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Survivable Optical Broadcast-and-Select Network with Centralized Multi-Carrier Light Source

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Abstract-**This paper presents a survivable optical broadcast-and-select network architecture with centralized multi-carrier light source for regional or metro-core network applications. A large number of optical carriers generated by the single multi-carrier light source are shared and utilized by all edge nodes of the regional network through dynamic wavelength/waveband broadcast and select. The design of this network architecture aims to reduce network cost and increase network survivability. Combined with optical couplers and 1 × 2 optical switches based protection architecture, the proposed network enables a fast failure-recovery scheme design. It recovers the network from different fiber cut failures in a fast and cost-effective way. The recovery time analysis and calculations under different situations are carried out to evaluate the performance of the proposed failure-recovery scheme. Results show that the recovery time is largely impacted by the switching time of 1 × 2 optical switches and it is small enough to meet the standard 50 ms requirements with 1ms switches.**

I. INTRODUCTION

Photonic network using wavelength division multiplexing (WDM) technology is one of the most promising solutions to meet the large bandwidth requirements of dramatically increasing internet traffic nowadays. With the development of WDM technology, over-1000-channel ultra-dense WDM transmission by using single super continuum multi-carrier source (SC-MCS) was demonstrated in the field experiment [1]. Moreover, it was reported that over 10,000 optical carriers with uniform channel spacing of 2.5GHz were successfully generated from SC-MCS with two super continuum (SC) conversion sections [2]. By optimization of SC source and utilization of optical amplifiers, it is believed that more than 10,000 channels can be realized for DWDM systems. How to efficiently utilize this kind of multi-carrier light source technology to design future super DWDM networks remains to be an open question.

Regional networks, also named as metro-core networks or feeder networks [3], aggregate high tributary traffic (eg. 2.5Gbps or 10 Gbps) collected from access networks and send them to backbone networks or the other access networks. There are two important regional network technologies nowadays. One is synchronous optical network/synchronous digital hierarchy (SONET/SDH). It is based on time division multiplexing (TDM) technology, and is not suitable and economical for bursty data traffic. The other one is reconfigurable optical add and drop multiplexer (ROADM) based networks. It enables dynamic wavelength add and drop at each edge node, and therefore provides flexibility and reconfigurability in the optical layer. Combined with generalized multi-protocol label switching (GMPLS) based control plane technology, ROADM network is a potential solution to regional networks [4], but network cost is high.

This paper proposes a survivable optical broadcast-and-select network architecture with centralized multi-carrier light source in order to reduce network cost and increase network survivability. A large number of optical carriers generated by the multi-carrier light source are distributed to all edge nodes for dynamic selection based on their dynamic bandwidth requirements. In this way, the proposed network achieves the same optical layer flexibility and reconfigurability as ROADM network but with lower network cost of optical transmitters, power consumptions, and network maintenance and so on. Network survivability is one of the most important factors for optical network architecture design because even a single fiber cut may result in great information loss (e.g. Tb/s). And therefore, fast failure-recovery scheme is indispensable for any survivable network. This paper also presents the optical couplers and 1 × 2 optical switches based protection architecture and a fast failure-recovery scheme based on it for the proposed network. The recovery time analysis and calculation results show that it is fast and efficient.

The rest of the paper is organized as follows: section II introduces the proposed network architecture, providing the details of network topology, node architectures, media access control (MAC) protocol, and network features; section III describes the proposed protection architecture and failure-recovery scheme for the network. Recovery time analysis and calculations are also presented to evaluate its performance; section IV concludes the research work.

II. NETWORK ARCHITECTURE

A. *Network Topology*

Our proposed network architecture has an overlay star-ring fiber network topology. There are two regional nodes (RN): RNs and RNr in the regional network for connecting it to the backbone network. RNs connects each edge node (EN) in a star topology while RNr is connected with them in a ring topology, as illustrated in Fig. 1. Both RNs and RNr are connected to two point of presence (PoP) of backbone network for protection purpose. Multi-carrier light source is placed at both RNs and RNr for backup purpose. One important feature of the proposed network architecture is to broadcast the generated optical carriers/wavelengths to all EN for selection and the star topology is used to implement it.

