PERFORMANCE ANALYSIS OF OPTICAL RING NETWORK

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Abstract

In this paper the background theory of the WAN protocols with their different ring topologies is given. The two architectures considered in this work are: 1) A circuit-switched ring, such as Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH) ring [1] and 2) A packet -switched ring, such as Spatial Reuse Protocol (SRP) [2]. Then we calculate the throughput under different traffic pattern before and after the ring failure and prove that SRP is better than SONET/SDH in term of throughput.

1. INTRODUCTION

With the advent of fiber optic transmission lines, the next step in the evolution of the digital time-division-multiplexing (TDM) scheme was a standard signal format called Synchronous Optical Network (SONET) in North America and Synchronous Digital Hierarchy (SDH) in the other parts of the world that intended to provide a specification for taking advantages of the high-speed digital transmission capability of optical fiber. This is called an STS-1 signal, where STS stands for synchronous transport signal. All other SONET signals are integer multiples of this rate, so that an STS-N signal has a bit rate equal to N times 51.84 Mb/s. In SDH the basic rate is equivalent to STS-3, or 155.52 Mb/s. This is called the synchronous transport module –level 1(STM-1).

2. SONET/SDH (STS-1) FRAME FORMAT

The basic STS-1 SONET frame format is illustrated in [3][4]. The frame format is typically depicted as a 9-row by 90-column matrix representing individual bytes of the synchronous signal. The entire frame is transmitted in 125 µs, which works out to be the STS-1 line rate of 51.84 Mb/s (6480 bits/125 µs=51.84 Mb/s). STS-1 frames

are divided into two main areas: the transport overhead (TOH), and the synchronous payload envelope (SPE). The first three columns of the 90-column matrix are occupied by the TOH. The remaining 87 columns make up the SPE.

3. DESCRIPTION OF FOUR RING ARCHITECTURES

The SONET/SDH rings are commonly called self-healing rings (SHR), since the traffic flowing along a certain path can automatically be switched to an alternate or standby path following failure or degradation of the link segment [4]. There are four architectures for Self-Healing Rings (SHR) [1], these include Bi-directional SHR with four fibers (B-SHR/4), Bi-directional SHR with two fibers (B-SHR/2), Unidirectional SHR (U-SHR) with two fibers in a folded architecture (U-SHR/APS), and USHR in a path protected architecture (U-SHR/PP).

The classification these architectures are [5][6][7], 4-fiber bi-directional ring, 2-fiber bi-directional ring, Unidirectional Line Switched Ring (ULSR), and Unidirectional Path Switched Ring (UPSR), respectively. The term Bi-directional Line Switched Ring (BLSR) is also commonly used for bi-directional rings. Unidirectional ring architecture is shown in Figure (1). In unidirectional rings, primary traffic is sent on the working ring (which in Figure (1.6) is the clockwise ring). There are two variants of unidirectional rings: ULSRs and UPSRs [8][9]. In ULSRs, traffic is only sent on the working ring. Traffic from node 1 to node 2 traverses the fiber from node 1 to node 2. Traffic from node 2 to 1 will go round the working ring from node 2 to node 3 to node 4 to node 1. Each node is an add/drop multiplexer, i.e., it adds some signals to the ring and removes others from the ring.

In a UPSR, to provide path protection for all signals, data from node 1 to node 2 is sent both on the short path (fiber from node 1 to node 2) and on the long path from node 1 to nodes 4, 3, 2 on the protection ring. The reason for sending the traffic on the second ring is that if a failure/fiber cut occurs, the node can quickly select data sent on the protection ring.

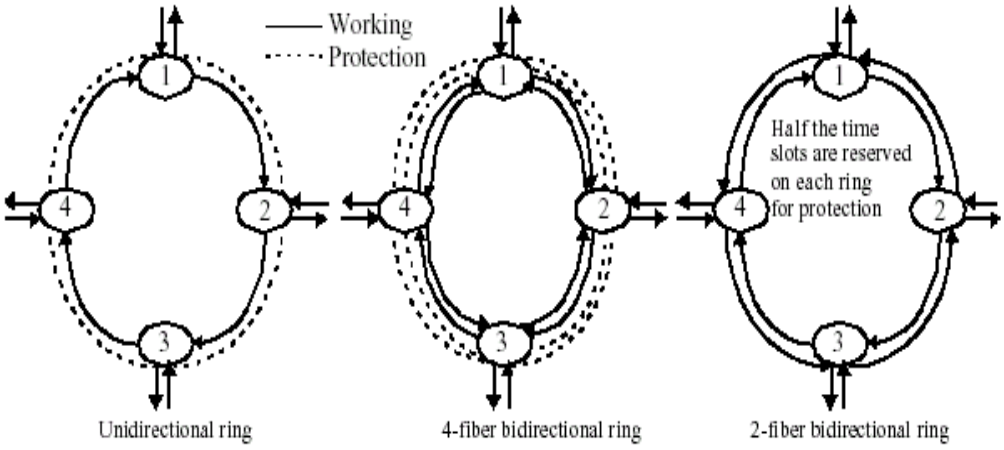

Figure 1. SONET ring architectures

In a ring with n nodes, data from node 1 to node n is sent on the working ring on the long path, 1, 2, 3,...., n-1, n as well as on the protection ring on the short span from node 1 to node n. Two bi-directional ring architectures are shown in Figure 1. In the 4-fiber case, data from node 1 to node 2 is sent on the fiber from node 1 to node 2. Data in the opposite direction is sent on a fiber from node 2 to node 1. The second pair of fibers is reserved for protection.

