Fiber Fault Management and Protection Solution for Ring-and-Spur WDM/TDM Long-Reach PON

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Abstract—**In this paper, a network fault management and protection system for the ring-and-spur long-reach passive optical network (LR-PON) is proposed. We exploit an adapted, enhanced performance, and inexpensive passive optical components in the field and electronic switches in the central office (CO). Our system allows detecting and localizing not only faulty segments but also faulty nodes, hence alleviating the false alarm probability encountered in previous systems. We show that using ring duplication protection in LR-PON can save half the cost compared to full duplication protection with relatively high reliability performance (99.972%). We describe the implementation strategy of our system in several well known metro network topologies including: (1) single ring, (2) double ring and (3) double fiber pair based ring. The architecture of the remote nodes and the central office is described in addition to the appropriate placement of the passive monitoring devices. We derive an expression for the upper bound notification and recovery times. Moreover, we found that our system can recover from a fault in about 0.5ms as an upper bound.**

Keywords-Long-reach PON; fault management; protection; network reliability; optical encoder; recovery time.

I. INTRODUCTION

Long-Reach Passive Optical Network (LR-PON), has been proposed as a cost-effective solution for next generation broadband optical access network. LR-PON extends the PONs coverage from the traditional 20km span to 100km and beyond. Fig. 1 illustrates the general architecture of the WDM/TDM LR-PON proposed by some demonstrations, so called ring-and-spur topology [1]. The network consists of the ring section which interconnects the optical line terminal (OLT) in the central office (CO) to a number of remote nodes (RNs) by optical fibers; and the access section that runs from the RN to the optical network units (ONUs) through the power splitter/combiner (PSC).

The downstream data in the waveband Λ_D, (example, C band) is transmitted from the CO in the counter clockwise direction. At RN_i, Λ_i sub-waveband that may include one or many wavelengths is de-multiplexed and dropped to the access network. The upstream sub-waveband from the access network will be added and multiplexed in RN_i and then transmitted in the counter clockwise direction.

Any fault in the network physical layer especially the ring will cause high data loss, customer dissatisfaction and complaints. Hence, an efficient management system for fault detection and protection is highly required. Network survivability has attracted more attention over the recent few years. Most of the conventional approaches of fault management in optical networks rely on diagnosis in higher layers, based on the status reports collected from various checkpoints on the managed optical networks. However, this would impose excessive overhead in the network signaling as well as in the network management system (NMS). It is recommended that fault detection takes place at the layer closest to the fault (physical layer) in optical networks [2]. This facilitates the network protection and restoration.

In this paper, we propose a management and protection system that uses passive components in the field. This system can identify and localize a fault in the ring and then notify the CO to initiate the protection process. Compared to previous approaches in [3-4] that uses active components in the RN, our system uses passive components for the monitoring. Hence it reduces the capital expenditure (CapEx) and operational expenditure (OpEx). Using passive components in the field to protect the ring failure is reported in [5-6]. These approaches detect a fault based on monitoring the upstream data wavelengths in the CO. However, this reported detection can lead to a false alarm. For example, a fault in RN_i will cause loss for upstream sub-waveband Λ_i from RN_i. When the CO detects this miss, it interprets this as a fault in the ring segment between RN_i and RN_{i+1}. This leads to wrongly activate the protection mechanism, hence increasing the OpEx by

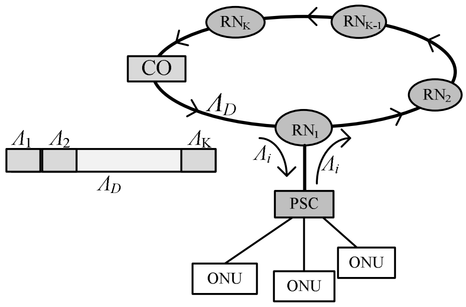

Figure 1. Ring-and-spur LR-PON architecture.

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dispatching technicians to fix a fault in the wrong location. Our proposed system overcomes this issue by monitoring also the RNs, not only the ring segments.