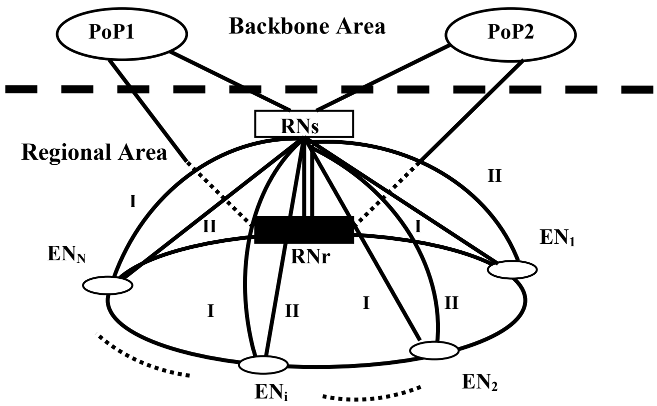

Figure 1. Proposed star-ring fiber network topology

There are two fibers: Fiber I and Fiber II connecting RNs with each EN. Fiber I is used for optical carriers/ wavelength broadcast while Fiber II is used for data transmission and receiving. Using star part network for data transmission and receiving enables simple network routing and control. On the other side, ring part network is used for network control and protection. Detailed fiber connections and configurations of ring part network will be described in next section.

B. *Node Architectures*

The RNs has three major function modules. First part is for wavelengths generation and broadcast. It generates a large number of wavelengths by multi-carrier light source and broadcasts them to all EN by optical coupler. Second one is waveband cross connect (WBX). WBX performs de-multiplexing, switching and multiplexing of modulated wavelength/waveband according to their different destinations. Third part is RNs overall controller. It controls the multi-carrier light source and performs configuration of WBX. One possible implementation of RNs is shown in Fig. 2.

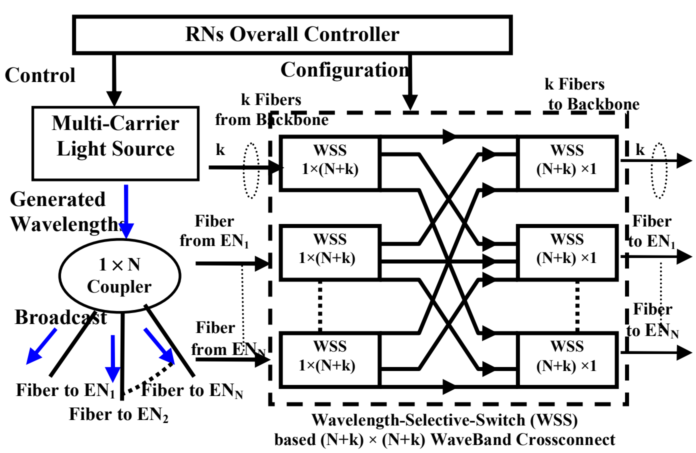

Figure 2. Scalable type RNs architecture

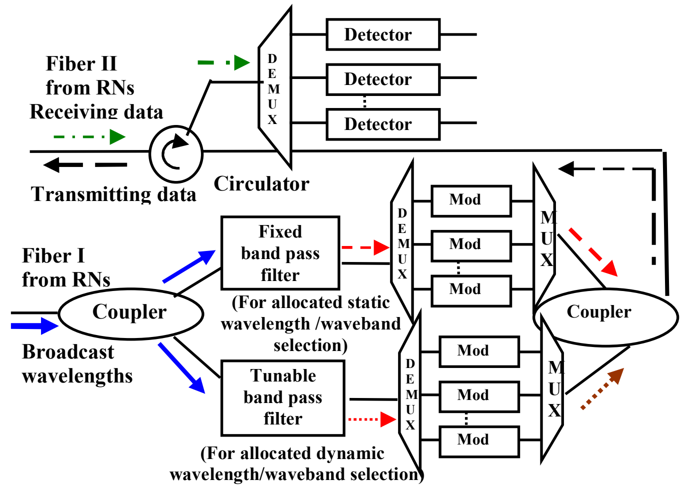

Figure 3. EN main architecture

Compared with RNs, EN is relatively simple and its main functions include: wavelength/waveband selection and modulation, data transmission and receiving. The detailed main EN architecture is shown in Fig. 3. Incoming broadcast wavelengths from Fiber I are duplicated by coupler first. Then the fixed and tunable band pass filters select the allocated static and dynamic wavelength/waveband respectively. After that, wavelength de-multiplexing and modulation are performed separately. Finally, modulated wavelengths are combined together by optical coupler and are sent back to RNs. EN bidirectional data transmission and receiving are enabled by optical circulator.