4. RECONFIGURATION OF FIBER UNDER LINK FAILURE

To see the function and versatility of the standby links in the four-fiber BLSR, consider first the case where a transmitter or receiver circuit card used on the primary ring fails in either node 3 or 4. In this situation, the affected nodes detect a loss-of-signal condition and switch both primary fibers connecting them to the secondary protection pair, as shown in Figure 2.

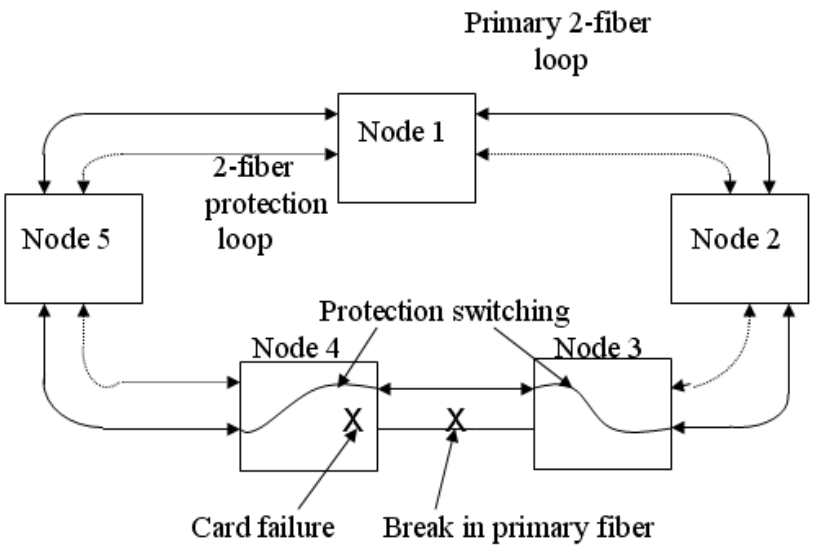

Figure 2. Reconfiguration of a four-fiber BLSR under transceiver or line failure

If an entire node fails, or both the primary and the protection fibers in a given span are severed, which could happen if they are in the same cable duct between two nodes. In this case, the nodes on either side of the failed inter-nodal span internally switch the primary-path connections from their receivers and transmitters to the protection fibers, in order to loop traffic back to the previous node. This process again forms a closed ring, but now with all of the primary and protection fibers in use around the entire ring, as shown in Figure 3[10] [4].

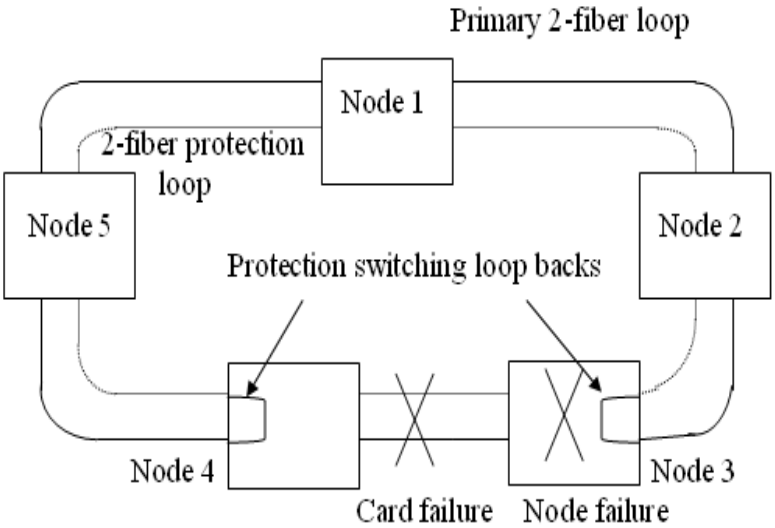

Figure 3. Reconfiguration of a four-fiber BLSR under node or fiber-cable failure

5. SRP BACKGROUND

SRP uses a bi-directional dual counter-rotating ring topology. The rings are referred to as “inner” and “outer” as illustrated in Figure 4. Both rings are concurrently utilized for transporting data and SRP control packets. SRP control packets handle tasks such as protection switching and bandwidth control. Control packets propagate in the opposite direction from the corresponding data packets thus, for data packets being transported by the outer ring, control packets are transported by the inner ring, as depicted in Figure (4) [11][12][13][14][15].

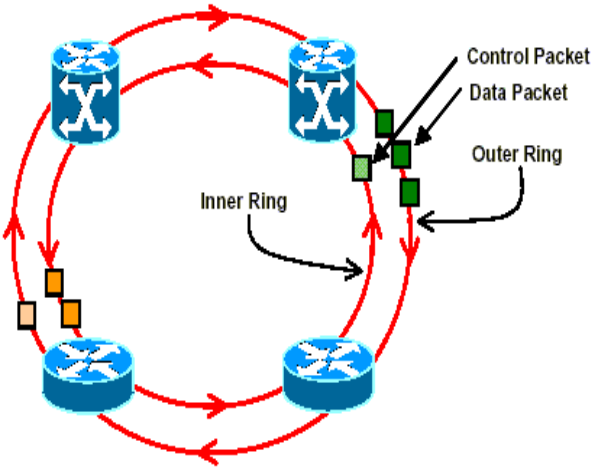

Figure 4. Four-Node SRP Ring

6. TRAFFIC PATTERNS ASSUMED FOR ANALYSIS

Network throughput depends upon the traffic pattern. Three patterns assumed commonly in existing chapter [1] [16] include centralized, mesh and cyclic patterns. The centralized traffic pattern corresponds to an access ring, where all nodes send/receive data to/from one node (for example, the node that provides access to the Internet). The mesh pattern is more common in interoffice configurations where traffic exists between any two offices. The access pattern occurs in access metro rings, where a data from/to different customer enterprise flows to a telecommunications service provider node.

