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Multi-Rate and Multi-Hop Optical Carriers in WDM Ring *

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Abstract

Transparency of the optical layer offers the possibility to design a network that operates at varying transmission bit rates. While variable bit rate interfaces are being tested and will soon provide the possibility to optimally select the transmission rate for each lightpath, the potential advantages of relying upon multiple transmission rates in the optical network are ready yet to be fully explored.

In this paper we define the concept of Multi-hop and Multi-rate (M&M) network in which the tributary signal is transmitted over a sequence of lightpaths, with each lightpath operating at its own transmission rate, which is determined by a number of factors including the end node's interface, amount of multiplexed traffic and cost of the network components. The potential advantages provided by the M&M network when compared to first generation optical networks (i.e., SONET/SDH), single- and multi-hop (constant bit rate) optical networks, are discussed in general and demonstrated numerically in a WDM ring. Presented results show that the network cost reduction achieved by the M&M design is a function of the cost ratio between the optical bandwidth (wavelengths) and the optical terminals.

1 Introduction

Novel multimedia services available over the Internet daily attract additional users who demand high speed connections. In addition, to cope with the exponentially augmenting traffic demands, the capacity of optical backbone and metro networks require almost continuous upgrades. Consequently, transmission rates in public networks are generally driven by short term traffic demands that change over time and require cyclic network upgrades.

In conventional first generation optical networks, i.e., SONET/SDH transport networks, the network capacity may be augmented by either adding additional lines, or by increasing the transmission rate of the optical carrier. In both cases, the network upgrade may be cumbersome as it requires the homogeneous upgrade of all nodes within the selected sub-network, i.e., ring, even when the offered traffic grows only at few nodes.

In Wavelength Division Multiplexing (WDM) networks the line capacity may be increased using multiple channels orthogonally deployed across the fiber wavelengths. Beside increased fiber capacity, WDM technology offers ***optical transparency*** [1], i.e., the wavelength channel may optically by-pass (low speed) intermediate nodes. Optical transparency enables end nodes to communicate all-optically choosing the most appropriate modulation technique and transmission rate for their connection. In the paper, we

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will use the term ***lightpath*** [2] to indicate a path of light (on a chosen wavelength) between two nodes that need not be physically adjacent.

Various lightpath-based networks have been extensively studied in the literature [3, 4]. Two possible approaches are generally considered: single-hop optical network [3] and multi-hop optical network [4]. The two approaches are now briefly summarized when applied to a WDM ring architecture.

In a single-hop network, the tributary signal is transmitted from source to destination in one single optical hop. Lightpaths are thus established between end nodes to support the various traffic demands. When compared to a WDM first generation optical network, the single hop network requires less optical terminals[1] but may end up using more wavelengths because optical grooming of the traffic demands is not possible and demands that do not have same source-destination pair cannot share the same lightpath [5].

In a multi-hop network, the tributary signal is transmitted using a sequence of lightpaths, thus requiring multiple optical hops. Since hopping between lightpaths requires signal conversion to electronics at specific intermediate nodes, efficient multiplexing of traffic demands with distinct source-destination pairs is possible at these nodes [5, 6, 7, 8, 9]. When compared to a WDM first generation network, the multi-hop network requires less optical terminals. When compared to a single-hop network, the multi-hop network requires less wavelengths due to the more efficient lightpath bandwidth utilization. Solutions considered so far generally assume constant and uniform bit rate for all lightpaths.

Our paper defines the concept of Multi-hop and Multi-rate (M&M) network in which lightpath rates may vary depending on the traffic distribution and available optical terminals at the end nodes. As we will demonstrate, in the M&M network, optical transparency is fully deployed to yield cost effective and easily upgradable optical networks.

In M&M networks, cost effectiveness is consistently achieved by the unique combination of multi-hop and multi-rate transmission applied to the same network. Multi-hop transmission yields reduced optical terminals (electronics) while multi-rate transmission allows to efficiently use the wavelength bandwidth. Consequently, for most cost ratios between wavelength mileage and optical terminals, the M&M network yields tangible cost reductions when compared to all other network designs, i.e., first generation optical networks, single- and multi-hop (constant rate) networks.

