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Symmetrically Multi-Connected Optical Fiber Wide Area Networks

by

Feng Liu, B.Sc., M.Sc.

A thesis submitted to
the School of Graduate Studies and Research
in partial fulfilment of the requirements
for the degree

Master of Applied Science

Ottawa-Carleton Institute for Electrical Engineering
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Abstract

Self-routing all-optical WAN design is becoming more and more important in broadband communications. However, little has been done in this field. In this thesis, we propose a Multi-Dual Ring Connected Shuffle Network and a Multi-Shuffle Connected Shuffle Network for a WAN environment.

The performance of the proposed architectures is studied under a uniform traffic pattern analytically and numerical results are provided.

The Multi-Dual Ring Connected Shuffle Connected Networks are studied under the nonuniform traffic patterns with an analytical method 'extreme value analysis' and a simulation method 'random load generation'.

All of the studies are done with respect to the Perfect Shuffle Networks. The proposed architectures outperform the conventional Perfect Shuffle Network proposed in the literature.

Acknowledgment

I wish to express my gratitude to my thesis supervisor, Dr. Mohsen Kavehrad, for his guidance and financial support through the course of my graduate study. It was his encouragements and many useful comments that made the publication of the two papers and the thesis a reality.

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Acronyms

AT&T	American Telephone and Telegraph Company.
Bellcore	Bell Communication Research Company
CDF	Cumulative Distribution Function
CDM	Code Division Multiplexing
DNA	Digital Network Architecture
DQDB	Distributed Queue Dual Bus
EMI	ElectroMagnetic Interface
EMP	ElectroMagnetic Pulses
FDDI	Fiber Digital Distributed Interface
GPS	Giga bits Per Second
HIPPI	High Performance Parallel Interface
IEEE	Institute of Electrical and Electronics Engineers
LAN	Local Area Network
MAN	Metropolitan Area Network
NIU	Network Interface Unit
NTT	Nippon Telephone and Telegraph Company
OSI	Open System Interconnect
PS	Perfect Shuffle network
RFI	Radio Frequency Interference
RS	multi-dual Ring shuffle connected Shuffle network
SNA	System Network Architecture
TDM	Time Division Multiplexing
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing

Symbols

γ_m	The traffic intensity of channel *m*
Δ	The derivative of E[no. of weighted hops] with respect to k
η	Channel efficiency
$\lambda_{i,j}$	Traffic intensity from user *i* to user *j*
μ	The average traffic intensity per node pair
σ	The standard deviation
db	Decibel
E[.]	Expectation Operator
E[hops], E[number of hops]	The average number of hops
E[no. of weighted hops]	The average number of weighted hops
$E[Y_W]$	The mean of the traffic intensity on the heaviest channel
f_b	Load balance factor
k	The number of columns in a Perfect Shuffle Network
L	The value assigned to a hop between different groups
M	The average number of *i* to *j* traffic pairs that use a particular channel
p	The degree of output of a NIU in a Perfect Shuffle Network
power	Measure of throughput over delay
$P_{extreme}$	Probability of the extreme worst case
R	Power improvement ratio
X	A random variable ~ N(0,1)
X_W	The random variable whose CDF is the Wth power of the CDF of X
Y_W	The traffic intensity on the heaviest channel
W	The total number of channels in a Perfect Shuffle Network
S	The integer associated with different probabilities 10^{-S}

Chapter 1

Introduction

The application of the lightwave technology has great influences on the communications industry and society. It opens a new era for the field of high speed communications and is considered the 'ultimate' technology in communications area.

Some advantages of optical fiber communications are [14]:

- **Enormous fiber bandwidth**

The optical carrier frequency in the range 10^{13} to 10^{16} Hz yields a far greater potential transmission bandwidth than alternatives such as metallic cable systems or radio systems.

- **Electrical isolation**

Optical fibers which are fabricated from glass or sometimes from a plastic polymer are electrical insulators and therefore, unlike their metallic counterparts, they do not exhibit earth loop and interface problems. Furthermore, this property makes optical fiber transmission ideally suited for communication in electrically hazardous environments as the fibers create no arcing or spark hazard at short circuits.

- **Immunity to interference and crosstalk**

Optical fibers form a dielectric waveguide and are therefore free from electromagnetic interface (EMI), radio frequency interference (RFI), or switching transients giving electromagnetic pulses (EMP).

- **Low transmission loss**

The development of optical fibers over the last 15 years has resulted in the production of optical fiber cables which exhibit very low attenuation or transmission loss in comparison with the best copper conductors. Fibers have been fabricated with losses as low as $0.2\ dBkm^{-1}$, and this feature has become a major advantage of optical fiber communications. It facilitates the implementation of communication links with extremely wide repeater spacing (long transmission distances without intermediate electronics), thus reducing both system cost and complexity.

- **Small size and weight**

Optical fibers have very small diameters which are often no greater than the diameter of a human hair. Hence, even when such fibers are covered with protective coatings, they are far smaller and much lighter than the similar copper cables.

Optical fiber's initial application was in long haul point-to-point transmission and this application is continuing. This is usually called the first generation system. One of the first generation systems is the High Performance Parallel Interface (HIPPI).

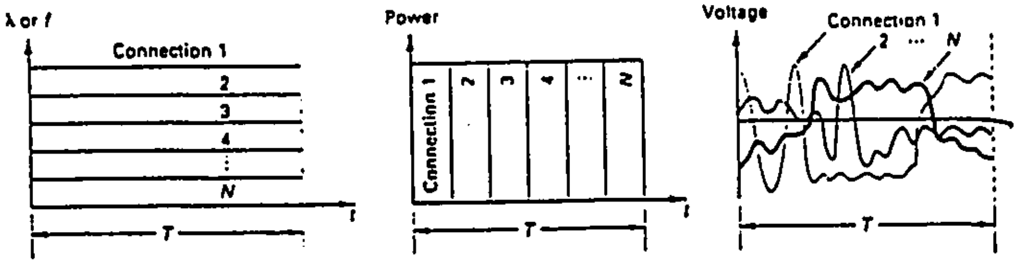
At the present time, the point-to-point transmission is being supplemented with applications to multi-user networks where many users couple onto and share the transmission capabilities of a single fiber. Only when many pairs of communicating users are provided concurrent access to an optical fiber will we begin to make use of its enormous bandwidth. This is called the second generation of the system. This generation is typified by such systems as the Fiber Digital Distributed Interface (FDDI, IEEE 802.5) and the Distributed Queue Dual Bus (DQDB, IEEE 802.6).

In the second generation system, there is a bottleneck of electrical-to-optical and optical-to-electrical conversions. The electronic bottleneck occurs because the speed available from silicon and gallium arsenide electronics is disproportionately small compared to the total network throughput demanded by the new applications. This bandwidth is in turn small compared to that of the fiber. Therefore, a new network with extremely high throughput is being introduced. There are two conversions between electrons and photons, at the transmitter and at the receiver. The electronics involved in a node can be responsible for the traffic needs of that node alone, without regard to the traffic of other nodes. This brings us to the third generation of networks called an 'all-optical' network [13].

The main objective of this thesis is to design some novel self-routing all-optical network architectures.

1.1 Access Methods for Lightwave Technology

Nowadays, the available technology makes it possible to fit a very large number of simultaneous connections within a large available bandwidth of a single fiber. One can build a multiple-access network in which connections between nodes use different optical wavelengths (Wavelength Division Multiplexing, WDM [24]), different time slots (Time Division Multiplexing, TDM [33]) or different signal waveforms (Code Division Multiplexing, CDM). The idea is that the signals agreed upon by the two communicating partners at the physical level are distinguishable from those used by other connections by virtue of occupying different parts of the wavelength domain, different parts of the time domain, or by having suitable different wave shapes. This is shown in Figure 1.1. This thesis will concentrate on the network architecture using WDM.



(A) WDMA (FDMA)   (B) TDMA   (C) CDMA (spread spectrum)

Figure 1.1 Three basic transmission formats. T is a bit duration

1.2 Physical Size of the Fiber-Optic Network

It is customary to classify networks (of any generation) into three categories with respect to their physical size.

- Local Area Networks, LANs (up to 10 kilometers total span, usually within an area of a company or a campus), such as Ethernets, token rings and token buses.

- Metropolitan Area Networks, MANs (up to 100 kilometers, usually within one metropolitan area), such as the telephone local exchange environment or cable television distribution system.

- Wide Area Networks, WANs (up to thousands of kilometers, usually nation wide), such as ARPPA net, System Network Architecture (SNA), Digital Network Architecture (DNA), and the Open System Interconnect (OSI) international standard.

The previous research work dealt predominately with situations that are most easily realized by LANs [18] [19] [32] and MANs [21] [27] [29]. How to achieve a third-generation WAN is a very new research issue. This can be done by interconnecting more localized subnetworks that are in the form of third-generation LANs and MANs [16] [20]. The thesis will explore the WANs area of which little is known.

1.3 Optical Network Configuration

1.3.1 Single-hop Optical Network

An approach that offers a great communication concurrency potential is Wavelength Division Multiplexing (WDM) [1]. The basic approach appears in Figure 1.2. Here, each receiver is assigned a unique wavelength, and a transmitter wishing to access that receiver tunes its transmitter to the receiver wavelength and sends its packet. All packets that are simultaneously transmitted are linearly combined in a passive star coupler, where the individual identities of packets addressed to different receivers are preserved by virtue of the different wavelengths assigned. This approach allows a multitude of non-interfering packets to be simultaneously resident in the network, thereby, achieving concurrency by spreading signals over a vast portion of the optical band.

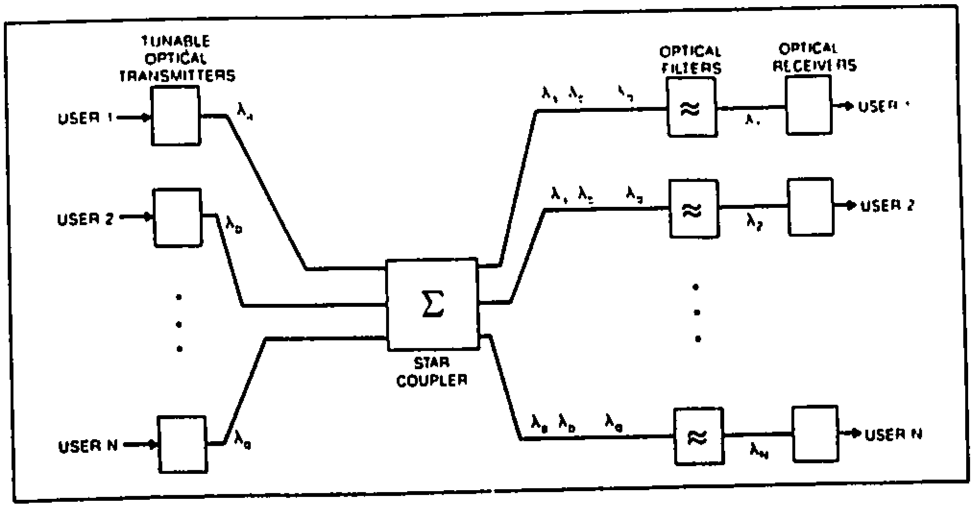


Figure 1.2 A Single-hop Optical Network

The primary drawback of a single-hop WDM approach, as illustrated above, is the need for wavelength tunability at each transmitter and/or receiver. Although transmitters and filters tunable over a broad optical range have been reported, these do not tune on the rapid time scale commensurate with packet switching, and the required filters are accordingly beyond the current state-of-the-art. Thus, we see that straight WDM, as described above, offers promise for highly-concurrent terabit networks, but that implementation must first await some difficult technological breakthroughs.

1.3.2 Multi-hop Optical Network

In contrast to the approaches we have so far considered, a multichannel multihop lightwave network achieves the concurrency needed to tap the vast optical bandwidth in a fully distributed lightwave network without requiring a technological breakthrough [5]. To illustrate the multihop approach to lightwave networking, Figure 1.3 shows a network with eight (electronic) users accessing a unidirectional optical bus thorough Network Interface Units (NIUs) distributed along the bus.

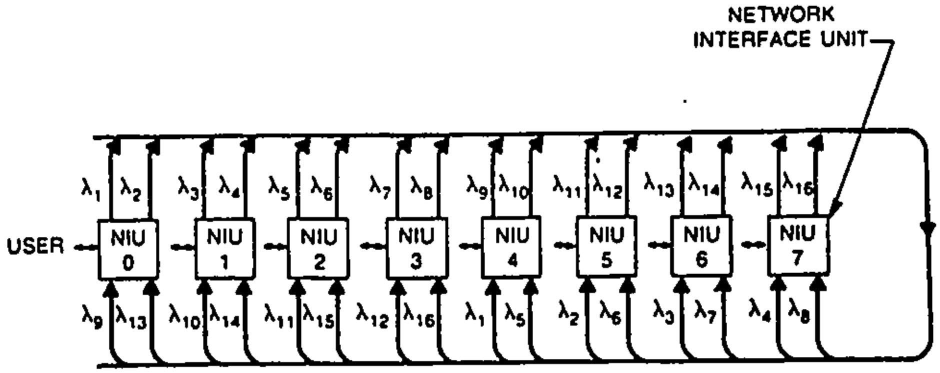


Figure 1.3 Multihop lightwave network

In general, since each NIU can access only a small, fixed set of the WDM channels, packets may need to be routed through intermediate NIUs to reach their destinations. In other words, packets may require multiple hops on different wavelengths to reach their destinations with the user interfaces themselves serving as active repeaters. The WDM channels must be assigned to the NIU transmitters and receivers in such a way that each user can communicate with every other user after one or more hops. For example, if a packet is transferred from NIU0 to NIU1, the transferring procedure is as follows: it is first transmitted from NIU0 to NIU4 through wavelength λ_1 and then transmitted from NIU4 to NIU1 through wavelength λ_{10}.

Note that, the multihop approach to lightwave networking does not impose the requirement that a direct, one-hop connection be established between a source and a destination before communication commences. That is, unlike the straight WDM approach described earlier, a pair of NIUs do not have to first agree (perhaps using a reservation or signaling channel) on a wavelength and transmit one or few times before they can exchange information. Some of the optical bandwidth is squandered by transmitting packets multiple times, but this simplifies the tapping of the remainder and allows a multitude of packets (corresponding to different user pairs) to be concurrently resident on different WDM channels in the network.

1.4 Self Routing All-Optical Network

The all-optical networks that most naturally exploit the fiber's bandwidth and offer low transmission error rates are those in which different connections are made over a single physical medium uninterrupted by optic-to-electronic conversions. The networks do not use intermediate buffers and require the routing process to be done 'on-the-fly'. Thus, we need to adopt simple self-routing schemes using the destination address in the header of each packet.

The realization of an all-optical network requires study of many subjects [30] [31] [34]. However, we will mainly deal with the logical topology side of the question.

1.5 Motivation and Outline of the Thesis

Most of the current research work in designing the architectures of the optical networks has been done in LANs and MANs and little study has been done in WANs.

The purpose of this thesis is to design some novel architectures for self routing all-optical WANs using WDM and the multihop approach.

In Chapter 2, a review of multi-channel, multihop lightwave network is presented. We review different logical topologies for the optical networks. We also show some available technologies and physical topologies for the Perfect Shuffle Network.

In Chapter 3, we present two optical WAN architectures: Multi-Dual Ring Connected Shuffle Network and Multi-Shuffle Connected Shuffle Network. We also complete the performance analysis under a uniform traffic pattern.

In Chapter 4, we give further analysis on the Multi-Dual Ring Connected Shuffle Network under the nonuniform traffic patterns. The reason for choosing this architecture is that it is easier to implement than the Multi-Shuffle Connected Shuffle Network. We use the so called 'extreme value analysis', which is an analytical method, and 'random load pattern generation', which is a simulation method in this study.

In Chapter 5, concluding remarks are given to finalize the work of the entire thesis.

The main contributions of the thesis are stated in Chapter 3 and Chapter 4.

Chapter 2

Multi-Channel Multi-hop Lightwave Networks

The multi-channel multi-hop lightwave network can be called a third-generation network because it exploits the very large bandwidth capability of fiber optic technology. There are many logical topologies that can be used in this kind of network architectures. We list a few in the following.

2.1 Logical Network Topologies

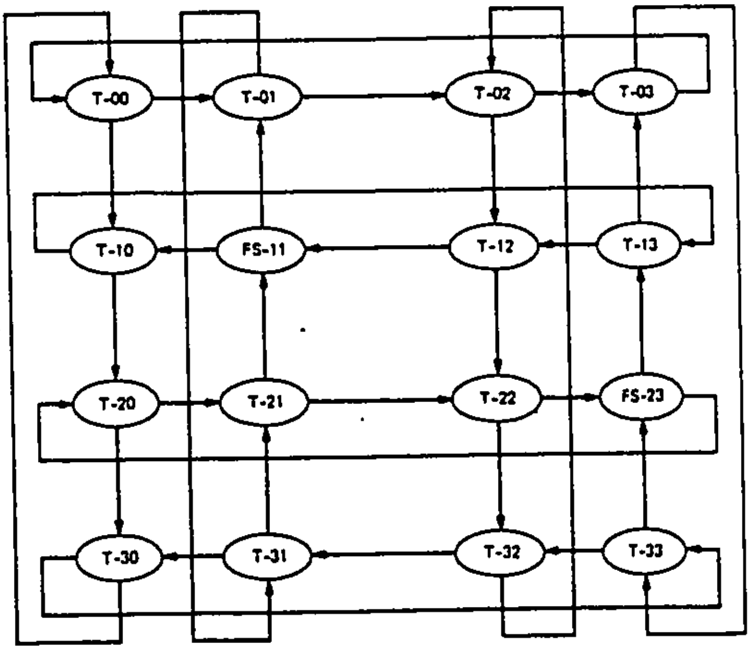


Figure 2.1 A 16-node Manhattan Street Network with two communities of seven terminals (T) and a file server (FS)..

Figure 2.1, Figure 2.2 and Figure 2.3 show the Manhattan Street Network, the De Bruijn Network and the Perfect Shuffle Network proposed by Maxemchuk[12], Sivarajan and Ramaswami [11] and Acampora, Karol and Hluchyj [2], respectively. The advantages of the Manhattan Street Network are high reliability and simple routing scheme. The advantage of the De Bruijn Network is that for a given maximum in and out degree of each node and average number of hops between nodes, the De Bruijn Network can support a larger number of nodes. Among them, the Perfect Shuffle Network is the one that has been most widely studied and it achieves the least average number of hops and the highest throughput under a uniform traffic pattern so that it achieves a better performance under certain conditions [3]. We will discuss this in more detail in later chapters.