C. *Media Access Control Protocol*

Reservation based MAC protocol is implemented at RNr for dynamic network resource (e.g. wavelengths/waveband) allocation while avoiding contention. Control frame issued from RNr collects bandwidth requirement information of each EN in its first loop in the network. Then RNr performs wavelength/waveband allocation according to the reservation information. After that control frame loops in the network again, and each EN performs node configuration according to the allocation information. In order to meet the dynamic traffic requirements of each EN and meanwhile reduce its cost, a hybrid static-dynamic wavelength/waveband allocation scheme was proposed [5]. Each EN has its own fixed allocated wavelengths according to their observed mean traffic volumes. Wavelengths in the common wavelength pool are shared by all EN and allocated to them dynamically according to their dynamic traffic situations. In this way, the wavelength /waveband selection process at each EN is simplified and the network cost is reduced. When allocating the wavelength, traffic grooming and waveband technologies are used to reduce the number of used optical switching ports at RNs. Those interested in it can find the details in [5].

D. Features of Proposed Network Architecture

The proposed network architecture exhibits some interesting and unique features when compared with traditional regional network architectures such as SONET/SDH and ROADM networks.

First of all, all EN in the same regional network share the centralized multi-carrier light source through optical broadcast and select. In this way, each EN can access more wavelengths without increasing the number of optical transmitters and the total transmitter cost is greatly reduced. And therefore, lower bit rate transmission can be deployed while maintain the same network capacity as traditional ones. As we all know, lower bit rate transmission is less susceptible to physical impairments such as chromatic dispersion, polarization mode dispersion, and nonlinear effects. At the same time, as there is only one working multi-carrier light source, the power consumption is much smaller than traditional ones and the maintenance cost is also minimized.

Secondly, hybrid static-dynamic wavelength/waveband allocation based MAC protocol can meet the dynamic traffic requirements. Especially, using waveband switching decreases the number of used optical switching ports of RNs and also simplifies EN architecture.

Thirdly, star part network is used for data transmission and receiving. Minimum hop distance and simple network routing make the network efficient and simple. In addition, star topology is also a good choice for wavelength broadcast.

Finally, network control and protection are performed in ring part network, which enables the proposed network to recover from different fiber cut failures in a fast and simple way. It is to be described in details in next section.

III. PROTECTION ARCHITECTURE AND FAILURE-RECOVERY SCHEME

Because photonic networks can potentially carry the tremendous amount of data, it is imperative for them to resolve their reliability and survivability issues in advance. Failures such as fiber cuts, equipment failure can happen because of construction work, natural disasters, human errors or hardware/software breakdown. And therefore, survivable network architecture is required to have the capabilities to quickly detect, isolate, and recover from a failure. Failure-recovery is to reestablish traffic continuity in case of a failure event affecting the traffic, by rerouting the signals on diverse facilities after the failure [6]. As in the proposed network, both RN and EN are dual-homed, and multi-carrier light source also has a backup, so fiber cut failure is the main focus, especially the star part working fibers.

A. Optical Protection Architecture

To cope with the fiber cut failure, an optical protection architecture based on optical couplers and 1 × 2 optical switches is proposed, as shown in Fig. 4. The protection architecture determines the fiber connection configuration of EN according to different situations by switching the 1 × 2 optical switches. Thanks to the splitting and combining functions of optical couplers and the broadcast capability of the network architecture, it can recover the single and multiple fiber cut failures. Under normal network situations, all 1 × 2 optical switches are switched to port 1. Optical couplers C2 and C4 of each EN are connected into two separate fiber rings. Switch B and D are in the fiber ring, while A and C are outside.