Cyclic upgrades of the optical network is simplified in M&M networks. Due to the multi-rate transmission feature, only selected nodes in the network need to be upgraded with higher transmission rates, thus increasing the network capacity only where needed and without requiring the wasteful homogeneous sub-network upgrade that is mandatory in constant bit rate network designs. The cost for node equipment upgrade is thus limited, as low capacity traffic lightpaths can still use low transmission rates, requiring relatively inexpensive optical terminals. The proposed concept is consistent with an ongoing effort led by a DARPA-sponsored Bellcore consortium [10] in which Variable Bit Rate Interfaces are deployed to optimally select the transmission rate between optical nodes.

To demonstrate the network cost reduction achievable with M&M network a WDM ring is considered in this paper. The ring is chosen as it represents a widely used topology whose properties are well known, e.g., self-healing protection mechanism, and results are available for all described network designs, i.e, first generation optical networks, single- and multi-hop optical networks. A fast and efficient grooming algorithm is proposed in the paper to obtain sub-optimal solutions in polynomial time. For any given traffic distribution, the algorithm provides the traffic grooming, determines the required lightpaths and, for each lightpath, selects the optimal transmission rate. Performance comparison with the described existing network designs shows that the M&M network design yields significant cost reductions in terms of both optical terminals and wavelength mileage. Last but not least, the traffic in the M&M ring can be protected by means of optical self-healing protection mechanisms [11].

It must be noticed that the above mentioned advantages of M&M network design can be extended in general, and are not restricted to ring topologies.

[1]With optical terminal we indicate the interface between optical and electrical path layers.

2 The Multi-Rate Multi-Hop (M&M) WDM Ring

This section describes the architecture of the M&M ring. Figure 1 shows the architecture of the M&M

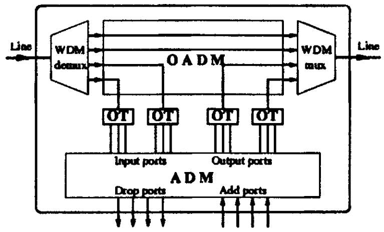


Figure 1: M&M node architecture

ring node. An Optical Add/Drop Multiplexers (OADM) demultiplexes the incoming wavelengths, and on each wavelength provides either by-pass optically transparent transmission or add/drop termination of the lightpath. Each dropped (added) wavelength is received (transmitted) by an Optical Terminal (OT) that feeds (is fed by) an electrical Add/Drop Multiplexer, ADM for short (Fig. 1). The bit rate of the Optical Terminal may vary between a minimum and a maximum value. For example, if SONET/SDH optical carriers are transmitted on the lightpaths, the OT bit rate may vary between OC-3 (155.52 Mb/ps) and OC-192 (10 Gb/ps). At the ADM the various tributary signals, e.g., STS-1s (51.84 Mb/ps), are demultiplexed to be handled individually. Electrical grooming of the STS-1s is performed in this module: low rate signals are multiplexed to form high speed aggregate traffic that can fully utilize the coarse bandwidth of one wavelength. Notice that individual low-speed electrical streams cannot be extracted from a wavelength without first converting the entire wavelength signal to electronics, thus requiring one OT.

In the M&M ring, different nodes may have different maximum and minimum OT rates. For example, two nodes may have OT maximum rate equal to OC-48, whereas the other nodes may have OT maximum rate equal to OC-12. The choice of the maximum rate for every node is made by the designer based on the offered traffic demands. In the paper we assume that this decision has been made already, and only optimal traffic grooming must be derived. The study of how the maximum speed for each node can be optimally selected is left to future study.

In the following section, we define the cost minimization problem in the M&M ring and we describe a fast and efficient grooming algorithm that computes sub-optimal solutions in polynomial time.

3 Optimal Design of M&M Ring

The cost of the M&M ring is determined by two factors: the fiber bandwidth and the node hardware required to transport the tributary signals. The bandwidth cost is assumed to be proportional to the total wavelength mileage. The node cost is assumed to be proportional to the transmission rate of each OT. The assumption is based on the observation that the optical hardware is designed to support transparent transmissions, and is a fixed cost in the network. On the other hand, the electrical hardware must be designed to operate at specific rates and its cost is somehow proportional to the rates of the lightpaths received or transmitted by the OTs[2].

