A network throughput comparison of optical metro ring architectures

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This paper compares three different metropolitan-area network (MAN) architectures from a network throughput perspective. We compare network throughput both before and after a fiber cut/restoration because a critical component of a MAN architecture is its ability to restore service rapidly after a fiber cut or other failure. The three architectures considered in this work are:

1. A circuit-switched ring, such as a Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH) ring [1]
2. A Resilient Packet Ring (RPR) such as that proposed in [2]
3. Village Networks’ ioPN solution [3].

In Section 1, we describe the traffic patterns assumed for the comparative analysis. Section 2 describes the circuit switched ring architectures and analyzes the network throughput of these rings before and after fiber cuts. Section 3 describes and analyzes the RPR ring.

1. Traffic patterns assumed for analysis

Network throughput depends upon the traffic pattern. Three patterns assumed commonly in existing literature [1][4] 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\(^1\) rings, where data from/to different customer enterprises flows to a telecommunications service provider node. On the other hand, the mesh pattern is common in core metro rings, where data flows between any two nodes on the ring. The cyclic pattern is included to allow us to compute maximum network throughput, i.e., the maximum traffic that can be carried between all pairs of nodes.

We allow for demand to be both split on to multiple paths or not split, i.e., all the demand between two nodes is sent on the same path. Furthermore, we assume that demand is uniformly the same between all node pairs for which a non-zero demand exists. The traffic pattern type determines whether

\(^{1}\) The shorthand notation “metro” is used for metropolitan-area networks.
a node pair has a non-zero demand or not. With the mesh traffic pattern, every node $i$ sends traffic of non-zero value $d$ to every other node on the ring. Thus, node $i$ sends $d$ Mbps to node $j$, where $j \neq i$, while simultaneously node $j$ sends $d$ Mbps to node $i$. In the centralized pattern, every node $i$ sends data to a central node (hub), say node 1, and receives data from the hub. Thus, $d_{ij} = d_{ji} = d$, $j \neq i$, while $d_{ij} = 0$, $i, j \neq 1$. Finally, the cyclic pattern is one in which data only flows between neighbor nodes. If nodes on a ring are numbered in sequence, $d_{ij} = d$ if $j = i + 1$ and 0 otherwise, node $n + 1$ is the same as node 1. In unidirectional rings, a simplex cyclic pattern yields the maximum network throughput.

For the initial analysis, we assume uniform loads, which means the traffic is the same for all node pairs that have a non-zero demand. But for subsequent analysis, we assume time-varying demands, which are not uniform. This is required to show the advantage of using packet-switched rings over provisioned circuit-switched rings.

2. Circuit-switched ring

2.1 Description of four ring architectures

Reference [1] describes four architectures for Self-Healing Rings (SHR). These include Bidirectional SHR with four fibers (B-SHR/4), Bidirectional 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). Drake [5] classifies these architectures as 4-fiber bidirectional ring, 2-fiber bidirectional ring, Unidirectional Line Switched Ring (ULSR), and Unidirectional Path Switched Ring (UPSR), respectively. The term Bidirectional Line Switched Ring (BLSR) is also commonly used for bidirectional rings. In this paper, we refer to these four ring architectures as 4-fiber BLSR, 2-fiber BLSR, ULSR, and UPSR.

A ring is bidirectional if signals in both directions of a duplex channel travel over the same path, while in a unidirectional ring the signals in the two directions of a duplex channel travel over opposite paths. The term fiber is used to represent one direction of a duplex channel. For example, in a 4-fiber ring, 2 fibers between two nodes constitute a duplex channel. The second 2 fibers are used to provide a protection duplex channel between the same two nodes.

A unidirectional ring architecture is shown in Fig. 1. In unidirectional rings, primary traffic is sent on the working ring (which in Fig. 1 is the clockwise ring). There are two variants of unidirectional
rings: ULSRs and UPSRs. 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. The protection ring is only used when there is a fiber cut or failure and the rings are reconfigured. 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 also 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. 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. The signal received on the long path is the one used under normal circumstances. It is only under failure conditions that the signal sent on the path node 1 to node n is used even though this path is shorter and hence delays will be lower. Thus, in a UPSR, traffic is sent on both rings under normal conditions, while in a ULSR, traffic is only sent on the working ring before a failure/fiber cut.