The demand to can be split on to multiple paths or not split, i.e., all the demand between two nodes is sent on the same path. The assumption is that the demand is uniformly the same between all node pairs for which a non-zero demand exists. The traffic pattern type determines whether a node pair has a non-zero demand or not.

With the mesh traffic pattern, every node i send traffic of non-zero value d to every other node on the ring.

7. COMPUTATION OF NETWORK THROUGHPUT BEFORE FIBER CUT/RESTORATION IN SONET/SDH RING

Let R be the transceiver rate used on each fiber (this rate is also referred to as the fiber "transmission rate"). This is the rate at which data is sent on each span (part of the ring between two adjacent nodes) in each direction (i.e., on a fiber). The total network throughput T is the demand between all pairs of nodes that can be carried on each type of ring with fiber transmission rates R. This is the total of all traffic that enters the ring at an add/drop node and exits at another add/drop node. The unit of measurement of both network throughput and transmission rate is Mb/s.

For the three traffic patterns, the relation between network throughput and d, the non-zero demand, is given in Table 1, where n is the number of nodes on the ring.

Table 1. Network throughput as a function of the non-zero (uniform) demand d

Traffic Pattern	**Network throughput (T)**
Mesh	2*(n (n-1)/ 2)*d
Centralized	2*(n-1)*d
Cyclic	2*n*d

For each traffic pattern and ring type, Table 2 shows the demand d, which can be determine by counting the number of non-zero demands routed on a fiber, and making the assumption that all non-zero demands are equal. The network throughput is computed by adding all the non-zero demands. Effectively, this is done by plugging in d from Table 2 into the entries in the second column of Table 1 that relate T to d. n is indicated as E (Even) or O (Odd), and demand is indicated as NS (Not Split), S (Split), or D/C (Don't Care), which means the result is independent of whether the demand is split or not split.

Table 2. Network throughput for different types of rings and different traffic patterns

Ring	**Traffic pattern**	**d (each non-zero demand)**	**Network throughput (T)**
ULSR/UPSR	Mesh	$\frac{R}{(n(n-1))/2}$	2R
	Centralized	$\frac{R}{n-1}$	2R
	Cyclic	$\frac{R}{n}$	2R
	Simplex cyclic	R	nR
4-fiber BLSR	Mesh	$\frac{8R}{n(n+2)}$ $\frac{8R}{n^2}$ $\frac{8R}{(n^2-1)}$	$8R\frac{(n-1)}{(n+2)}$ n: E; demand: NS $8R\frac{(n-1)}{n}$ n: E; demand: S $8R\frac{n}{(n+1)}$ n: O; demand: D/C
	Centralized	$\frac{2R}{n}$ $\frac{2R}{(n-1)}$ $\frac{2R}{(n-1)}$	$4R\frac{(n-1)}{n}$ n: E; demand: NS $4R$ n: E; demand: S $4R$ n: O; demand: D/C
	Cyclic	R	2nR
2-fiber BLSR	Mesh	$\frac{4R}{n(n+2)}$ $\frac{4R}{n^2}$ $\frac{4R}{(n^2-1)}$	$4R\frac{(n-1)}{(n+2)}$ n: E; demand: NS $4R\frac{(n-1)}{n}$ n: E; demand: S $4R\frac{n}{(n+1)}$ n: O; demand: D/C n: E; demand: NS

	Centralized	$\frac{R}{n}$ $\frac{R}{n-1}$ $\frac{R}{n-1}$	$2\frac{R(n-1)}{n}$ $2R$ n: E; demand: S $2R$ n: O; demand: D/C
	Cyclic	$\frac{R}{2}$	nR

8. UNIDIRECTIONAL RINGS (UPSR, ULSR)

Figure 5 illustrates how the centralized traffic pattern is supported on a unidirectional ring.

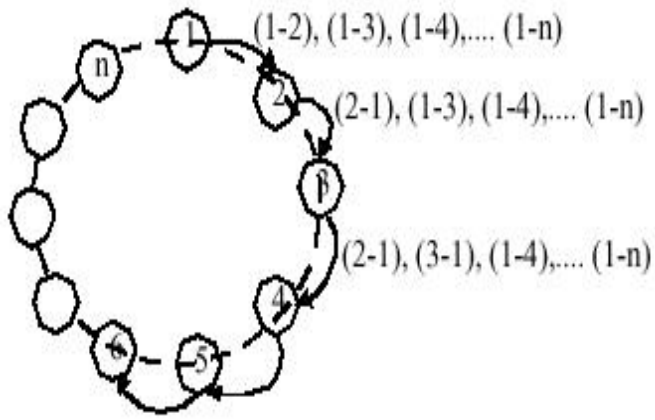

Figure 5. Unidirectional ring: centralized demand

Each fiber carries traffic from (n-1) node pairs. For example, the fiber from node 2 to 3 carries traffic from node 1 to nodes 3, 4...n, and also traffic from node 2 to node 1 (because the ring is unidirectional, this traffic is routed on the long path). Therefore, in a UPSR or ULSR, because each fiber supports traffic (n-1) node pairs, under the uniform demand assumption, the demand d between any two nodes is

$$d=\frac{R}{n-1} \tag{1}$$

Figure 6 illustrates how the mesh demand traffic pattern is supported on a unidirectional ring.