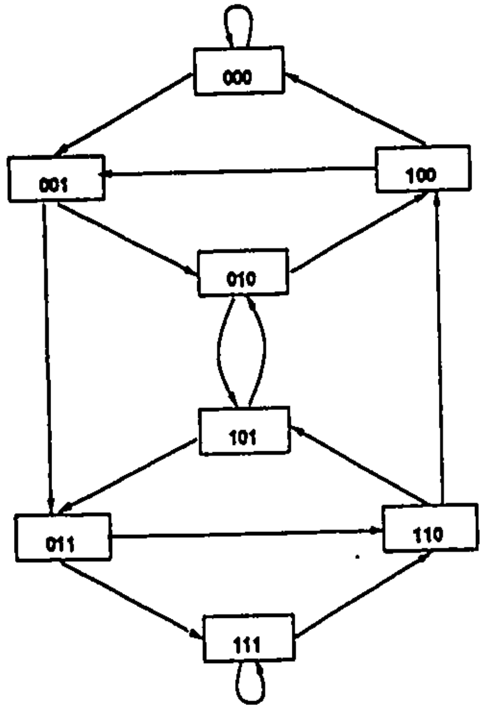


Figure 2.2 The De Bruijn Network G(2,3) where the code word in each box represents the address of the node.

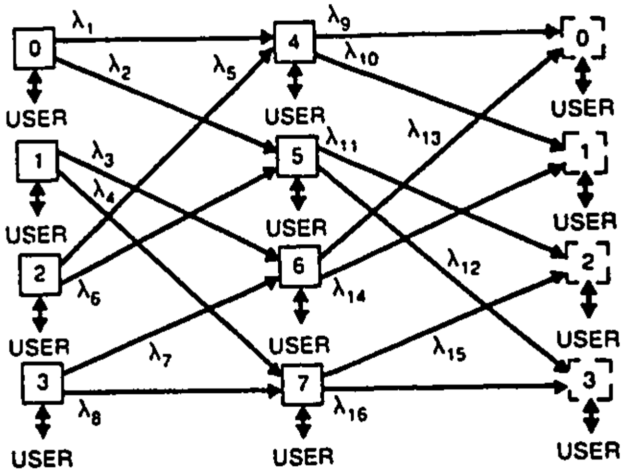


Figure 2.3 8-NIU Perfect Shuffle Network

2.2 Available Subsystems and Physical Topologies For the Perfect Shuffle Network

For a specific network, the physical topology can take a variety of forms different from the logical topology. For the Perfect Shuffle Network, several physical topologies can be applied.

2.2.1 Physical Topologies

Figure 2.4, Figure 2.5 and Figure 2.6 show the physical topology of a tree, a ring and a bus of a 8-node or 24-node Network connected in a logical topology of the Perfect ShuffleNet.

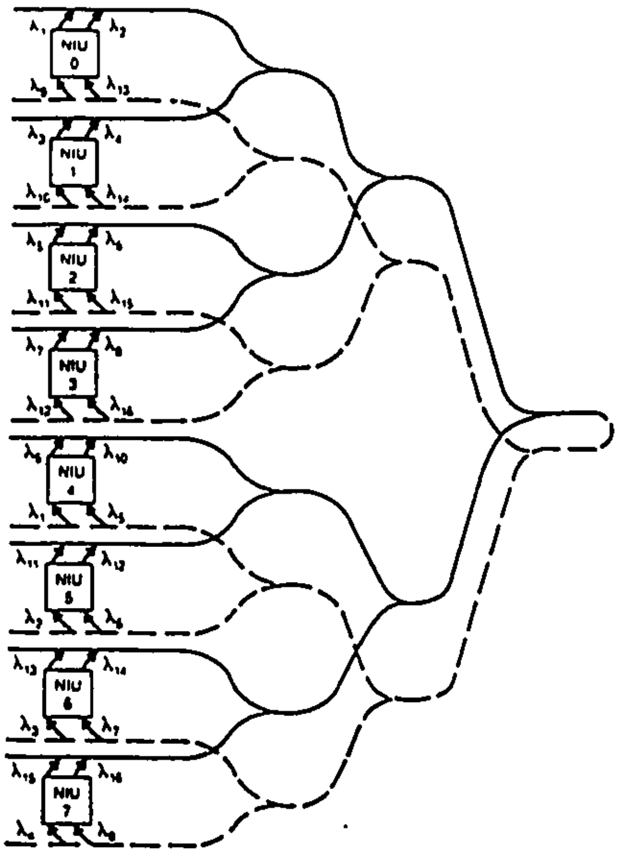


Figure 2.4 A tree physical topology for ShuffleNet

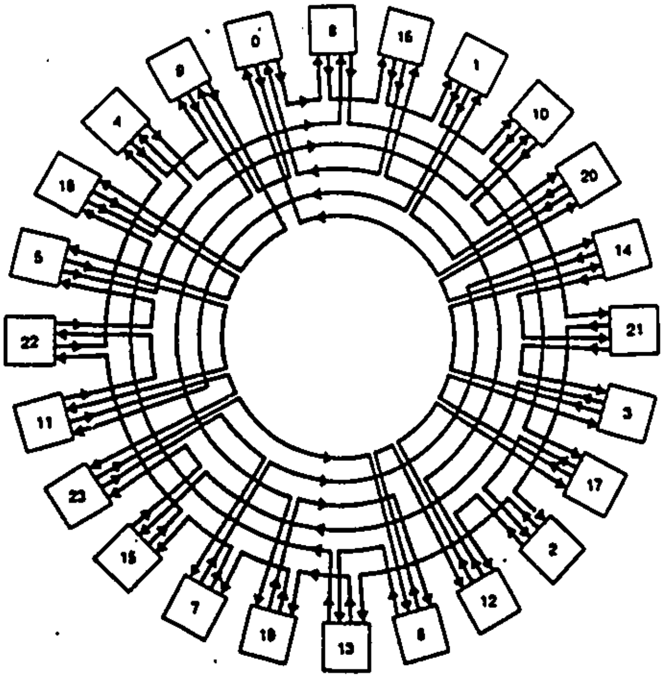


Figure 2.5 A ring physical topology for ShuffleNet

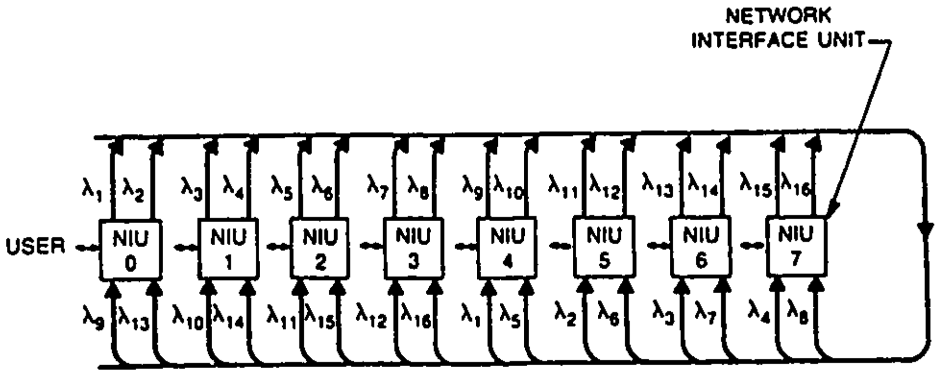


Figure 2.6 A bus physical topology for ShuffleNet

2.2.2 Selective-Broadcasting Passive Star Coupler

The Selective-Broadcasting Passive Star Coupler was proposed by M. Kavehrad and M. Tabiani in 1991 [6]. Figure 2.7 shows a connectivity graph of 8 node ShuffleNet. Actually, this coupler connects the nodes in a bus physical topology. One advantage of this coupler over other broadcasting couplers is that every input only transmits to a small number of selected outputs so that each receiving end can get more transmitting power. We can use this coupler to implement the network architecture we propose in the later chapters.

After a careful comparison of the performance in terms of 'average number of hops' and 'throughput', we think the Perfect Shuffle Network is a suitable architecture for LANs and MANs, and we will use it as a subnetwork to form the WANs' architecture which we propose in the following chapters.

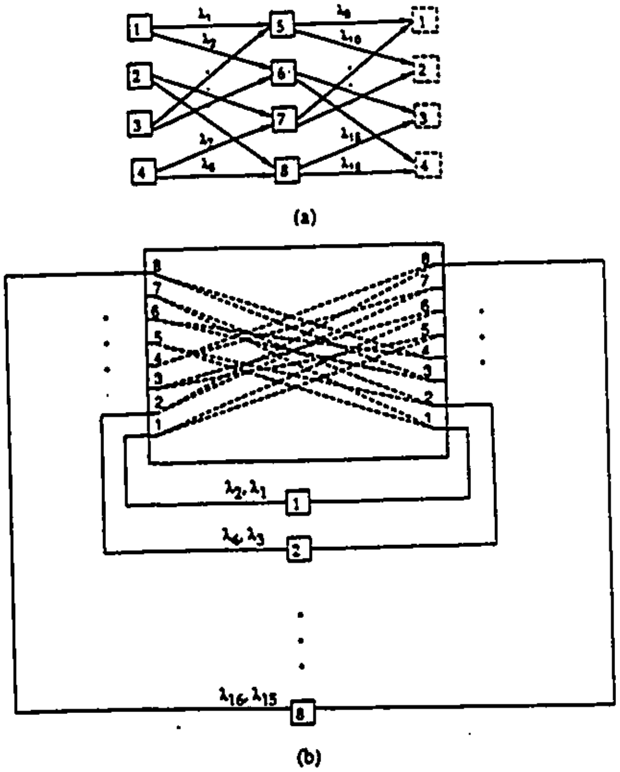


Figure 2.7 A Selective-Broadcasting (WDM Cross Connect) Passive Star Coupler in a 8-NIU ShuffleNet

Chapter 3

Performance Analysis of the Symmetrically Multi-Connected Optical WAN Network Architectures Under A Uniform Traffic Pattern

3.1 Introduction

For multi-user communications networks, optical fiber offers the potential to supply a pool of capacity--to be shared among users--far above that provided by any available alternative. To tap this huge capacity, it is necessary to bring as much communications concurrency as possible in the multi-user networks. However, the processing speed of the electro-optic converters prevents any user from accessing more than a tiny fraction of the overall capacity. One good approach to tap the vast band of fiber without requiring a technological breakthrough is the Perfect Shuffle Network proposal [1] using Wavelength Division Multiplexing (WDM) and multi-hop approach [5]. Since its graph connectivity has a homogeneous structure [2] and the communications traffic pattern for Wide Area Network (WAN) is not homogeneous, the Perfect Shuffle Network architecture is not suitable for WANs. In this chapter, we propose two symmetrically multi-connected optical network architectures: the Multi-Dual Ring Connected and Multi-Shuffle Connected Shuffle Networks. We then make some analysis of the performance under a uniform traffic pattern. These architectures require the same type of Network Interface Units (NIU) as in the Perfect Shuffle Networks while achieving a better performance for the WAN environment in terms of the average weighted hops, power, alternative routing schemes, etc., because they can distinguish the local traffic from the remote traffic [9].

3.2 Perfect Shuffle Network Performance Analysis

3.2.1 Perfect Shuffle Network

In general, the (p, k) ShuffleNet consists of $N = kp^k$ $(k=1,2,3....; p=1,2,3...)$ NIUs arranged in k columns of p^k NIUs in each column [4]. Moving from left to right (in Figure 3.1), successive columns are connected by p^{k-1} direct arcs, arranged in a fixed shuffle pattern, with the last column connected to the first as if the entire graph were wrapped around a cylinder. Each of the p^k users in a column has p arcs directed to p different users in the next column. Numbering the users in a column from 0 to p^k-1, user i has arcs directed to users j, $j+1$,... and $j+p-1$ in the next column, where $j = (i \bmod p^{k-1})\,p$. The resulting pattern of arcs between adjacent columns is referred to as a p-shuffle.

3.2.2 Performance Analysis

For a recirculating perfect-shuffle connectivity graph, a path having at most $2k-1$ hops exists from each NIU to all others. Figure 3.1 illustrates this for the $(p=2,k=2)$ 8-NIU connectivity graph, where we show a spanning tree for routing packets from the first NIU to all other NIUs. Because of the symmetrical nature of the graph, we can draw a topologically equivalent spanning tree for all other NIUs. Notice, in Figure 3.1 that the depth of the spanning tree grows as $2k-1$. This is proportional to the base p logarithm of the number of NIUs[2]. More specifically, we have the following formula:

$$\text{The number of NIUs } h \text{ hops away} = \begin{cases} p^k & h = 1,2,\ldots, k-1 \\ p^k - p^{h-k} & h = k,k+1,\ldots\ldots,2k-1 \end{cases} \qquad \text{<3-1>}$$

(k, p) **k = 2, p = 2**

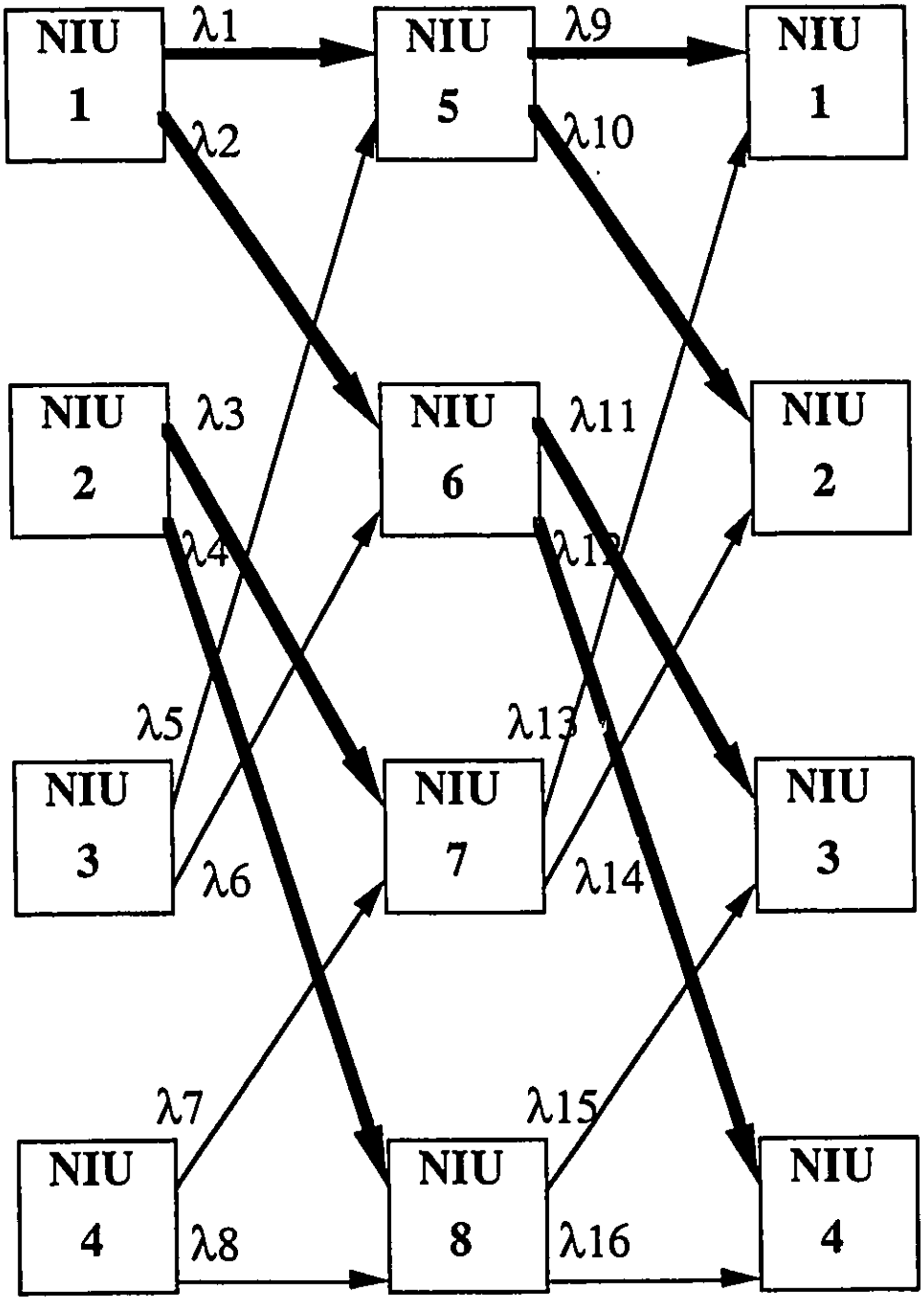


Figure 3.1 Perfect Shuffle Network Connectivity and the Spanning Tree from NIU1

Thus the average number of hops between two randomly selected users is given by this formula:

$$E[\text{number of hops}] = \frac{kp^k(p-1)(3k-1)-2k(p^k-1)}{2(p-1)(kp^k-1)} \qquad <3\text{-}2>$$

If the network is uniformly loaded (i.e., each user generates an equal amount of traffic destined for all other users and all WDM channels are loaded equally), the channel efficiency η for the network is given by

$$\eta = \frac{1}{E[\text{number of hops}]} = \frac{2(p-1)(kp^k-1)}{kp^k(p-1)(3k-1)-2k(p^k-1)} \qquad <3\text{-}3>$$

The total network throughput and the throughput per NIU are simply $\eta W = k\eta\, p^{k+1}$ and ηp, respectively, normalized to the channel transmission rate where $W = k \cdot p^{k+1}$ is the total number of channels in a Perfect Shuffle Network.

Wide area optical networks differ with LANs in that the whole WAN (for example: a nation wide network) consists of many groups of NIUs where each group is a set of NIUs within a city. The distance between NIUs in different cities is by far larger than that between the NIUs within a city. Therefore, it cannot be assumed that all the hops are equal. Instead, each hop is assigned a value (or a weight or a distance). Usually, in real case, the distances between different cities are not the same and they are not located geographically in a circle. However, for simplicity, we assume that (1) all the groups have the same size; (2) the value assigned to a hop within a group is *unity*; (3) the value assigned to a hop between different groups is *L*; (4) the NIU groups are geographically positioned in a circle, as shown in Figure 3.2.

We define a measure:

$$\begin{aligned} Power &= \frac{\text{aggregate throughput}}{\text{mean delay in transit}} \qquad [\text{packet / second}^2] \\ &= \frac{\text{no. of channels } (W)}{\text{average no. of hops} \times \text{mean delay}} = \frac{\text{no. of channels } (W)}{\text{average no. of weighted hops}} \end{aligned} \qquad <3\text{-}4>$$

This value is quite suitable as a measure of network performance because both high throughput and low delay in transit characterize the efficiency of the networks [8].