Two bidirectional ring architectures are shown in Fig. 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 are reserved for protection. In the 2-fiber BLSR, data from node 1-2 is sent on the direct span from 1 to 2 and data from node 2 to 1 is sent on the direct span from 2 to 1. But because there is no additional pair of fibers to serve as a protection ring, half the time slots on each fiber are reserved as protection bandwidth. This means that the transceivers on a 2-fiber BLSR
should be capable of sending and receiving data at twice the bandwidth of transceivers on a 4-fiber BSLR.

2.2 Computation of network throughput before fiber cut/restoration

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,

\[
\begin{array}{|c|c|}
\hline
\text{Trafﬁc Pattern} & \text{Network throughput } T \\
\hline
\text{Mesh} & 2^{n(n-1)/2}d \\
\hline
\text{Centralized} & 2(n-1)d \\
\hline
\text{Cyclic} & 2nd \\
\hline
\end{array}
\]

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

defined in Section 1., is given in Table 1, where \( n \) is the number of nodes on the ring.

For each traffic pattern and ring type, Table 2 shows the demand \( d \), which we 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 \( d \). Explanations for \( d \) are provided in the three sub-sections 2.2.1-2.2.3. \( n \) 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

<table>
<thead>
<tr>
<th>Ring</th>
<th>Traffic pattern</th>
<th>( d ) (each non-zero demand)</th>
<th>Network throughput ( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULSR/UPSR</td>
<td>Mesh</td>
<td>( \frac{R}{(n(n-1))/2} )</td>
<td>2R</td>
</tr>
<tr>
<td></td>
<td>Centralized</td>
<td>( \frac{R}{n-1} )</td>
<td>2R</td>
</tr>
<tr>
<td></td>
<td>Cyclic</td>
<td>( \frac{R}{n} )</td>
<td>2R</td>
</tr>
<tr>
<td></td>
<td>Simplex cyclic</td>
<td>( R )</td>
<td>( nR )</td>
</tr>
</tbody>
</table>
| 4-fiber BLSR | Mesh           | \( \begin{align*}
   \frac{8R}{n(n+2)} & \quad \text{n: E; demand: NS} \\
   \frac{8R}{n^2} & \quad \text{n: E; demand: S} \\
   \frac{8R}{(n^2-1)} & \quad \text{n: O; demand: D/C}
\end{align*} \) | \( \begin{align*}
   \frac{8R(n-1)}{(n+2)} & \quad \text{n: E; demand: NS} \\
   \frac{8R(n-1)}{n} & \quad \text{n: E; demand: S} \\
   \frac{8R}{n(n+1)} & \quad \text{n: O; demand: D/C}
\end{align*} \) |
|              | Centralized    | \( \begin{align*}
   \frac{2R}{n} & \quad \text{n: E; demand: NS} \\
   \frac{2R}{n-1} & \quad \text{n: E; demand: S} \\
   \frac{2R}{(n-1)} & \quad \text{n: O; demand: D/C}
\end{align*} \) | \( \begin{align*}
   \frac{4R(n-1)}{n} & \quad \text{n: E; demand: NS} \\
   4R & \quad \text{n: E; demand: S} \\
   4R & \quad \text{n: O; demand: D/C}
\end{align*} \) |
|              | Cyclic         | \( R \)                        | \( 2nR \)                |
Table 2: Network throughput for different types of rings and different traffic patterns

<table>
<thead>
<tr>
<th>Ring</th>
<th>Traffic pattern</th>
<th>(d) (each non-zero demand)</th>
<th>Network throughput (T)</th>
</tr>
</thead>
</table>
| 2-fiber BLSR | Mesh \[
\begin{align*}
\frac{4R}{n(n+2)} & \quad n: E; demand: NS \\
\frac{4R}{n^2} & \quad n: E; demand: S \\
\frac{4R}{(n^2-1)} & \quad n: O; demand: D/C
\end{align*}
\] | \[
\begin{align*}
4R\frac{(n-1)}{(n+2)} & \quad n: E; demand: NS \\
4R\frac{(n-1)}{n} & \quad n: E; demand: S \\
4R\frac{n}{(n+1)} & \quad n: O; demand: D/C
\end{align*}
\] |
| Centralized | \[
\begin{align*}
\frac{R}{n} & \quad n: E; demand: NS \\
\frac{R}{n-1} & \quad n: E; demand: S \\
\frac{R}{n-1} & \quad n: O; demand: D/C
\end{align*}
\] | \[
\begin{align*}
2R\frac{(n-1)}{n} & \quad n: E; demand: NS \\
2R & \quad n: E; demand: S \\
2R & \quad n: O; demand: D/C
\end{align*}
\] |
| Cyclic | \[
\frac{R}{2}
\] | \(nR\) |

Under the mesh traffic pattern assumption, for a unidirectional ring, network throughput is twice the rate of the transceiver. For bidirectional rings, for large \(n\), in the 4-fiber case, the network throughput approaches 8 times the transceiver rate, while in the 2-fiber case, the network throughput approaches 4 times the transceiver rate. Also, as noted in Section 2.1, the network throughput remains unchanged after a fiber or cable cut for all four rings.