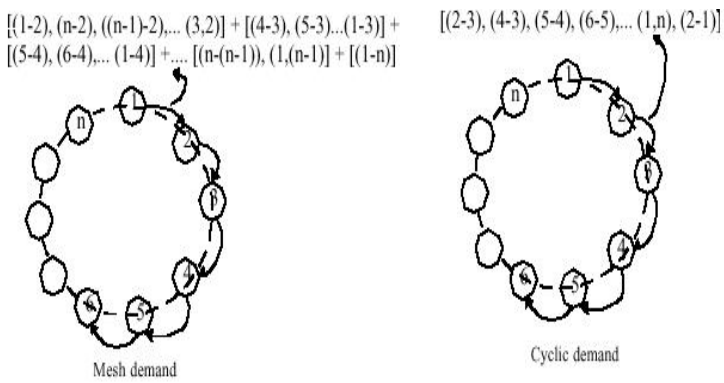

Figure 6. Unidirectional ring: mesh and cyclic demand patterns

The total number of non-zero demands carried on the fiber from node 1 to node 2 is (n-1)+(n-2)+…+1=n (n-1)/2. The assumption is that all non-zero demands are equal; we divide the fiber transmission rate equally among all these demands. Therefore

$$d = \frac{R}{(n(n-1))/2} \tag{2}$$

Figure 6 illustrates the cyclic pattern on a unidirectional ring. The fiber from node 2 to node 3 carries the demand from 2 to 3, from 4 to 3, from 5 to 4, etc., because traffic is only sent between neighbors with this cyclic pattern. There are n demands and hence

$$d=\frac{R}{n} \tag{3}$$

With the simplex cyclic pattern [17], traffic demand from node 1 to node 2 is, but the demand from node 2 to node 1 is 0. Therefore, on any fiber, only one demand d is carried. Therefore d=R.

9. 4-FIBERS BLSR

A 4-fiber BLSR with the centralized traffic pattern is considering. In this case demand d depends upon whether n, the number of nodes on the ring, is even or odd, and if it is even, whether demand is split on two paths or not. If n is even and demand is not split, then it consider the worst-case path to limit d so that a fiber with transmission rate R can support the total demand among all node pairs.

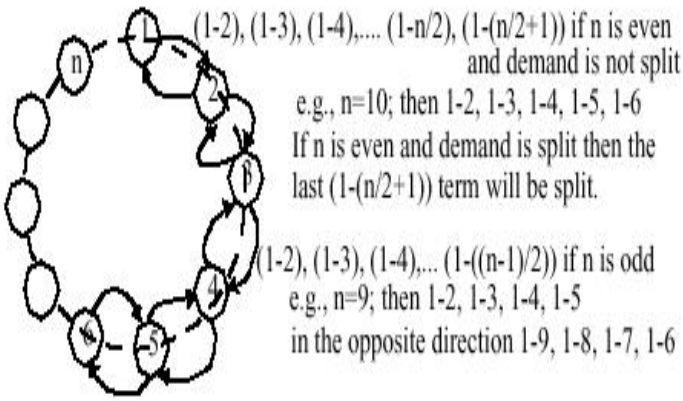

Figure 7. 4-fiber bi-directional ring: centralized traffic patterns

As illustrated in Figure 7, the traffic from node 1 to node 6 is carried on the clockwise ring. Thus, fibers in the counter-clockwise direction from node 1 to node 10, 10 to 9... 7 to 6, carry less load. If demand is split then the 1-6 demand is divided equally on the two rings. Therefore,

$$d=\begin{cases} \dfrac{R}{n/2} & \text{if n is even \& d is not split} \\ \dfrac{R}{(n-1)/2} & \text{if n is even \& d is split equally} \\ \dfrac{R}{(n-1)/2} & \text{if n is odd} \end{cases} \tag{4}$$

For the mesh case in Figure 8 shows how the traffic demand is routed on the 4-fiber bi-directional ring.

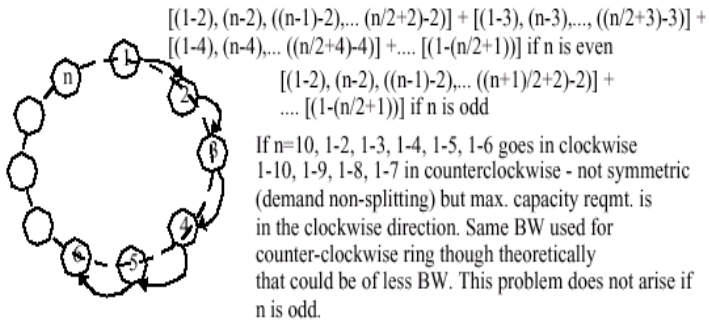

Figure 8. 4-fiber bi-directional ring: mesh traffic pattern

From Figure 8, it notes that there are n+1-(n/2+2)+1 terms in the first term of the demand carried on the fiber from node 1 to node 2, i.e., there are n/2 terms. The last term has 1 term. Therefore, it adds to n/2 +(n/2-1)+…+1, which is ((n/2)(n/2+1))/2.