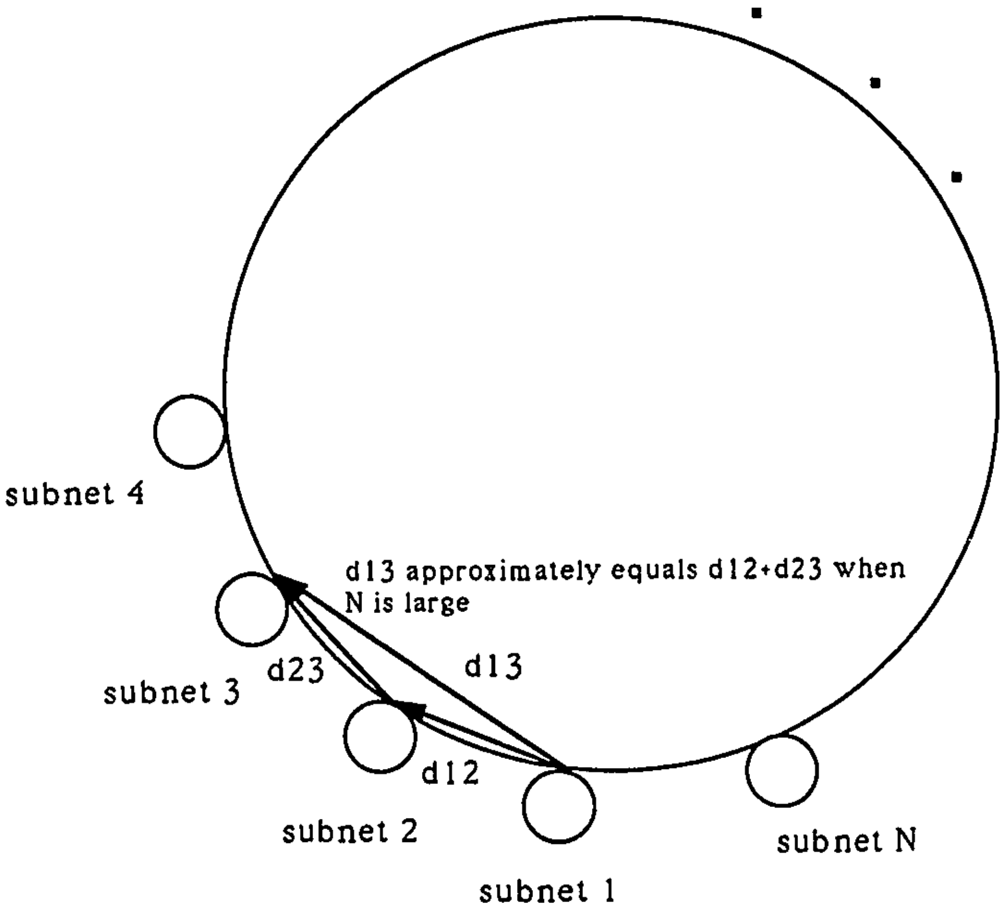


Figure 3.2 Geographical positions of the NIU groups

Under the uniformly loaded traffic pattern and the ShuffleNet fixed routing algorithm assumption, the average number of weighted hops and the power are calculated in the case of L= 10 and L = 50 where the former is the case in the U.S. in which cities are large and densely related and the latter is the case in Canada in which cities are small and sparse. The results, which are calculated through the implementation of the routing scheme by a computer program, are shown in Table 3.1. In this table, the "No. of NIUs" means the total number of NIUs in a WAN; "No. of subnets" means the number of subnetworks in the WAN; "No. of NIUs per subnet" means the number of NIUs in each identical subnetwork and "E[hops]" stands for the average number of weighted hops. The detailed explanation and the definition of "Delta" and "R" will be given in the next section.

3.3 Proposed Multi-Dual Ring Connected Shuffle Network and its Performance Analysis

3.3.1 Proposed Multi-Dual Ring Connected Shuffle Network

Provided that the assumptions in Chapter 3.2.2 are valid, we can assume that each group of NIUs are connected in a Perfect ShuffleNet within the group (we call this a subnetwork). In the proposed logical topology, all the subnetworks are connected symmetrically in a ring in which every NIU in a subnetwork is connected to the corresponding one in the adjacent subnetwork (see Figure 3.3). Also, there are two rings connecting each NIU: one clockwise and one counter-clockwise. Therefore, this architecture is called a Multi-Dual Ring Connected Shuffle Network.

A simple routing scheme is applied to the proposed architecture: the ShuffleNet fixed routing scheme is adopted within a subnetwork and the dual ring routing scheme is adopted between the subnetworks. A NIU's address is composed of two parts: (the address of its subnetwork, its address within the subnetwork). Thus, if a packet is to be transferred from (a_1,b_1) to (a_2,b_2), it is first transferred through the ring (the packet itself decides if the direction is clockwise or counter-clockwise, whichever is shorter in distance) to the subnetworka_2, then transferred from (a_2,b_1) to (a_2,b_2) within the subnet a_2 in a fixed ShuffleNet self-routing scheme. It is obvious that the above routing scheme applied to the proposed architecture can thoroughly distinguish the local traffic from the remote traffic.

3.3.2 Performance Analysis

We now present a performance analysis for the Multi-Dual Ring Connected Shuffle Network with regard to the Perfect Shuffle Network. The assumptions of the same number of NIUs, the same L, the same number of transceivers (in Figure 3.3, p=4) and the uniform traffic pattern apply to both network architectures. In other words, we study both network architectures under the same conditions and scenarios.

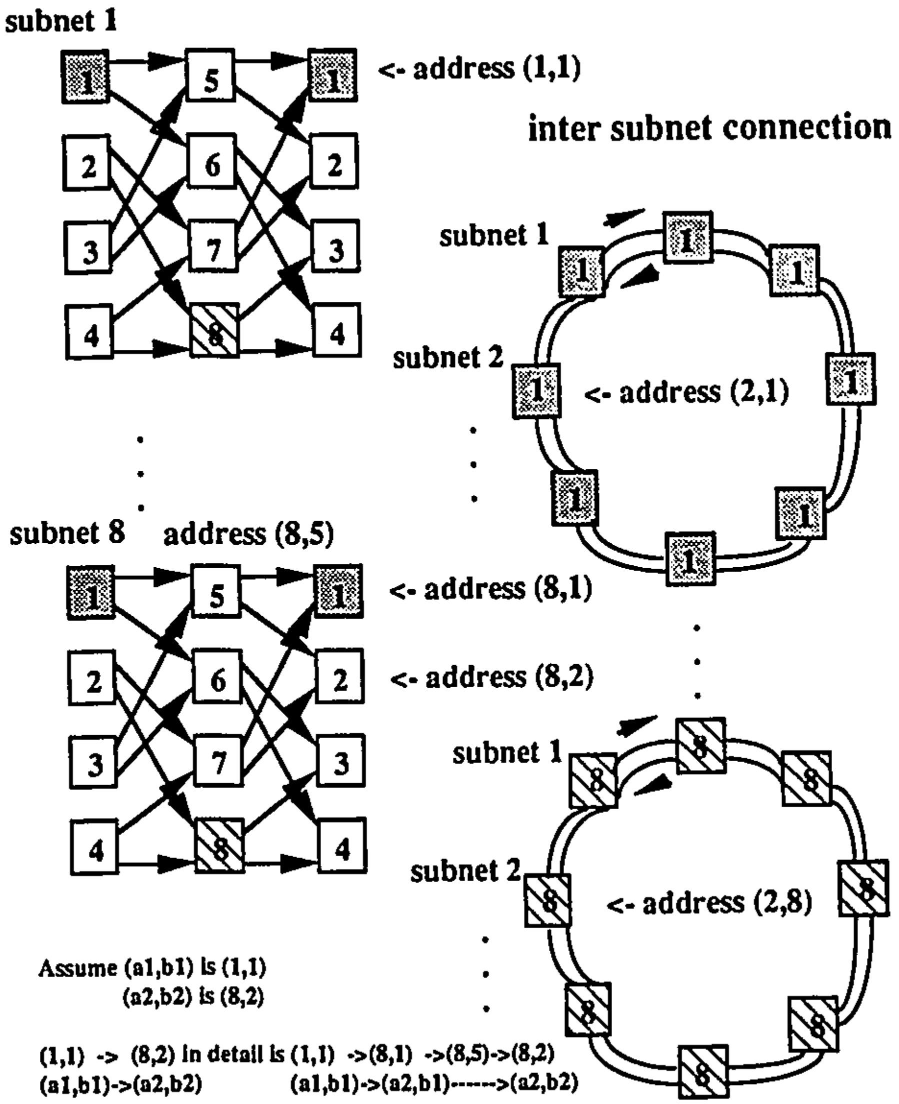


Figure 3.3 Logical topology of the Multi-Dual Ring Connected Shuffle Network

It is assumed that the Perfect Shuffle Network is a *(k,4)* ShuffleNet ($p=4$) and the subnetwork in the Multi-Dual Ring Connected Shuffle Network is a *(k', 2)* ShuffleNet ($p'=2$). The remaining two transceivers are there for ring connections. The number of subnetworks is N.

$$N = \frac{Total\ No.\ of\ NIUs}{No. of\ NIUs\ in\ a\ subnetwork} = \frac{k \cdot 4^{k}}{k' \cdot 2^{k'}} \qquad <3\text{-}5>$$

The weight of a hop between the subnetworks is assumed to be L and the weight of a hop within a subnetwork is unity. The average number of weighted hops:

$$\begin{aligned}
&E[no. of\ weighted\ hops] \\
&= E[number\ of\ hops\ between\ the\ subnetworks] \\
&\quad + E[number\ of\ hops\ within\ a\ subnetwork] \\
&= \frac{N}{4} \times L + \frac{k' \cdot 2^{k'}(2-1)(3k'-1) - 2k'(2^{k'}-1)}{2(2-1)(k' \cdot 2^{k'}-1)} \qquad <3\text{-}6> \\
&= \frac{N}{4} \times L + \frac{3(k')^2 \cdot 2^{k'} - 3k' \cdot 2^{k'} + 2k'}{2(k' \cdot 2^{k'}-1)}
\end{aligned}$$

For the proposed network architecture, different network configurations (larger and fewer subnetworks or smaller and more subnetworks which correspond to different values of k'), the average number of hops varies. To get the minimum value of *E[hops]*, let us take:

$$\Delta = \frac{dE[hops]}{dk'} = 0 \qquad <3\text{-}7>$$

i.e., the value for E[hops] of this architecture reaches its minimum when:

$$\begin{aligned}
&\Delta = \\
&\frac{[y(k')-1] \cdot [3y(k')+2]dk' - (k'+1) \cdot d[y(k')]}{2[y(k')-1]^2} - \frac{k \cdot 4^{k'} \cdot d[y(k')]}{4 \cdot y^2(k')} \times L \qquad <3\text{-}8> \\
&= 0 \\
&where\ y(k') = k' \cdot 2^{k'}\ and\ d[y(k')] = [2^{k'} + k' \cdot 2^{k'} \cdot \ln 2] \cdot dk'
\end{aligned}$$

Under a uniform traffic pattern, we maintain

$$Power = \frac{No.\ of\ channels\ W}{Average\ no.\ of\ weighted\ hops} \qquad <3\text{-}9>$$

$$
\begin{aligned}
&\textit{The number of channels in a Multi-Dual Ring connected Shuffle Network}\\
&= \textit{The number of channels between subnetworks} + \textit{The number of channels}\\
&\quad \textit{within a subnetwork}\\
&= 2 \cdot k' \cdot 2^{k'} \cdot N + k' \cdot 2^{k'+1} \cdot N\\
&= 2k' \cdot 2^{k'} \cdot \frac{k \cdot 4^{k}}{k' \cdot 2^{k'}} + k' \cdot 2^{k'+1} \cdot \frac{k \cdot 4^{k}}{k' \cdot 2^{k'}}\\
&= k \cdot 4^{k+1}\\
&= \textit{The number of channels in the corresponding Perfect Shuffle Network}
\end{aligned}
\qquad \textit{<3-10>}
$$

Thus, for both network architectures, the number of required channels is the same. So in order to maximize the "Power" measure one has to minimize the value of E[hops].

3.3.3 Numerical Results

From Table 3.1, it is clear that the average weighted hops number for the Multi-Dual Ring Shuffle Network is much less than that for the Perfect Shuffle Network. The "power" measure in the proposed network architectures should be increased according to equation <3-9> (see Figure 3.4). So we define a Power Improvement Ratio as:

$$
R = \frac{\textit{The Power of the Proposed Architecture}}{\textit{The Power of the Perfect Shuffle Network}} \qquad \textit{<3-11>}
$$

Several conclusions can be drawn from the numerical results.

First, it is stated in Table 3.1 that for a particular number of NIUs, when the parameter Δ (Delta) is the closest to zero, the corresponding *E[hops]* value is minimum --- for the largest subnetwork in which case k' is the largest and the smallest number of subnetworks. However, changing the parameter Δ does not change the ratio R, significantly.

L = 10

No.of NIUs			Perfect Shuffle		Multi-Dual Ring Connected Shuffle			
	No.of subnets	No.of NIUs per subnet	E[hops]	Power	Delta	E[hops]	Power	R
32	4	3	23.15	5.53	-10.36	12	10.67	1.929
192	24	8	221.07	3.47	-70.02	62	12.39	3.566
1024	128	8	1653.40	2.48	-380.24	322	12.72	5.135
5120 k'=2	640	8	10665.9	1.92	-1907.5	1602	12.78	6.658
5120 k'=4	80	64	1333.28	15.36	-187.13	204.64	100.08	6.515
24576 k'=2	3072	8	62718.4	1.57	-9161.8	7682	12.797	8.164
24576 k'=3	1024	24	20907.8	4.70	-2626.3	2563.26	38.351	8.157
24576 k'=4	384	64	7839.83	12.54	-903.92	964.63	101.91	8.127

L = 50

No.of NIUs			Perfect Shuffle		Multi-Dual Ring Connected Shuffle			
	No.of subnets	No.of NIUs per subnet	E[hops]	Power	Delta	E[hops]	Power	R
32	4	8	113.46	1.13	-58.09	52	2.46	2.182
192	24	8	1104.69	0.695	-356.37	302	2.54	3.658
1024	128	8	8266.83	0.496	-1907.4	1602	2.56	5.160
5120 k'=2	640	8	53329.6	0.384	-9543.6	8002	2.56	6.665
5120 k'=4	80	64	6666.04	3.072	-941.64	1004.64	20.39	6.635
24576 k'=2	3072	8	313592	0.314	-45815	38402	2.56	8.166
24576 k'=3	1024	24	104538	0.940	-13137	12803.3	7.678	8.165
24576 k'=4	384	64	39199.0	2.51	-4525.6	4804.64	20.460	8.159

Table 3.1 The Computer Calculated Numerical Results of the Multi-Dual Ring Connected Shuffle Networks with respect to the Perfect Shuffle Networks

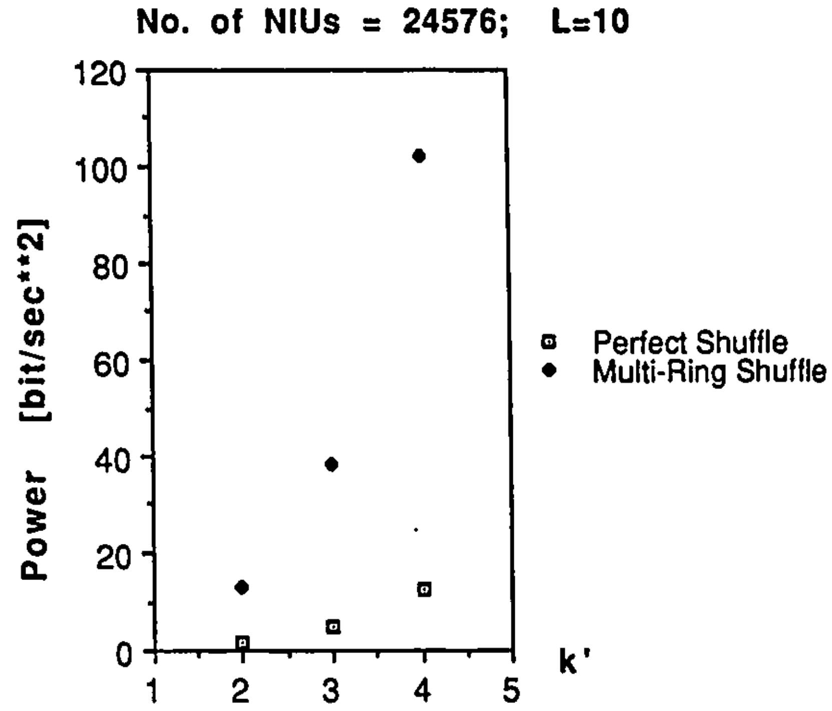


Figure 3.4 Comparison of the power between the Perfect Shuffle Network and the Multi-Dual Ring Connected ShuffleNet (according to equation <3-9>)

Second, it is clear from Figure 3.5 that for a particular number of NIUs, increasing parameter *L* does increase *R*, however, *R* begins to saturate when *L* = *3*. That is why *L* = *10* (U.S. nation wide WAN) and *50* (Canadian nation wide WAN) do not make much difference in the value of *R* as in Table 3.1.

Finally, it can be seen from Figure 3.6 that increasing the number of NIUs does increase the ratio *R*, significantly. This means the proposed Multi-Dual Ring Connected Shuffle Network architecture achieves a relatively better performance as the network size grows.

