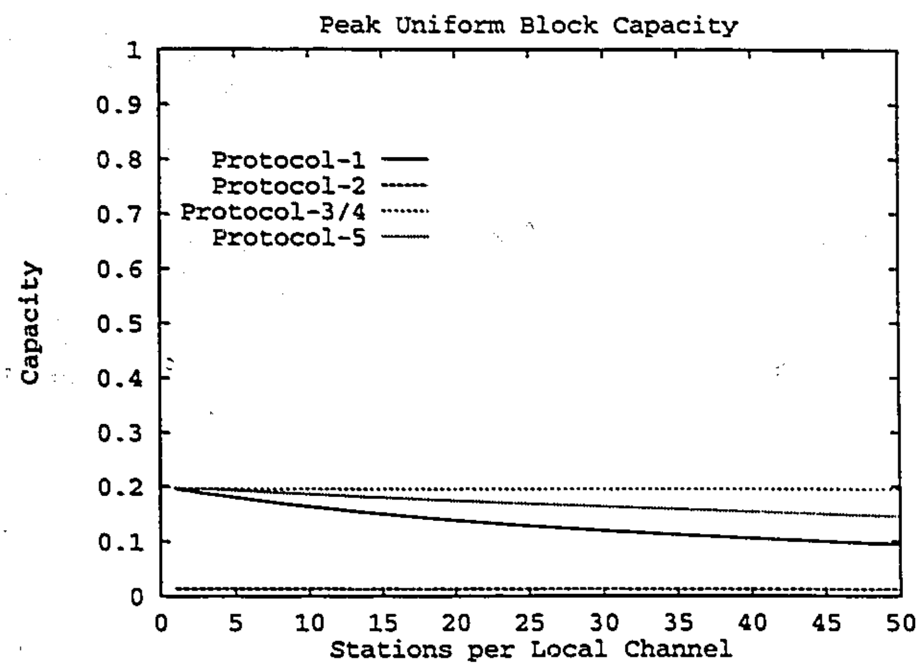

Figure 5.18: Uniform Block Capacity vs. Stations

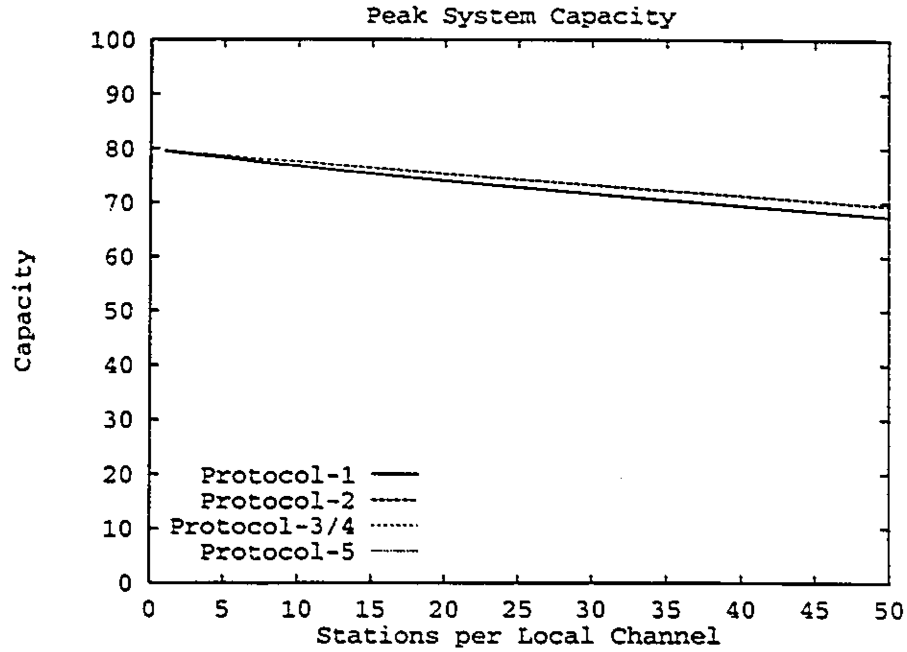

Figure 5.19: System Capacity vs. Stations

for protocols 1, 3, 4 and 5 is very low, but affected only by remote channel efficiency as N_L increases. Protocol 5 uniform block capacity remains extremely low due to a large number of slot blocks, but insensitive to increasing N_L. Figure 5.19 shows that system capacity for all protocols decreases only slightly as N_L increased due to decreased local and remote channel efficiencies. Spatial channel reuse remains constant as N_L increases.

5.4 Delay-Throughput Analysis

Average remote channel packet access delay for the five remote medium access protocols is analyzed and compared using discrete event network simulators and queuing theory models. Access delay is defined as the time between the arrival of a remote data packet and the time when it begins transmission on the destination channel.

Results from the queue theory models are compared with results from the simulators, for each remote protocol, and used to validate network simulator operation.

Then, results from single destination channel, uniform and non-uniform data packet loading scenarios are presented and discussed. The dynamics of multiple destination channel delay-throughput performance, for similar reservation medium access protocols were investigated and discussed using the DCCN architecture of the previous chapter. Network simulation results are generated using 10^5 remote frames, with final results averaged from repeated simulations using different random number generator seeds to increase confidence intervals.

The network simulator considers a subset of a full EDCCN network, consisting of a single local channel i and a single remote channel j and one of the LONs k. Further, interaction between the local channel controller i of LON k, the remote channel controller j, and the N stations on LON k with these LHOME and RHOME channel assignments is considered. Finally, of the N stations only a subset N_A actively generate data packets, the remaining $N - N_A$ are idle. Data packet arrival rates are Poisson distributed and have a length equal to one data slot. Remote channel slot block configurations are pre-configured and static.

Theoretical queue models are developed to investigate delay-throughput and validate the network simulators, using the same network subset described for the simulator. The network is modeled as a single packet source, a single queue and a single server. The single source has a packet arrival rate equal to the aggregate Poisson packet arrival rate of all active stations, all data packets are destined to a single remote channel. The queue is located at the remote passive star, and has infinite size. The server is deterministic with a service period equal to one remote frame, this models the remote minislot arbitration protocol and the remote data slot allocation process. The server can remove up to B data slots per service time, where B is equal to the slot block size on the remote channel. The average packet access delay for each protocol is calculated as

$$\overline{d(1)} = 2P + 2t_{rf} - (2P) \bmod t_{rf} + \overline{m} \cdot t_{rf}, \quad (5.33)$$

$$\overline{d(2)} = 2P + t_{rf} - (2P) \bmod t_{rf} + \overline{m} \cdot t_{rf}, \quad (5.34)$$

$$\overline{d(3)} = \overline{n} \cdot \frac{t_{rf}}{2} + 2P + t_{rf} - (2P) \bmod t_{rf} + \overline{m} \cdot t_{rf} + \frac{t_{rf}}{2}, \quad (5.35)$$

$$\overline{d(4)} = \overline{n} \cdot \frac{t_{rf}}{2} + 2P + t_{rf} - (2P) \bmod t_{rf} + \overline{m} \cdot t_{rf} + \frac{t_{rf}}{2}, \quad (5.36)$$

$$\overline{d(5)} = 2P + \frac{t_{lf}}{2} + t_{rf} - (2P) \bmod t_{rf} + t_{rf} \cdot \overline{m}, \quad (5.37)$$

where t_{rf} is the remote frame duration, t_{lf} is the local frame duration, P is the station to remote star propagation delay and $\overline{m}$ is the average number of remote frames a remote request remains queued before a data slot allocation is generated. The parameter $\overline{n}$ is for protocols 3 and 4, it is the average number of frames a station has to wait for remote minislot pair assignment. Detailed development of these equations is provided by appendix A.

Theoretical results were generated using a remote slot block size of $B = 20$ slots, a station to remote star propagation delay of $P = 150$ minislots, $N_A = 10$ stations competing for remote data slots, $R = 4$ shared remote request minislots and a remote request hold time of $H = 2$ frames. Parameters N, R and H are required only for Protocols 3 and 4. Graphs comparing theoretical results with those generated by the network simulators are provided by figures 5.20 through 5.24. The queuing model results for Protocols 1, 2 and 5 correlate very closely with the simulation results, however the theoretical results for protocols 3 and 4 do not track the network simulation results accurately throughout the low delay region. This is a consequence of simplified theoretical modeling assumptions which are unable to characterize the early release of the shared remote minislots before the preset maximum hold time H. The simulation results show that the actual number of frames which a station holds the remote request is a function of the aggregate arrival rate and the slot block size. Regardless, the queue models provides a close enough match to validate operation of the Protocol 3 and 4 simulators.

5.4.1 Uniform Packet Loading

This experiment investigates remote channel packet access delay for $N_A = 10$ active stations generating data at the same Poisson arrival rate to a single remote destination channel. The network was configured with $C_L = 15$ local channels, $C_R = 5$ remote channels, a relative remote data slot duration of $L = 5$, a relative allocation minislot duration $\alpha = 0.5$, $A = 5$ LONs, $N_S = 1000$ stations in the network, $D_R = 200$ data slots per remote frame, $D_L = 100$ data slots per local frame, and a station to remote

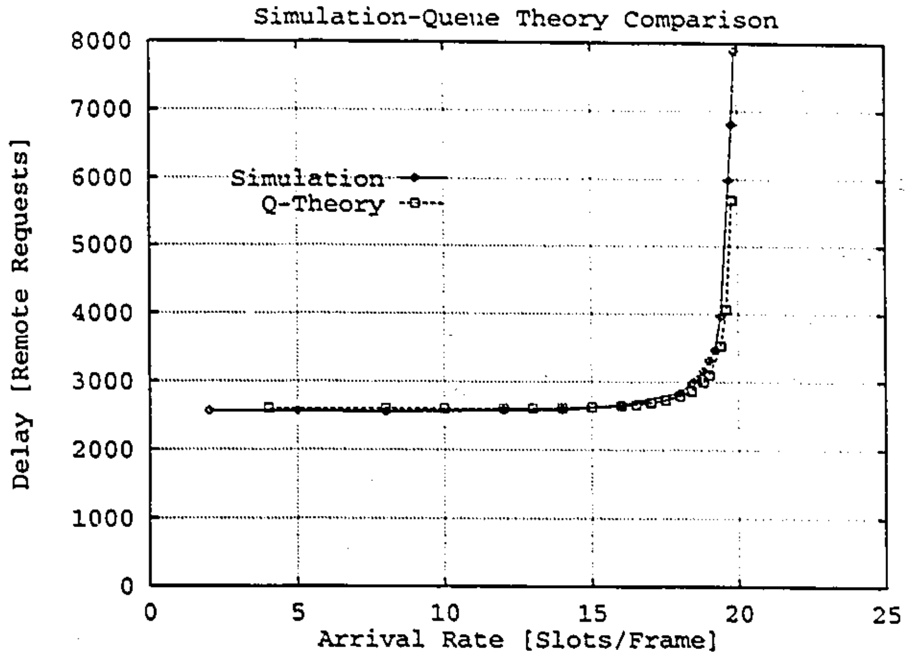

Figure 5.20: Protocol 1: $t_{rf} = 1300$

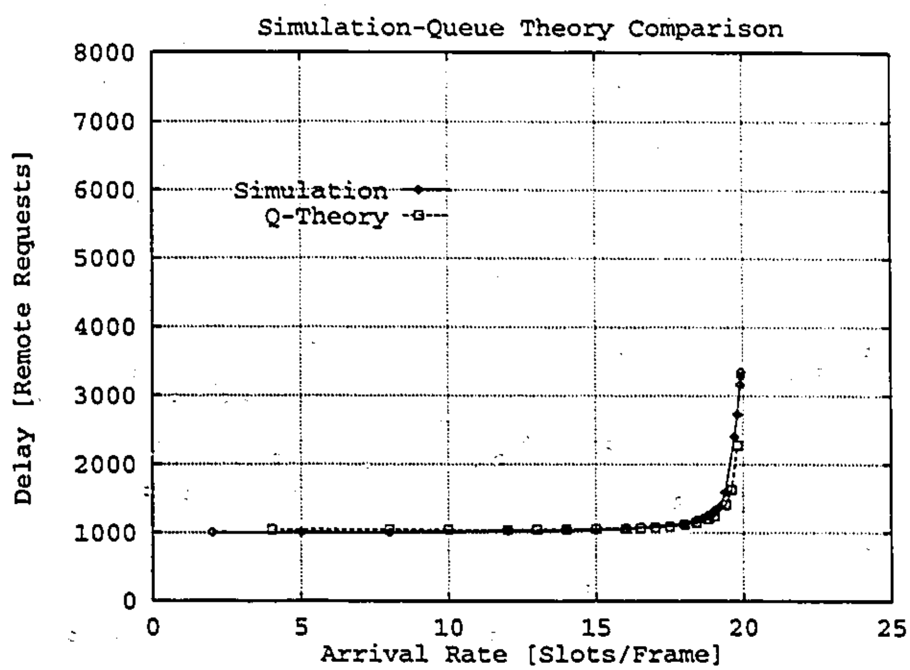

Figure 5.21: Protocol 2: $t_{lf} = t_{rf} = 521$

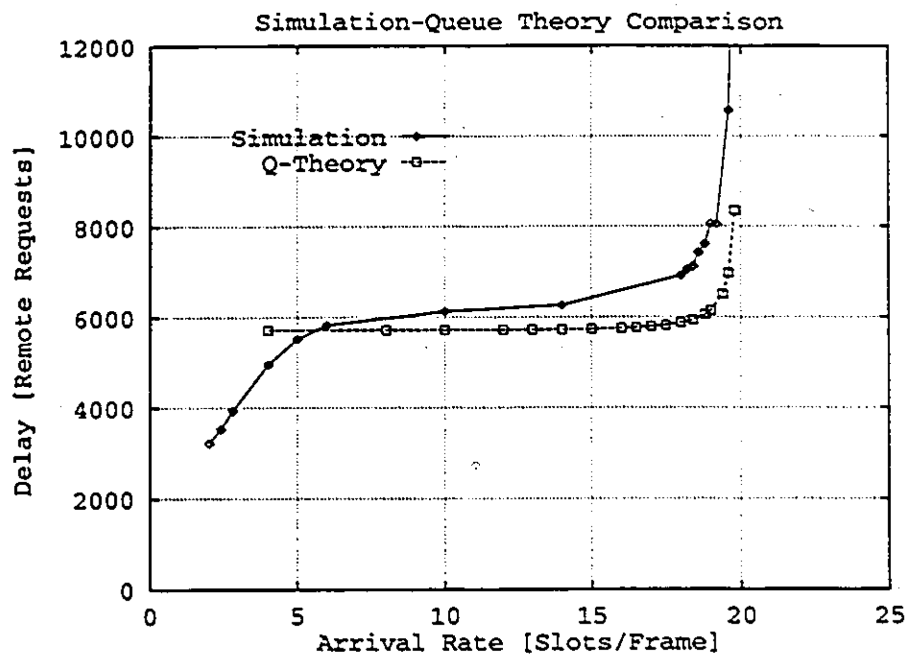

Figure 5.22: Protocol 3: $t_{rf} = 1090$

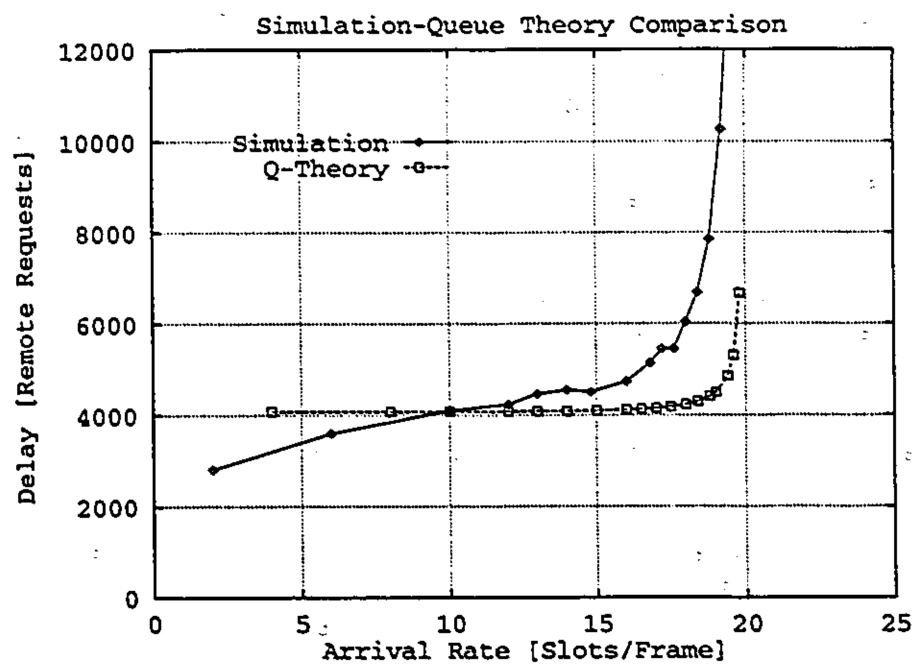

Figure 5.23: Protocol 4: $t_{rf} = 1090$

star propagation delay of $P = 5$ request minislots. A remote slot block size of 100 data slots was used for protocols 1, 3, 4, 5, while Protocol 2 used a slot block of 25 data slots due to its constrained remote frame size and large number of slot blocks. Figures 5.25 through 5.29 present the uniform packet access delay-throughput results for protocols 1 through 5. Delay is normalized to the request minislot duration, and throughput is the aggregate channel throughput, normalized to the full bandwidth of a remote channel, expressed as a percentage. A throughput of 100% indicates the entire bandwidth of the remote channel is used for useful data transmission. Results for protocols 1, 2 and 5 show access delay versus throughput curves with similar shapes, a low relatively constant access delay which increases rapidly as the slot block capacity is approached. Protocols 3 and 4 exhibit slightly different behavior due to sharing of remote minislots, this is a function of the number of remote minislots to active station ratio, and the remote request hold time. The plots of figures 5.27 and 5.28 show cases with $R = 8$ and $R = 5$ remote minislots, for $N_A = 10$ active stations and a hold time of $H = 2$ frames. As R approaches N_A the delay curves tend to move towards that of Protocol 1, while as R decreases with respect to N_A the access delay increases approximately linearly with increasing throughput, nearly to channel capacity. A decrease in maximum achievable throughput occurs due to an increase in overhead caused by an increase in the number remote minislots is also shown for protocols 3 and 4.

5.4.2 Non-Uniform Traffic Loading

In this experiment, the group of active stations generates data packets with different Poisson arrival rates, to observe the ability of the remote medium access protocols to share unused capacity among heavily loaded stations, and investigate delay coupling effects. Ideally, unused bandwidth from a low loaded station which requires less than its fair share of remote channel capacity should be shared fairly among heavily loaded stations without adverse effects on the low loaded stations. From a group of $N_A = 10$ active stations generating data to a single destination remote channel, eight have a low packet throughput of approximately 5% of slot block capacity, while the remaining two stations have their packet generation rate varied. Figures 5.30

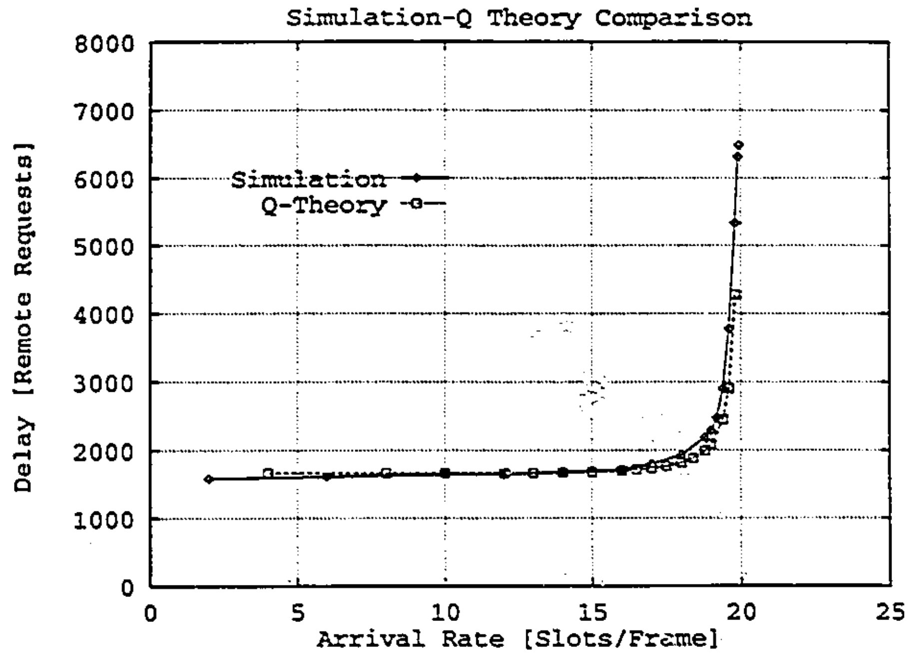

Figure 5.24: Protocol 5: $t_{rf} = 1300, t_{LF} = 521$

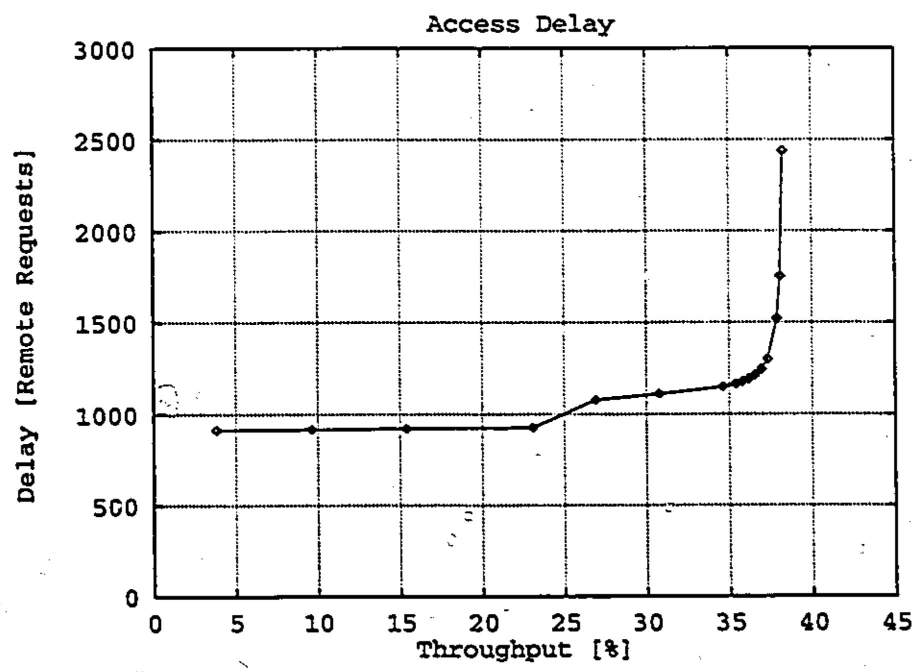

Figure 5.25: Protocol 1 (Slot Block Size=100)