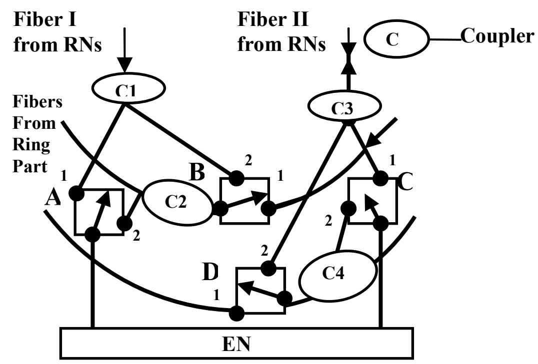

Figure 4. Optical protection architecture

B. Failure-Recovery Scheme

Fibers in the working star part network are divided into two types: Fiber I and Fiber II, by their different functions as mentioned above. As one cable may carry many optical fibers and the destruction of one cable can result in multiple fiber failures, which is the common situation in real networks. In the proposed network, one cable cut means hybrid Fiber I and Fiber II failures. In order to explain the proposed failure-recovery scheme more clearly, we analyze both single and multiple fiber failure situations. Recovery operation of single fiber cut failure is the basic operation for any complex multiple fiber failures. Table 1 summarizes the typical fiber cut failure situations and their respective protection methods and recovery operations.

Table.1 Summary of typical failure types and their recovery scheme

Failure Type	Protection Method	Main Recovery Operations					
		Node	Switch	A	B	C	D
Single Fiber I Failure	Neighbor Protection	ENr	Port	1	2	1	1
		ENf	Port	2	1	1	1
Single Fiber II Failure	Neighbor Protection	ENl	Port	1	1	1	2
		ENf	Port	1	1	2	1
Multiple Failures/ Hybrid Fiber I & II Failures	Cluster Protection	ENcr	Port	1	2	1	2
		ENcl	Port	1	2	1	2
		All ENf	Port	2	1	2	1

For single Fiber I or Fiber II failure, the right side neighbor ENr or the left side neighbor ENl of failure happening ENf is used for protection and recovery, as shown in Fig. 5. For single Fiber I failure, B switch of ENr is turned to port 2, while ENf switches its A switch to port 2. In this way, broadcast wavelengths to ENr can also go through the ring part fiber to ENf, and the recovered wavelength broadcast route is shown in

Fig. 6. For single Fiber II failure, detailed operations include: C switch of ENf and D switch of ENl are both turned to port 2. In this way, the transmitted data of ENf goes through ring part fiber to ENl, combined with transmitted data of ENl by optical coupler and then sent to RNs. The receiving data of ENf and ENl both go through the Fiber II of ENl and duplicated by the coupler. Each of them just selects their own data respectively, ENl from the star part fiber, and ENf from the ring part fiber as shown in Fig. 7.