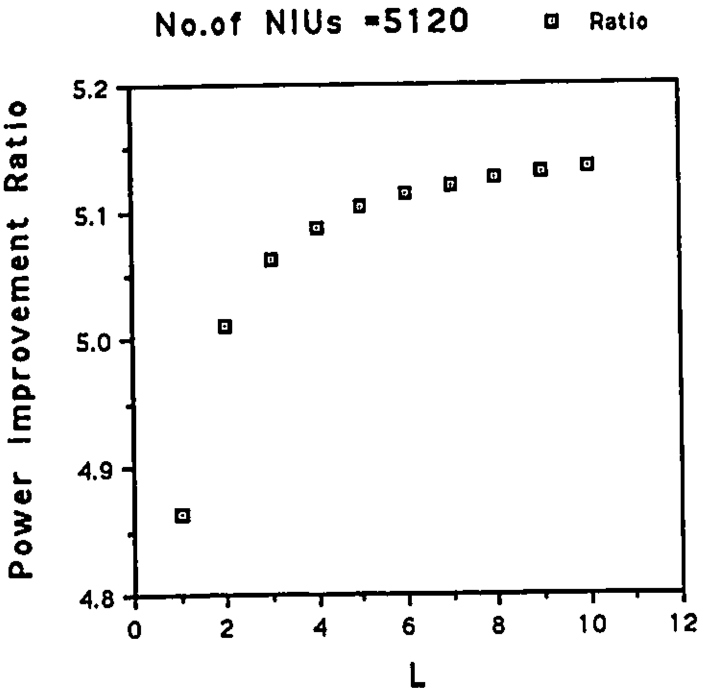


Figure 3.5 Power Improvement Ratio as a Function of Hop Weights

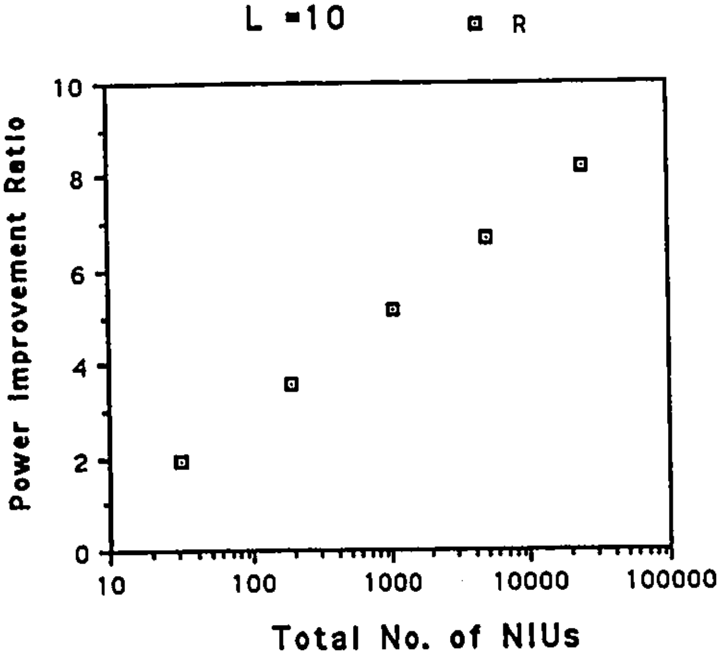


Figure 3.6 Power Improvement Ratio versus Total No. of NIUs

3.4 Proposed Multi-Shuffle Connected Shuffle Network and its Performance Analysis

3.4.1 Proposed Multi-Shuffle Connected Shuffle Network Architecture

In the Multi-Shuffle Connected Shuffle Network, the corresponding NIUs in different subnetworks are symmetrically multi-connected in a similar way as the previously proposed architecture. That is, instead of a Multi-Dual Ring we use a Multi- ShuffleNet (see Figure 3.7).

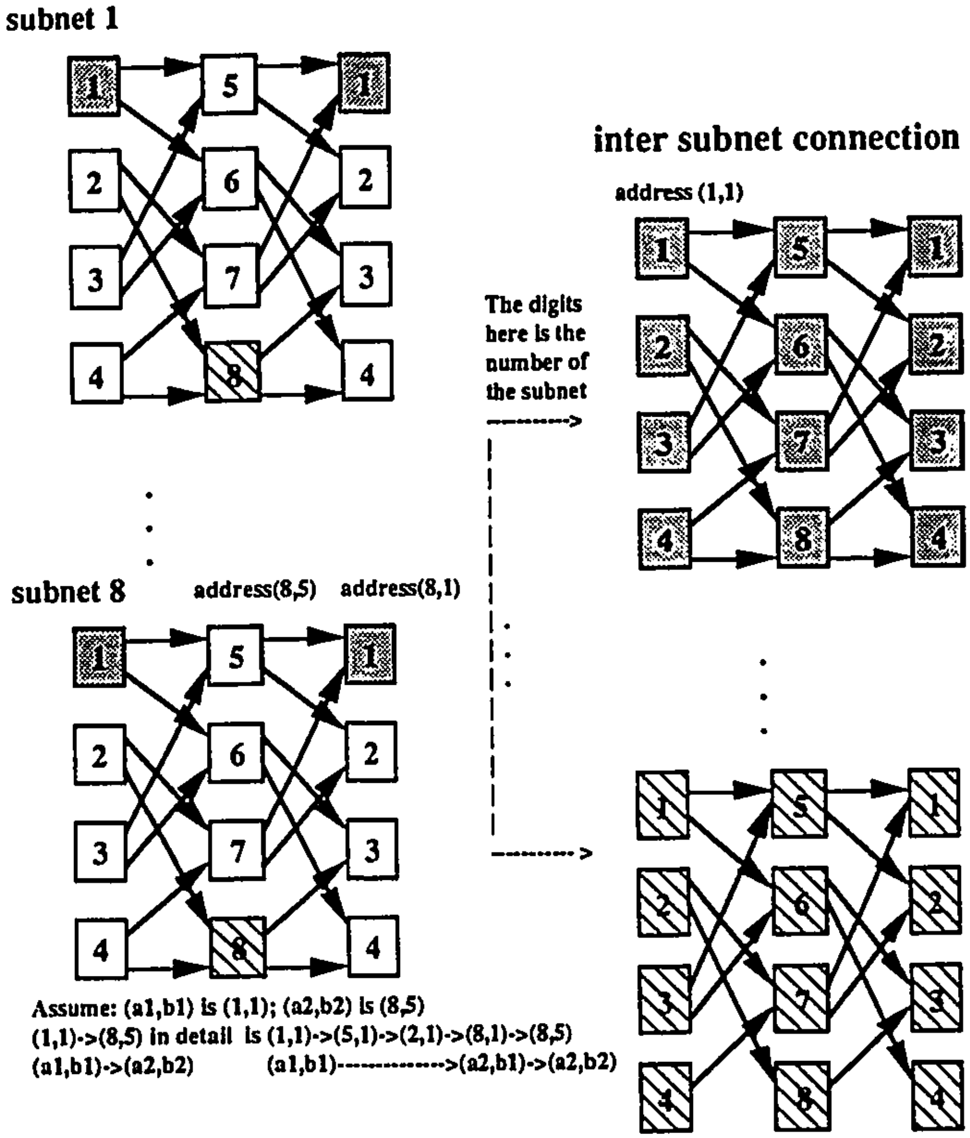
The NIU's address is the same as that in the last proposed architecture (a, b). If a packet is to be transmitted from (a_1,b_1) to (a_2,b_2), it is first sent through the ShuffleNet between the subnetworks to subnetwork a_2, by the ShuffleNet fixed routing scheme. Then it is sent from (a_2,b_1) to (a_2,b_2) within the subnet a_2 also by the Shuffle fixed routing scheme. The routing scheme applied to this proposed architecture can also distinguish between the local traffic and the remote traffic.

3.4.2 Performance Analysis

In this section we provide a performance study of the architecture. It is assumed that the ShuffleNet between the subnetworks is a (k_1,p) ShuffleNet, the ShuffleNet within the subnetworks is a (k_2,p) ShuffleNet and the Perfect Shuffle Network is a $(k,2p)$ ShuffleNet so that the number of transceivers in the NIU for both architectures is the same. It is also assumed that both architectures have the same total number of NIUs and the same value for parameter L.

The average no. of weighted hops =

$$\frac{k_1p^{k_1}(p-1)(3k_1-1)-2k_1(p^{k_1}-1)}{2(p-1)(k_1p^{k_1}-1)}\times L+\frac{k_2p^{k_2}(p-1)(3k_2-1)-2k_2(p^{k_2}-1)}{2(p-1)(k_2p^{k_2}-1)} \quad \text{<3-12>}$$



Assume: (a1,b1) is (1,1); (a2,b2) is (8,5)
(1,1)->(8,5) in detail is (1,1)->(5,1)->(2,1)->(8,1)->(8,5)
(a1,b1)->(a2,b2) (a1,b1)------------->(a2,b1)->(a2,b2)

Figure 3.7 Logical topology of Multi-Shuffle Connected Shuffle Networks

Since the total number of NIUs for both architectures are the same, we have

$(k_1 p^{k_1})(k_2 p^{k_2}) = k \cdot (2p)^k = Constant$

Define: $y_i = k_i p^{k_i}$, $i = 1,2$. $\therefore$ $y_1 \cdot y_2 = Constant = C$ <3-13>

Since p *is fixed, we have* k_i *change* ⇔ y_i *change*

$$\text{Define: } f(y_i) = \frac{k_i p^{k_i}(p-1)(3k_i-1) - 2k_i(p^{k_i}-1)}{2(p-1)(k_i p^{k_i}-1)}$$

<3-14>

$$E[hops] = f(y_1) \times L + f(y_2) = f(\frac{C}{y_2}) \times L + f(y_2)$$

$$E[hops] \text{ reaches its minimum when } \frac{dE[hops]}{dy_2} = 0,$$

$$\text{i.e., } f'(\frac{C}{y_2})(-\frac{C}{y_2})dy_2 \times L + f'(y_2)dy_2 = 0 \qquad <3\text{-}15>$$

Therefore, in the case of L = 1, the value of E[hops] reaches its minimum when $k_1 = k_2$ which means the ShuffleNet (k_1,p) between the subnetworks is the same as the (k_2,p) one within the subnetworks.

3.4.3 Numerical Results

L = 10

No.of NIUs	Perfect Shuffle		Multi-Shuffle Connected Shuffle					
	No.of subnets	No.of NIUs per subnet	E[hops]	Power	Delta	E[hops]	Power	R
5184	72	72	703.836	88.38	-411.1	25.718	2418.82	27.367

Table 3.2 The Computer Calculated Numerical Results of the Multi-Shuffle Connected Shuffle Networks with respect to the Perfect Shuffle Networks

The results in Table 3.2 show that the Multi-Shuffle Connected Shuffle Networks achieve a much better performance (Power Improvement Ratio > 27) than the Perfect Shuffle Networks.

3.5 Concluding Remarks

In this chapter, the performance of the proposed network architectures was studied under a uniform traffic pattern. A criterion was found for achieving the minimum average weighted hops number and the maximum "power" measure. The truth of the criterion is that it is a measure of grouping: the larger the size of the subnetworks, the smaller the average number of weighted hops. Both proposed architectures achieve a greater power than that of the Perfect Shuffle Network. The Power Improvement Ratio increases as the network size increases.

As the network grows, the number of required channels will increase considerably. To reduce the required number of wavelengths, a frequency-reuse method is applied to the proposed architectures [23]. Since the channels in each individual subnetwork are mutually isolated, the same set of wavelengths is reused in each subnetwork so that the number of required wavelengths can be reduced, greatly.

The Multi-Ring Connected Shuffle Network can be easily implemented [6] (see Figure 3.8). In each subnetwork, a selective-broadcast coupler is used to form a ShuffleNet connection, and then each NIU is connected to another NIU attached to the next coupler. In this way, the proposed logical network topology is transformed into a "realistic" network. We consider two categories of the routing schemes for this architecture: ring routing and shuffle routing each of which consists of a large number of hops. By rearranging the ring and shuffle routing sequences, the combinations of different hop sequences produce many alternative equivalent shortest routing paths. This feature is very important when there is a communication link failure or congestion: a packet can go around the "failed" link and reach its destination without having to go through longer paths.

The idea of Multi-Shuffle Connected Shuffle Network can be generalized to other existing network topologies, such as the Manhattan Street Network, in order to create some new network architectures.

The proposed routing schemes are so simple that they can make the packet networks self-routing without much cost in the system processing time. Therefore, the proposed network architectures can also be considered as candidates for an all-optical WAN. Because these require exactly the same technologies as the Perfect Shuffle Networks and exhibit a better performance in the WAN environments, the proposed architectures may be better choices for WANs.

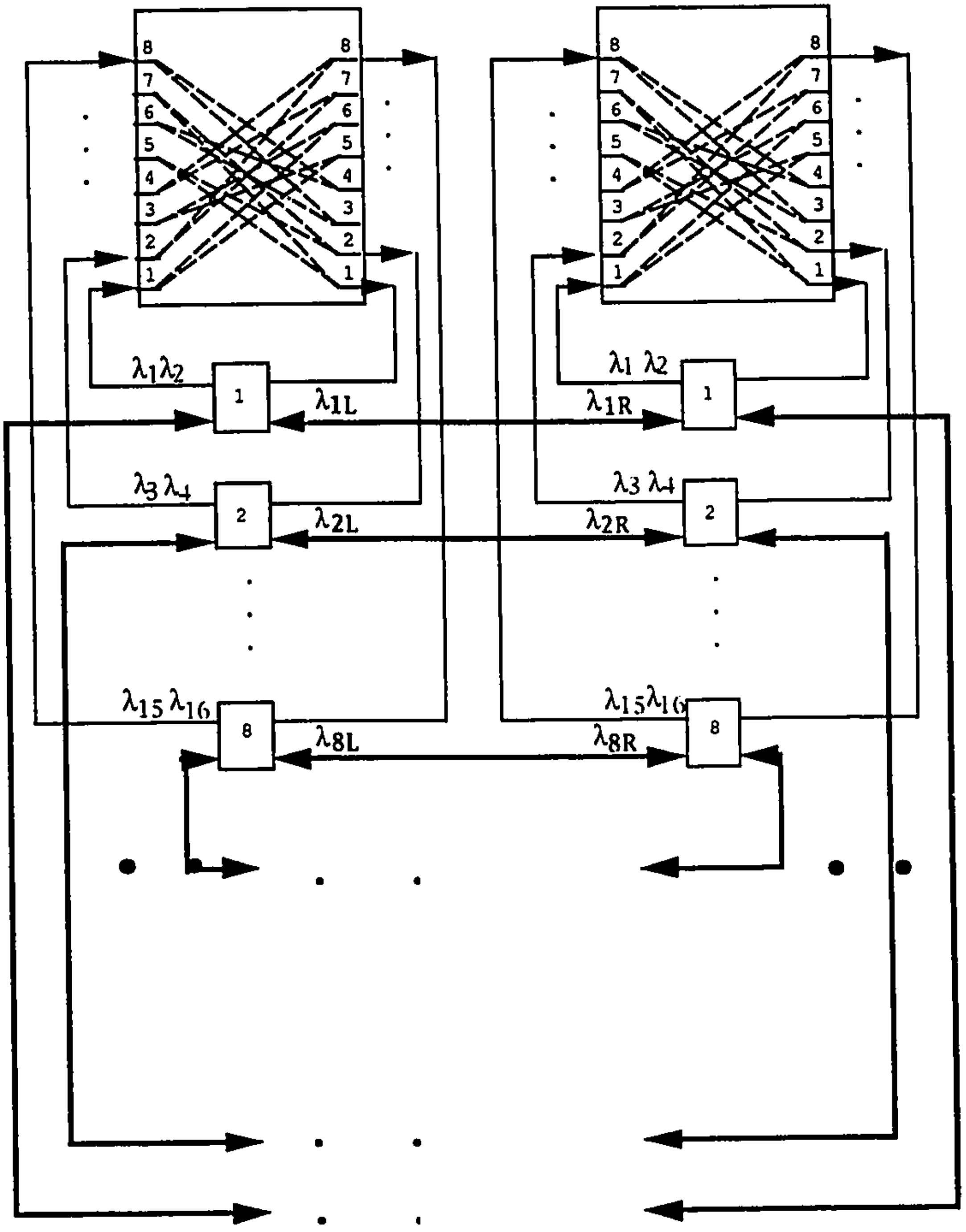


Figure 3.8 An implementation of the Multi-Dual Ring Connected Shuffle Network

Chapter 4

Performance Analysis of the Multi-Dual Ring Connected Shuffle Networks Under Nonuniform Traffic Patterns

4.1 Introduction to the Study Approaches in Nonuniform Traffic Patterns

In the study of the last chapter, it was assumed that the traffic on the network is uniformly distributed. In this chapter, the case of nonuniform traffic patterns is considered. Obviously, in practice, the load distribution offered to the system will often be nonuniform, and to properly assess the capacity of the network, it is necessary to determine how much traffic it can handle for realistic load distributions.

Although unbalanced loads can occur in a multitude of ways, their natures are decided by two factors: traffic intensity and traffic destination. Thus, we use two different approaches to assess the impact of load imbalance. The first, which we refer to as "extreme value analysis" is an approximate analytical technique that assumes the distribution of the load is uniform, but the intensity of the traffic from the individual users has a normal distribution. With these assumptions, it is possible to evaluate the probability that a given channel is overloaded, given the overall average and the variance of the load intensity. In the second approach, which is a simulation method called "random load generation", the load intensity generated by each user is assumed to be equal, but the pattern of the load is a variable. In this approach, many load patterns are generated randomly, and the utilization of all channels for each pattern is determined exactly by following a specific traffic routing algorithm. This approach is useful in obtaining not only an estimate of the extreme worst case (i.e., the capacity reduction when the load is distributed most adversely), but also an estimate of a "normal bad case" (i.e., capacity reduction when the degree of the load nonuniformity is about as bad as what could be expected in practice).

4.2 Extreme Value Analysis

4.2.1 Study of the Perfect Shuffle Networks

We now study the Perfect Shuffle Networks in "extreme value analysis" approach[10]. We assume: N is the total number of NIUs and W is the total number of channels.

Let $\lambda_{i,j}$ $(1 \le i \le N, 1 \le j \le N)$ and γ_m $(1 \le m \le W)$ be the traffic intensity from user i to user j and the traffic intensity of channel m, respectively. Also assume independence between $\lambda_{i,j}$'s and independence between γ_m 's.

Assume $\lambda_{i,j}$ $(1 \le i \le N, 1 \le j \le N)$ are random variables of Normal Distribution $N(\mu,\sigma)$ (since each user's traffic is uniformly destined to all other users, $\lambda_{i,j}$s are independent identical distributed). Due to the multihopping, the total traffic on each channel is the sum of a number of traffic streams generated by different users. Let M be the average number of i to j traffic pairs that use a particular channel.

$$M = \frac{N^2 \cdot E[hops]}{W} \qquad \text{<4-1>}$$

Therefore, γ_m is distributed according to $N(M\mu/N, \sqrt{M}\sigma/\sqrt{N})$.

$$Let\ Y_W = Max.\gamma_m \quad (1 \le m \le W)$$

$$\therefore\ The\ CDF\ of\ Y_W\ is\ the\ W\text{-}th\ power\ of\ the\ CDF\ of\ \gamma_m \qquad \text{<4-2>}$$

$$i.e.,\ F_{Y_W}(y_W) = [F_{\gamma_m}(\gamma_m)]^W$$

There is a probability that the traffic intensity on the heaviest channel Y_W can exceed the channel capacity which is assumed to be one giga bit per second

P[extreme>1Gbps]. For the Perfect Shuffle Network, we calculate the maximum average traffic intensity μ from one node to another under the condition that only with a very small probability of 10^{-S} (S an integer), the traffic intensity on the heaviest channel would exceed the channel capacity of 1Gbps. We define the deloading factor as:

$$\textit{Deloading factor} = \frac{Max.\ \mu\ (non\text{-}uniform\ )}{\mu_{ideal}(\,uniform\,)} \qquad <4\text{-}3>$$

The results are shown in Figure 4.5 and Figure 4.6. In these figures, we define:
$\textit{Coefficient of variation} = \frac{\sigma}{\mu}$ as the normalized variation.