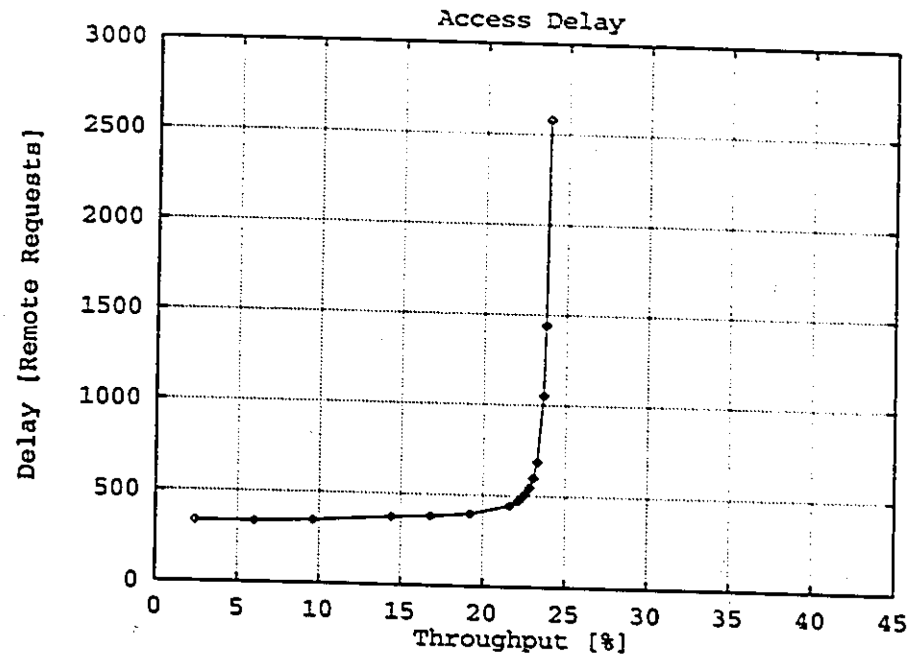

Figure 5.26: Protocol 2 (Slot Block Size=25)

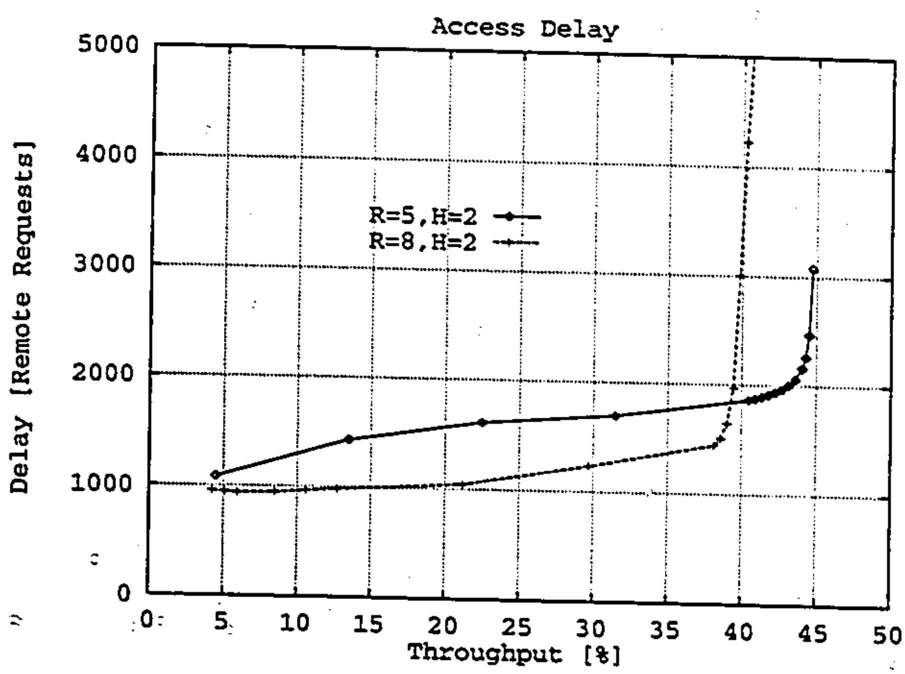

Figure 5.27: Protocol 3 (Slot Block Size=100)

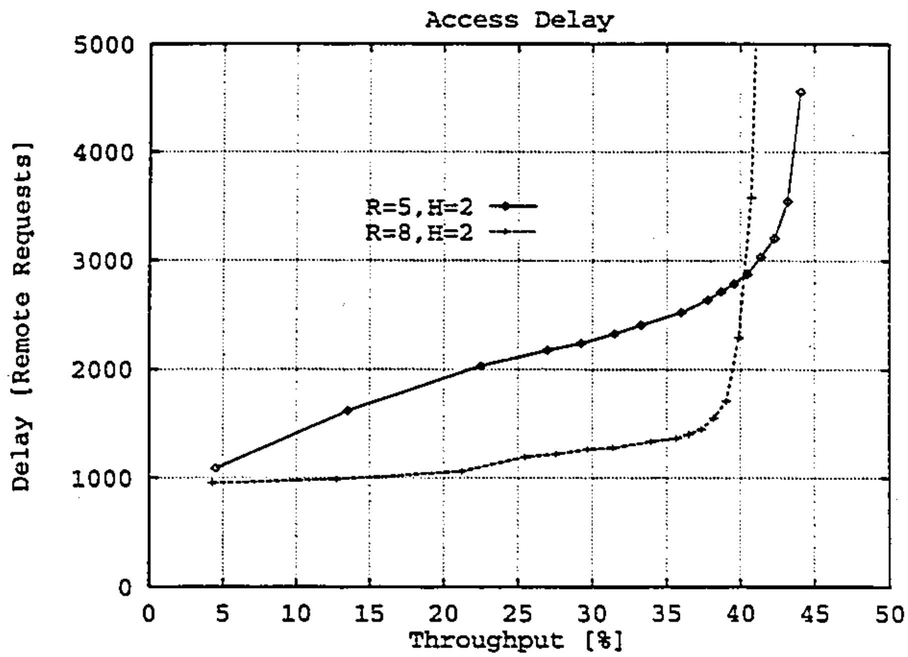

Figure 5.28: Protocol 4 (Slot Block Size=100)

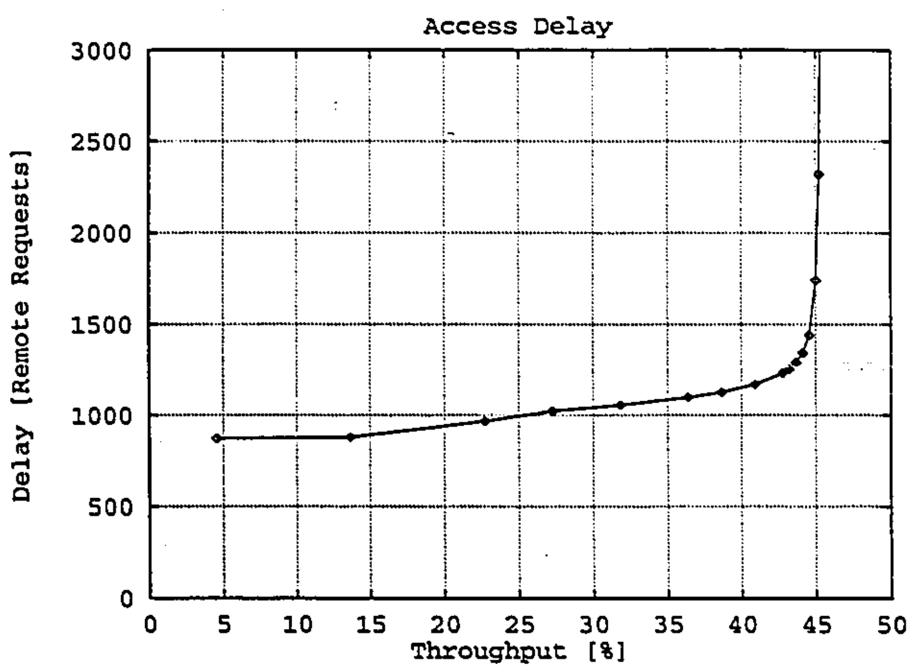

Figure 5.29: Protocol 5 (Slot Block Size=100)

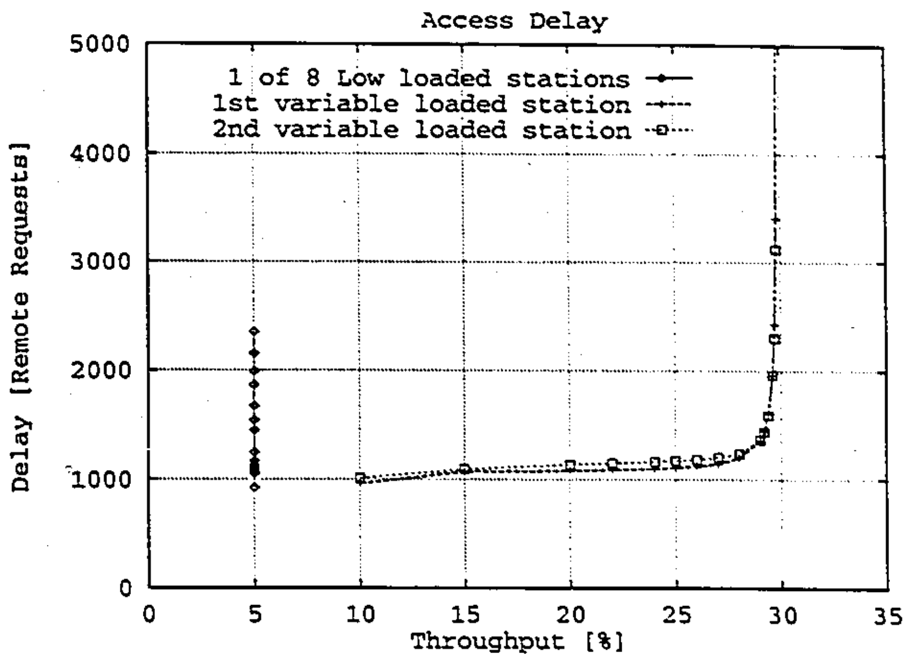

Figure 5.30: Protocol 1 (Slot Block Size=100)

through 5.34 illustrate non-uniform delay-throughput plots for one low loaded station and both variable loaded stations, for protocols 1 through 5. Throughput is the station throughput, normalized to remote slot block capacity expressed as a percentage, therefore a throughput of 100% indicates that all data slots within the slot block are used by the station. Four features are evident for all five remote protocols. First, the two fixed loaded stations do not suffer a loss in throughput on the remote channel as the heavily loaded stations increase channel throughput to near capacity. Second, the access delay experienced by fixed loaded stations increases as the aggregate throughput on the channel increases, this is delay coupling which was discussed in relation to the DCCN architecture of the previous chapter. Third, the two heavily loaded stations are able to share unused remote channel capacity equally, providing a degree of fairness among stations. Fourth, aggregate remote channel throughput from all stations approaches the full capacity of the slot block, demonstrating the dynamic ability of the reservation protocols to utilize the full channel bandwidth.

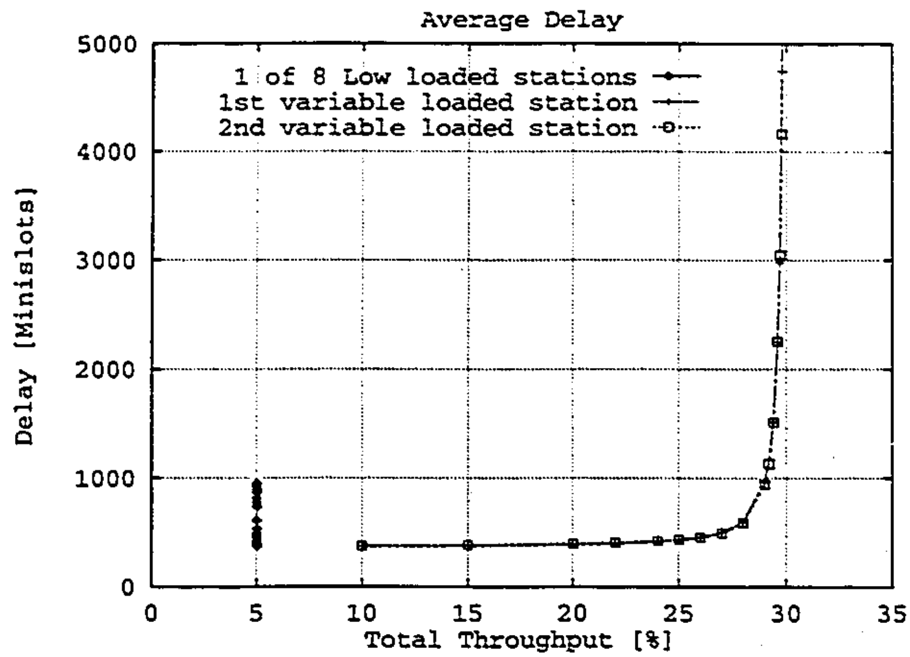

Figure 5.31: Protocol 2 (Slot Block Size=25)

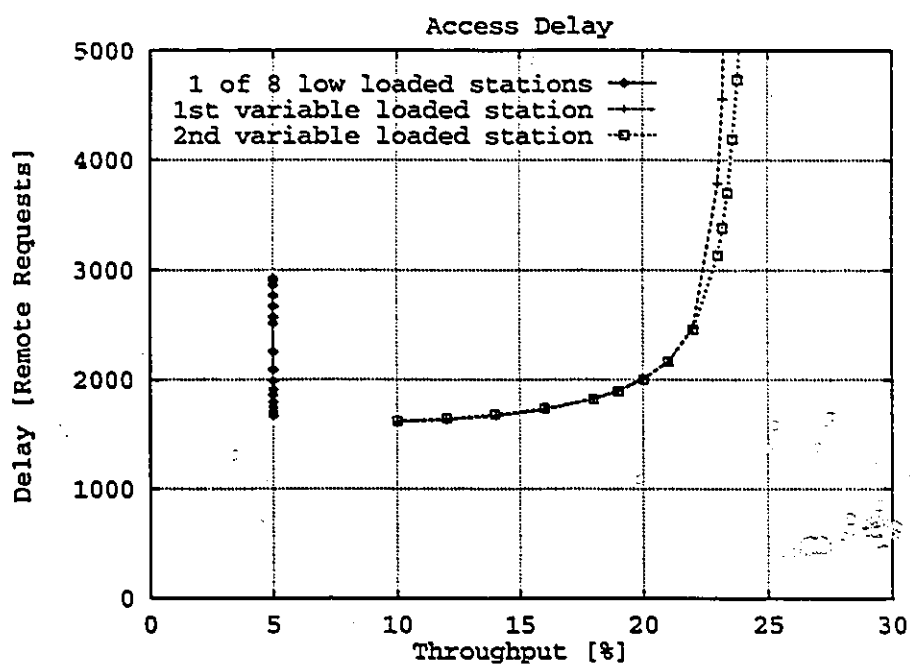

Figure 5.32: Protocol 3 (Slot Block Size=100)

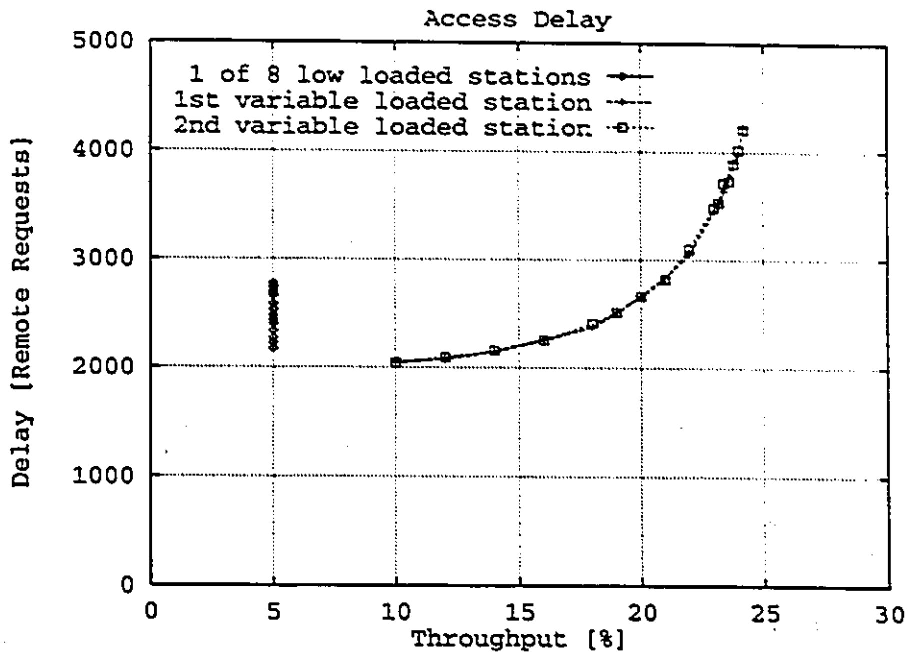

Figure 5.33: Protocol 4 (Slot Block Size=100)

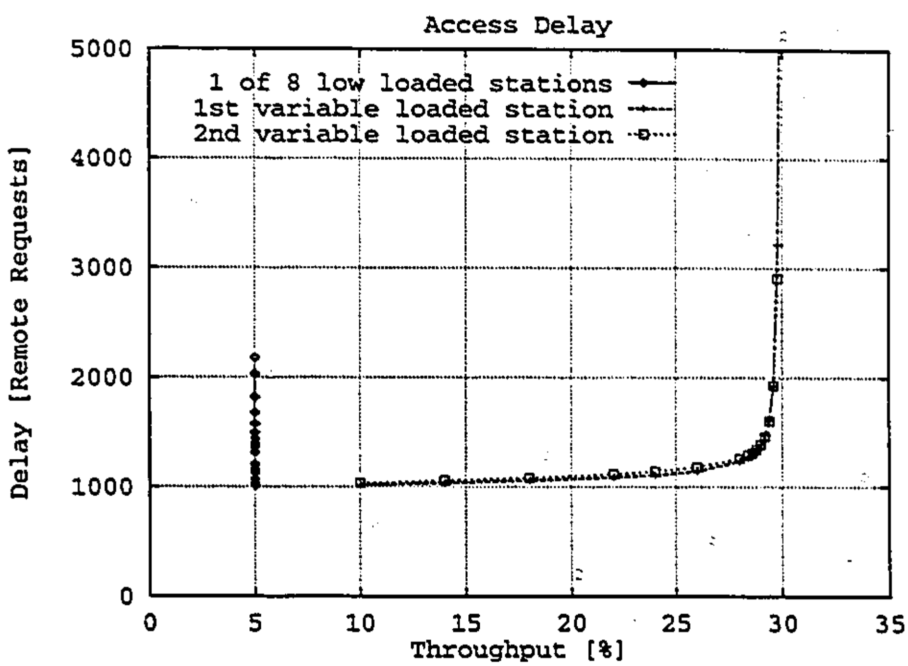

Figure 5.34: Protocol 5 (Slot Block Size=100)

5.5 Discussion

In this chapter a single-hop network using two level hierarchical spatial wavelength reuse was presented. Station hardware was increased by only a single fixed receiver per station over that required for DCCN, while maintaining the single hop nature of the network. Wavelength channels are divided into local channels which are spatially reused within each LON, and remote channels which are shared by all stations. The network extended the use of channel controllers from the fully broadcast and select environment, to the partial broadcast and select environment, by introducing both local and remote channel controllers. As a consequence of the two level hierarchy, both a local and remote medium protocol were used. The local protocol was identical to that used for DCCN, while five single hop remote packet switched medium access protocols were described and analyzed. Since the remote channels are a shared resource among a large number of stations, efficient channel utilization was a key design requirement, achieved through a coupling of the remote medium access protocol with the local medium access protocol. All five remote protocols were able to allocate data slots dynamically to stations with non-uniform packet demands, with varying degrees of delay coupling. Protocols 3 and 4 introduced sharing of remote request minislots among stations, this allowed remote channel controller processing loads to be reduced at the expense of some degradation in delay performance. Protocol 5 was able to increase remote channel capacity by spatially reusing local wavelength channels on the RON for request signaling purposes.

Although the hierarchical network topology increases total network capacity, it also has inherent disadvantages. If the packet loading patterns do not indicate that strong communities of interest exist among stations connected to the same local optical network then a majority of the channels must be used as remote channels, reducing total network capacity, or the remote channels become a point of packet congestion. A number of specific disadvantages are also present in the proposed design. Each station requires an additional fixed tuned receiver, separate local and remote medium access protocols and additional remote channel controllers to coordinate remote channel access. In the next chapter another single hop wavelength routed network based on non-hierarchical wavelength reuse, rather than a hierarchical mechanism is presented and analyzed. Using this approach individual wavelength channels are routed between local optical networks rather than wavebands. As a result, more complex wavelength routing devices and medium access protocols are required.

Chapter 6

Non-Hierarchical Wavelength Reuse

Hierarchical wavelength reuse as a mechanism to increase network capacity with a limited number of wavelength channels is restricted to networks which exhibit a significant degree of stable long term traffic locality among stations connected to the same local optical network. If this criterion is not satisfied then network throughput can be degraded, or congestion can occur on the shared internetwork wavelength channels. A number of researchers have proposed a different technique to increase network capacity based on non-hierarchical, or flat wavelength spatial reuse, the general topology and characteristics of which were discussed in chapter 3. An attractive feature of hierarchical partial broadcast and select networks, including those presented in the previous chapters is the ability of a station to receive its own data and control packet transmissions from the channel. This feature can be exploited by the medium access protocol to provide synchronization and channel status information, as was done for the reservation medium access protocols of EDCCN. Non-hierarchical networks are different, a station is not able to receive its own data or control packets, and as a result network topology and medium access protocol complexity increases.