2.2.1 Unidirectional rings (UPSR, ULSR)

Fig. 2 illustrates how the centralized traffic pattern is supported on a unidirectional ring. 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

\[
d = \frac{R}{n - 1}
\]

EQ(1)

Fig. 3 illustrates how the mesh demand traffic pattern is supported on a unidirectional ring. The fiber from node 1 to 2 carries traffic from all nodes to node 2, the traffic from all nodes to node 3 except from node 2 (which is carried on the short span fiber from node 2 to node 3), the traffic from all nodes to node 4 except from nodes 2 and 3, and so on. The last term shows the traffic to node \(n\); this consists of only the traffic from node 1 because traffic from all other nodes to node \(n\) is carried on other spans. No traffic to node 1 is carried on the fiber from node 1 to node 2. The total number of non-zero demands carried on the fiber from node 1 to node 2 is \((n - 1) + (n - 2) + \ldots + 1 = n(n - 1)/2\). Assuming that all non-zero demands are equal, we divide the fiber transmission rate equally among all these demands. Therefore

\[
d = \frac{R}{n(n-1)/2}
\]

EQ(2)

Fig. 3 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

$$d = \frac{R}{n} \quad \text{EQ}(3)$$

With the simplex cyclic pattern [6], traffic demand from node 1 to node 2 is $d$, but the demand from node 2 to node 1 is 0. Therefore on any fiber, only one demand $d$ is carried. Therefore $d = R$.

### 2.2.2 4-fiber BLSR

Next, consider a 4-fiber BLSR with the centralized traffic pattern. 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 we 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. As illustrated in Fig. 4, 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.

![Fig. 4 4-fiber bidirectional ring: centralized traffic pattern](image)

$$d = \begin{cases} 
R/(n/2) & \text{if } n \text{ is even and demand is not split} \\
R/((n-1)/2) & \text{if } n \text{ is even and demand is split equally} \\
R/((n-1)/2) & \text{if } n \text{ is odd} 
\end{cases} \quad \text{EQ}(4)$$
For the mesh case, see Fig. 5 for how the traffic demand is routed on the 4-fiber bidirectional ring.

From Fig. 5, we note 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 \( n/2 + (n/2 - 1) + \ldots + 1 \), which is \((n/2)(n/2 + 1)/2\). A similar reasoning can be applied for the case when \( n \) is odd. If we allow demand splitting, then instead of the asymmetric traffic distribution pattern shown in Fig. 5, 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

\[
[(1-2), (n-2), ((n-1)-2), \ldots, ((n/2+3)-2)] + 0.5((n/2+2)-2) + [(1-3), (n-3), \ldots, ((n/2+4)-3), 0.5((n/2+3)-3)] + \ldots + 0.5([(1-(n/2+1))].
\]

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 term. The last [] term has 1 term, which is a 0.5 term. Therefore, it adds to \( (n/2 - 1) + ((n/2) - 2) + \ldots + 1 \), which is \((n/2)(n/2 - 1)/2 + 0.5 \) \( n/2 \) terms, which is equal to \( n^2/8 \). Therefore,

\[
d = \begin{cases} 
R/\left(\frac{n}{2}\left(\frac{n}{2} + 1\right)\right)^{\frac{1}{2}} & \text{if } n \text{ is even and demand is not split} \\
(R/(n^2/8)) & \text{if } n \text{ is even and demand is split} \\
R/\left(\left(\frac{n+1}{2}\right)(\frac{n+1}{2} - 1)^{\frac{1}{2}}\right) & \text{if } n \text{ is odd}
\end{cases} \quad \text{EQ(5)}
\]