As we can see, the deloading factor shows the sensitivity of a network architecture to a nonideal traffic pattern. A smaller deloading factor means that the achievable throughput in the unbalanced traffic situation is smaller or the throughput decrease is more. Therefore, the smaller a deloading factor is, the more sensitive to the nonideal traffic pattern is the corresponding architecture. The deloading factor decreases with the increase of the coefficient of variation, as expected. In the next section, we will compare the deloading factor with the Multi-Dual Ring Connected Shuffle Networks.

4.2.2 Study of the Multi-Dual Ring Connected Shuffle Networks

4.2.2.1 Balanced Mode

In the last section, we assumed that the traffic from each node is uniformly destined to all other nodes. If we apply this assumption to the Perfect Shuffle Network, we get evenly distributed traffic among all channels due to its homogeneous connectivity. However, the traffic is not distributed evenly if we apply this assumption to the Multi-Dual Ring Connected Shuffle. The above conclusion can be drawn from the following analysis:

Assume: N: No. of subnetworks

n: No. of nodes in a subnetwork
μ :Average traffic intensity per node pair
E[hops]: Average number of hops within a subnetwork

We maintain:

$$\begin{aligned}
&\textit{The traffic intensity per channel within the subnetworks}\\
&= \frac{\begin{array}{l}\textit{The total traffic intensity from n local nodes to other}\\ \textit{n nodes (including the relay traffic to all other nodes)}\end{array}}{\textit{Total number of channels within the subnetwork}} \qquad <4\text{-}4>\\
&= \mu \times \frac{n \cdot n \cdot N \cdot E[hops]}{2n} = \frac{\mu \cdot n \cdot N}{2} \times E[hops]
\end{aligned}$$

$$\begin{aligned}
&\textit{The traffic intensity per channel between the subnetworks}\\
&= \frac{\begin{array}{l}\textit{The total traffic intensity from one subnetwork to all}\\ \textit{other subnetworks (including the relay traffic)}\end{array}}{\textit{Total number of channels between subnetworks}}\\
&= \mu \times \frac{n \cdot n \cdot [\frac{N}{2} + (\frac{N}{2} - 1) + \cdots + 1] \times 2}{2n} \qquad <4\text{-}5>\\
&= \frac{\mu \cdot n \cdot N}{2}(\frac{N}{2} + 1) = \mu \times \frac{N^2 n}{4}
\end{aligned}$$

Therefore, the traffic intensity per channel within the subnetworks is not necessarily equal to that between the subnetworks.

In a WAN, the assumption that the traffic intensity of each node is uniformly destined to all other nodes is not true -- because the local traffic intensity is usually higher than the remote traffic intensity. Thus, we define:

Local traffic intensity as I_1 (node pair)
Remote traffic intensity as I_2 (node pair)
Assume: $I_1 = f_b I_2$ where f_b *is the load balance factor and* $f_b \geq 1$ <4-6>

The traffic intensity per channel within the subnetworks

$$= \text{The local intensity} + \text{The remote intensity}$$

$$= I_1 \times \frac{n \times n \cdot E[hops]}{2n} + I_2 \times \frac{n \times n \cdot (N-1)E[hops]}{2n} \qquad \text{<4-7>}$$

$$= \frac{nE[hops]}{2} \times (f_b - 1 + N) I_2$$

The traffic intensity per channel between the subnetworks

$$= I_2 \times \frac{n \cdot n \cdot \frac{N}{2}(\frac{N}{2} + 1) \times 2}{2n} \qquad \text{<4-8>}$$

$$\approx \frac{nN^2}{4} I_2$$

In fact, we have

$$nN\mu = I_1 n + (N-1)nI_2 = I_2(f_b - 1 + N)n \quad or$$

$$I_2 = \frac{N\mu}{f_b - 1 + N} \qquad \text{<4-9>}$$

If $f_b = 1$, that is the case when the traffic of each node is uniformly destined to all other nodes. We can verify this by inserting equation *<4-9>* into equation *<4-7>* and equation *<4-8>*, we get equations *<4-4>* and *<4-5>*.

If we wish to get the traffic distributed evenly among all the channels, let the traffic intensity per channel within the subnetworks be equal to the traffic intensity per channel between the subnetworks.

i.e.,

$$\frac{nE[hops]}{2}(f_b - 1 + N)I_2 = \frac{nN^2}{4} I_2 \quad or \qquad \text{<4-10>}$$

$$f_b = 1 + N\left(\frac{N}{2E[hops]} - 1\right)$$

We name this case "balanced traffic mode" (different from the "uniform traffic").

Under the 'balanced traffic' assumption, we can see from Table 4.1 that the average number of hops for Multi-Dual Ring Connected Shuffle Networks is smaller than that for the Perfect Shuffle Networks when $f_b > 1$. However, the fact that the former achieves fewer average number of hops than the latter does not necessarily mean that it can achieve a higher throughput, because comparisons are made under the 'balanced traffic' assumption in which case the channels in Perfect Shuffle Network are not evenly loaded.

	Perfect ShuffleNet	Multi-Dual Ring Connected Shuffle Network
No. of NIUs = 32, fb = 1	2.258	3.000
No. of NIUs = 192, fb = 121	7.322	4.066
No.of NIUs =1024,fb= 3969	10.343	4.015

Table 4.1 Average No. of Hops under the Balanced Traffic Mode

4.2.2.2 Performance Evaluation under Extreme Value Analysis

Under the balanced traffic mode assumption, the traffic intensity per channel 'within a subnetwork' equals the one 'between subnetworks', we can use 'γ_m' to represent either of them. Therefore, the traffic intensity of a channel

$$\gamma_m = \frac{nN^2}{4} I_2 = \frac{nN^2}{4} * \frac{I_1}{f_b} \quad (\textit{from equation} < 4\text{-}8 > \textit{and} < 4\text{-}6 >) \qquad <4\text{-}11>$$

$$\textit{where} \quad 1 \le m \le W$$

$$\textit{if } I_1\textit{'s distribution is } N(\mu_1, \sigma_1)$$

$$I_2\textit{'s distribution is } N(\mu_2, \sigma_2)$$

$$\textit{from equation} < 4\text{-}11 >, \textit{we have} \qquad <4\text{-}12>$$

$$\gamma_m\textit{'s distribution is } N(\frac{nN^2}{4}\mu_2, \sqrt{\frac{nN^2}{4}}\sigma_2) \textit{ or}$$

$$\gamma_m\textit{'s distribution is } N(\frac{nN^2}{4f_b}\mu_1, \sqrt{\frac{nN^2}{4f_b}}\sigma_1)$$

For the traffic intensity of heaviest traffic channel Y_W, we have the same formula as the equation <4-2>

$$F_{Y_W}(y_W) = [F_{\gamma_m}(\gamma_m)]^W$$

Concerning the characteristics of the heaviest channel, we now study the following aspects:

Mean traffic intensity on the heaviest channel.

To evaluate the $E[Y_W]$, which is the mean traffic intensity on the heaviest channel, we first find $E[X_W]$ where the CDF of X_W is the W-th power of the CDF of X (X has the distribution of $N(0,1)$).

Assume $a = \frac{nN^2}{4}$ for remote traffic or $a = \frac{nN^2}{4f_b}$ for local traffic and

$$b = \sqrt{a}$$

$$E[Y_W] = E[b\sigma X_W + a\mu] = b\sigma \times E[X_W] + a\mu \qquad \text{<4-13>}$$

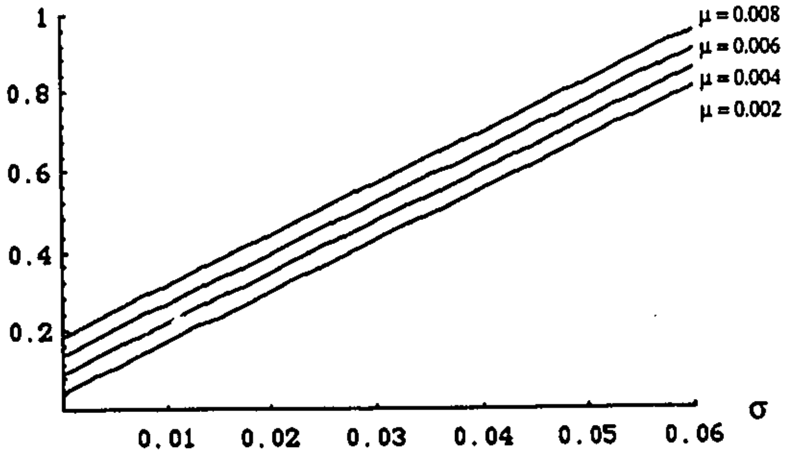
For a total number of channels W = 128, the numerical results are shown in Figure 4.1.

We can get $E[X_W]$ and then get $E[Y_W]$ from the table when $W \leq 400$. When W is larger, according to "Order Statistics" by David [15],

asymptotically, we will have, $Y = (2\log W)^{1/2}[X_W - (2\log W)^{1/2}]$ <4-14>

which has a CDF of $\exp(-e^{-y})$, $-\infty < y < \infty$.

Mean Traffic Intensity on the Heaviest Channel (Gbps)



Multi-Dual Ring Connected ShuffleNet
No. of NIU = 32 and W = 128
mu: mean traffic intensity per node pair

Figure 4.1 Mean Traffic Intensity on the Heaviest Channel

The mean of the r.v. with CDF $exp(-e^{-y})$ $E[Y]$ is 0.577, thus from equation <4-14>, we obtain

$$E[X_w] = \frac{E[Y]}{(2\log W)^{1/2}} + (2\log W)^{1/2} = \frac{0.577}{(2\log W)^{1/2}} + (2\log W)^{1/2} \qquad \text{<4-15>}$$

The function $E[X_W]$ versus W is shown in Fig. 4.2: $E[X_W]$ increases with W.

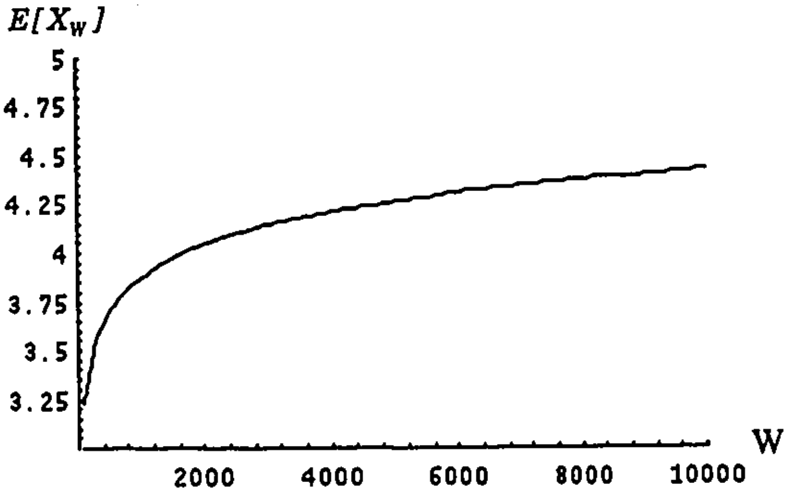


Figure 4.2 $E[X_W]$ versus W

Probability that the traffic intensity on the heaviest channel exceeds the channel capacity (*1*Gbps)

The results are shown in the following for the case of "remote traffic" in Figure 4.3 and for the case of "local traffic" in Figure 4.4. As expected, the probability that the traffic intensity on the worst channel ($P_{extreme}$) is greater than *1Gbps* increases with μ and σ.

Deloading factor when imbalanced traffic occurs

Although in the "uniform" traffic pattern and the " balanced" traffic pattern, the communication channels are evenly loaded, the condition of both are not the same. In "uniform" traffic pattern, the traffic pattern from one node to other nodes are equal while in "balanced" traffic, the traffic intensity from a node to the local nodes is different from that to the remote nodes. Since no single condition can apply to both traffic patterns, it is not suitable to compare the performance of the Perfect

Shuffle Network and the Multi-Dual Ring Connected Shuffle Network under the same "uniform" traffic pattern or "balanced" traffic pattern. Therefore, we would assume that "uniform traffic" is the "ideal" pattern for the Perfect Shuffle Networks and "balanced traffic" is the "ideal" pattern for the Multi-Dual Ring Shuffle Networks. We will compare the deloading factors between them to compare their sensitivities to the "nonideal" traffic with respect to their "ideal" traffic. The results are shown in the following section. The definitions of the Deloading Factor and the Coefficient of Variation are the same as in 4.2.1.

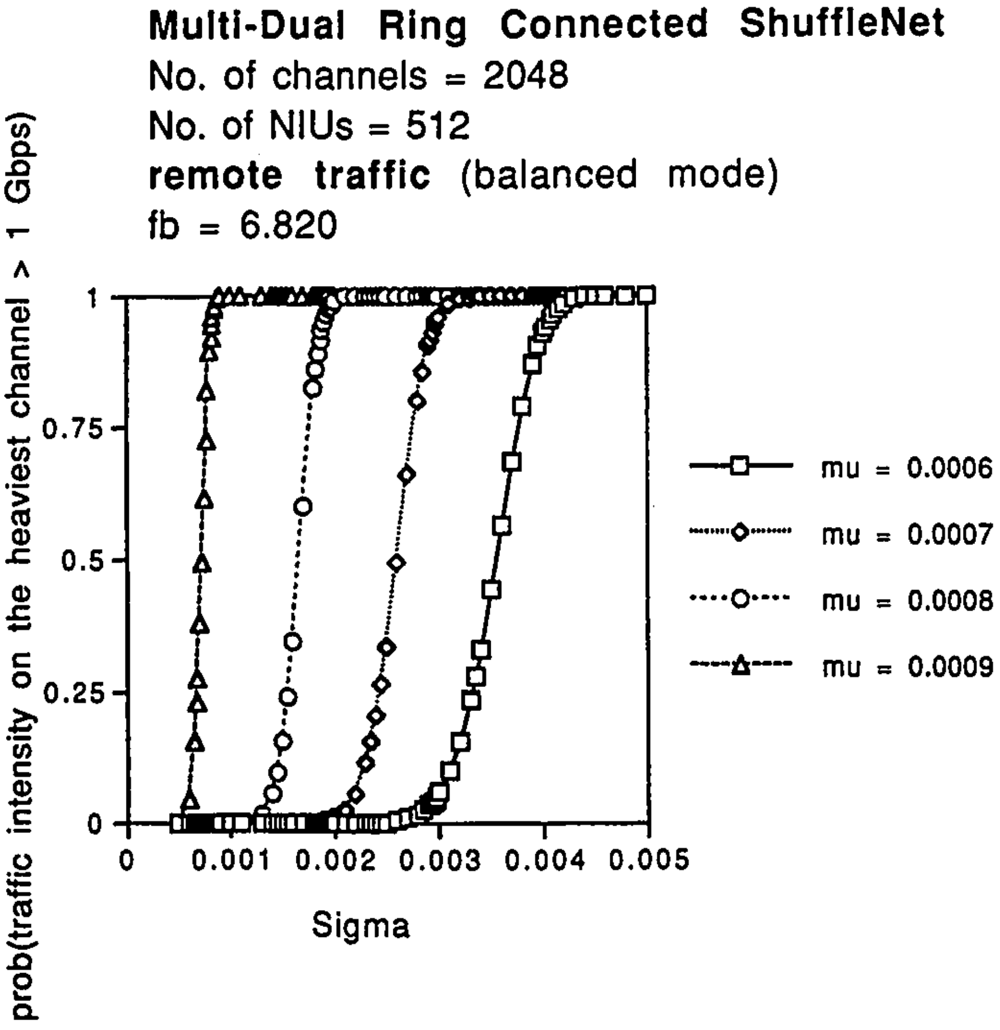


Figure 4.3 Probability of the traffic intensity on the heaviest channel (remote)

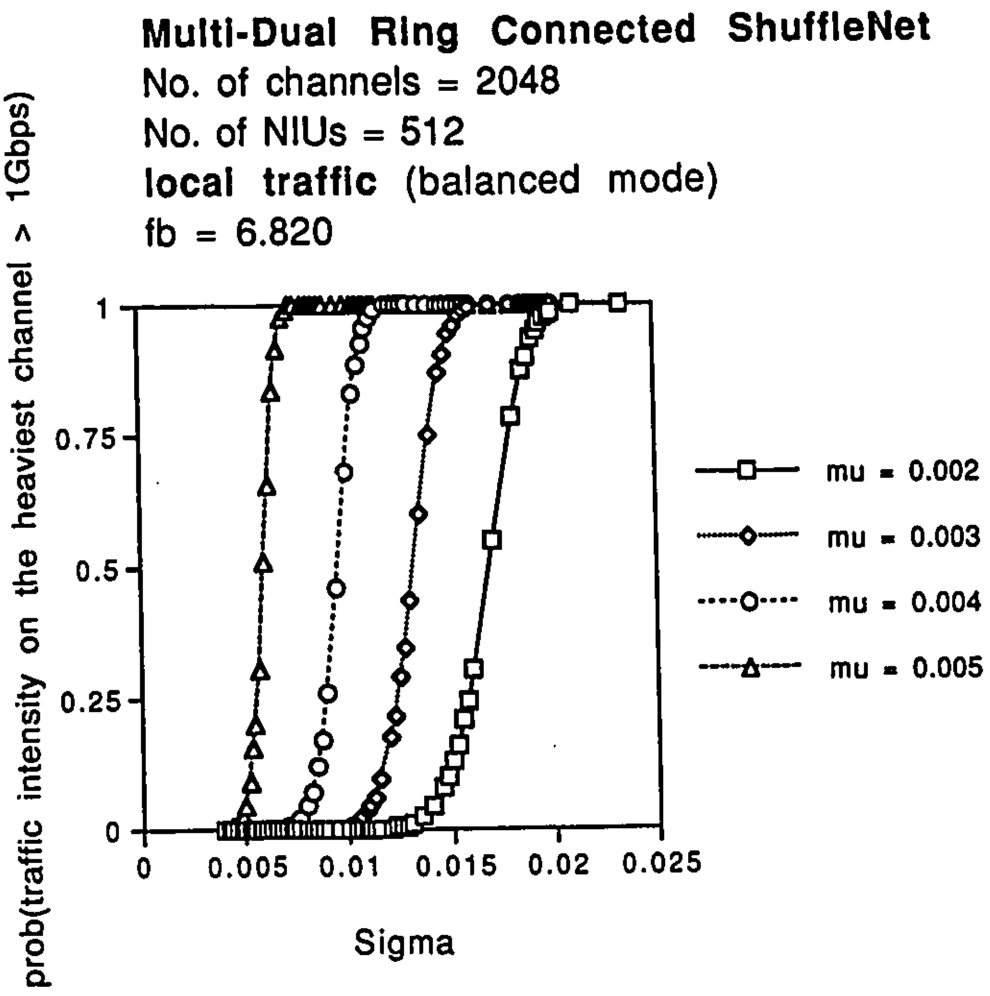


Figure 4.4 Probability of the traffic intensity on heaviest channel (local)

4.2.2.3 Comparison of the two architectures

As we can see from Figure 4.5 and Figure 4.6, the deloading factors decrease with the increase of the Coefficient of Variation. The deloading factor of the case "RS remote" is higher than that of the case "PS" and the deloading factor of the case "RS local" is the smallest, which means the local traffic of the Multi-Dual Ring Shuffle Networks is the most sensitive to "imbalanced traffic". Since we wish to compare the performance of the two architectures, we have to study the network with the same number of NIUs for both. Unfortunately, in this case the subnetworks are very small and the number of subnetworks is very large. This makes the f_b unusually large so that the Deloading Factors of "RS remote" and "RS local" are far apart. Therefore, another case with a relatively realistic $f_b = 6.820$ is studied, and the result in Figure 4.7 shows that the Deloading Factors of "RS remote" and "RS local" are very close. Also, we study the "$f_b = 6.820$" case with different constraints of 10^{-S} ($S = 2, 4$ *and* 6) and find (see Figure 4.8) that the Deloading Factor decreases with the increasing S.