In this chapter the work undertaken on the development of a single hop packet switched network referred to as the Flat Channel Controller Network, or FCCN as presented in [JT96] is described and analyzed. Stations are divided into local optical clusters according to their geographic location and interconnected via a wavelength cross connect which performs static wavelength routing. Channel controllers are incorporated into each local optical cluster as a mechanism to reduce station optical hardware and medium access protocol complexity. Two local optical cluster variations are investigated. The first uses a control channel time multiplexed on the data channels, similar to the medium access protocols of DCCN and EDCCN, while the second uses a dedicated spatially reused control channel within each local optical cluster. Wavelength converters are also introduced into the design of the local optical clusters, these map packets from their transmitted wavelength to a local wavelength channel, allowing stations to use a single fixed receiver rather than a tunable receiver for data packet reception. Three medium access protocols are considered with the proposed network, fixed TDMA and two collision free reservation protocols. Using the fixed TDMA protocol, each station has dedicated data slots pre-assigned on each wavelength channel, while the reservation protocols assign data slots on a demand basis using channel controllers. Capacity and delay-throughput performance results are presented using network simulators and queuing theory models. In addition, comparisons are made with the proposed MANDALA network [Mat93] which uses a similar network topology and random medium access protocol.

The contributions of this work are the advancement of non-hierarchical wavelength routed networks through the introduction of channel controllers, wavelength converters and collision free reservation medium access protocols. It was found that the reservation protocols allowed better utilization of spatially reused channels than the single global control channel random access protocol of MANDALA.

6.1 Network Architecture

The physical network architecture of FCCN is motivated in part by the flat interconnection pattern of the MANDALA network and by the channel controllers of DCCN as illustrated by figure 6.1. The network uses a partial broadcast and select topology created with a static wavelength routing cross connect. Stations are divided into local optical clusters, or LOCs based on their geographic location. The LOCs are optically

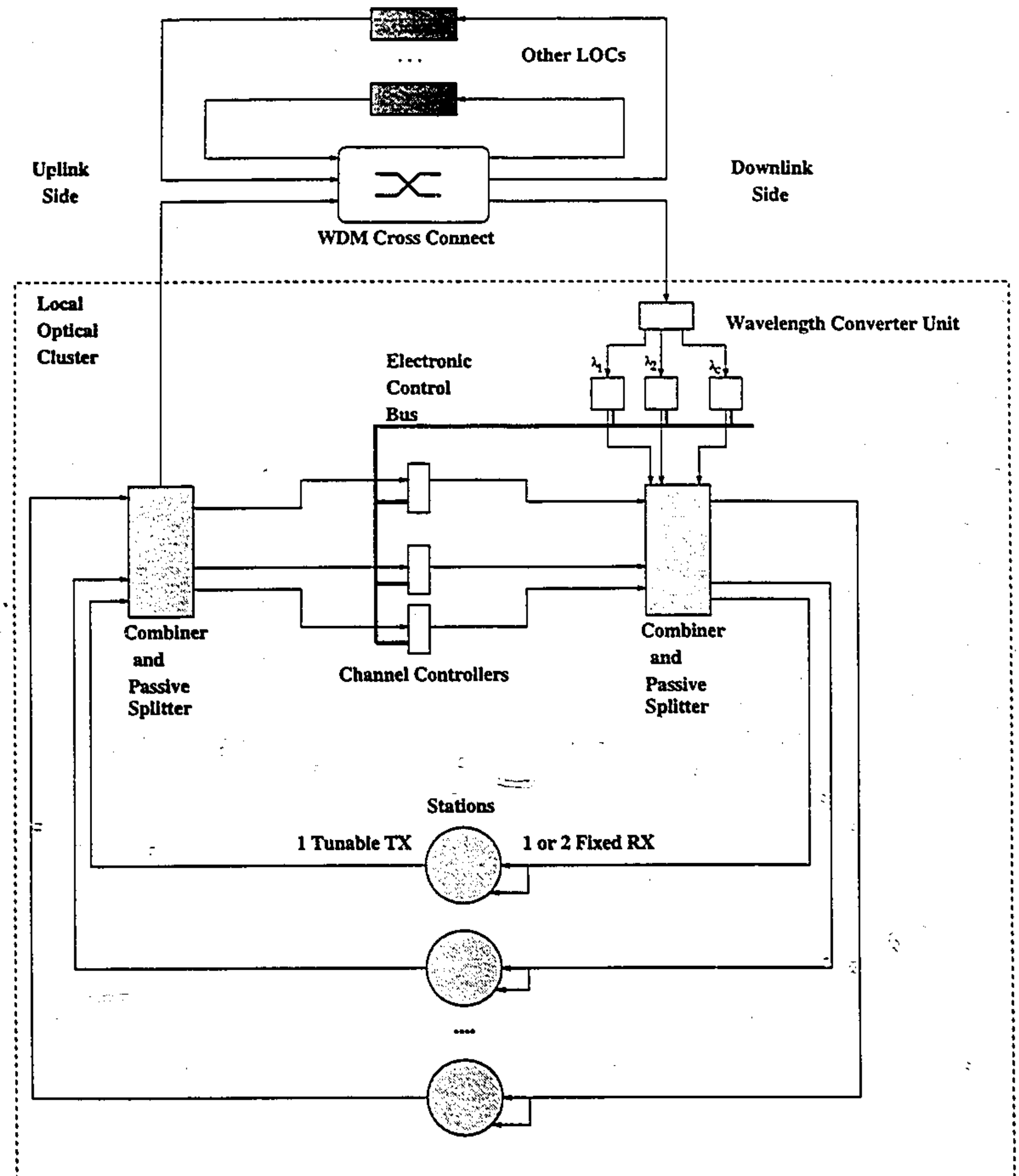

Figure 6.1: FCCN Physical Network Architecture with expanded detail of a Local Optical Cluster (LOC)

interconnected to a single WDM cross connect, using an uplink and downlink fiber pair, which maps a wavelength λ_i on input port P_{in} to output port P_{out}. This mapping function can be described as

$$P_{out} = \omega(P_{in}, \lambda_i). \tag{6.1}$$

Spatial wavelength reuse is achieved by routing a single wavelength channel from each source LOC to a single destination LOC, with the constraints that the same wavelength channel from different input ports does not map to the same output port,

$$\omega(i, \lambda_k) \neq \omega(j, \lambda_k), \quad i, j, k = \{1 \cdots C\}, i \neq j, \tag{6.2}$$

and multiple wavelength channels from the same input port do not map to the same output port,

$$\omega(k, \lambda_i) \neq \omega(k, \lambda_j), \quad i, j, k = \{1 \cdots C\}, i \neq j. \tag{6.3}$$

Using this configuration a total of C^2 spatial-wavelength channels are created from C wavelength channels, and C LOCs can be connected to the network. An example cross connect for a network with $C = 4$ wavelength channels is illustrated by figure 6.2. For channels from source LOC 1, wavelength λ_1 is routed to LOC 1, λ_2 to LOC 2, λ_3 to LOC 3 and λ_4 is routed to LOC 4. Other channel connection patterns between LOCs are also possible, for example multiple wavelength channels can be routed between pairs of LOCs, a single wavelength channel from source LOC i can be routed to many destination LOCs, or a common wavelength λ_i from many source LOCs can be routed to the same destination LOC j. Each of these variations adds complexity to medium access protocol design, and are not considered in this thesis.

A local optical cluster connects a set of stations to the network, each is connected to the WDM cross connect via a direct uplink fiber, and a downlink fiber which passes through a wavelength converter unit. This unit consists of C independent wavelength converters, one for each incoming wavelength channel, as depicted by figure 6.1. At this point some common terminology is presented to simplify the remainder of the discussion. The *Local Uplink Channels* are wavelength channels sourced by station transmitters within a LOC, while *Remote Uplink Channels* are those between the LOC

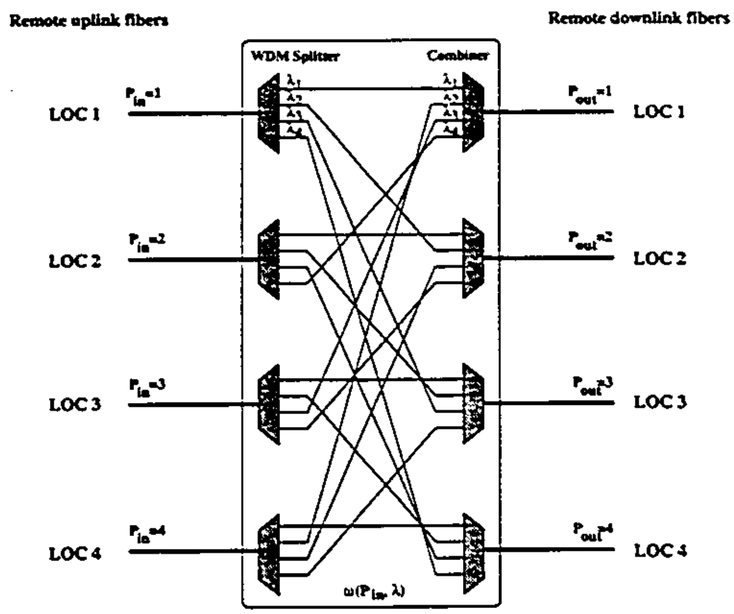

Figure 6.2: WDM cross connect internal routing detail for a four channel four LOC network

and the input side of the WDM cross connect. For all networks under consideration local uplink channels map directly to remote uplink channels. The *Remote Downlink channels* are those between the output side of the WDM cross connect and the input to the wavelength converter unit, while the *local downlink channels* originate at the output of the wavelength converter unit and terminate at the station receivers. Each wavelength converter is assigned a unique input wavelength on the remote downlink side and maps this to a single output wavelength λ_{out} on the local downlink side. The output wavelength is a function of time and is based on a fixed and repetitive tuning schedule provided by one of the channel controllers via the electronic control bus. The wavelength translation function is dependent on the LOC, the wavelength converter and time, and can be described as

$$\lambda_{out} = \Omega(loc, wlc, t), \tag{6.4}$$

where *loc* is the LOC, *wlc* is the wavelength converter within the LOC, and $0 < t < t_f$ is time. Output contention arbitration, information interpretation or buffering are not provided by these devices. If two or more attempt to output to the same local downlink channel at the same instant of time then the information is garbled.

Two variations of the LOC architecture are considered. The first uses a control channel time multiplexed on the data channels within each LOC, and is referred to as Distributed Control with Wavelength Converter, or DCWC. The second uses a dedicated control channel within each LOC, and is referred to as Common Control with Wavelength Converter or CCWC.

The DCWC variation uses all C wavelength channels, $\{\lambda_1 \dots \lambda_C\}$ as data channels. Channel controllers are configured with a single fixed or slow tunable transmitter and receiver pair, tuned to a unique channel. Each station is configured with a single fast discrete tunable transmitter and a single fixed or slow discrete tunable receiver. The receiver is fixed tuned to a pre-assigned local home channel from which it receives both data and signaling information, while the tunable transmitter is able to tune to all channels, and is used for data and signaling information. The number of stations assigned to home channel j of loc i is defined as $N(i,j)$ while the total number of stations within the LOC is defined as $N_{loc}(i) = \sum_{j=1}^{C} N(i,j)$. The salient features of the network are described with the logical architecture of figure 6.3. This shows the local and remote uplink channels, the local and remote downlink channels, channel controllers, wavelength converters, and their interconnection topology.

The CCWC variation dedicates one wavelength channel, λ_1 as a common control channel, while the remaining $C-1$ wavelength channels are data channels. Each station contains a single fast discrete tunable transmitter, a single slow discrete tunable or fixed receiver and a second fixed receiver. The first receiver is fixed tuned to a pre-assigned local home channel from which it receives only data packets, while the tunable transmitter is able to tune to all channels and is used for data and signaling information. The second receiver is fixed tuned to the control channel and is used exclusively for reception of control and synchronization information. The number of stations assigned to home channel j of LOC i is defined as $N(i,j)$ while the total number of stations within the LOC is defined as $N_{loc}(i) = \sum_{j=2}^{C} N(i,j)$. The logical architecture, illustrated by figure 6.4 differs slightly from that of DCWC. Channel controllers are configured with a single fixed transmitter and receiver pair, and communicate using the dedicated control channel rather than a time multiplexed portion

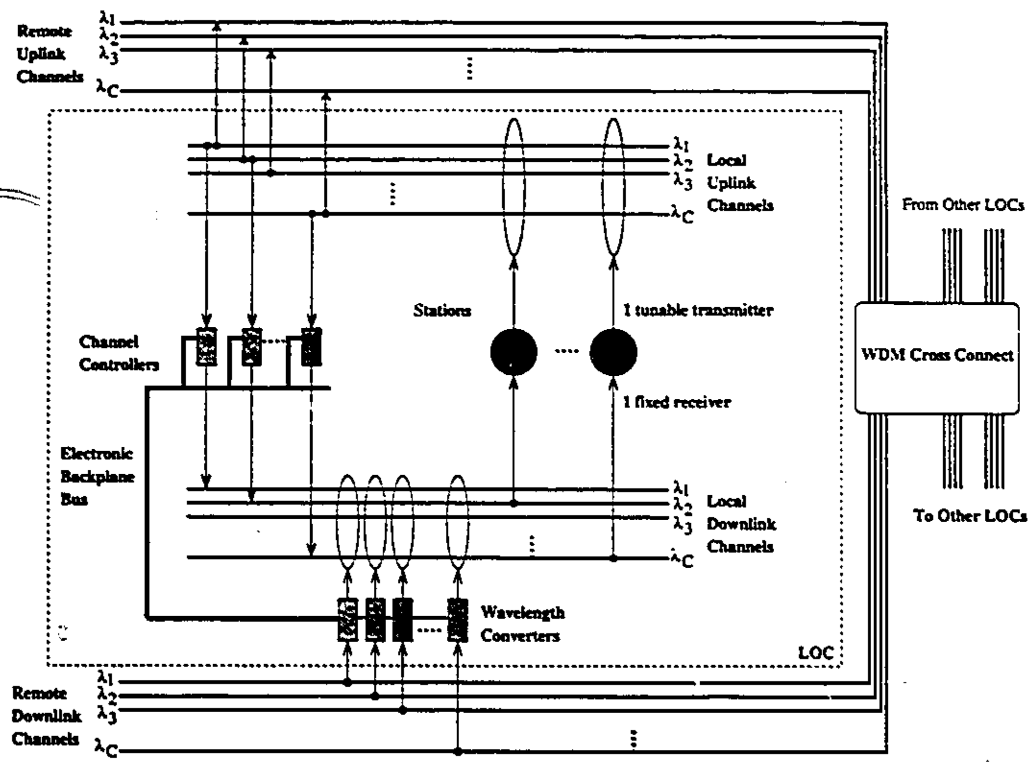

Figure 6.3: DCWC Logical Architecture

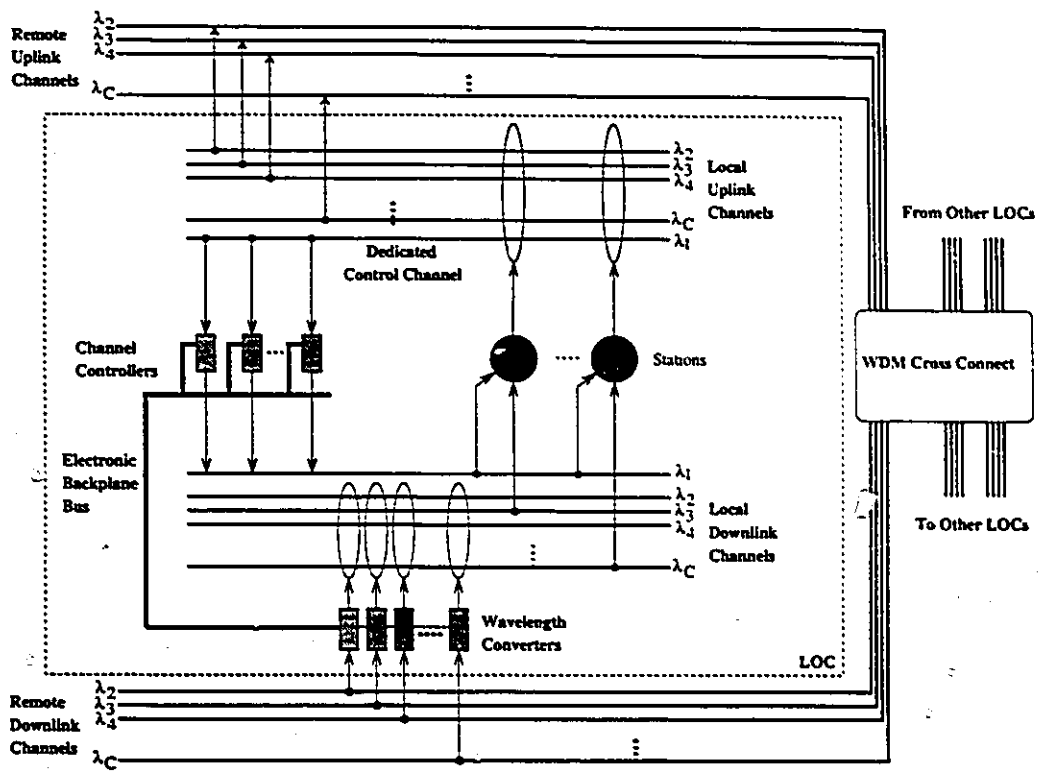

Figure 6.4: CCWC Logical Architecture

of the data channels.

6.2 Network Operation

A number of packet switched single hop medium access protocols are proposed and investigated for the DCWC and CCWC networks. The first protocol uses interleaved TDMA, while two others, RES1 and RES2 are collision free reservation protocols. The TDMA and RES1 protocols are considered for use with the DCWC network, while the RES1 and RES2 protocols are considered for use with the CCWC network, and referred to as DCWC-TDMA, DCWC-RES1, CCWC-RES1 and CCWC-RES2. For each protocol a description of the frame formats imposed over data and control channels is provided along with descriptions of the procedures and protocols used to control the wavelength converters, channel controllers and stations.

6.2.1 DCWC-TDMA

A repetitive time multiplexed frame of duration t_f is imposed on each local uplink wavelength channel consisting of a control subframe and an information subframe as illustrated by figure 6.5a. The control subframe has significance only within the local cluster. The downlink control subframe is of duration t_{dlc} consisting of a synchronization marker generated by the channel controller, while the uplink control subframe is unused since signaling information is not transmitted by stations to their channel controllers. The information subframe is of duration t_{info} and consists of D data slots of fixed size δ time units. Subframe and total frame durations can be calculated as

$$t_{dlc} = \gamma + \sigma, \tag{6.5}$$

$$t_{info} = D \cdot (\gamma + \delta), \tag{6.6}$$

$$t_f = t_{sync} + t_{info}, \tag{6.7}$$

where γ is the duration of a guard time and preamble. Since single-hop packet communication is required each station in a LOC must have a dedicated data slot on each local downlink channel of each cluster. This is accomplished by pre-assigning C

data slots on each of the C local uplink channels to each station in the LOC, for a total of

$$D = N_{loc}(i) \cdot C \tag{6.8}$$

data slots per frame in LOC i. The location of these is considered after discussing the tuning schedules assigned to the wavelength converter banks. The converters are provided with a fixed conversion schedule which allows each to translate the input wavelength on the remote downlink side to all of the local downlink wavelengths on the output side once per frame. Since a wavelength is sourced by stations on a particular LOC, the converter translates data packets transmitted from one source LOC to the local wavelengths of its own LOC, therefore the set of converters translates data packets from the entire network onto its own local set of spatial-wavelength channels. An example tuning schedule for a $C = 4$ channel network is illustrated by figure 6.5b. The tuning portion labeled as "idle" indicates a period when the wavelength converters do not output to allow the control subframe to circulate on the local downlink channels. Considering the wavelength converter with input channel λ_1, it translates packets first to λ_1, then λ_2, then λ_3, and finally λ_4. This sequence repeats, and does not conflict with the output of the remaining three wavelength converters. A station must have one of its pre-assigned data slots in each slot block of each local uplink channel to have full single-hop connectivity, this is achieved by simple slot interleaving. Figure 6.5c illustrates data slot assignments for a $C = 4$ channel, $N_{loc}(i) = 6$ station per LOC network, numbers in the data slot indicate station assignment. In this case wavelength converters are required to switch output channel every $N_{loc}(i)$ data slots. When a station has a data packet to transmit, it must determine the local wavelength channel associated with the LOC of the destination station, the home channel of the destination station and then transmit the data packet into the appropriate data slot.

The TDMA protocol requires all frames on all local channels of all LOCs to be of the same duration and aligned with respect to the output side of the WDM cross connect. This protocol has no dynamic data slot assignment capability, and as a result channel controllers are only required to provide frame synchronization signals

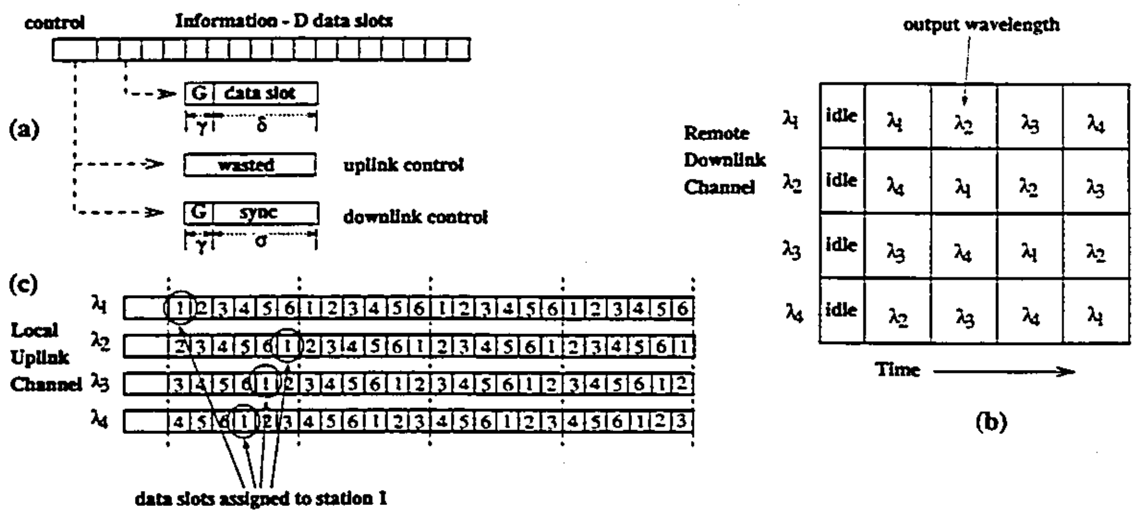

Figure 6.5: DCWC-TDMA network. (a) Data channel frame format. (b) Wavelength converter tuning schedule for $C = 4$ wavelengths. (c) Interleaved data slot assignments for $C = 4$ channels, $N_{loc}(i) = 6$ stations.

and control the wavelength converters.