A similar reasoning can be applied for the case when n is odd. If it allows demand splitting, then instead of the asymmetric traffic distribution pattern shown in Figure (8), the traffic distribution is symmetric. Half of the 1-6 traffic goes clockwise and the remaining counter-clockwise. Under this assumption, the traffic to node 2 will be [(1-2), (n-2), ((n-1)-2)... (n/2+3)-2) + 0.5((n/2+2)-2)] + [(1-3), (n-3),..., ((n/2+4)-3), 0.5((n/2+3)-3)] +... + 0.5([(1-(n/2+1))]. There are n+1-(n/2+3)+1 terms in the first term, i.e., there are n/2-1 terms, without counting the 0.5 terms. The last term has 1 term, which is a 0.5 term. Therefore, it adds to (n/2-1)+((n/2)-2)+…+1 which is ((n/2)(n/2-1))/2 + 0.5(n/2) terms, which is equal to n2/8 Therefore,

$$d=\begin{cases} \dfrac{R}{2(n/2(n/2+1)*1/2)} & \text{if n is even \&d NC} \\[2ex] \dfrac{R}{n^2/8} & \text{if n is even \& d is split} \\[2ex] \dfrac{R}{(((n+1)/2((n+1)/2-1)*1/2)} & \text{if n is odd} \end{cases} \tag{5}$$

For the cyclic pattern, in a 4-fiber bi-directional ring, the only demand carried on a fiber is from one node to its neighbor. Hence,

$$d = R \tag{6}$$

10. 2-FIBER BLSR

A 2-fiber BLSR is equivalent to a 4-fiber BLSR with 4 logical fibers [18]. Only half the slots in the two fibers are used to carry “working” traffic and the remaining half the time slots are reserved for “protection” reasons. Since the ring is bi-directional, both rings carry working traffic in opposite directions. Therefore, the demand that can be carried on a fiber in a 2-fiber BLSR is always half the demand that can be carried on a fiber in a 4-fiber BLSR. Figure 9 shows the centralized demand traffic.

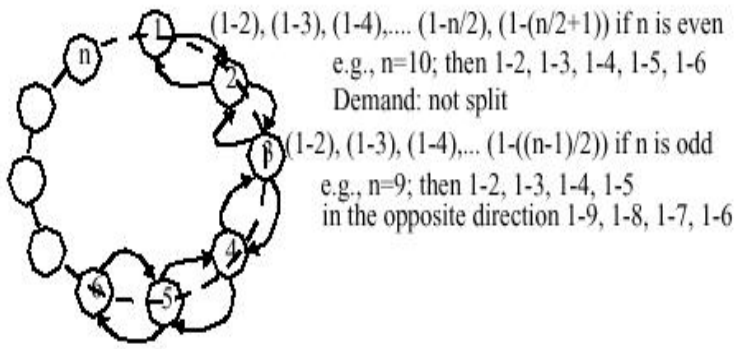

Figure 9. 2-fiber bi-directional ring: centralized demand

If n is even and demand is not split, then the number of demands carried on the 1-2 fiber is n/2. Since only half the fiber transmission rate R can be used for these demands, with the remaining half set aside for restoration, demand d is (R/2)/(n/2), which is R/n as shown below. The remaining two cases in equation. (7) can be reasoned through similarly.

$$d=\begin{cases} \dfrac{R}{n} & \text{if n is even \&d is NC} \\[2ex] \dfrac{R}{(2(n/2-1+0.5))} & \text{if n is even \& d is split} \\[2ex] \dfrac{R}{n-1} & \text{if n is odd} \end{cases} \qquad (7)$$

For the other two traffic patterns, mesh and cyclic, the result is the same, i.e., demand d between any two nodes is half the demand that can be carried in a 4-fiber BLSR. Table 2 shows the values for d in a 2-fiber BLSR for these traffic patterns.

11. RECOVERY PROCEDURE FOLLOWING FIBER CUTS IN SONET/SDH RING

The description of how each ring performs restoration after a fiber or cable cut is shown below. In a UPSR, since traffic is sent on both fibers in two opposite directions, the receiving node receives two identical signals with different delays. During normal operation, only the primary signal is used, but both signals are monitored for alarms and maintenance signals. After a cable cut, where both fibers on a span are lost, several signals are sent by the two nodes on either ends of the cable cut on all the paths. Upon detecting the signals, the 2:1 selector devices at all the nodes receiving the path signals make a switch to the protection signal if necessary. The signal [1] [14] is sent at the path level and is hence not examined by intermediate nodes.

Restoration in ULSRs can be done in one of two ways. Both follow the automatic protection switching (APS) protocol [19]. At the end of the restoration, the ring has loop backs at the two ends of the failed link. In a 4-fiber BLSR, the APS procedure is used to reconfigure the ring after a fiber cut [7]. If one fiber in a span is cut, the short path span protection APS procedure can be carried out. If both fibers in a cable (across a span) are cut, the long path ring protection APS procedure is carried out. In a 2-fiber BLSR, the recovery procedure also uses the APS scheme with two loop backs occurring at the two OADMs (Optical Added Drop Multiplexer) on either side of the cable cut.