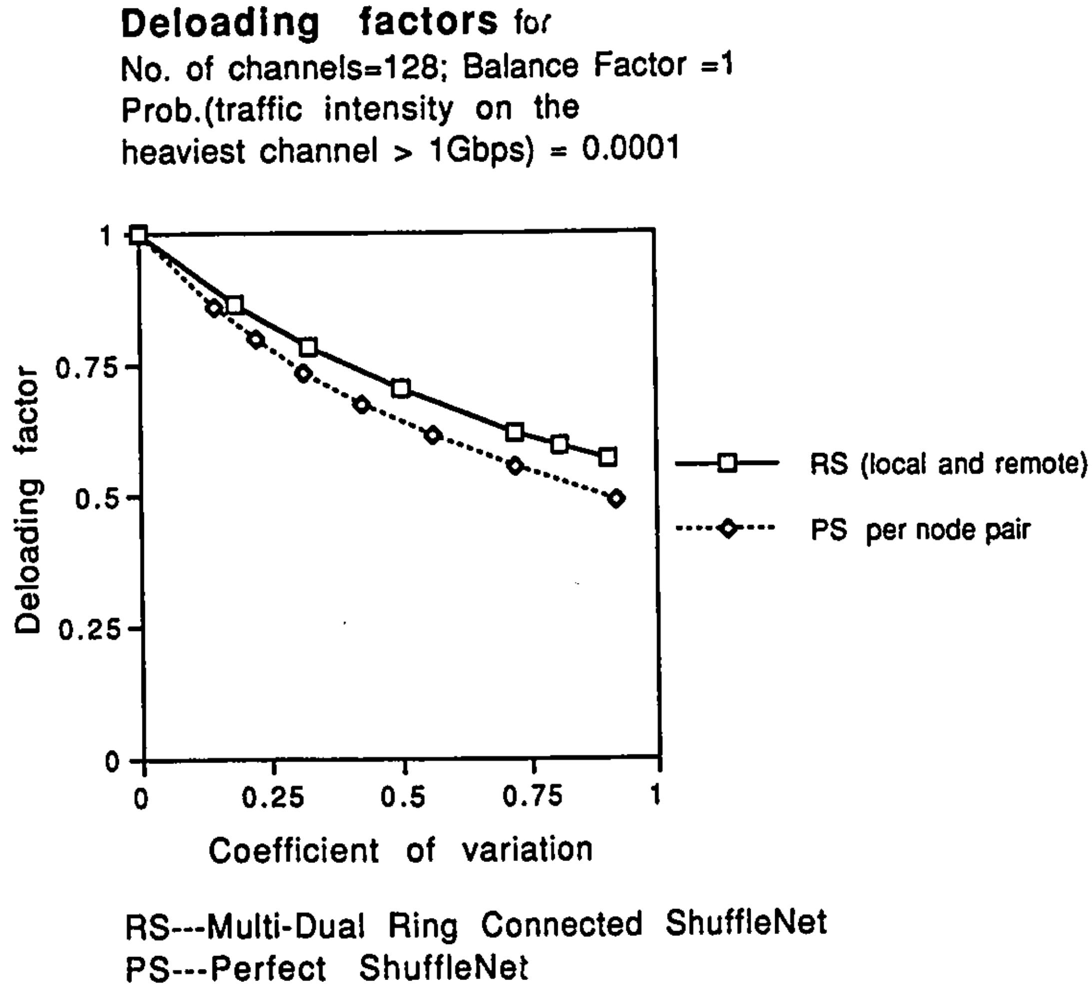
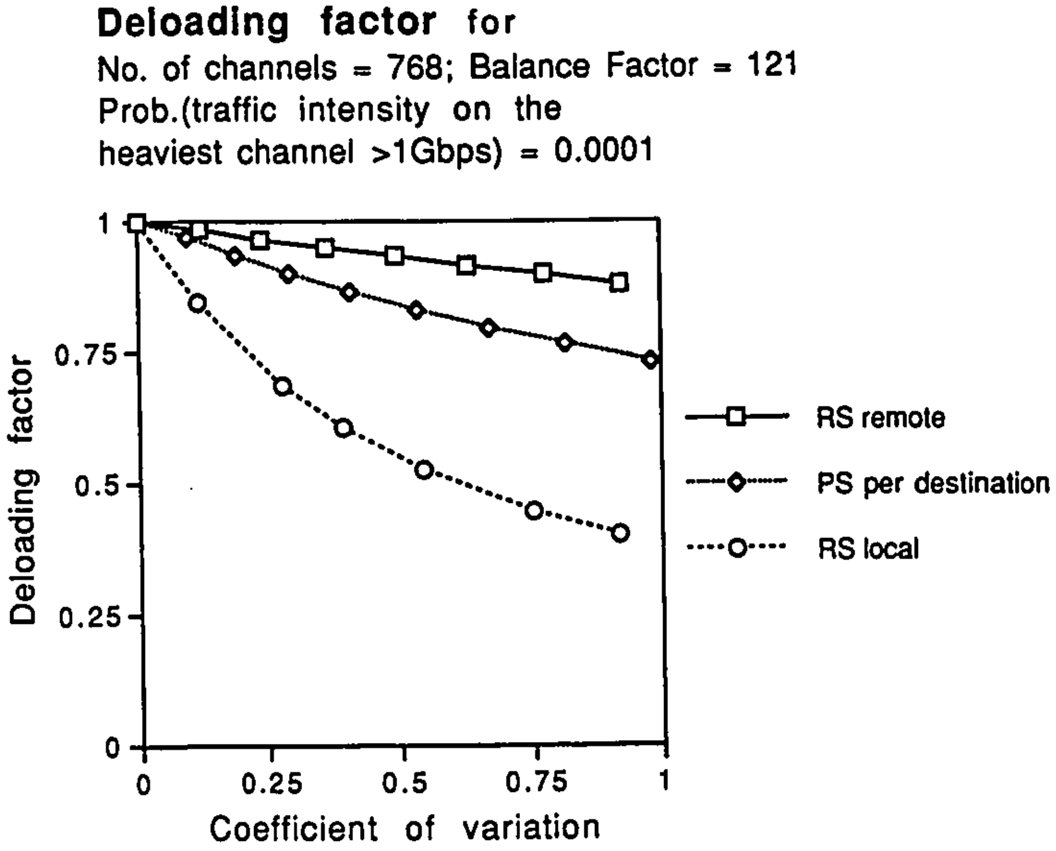


Figure 4.5 Deloading Factors for W = 128



RS---Multi_Dual Ring Connected ShuffleNet
PS---Perfect ShuffleNet

Figure 4.6 Deloading Factors for W = 768

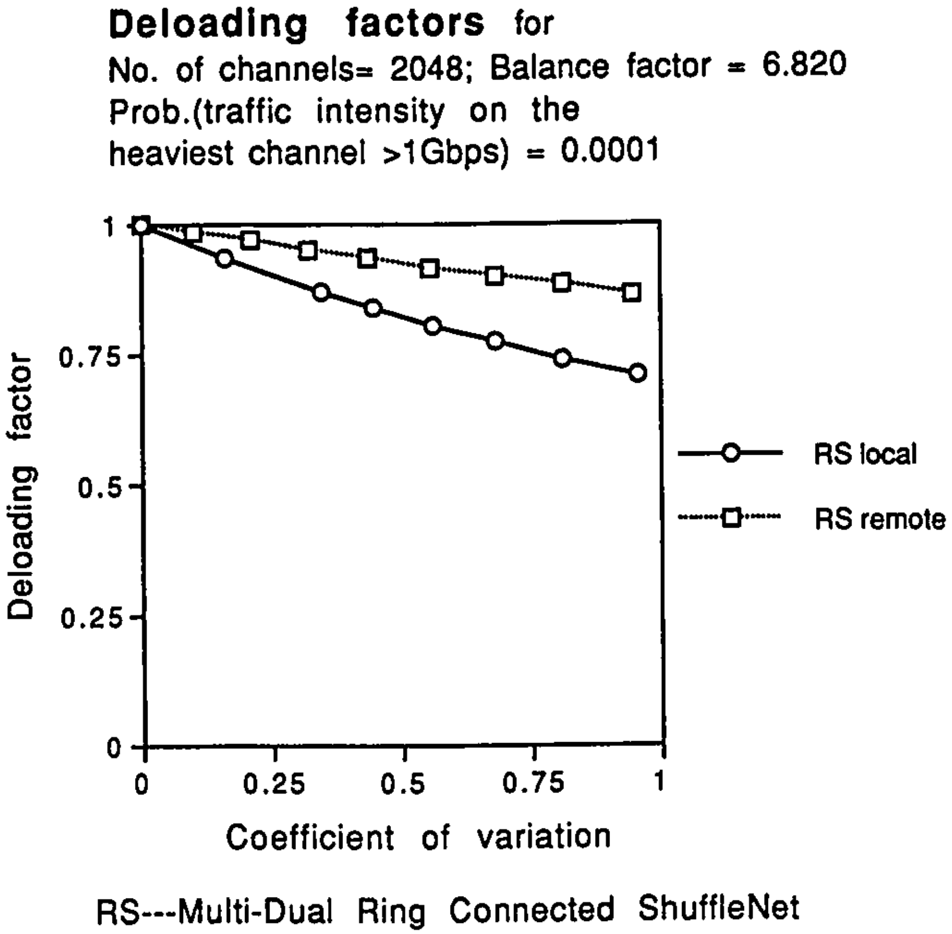
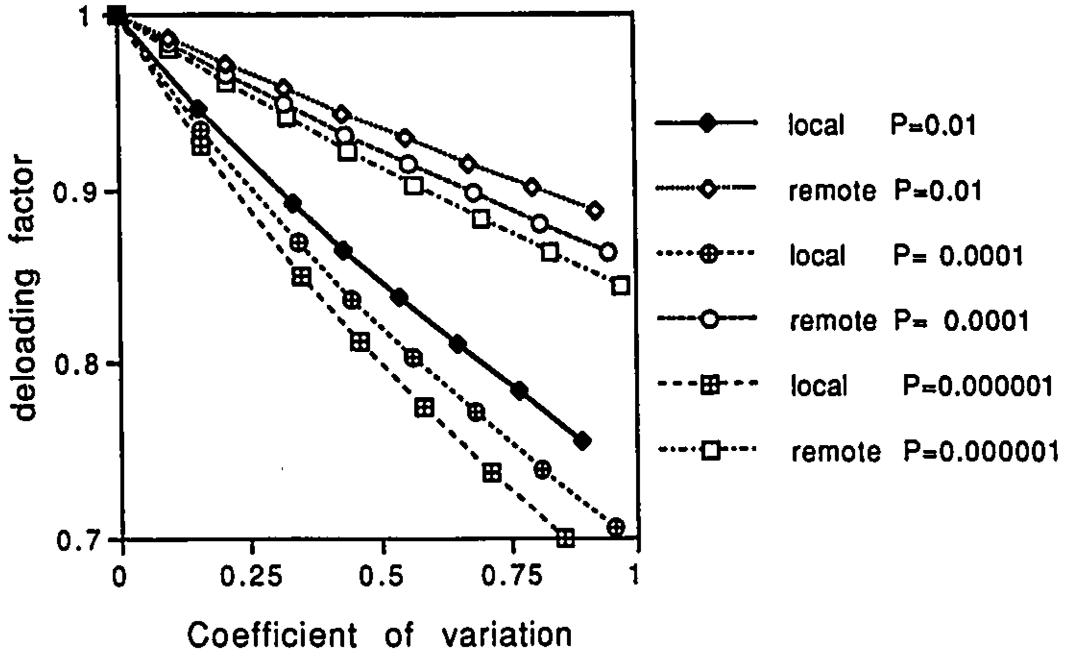


Figure 4.7 Deloading Factors for W = 2048



Deloading factors for
different Prob.(traffic intensity on the heaviest channel>1Gbps)

P means Probability of traffic intensity on the heaviest channel >1 Gbps

Figure 4.8 The effects of different constraints on the Deloading Factors

4.3 Random Load Pattern

In the previous section, it was assumed that the pattern of load is uniform or balanced, but the intensity of individual traffic items has a normal distribution. In this section, we take an alternative approach. Namely, we assume that the amount of traffic generated by all users is the same, but the pattern is random [10]. Specifically, we assume that each user generates traffic at its maximum rate and that all the traffic generated by a user is destined to one other user at random.

For each randomly generated load pattern, the traffic is distributed over the multihop network using a specific "fair" routing algorithm. The number of traffic items on each channel is calculated for each load pattern, and the number of users on the most used channel is recorded. This process is repeated for very many traffic patterns, producing a histogram of usage of the most used channel. This histogram can be employed to determine the maximum amount of traffic that each user is allowed to generate. We now describe the approach in more detail.

A load pattern in our approach is specified by a specific permutation of the integer *1, 2,..., N*, where *N* is the number of NIUs in the multihop network. Thus, the first integer in the permutation specifies the destination of the traffic generated by NIU *1*, the second specifies the destination of the traffic generated by NIU *2* and so on. Note that, this class of load patterns has the important property that no destination NIU receives more than one NIU's traffic. This is an important characteristic of traffic patterns used in the evaluation of multihop network capacity, since it is obviously impossible for an NIU to receive traffic more than its capacity. This class of traffic pattern is the "worst case" in the sense that any pattern satisfying the constraint that no destination is overloaded and which causes a multihop channel to be maximally loaded will fall into this class.

Having randomly generated a load pattern (by generating a random permutation of *N* integers), the next step is to distribute this load over the multihop network. Thus, for each node, we must determine the sequence of channels (and intermediate NIU's) taken by its traffic to reach its destination.

4.3.1 Study of the Perfect Shuffle Networks

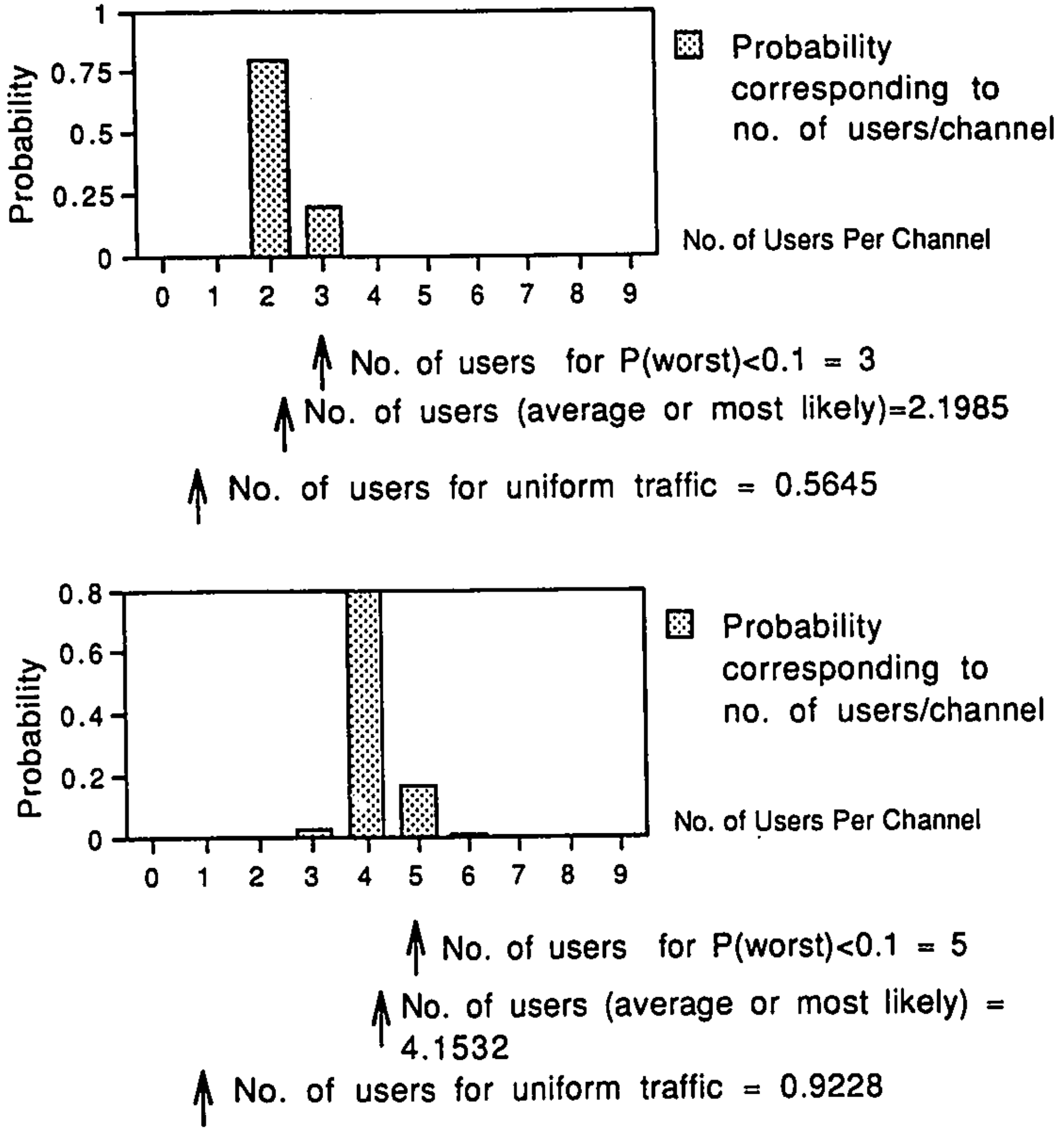


Figure 4.9 Histogram of usage of most used channel for Perfect ShuffleNet (32 and 192 NIUs)

In the Perfect Shuffle Networks, we adopt the fixed routing scheme. For example, in Figure 3.1, if a packet is transmitted from NIU *1* to NIU *2*, its route is

NIU1 -> NIU 5 -> NIU 2. Through this routing implementation, the count of the number of users of λ_1 and λ_{10} channel will increase by one. After the N point-to-point traffic items in each traffic pattern are distributed over the network, and from the resulting distribution we determine the usage of the most used channel. In particular, we make note for each traffic pattern of the usage of the most used channel. By randomly generating a large number of traffic patterns, we derive a histogram of usage of the most used channel. Histogram for the cases : the number of NIUs =32 (k = 2, p = 4) and the number of NIUs = 192 (k = 3, p = 4) are shown in Figure 4.9.