6.2.2 DCWC-RES1

The RES1 medium access protocol is a reservation protocol similar to that described for the DCCN. Each local uplink channel in a LOC is controlled by a single channel controller, and stations make requests to their channel controller using the uplink control channel and receive data slot allocations on the downlink control channel. A repetitive time multiplexed frame structure is imposed on each data channel consisting of a control subframe and an information subframe as illustrated by figure 6.6. The information subframe is of duration t_{info}, and contains D data slots of fixed duration δ time units. The uplink control subframe is of duration t_{ulc}, and divided into R request minislots of duration ρ time units, while the downlink control subframe is of duration t_{dlc}, and divided into a synchronization marker of duration σ, and A allocation minislots of duration α time units. All request minislots and the downlink control subframe are preceded by a guard time of duration γ time units to absorb timing errors and provide receiver bit synchronization. Subframe and total frame

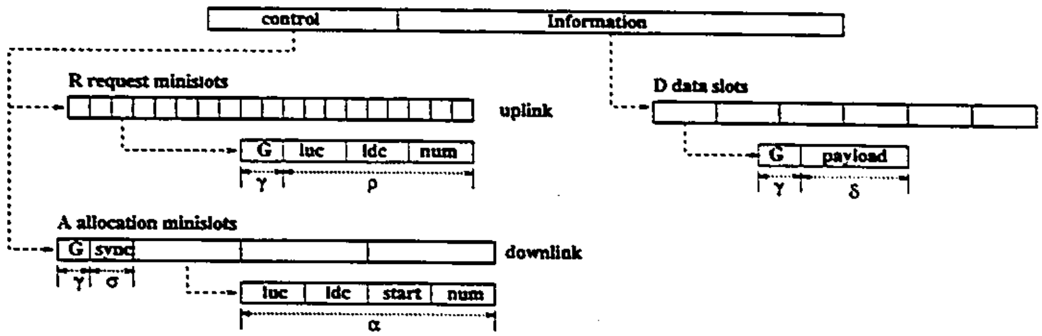

Figure 6.6: Data channel frame format for the RES1 medium access protocol on the DCWC network.

durations can be calculated as

$$t_{info} = D \cdot (\gamma + \delta), \quad (6.9)$$

$$t_{ulc} = R \cdot (\gamma + \rho), \quad (6.10)$$

$$t_{dlc} = \gamma + \sigma + A \cdot \alpha, \quad (6.11)$$

$$t_f = t_{info} + \max(t_{ulc}, t_{dlc}). \quad (6.12)$$

Each station in the LOC is pre-assigned a dedicated request and allocation minislot within the control subframe on its assigned home channel, consisting of a destination local uplink channel identifier (luc), a destination local downlink channel identifier (ldc) and the number of data slots reservations (num). Allocation minislots are generated by a channel controller, are used to inform stations when and where they can transmit data slots, and consist of an uplink channel identifier (luc), a downlink channel identifier (ldc), the start slot within the frame for transmission (start) and the number of contiguous data slots (num) which can be transmitted. Slot allocations are determined by a station's home channel controller using a combination of fixed slot block assignments for inter-cluster and channel controller to cluster communication, and dynamic slot assignment using station data slot requests.

Inter-cluster slot block assignment is the first level of data slot blocking imposed on each frame. Considering each LOC separately, data slots within a frame on each local uplink channel i are divided into sets of contiguous slot blocks, one for each local downlink channel j at the destination LOC associated with the local uplink

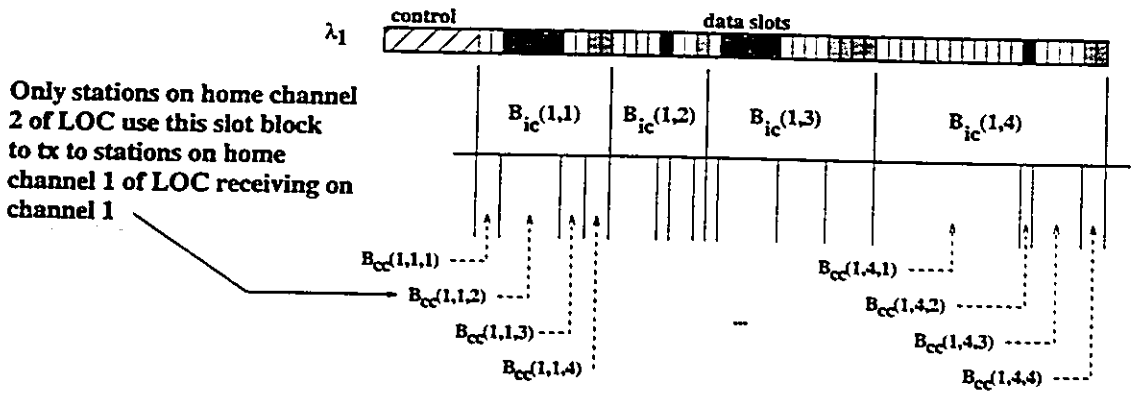

Figure 6.7: Data Slot Blocking for the RES1 protocol on the DCWC network. Example showing channel λ_1 of a $C = 4$ channel network.

channel, and identified as slot block $B_{ic}(i,j)$. These block allocations also dictate the tuning schedule for the wavelength converter at the destination LOC. Complexity arises in the system wide inter-cluster slot block allocations due to the constraint that non-overlapping slot blocks must exist on each local downlink channel, however algorithms for determining the inter-cluster block allocation are not investigated by this thesis, and not discussed any further.

Channel controller slot block assignment is the second level of slot blocking. Each inter-cluster slot block, $B_{ic}(i,j)$ is further divided into C contiguous blocks of data slots, one for each channel controller k in the LOC, and identified as slot block $B_{cc}(i,j,k)$. Thus, the total number of contiguous data slot blocks per local uplink channel is C^2. Data slots within slot block $B_{cc}(i,j,k)$ are reserved for exclusive use of stations associated with channel controller k, to which the slot blocks have been assigned.

Figure 6.9 illustrates an example frame on channel λ_1 for a system with $C = 4$ wavelength channels. This shows the data slots divided into four large slot blocks $B_{ic}(1,j)$, one for each channel $j = \{1,2,3,4\}$, at the destination cluster, which are mapped by the wavelength converter at the destination cluster. The figure also shows each of the slot blocks further divided into four smaller slot blocks $B_{cc}(1,j,k)$, one assigned to each channel controller $k = \{1,2,3,4\}$, within each inter-cluster slot block $j = \{1,2,3,4\}$.

Individual data slot assignment to stations is achieved through a reservation protocol. A station makes slot requests to its home channel controller once per frame using its dedicated request minislot, while the channel controller processes requests from its set of stations and makes slot allocations once per frame. Stations listen to their dedicated allocation minislot for transmit authorization into one or more contiguous slots on a specified channel. This protocol is identical to that described for the DCCN, with the requirement that a source station know both the LOC and local home channel assignment of the destination station. Similar to the TDMA medium access protocol, this requires global frame synchronization across all channels of all LOCs due to the use of tuning schedules at the destination LOC wavelength converters.

6.2.3 CCWC-RES1

The RES1 protocol used with the CCWC network configuration is similar to the DCWC network, the differences are the use of a single dedicated control channel, and stations no longer associated with a home channel controller. Each channel controller must be able to generate data slot allocations to *all* stations in the LOC. A repetitive time multiplexed frame structure is imposed on each data channel and the control channel, as illustrated by figure 6.8. The data channel frame is of duration t_{info} and consists of D data slots of fixed duration δ time units. The uplink control channel frame is of duration t_{ulc}, consisting of R request minislots, one for each station in the LOC, with the same fields (*luc, ldc, num*) as described for DCWC. The downlink control channel frame is of duration t_{dlc}, consisting of S status subframes, one generated by each channel controller in the LOC. Each subframe consists of a A allocation minislots, one for each station in the LOC, with the same fields (*luc, ldc, start, num*) as described for DCWC. Subframe and total frame durations can be calculated as

$$t_{info} = D \cdot (\gamma + \delta), \tag{6.13}$$

$$t_{ulc} = R \cdot (\gamma + \rho), \tag{6.14}$$

$$t_{dlc} = \gamma + \sigma + S \cdot (\gamma + A \cdot \alpha), \tag{6.15}$$

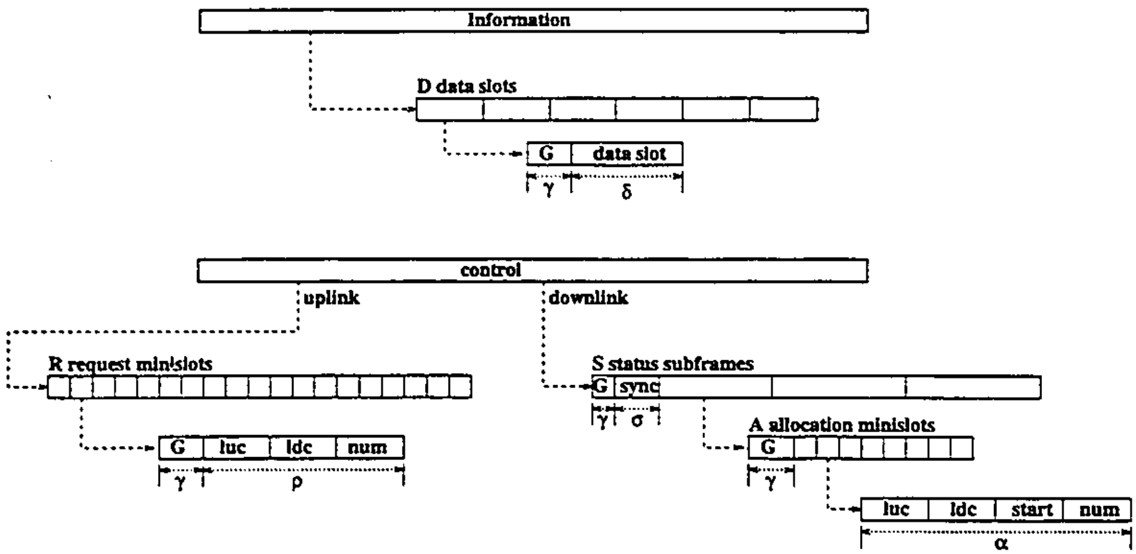

Figure 6.8: Data and control channel frame formats for the RES1 protocol on the CCWC network.

$$t_f = \max(t_{info}, t_{ulc}, t_{dlc}). \tag{6.16}$$

Similar to DCWC, data slots on each local uplink channel i are divided into $C-1$ contiguous inter-cluster slot blocks, $B_{ic}(i,j)$, where $j = \{2 \cdots C\}$ is the local downlink channel at the destination LOC of local uplink channel $i = \{2 \cdots C\}$. However, unlike DCWC the second level of slot blocking is not required, and a channel controller has direct control over a single local uplink channel, since it makes data slot allocations exclusively on a single local uplink channel rather than into multiple slot blocks on $C-1$ local uplink channels.

An example of data channel slot blocking for a $C = 4$ channel network is illustrated by figure 6.9, showing three data slot blocks on local uplink channel λ_2. At the destination LOC associated with channel λ_2 these slot blocks are demultiplexed onto three local downlink channels by the wavelength converter. The data slot assignment protocol is identical to that described for DCWC-RES1. Dynamic performance of this network may improve over that of DCWC-RES1 since fewer slot blocks are required on a local uplink channel. This is achieved at the expense of an added fixed receiver per station, and increased request and allocation processing by channel controllers.

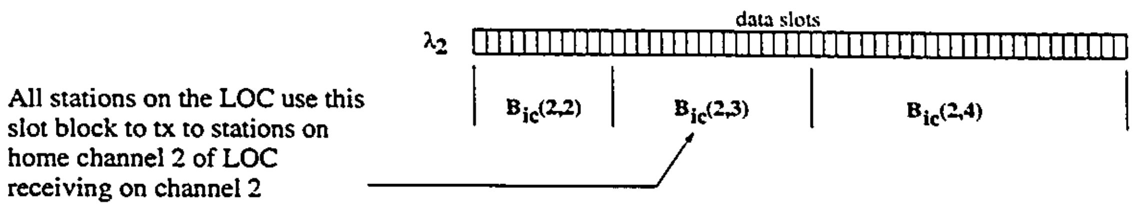

Figure 6.9: Data Slot Blocking for the RES1 protocol on the CCWC network. Example showing channel λ_2 of a $C = 4$ channel network.

6.2.4 CCWC-RES2

The RES2 protocol used with the CCWC network configuration eliminates the requirement that each channel controller be capable of processing requests and generating allocations for all stations in the LOC. This is achieved through channel controller resource sharing, with a similar technique proposed with the remote channel medium access protocols of the EDCCN. Rather than assigning each station in the LOC dedicated allocation processing resources and allocation minislots with each channel controller, the RES2 medium access protocol provides each channel controller with a limited set of allocation processing resources, and requires a station to acquire permission to use an allocation minislot before making data slot requests. As with the CCWC-RES1 configuration, each local channel controller has domain over a single local uplink channel, and handles all requests to that channel.

Control and data channel frame formats are illustrated by figure 6.10. The uplink and downlink control channels are similar to those of CCWC-RES1 with the addition of a command field (*cmd*) to a stations dedicated request minislot, and a status field (*status*) to the allocation minislot. The data channel format, subframe and total frame durations, data channel slot blocking and the reservation medium access protocol are all identical to that described for CCWC-RES1.

The difference between protocol RES1 and RES2 is the addition of a mechanism for stations to dynamically acquire use of allocation minislots from a channel controller by using the command and status fields of the uplink and downlink control channels, and a channel controller arbitration protocol. In every uplink control frame a station generates one of four possible commands using the *cmd* field, these are

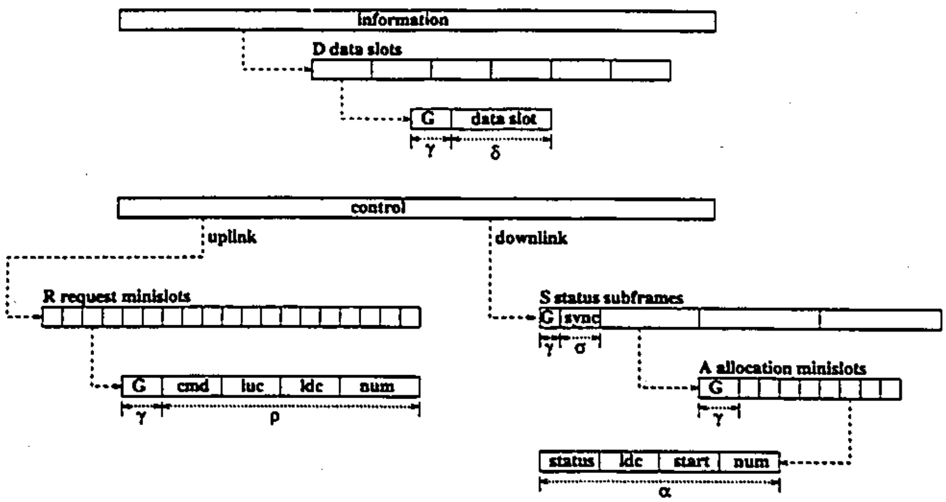

Figure 6.10: Data and control channel frame formats for the RES2 protocol on the CCWC network.

request, *reservation*, *release* or *idle*. The command is addressed to the channel controller specified by the *luc* field of the request minislot. Using the *status* field of an allocation minislot a channel controller generates one of three possible commands, these are *assigned*, *release* or *idle*. The state of the arbitration protocol between a station i and a channel controller j is divided into two phases of operation, acquisition and utilization.

During the acquisition phase station i does not have use of an allocation minislot with channel controller j. Station i issues a *request* command addressed to channel controller j indicating that it requires data slots on its local uplink channel. After receiving this command, channel controller j determines if it has free allocation minislots available. If one is free then the allocation minislot is marked as busy and an *assigned* command is returned in the allocation minislot of subsequent frames, addressed to the appropriate station. If an allocation minislot is not available then the request is queued and processed when one becomes available.

The utilization phase of the arbitration protocol occurs as long as station i receives allocation minislots from channel controller j with the *assigned* command. During this phase station i can make data slot requests to channel controller j using the *num* and *ldc* fields and the *reservation* command. Use of an allocation minislot can be terminated by a station or by a channel controller. A station can issue the *release* command, after reception the channel controller frees the allocation minislot. A channel controller can force a station to stop using an allocation minislot by issuing a *release* command, this is a mechanism to prevent heavily backlogged stations from using too many data slots. After reception of this command the station can no longer use the allocation minislot and must re-execute the arbitration protocol.

A minimum hold policy is used with the RES2 protocol, a station is allowed to hold an allocation minislot for a minimum of H frames. After the minimum number of frames has expired, a channel controller forces the station to stop using the allocation resources if other stations are waiting. As long as other stations are not waiting for allocation resources, currently assigned stations can continue to use the allocation minislot.

The *idle* command is issued by a station if it does not need to execute the arbitration protocol, or if it has no data slot requests to make. Similarly, unused allocation minislot are marked by the channel controller using the *idle* command.

6.3 Capacity Analysis

Capacity under typical network configurations is investigated as a function of the number of available wavelength channels and as a function of the total number of stations in the network for all four network and medium access protocol combinations, as well as for the MANDALA network. Table 6.1 provides a summary of the parameters used in the capacity analysis. Three capacity measures are used to characterize each of the network and medium access protocol combinations, channel capacity, uniform block capacity and system capacity. Channel capacity, C_{CH} is defined as the number of useful data slot transmissions which can occur over a single data channel. Uniform block capacity, C_{BU} is defined as a measure of how many data slot allocations can exists between two stations on different LOCs assuming a uniform inter-LOC data traffic loading condition. This is used as a measure of dynamic bandwidth adaptability, and is particularly revealing for medium access protocols which sub-divide the data channel frame into slot blocks. System capacity, C_{SY} is defined as a measure

C	number of wavelength channels
N	stations in the network
D	data slots per frame
ρ	request minislot duration
α	allocation minislot duration
σ	synchronization duration
δ	data slot duration
γ	guard and preamble duration
B	slot block size
R	number of request minislots in a frame
A	number of allocation minislots in a frame

Table 6.1: Network parameters used for capacity analysis

of the total capacity available in the network, and considers overhead effects due to dedicated control channels, spatial wavelength reuse and data channel capacity. These capacity measures take into account effects of channel overhead, but do not consider such things as traffic loading conditions or the random nature of medium access protocols, this is left to the delay-throughput analysis.

Capacity equations for DCWC-TDMA can be expressed as

$$C_{CH} = \frac{D \cdot \delta}{D \cdot (\delta + \gamma) + \sigma + \gamma}, \tag{6.17}$$

$$C_{BU} = \frac{1}{D} \cdot C_{CH}, \tag{6.18}$$

$$C_{SY} = C^2 \cdot C_{CH}. \tag{6.19}$$

Assuming the total number of stations N in the network are equally divided among the C^2 LOCs, the number of data slots per frame is

$$D = C \cdot \left\lceil \frac{N}{C^2} \right\rceil. \tag{6.20}$$

Capacity equations for DCWC-RES1 are given by

$$C_{CH} = \frac{D \cdot \delta}{D \cdot (\delta + \gamma) + \max(R \cdot (\rho + \gamma), \gamma + \sigma + A \cdot \alpha)}, \tag{6.21}$$

$$C_{BU} = \frac{1}{C^2} \cdot C_{CH}, \tag{6.22}$$

$$C_{SY} = C^2 \cdot C_{CH}. \tag{6.23}$$

If the total number of stations N in the network is equally divided among the C^2 LOCs, and further equally divided among the C local home channels of each LOC, the number of request and allocation minislots per frame is

$$A = R = \left\lceil \frac{\left\lceil \frac{N}{C^2} \right\rceil}{C} \right\rceil. \tag{6.24}$$

For CCWC-RES1 the capacity results are

$$C_{CH} = \frac{D \cdot \delta}{\max(D \cdot (\delta + \gamma), R \cdot (\rho + \gamma), \gamma + \sigma + (C-1) \cdot (\gamma + A \cdot \alpha))}, \tag{6.25}$$

$$C_{BU} = \frac{1}{C-1} \cdot C_{CH}, \tag{6.26}$$

$$C_{SY} = (C-1)^2 \cdot C_{CH}. \tag{6.27}$$

If the total number of stations N in the network is equally divided among the $(C-1)^2$ LOCs, the number of request and allocation minislots per frame is

$$A = R = \left\lceil \frac{N}{(C-1)^2} \right\rceil. \tag{6.28}$$

Finally, CCWC-RES2 capacities are expressed as

$$C_{CH} = \frac{D \cdot \delta}{\max(D \cdot (\delta + \gamma), R \cdot (\rho + \gamma), \gamma + \sigma + (C-1) \cdot (\gamma + A \cdot \alpha))}, \tag{6.29}$$

$$C_{BU} = \frac{1}{C-1} \cdot C_{CH}, \tag{6.30}$$

$$C_{SY} = (C-1)^2 \cdot C_{CH}. \tag{6.31}$$

If the total number of stations N in the network is equally divided among the $(C-1)^2$ LOCs, the number of request minislots per frame is

$$R = \left\lceil \frac{N}{(C-1)^2} \right\rceil, \tag{6.32}$$

while the number of allocation minislots, A is a configurable parameter. For MANDALA, the capacity is given by

$$C_{CH} = \frac{\delta}{\max(\delta + \gamma, \frac{C \cdot (C-1)}{2}(\rho + \gamma))}, \tag{6.33}$$

$$C_{BU} = C_{CH}, \tag{6.34}$$

$$C_{SY} = \frac{C \cdot (C-1)}{2} \cdot C_{CH}. \tag{6.35}$$

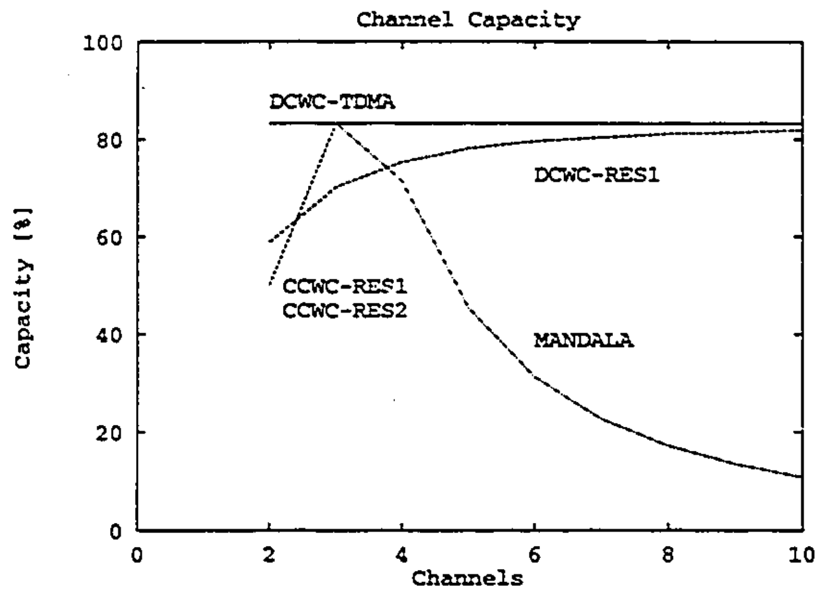

Figure 6.11: Channel capacity as a function of the number of channels

Full details of the MANDALA network and random medium access protocol are provided in chapter 3.