In Section II, we study the network reliability performance versus cost and show that ring duplication protection has high reliability performance with lower cost. Hence we focus on this topology in Section III and IV, where we respectively describe different ring protection architectures and our NMS proposal. Fault notification and recovery times are investigated in Section V and we conclude in Section VI.

II. NETWORK RELIABILITY AND COST

Any network management and protection system should take into account two critical factors: level of service reliability and network cost. Fig. 2 shows the reliability model illustrated by reliability block diagrams (RBDs) derived from the WDM/TDM LR-PON shown in Fig. 1. RBD is a graphical representation of the system reliability architecture. It is a representation method for the effects of all possible configurations of functioning and failed components in the system. Fig. 2(a) shows the basic network RBD without protection. The RBD includes all the optical components and devices in the signal path from the CO to the ONU. This includes the OLT, ring fiber (RF), arrayed waveguide grating (AWG) in the RNs, distribution fiber (DF) from the RN to the PSC, PSC, drop fiber (DRF) from the PSC to the ONU and the ONU. Each component or device is represented by a box. Access network duplication RBD is similar to Fig. 2(b) but the access part is duplicated and an optical switch (OS) is used to select between one of the two access networks. Ring duplication RBD is shown in Fig. 2(b) where two synchronous OSs are used to route the data on one of the two rings. Full duplication RBD is similar to Fig. 2(b) but with OLT and access section duplication. A failure occurs only when the connection (path) between the OLT and the ONU is interrupted due to the failure of system components in this path. The system is working when there is at least one path runs from the OLT to the ONU. The unavailability of a component i (U_i) corresponds to the probability that the component i is failed which is given as

$$U_i = 1 - \frac{MTBF}{MTBF + MTTR} \tag{1}$$

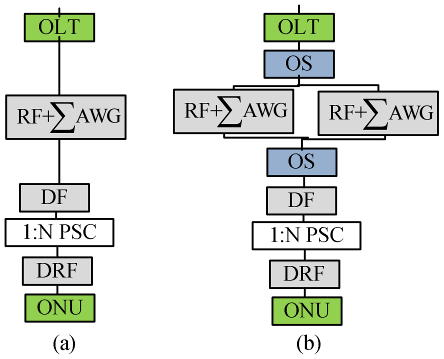

Figure 2. RBD for different LR-PON protection architectures.

where MTBF is the mean time between failures and MTTR is the mean time to repair. The component i availability is $A_i = 1 - U_i$. Hence the full system availability is given as

$$A = 1 - \sum_{i=1}^{n} U_i \tag{2}$$

where n is the number of components in the path.

A detailed description of the system components' unavailability and cost obtained from [7] is given in Table 1 where N denotes the number of ONUs in each access network connected to RN. We assume that the ring length is 100km. Moreover, we consider there are 32 RNs with 32 ONUs in each TDM access network and we calculate the unavailability for an ONU connected to the middle of the network, i.e. connected to RN_{16}. The deployment scenario that is considered here is a dense populated area (collective). In this scenario DF and DRF are 19.5 and 0.5km long respectively. Our results for the different architectures are shown in Table 2. It is shown that the total network cost of no-duplication is about 9.312$ millions with 99.904% reliability. The access-region duplication cost is close to the full-duplication cost (17.8$ millions), but the reliability is just 99.932% compared to 99.9997% for the full duplication. However the metro-ring duplication has relatively high availability, 99.972%, and the cost is slightly higher than that of the no-duplication architecture (10.07$ millions). Hence, it is clear that half the cost can be saved with high reliability performance if only ring duplication protection is used.

III. METRO RING BASED LR-PON PROTECTION ARCHITECTURES

Different widely used ring protection architectures exits in metro ring networks. Any deployment of LR-PON needs to consider the specific constraint to each of these architectures. Consequently, an appropriate NMS should take into account most of or all these architectures in order to detect, localize the fault and then recover the network. In this section, we describe the key metro ring architectures. The NMS will be addressed in section IV.