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

\[
d = R \quad \text{EQ(6)}
\]
2.2.3 2-fiber BLSR

As explained in [7], a 2-fiber BLSR is equivalent to a 4-fiber BLSR with 4 logical fibers. 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 bidirectional, 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. As an illustration, consider the centralized demand traffic as shown in Fig. 6. 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 restoral, demand \( d \) is \((R/2)/(n/2)\), which is \( R/n \) as shown below. The remaining two cases in EQ(7) can be reasoned through similarly.

\[
d = \begin{cases} 
\frac{R}{n} & \text{if } n \text{ is even and demand is not split} \\
\frac{R}{2 \left(\frac{n}{2} - 1 + 0.5\right)} & \text{if } n \text{ is even and demand is split} \\
\frac{R}{n - 1} & \text{if } n \text{ is odd}
\end{cases}
\]

EQ(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.

2.2.4 Numerical results

The network throughput for an OC-48 ring of all four architectures under a mesh traffic pattern assumption is illustrated in Fig. 7. Given \( R \) (transceiver rate), maximum throughput will be achieved in 4-fiber BLSR with demand splitting. Since demands from fewer node pairs share the fiber transmission...
rate in bidirectional rings, each non-zero demand can be higher and hence the total network throughput is higher. As explained in Section 2.2.3, only half the demand and hence network throughput of a 4-fiber BLSR can be supported on a 2-fiber BLSR. The reason network throughput is higher for the demand splitting case relative to the non-splitting case is that demand from some node pairs is completely routed on one path in the latter case, making the per node pair demand smaller. The difference in the two cases, demand splitting and demand non-splitting is only seen when $n$ is even as is evident from Section 2.2.

Figs. 8 and 9 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 bidirectional rings.

Since network throughput depends on $R$ and $n$ as shown in Table 2, we vary $R$ for a fixed ring size $n = 8$. In this case, we also plot the network throughput versus $R$ for all the architectures under different traffic patterns. These are shown from Fig. 10 to Fig. 12. The values of $R$ are OC3, OC9, OC12, OC18, OC24, OC36, OC48, OC192 as shown in the SONET hierarchy [8]. Summing up the characteristics shown in Fig. 10 to 12, 4-fiber BLSR with demand splitting gives us best choice to get maximum
throughput. The number of DS3s that can be supported as R increases to OC192 is quite large relative to an OC48 ring.
2.3 Recovery procedures following fiber cuts

In this section, we describe how each ring performs restoration after a fiber or cable cut. 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, AIS signals are sent by the two nodes on either ends of the cable cut on all the paths. Upon detecting an AIS, the 2:1 selector devices at all the nodes receiving the path signals make a switch to the protection signal if necessary. AIS is sent at the path level and is hence not examined by intermediate nodes. Reference [1] has a more detailed explanation of path protection restoration.

Restoration in ULSRs can be done in one of two ways. Both follow the automatic protection switching (APS) protocol using the K1 and K2 bytes of the LOH [9]. At the end of the restoration, the ring has loopbacks 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. Reference [5] explains the APS procedure in detail. 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. The difference lies in how the K1/K2 signals are sent.

In a 2-fiber BLSR, the recovery procedure also uses the APS scheme with two loopbacks occurring at the two OADMs on either side of the cable cut.

Following restoration after single fiber or cable cuts, the unidirectional rings and 4-fiber bidirectional ring continue supporting the same network throughput because an equal amount of protection bandwidth lies unused before the cut. A fiber cut is a cut of a single fiber, i.e., transmission in one direction between nodes is interrupted. We assume 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 Fig. 13, 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 Fig. 13. 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

\[
d = \frac{R}{(n - 1)}. \tag{8}
\]

When this demand is compared to the demand listed for the 2-fiber BLSR in Table 2, we see that the total demand carried before the fiber cut/restoration can continue to be carried after the cut, even when the worst case cut occurs (if a fiber between two nodes neither of which is the hub occurs, then the maximum number of demand pairs routed on a single fiber will be lower than with this worst case cut illustrated in Fig. 13). Only, if the ring has an even number of nodes and demand is not split, then before the cut, the pairwise demand supported is \( R/n \) (see Table 2), which will be less than the demand that can be supported after the cut.