Capacities as a function of the number of wavelength channels are presented by figures 6.11, 6.12 and 6.13. Results were generated using a network configured with $N = 500$ stations, a data slot duration of $\delta = 5$, a request minislot duration of $\rho = 1$, a synchronization duration of $\sigma = 1$, an inter-frame guard and preamble duration of $\gamma = 1$, an allocation minislot duration of $\alpha = 0.5$, $D = 100$ data slots per frame and $A = 10$ allocation minislots per channel controller for the RES2 protocol. Stations were equally distributed among the LOCs, and home channel assignments were equally distributed among the wavelength channels.

Examining the channel capacity of figure 6.11, it is observed that DCWC-TDMA, CCWC-RES1 and CCWC-RES2 all achieve very high capacity since signaling information is not present on the data channels. The CCWC-RES1 and CCWC-RES2 configurations experience degradation for a low number of channels under the stated configuration due to the duration of the frame on the control channel exceeding that of the frame on the data channels. This can be fixed by increasing the number of data slots per frame. With DCWC-RES1, increasing capacity occurs as the number

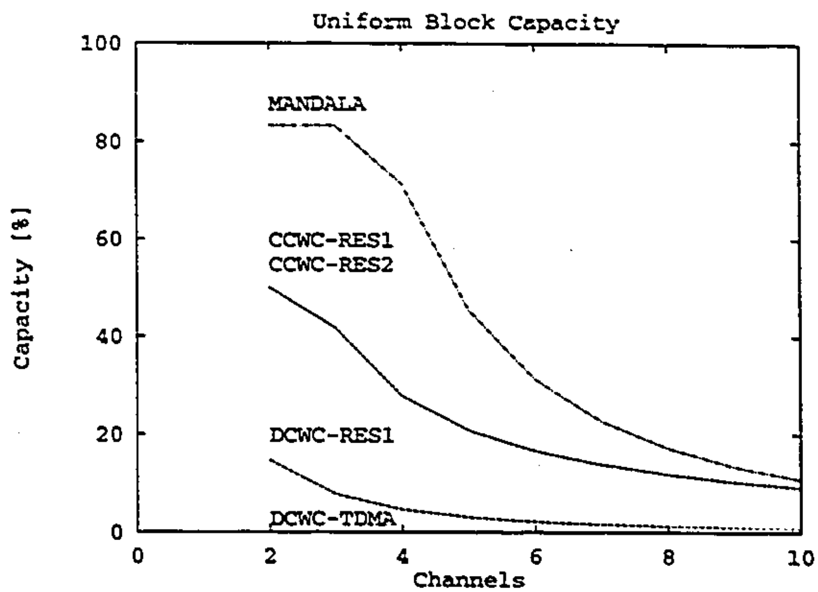

Figure 6.12: Uniform block capacity as a function of the number of channels

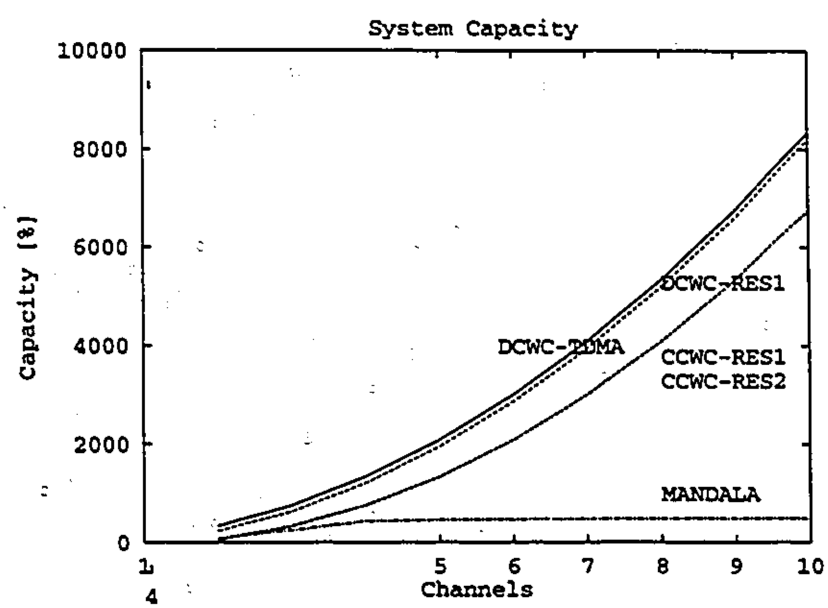

Figure 6.13: Total network capacity as a function of the number of channels

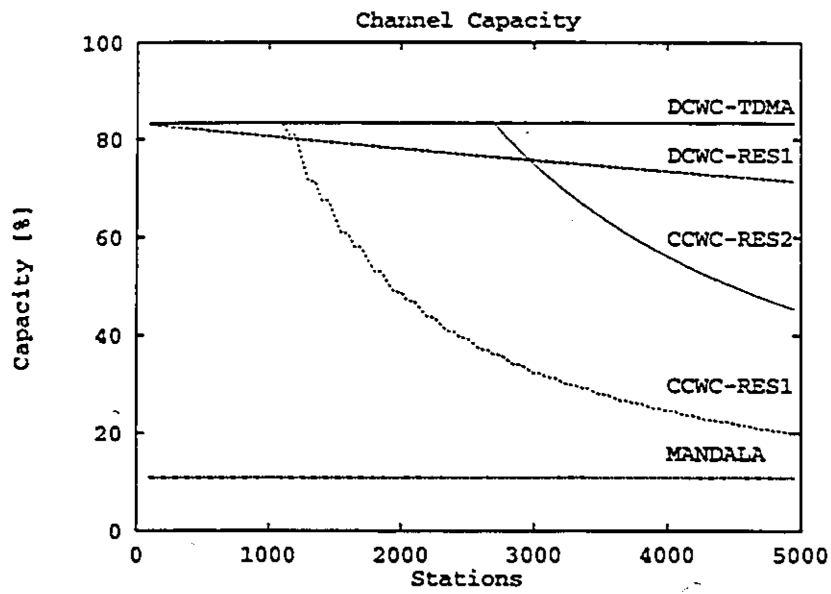

Figure 6.14: Channel capacity as a function of the number of stations N

of channels increases due to a reduction in signaling overhead per channel as stations are divided among more LOCs and more home channels. MANDALA displays a dramatic decrease in per channel throughput due to control channel congestion, this can only be remedied by increasing the relative size of a data slot since the protocol does not allow for more than one data slot per frame.

The uniform block capacity curves of figure 6.12 demonstrate that MANDALA allows more potential bandwidth between any pair of stations than either the DCWC or CCWC network configuration since MANDALA does not use slot blocking. This allows the full capacity of a data channel for communication, rather than a single slot block. As expected, DCWC-TDMA has the worst uniform block capacity performance since only a single data slot is available for communication between any two stations.

The total network capacity curves of figure 6.13 illustrate that all networks except MANDALA are able to provide a gain in capacity as a result of spatial wavelength reuse. However, MANDALA performs poorly as a consequence of its poor channel capacity, and not because of its inability to make use of spatial wavelength reuse.

Channel capacity as a function of the total number of stations in the network is provided by figure 6.14. Results were generated with a network configured with

$C = 10$ wavelength channels, a data slot duration of $\delta = 5$, a request minislot duration of $\rho = 1$, a synchronization duration of $\sigma = 1$, an inter-frame guard time and preamble of $\gamma = 1$, an allocation minislot duration of $\alpha = 0.5$, $D = 100$ data slots per frame and $A = 10$ allocation minislots per channel controller for the RES2 protocol. Stations were equally distributed among the LOCs and home channel assignments were equally distributed among the channels. The curves show the limit of high capacity for CCWC-RES1 and CCWC-RES2 due to control channel congestion, beyond this operating point control channel frame duration exceeds that of the data channel frame. DCWC-RES1 slowly degrades in capacity as the number of stations assigned per home channel increases due to added request minislots within the uplink control subframe. Under the stated configuration MANDALA performs very poorly due to control channel congestion, control channel frame duration far exceeds the duration of a data channel frame.

6.4 Delay-Throughput Analysis

Packet access delay is defined as the difference in time between data packet generation and the end of data packet transmission. Table 6.2 provides a summary of additional parameters used in the delay-through analysis. Network simulation is the primary

t_f	total frame duration
t_{ulc}	uplink control subframe duration
t_{dlc}	downlink control subframe duration
P_s	station to station propagation delay
P_c	station to channel controller propagation delay
H	Minimum hold time in frames frames for protocol RES2
B	slot block size

Table 6.2: Additional network parameters used for delay-throughput analysis

tool used for delay-throughput analysis of FCCN, however queuing models are also developed as a means to validate the operation of these simulators.

Theoretical average packet access delay equations are based on queue theory models of each network and protocol combination, which attempt to capture the salient features of the network without involving detailed protocol interactions. Appendix A provides a thorough treatment of the models used, along with assumptions and derivation of equations, final delay-throughput equations for each network and protocol combination presented as a summary.

The average packet access delay for DCWC-TDMA is based on equations derived in [Hay84], and can be expressed as

$$\overline{d} = \frac{1}{(1-\rho)} \cdot \frac{t_f}{2}. \tag{6.36}$$

This is the average packet access delay experienced by a single station generating a data packet load of ρ [packets/slot] to one of its dedicated data slots.

The average delay for DCWC-RES1 is based on the model used for the DCCN and can be expressed as

$$\overline{d} = 2P_c + (\overline{m}+1) \cdot t_f - (2P_s) \bmod (t_f) + d_1, \tag{6.37}$$

$$d_1 = (2P_s) \bmod (t_f) + i \cdot t_f - 2P_c, \tag{6.38}$$

where the smallest value of i is chosen such that $d_1 > 0$, and $\overline{m}$ (≥ 1) is the average number of frames a station request remains queued at a channel controller before a matching allocation is granted. The value of $\overline{m}$ depends on the data packet loading state of a set of active stations and the slot block size on the destination channel.

The average delay for CCWC-RES1 is also based on the model used for the DCCN and can be expressed as

$$\overline{d} = \left\lceil \frac{2P_c + t_{ulc} + t_{dlc}}{t_f} \right\rceil \cdot t_f + \overline{m} \cdot t_f, \tag{6.39}$$

where $\overline{m}$ is the same as described for DCWC-RES1.

The average delay for CCWC-RES2 is based on the model used for Protocol 3 of the EDCCN and can be expressed as

$$\overline{d} = \overline{n} \cdot \frac{t_f}{2} + \left\lceil \frac{2P_c + t_{ulc} + t_{dlc}}{t_f} \right\rceil \cdot t_f + (\overline{m}-1) \cdot t_f + \frac{t_f}{2}, \tag{6.40}$$

$$\overline{n} = \frac{H + H \cdot \max(N_A - A, 0) + \left\lceil \frac{2P_c + t_{ulc} + t_{dlc}}{t_f} \right\rceil \max(N_A - A, 0)}{H}. \tag{6.41}$$

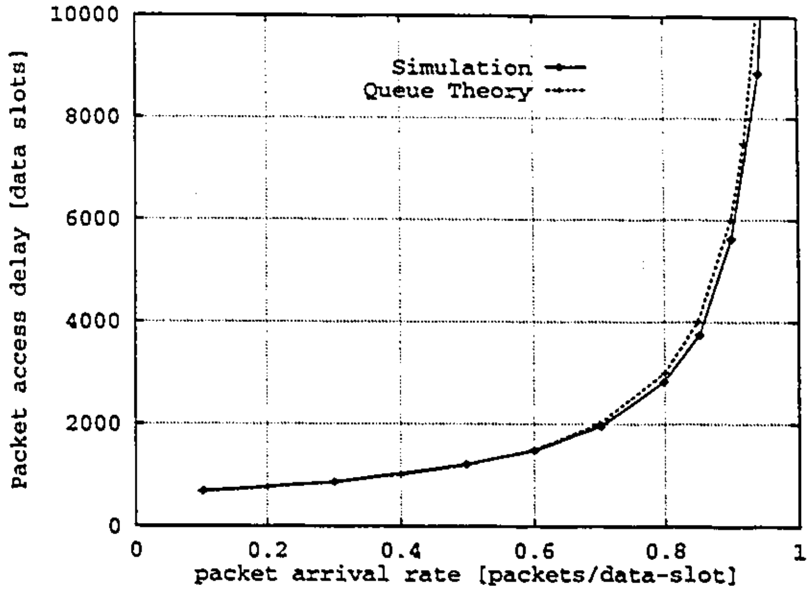

Figure 6.15: DCWC-TDMA Access delay-throughput simulation validation.

The added complexity arises due to the channel controller allocation arbitration protocol.

A set of results comparing the theoretical packet access delay and simulated packet access delay were generated for a network configured with $C = 10$ channels, $D = 100$ data slots per frame, a data slot duration of $\delta = 5$, a request minislot duration of $\rho = 1$, an allocation minislot duration of $\alpha = 0.5$, a guard duration of $\gamma = 1$, a synchronization duration of $\sigma = 1$, a minimum frame hold of $H = 5$ frames for RES2, $A = 5$ allocation minislots per channel controller for RES2, $N = 1000$ stations in the network and $N_A = 10$ active stations in LOC i generating data packets exclusively to local uplink channel j and local downlink channel k. All active stations had the same data packet generation rate and data packet size equal to one data slot. Two specific cases were examined, the first used a station to station propagation delay of $P_s = 200$ and a station to channel controller propagation delay of $P_c = 50$, while the second used a much larger network span with $P_s = 4000$ and $P_c = 1000$. Figures 6.15 through 6.18 illustrate the results for each FCCN network and medium access protocol combination. The packet access delay of one active station is plotted normalized to data slot duration, while packet arrival rate is expressed in units of arrivals per

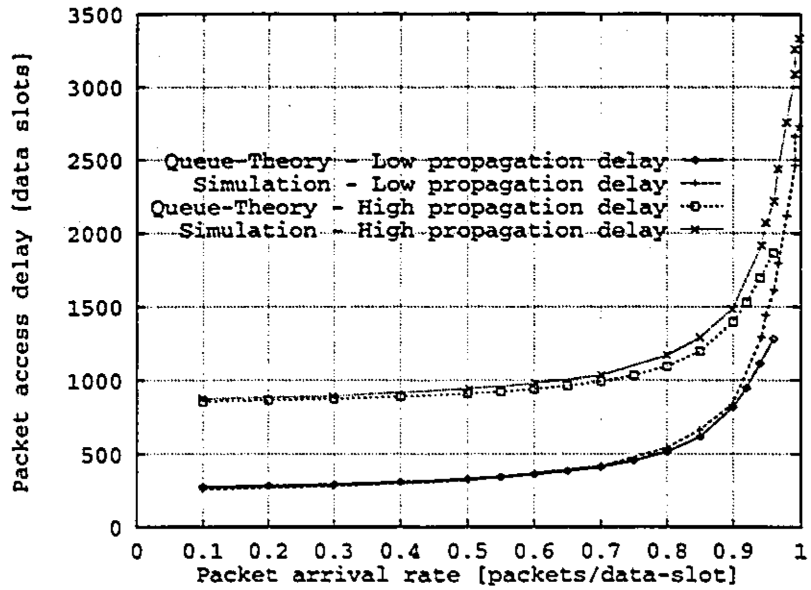

Figure 6.16: DCWC-RES1 Access delay-throughput simulation validation

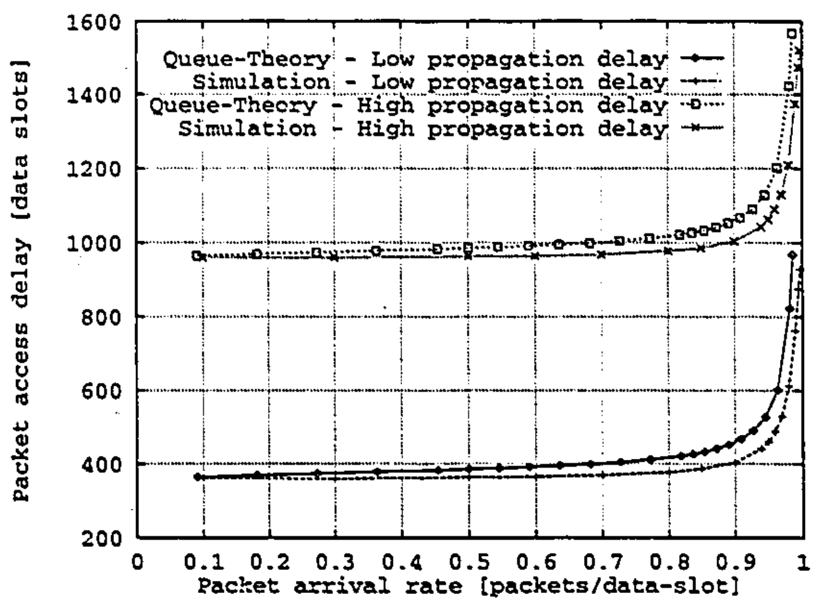

Figure 6.17: CCWC-RES1 Access delay-throughput simulation validation

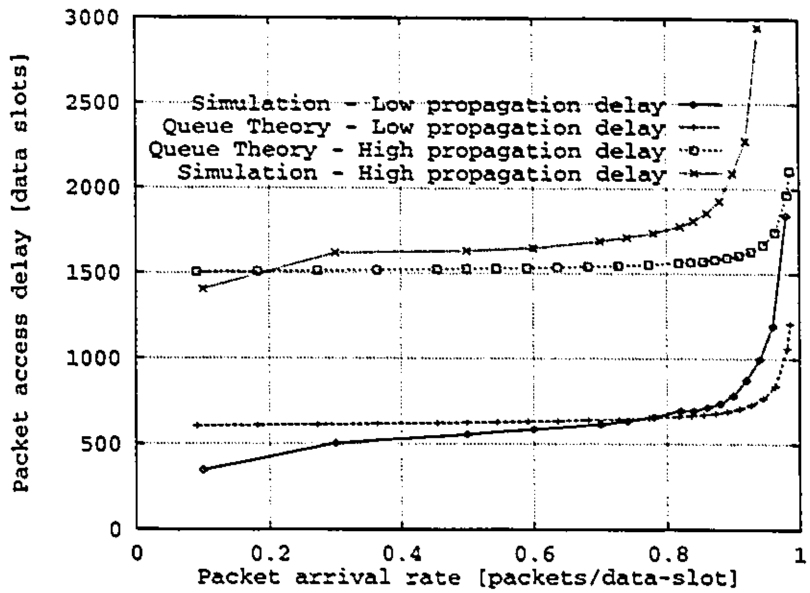

Figure 6.18: CCWC-RES2 Access delay-throughput simulation validation

data slot, normalized to the size of the data slot block on the local uplink channel of interest. Thus, an arrival rate of 1 indicates the average aggregate arrival rate from all N_A active stations is equal to the number of slots in the slot block. For all network simulators a good fit to the theoretical queue models is observed. Network CCWC-RES2 deviates the most from the queuing model due to complexities with the allocation arbitration protocol which are not fully captured by its theoretical queue model. However, the results are close enough to validate the network simulators and allow more complex network configuration to be investigated.

A set of experiments was performed to compare the packet access delay of each network. As with previous delay-throughput performance analysis, a subset of a full network is considered. Specifically, network simulation considered a set of N_A active stations from a single home channel of a single cluster generating data packets. All active stations were configured with an identical Poisson data packet generation rate. Further, these stations generated data packets to a single local downlink channel λ_{dn} of a single LOC, reached using local uplink channel λ_{up}. Slot block assignments are identical in size and static. For the MANDALA network, stations on a single source cluster generating data packets to a single destination cluster were considered, and

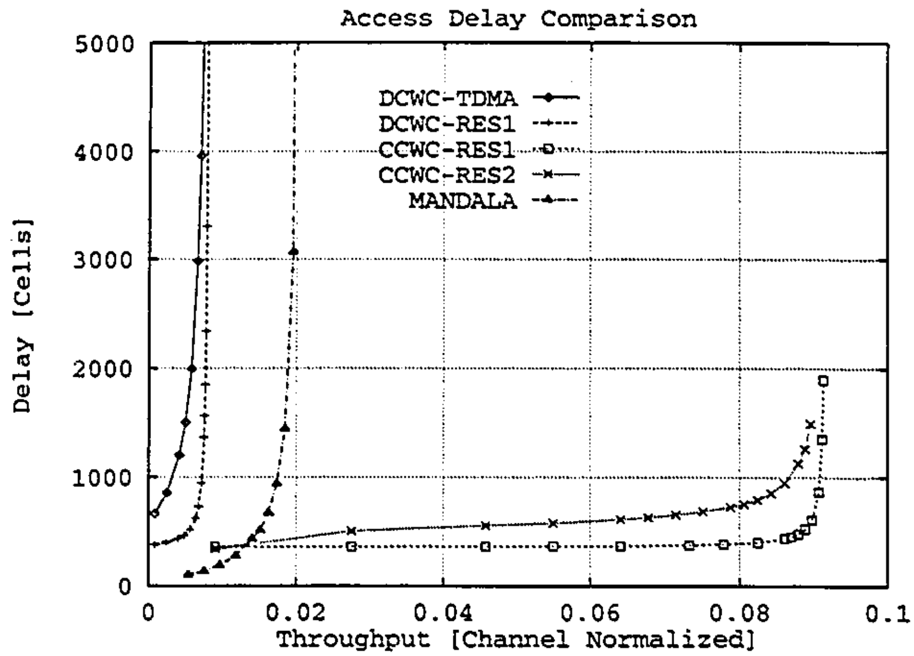

Figure 6.19: Packet access delay-throughput comparison between DCWC-TDMA, DCWC-RES1, CCWC-RES1, CCWC-RES2 and MANDALA

receiver conflicts assumed non-existent. The network was configured with a station to station propagation delay of $P_s = 10$, a station to channel controller propagation delay of $P_c = 4$, a total of $N = 1000$ stations in the network, $N_A = 10$ active stations, $C = 10$ wavelength channels, $D = 100$ data slots per frame, an allocation minislot duration of $\alpha = 0.5$, a request minislot duration of $\rho = 1$, a synchronization duration of $\sigma = 1$, a data slot duration of $\delta = 5$, a guard duration of $\gamma = 1$, $A = 5$ allocation minislots assigned per channel controller for CCWC-RES, and a minimum hold time of $H = 5$ frames. The data slot block size on the channel of interest was set at $B = 1$ data slot for DCWC-RES1, at $B = 11$ data slots for CCWC-RES1, and at $B = 11$ data slots for CCWC-RES2.