A. Single Bidirectional Ring Protection

In this architecture, only one bidirectional ring is used for the downstream and upstream data signals. In normal mode (no fault), the downstream signals are transmitted through the west as shown in Fig. 3(a). At each RN, a sub-waveband is dropped. The upstream from the access network is transmitted in both directions of the ring by the 3dB PSC shown in Fig. 3(b). Hence, the 3dB PSC provides a protection function, so that up/down-stream data signals can be received either from west or east. The monitoring waveband (Λ_m) bypasses the RN as shown in Fig. 3(b) by using wavelength selectors (WSs). At the CO, the upstream signals from the east are chosen by switches shown in Fig. 3(c) whereas the upstream signals from the west are neglected. The circulators in Fig. 3(c) are used to route the downstream data signals to the

TABLE 1
COMPONENT UNAVAILABILITY AND COST [7]

COMPONENTS/DEVICES	UNAVAILABILITY	COST($)
OLT(WDM PON) 3.2Gbps	5.12E-07	40,000
ONU (TDM PON)	1.54E-06	350
1:*N* splitter	7.20E-07	800
Optical switch	1.20E-06	100
AWG	1.20E-6	1200
Fiber (/km)	1.37E-05	160
Burying Fibers (/km)	---	7000

TABLE 2
UNAVAILABILITY AND COST FOR LR-PON PROTECTION ARCHITECTURES

PROTECTION TYPE	UNAVAILABILITY	TOTAL COST ($)	COST/ONU ($)
No protection	9.60210E-04	9,312,160	9,094
Access protection	6.84718E-04	17,833,120	17,415
Double ring protection	2.79670E-04	10,069,860	9,834
Full protection	2.97178E-06	18,627,620	18,191

ring and route the upstream data signals to the receivers.

When a fault occurs as shown in Fig. 3(a) between RN_2 and RN_3, the downstream data to RN_3 and also the upstream data from RN_1 and RN_2 are lost. Once the NMS localizes this fault, the network enters to the protection mode. In this mode, the downstream and upstream data for RN_1 and RN_2 is transmitted and received from the west whereas that for RN_3 is transmitted and received from the east.

B. *Double Ring Protection*

Although the single bidirectional ring protection can recover from a single fault in the ring, two faults in different segments will make the protection useless. Using two rings will solve this issue as shown in Fig. 4(a); one is primary (inner ring) and one for protection (outer ring). In normal mode, the OLT transmits data on the primary ring (west) and nothing is transmitted in the protection ring (east). The 3dB coupler in the RN shown in Fig. 4(b) divides the upstream signals from the access network to both rings. So the upstream data can be received from the primary (east) or protection (west). At the CO, the received signals from the primary ring (east) are chosen by switches shown in Fig. 4(c), whereas the protection received signals (west) are ignored.

In protection mode we can define two scenarios of operation. The first scenario corresponds to single or multiple faults occurring in the primary ring. In this case, the NMS chooses the protection ring. The second scenario corresponds to faults on both segments between two RNs. For example, Fig. 4(a) shows faults on both rings segments between RN_1 and RN_2. In this case the downstream data to RN_2 and RN_3 are lost in addition to the upstream data from RN_1. Once these faults are detected and localized by the NMS, a control signal is applied to the switches. The downstream data for RN_1 is transmitted on the primary ring (west) whereas the downstream data for RN_2 and RN_3 is transmitted on the protection ring (east). For the upstream data, the switches are controlled to receive the upstream data form RN_1 on the protection ring (west) and the upstream for RN_2 and RN_3 on the primary ring (east).

C. *Double Ring Pairs Protection*

Similar to bidirectional line switched ring (BLSR) protection in SONET networks, the same principle of protection can be applied for LR-PON to increase the reliability of the network. Fig. 5(a) shows the protection architecture where two ring pairs (inner and outer) are used. Each pair has primary and protection rings. This architecture can protect the network when there is more than double failure in the rings as shown in Fig. 5(a) where the outer ring pair is faulty. In this case the inner pair is used. Another fault scenario is shown in Fig. 5(b) where a fault happens in the protection ring of the inner pair and the primary ring of the outer pair. In this case the NMS will use the primary of the inner pair and the protection of the outer pair to protect the network.