It can be shown that the minimization of the wavelength cost does not necessarily lead to the minimization of the OT cost. Therefore, designing the M&M ring with overall minimum cost is not a trivial problem and requires a tradeoff solution between the above two cost factors.

In our definition of optimal M&M ring design problem, we assume that multiple tributary signals with common source-destination pair need not be groomed together on the same lightpath. The choice

[2] For example, in SONET/SDH network a often used assumption is that the line terminal cost doubles as the transmission rate quadruples.

to allow transmission of these tributary signals using different lightpaths makes the optimal grooming problem less complex and better exploits the wavelength coarse bandwidth [8].

We also assume that the ring is unidirectional. Thus, the routing of traffic demands is predetermined.

The M&M problem can be formalized as follows. Node i is assigned a minimum transmission rate $r_l(i)$ and a maximum transmission rate $r_u(i)$. For demonstration purpose, we assume that this rate bounds are represented, respectively, by the minimum and maximum SONET/SDH OC levels that the node can handle. The same concept can however be applied to other standard and non standard transmission rates.

Let $t_{s,d}$ be the number of tributary signals that need to be transmitted from node s to node d. For consistency with the previous assumption, $t_{s,d}$ represents the number of STS-1 exchanged by the node pair. Traffic needs not be symmetric nor uniform. Let c_{wvl} be the cost of one mile of wavelength and $c_{OT(OC-m)}(i)$ be the cost of an OT at node i operating at rate $OC-m$, with $r_l(i) \leq m \leq r_u(i)$. Let $l^m_{i,j}$ be the number of lightpaths from node i to node j transporting an $OC-m$ signal. The lightpath transmission rate, m, is limited by the end nodes' OT, i.e., $r_l(i,j) = \max(r_l(i), r_l(j)) \leq m \leq r_u(i,j) = \min(r_u(i), r_u(j))$. Each lightpath can carry up to m tributary signals, STS-1s.

The objective of the M&M problem is to select the set of lightpaths, $\{l^m_{i,j}\}$, with respective rates, m, that are sufficient to support the offered traffic demands, $\{t_{s,d}\}$, while minimizing the overall network cost:

$$\sum_{(i,j),m} l^m_{i,j} \cdot (d_{i,j} \cdot c_{wvl} + c_{OT(OC-m)}(i) + c_{OT(OC-m)}(j)) \tag{1}$$

where $d_{i,j}$ represent the $l^m_{i,j}$ mile length.

It is important to notice that the modeling framework defined for the M&M ring can serve also the purpose of modeling the other network designs reviewed in the introduction of the paper. In a WDM first generation network, for example, lightpaths can be established only between physically adjacent nodes. In a single-hop network any tributary signal must be transported by one lightpath only, i.e., $(i,j) = (s,d)\ \forall i,j$. In a constant (single) rate network, nodes make use of one transmission rate, i.e., $r_l(i) = r_u(j)\ \forall i,j$.

Given the complexity of the problem, the next section describes an heuristic algorithm designed to identify sub-optimal solutions in polynomial time.

3.1 Grooming Algorithm for Sub-Optimal M&M Ring Design

This section describes a "greedy" approach to minimizing the M&M ring cost whose complexity is polynomial in the number of nodes n and number of traffic demands $\sum_{s,d} t_{s,d}$.

The algorithm assigns tributary signals, or segments of tributary signals, to lightpaths using a Higher-Rate First, Longer-Lightpath First approach, hence the name HRF-LLF algorithm. A lightpath, $l_{i,j}$ is selected to exists only when its cost can be demonstrated to be unbeatable by the lower rate lightpaths capable of supporting the same set of tributary signals over the span of $l_{i,j}$. Grooming is achieved by sequentially applying two steps: first *homogeneous grooming*, i.e., only tributary signals with same (s,d) are groomed on the same lightpath, then *heterogeneous grooming*, i.e., any set of tributary signals may be groomed on the same lightpath.

A detailed description of the algorithm follows.

Let $m_u = \max_{(i,j)}(r_u(i,j))$ be the upper rate and $m_l = \min_{(i,j)}(r_l(i,j))$. be the lower rate of the network.

Let $L_{M\&M}$ be the multiset (each element may appear multiple times) of lightpaths used in the M&M ring design.

Let $L_m = \{l_{i,j} : r_l(i,j) \leq m \leq r_u(i,j)\}$, be a set of lightpaths sorted out by descending length, e.g., hop count.