Figure 6.19 illustrates delay-throughput curves for each network-protocol combination. Under the stated configuration the channel capacity for the MANDALA network is only $C_{ch} = 0.056$ due to control channel congestion. Further, this network is only able to achieve a throughput of approximately 36% of this channel capacity as a result of its random medium access protocol which is based on slotted aloha. However, MANDALA exhibits the lowest packet access delay due to the non-existence of reservation signaling overhead, a data packet can potentially begin transmission immediately after generation. The DCWC-TDMA configuration operates as expected, with an average low load packet delay equal to approximately one half of a frame duration and able to achieve a throughput equal to its full slot block capacity. Configurations DCWC-RES1 and CCWC-RES1 have similar packet delay-throughput curves, except that slot block sizes with CCWC-RES1 are much larger than DCWC-RES1 under the stated network configuration. The most significant comparison is made between the packet delay-throughput curves of the CCWC-RES1 and CCWC-RES2 networks. Sharing of allocation minislots and the allocation arbitration protocol have minimal impact on the packet delay-throughput performance of the CCWC-RES2 network. With the CCWC-RES1 network each station is configured with a dedicated allocation minislot and accompanying processing resources with each channel controller, while the CCWC-RES2 network is configured to share one allocation minislot among two stations. The consequence is a small increase in low load access delay and almost no penalty in maximum achievable channel throughput.

Another set of experiments was performed to further investigate the effect of changing the number of allocation minislots assigned to each channel controller. The network configuration was identical to that used with the previous experiment, and the number of allocation minislots per channel controller set to $A = \{2,3,4,5,6,7,8,10\}$. Results are illustrated by figure 6.20. The curves show the packet access delay of one of the active stations and the aggregate throughput on the uplink data channel, normalized to the full bandwidth of the channel. Under the stated configuration the capacity available to the active stations is 0.092 with respect to the full bandwidth of a channel. The results show that as the number of allocation minislots is reduced only the packet access delay increases, while the full capacity of the slot block is able to be utilized.

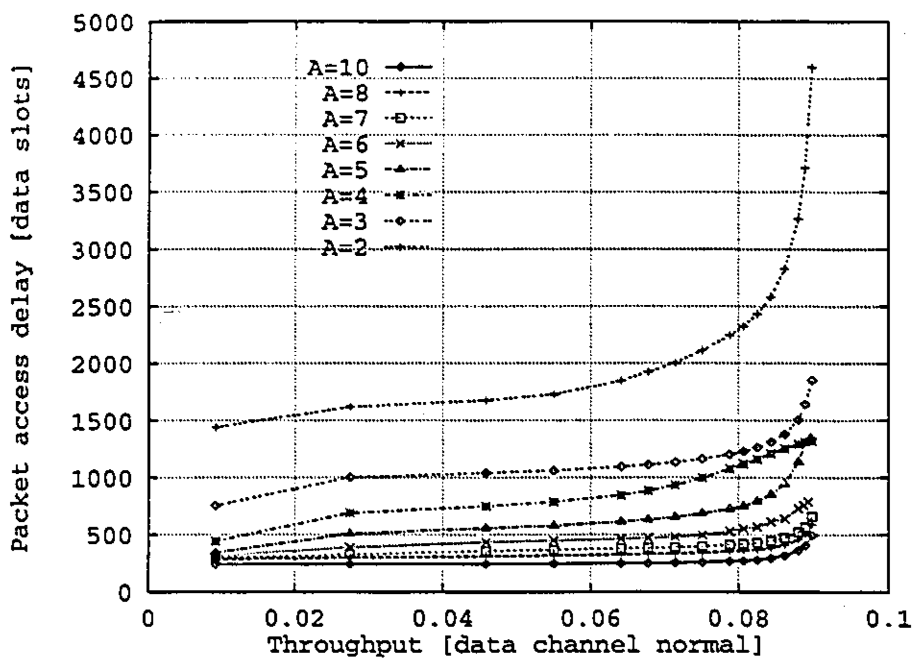

Figure 6.20: Effect of changing the number of allocation minislots allocated to a channel controller, $A = \{2,3,4,5,6,7,8,10\}$ with $N_A = 10$ active stations.

6.5 Discussion

In this chapter a single-hop, non-hierarchical wavelength routed network was presented, which consisted of many local optical clusters interconnected using a single WDM cross connect. Two variations of the local optical cluster were examined, the first used time multiplexed control channels and required a station to be configured with a single tunable transmitter and a single fixed receiver, while the second used a single dedicated control channel for each cluster and required a station to be configured with an additional fixed receiver for control channel communication. Channel controllers were used within each cluster as a mechanism to reduce station hardware and medium access protocol complexity. A static time division multiplexed packet switched medium access protocol and two collision free reservation packet switched medium access protocols were investigated for use with the network. The RES2 protocol addressed the issue of channel controller processing overload by introducing allocation minislot sharing and an allocation arbitration protocol. This allowed allocation processing resources within a channel controller to be decoupled from the number of stations in the local cluster with minimal impact on packet access delay. The FCCN network was also compared to the proposed MANDALA network, which used a similar non-hierarchical wavelength routed configuration, a single global control channel and a random medium access protocol. The network did not scale as well as FCCN due to the channel interconnection pattern, control channel congestion, receiver packet collision and low channel throughput resulting from the random nature of its medium access protocol.

The increase in network capacity from a relatively small number of wavelength channels makes the FCCN configuration attractive. As an example assume the availability of $C = 25$ wavelength channels, a channel capacity of $C_{ch} = 0.90$, a bit rate on the channels of $b = 2.5GBps$ and the CCWC network configuration. This provides a network capable of supporting 24 local optical clusters and a total network capacity of

$$C_{total} = (C-1)^2 \cdot C_{ch} \cdot b, \qquad (6.42)$$

or approximately 1.3 Terabits per second. This is far greater than that achievable with the fully broadcast and select DCCN configuration, which is only capable of offering a network capacity of approximately 56 Gigabits per second using the same assumptions.

Chapter 7

Discussion

The work described in this thesis involves the design and analysis of multichannel single hop optical networks and multichannel packet switched medium access protocols. This has been published in the IEEE Journal of Lightwave technology [JT94a], in a number of IEEE conferences [JT93b] [JT93a] [JT94b] [JT96], and submitted for publication [JT95]. Design goals were to minimize the number of transmitters and receivers required at a station, as well as reduce station medium access protocol complexity. The major contribution of the research was the introduction of channel controllers to reduce complexity in the multichannel broadcast and select network environment. Channel controllers are able to reduce the number of transmitters and receivers, and reduce the complexity of the medium access protocol at a station by reducing the volume of network state information which a station must track and process.

Specific contributions were the development of three network architectures, DCCN, EDCCN and FCCN, all single hop networks using packet switched medium access protocols. The DCCN architecture uses a fully broadcast and select topology, ED-CCN is partial broadcast and select and introduced hierarchical spatial wavelength reuse into the network, finally the partially broadcast and select FCCN introduced non-hierarchical spatial wavelength reuse and wavelength converters. Stations are equipped with a single tunable transmitter, and either a single fixed tunable receiver or in some cases two fixed tunable receivers.

As was stated in the introduction, optical wavelength division multiplexed device technology is in an early stage of development. The multichannel network architectural research undertaken by this thesis has presupposed the existence of many optical devices based on the current state of the optical device literature. If and when these devices can be economically constructed and mass produced then this and similar research will allow the network engineer to be prepared for the design problems encountered in the multichannel network environment.

7.1 Future Work

A number of areas for possible future work uncovered as a result of this work are identified and discussed.

Station Home Channel Assignment: In all of the networks proposed a station is assigned a home channel to which it fix tunes an optical receiver for data packet reception. In the current work stations are simply assigned to home channels in a uniform manner regardless of the data packet traffic each generates to a particular destination channel. It may be possible to optimize network throughput by using a more intelligent home channel assignment algorithm based on station to station traffic loading patterns.

Inter-Channel Bandwidth Allocation: In all of the proposed networks and medium access protocols the data slots within a frame are divided into data slot blocks. Currently very little work beyond the determination of constraints on these data slot block assignments has been examined. Additional investigation is required for techniques to determine optimal slot block assignments and to allow for dynamic update of these slot blocks. In the current work data slots on channels are assigned without regard to station loading patterns. If station to station traffic loading requirements are known, optimal slot block assignment algorithms which can maximize the network throughput could be developed. This is a similar problem to that encountered with the uplink to downlink beam switching matrix in satellite switch TDMA (SS/TDMA) networks [GBW81] [Gan92]

[Inu79]. Dynamic control of data slot block allocations is another area of possible investigation. Since channel controllers communicate among themselves using a parallel backplane bus it is possible that slot block assignments can be updated as station to station traffic patterns change. Channel controllers are able to monitor actual traffic demand by their associated stations, and exchange these loading patterns among themselves. Techniques could be investigated to determine which parameters of traffic flow a channel controller needs to monitor, how to optimally perform the slot block update, and the processing requirements of such algorithms. The problem becomes more difficult with the FCCN architecture since wavelength converters are introduced into the network, which place additional constraints on slot block size and location.

DCCN Architectural Variations: The DCCN architecture presented and analyzed used a single passive star coupler and stations configured with a single tunable transmitter and a single fixed receiver. Two additional architectures were developed but not analyzed. The first variation used stations with a single fixed tuned receiver and a single fast tunable receiver. Each station is preassigned a home channel to which it fixed tunes its transmitter. To maintain single hop connectivity stations on the same home channel tune their receivers in a fixed and repetitive pattern as determined by their channel controller. The second variation used wavelength routing devices in place of the passive star coupler and eliminated wavelength tunability from the stations. This is accomplished by using of a bank of wavelength converters located with the wavelength routers as illustrated by figure 7.1. The benefit of this architecture is a reduction of station complexity and a concentration of all wavelength tunability at a central location. An investigation is required to determine if the reservation medium access protocols could be applied to these networks, the inter-channel slot blocking constraints, and how network performance compares with that of the original DCCN architecture.

EDCCN Improvements A number of areas remain for investigation regarding the EDCCN architecture. With this network the C wavelength channels are divided

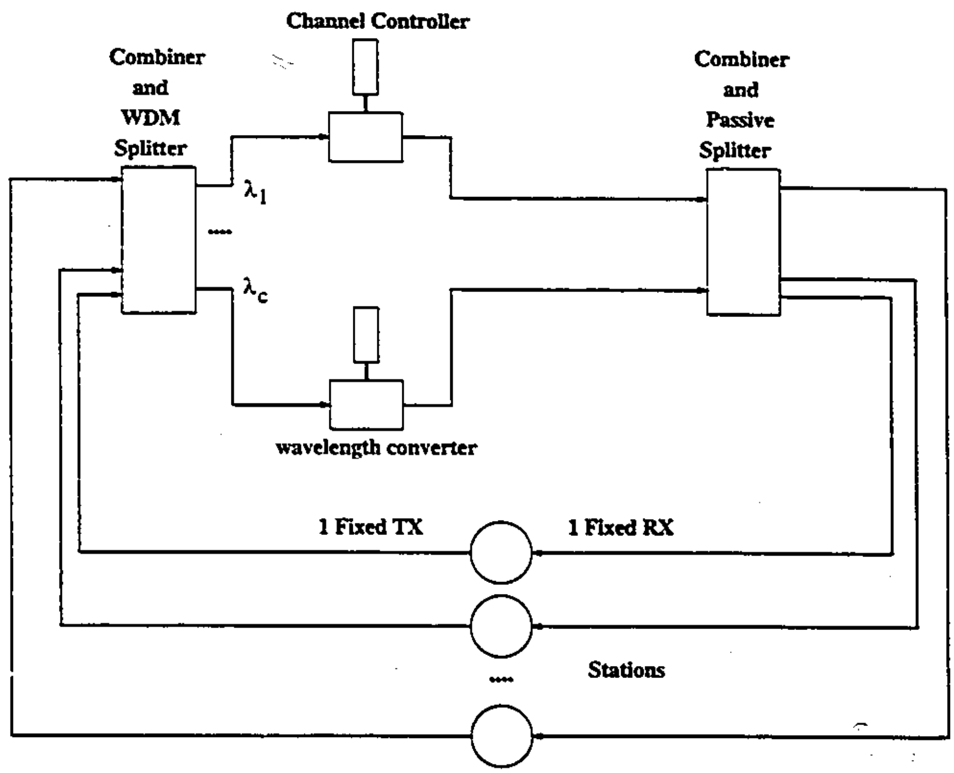

Figure 7.1: DCCN Variation without station tunability and C wavelength converters

into a local and remote waveband consisting of C_L local and C_R remote channels. The local channels are spatially reused in the LONs while the remote channels are used over the RON for data packet communication. Using this architecture, the C_L local channels are reused over the RON, however in the current design this capacity remains essentially unused. The exception was remote protocol 5, which used these channels to offload remote data channel signaling. An investigation of techniques to utilize these channels for data packet transmission through changes in network architecture and medium access protocols could be undertaken. This would allow total network throughput to increase. In addition, little work was done in considering the local and remote channel split. Investigation could be undertaken to examine the optimal division of the total wavelength channels into local and remote channels based on station local and remote home channel assignments and station to station traffic requirements.

FCCN Architectural Variations: Two local optical cluster variations were proposed for use with the FCCN architecture. Both used wavelength converters to translate data packets from the remote downlink channels to the local downlink channels, and both used single hop packet switched medium access protocols. Another variation on the local optical cluster configuration which replaced the wavelength converter bank with a $C \times C$ electronic data slot switch was also developed but not investigated. Figure 7.2 illustrates the physical topology of the network. This eliminates the constraint of inter-cluster frame synchronization, but as a tradeoff changes the network to a two hop configuration with a finite probability of data slot loss due to queue overflow in the data slot switch. The performance of this local optical network configuration has not yet been analyzed and compared to that of the other configurations.

Improved Multichannel Station Model: The configuration of a station used in a multichannel network has many options. For the work presented in this thesis a station is configured with multiple queues, one for each destination channel with a round robin service policy. Many other configurations and queue servicing techniques are possible. A station can use a single queue, or one queue for a

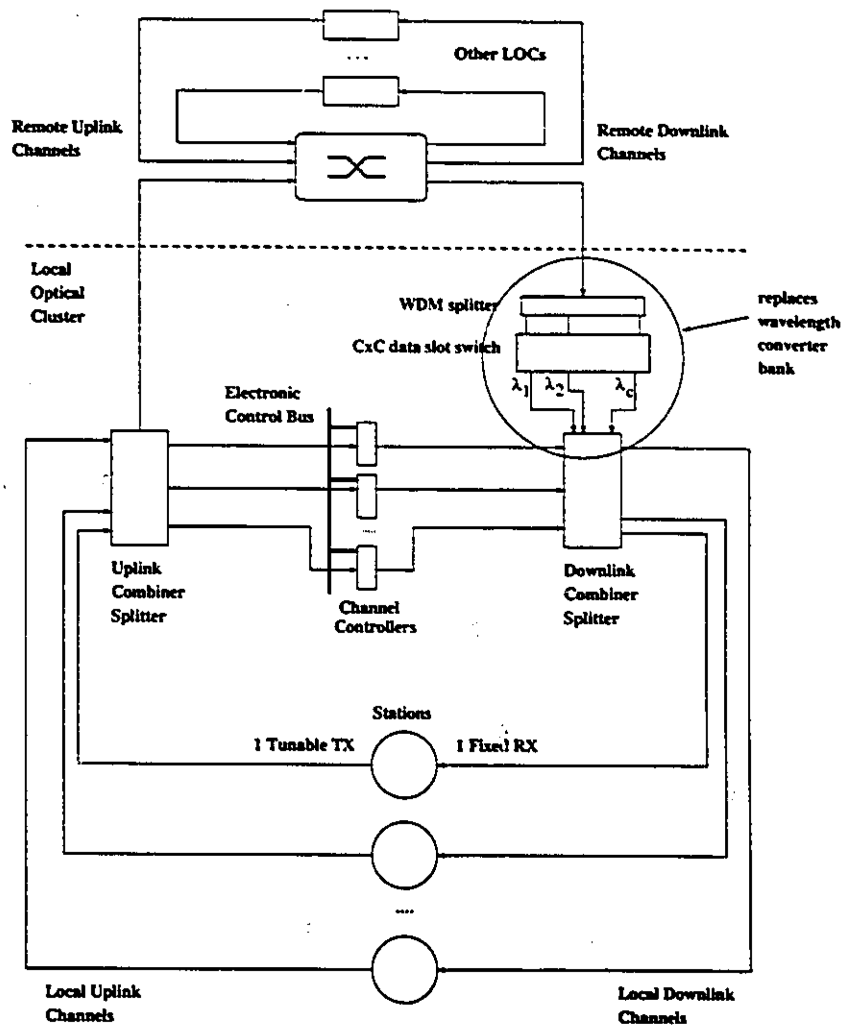

Figure 7.2: FCCN Local optical cluster variation using a data slot switch rather than wavelength converters

subset of channels. In addition the set of channels associated with a queue could change with changing station packet generation rate. Further investigation is required to determine the effects that the station model has on network performance under various traffic loading conditions.

Synchronization and Timing: All network configurations investigated used passive stars or couplers to combine time multiplexed data and control slots from different stations. Although guard times and preambles times were included in the frames and capacity calculations, experimental data were not used to determine the actual duration of these components with respect to the duration of control and data slots. A set of experiments could be performed to determine how accurately the stations and channel controllers connected to a passive star can synchronize themselves at the control minislot and frame levels by using feed back from the channel controllers. This would allow a good estimate of the guard duration and preamble duration required between various subframe components.

Network Performance Evaluation with Better Traffic Models: Currently all network performance analysis is based on either uniform data packet loading of stations or some degree of skewed data packet loading, with packet arrivals generated using a Poisson distributed arrival process. A better characterization of performance of the proposed networks and packet switched medium access protocols could be obtained through the use of data traffic which closely models that of traffic from real data communication networks. This may allow deficiencies in the architectures and medium access protocols to be located and corrected.

Construction of a Prototype Network: An experimental multichannel broadcast and select network could be constructed. If WDM components can not be acquired, or if their cost is too high then spatial division techniques can be substituted for wavelength division techniques for the construction of the multiwavelength fabric. This is illustrated by figure 7.3. The example shows a three channel fabric created with 1×4 and 4×1 optical switches and three single

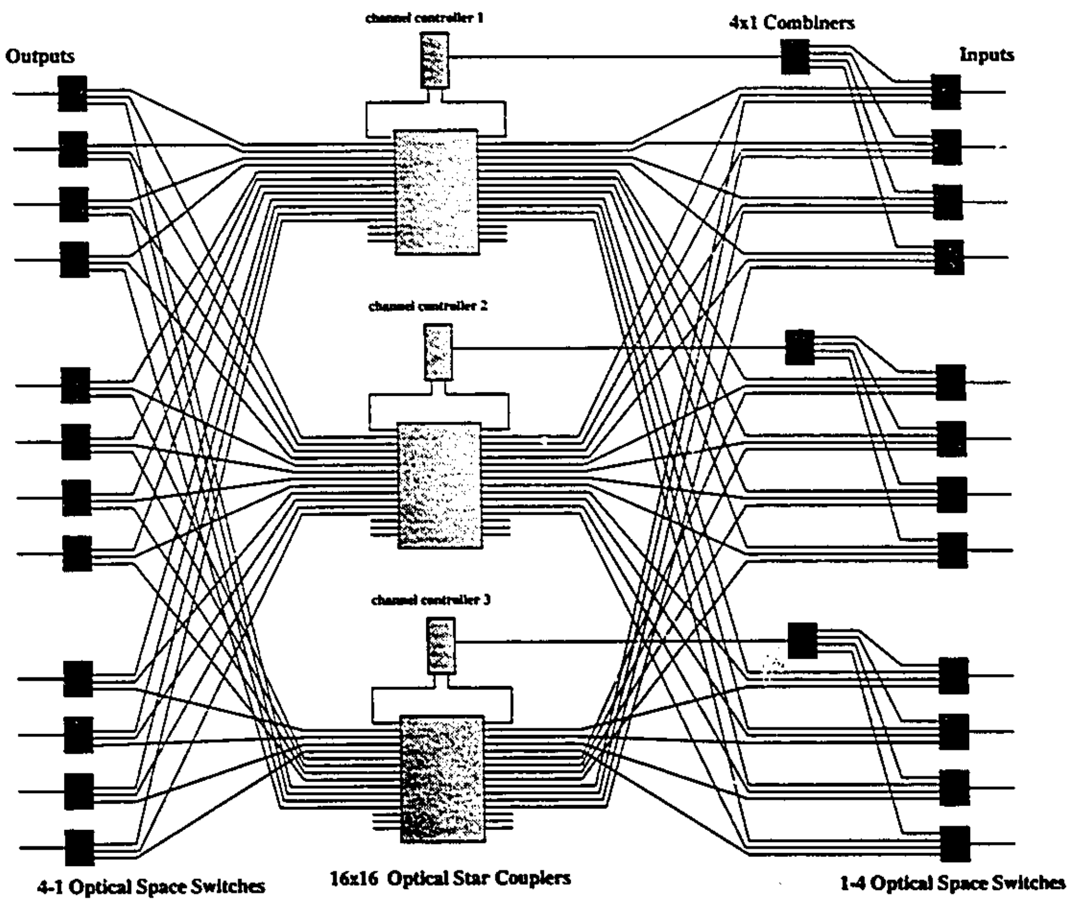

Figure 7.3: Substitution of spatial techniques for WDM in multichannel network prototype construction. $C = 3$ channel, $N = 12$ station optical fabric

channel passive star couplers. Also shown are the location of the channel controllers. Prototype construction would also involve the design and construction of channel controllers and stations. This could be based on the high level design for a channel controller presented in chapter 4. The prototype would require detailed design for a channel bite rate of $b = 1 - 2GBps$. Using current ASIC technology this should be an achievable goal.