A fiber cut is a cut of a single fiber, i.e., transmission in one direction between nodes is interrupted. The assumption is a cable cut to be a cut of both fibers between two nodes, i.e., in both directions. Recovery mechanism for both these types of cuts leaves the network throughput unchanged with these SONET rings. In the 2-fiber BLSR case, the traffic carried before the cut has to be supported with different routing after the cut. The architecture becomes that of a linear network. The worst case cut is if one of the two spans connected to the hub fail. For example in Figure 10, if node 1 is the hub, and the fiber from node n to node 1 fails, then the ring will be wrapped around at nodes 1 and n. The link with the heaviest load will be the link from node 1 to node 2, which carries demand pairs as shown in Figure 10. The link from node 2 to 3 carries demand from one less node pair; link 3 to 4 carries demand from two less

node pairs and so on because under the centralized traffic demand pattern, each node only sends to and receives from the hub. Thus, under this configuration, d can be

$$d=\frac{R}{n-1} \tag{8}$$

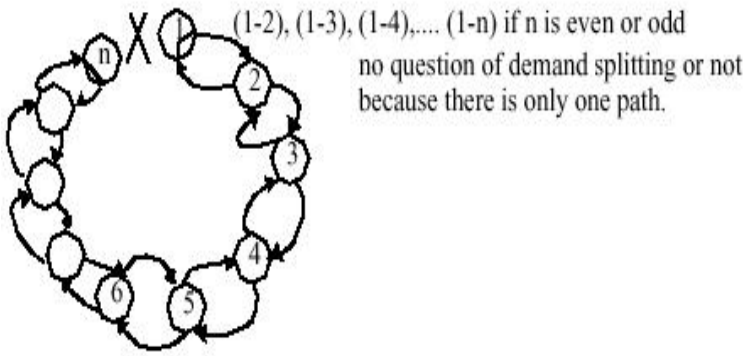

Figure 10. 2-fiber bi-directional ring after a cut: centralized traffic pattern

To determine which link will experience the most loads under the mesh traffic pattern, assume it is the link from node k+1 to node k (the linear network of Figure 11).

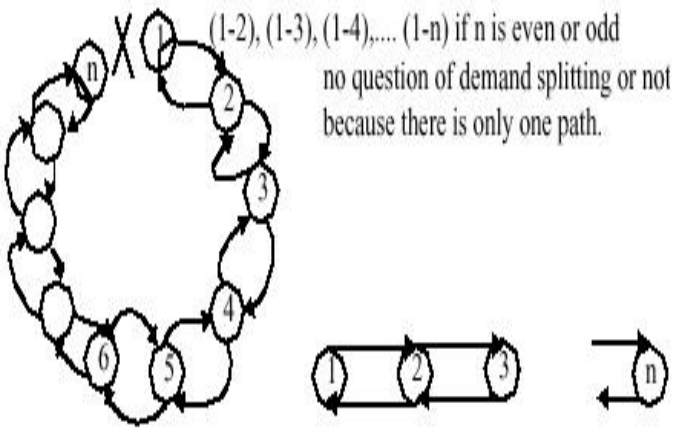

Figure 11. 2-fiber bi-directional ring after a cut: mesh traffic pattern

This link will carry load from nodes 1-(k+1), 1-(k+2)... 1-n, 2-(k+1), 2-(k+2)... 2-n... k- (k+1), k- (k+2)... k-n. This is a total of (n- (k+1)+1)(k)=(n-k) k demand pairs. To find the value of k for which this term is maximum, take the derivative

$$\frac{d(n-k)k}{dk} = n - 2k = 0 \tag{9}$$

Therefore if n is even, k=n/2. If n is odd, the link with the maximum load will have more nodes to the left of the link than to the right for the link direction from left to right (in the linear network) and vice versa for the link in the opposite direction. Therefore, the link from node (n+1)/2 to node ((n+1)/2+1) will have the maximum number of demand pairs in the left to right direction and for the opposite direction, the link from node (n+1)/2 to node ((n+1)/2-1) will have the maximum load. The maximum non-zero demand value is hence

$$d = \begin{cases} \dfrac{R}{n^2/4} & \text{n is even} \\[2ex] \dfrac{R}{((n^2-1)/4} & \text{n is odd} \end{cases} \tag{10}$$

Similar to the centralized traffic pattern case, under the mesh traffic pattern, equation. (10) is almost the same as for the 2-fiber BLSR before the fiber cut as shown in Table 2. Only when n is even, if the demand is not split, then the demand supported before the cut is less than the demand that can be supported after the cut.

12. COMPUTATION OF NETWORK THROUGHPUT BEFORE FIBER CUT/RESTORATION IN SRP RING

The network throughput of an SRP ring before a fiber cut is the same as that of a 4-fiber BLSR because the SRP ring, being bi-directional and a dual counter-rotating ring, is similar to a 2-fiber BLSR. But because the whole bandwidth is used for data traffic and no bandwidth is set aside for protection unlike in the 2-fiber BLSR, the

network throughput is equal to that of a 4-fiber BLSR. For example, for the mesh traffic pattern:

$$\text{TSRP} = \begin{cases} 8 * R\dfrac{(n-1)}{(n+2)} & \text{if } \mathbf{n} \text{ is even \& } \mathbf{d} \text{ is not split} \\ 8 * R\dfrac{(n-1)}{n} & \text{if } \mathbf{n} \text{ is even \& } \mathbf{d} \text{ is split} \\ 8 * R\dfrac{n}{(n+1)} & \text{if } \mathbf{n} \text{ is odd} \end{cases} \tag{11}$$