Since each NIU or user only sends one traffic item to its destination, we can interchangeably use the terms: "user", "NIU" and "traffic item". Therefore, the average number of users per channel under a uniform traffic pattern is given by the following formula:

$$E(user\,/\,channel)_{uniform}$$

$$= \frac{Total\ No.\ of\ NIUs\ or\ users}{Aggregate\ Throughput\ in\ the\ Unit\ of\ Channel\ (1\ Gb\,/\,s)} \qquad \text{<4-16>}$$

$$= \frac{Total\ No.\ of\ Users}{\dfrac{Total\ No.\ of\ Users \times p}{E[hops]}} = \frac{E[hops]}{p}$$

The *Deloading Factor* here is in similar but not exactly the same sense as the one in 4.2.1. It is defined as follow:

$$The\ Deloading\ Factor$$

$$= \frac{Achievable\ Traffic\ Intensity\ per\ User\ (nonideal\ traffic)}{Achievable\ Traffic\ Intensity\ per\ User\ (ideal\ traffic)}$$

$$= \frac{1/No.\ of\ Users\ per\ Channel\ (non\ ideal\ traffic)}{1/No.\ of\ Users\ per\ Channel\ (ideal\ traffic)} \qquad \text{<4-17>}$$

$$= \frac{No.\ of\ Users\ per\ Channel\ (ideal\ traffic)}{No.\ of\ Users\ per\ Channel\ (non\ ideal\ traffic)}$$

If one must guard against the eventuality of a worst case load pattern, one should use the "maximum number of users per channel" in the nonideal traffic case.

However, it is ordinarily not economical to guard against very low-likelihood, extreme situations. If we are willing to accept the small risk of assuming that an absolute worst case load pattern will not occur, we can assume the probability of the worst case is *0.1* and we use the maximum number of users per channel when the worst case does not happen. In this way, we can get the Deloading Factor (P<0.1) from the Figure 4.9 and Figure 4.10. Since the results are still too conservative, to obtain a less conservative, more realistic estimate, we choose the average number of users per channel which is the most likely 'happened' case of the measurement. Then we find the most likely Deloading Factor. Results for the Deloading Factors are shown in Table 4.2.

		Perfect Shuff	e Multi-Dual Ring Connected Shuffl	
			Fixed Routing	Adaptive Routing
32 NIUs 10000 patterns	P<0.1	0.1882	0.2500	0.2500
	most likely	0.2568	0.2742	0.3073
192 NIUs 20000 patterns	P<0.1	0.1846	0.2500	0.2500
	most likely	0.2222	0.2841	0.2953

Table 4.2 Deloading Factors for the Methods " Random Load Pattern"

4.3.2 Study of the Multi-Dual Ring Connected Networks

In this section, we use the same method and definition of Deloading Factors as in the last section for the study of a different architecture -- Multi-Dual Ring Connected Shuffle Networks and the study of different routing schemes.

Fixed Routing Scheme

The routing scheme works in this way: suppose a packet is transmitted from NIU b_1 in subnet a_1 with the address (a_1, b_1) to the NIU b_2 in the subnet a_2 with the address (a_2, b_2). First, the packet is transmitted from (a_1, b_1) to (a_2, b_1) between the subnetworks, and then transmitted from (a_2, b_1) to (a_2, b_2) within the subnetwork a_2 in a ShuffleNet routing scheme. For example, in Figure 3.3, a packet is going from (1,1) to (8,2), it is going through (1,1) -> (8,1) -> (8,5) -> (8,3). Using this routing scheme, we repeat the investigation and obtain the results in Figure 4.10 and Table 4.2.

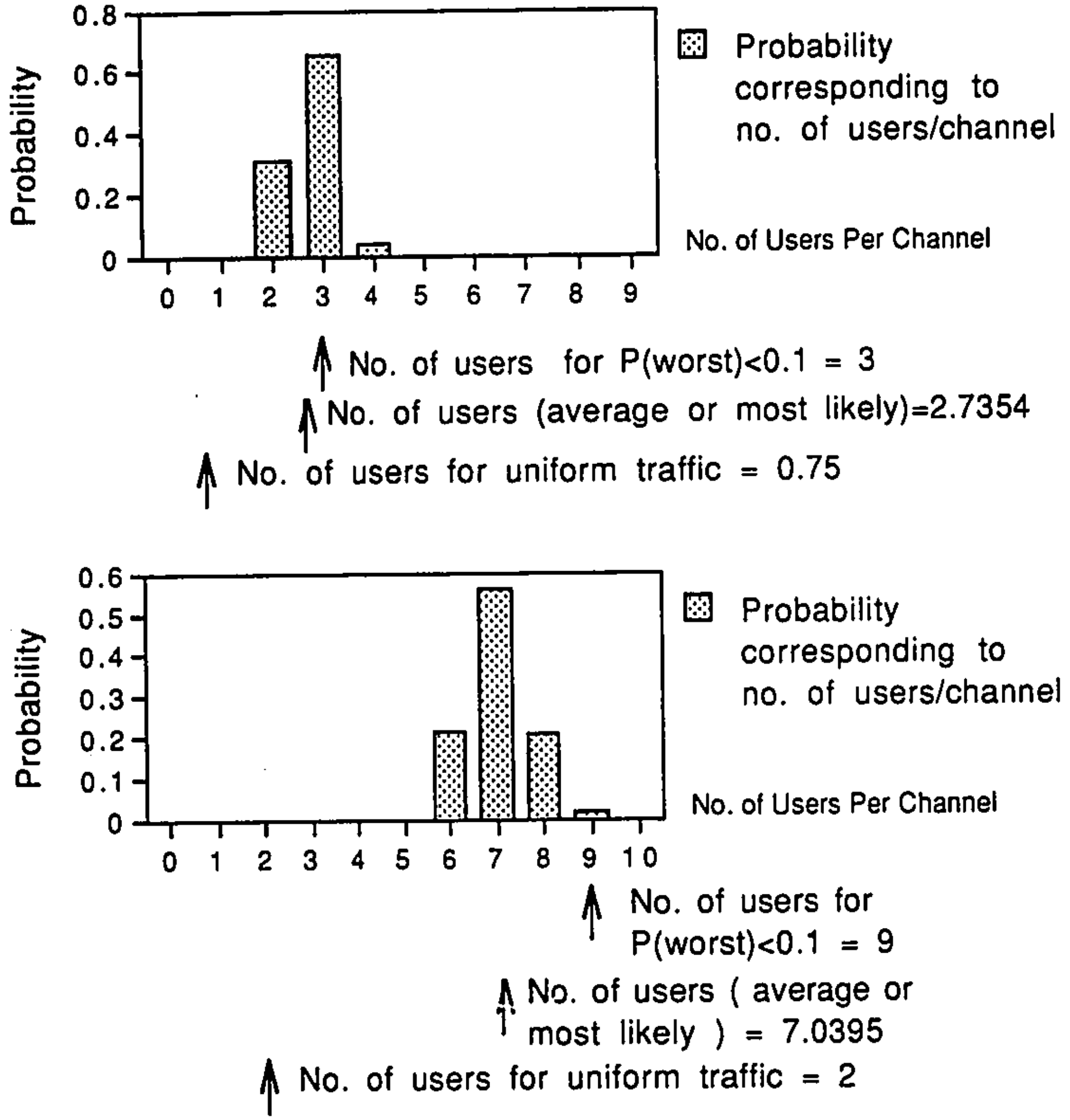


Figure 4.10 Histogram of usage of most used channel for Multi-Dual Ring Connected ShuffleNet (32 and 192 NIUs and fixed routing scheme)

The fixed routing scheme is the simplest and shows a very good performance under an ideal traffic pattern assumption. However, it is not suitable for the nonideal traffic pattern because it cannot reroute the traffic as the need arises. Therefore, we propose an adaptive routing scheme.

Adaptive Routing Scheme

The advantage of this routing scheme is that it can readjust to the appropriate 'light traffic' route, if a congestion or a link failure occurs, without having to go through more hops than that in the case of a fixed routing scheme.

The routing scheme is based on the fact that there exist many alternative equivalent length routing paths. For example, in Figure 3.3, from *(1,1)* to *(8,2)*, a path can be defined as: *(1,1) -> (8,1) -> (8,5) -> (8,2) or (1,1) -> (1,5) -> (1,2) ->(8,2) or (1,1) -> (1,5) -> (8,5) -> (8,2)*. We can see that all these paths possess the same number of hops. For each NIU, there are four output waiting queues (since p =4), a packet always chooses the output path with the shortest queue length -- which means choosing the lightest traffic path among the available alternatives. In this way, the traffic is distributed as evenly as possible over the network. Another advantage of the adaptive routing scheme is that because the routing decisions are made within a local NIU, its implementation does not require a central server so that the routing scheme fits into the self-routing network schemes. The results are shown in Figure 4.11 and Table 4.2.

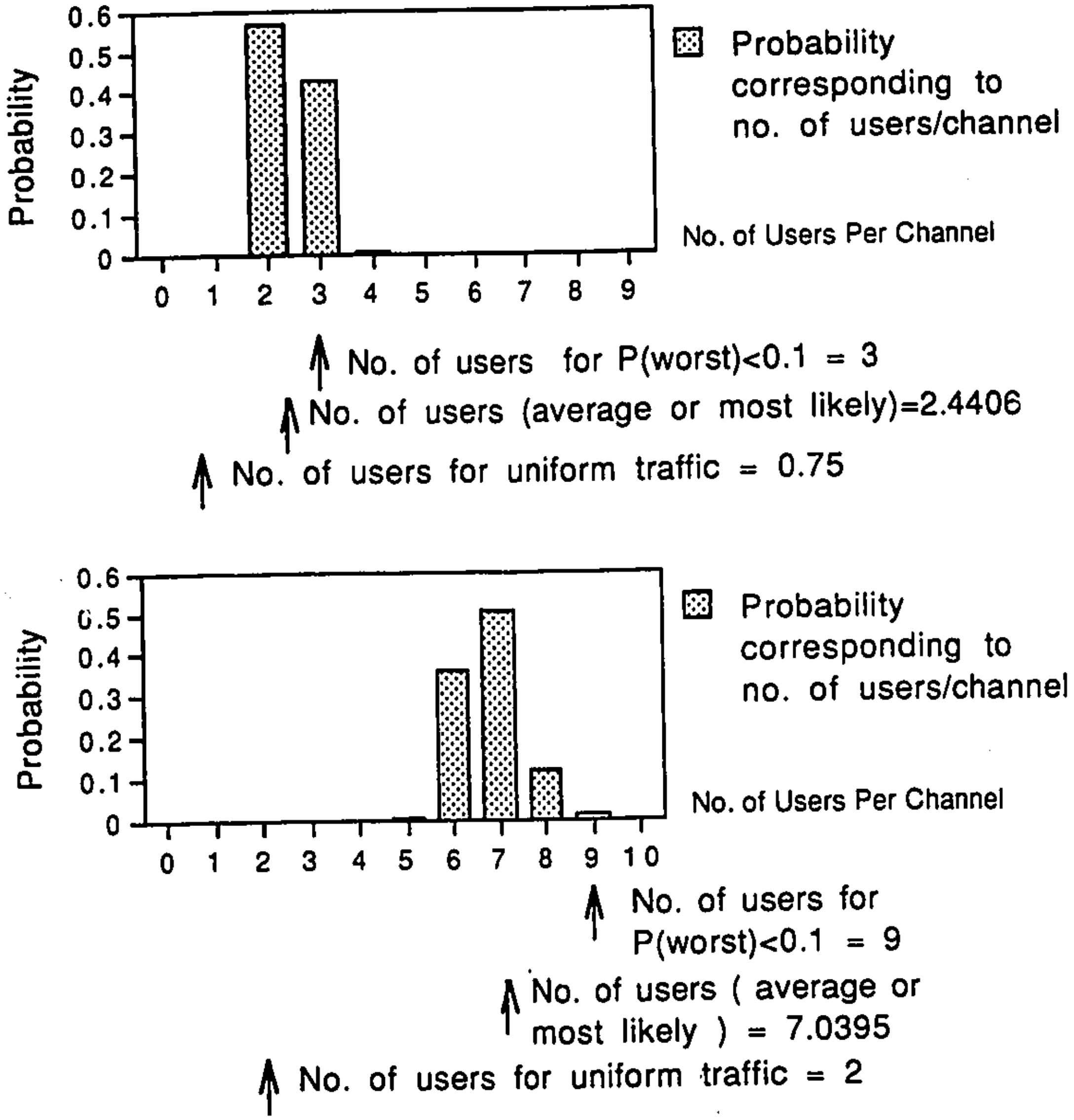


Figure 4.11 Histogram of usage of most used channels for Multi-Dual Ring Connected ShuffleNet (32 and 192 NIUs and adaptive routing scheme)

Architectures

In Table 4.2, we can see that the Deloading Factors of Multi-Dual ring Connected Shuffle Network are higher than those for the Perfect Shuffle Network under the same conditions. In the proposed architecture, the results of the adaptive routing are better than those of the fixed routing scheme. This shows the advantage of the improved routing scheme. The improvements are not so great because each NIU is only destined to one NIU in which case the traffic pattern is simpler than that in the realistic case. In a real traffic environment, where each NIU has multiple destinations, the chances of congestion are far greater, so the optimized routing scheme will show a greater improvement over the fixed routing scheme. In the most realistic case, the Deloading Factors for the adaptive routing are around 0.3. Also, the same deloading factors in different network size simulations are very close. Thus, there is not much sensitivity to the network size. This shows the architecture and the routing scheme are better choices than what the Perfect Shuffle Network can offer [26] [28].

4.4 Concluding Remarks

In this chapter, the effect of load imbalance on the Multi-Dual Ring Connected Shuffle Network, due to either traffic intensity variability or traffic pattern variability, are studied, and the results show a better performance than those of the Perfect Shuffle Network. The Deloading Factors of the proposed architecture are within a reasonable range and are insensitive to the network size. Therefore, in a realistic traffic environment, the Multi-Dual Ring Connected Shuffle Network is still a better choice.

Chapter 5

Conclusions

In the present world, the demand to support different types of nationwide traffic (data, voice, video, etc.) requires a high bandwidth and a suitable network topology. In addition, real time traffic, i.e., voice and video, requires a low average and variance of packet delay. These demands for highly-efficient high-speed communications networks in WAN environments are opening new research horizons. Among the existing lightwave networking approaches, WDM and multi-hop are both effective means. WDM provides a powerful mean to solve the electro-optic bottleneck and offers significant opportunities for ultra high-speed networks. The multihop scheme could be called a third-generation fiber optic network, because, whether or not it uses wavelength division, it exploits the very larger bandwidth capability of the fiber rather than substituting the fiber for the copper in some existing scheme. This has led to the development of a new generation of WANs, based on passive optical components, WDM techniques and a multihop scheme.

In this thesis, after reviewing the existing access methods and optical topologies, we propose two self-routing all-optical WAN architectures using WDM and multihop approach, and appropriate routing schemes for the architectures [22] [25]. The architectures are named Multi-Dual Ring Connected Shuffle Network and Multi Shuffle Connected Shuffle Network.

Then, we do some analytical and simulation studies on the proposed architectures. The proposed architecture's outperform the conventional Perfect Shuffle Network not only under the uniform traffic pattern but also under the nonuniform traffic pattern, which means that the proposed architectures show superior performance in realistic environments.

means less downgrade in throughput under nonideal traffic patterns. The adaptive routing scheme can provide a more realistic way to avoid traffic congestion, and to further improve the performance.

Finally, we give an implementation suggestion for the proposed architectures in order to let the industry make the prototype test easily by using the existing components.

When the computer communication community discovered the third-generation optical networking as a possibility [20], many of the building blocks were already moving out of the research laboratories and into commercial practice. Wavelength-division multiplexing (WDM) networks have been investigated and prototyped at the laboratory level by a number of groups such as NTT's 100· Wavelength Network, AT&T Bell Lab's Wavelength-Division Networks, Bellcore's Lambdanet and British Telecom's Wavelength-Routing Network.

Since the proposed network architecture can achieve a superior performance and can be easily implemented by the existing technology, we believe that it is a very promising realistic architecture. Therefore, we hope that the architecture will be seriously considered as an alternative for Wide Area Networking.