To determine which link will experience the most load under the mesh traffic pattern, assume it is the link from node \( k \) to node \( k + 1 \) (see the linear network of Fig. 14). 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

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

EQ(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 $\frac{n+1}{2}$ to node $\left(\frac{n+1}{2} + 1\right)$ will have the maximum number of demand pairs in the left to right direction and for the opposite direction, the link from node $\frac{n+1}{2}$ to node $\left(\frac{n+1}{2} - 1\right)$ will have the maximum load. The maximum non-zero demand value is hence

$$d = \begin{cases} \frac{R}{n^2/4} & \text{n is even} \\ \frac{R}{(n^2-1)/4} & \text{n is odd} \end{cases}$$

EQ(10)

Similar to the centralized traffic pattern case, under the mesh traffic pattern, EQ(10) is almost the same as for the 2-fiber BLSR before the fiber cut (see 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.

In summary, if we ignore the demand non-splitting case, even with the 2-fiber BLSR, the network throughput supported after a fiber cut/restoration is the same as before the cut.
3. Reliable Packet Rings (RPR)

Reliable Packet Ring (RPR) solutions are being defined for the MAN application. The main intent of defining a new packet-switched protocol for MANs is that packet-switched networks support data traffic more efficiently than circuit-switched networks, such as SONET rings. This is because packet switches can accommodate changing traffic patterns better than circuit-switched networks that are operated in a provisioned mode. Before we compare RPR architectures with SONET rings under varying traffic patterns, we first describe an example RPR architecture and study the network throughput it can support following a fiber cut.

3.1 Description of an RPR architecture

We describe the Spatial Reuse Protocol (SRP) based RPR architecture proposed by Cisco [2]. In this solution, each node on the ring is a packet switch that examines packet headers to determine whether to “drop” the packet (at that node) or whether to forward it on the ring. It is a bidirectional dual counter-rotating ring. ARP is used for ring selection. The section about ring selection in [2] appears to be somewhat unclear. First, hashing on the destination address (which is all one’s for a broadcast address) is said to be used to decide on which ring to send an ARP request. Hashing on the same key (address of all ones) will always yield the same choice. Therefore it is unclear why hashing is needed here. Second, [2] suggests that when the ring is wrapped, if the destination is equidistant on the inner or outer rings, then hashing is used to determine which ring to use. But when the ring is wrapped, it becomes a linear network as in the case of a 2-fiber BLSR as shown in Fig. 14, and hence there is only one choice if the shortest path is to be chosen.

3.2 Computation of network throughput in an SRP ring

Assuming that the ARP procedure in combination with the topology map results in the shortest path (from a hop count point of view) being chosen for data packets, the network throughput of an SRP ring before a fiber cut is the same as that of a 4-fiber BLSR. The SRP ring, being bidirectional 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
After a fiber cut, the ring wraps around at the two edges of the cut using a procedure called IPS (Intelligent Protection Switching). 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

\[
T_{SRP} = \begin{cases} 
8R \frac{(n-1)}{(n+2)} & n: \text{E; demand: NS} \\
8R \frac{(n-1)}{n} & n: \text{E; demand: S} \\
8R \frac{n}{(n+1)} & n: \text{O; demand: D/C}
\end{cases} \tag{11}
\]

where the per node pair demand is given by EQ(10).

In summary, in SRP rings, the network throughput drops to half after a fiber cut/network restoration.

4. OPN (Optical Packet Node) based rings

4.1 Description of an OPN ring architecture

This OPN (Optical Packet Node) solution leverages recent advances in optical and data processing device technology for developing a new network architecture, called optical flow networking [3], which utilizes IP as the basic networking technology and re-configurable, multi-wavelength optics as the transport mechanism in a highly-integrated, single networking device. It combines IP router, Multi-Protocol Label Switching (MPLS) switch and WDM crossconnect functionality in one node.

OPNs are capable of routing IP packets as well as switching wavelengths, enabling single-hop or multi-hop add/drop optical flow topologies. As IP traffic changes or increases, existing lightpaths may be reconfigured or additional lightpaths may be created using the appropriate OPNs. Alternatively, existing Label Switched Paths (LSPs) can be reconfigured or additional LSPs may be created. In the instance of a fiber cut or node failure, OPNs detect and isolate the fault and redirect optical flows onto alternate lightpaths (pre-determined or dynamically selected) for minimal IP service disruption.

An OPN is comprised of packet processors (e.g. L3 packet classification, filtering, forwarding,
multi-class-per-flow queuing, label switching, packet-over-lightpath adaptation/de-adaptation), WDM transponders, photonic switching devices, WDM filters, variable optical attenuators and optical amplifiers. These components are integrated in a single unit chassis with common control and management. The OPNs may then be used to construct two-fiber ring physical network topologies with logical mesh lightpath connectivity.