After a fiber cut, the ring wraps around at the two edges of the cut using a procedure called IPS (Intelligent Protection Switching) [2]. The wrapped ring is exactly the same as a wrapped 2-fiber BLSR. Therefore, after a fiber cut and IPS restoration, the network throughput of an SRP ring drops to that of a wrapped 2-fiber BLSR. Under a mesh traffic pattern assumption, this throughput is [8] [19]:

$$\text{TSRP} = \begin{cases} 4 * \mathrm{R}\dfrac{(\mathrm{n}-1)}{\mathrm{n}} & \text{if } \mathbf{n} \text{ is even} \\ 4 * \mathrm{R}\dfrac{\mathrm{n}}{(\mathrm{n}+1)} & \text{if } \mathbf{n} \text{ is odd} \end{cases} \tag{12}$$

13. NETWORK THROUGHPUT COMPARISON OF OPTICAL RING ARCHITECTURE BEFORE FIBER CUT /RESTORATION

The network throughput for an OC-48 (2488 Mbps~2.5 Gbps) ring of all four architectures under a mesh traffic pattern assumption is illustrated in Figure 12. Given R (transceiver rate), maximum throughput will be achieved in 4-fiber BLSR with demand splitting.

Figure 13 and 14 show similar plots but with different traffic patterns, i.e., the centralized and cyclic cases. In the centralized case, there is no difference between a 2-fiber BLSR and a unidirectional ring. Interestingly, the total network throughput is more with the mesh traffic pattern than the centralized even though the per node pair non-zero demand value d is smaller. The highest network throughput is achieved under the cyclic pattern assumption; this is the maximum achievable for the bi-directional rings.

Since network throughput depends on R and n as shown in Table 2, it can be vary for a fixed ring size n = 8. In this case, it also plots the network throughput versus R for all the architectures under different traffic patterns. These are shown figures 15, 16 and 17.

The values of R are OC3, OC9, OC12, OC18, OC24, OC36, OC48, and OC192 as shown in the SONET hierarchy [8]. Summing up the characteristics shown in figures 15, 16 and (3.6), 4-fiber BLSR with demand splitting gives us best choice to get maximum throughput.

Figure 18 and 19 show the comparison of network throughput between 2-fiber ring: (SONET/SDH) BLSR, and (SRP) ring under mesh traffic pattern before and after link failures, and shows that by using SRP, the network throughput is increased before link failures by a factor of two when compared to a SONET/SDH BLSR. After link failure/restoration the throughput of an SRP ring decreases to that of SONET/SDH ring (lower line), while 2-fiber SONET/SDH BLSRs sacrifice network throughput before failures, and SRP sacrifice network throughput after a failure/restoration.