Transfer of Concepts from LAN/MAN to a Switch Configuration: All of the networks and medium access protocols developed in this thesis have been directed at the LAN and MAN environment. An investigation into the applicability of these architectures and protocols in a switch environment could be undertaken. In this configuration the entire network would be contained within a card rack, and a station would become a card terminating a line protocol such as SONET, T1 or Ethernet. As a result components would be located in very close geographic proximity which can lead to improved protocol performance.

Appendix A

Theoretical Delay Models

This appendix contains detailed calculations and assumptions used in the development of theoretical delay models based on queuing theory for the DCCN, EDCCN and FCCN architectures.

A.1 DCCN Delay Model

The delay model consists of two parts, determination of a queue model which captures the major salient features of the DCCN architecture, and determination of fixed delays due to overhead and propagation delay effects. The queue model is considered first and then the fixed overhead delays.

A.1.1 Queue Model and Queue Delay

The queue model is based on a subset of a full DCCN network as described by chapter 4. This consists of N active stations on the same home channel generating data packets to a single destination channel. All stations are assumed to have an identical data packet generation rate based on a Poisson distribution, and all packets are a single data slot in size. The queue model is illustrated by figure A.1. Network traffic is modeled as generated by a single station with an aggregate data packet generation rate of λ packets per frame, and equal to the sum of the individual station

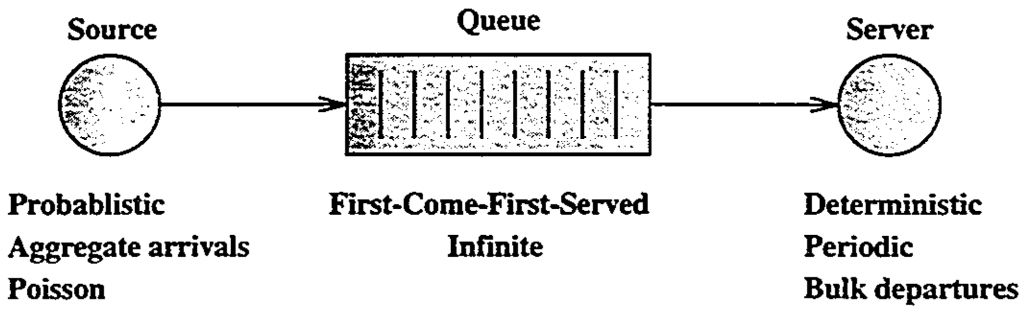

Figure A.1: DCCN queue model consisting on a single source a single queue and a single server.

packet generation rates. The reservation and allocation process is modeled by a single queue located at the passive star through which all data packets pass. Due to the request nature of the protocol and the contiguous slot block of b data slots allocated on the destination channel, packet departures from the queue are modeled as arising due to a single server. The server removes packets from the queue in blocks of up to b packets at deterministic periodic intervals of a frame duration t_f. Consequently, the queuing theory model is based on the $M/D^K/1$ queue model. System time is slotted into frames consisting of D data slots per frame. All packet departures are modeled as occuring at the beginning of a frame. The objective of this part of the analysis is to calculate mathematically the average queuing delay experienced by a data packet. Delay is defined as the time between packet arrival into the queue and packet removal from the queue. The analysis begins by embedding a Markov chain at the end of each frame. The state equation for the number of packets in the queue can be written as

$$n_{i+1} = \max(n_i - b, 0) + a_{i+1}. \tag{A.1}$$

The probability generating function $N(z)$ of this equation can be written as

$$\begin{aligned} N(z) &= E[z^{n_{i+1}}] = E[z^{max(n_i-b,0)}]E[z^{a_{i+1}}] && \text{(A.2)} \\ &= \left[\sum_{i=1}^{b-1} P_i z^b - \sum_{i=1}^{b-1} P_i z^i - P_0(1 - z^b)\right] e^{-\lambda(1-z)} && \text{(A.3)} \\ &= \sum_{i=0}^{b-1} P_i(z^b - z^i)\frac{e^{-\lambda(1-z)}}{z^b - e^{-\lambda(1-z)}}. && \text{(A.4)} \end{aligned}$$

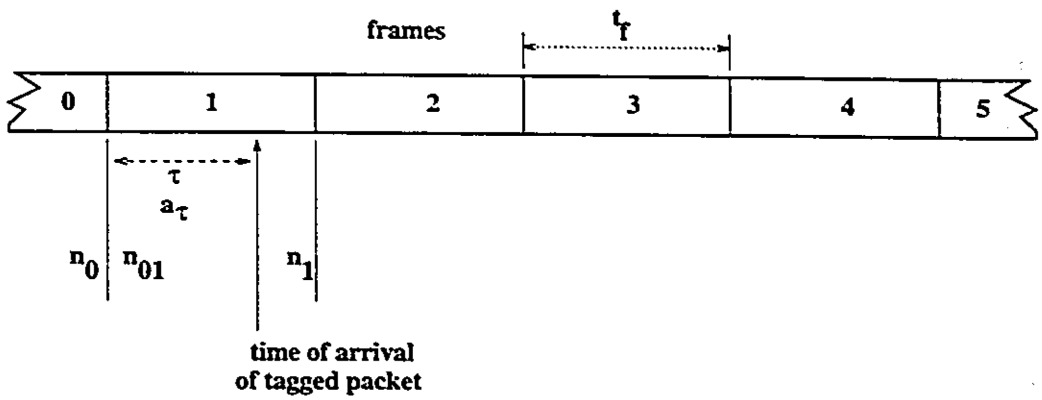

Figure A.2: Delay Model

Rouchés theorem, as described in [Hay84] can be used to solve for $P_i, i \in \{0, \cdots, (b-1)\}$ by forming a linear set of equations which can be written in matrix form as

$$\begin{bmatrix} z_1^b - 1 & z_1^b - z_1 & \cdots & z_1^b - z_1^{b-1} \\ z_2^b - 1 & z_2^b - z_2 & \cdots & z_2^b - z_2^{b-1} \\ \vdots & \vdots & & \vdots \\ z_{b-1}^b - 1 & z_{b-1}^b - z_{b-1} & \cdots & z_{b-1}^b - z_{b-1}^{b-1} \\ 1 & \frac{b-1}{b} & \cdots & \frac{b-(b-1)}{b} \end{bmatrix} \begin{bmatrix} P_0 \\ P_1 \\ \vdots \\ P_b \\ P_{b-1} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}, \qquad \text{(A.5)}$$

where z_0 through z_{b-1} are the b roots of the denominator of equation A.4 with z_0 set equal to the root at 1. With these known values it is possible to calculate any other P_i value by taking the inverse Fourier transform of $N(z)$. This can be calculated numerically, as described in [Hay84] by evaluating $N(z)$ at a sufficiently large number of points, K around the unit circle of the complex Z-plane.

$$P_i = \frac{1}{K} \sum_{k=0}^{K-1} N(e^{\frac{-j2\pi k}{K}}) e^{\frac{j2\pi ik}{K}} \qquad \text{(A.6)}$$

Using a similar analysis as [TB92], the delay experienced by a "tagged" packet is determined. The derivation is formulated as shown in figure A.2. Define n_0 as the number of packets queued at the end of an arbitrary frame labeled as frame 0, and n_{01} as the number of packets in the queue at the start of frame 1 after packets have been removed by the server. At some time τ after the start of the frame the tagged packet arrives into the queue. At the end of frame 1 the number of packets n_1 queued in front of the tagged packet including the tagged packet is equal to the number of packets carried over from the previous frame, n_{01} and the number of new packets, a_τ arriving in the interval τ can be expressed as

$$n_1 = n_{01} + a_\tau + 1. \tag{A.7}$$

If m is defined as the number of frames required to service n_1 packets then $E(m)$ is the average number of frames the tagged packet remains queued. To determine this the Probability Distribution Function (PDF)0 of m, $P_m(i)$ needs to be calculated. First consider $P_m(i)$ conditioned on n_1 written as $P_m(i|n_1)$. This can be expressed as

$$P_m(0|n_1) = \begin{cases} 1, & n_1 = 0 \\ 0, & n_1 > 0 \end{cases} \tag{A.8}$$

$$P_m(1|n_1) = \begin{cases} 1, & 0 < n_1 \leq b \\ 0, & n_1 > b \end{cases} \tag{A.9}$$

$$\vdots$$

$$P_m(i|n_1) = \begin{cases} 1, & (i-1)b < n_1 \leq ib \\ 0, & n_1 > ib \end{cases}, \tag{A.10}$$

and after removing the conditioning can be expressed as

$$\begin{aligned} P_m(i) &= \sum_{j=0}^{\infty} P_m(i|j) P_{n_1}(j) \\ &= \sum_{j=(i-1)b-1}^{ib} P_{n_1}(j). \end{aligned} \tag{A.11}$$

Now P_{n_1} must be determined. From equation A.7 n_1 is a function of two independent random variables, therefore the PDF of n_1 can be written as a convolution of the PDFs of these variables.

$$P_{n_1}(j) = \begin{cases} \sum_{i=0}^{j-1} P_{n_{01}}(i) P_{a_\tau}(j-i-1) & ,j > 0 \\ 0 & ,j = 0 \end{cases}. \tag{A.12}$$

To calculate this $P_{a_\tau}(i)$ and $P_{n_{01}}(i)$ need to be determined. $P_{a_\tau}(i)$ is the probability of i arrivals in the interval before the arrival of the tagged packet, and $P_{n_{01}}(i)$ is the probability of i packets remaining in the queue at the beginning of the frame, but after b packets have been removed. $P_{a_\tau}(i)$ is found by first conditioning on τ where

$$P_{a_\tau}(i|\tau) = \frac{(\lambda\tau)^i e^{-\lambda\tau}}{i!}. \tag{A.13}$$

After removing the condition and considerable manipulation this can be expressed as in [TB92]

$$P_{a_\tau}(i) = \frac{1}{\lambda} - \frac{e^{-\lambda}\lambda^{i-1}}{i!}[1 + \sum_{j=1}^{i} \frac{i!}{(i-j)!\lambda^j}]. \tag{A.14}$$

$P_{n_{01}}$ is found by considering that $n_{01} = max(n_0 - b, 0)$ which has a PDF given by

$$P_{n_{01}}(i) = \begin{cases} \sum_{j=0}^{b} P_{n_0}(j) & ,i = 0 \\ P_{n_0}(b+i) & ,i > 0 \end{cases}. \tag{A.15}$$

And since $P_{n_0}(i)$ is equal to P_i of equation A.6, $E(m)$ can be calculated as

$$\overline{m} = \sum_{i=0}^{\infty} iP_m(i), \tag{A.16}$$

where $\overline{m} \geq 1$.

A.1.2 Total Packet Access Delay

The total delay experienced by a packet arriving at a station is composed of a queuing delay plus additional overhead delay due to the reservation nature of the protocol and due to propagation delay. The best way of examining this is to consider a time line of activity at a station and its home channel controller as illustrated by figure A.3. The diagram shows the locations where a station can transmit requests, and channel controllers can transmit allocations. Frame synchronization is relative to a stations transmitter, channel controllers must synchronize their allocation subframe transmission such that it arrives within the allocation subframe at the station receivers. The model assumes that the channel controller to passive star propagation delay is negligible, and that request and allocation subframe duration are small compared to a full frame. The shaded request and allocation minislots trace a particular slot request

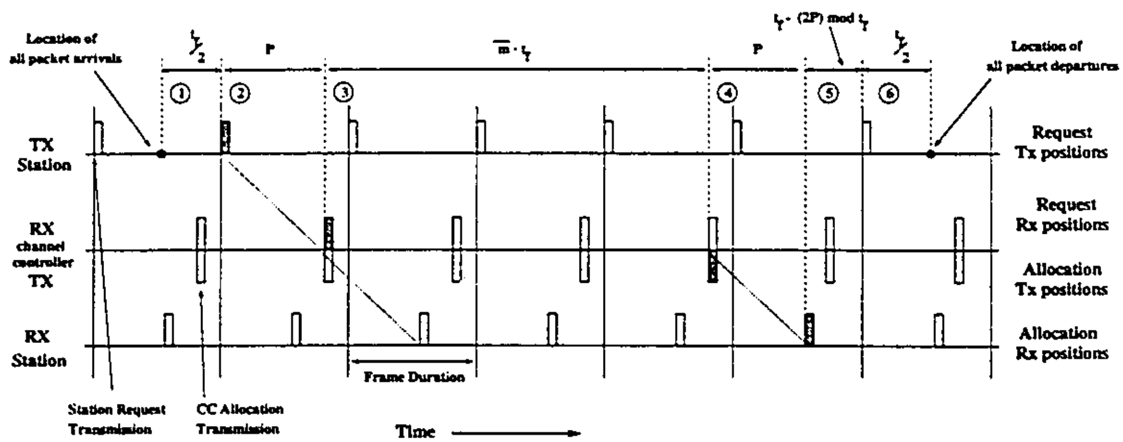

Figure A.3: DCCN total packet delay model.

and matching allocation as a mechanism to illustrate all of the components which make up the total packet delay. The station-star propagation delay is P. Total delay consists of six components. The first component is due to new packets which arrive at a station, all are modeled as arriving one half frame duration before a station transmits its request minislot. The second component of delay is due to request subframe propagation delay between the station and channel controller. The third component is the queuing delay of $\overline{m}$ frames at the channel controller. The fourth component is a result of allocation subframe propagation delay between the channel controller and station. The fifth component is incurred as a result of a difference in time between the arrival of the allocation subframe at a station and the start of the next frame. Finally, the sixth component is due to the position of data slot transmission within the information subframe, all are modeled as occurring in the middle of the frame immediately after reception of an allocation minislot. The total delay can be written as

$$\overline{d} \;=\; 2P + 2t_f - (2P) \bmod t_f + \overline{m} \cdot t_f. \tag{A.17}$$

A.2 EDCCN Delay Model

The delay model used for the EDCCN remote medium access protocols builds on the results derived for DCCN. As with DCCN the total delay consists of the average queuing delay $\overline{m}$, plus fixed delays due to station star propagation delay, and for protocols 3 and 4 a probabilistic delay due to sharing of remote request minislots. The general structure of the total packet delay for protocols 1, 2, 3 and 4 is identical to that of DCCN, as illustrated by figure A.3. This shows a time line for a station and remote channel controller along with the locations of remote request minislot and remote allocation minislot transmission and reception. The shaded request and allocation minislots trace a particular sequence of events executed by a station to request remote data slots. Details for each of the five protocols are treated separately. Protocol 1 is identical to the DCCN reservation protocol with fixed delays due to station to remote channel controller propagation delay and request signaling. The total delay can be expressed as

$$\overline{d} = 2P + 2t_{rf} - (2P) \bmod t_{rf} + \overline{m} \cdot t_{rf}. \tag{A.18}$$

Protocol 2 places additional constraints on frame sizes over that of Protocol 1 but has the same packet delay structure, thus

$$\overline{d(2)} = 2P + 2t_{rf} - (2P) \bmod t_{rf} + \overline{m} \cdot t_{rf}. \tag{A.19}$$

Protocol 3 is similar to Protocols 1 and 2, however the remote request transmission points do not occur at periodic intervals of t_{rf}, but rather at intervals of $t_{rf} \cdot \overline{n}$, where $\overline{n}$ is the average number of remote frames between a station being able to use a remote request minislot. This is a result of the remote request minislot sharing protocol. The average packet delay can be expressed as

$$\overline{d(3)} = \overline{n} \cdot \frac{t_{rf}}{2} + 2P + t_{rf} - (2P) \bmod t_{rf} + \overline{m} \cdot t_{rf} + \frac{t_{rf}}{2}. \tag{A.20}$$

A reasonable estimate of $\overline{n}$ can be calculated as

$$\overline{n} = \frac{n_{min} + n_{max}}{2} \tag{A.21}$$

$$= \frac{1 + (max(N_A - R, 0) \cdot H + 1)}{2} \quad (A.22)$$

$$= 1 + \frac{max(N_A - R, 0) \cdot H}{2}. \quad (A.23)$$

where n_{min} and n_{max} are the minimum and maximum number of frames a station must wait for use of a remote request minislot respectively, H is the maximum number of frames a station can hold a request minislot and N_A is the number of active stations competing for use of R remote request minislots. In the general case $\overline{n}$ is a function of the remote slot block size b and the aggregate arrival rate λ due to early release of the remote request minislot, this is not taken into account by the model. Since Protocol 3 uses the stations local request and allocation minislots to execute the remote request minislot sharing protocol it was found that equation A.20 is accurate provided that

$$\frac{t_{lf}}{t_{rf}} < \frac{1}{2}. \quad (A.24)$$

Protocol 4 is similar to Protocol 3 with an average packet delay expressed as

$$\overline{d(4)} = \overline{n} \cdot \frac{t_{rf}}{2} + 2P + t_{rf} - (2P) \bmod t_{rf} + \overline{m} \cdot t_{rf} + \frac{t_{rf}}{2}. \quad (A.25)$$

The difference is the calculation of $\overline{n}$ since remote request and allocation minislots are assigned randomly to stations. The analysis begins by assuming that P_a is the probability that a station is assigned the use of a remote request minislot in a remote frame. In this case the probability of waiting k frames for an assignment can be expressed as

$$P_a = P_a(1 - P_a)^k. \quad (A.26)$$

Since this is a geometric distribution the average number of frames to wait can be calculated as

$$\overline{n} = \frac{1}{P_a}. \quad (A.27)$$

The calculation of P_a as a function of N, R and H is required. As with Protocol 3 the early release capability of the protocol is not taken into account by these equations. Consider P_{ai}, which is the conditional probability that a remote request is assigned to a station in the frame given that i remote requests are available for assignment by the local channel controller, this can be expressed as

$$P_{ai} = \begin{cases} \frac{i}{N-R+i} & 0 < i \leq R \\ 0 & i = 0 \end{cases}. \tag{A.28}$$

To remove the condition from P_{ai} the determination of P_{ri}, the probability that the local channel controller has i remote requests to assign is required. If P_r, the probability of a particular remote request being available is $\frac{1}{H}$, then P_{ri} can be expressed as

$$P_{ri} = \binom{R}{i} P_r^{\,i}(1-P_r)^{r-i}. \tag{A.29}$$

Now the expression for P_a can be written as

$$P_a = \sum_{i=0}^{R} P_{ai} \cdot P_{ri}. \tag{A.30}$$

As with Protocol 3 this result is accurate for

$$\frac{t_{lf}}{t_{rf}} < \frac{1}{2}. \tag{A.31}$$

The model for Protocol 5 is slightly different due to the use of local request minislots and remote allocation minislots. Figure A.4 illustrates a time line of activity at a stations transmitter and receiver, and a remote channel controller, showing the locations of local request minislot transmission, local request minislot reception, remote allocation minislot transmission and remote allocation minislot reception. The shaded request and allocation minislots trace a particular sequence of events executed by a station to request remote data slots. The delay consists of seven components using similar reasoning as described for DCCN, and the average access delay can be expressed as

$$\overline{d(5)} = 2P + \frac{t_{lf}}{2} + t_{rf} - (2P) \bmod t_{rf} + t_{rf} \cdot \overline{m}, \tag{A.32}$$

provided that $t_{lf} < t_{rf}$.