IV. FIBER FAULT MANAGEMENT SYSTEM

The NMS proposed in this paper has the capability to detect and localize any fault occurred in the ring. This NMS is based on using distributed optical passive monitors like mirrors, fiber Bragg gratings (FBGs), optical encoders, etc. These monitors can be designed to reflect a specific wavelength(s) of the troubleshooting, surveillance and monitoring band.

Passive optical encoders are one type of these passive monitors that combine two functions in the same time: coding and monitoring. These intrinsic functions mainly enable

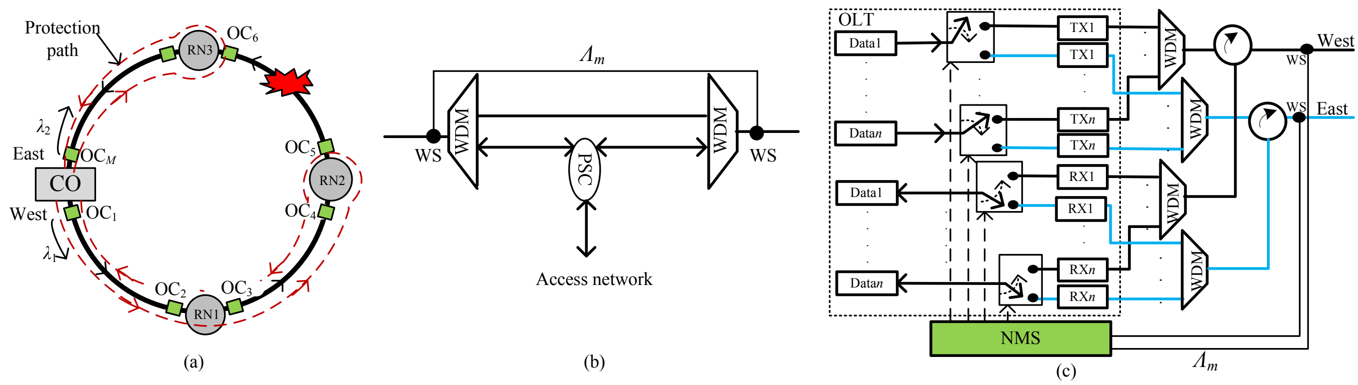

Figure 3. Single bidirectional LR-PON ring protection: (a) Ring design, (b) RN architecture and (c) OLT architecture.

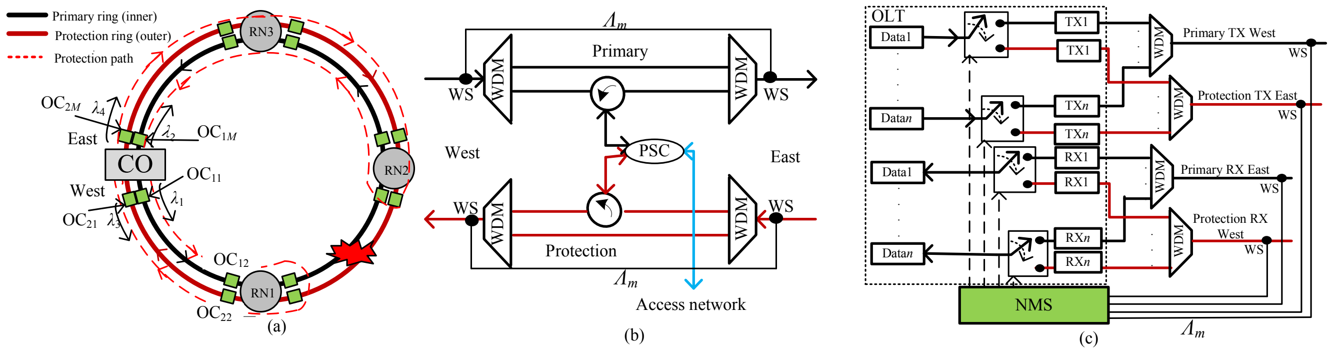

Figure 4. Double ring LR-PON protection: (a) Ring design, (b) RN architecture, and (c) OLT architecture.

scalability for network extensions, ability to distinguish between two or more faults co-located at the same distance from the CO, centralized and real time monitoring from the CO, in addition to making practical demarcation between network segments. The performance of these passive optical encoders have been demonstrated practically in [8] for standard tree architecture PON monitoring.