Let T be the set of pairs (tributary signals ring link) not yet groomed by the algorithm. T is updated every time a new lightpath is added to $L_{M\&M}$.

Let g be a set of tributary signals that may be groomed together. Let $g - ho(T, l_{i,j}, m)$ be the function that returns the set of m tributary signals in T that may be homogeneously groomed on lightpath $l_{i,j}$ with transmission rate m. Let $g - he(T, l_{i,j}, m)$ be the function that returns a set of m (or less, if m are not available) tributary signals in T that may be heterogeneously groomed on lightpath $l_{i,j}$ with transmission rate m.

While grooming, tributary signals are selected using the following decreasing priority: 1) $s = i$ and $d = j$; 2) $s = i$ and $d \neq j$, or, $s \neq i$ and $d = j$; 4) $s \neq i$ and $d \neq j$. When $s \neq i$, let $r_u(i-) = \min(\max(r_u(n) : n = s, \ldots, i-1), r_u(i))$ ($r_l(i-) = \max(\min(r_l(n) : n = s, \ldots, i-1), r_l(i))$) be the highest (lowest) reception rate at i for the incoming (from s) tributary signals. When $d \neq j$, let $r_u(j+) = \min(\max(r_u(n) : n = j+1, \ldots, d), r_u(j))$ $r_l(j+) = \max(\min(r_l(n) : n = j+1, \ldots, d), r_l(j)))$ be the highest (lowest) transmission rate at j for the outgoing (to d) tributary signals. Let $cost(g, l_{i,j}, m)$ be the cost *estimated* for grooming g on $l_{i,j}$ with rate m.

The cost is given by (1) with an additional term that takes into account the cost of the (highest rate) OT(s) at node i (j) that is necessary to receive (transmit) the tributary signals in g, i.e., $(1 - \delta_{i,s}) \cdot c_{OT(OC-r_u(i-))}(i) + (1 - \delta_{j,d}) \cdot c_{OT(OC-r_u(j+))}(j)$, where $\delta_{x,y}$ is the Kronecker delta function. Let $cost'(g, l_{i,j}, m)$ be the cost *estimated* for grooming g tributary signals on the *span* of $l_{i,j}$ using lighpaths with rate m and maximal span between s and d that includes the $l_{i,j}$ span.

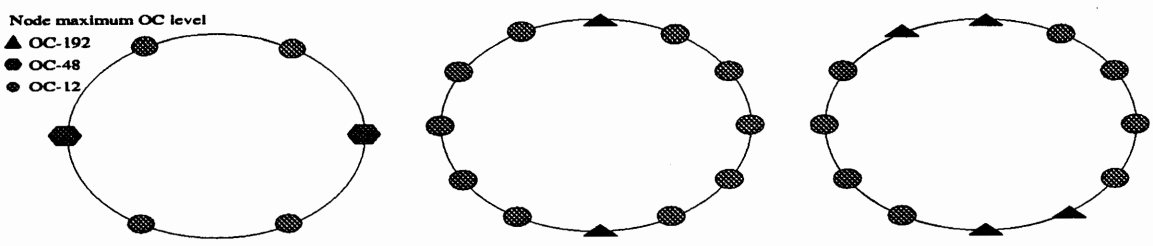
Notice that the maximal span lightpath is longer than $l_{i,j}$ when either $s \neq i$ and $r_l(i-) \leq m \leq r_u(i-)$, or, $d \neq j$ and $r_l(j+) \leq m \leq r_u(j+)$. The cost returned by function $cost'$ is the sum of two contributions: the cost of the lightpath(s) $l_{i,j}$ calculated as defined for function $cost$; and the cost for every lightpath other than $l_{i,j}$, defined as $d_{i,j} \cdot c_{wvl}$, i.e., only the bandwidth cost of the lighpath over the $l_{i,j}$ span.

```
L_M&M = empty;
Begin
  For m = m_u, m_u - 1, ..., m_l + 1, m_l
    For l_i,j in L_m
      Repeat
        g = g - ho(T, l_i,j, m);
        if cost(g, l_i,j, m) < cost'(g, l_i,j, m - 1)
          add l_i,j to L_M&M
      Until homogeneous grooming is completed
    Endfor
    For l_i,j in L_m
      Repeat
        g = g - he(T, l_i,j, m);
        if cost(g, l_i,j, m) < cost'(g, l_i,j, m - 1)
          add l_i,j to L_M&M
      Until heterogeneous grooming is completed
    Endfor
  Endfor
End
```

Numerical results obtained using the proposed greedy algorithm are discussed in the next section.