In the OPN network, IP QoS is provided through the use of packet classification and policy control, bandwidth-guaranteed per-flow queuing, and traffic congestion control. With these capabilities, optical flows are created from end-user source packets with defined class of service (CoS) attributes or policies and delivered across lightpaths to destinations in the OPN subnet. The policies and CoS attributes are known throughout the subnet, so service performance and reliability is guaranteed.

Service protection may be provided at the packet level and/or optical level, depending on the service provider's network protection strategy and differentiated service requirements. For example, OPN network protection can be provided by both MPLS alternate rerouting and lightpath protection. Services may be protected by one method or the other (or un-protected) depending on the service provider's CoS offerings and end-users needs.

For this analysis, the throughput of the OPN ring network is compared before and after recovery from a bi-directional fiber cut. A transparent two-fiber WDM optical channel shared protection ring architecture is used for recovery. In this protection scheme, the ring supports WDM traffic with multiple wavelengths on two uni-directional fibers. In each fiber, the wavelengths are partitioned into two groups: one for working traffic and the other for protection. Although there are several wavelength allocation schemes, the one adopted here is that the same wavelength is used for the working and protection channels. This avoids the need for wavelength conversion for protection switching. Control links are established on a node-to-node basis for enabling real-time link fault detection, protection triggering, signaling, coordination and switching. Protection switching may be performed at nodes directly adjacent to the failure or at the end-nodes of the optical channel. The latter switching configuration avoids unnecessary loop-backs in adjacent-node switching, resulting in shorter protection paths.

4.2 Computation of network throughput in an Optical Packet Node (OPN) ring

For an OPN ring, the ring supports WDM traffic with multiple wavelengths (say \( k \) wavelengths) on each fiber. In each fiber, half of wavelengths (say \( \lambda_1, \lambda_2, \ldots, \lambda_{k/2} \) if \( k \) is divisible by two) are set for working traffic and the other half (say \( \lambda_{k/2+1}, \ldots, \lambda_k \)) is reserved for protection. Although there are several
wavelengths allocation schemes, same wavelengths are used for the working and protection channels because of avoiding the need for wavelength conversion for protection switching. It means that for example, if we set wavelengths of the working group as ‘\(\lambda_1\) and \(\lambda_2\)’ for one fiber, then we should set wavelengths of the protection group as ‘\(\lambda_1\) and \(\lambda_2\)’ for the other fiber. To make a consistent throughput comparison with previous analysis, we make a following assumption:

\[
R = \sum_{i=0}^{k} \lambda_i \quad \text{where} \quad k = \text{number of wavelengths support in each fiber}
\]

EQ(13)

For normal flow, the OPN with two fiber DWDM ring will support the same amount of throughput as a 4-fiber BLSR or SRP Ring case regardless of the traffic pattern because all the demands can be carried on different number of working wavelengths. For example, for the mesh traffic pattern:

\[
T_{OPN} = \begin{cases}
8R \frac{(n-1)}{(n+2)} & \text{n: E; demand: NS} \\
8R \frac{(n-1)}{n} & \text{n: E; demand: S} \\
8R \frac{n}{(n+1)} & \text{n: O; demand: D/C}
\end{cases}
\]

EQ(14)

After a cable cut, network throughput remains same by using unused protection wavelengths. From Fig. 15, after a cable cut, the transmitter from OPN 1 to 2 continues sending traffic on the working wavelengths \(\lambda_1, \lambda_2, \ldots, \lambda_{k/2}\). After wrapping occurs, the receiver at OPN 1 sends theses traffic on the protection wavelengths in an inner ring \((\lambda_1, \lambda_2, \ldots, \lambda_{k/2})\) from OPN 1 to OPN 5. At OPN 5, OPN 4 and OPN 3, those wavelengths bypass the electronic layer and then transmit to OPN 2. Similar restoration method occurs at OPN 2. One more thing to notice is that we can use path-level protection to avoid loop-backs in adjacent node switching.

5. Related work

Other analyses of SONET networks include analyses of rings with DCS (Digital CrossConnects) [10], interconnected rings [4], combinations of SONET and WDM rings [11] [12] [13], SONET and ATM networks [14], traffic grooming computations [15], design problems [16], comparison of service restoration times [17], and analysis of the Automatic Protection Switching (APS) protocol [18].

References