The operation of the NMS is based on installing optical encoders at the end of each fiber segment between two RNs. In normal mode as shown in Fig. 3 (a), the NMS sends a monitoring pulse with duration T_s and wavelength λ_1 from the CO through the west. Each optical encoder will generate and reflect a code by coupling a part of the monitoring pulse. This reflected code will be received at the CO from the west and then decoded to determine the specific ring segment status.

When a fault occurs as shown in Fig. 3(a), the optical code OC_6 is missed at the CO and then an alarm is generated by the NMS. This alarm signal will control the switches to transmit and receive data for RN_3 through the east, and transmit and receive data for RN_1 and RN_2 through the west. This allows successful recovery from fault. However, the fault between RN_2 and RN_3 will block the monitoring pulse to propagate to RN_3 and then to the CO. In this condition, the ring becomes divided into two parts: one from the CO to the fault (west) is monitored by λ_1 and the other part from the fault to the CO (east) is without monitoring. If a second fault in the second part of the ring between RN_3 and the CO occurs, the NMS cannot detect this fault. We propose to send a second monitoring pulse carried by a different wavelength (λ_2) on the east to continue monitoring the ring after the first fault is detected.

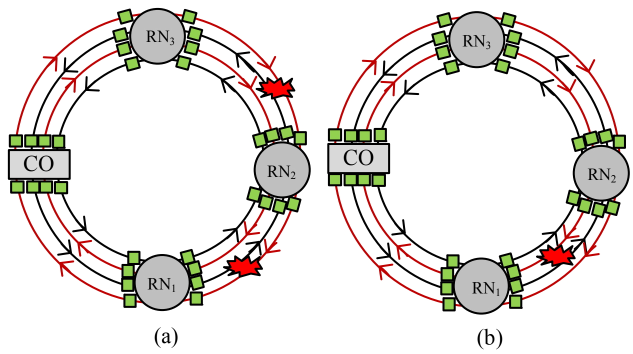

Figure 5. Double ring pairs LR-PON protection (OCs shown as squares).

Sending two monitoring pulses with two different wavelengths in opposite directions through the ring requires developing a novel type of optical encoders that has the ability to generate and reflect a code toward the CO from any direction. We call these encoders symmetrical optical encoders (SOEs). The symmetric propriety comes from the fact that the generated codes from both sides are the same but have different wavelengths. Fig. 6 shows the FBG-SOE which is an enhanced implementation of the dual grating asymmetric encoder of [8]. In the figure, we also show in insets the transfer function of each Bragg grating. The first from the left is 38% reflector of λ_1 and passes all other wavelengths. The second grating is a double wavelength (λ_1 and λ_2) 100% reflector. This serves for the generation of a code carried by λ1 in the left and a second code carried by λ_2 in the right. The third grating is a 38% reflector of λ_2 only.

When the received monitoring pulse arrives to the encoder input, a WS is used to separate the data from the monitoring waveband. The monitoring pulse coming from the west with wavelength λ_1 will enter the SOE form the left side and then the PSC will couple a part of the monitoring pulse to the FBG. The remaining of the monitoring pulse will continue its propagation to the output of the SOE and then to the next SOEs. In Fig. 6, when the monitoring pulse arrives to the 38% FBG, a part of the pulse will be reflected creating the first subpulse of the code. The remaining of the pulse will propagate through the patch-cord that has a length l_i and then reflected back by 100% FBG. The reflected pulse will create the second subpulse of the code when it arrives the 38% FBG. This process continues to produce a multi level periodic code with a period proportional to the patch-cord length. The generated code will be reflected back to the CO in the clockwise direction. The second monitoring pulse carried by the wavelength λ_2 that is transmitted through the east when a fault occurs will observe similar process except that this enters the SOE form the right side. The generated code will then propagate in the counter clockwise direction to the CO.

Sometimes the fault cause is not the ring segment but the RN itself. For example, if RN_1 in figure 3(a) is faulty. Then the NMS will interpret this as a fault in the ring segment between RN_1 and RN_2. To solve this issue, we install another SOE after each RN so that we can determine the exact source of fault. If no code is received from this new encoder, then we decide that RN_1 is faulty.