4 Results

In this section, we consider the numerical results obtained running some experiments on few WDM ring networks with the following assumptions. The traffic matrix is complete and uniform with k STS-1 tributary signals exchanged between each node pair. All links have length one. The OT cost doubles for a 4-fold growth of the capacity, i.e., $c_{OT(OC-4n)} = 2 \cdot c_{OT(OC-n)}$. To explore varying cost ratios between



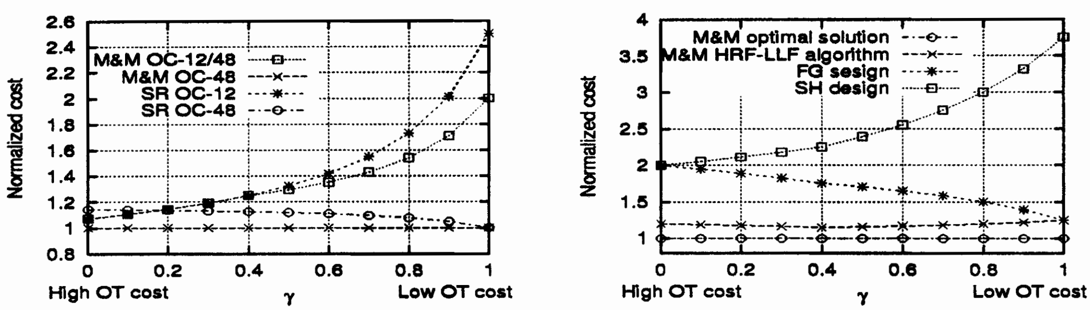
(a) (b) (c)

Figure 2: M&M ring networks

the optical bandwidth and the OT, we define the following parameter:

$$\gamma = \frac{c_{wvl}}{c_{OT(OC-3)} + c_{wvl}} \tag{2}$$

Parameter γ can take on $[0, 1]$ values. When $\gamma = 1$ the OT cost is negligible. When $\gamma = 0$ the wavelength cost is negligible. The other values represent intermediate cost ratios. Optimum solutions for the various network designs are obtained using an Integer Linear Problem (ILP) solver [12]. Figure 3(a) plots the

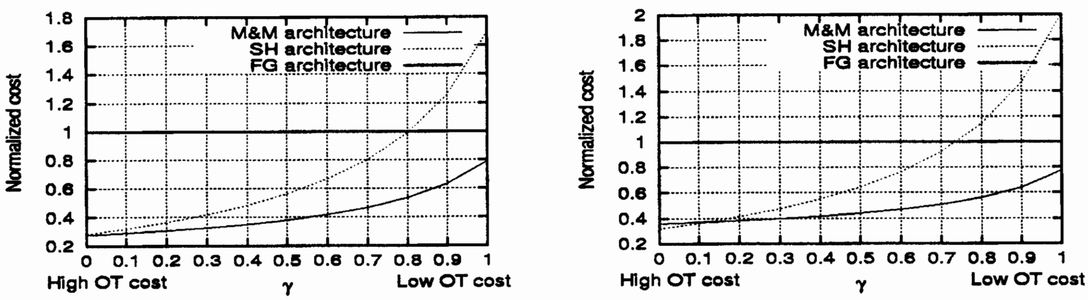


(a) (b)

Figure 3: Normalized network cost vs. γ, in a 6 ring network with traffic $k = 4$. (a): multi-hop ring perfomance comparison; (b): first generation, single-hop, and grooming algorithm performance comparison.

network cost versus γ for four multi-hop designs applied to a six node ring. Two multi-hop designs are constant bit rate designs:
SR design OC-12: $r_l(i) = r_u(i) = 12 \ \forall i$;
SR design OC-48: $r_l(i) = r_u(i) = 48 \ \forall i$.
The other two multi-hop designs are multi-rate designs: *M&M design OC-12/48*: $r_l(i) = 3$, $r_u(i) = 48 \ \forall i = 1, 4$, $r_l(i) = 3$, $r_u(i) = 12 \ \forall i = 2, 3, 5, 6$ design shown in Figure 2(a)) ;
M&M design OC-48: $r_l(i) = 3$, $r_u(i) = 48 \ \forall i$.
Network cost is normalized to the cost of M&M design OC-48. Traffic load is $k = 4$. As expected, M&M design OC-48 always provides the minimum network cost. Even with only two nodes operating at OC-48, M&M design OC-12/48 is better than SR design OC-12 for $\gamma > 0.4$ and better than SR design OC-48 for $\gamma < 0.2$.