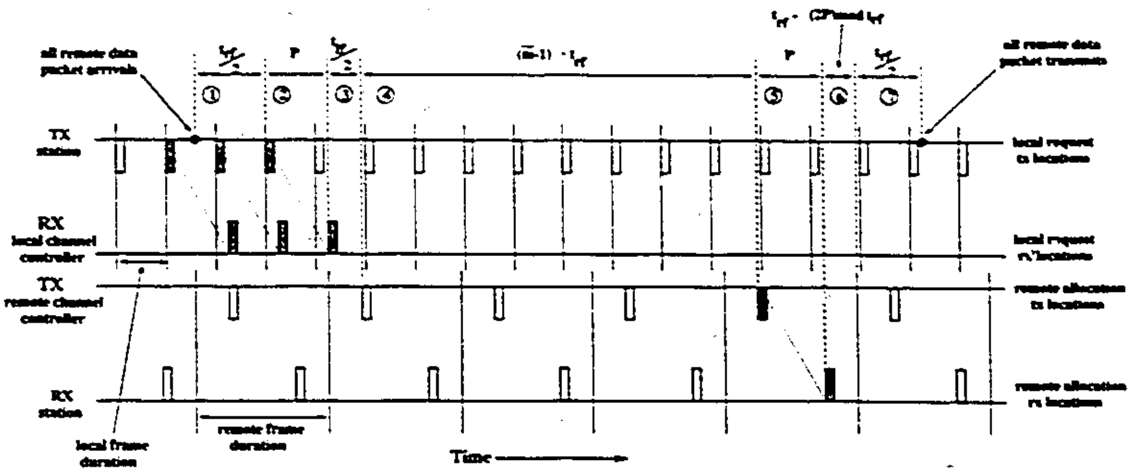

Figure A.4: Protocol 5 total packet delay model

A.3 FCCN Queue Model

The queue models used for the DCWC-RES1, CCWC-RES1 and CCWC-RES2 networks build on the results from DCCN. The total packet delay consists of the queuing delay $\overline{m}$, plus fixed delays due to station-channel controller propagation delay, station-cross connect propagation delay, and for CCWC-RES2 the allocation sharing protocol. The model considers N stations on a single local optical cluster, of which a subset N_A are actively generating data packets. Data packets are destined for a single local downlink channel C_{down} of a single local uplink channel C_{up}. All stations are assumed to have the same packet generation rate of λ packets per frame and a data packet size equal to one data slot. Considering the DCWC-RES1 network, the structure of the overhead components are more complex than the DCCN since the channel controllers are not connected to the broadcast star and the station to channel controller propagation delay P_c is different than the station to cross connect delay P_s. In addition, the channel controllers are required to synchronize their downlink control subframes to the total frame structure on the local downlink channels. The duration of the uplink and downlink control subframes are assumed to be small relative to the frame duration. Figure A.5 illustrates a time line of activity at the station and channel controller transmitters and receivers. Total packet access delay $\overline{d}$ consists

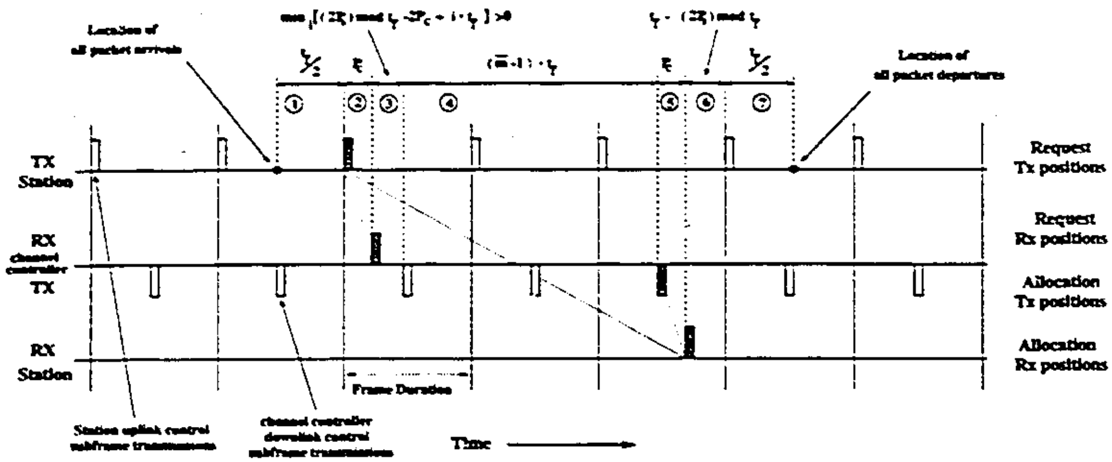

Figure A.5: DCWC-RES1 total packet delay timing diagram

of seven components. The first component is due to the difference in time between packet generation and time of request minislot transmission to the channel controller. All packet arrivals are modeled as occuring in the middle of each frame. The second component is due to station to channel propagation delay of duration P_c. The third component is due to a timing difference between arrival of the uplink control subframe at a channel controller and generation of a downlink signaling subframe. This delay can be calculated as

$$d_1 \;=\; (2P_s) \bmod (t_f) + i \cdot t_f - 2P_c \tag{A.33}$$

where the smallest value of i is chosen such that $d_1 > 0$. The fourth component is due to queuing of the data slot requests at the channel controller and is calculated using the same technique as described for DCCN. The fifth component is due to the propagation delay of the downlink control subframe to the station. The sixth component is a delay between the arrival of the downlink control subframe at a station and the start of the next frame into which data slots can be transmitted. Finally, the seventh component is due to the position of the data packet transmission within the information subframe. All data packet transmissions are modeled as occuring in the middle of the frame. Summing all of the components results in a total packet access delay of

$$\overline{d} = \frac{t_f}{2} + P_c + d_1 + (\overline{m} - 1) \cdot t_f + t_f - (2P_s) \bmod (t_f) + \frac{t_f}{2} \qquad (A.34)$$

$$= 2P_c + (\overline{m} + 1) \cdot t_f - (2P_s) \bmod (t_f) + d_1. \qquad (A.35)$$

The CCWC-RES1 network uses a similar delay model except that overheads are different due to a dedicated control channel. Since all signaling information from all stations in the cluster is concentrated on the control channel the uplink and downlink control frame durations are significant compared to the duration of an information frame. The channel controllers are synchronized such that the downlink control subframe completes arrival at a station just at a start of frame marker. Figure A.6 illustrates a time line of activity on the control channel at the station and channel controller transmitters and receivers. The shaded uplink and downlink control frames

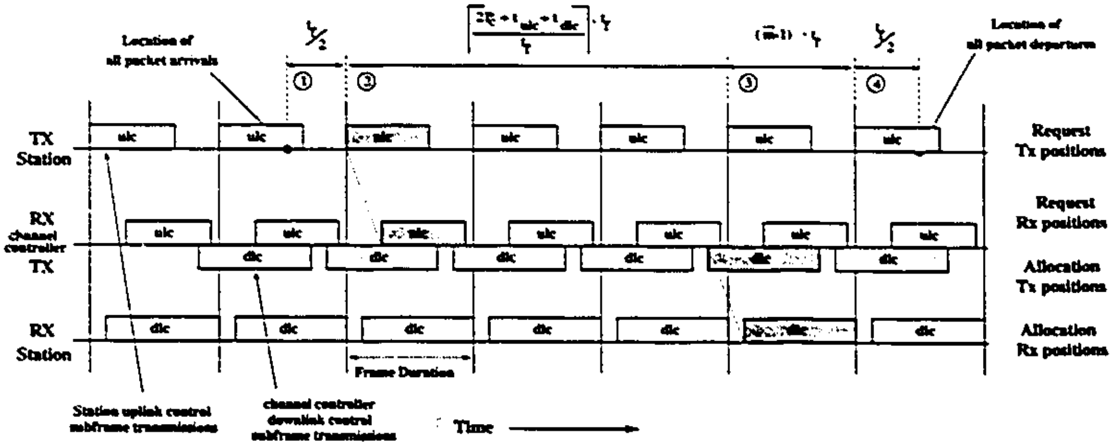

Figure A.6: CCWC-RES1 total packet delay timing diagram

trace a particular request from a station and its matching allocation from the channel controller. The delay consists of four components. The first is due to the arrival of data packets, modeled as arriving one half frame before the uplink control subframe transmission from a station. The second component is due to station-channel controller propagation delay and control subframe duration and is equal to an integer number of frames. This is the minimum delay a station experiences in receiving a downlink control subframe with allocations from a particular uplink control subframe.

The third component is due to request queuing at the channel controller, while the fourth component is due to data packet transmission position within the information subframe. All packets are modeled as being transmitted from the middle of the frame. The total packet access delay is the sum of all components which results in a delay of

$$\overline{d} = \frac{t_f}{2} + \left\lceil \frac{2P_c + t_{ulc} + t_{dlc}}{t_f} \right\rceil \cdot t_f + (\overline{m} - 1) \cdot t_f + \frac{t_f}{2} \quad (A.36)$$

$$= \left\lceil \frac{2P_c + t_{ulc} + t_{dlc}}{t_f} \right\rceil \cdot t_f + \overline{m} \cdot t_f \quad (A.37)$$

The CCWC-RES2 network delay model is similar in structure to CCWC-RES1 except that it considers the allocation arbitration protocol. In this case a station can not use a request minislot to a channel controller in every frame, but rather on average in every $\overline{n}$ frames. Using the results of equation A.37 the packet access delay of CCWC-RES2 can be calculated as

$$\overline{d} = \overline{n} \cdot \frac{t_f}{2} + \left\lceil \frac{2P_c + t_{ulc} + t_{dlc}}{t_f} \right\rceil \cdot t_f + (\overline{m} - 1) \cdot t_f + \frac{t_f}{2}. \quad (A.38)$$

The average number of frames a station must wait for an allocation minislot assignment can be determined as a function of the number of allocation minislots a channel controller has available, A, the minimum number of frames a station can hold an allocation minislot with the channel controller, H and the number of stations actively competing for allocation minislots, N_A. This is calculated as

$$\overline{n} = \frac{H + H \cdot max(N_A - A, 0) + \left\lceil \frac{2P_c + t_{ulc} + t_{dlc}}{t_f} \right\rceil max(N_A - A, 0)}{H}. \quad (A.39)$$

If the number of active stations is less than the number of available allocation minislots then $\overline{n} = 1$ and the average packet delay is the same as CCWC-RES1. This model does not consider the early allocation minislot release capability of the stations. The DCWC-TDMA network model is slightly different than the others. Since stations operate completely independent of each other the model considers the packet delay of a single station on a single local cluster. The model consists of a single source generating data packets at a rate of ρ data packets per frame, a single infinite queue and a single server which is able to remove one data packet from the queue per service interval of t_f. This is the $M/D/1$ queue model as described by [Hay84]. The average packet delay for the station can be expressed as

$$\bar{d} = \frac{1}{(1-\rho)} \cdot \frac{t_f}{2}. \tag{A.40}$$

Bibliography

[Abu88] Maurice F. Aburdene. *Computer Simulation of Dynamic Systems.* Wm. C. Brown Publishers, 1988.

[AT95] Nima Ahmadvand and Terrence D. Todd. Dual hop lans using station wavelength routing. In *ICCCN*, pages 622–629. IEEE, September 1995.

[BCD92] Kalyani Bogineni, Michael Carrato, and Patrick W. Dowd. Collisionless multiple access protocols for wavelength division multiplexed star-coupled photonic networks. *to appear in the International Journal in Computer Simulation*, 1992.

[Bra90] Charles A. Brackett. Dense wavelength division multiplexing networks: Principles and applications. *IEEE Journal On Selected Areas In Communications*, 8(6):948–964, August 1990.

[CDR90] Mon-Song Chen, Nicholas Dono, and Rajiv Ramaswami. A medi-access protocol for packet-switched wavelength division multiaccess metropolitan area networks. *IEEE Journal On Selected Areas In Communications*, 8(6):1048–1057, August 1990.

[CF91] Imrich Chlamtac and Andrea Fumagalli. Quadro-stars: High performance optical wdm star networks. In *Globecom*, pages 1224–1229. IEEE, 1991.

[CF92] Imrich Chlamtac and Andrea Fumagalli. Performance of reservation based (quadro) wdm star networks. In *Infocom*, pages 2115–2123. IEEE, 1992.

[CSR90] S. Cusworth, J. Senior, and A. Ryley. Wavelength division multiple access on a high-speed optical fibre LAN. *Computer Networks and ISDN Systems*, pages 323–333, 1990.

[CY91] Ming Chen and Tak-Shing Yum. A conflict-free protocol for optimal wdma networks. In *Globecom*, pages 1276–1281. IEEE, 1991.

[CY92] Ming Chen and Tak-Shing Yum. Buffer sharing in conflict-free wdma networks. In *Infocom*, pages 664–670. IEEE, 1992.

[CZA92] R. Chipalkatti, Z. Zhang, and A. Acampora. High speed communication protocols for optical star coupler using wdm. In *Infocom*, pages 2124–2133. IEEE, 1992.

[CZA93] Renu Chipalkatti, Zhensheng Zhang, and Anthony Acampora. Protocols for optical star-coupler network using wdm: Performance and complexity study. *IEEE Journal on Selected Areas in Communication*, 11(4):579–589, May 1993.

[Dow91] Patrick Dowd. Random access protocols for high-speed interprocessor communication based on an optical passive star topology. *Journal Of Lightwave Technology*, 9(6):799–808, June 1991.

[DPM+93] T. Durhuss, R.J.S. Pedersen, B. Mikkelsen, K.E. Stubkjaer, M. Oberg, and S. Nilsson. Optical wavelength conversion over 18nm at 2.5gb/s by dbr laser. In *Photonics Technology Letters*, volume 5, pages 86–88. IEEE, January 1993.

[DS94] Patrick Dowd and Krishna Sivalingam. A multi-level wdm access protocol for an optically interconnected parallel computer. In *Infocom*, pages 400–408. IEEE, 1994.

[Gan92] Aura Ganz. An efficient ss/tdma time slot assignment algorithm. *IEEE Transactions on Communications*, 40(8):1367–1374, August 1992.

[GBW81] D. Coppersmith G. Bongiovanni and C. K. Wong. An optimum time slot assignment algorithm for an ss/tdma system with variable number of transponders. *IEEE Transactions on Communications*, COM-29(5):721–726, May 1981.

[GG92] Aura Ganz and Yao Gao. A time-wavelength assignment algorithm for a wdm star network. In *Infocom*, pages 2144–2150. IEEE, 1992.

[GK91] Aura Ganz and Zahava Koren. Wdm passive star - protocols and performance analysis. In *Infocom*, pages 991–1000. IEEE, 1991.

[GL93] Aura Ganz and Bo Li. A packet-switched wdm passive optical star based metroplitan area network. In *Infocom*, pages 57–64. IEEE, 1993.

[Gre93] Paul E. Green. *Fiber Optic Networks*. Prentice Hall, 1993.

[GWK+92] B. Glance, J.M. Wiesenfeld, U. Koren, A.H. Gnauck, H.M. Presby, and J. Jourdan. High performance optical wavelength shifter. In *Electronic Letters*, volume 28, pages 1714–1715, August 1992.

[GYZ94] Duanyang Guo, Yechiam Yemini, and Zhensheng Zhang. Scalable high-speed protocols for wdm optical star networks. In *Infocom*, pages 1544–1551. IEEE, 1994.

[Hay84] Jeremiah Hayes. *Modeling and Analysis of Computer Communications Networks*. Plenum Press, 1984.

[Hel94] Gilbert Held. *Token Ring Networks*. John Wiley and Sons, 1994.

[HKS87] Isam Habbab, Mohsen Kavehrad, and Carl-Erik Sundberg. Protocols for very high-speed optical fiber local area networks using a passive star topology. *Journal Of Lightwave Technology*, LT-5(12):1782–1794, December 1987.

[HL93] Heinz-Gerd Hegering and Alfred Lapple. *Ethernet - Building a Communications Infrastructure*. Addison-Wesley, 1993.

[Hui90] Joseph Y. Hui. *Switching and Traffic Theory for Integrated Broadband Networks*. Kluwer Academic Press, 1990.

[HWM94] Nen-Fu Huang, Chiung-Shien Wu, and Gin-Kou Ma. A time-wavelength scheduling algorithm for interconnected star networks. In *Infocom*, pages 552–559. IEEE, 1994.

[Inu79] Thomas Inukai. An efficient ss/tdma time slot assignment algorithm. *IEEE Transactions on Communications*, COM-27(10):1449–1455, October 1979.

[JM93a] Feiling Jia and Biswanath Mukherjee. Multis-net: A high capacity, packet switched, multichannel, single-hop local lightwave network. In *Submitted to ACM Transactions on Networking*. IEEE, 1993.

[JM93b] Feiling Jia and Biswanath Mukherjee. The receiver collision avoidance (rca) protocol for a single-hop wdm lightwave network. *Journal of Lightwave Technology*, 11:1053–1065, May/June 1993.

[JT93a] Mark Janoska and Terry Todd. A simplified optical star network using distributed channel controlers. In *Globecom*. IEEE, November 1993.

[JT93b] Mark Janoska and Terry Todd. Simplified single hop photonic lans. In *6th LAN/MAN Workshop*. IEEE, October 1993.

[JT94a] Mark Janoska and Terry Todd. A simplified optical star network using distributed channel controllers. *IEEE Journal of Lightwave Technology*, 12(11):2011–2022, November 1994.

[JT94b] Mark Janoska and Terry Todd. A single hop wavelength routed local area network. In *International Conference on Applications of Photonic Technology (ICAPT)*. IEEE, June 1994.

[JT95] Mark Janoska and Terry Todd. Reservation based protocols for hierarchical single-hop photonic networks. In *Submitted for Publication*, 1995.

[JT96] Mark Janoska and Terry Todd. A single hop wavelength routed lan/man architecture. In *Infocom (to appear)*, 1996.

[KFG94a] B. Kannan, Shivi Fotedar, and Mario Gerla. A protocol for wdm star coupler networks. In *Infocom*, pages 1536–1543. IEEE, 1994.

[KFG94b] B. Kannan, Shivi Fotedar, and Mario Gerla. A two level optical star wdm metropolitan area network. In *Globecom*, pages 563–566. IEEE, 1994.

[KKYW92] K. Kondo, M. Kuno, S. Yamakoshi, and K. Wakao. A tunable wavelength-conversion laser. *IEEE Journal of Quantum Electronics*, 28(5):1343–1348, May 1992.

[LA95] David A. Levine and Ian F. Akyildiz. Proton: A media access control protocol for optical networks with star topology. *IEEE/ACM Transactions on Networking*, 3(2):158–167, April 1995.

[LK92] Jonathan Lu and Leonard Kleinrock. A wavelength division multiple access protocol for high-speed local area networks with a passive star topology. In *Performance Evaluation 16*, pages 223–239, 1992.

[LL93] Kuo-Chun Lee and Victor O. K. Li. Routing and switching in a wvelength convertible optical netowrk. In *Infocom*. IEEE, 1993.

[Mat93] Takao Matsumoto. Multiple-access optical network architecture employing a wavelength-and-network-division technique: Mandala. In *Globecom*, pages 463–467. IEEE, November 1993.

[Meh89] Nader Mehravari. Improved multiple access schemes for very high speed optical fiber local area networks using a passive star topology. In *Globecom*, pages 272–277. IEEE, 1989.

[Mid93] John Midwinter. *Photonics in Switching*, volume Vol 1, Background and Components. Academic Press Inc, 1993.

[MR83] Marco Ajmone Marsan and Daniele Roffinella. Multichannel local area network protocols. *IEEE Journal On Selected Areas In Communications*, SAC-1(5):885–897, November 1983.

[Nil90] Jesper Nilausen. *Token Ring Networks*. Prentice Hall International, 1990.

[otICS85a] Technical Committee Computer Communications of the IEEE Computer Society. *Local Area Networks 802.3, Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method, ANSI/IEEE Std 802.3-1985, ISO Draft Proposal 8802/3*. Institute of Electrical and Electronics Engineers, Inc, 1985.

[otICS85b] Technical Committee Computer Communications of the IEEE Computer Society. *Local Area Networks 802.5 Token Passing Bus Access Method, ANSI/IEEE Std 802.4-1985, ISO Draft Proposal 8802/4*. Institute of Electrical and Electronics Engineers, Inc, 1985.

[otICS85c] Technical Committee Computer Communications of the IEEE Computer Society. *Local Area Networks 802.5 Token Ring Access Method, ANSI/IEEE Std 802.5-1985, ISO Draft Proposal 8802/5*. Institute of Electrical and Electronics Engineers, Inc, 1985.

[Ram93] Rajiv Ramaswami. Multiwavelength lightwave networks for computer communication. *IEEE Communication Magazine*, pages 78–88, February 1993.

[Rob73] L. Roberts. Dynamic allocation of satellite capacity through packet reservation. In *NCC*, pages 711–716, 1973.

[SBD93] Krishna Sivalingam, Kalyani Bogineni, and Patrick Dowd. Pre-allocation media access control protocols for multiple access wdm photonic networks. *Unknown*, 1993.

[Sen92] John Senior. *Optical Fiber Communications Principles and Practice*. Prentice Hall, 2nd edition, 1992.

[SGK91] Ganti Sudhakar, Nicolas Georganas, and Mohsen Kavehrad. Slotted aloha and reservation aloha protocols for very high-speed optical fiber local area networks using passive star topology. *Journal of Lightwave Technology*, 9(10):1411–1422, October 1991.

[SGK92] G. Sudhakar, N. Georganas, and M. Kavehrad. A multi-channel optical star lan and its application as a broadband switch. In *ICC*, pages 843–847. IEEE, 1992.

[SH93] Ghassan Semaan and Pierre Humblet. Timing and displersion in wdm optical star networks. In *Infocom*. IEEE, 1993.

[SK91] Haixing Shi and Mohsen Kavehrad. Aloha/slotted csma protocol for a very high speed optical fiber local area network using passive star topology. In *Infocom*, pages 1510–1515. IEEE, 1991.

[SKG91] G. Sudhakar, M. Kavehrad, and N. Georganas. Multi-control channel very high-speed optical fiber local area networks and their interconnections using a passive star topology. In *Globecom*, pages 624–628. IEEE, 1991.

[SM85] Robyn E. Shotwell and Robert M. Metcalfe. *The Ethernet Sourcebook*. Elsevier Science Publishing, 1985.

[SPE+93] R. Schnabel, W. Pieper, M. Ehrhardt, M. Eiselt, and H.G. Weber. Wavelength conversion and switching of high speed data signals using semiconductor laser amplifiers. In *Electronics Letters*, volume 29, pages 2047–2048, November 1993.

[Spr91] John D. Spragins. *Telecommunications Protocols and Design*. Addison-Wesley, 1991.

[Sta87] William Stallings. *Handbook of Computer Communications Standards - Local Network Standards Vol.2*. Macmillan Publishing Co., 1987.

[Sun89] Carl A. Sunshine. *Computer Network Architectures and Protocols*. Plenum Press, 1989.

[Tan89] Andrew Tanenbaum. *Computer Networks*. Prentice Hall, 2nd edition, 1989.

[TB92] T.D. Todd and A. M. Bignell. Traffic processing algorithms for the signet metropolitan area network. *IEEE Transactions on Communications*, 40:586–576, March 1992.

[TKY+94] K. Takahata, K. Kasaya, H. Yasaka, Y. Kondo, and M. Ikeda. A unidirectional output optical frequency conversion device with an asymetric-k dbr structure. *IEEE Journal of Quantum Electronics*, 30(5):1219–1226, May 1994.

[TMS94] Srini Tridandapani, James Meditch, and Arun Somani. The matpi protocol: Masking tuning times through pipelining in wdm optical networks. In *Infocom*, pages 1528–1535. IEEE, 1994.

[TWB95] Vivek Tandon, Mark Wilby, and Fraser Burton. A novel upgrade path for transparent optical networks based on wavelength reuse. In *Infocom*. IEEE, 1995.

[YIT+94] H. Yasaka, H. Ishii, K. Takahata, K. Oe, Y. Yoshikuni, and H. Tsuchiya. Broad-range wavelength conversion of 10 gbit/s signal using a superstructure grating distributed bragg reflector laser. In *Electronic Letters*, volume 30, pages 132–133, January 1994.

[YIYO95] H. Yasaka, H. Ishii, Y. Yoshikuni, and K. Oe. Repeated wavelength conversion of 10 gbit/s signal using wavelength-tunable semiconductor lasers. In *Photonics Technology Letters*, volume 7, pages 161–163. IEEE, February 1995.

[ZPD+94] J. Zhou, N. Park, J.W. Dawson, K.J. Vahala, M.A. Newkirk, and B.I. Miller. Efficiency of broadband four-wave mixing wavelength conversion using semiconductor traveling-wave amplifiers. In *Photonics Technology Letters*, volume 6, pages 50–52. IEEE, January 1994.