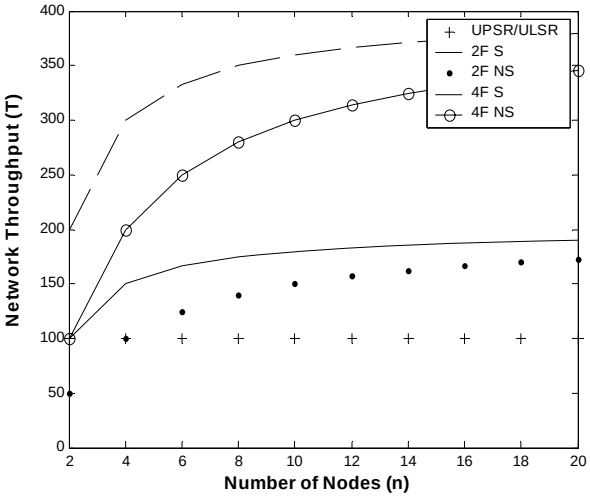

Figure 12. Network Throughput of rings under mesh traffic pattern

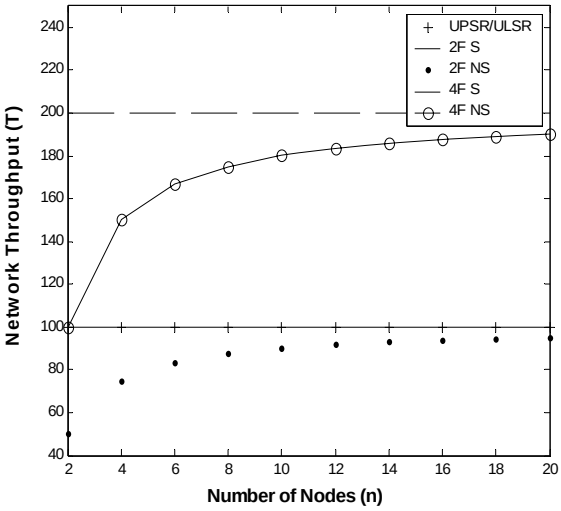

Figure 13. Network Throughput of rings under centralized traffic pattern

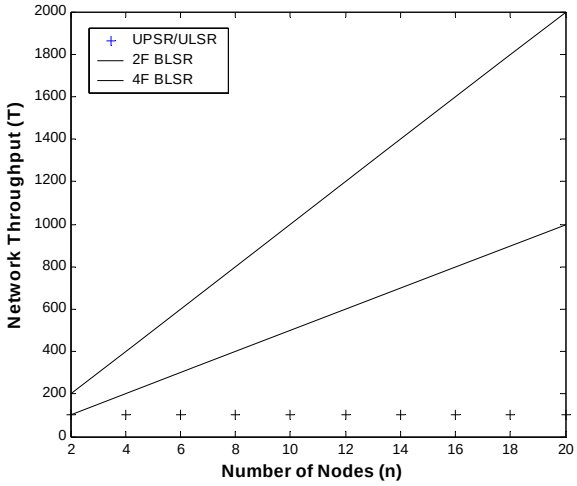

Figure 14. Network Throughput of rings under cyclic traffic pattern

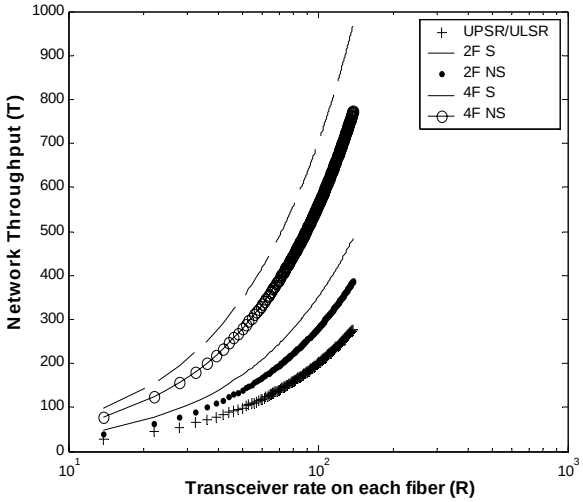

Figure 15. Network Throughput of rings vs R for mesh traffic pattern (n=8)

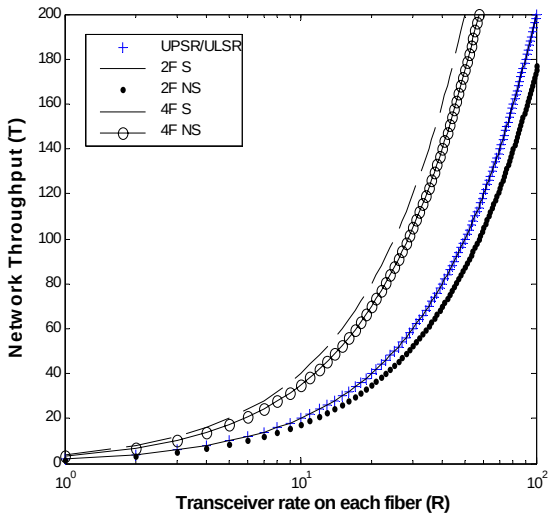

Figure 16. Network Throughput of rings vs R for centralized traffic pattern (n=8)

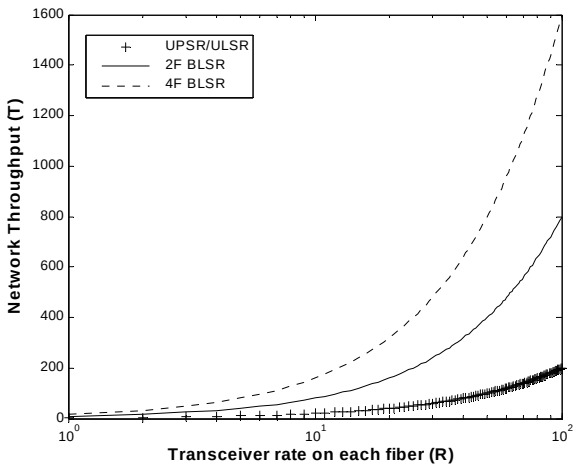

Figure 17. Network Throughput of rings vs R for cyclic traffic pattern (n=8)

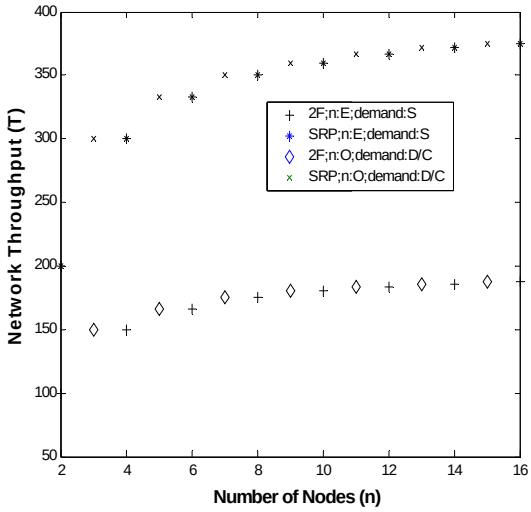

Figure 18. Network Throughput of rings vs (n) for mesh traffic pattern before any link failures

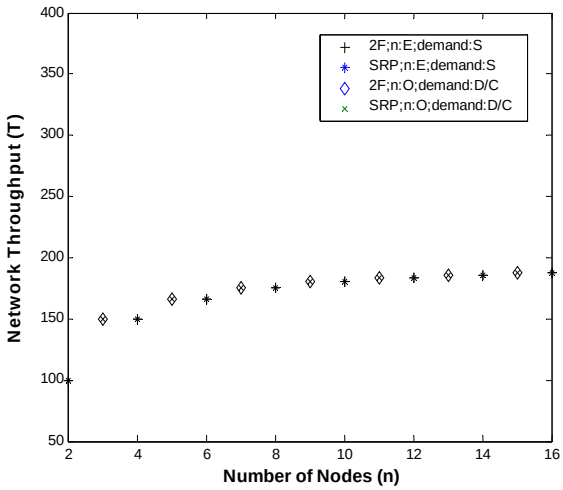

Figure 19. Network Throughput of rings vs (n) for mesh traffic pattern after link failure/restoration

14. CONCLUSION

From the analysis above we shows that by using SRP, the network throughput is increased before link failures by a factor of two when compared to a SONET/SDH and after link failure/restoration the throughput of an SRP ring decreases to that of SONET/SDH ring, so SRP is better than SONET/SDH in term of throughput.

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