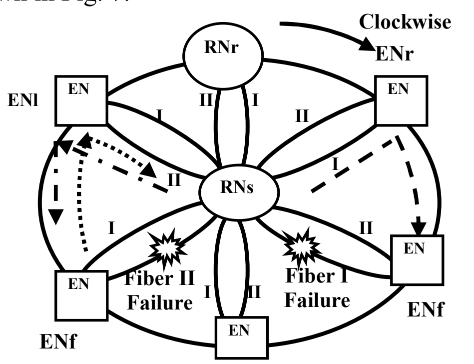

Figure 5. Neighbor protection and restoration for single fiber failure

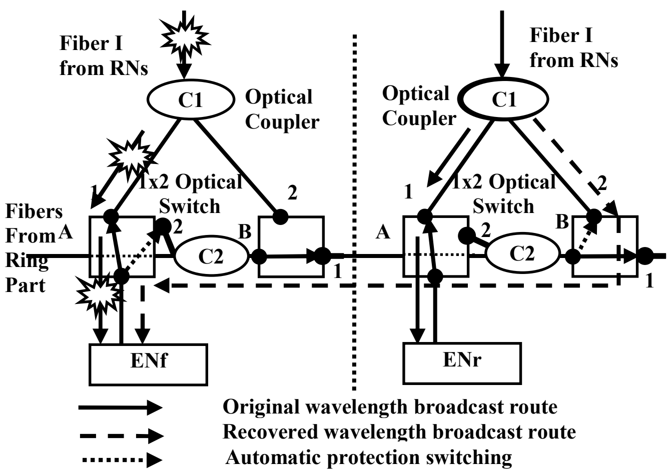

Figure 6. Single Fiber I failure and its recovery route

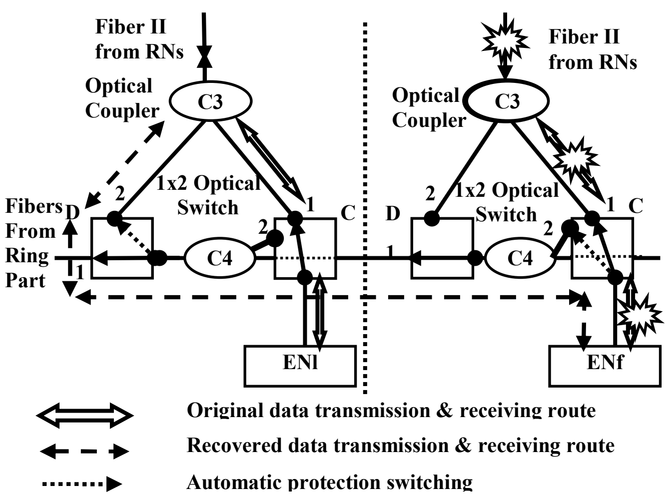

Figure 7. Single Fiber II failure and its recovery route

For multiple fiber failures or hybrid Fiber I and Fiber II failures, which may happen because of single or multiple cable cuts, cluster protection and restoration method are used. First step is to choose cluster area, which should cover all ENf, and its two edge EN: ENcr and ENcl should have no failure. All ENf switch their fiber connections to ring part network, while B and D switches of ENcr and of ENcl are all switched to port 2. In this way, traffic can be deflected and recovered through ring part network, as shown in Fig. 8.

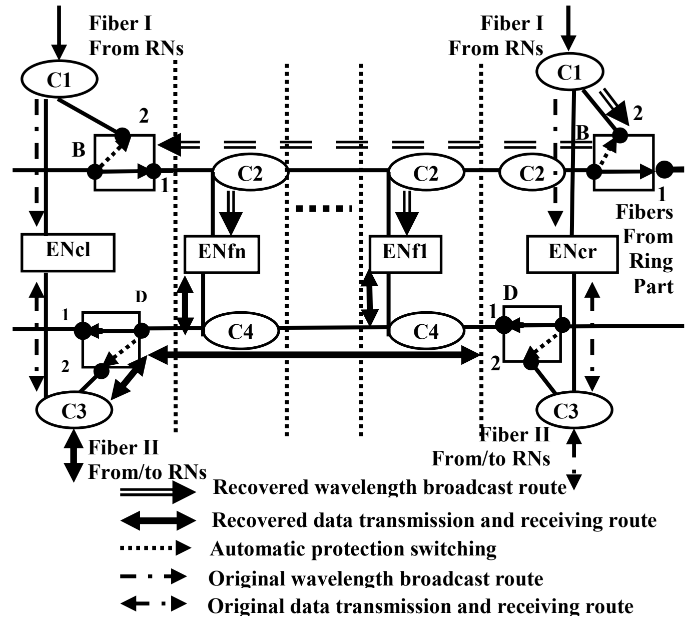

Figure 8. Multiple fiber failures and their recovery routes

C. *Performance Evaluation*

In order to evaluate the proposed failure-recovery scheme, recovery time analysis and calculations are performed under different network parameters. The whole recovery procedure is as follows: Once the fiber cut failure happens, EN detects it by loss of light/signal and writes the failure message into the control frame. Then control frame is sent to RNr through ring part network. RNr decides the protection and restoration method according to failure types, and writes the configuration information for failure recovery into the control frame. It loops in the network again. All recovery-involving EN perform configuration and switching according to the information. After that, affected wavelength broadcast route and traffic route are changed to the recovered ones.

The failure recovery time *Tr* consists of: EN fiber failure detection time, failure signifying time, and recovery configuration time, which further includes: control frame propagation time, switch control time and switching time. Several important factors affecting *Tr* are as follows:

- *N*: number of EN in the regional network
- *Tp*: propagation time between two adjacent EN
- *Td*: EN fiber failure detection time
- *L*: fiber span length of two adjacent EN
- *Ts*: switching time of 1×2 optical switches

- *Tc*: control time of 1×2 optical switches
- *n*: number of EN that has hybrid Fiber I and II failures