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Appendix

Simulation Code A

ShuffleNet under Uniform Traffic Pattern

```
/* cc -g -o ontime  ontime.c -lm */
#include  <stdio.h>
#include  <math.h>

#define        K    3    /* K columns in a shuffle */
#define        P    4    /* P degree of output of NIU */
#define        KK   2    /* KK columns in a sub shuffle net */
#define   PP   2    /* PP degree of output of NIU within subnet
*/
#define        L    50   /*length ratio=between subnet/within
subnet */

/* the following variables depend on the above variables */
#define        TOTAL_NO_NIU    (K*power(P,K))
                    /* =K*pow(P,K) total no. of NIUs */

#define        COLUMN_NO_NIU  (power(P,K))
                    /* =pow(P,K)  no.of NIUs in a column */

#define        SUBNET_NO_NIU   (KK*power(PP,KK))
                    /* =KK*pow(PP,KK) no.of NIUs in a subnet */

#define        SUBNET_NO        (TOTAL_NO_NIU/SUBNET_NO_NIU)
                    /* =TOTAL_NO_NIU/SUBNET_NO_NIU=no.of

subnet */

typedef        struct
{
    int        group;
    int        column;
    int        row[K];
}niu;
```

```
int power(base, expt)
int base, expt;
{
    int i, result = 1;
    if (expt == 0)
       return 1;
    for (i = 1; i<=expt; i++)
       result = result * base;
    return result;
}/* end power */

grouping(sniu)
niu  *sniu;
{
    int        i,ii,j,jj,tem;

    for (i=0;i<TOTAL_NO_NIU;i++)
    {
     sniu[i].column=i/COLUMN_NO_NIU;
                    /* assign column and row */
        tem = i - (i/COLUMN_NO_NIU)*COLUMN_NO_NIU;
     for (j=0;j<K;j++)
     {
         sniu[i].row[j]=tem % P ;
         tem=tem/P;
     }
    }
                    /* grouping */
    j=0;jj=0;
    for (i=0;i<COLUMN_NO_NIU;i++)
     for (ii=0;ii<K*COLUMN_NO_NIU;ii=ii+COLUMN_NO_NIU)
     {
         sniu[i+ii].group=j;
         jj++;
         if (jj==SUBNET_NO_NIU)
            {
          jj=0;
          j++;
            }
```

```
     }
   return;
}/* end grouping */

void hop(pgroup, hop_dist, ct, rt, rd, cd, sniu, ehop)
int    *pgroup,
       hop_dist,
       *ct,
       *rt,
       *rd,
       cd;
niu    *sniu;
double *ehop;
{
int  lgroup, i, j, tem;

     do
     {              /* a hop */
         hop_dist--;
         lgroup = *pgroup/* record the last group */
         *ct = (*ct + 1)%K;
         for (j=K-1;j>0;j--)
          rt[j]=rt[j - 1];
         rt[0] = rd[hop_dist];

         tem = 0;   /* find the present NIU in which  group */

         for (j=0; j<K; j++)
          tem =  tem + rt[j]*power(P,j);
         *pgroup = sniu[(*ct) * COLUMN_NO_NIU + tem].group;

         if (lgroup != *pgroup)
                   /* calculating the weighted hop */
         {
          if (abs(lgroup - *pgroup)>(SUBNET_NO/2))
              *ehop = *ehop + L*(SUBNET_NO - abs(lgroup -
 *pgroup));
          else
              *ehop = *ehop+L*abs(lgroup - *pgroup);
         }
         else
```

```
          (*ehop)++;
      }while (*ct != cd);
         return;
}/* end hop */

double routing(sniu)
niu       *sniu;

{   double      ehop = 0;
    int         i,j,tem, source;
    int    lgroup,pgroup; /* last and present group */
    int         hop_dist;      /* distance in hop */
    int         cs,cd,ct; /* column */
    int         match;         /* sign if match */
    int         rs[K],rd[K],rt[K];
                    /* row */

    for (source=0; source<TOTAL_NO_NIU; source++)
    {
    cs=sniu[source].column;   /* NIU 0 as the source */
    for (j=0; j<K; j++)
     rs[j]=sniu[source].row[j];

    for (i=0; i<TOTAL_NO_NIU; i++)
    {
        if (i!= source)
     {
        ct=cs;           /* source -> temporary */
           cd=sniu[i].columndestination */
        tem=0;           /* find the first NIU in which  group */
        for (j=0;j<K;j++)
        {
         rt[j]=rs[j];
         rd[j]=sniu[i].row[j];
         tem = tem + rt[j]*(int)(power(P,j));
        }

            if (cd!=cs)  /* decide d */
            hop_dist = (K+cd-cs)%K;
            else
            hop_dist = K;
```

```
          pgroup=sniu[ct*COLUMN_NO_NIU+tem].group;
             hop(&pgroup, hop_dist, &ct, rt, rd, cd, sniu, &ehop);
          match = 1;         /* check if match */
          for (j=0; j<K; j++)
          {
           if (rt[j]!= rd[j])/* no match */
            match = 0;
          };

          if (match == 0)   /* no match, continue routing */
          {
           hop_dist = K;
              hop(&pgroup, hop_dist, &ct, rt, rd, cd, sniu, &ehop);
          }/* end if (match=0) */
          }/* end  if (i!= source) */
      }/* end  for (i=0;i<TOTAL_NO_NIU;i++) */
      }  /* end  for (source=0;source<TOTAL_NO_NIU;source++) */
      return ehop;
  }/* end routing */


  double y(ks,ps)
  int        ks,ps;
  {
      return(ks*power(ps,ks));
  }/* end y */

  double dy(ks,ps)
  int        ks,ps;
  { double dy_result, kks, pps;

      kks=ks;pps=ps;
      dy_result = power(ps,ks)+kks*log(pps)*power(ps,ks);
      return(dy_result);
  }/* end dy */

  double delta_value()
  {
      double     temp, y_value,dy_value,temp1,temp2,temp3,result;
```

```
    temp = PP-1;
    y_value = y(KK,PP);
    dy_value = dy(KK,PP);
    temp1 = (y_value-1)*(3*y_value*temp+2)   - (temp*(3*KK-1)+2-
2*KK)*dy_value;
    temp2 =(2*temp*(y_value - 1)) * (y_value - 1);
    temp3 =L*y(K,P)*dy_value / (4*y_value*y_value);

    result = temp1 / temp2 - temp3;
    return result;
}/* end delta */

double E(input_K, input_P)
int input_K, input_P;
/* The average hop in perfect shuffle */
{   double average, temp1, temp2, temp3;

    temp1 = input_K*power(input_P, input_K)*(input_P-
1)*(3*input_K -1);
    temp2 = 2*input_K*(power(input_P, input_K) - 1);
    temp3 = 2*(input_P - 1)*(input_K * power(input_P, input_K) - 1);
    average = (temp1 - temp2) / temp3;
    return average;
}


printout(ehop)
double   ehop;
{
    printf("Total No.of NIUs        = %d\n",TOTAL_NO_NIU);
    printf("No.of NIUs in a subnet  = %d\n",SUBNET_NO_NIU);
    printf("No.of subnetworks       = %d\n",SUBNET_NO);
    printf("Ratio L                 = %d\n",L);
    printf("K                       = %d\n",K);
    printf("P                       = %d\n",P);
    printf("K'                      = %d\n",KK);
    printf("P'                      = %d\n",PP);
    printf("delta                   = %lf\n",delta_value());
    printf("Average weighted hops   = %f\n",ehop);
    printf("Throughput              = %f\n",TOTAL_NO_NIU*P/ehop);
```

```
    printf("Ring Shuffle ehop        = %f \n", (SUBNET_NO/4)*L+E(KK,
PP));
    printf("Improvement Ratio        = %f\n\n",
ehop/((SUBNET_NO/4)*L+E(KK, PP)));
}/*end printout */



void main()

{
double          ehop;           /* average no. of hops */
niu       sniu[24576];

     ehop = 0;
     grouping(sniu);
        ehop = routing(sniu);
        ehop = ehop/(TOTAL_NO_NIU*(TOTAL_NO_NIU-1));
                    /* calculating the average weighted hop */
     printout(ehop);

 }/* end main */
```

Simulation Code B

"Random Load Generation"

```
/* cc -g -o ontime  ontime.c -lm */
#include  <stdio.h>
#include  <math.h>
#include  <stdlib.h>

#define         K    3    /* K columns in a shuffle */
#define         P    4    /* P degree of output of NIU */
#define         KK   2    /* KK columns in a sub shuffle net */
#define   PP    2    /* PP degree of output of NIU within subnet
*/
#define         MAX_NO_USER    20
                     /* maximum number of users per channel */

/* the following variables depend on the above variables */
#define         TOTAL_NO_NIU    (K*power(P,K))
                     /* =K*pow(P,K) total no. of NIUs */

#define         COLUMN_NO_NIU   (power(PP,KK))
                     /* =pow(PP,KK)  no.of NIUs in a column */

#define         SUBNET_NO_NIU    (KK*power(PP,KK))
                     /* =KK*pow(PP,KK) no.of NIUs in a subnet */

#define         SUBNET_NO         (TOTAL_NO_NIU/SUBNET_NO_NIU)
                     /* =TOTAL_NO_NIU/SUBNET_NO_NIU=no.of
subnet */

typedef         struct
{
    int   sub_address;   /* subnet no. */
```

```
    int         ch_L, ch_R;     /* counter clockwise and
clockwise channel */
    int         channel[PP];
    int         column;
    int         row[KK];
}niu;


int power(base, expt)
int base, expt;
{
    int i, result = 1;
    if (expt == 0)
       return 1;
    for (i = 1; i<=expt; i++)
       result = result * base;
    return result;
}/* end power */


initialize(sniu,user_per_ch)

niu        *sniu;
int        *user_per_ch;

{
    int          i,j,k,
          tem,tem_node;

    for (k=0; k< SUBNET_NO; k++)
    {
     for (i=0; i< SUBNET_NO_NIU; i++)
     {
        tem_node = k * SUBNET_NO_NIU +i;
                   /* current node number */

        sniu[tem_node].sub_address = k;
                   /* assign subnet no. */
        for (j=0; j< PP; j++)
        {
         sniu[tem_node].channel[j] = 0;
```

```
        };
        sniu[tem_node].ch_L = 0;
        sniu[tem_node].ch_R = 0;

        sniu[tem_node].column=i/COLUMN_NO_NIU;
                   /* assign column and row */
           tem = i - (i/COLUMN_NO_NIU)*COLUMN_NO_NIU;
                   /* tem is the number of the NIU in a column
*/
        for (j=0;j<KK;j++)
        {
         sniu[tem_node].row[j]=tem % PP ;
         tem=tem/PP;
        }
    }
   }/* end for (k=0; k< SUBNET_NO; k++) */

   for (i=0; i< MAX_NO_USER; i++)
   {
    user_per_ch[i] = 0;
   };


   return;
}/* end initialize(sniu,user_per_ch) */

ini_ch(sniu)

niu        *sniu;

{
    int          i,j;

    for (i=0; i< TOTAL_NO_NIU; i++)
    {
     for (j=0; j< PP; j++)
     {
         sniu[i].channel[j] = 0;
     };

     sniu[i].ch_L = 0;
```

```
     sniu[i].ch_R = 0;

    }
    return;

}/* end ini_ch(sniu) */


rdm(pattern,no_shift)
int          *pattern,
             *no_shift;

{
    int          i,j,
             tem_pattern,tem_dest,
             OK;

    if ((*no_shift) == 0)
    {
      (*no_shift) = TOTAL_NO_NIU;
      for (i=0; i< TOTAL_NO_NIU; i++)
      {
            do
            {
             tem_pattern = floor(((double)rand() /2.147483e+9)*
 (double)(TOTAL_NO_NIU-1));
             OK =1;
             for (j=0; j<i; j++)
             {
                  if (tem_pattern == pattern[j])
                   OK = 0;   /* random number already exist, choose
 again */
             }
            }while( OK == 0);
                       /* until find not yet exist random number */
            pattern[i] = tem_pattern;
      }/* end for (i=0; i< TOTAL_NO_NIU; i++) */
     }
     else              /* shift  pattern a digit to get a new pattern
 */
     {
```

```
     tem_dest = pattern[0];
     for (i=1; i<TOTAL_NO_NIU; i++)
         pattern[i-1] = pattern[i];
     pattern[TOTAL_NO_NIU-1] = tem_dest;
    };
    (*no_shift)--;
    return;
}/* end rdm(pattern,no_shift) */


direction(s_sub,d_sub,dire)

int  s_sub,d_sub,
     *dire;

{
    if (d_sub >= s_sub)
    {
     if ((d_sub - s_sub) >= SUBNET_NO/2)
         *dire = 0;      /* counter clockwise */
     else
         *dire = 1;      /* clockwise */
    }
    else
    {
     if ((s_sub - d_sub) >= SUBNET_NO/2)
         *dire = 1;      /* clockwise */
     else
         *dire = 0;      /* counter clockwise */
    };
    return;
}/* end direction(s_sub,d_sub,dire) */


shuffle_hop(tem_node, hop_dist, ct, rt, rd,sniu)

int  tem_node,
     *hop_dist,
     *ct,*rt,*rd;
niu  *sniu;
```

```
{
    int          j;

    (*hop_dist)--;

    (sniu[tem_node].channel[rd[*hop_dist]])++;

    *ct = (*ct + 1)%KK;
    for (j=KK-1;j>0;j--)
     rt[j]=rt[j - 1];
    rt[0] = rd[*hop_dist];
    return;

}/* end shuffle_hop(tem_node, hop_dist, ct, rt, rd) */


ring_hop(tem_node, t_sub, sniu, dire)

int  tem_node,
     *t_sub,
     dire;
niu  *sniu;

{
    if (dire == 1)  /* clockwise */
    {
     sniu[tem_node].ch_R++;
     (*t_sub)++;
     if (*t_sub == SUBNET_NO)
         (*t_sub) = 0; return to start '0' in ring */
    }
    else               /* counter clockwise */
    {
     sniu[tem_node].ch_L++;
     (*t_sub)--;
     if (*t_sub == -1)
         (*t_sub) = SUBNET_NO -1 ;
    };

    return;
 }/* end ring_hop(tem_node, t_sub, sniu, dire) */
```

```
void hop(hop_dist, ct, rt, t_sub, rd, cd, d_sub, sniu, dire)
int  hop_dist,
     *ct,*rt,*t_sub,
     *rd,cd,d_sub,
     dire;
niu  *sniu;

{
int  i, j, tem,
     match,match1,
     ctequalcd,
     tem_node;

     match = 1;          /* check if match */

     if (*ct == cd)
     {
         ctequalcd = 1;
         for (j=0; j<KK; j++)
         {
          if (rt[j]!= rd[j]) *ct == cd but nc match */
          match = 0;
         };
     }
     else
         ctequalcd = 0;
     do
     {               /* a hop */

         tem = 0;    /* the present routing channel user number+
1 */
         for (j=0; j<KK; j++)
          tem =  tem + rt[j]*power(PP,j);
         tem_node = (*ct) * COLUMN_NO_NIU + tem + (*t_sub) *
SUBNET_NO_NIU;

         match1 = 1;          /* check if match */
         for (j=0; j<KK; j++)
         {
```

```
          if (rt[j]!= rd[j])no match */
          match1 = 0;
         };

         if (*t_sub != d_sub)
         {
          if (dire == 1)
                    /* clockwise */
           {
              if ((sniu[tem_node].ch_R >
sniu[tem_node].channel[rd[hop_dist-1]])&&((match1 != 1)||(*ct != cd)

               shuffle_hop(tem_node, &hop_dist, ct, rt, rd,sniu);
              else
               ring_hop(tem_node, t_sub, sniu, dire);
           }
           else      /* counter clockwise */
           {
              if ((sniu[tem_node].ch_L >
sniu[tem_node].channel[rd[hop_dist-1]])&&((match1 != 1)||(*ct != cd)

               shuffle_hop(tem_node, &hop_dist, ct, rt, rd,sniu);
              else
               ring_hop(tem_node, t_sub, sniu, dire);
           }
          }
          else
          {
           if ((match1 != 1)||(*ct != cd))
               shuffle_hop(tem_node, &hop_dist, ct, rt, rd,sniu);
          };
          if ((ctequalcd == 1)&&(*ct != cd))
           match = 1;
                     /* get out of the loop when reaching ct = cd
 again */
      }while ((*ct != cd)||((*ct == cd)&&(match != 1)));
         return;
 }/* end hop */

 routing(sniu, pattern)
 niu       *sniu;
```

```
int       *pattern;

{
    int         i,j,tem, tem_node, source;
    int         s_sub, t_sub, d_sub;/* subnet address */
    int         hop_dist;      /* distance in hop */
    int         cs,cd,ct;      /* column */
    int         match;              /* sign if match */
    int         dire;          /* direction */
    int         rs[KK],rd[KK],rt[KK];
                          /* row */

    for (source=0; source<TOTAL_NO_NIU; source++)
    {
     cs=sniu[source].column;       /* NIU 0 as the source */
     for (j=0; j<KK; j++)
         rs[j]=sniu[source].row[j];

     if (pattern[source]!= source)
     {
         t_sub = s_sub = sniu[source].sub_address;
         d_sub = sniu[pattern[source]].sub_address;

         direction(s_sub,d_sub,&dire);
                         /* get direction clockwise or counter
clockwise*/
         ct=cs;          /* source -> temporary */
            cd=sniu[pattern[source]].column;
                         /* destination */

         for (j=0; j<KK; j++)
         {
          rt[j] = rs[j];
          rd[j] = sniu[pattern[source]].row[j];
         };              /* set tem and destination row */

            if (cd!=cs)       /* decide d */
          hop_dist = (KK+cd-cs)%KK;
            else
          hop_dist = KK;
```

```
      hop(hop_dist, &ct, rt, &t_sub, rd, cd, d_sub, sniu, dire);
      match = 1;          /* check if match */
      for (j=0; j<KK; j++)
      {
       if (rt[j]!= rd[j])no match */
       match = 0;
      };
      if (match == 0) /* no match, continue routing */
      {
       hop_dist = KK;
       hop(hop_dist, &ct, rt, &t_sub, rd, cd, d_sub, sniu, dire);
      }/* end if (match=0) */

      while(t_sub != d_sub)
      {
       tem = 0;       /* the present routing channel user
number+ 1 */
       for (j=0; j<KK; j++)
           tem =  tem + rt[j]*power(PP,j);
       tem_node = ct * COLUMN_NO_NIU + tem + t_sub *
SUBNET_NO_NIU;
       ring_hop(tem_node, &t_sub, sniu, dire);
       }
    }/* end  if (pattern[source]!= source) */
   }  /* end  for (source=0;source<TOTAL_NO_NIU;source++) */
   return;
}/* end routing */

cal(sniu,user_per_ch)

niu  *sniu;
int  *user_per_ch;

{
   int        j,k,l,
          max;

   max = 0;
   for (k=0; k< TOTAL_NO_NIU; k++)
   {
    for (l=0; l< PP; l++)
```

```
      {
         if (sniu[k].channel[l] > max)
           max = sniu[k].channel[l];
      };
      if (sniu[k].ch_L > max)
          max = sniu[k].ch_L;
      if (sniu[k].ch_R > max)
          max = sniu[k].ch_R;
     };

    user_per_ch[max]++;

    return;
}/* end */


printout(user_per_ch, no_loop)

int  *user_per_ch,
     no_loop;

{
    int         i;

    printf("no. of loops = %d\n",no_loop);
    for (i=0; i < MAX_NO_USER; i++)
    {
     printf("Probability of  %d  users per channel = %f\n",i,
(double)user_per_ch[i]/(double)no_loop);
    }
}/*end printout */



void main()

{
niu        sniu[24576];
int        no_loop,l,
           no_shift,
           pattern[TOTAL_NO_NIU],
```

```
          user_per_ch[MAX_NO_USER];

     initialize(sniu,user_per_ch);

/*   printf("please input No. of Loops\n");
     scanf("%d",&no_loop);*/

     no_loop = 20000;
     no_shift = 0;
     for (l=0; l < no_loop; l++)
     {
         ini_ch(sniu);
         rdm(pattern, &no_shift);
            routing(sniu,pattern);
         cal(sniu,user_per_ch);
     };

     printout(user_per_ch, no_loop);

}/* end main */
```