In Figure 3(b) four solutions are compared for M&M design OC-12/48: *M&M optimal solution* minimum cost;
M&M HRF-LLF algorithm using the HRF-LLF algorithm;
FG design: First Generation optical ring;
SH design: optical Single-Hop ring.
The minimum cost of M&M design OC-12/48 is about half the cost of FG design, and one third of the SH design cost. Notice that the M&M design is better than FG design even when γ equals to one (i.e., only wavelength cost is relevant). This counter intuitive result is due to the high transmission rates between non-adjacent nodes allowed by the optical transparency. The cost of SH design is not competitive in this ring configuration due to the inefficent use of the wavelength coarse bandwidth. Compared to the optimum, the solution achieved by the HRF-LLF algorithm has got 20% higher cost. Figures 4 plot



(a) (b)

Figure 4: Normalized cost of M&M heuristic algorithm and FG and SH architecture versus γ for $k = 7$, in 12 node ring with Architecture 2-10 (a) (Fig 2(b)) and Architecture 4-8 (b) (Fig. 2(c))

the network cost versus γ for two possible architectures applied to a twelve node ring : *Architecture 2-10*: $r_l(i) = 3,\ r_u(i) = 192 \forall i = 1, 7,\ r_l(i) = 3,\ r_u(i) = 12 \forall i = 2, 3, 4, 5, 6, 8, 9, 10, 11, 12$ in Figure 2(b); *Architecture 4-8*: $r_l(i) = 3,\ r_u(i) = 192 \forall i = 1, 2, 7, 8,\ r_l(i) = 3,\ r_u(i) = 12 \forall i = 3, 4, 5, 6, 9, 10, 11, 12$ in Figure 2(c). Traffic is $k = 7$. Network cost is normalized to the cost of Fg. We first compare the two designs: FG and SH. For small values of γ SH design is better than FG design. For large values of γ FG design becomes more inexpensive due to the fact that the relative cost of the OTs is negligible when compared to the bandwidth cost, thus efficient grooming becomes essential. In architecture 4-8, FG design provides slightly better results as it can take advantage of the adjacent positions of two high speed nodes.

The cost reduction of the M&M approach (using the HRF-LLF algorithm) over the FG and SH designs is clearly documented by the curves. For same values of γ the SH design is however slightly more inexpensive than the M&M design cause the HRF-LLF algorithm is not optimum.

5 Summary

The paper introduced the concept of Multi-hop and Multi-rate (M&M) optical network, in which the tributary signal is transported from the source to the destination through a sequence of lightpaths. Every lightpath's transmission rate is optimally selected to minimize the overall network cost. The advantage offered by the M&M network is twofold. First, the transmission capability of each node is individually determined based on the traffic distribution, as opposed to the conventional constant bit rate network in which all nodes in a sub-network, e.g., a SONET/SDH ring, must transmit at the same rate. This characteristic makes M&M networks simple to upgrade and ideal for cyclic network planning. Second, by relying upon a fast and efficient grooming algorithm, it was demonstrated that in a M&M ring the overall network cost can be significantly reduced when compared to other existing network designs, including

WDM first generation optical networks, single- and multi-hop optical networks. Numerical results showed that under uniform traffic distribution, the proposed solution yields significant cost reduction for a variety of cost ratios between wavelength mileage and optical terminal. The cost reduction is expected to be even more significant in presence of non-uniform and asymmetric traffic demands. To the best of our knowledge, this is the first time that optical transparency is quantitatively demonstrated to yield a reduction of the network wavelength mileage.

By virtue of its optical transparency, M&M ring survivability to network faults is achievable using optical self-healing protection mechanisms.

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