Then *Tr* is calculated by the following equation:

$$Tr = n \times Td + 2(N+1)Tp + (n+2) \times 2(Tc + Ts) \qquad (1)$$

Single cable cut is most likely to happen in real networks. It usually results in hybrid Fiber I and Fiber II failures of one EN. Although *n* EN has the same failure at same time may happen, the chance is very small, and therefore in calculation, single failure is especially considered ($n = 1$). Here we assume that the fiber span length is uniformly distributed and if we find the maximum *Tp*, then the calculated *Tr* is the upper bound of failure recovery time. From practical perspective, we assume $Td = 1ms, Tc = 0.1ms$ in calculation, trying to identify the most suitable devices to be used. A reference network model, which has 10 EN, spaced at 10km, and switching time is 1ms, has been chosen in the calculation. Calculations were performed under varying network parameters (*Tp* or *L*, *Ts* and *N*), aiming at testing different aspects of the proposed failure-recovery scheme. Results are shown in Fig. 9 and Fig. 10, respectively:

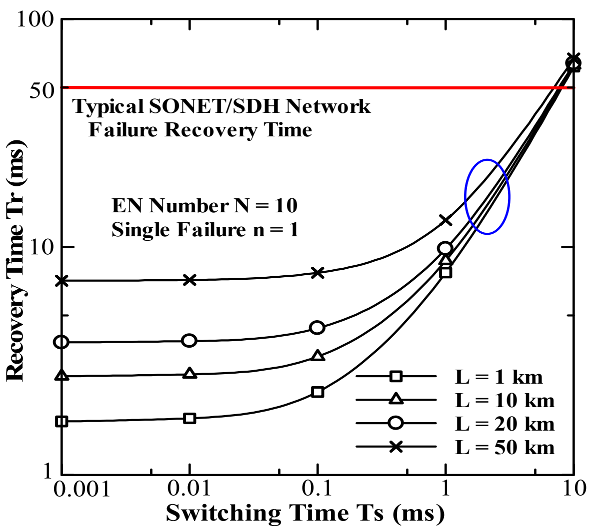

Figure 9. Recovery time vs. switching time and span length

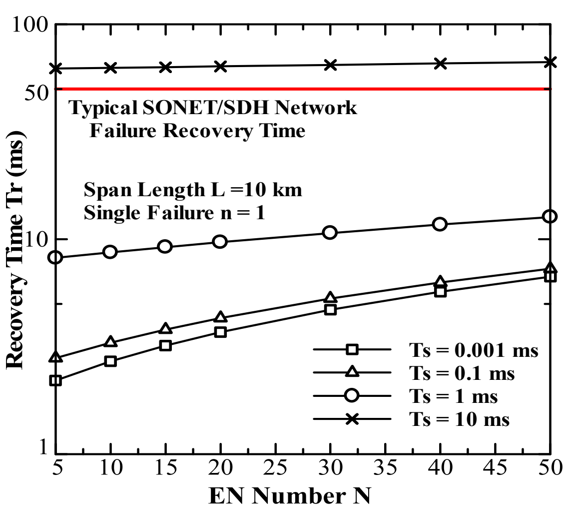

Figure 10. Recovery time vs. EN number and switching time

Fig. 9 shows that when *Ts* is much smaller (less than 0.1ms) compared with *Tp*, the fiber span length *L* dominates the recovery time *Tr*. As *L* increases, *Tr* also increases proportionally but it is around 10ms. When *Ts* is larger than 1ms, *Ts* dominates the *Tr*, and *L* has very small impact on *Tr*. When *Ts* is larger than 10ms, *Tr* is lager than 50ms, which is a typical failure recovery time in current SONET/SDH networks.

The impact of number of EN *N* on recovery time *Tr* is also considered. In other words, this can be seen as the scalability of the proposed failure-recovery scheme. As *Ts* has an important impact on *Tr*, we consider 4 typical optical switches of different switching times and plot *Tr* when increasing the number of EN. As shown in Fig.10, when *Ts* is lower than 1ms, *Tr* increases very slowly with the increasing of *N* and *Tr* is around 10ms. But, when *Ts* is larger than 10ms, even in 5 EN network, the *Tr* is larger than 50ms. It shows that this kind of slow switches can not be used in the proposed scheme.

IV. Conclusion

This paper proposes a survivable optical broadcast-and-select network architecture with centralized multi-carrier light source. The unique features of the proposed network architecture enable cost-effective network design with high network survivability. Optical couplers and 1×2 optical switches based protection architecture combined with the failure-recovery scheme enable the proposed network to survive from different working fiber cut failures. The switching time of 1×2 optical switches has an important impact on the recovery time. Numerical results under different networking parameters show that when the switching time is less than 1ms, the recovery time is around 10ms, which is small enough for most applications.

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