The NMS applies cyclic electronic decoding for the entire received signal. The decoding process is an autocorrelation function that searches for a peak in the received sequence of codes. If the peak is greater than a threshold, the NMS will assume that the ring segment assigned to this code is healthy; otherwise it will declare an alarm and initiate the protection mode.

For double ring and double pair rings protection architectures, SOEs are installed on each ring to completely monitor the network. The SOEs in each ring are the same in the other rings but operate on different wavelengths. In a fault case, each ring will use two different wavelengths. However, only two wavelengths (λ_1- λ_2) can be used for all the rings in these two architectures in expense of increasing interference between codes. In this case the SOEs in each ring will be different from that used on the other rings but all operate on the same wavelengths.

Monitoring signal encounters high loss due to the long round trip distance and pulse coupling in each SOE. Hence some optical amplifiers are needed at the RNs.

V. Upper Bound Notification and Recovery Times

The notification time is defined as the time elapsed between a failure in the physical layer of the network and the localization of the fault by the NMS. The monitoring pulses are transmitted with time delay between them equals to the code duration T_c to avoid overlap between successive pulses. Hence the upper bound notification time is given as

$$T_N \leq T_r / 2 + T_c + T_p \quad (3)$$

where T_r is RTT for a pulse to cross the ring forward and backward, and T_p is the processing time taken by the NMS to decode, localize and generate an alarm. The recovery time depends on the type of the switches in the OLT. If the switches are optical, the delay time is about 10ms which is relatively very high compared to the electronic switch that has time delay in nanosecond. The upper bound recovery time is given as

$$T_R \leq T_N + T_{sw} \quad (4)$$

where T_{sw} is the time delay of the switch. So the recovery time is dominated by the RTT. Fig. 7 shows the simulation result for the recovery time as a function of the fault location in 100km ring length. We assumed there is 32 equidistant RNs

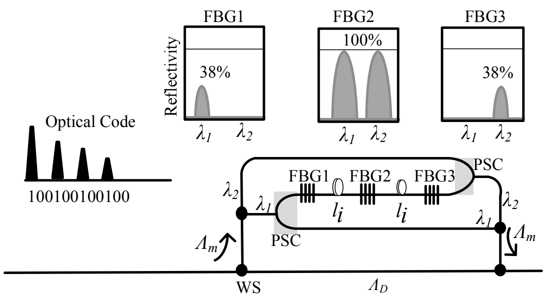

Figure 6. FBG symmetrical optical encoder (FBG-SOE)

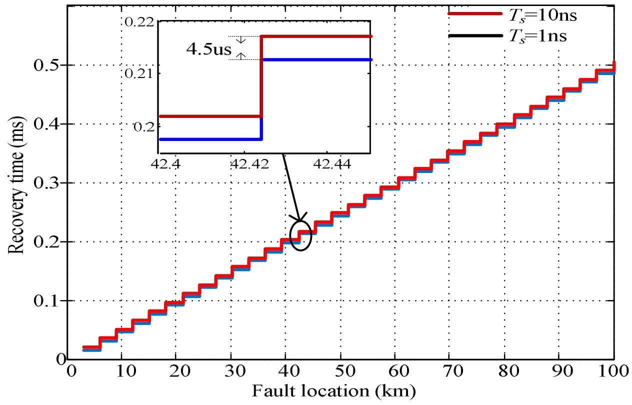

Figure 7. Recovery time versus fault location

and 500 bits OCs with T_s=1ns and 10ns. We also neglected the processing and switching times because their time is small compared to the RTT and code duration. The results show that using wider pulses in order to increase the code power from 1ns to 10ns will increase the recovery time by 4.5us. The simulation also shows that the maximum recovery time is about 0.5ms for a code located at the end of the ring.

VI. Conclusion

We show a passive fault management and protection system based on using passive optical encoders for LR-PON. We found that ring duplication protection can reduce the cost to half compared to full duplication with high reliability performance. We also show that our management and protection system can localize the exact location of fault compared to other proposed systems that can make false alarms. We found that the recovery time can take about 0.5ms as an upper bound.

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