Chapter 6

# Protection Architectures for Passive Optical Networks

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## 6.1 INTRODUCTION

Over the last decade, passive optical networks (PONs) have emerged as an attractive and promising approach to deliver broadband services to a large number of subscribers. In a typical PON, services are originated from the optical line terminal (OLT) at a head end or central office (CO) and carried along an optical-fiber feeder for about 10–15 km, before the optical power is split into multiple output distribution fibers, via an optical power splitter located at the remote node (RN). Each distribution fiber, usually less than 5 km in length, then forwards the services toward the destined optical network unit (ONU), where the optical signal is terminated before being further distributed to all the subscribers attached to this ONU via other media, such as copper wire, etc. With such high fiber penetration into the access arena, the system cost of PONs has to be kept low in order to make them economically viable and competitive. PON features its passive remote node, which greatly relaxes the cost of managing optical elements in outside fiber plants. Besides, both the RN and the ONUs have to be kept simple and low-cost. Traditionally, the downstream services delivered over a PON are mostly distributive videos. Nevertheless, an upstream channel is often provisioned to carry subscribers' requests back to the OLT. Thus this upstream channel is usually of low data rate. Due to such distributive nature of the traffic as well as the low-cost concern of PONs, not much effort has been paid on the issue of network survivability.

With the recent huge popularity of the Internet and the multimedia services it carries, conventional PONs are evolving to carry two-way broadband interactive data signals. Bandwidth demands in both enterprise and residential broadband access networks have been increasing drastically and the services carried on

PONs are becoming more and more data-centric. Several variants of PONs such as B-PON (ITU-T G.983) [1–4], E-PON (IEEE 802.3ah) [5], and G-PON (ITU-T G.984) [6, 7] have been widely deployed recently to cope with the increasing demand for access bandwidths. With the recent availability of low-cost optical components, PONs using the wavelength division multiplexing (WDM) technique have been emerging as the next generation optical access networks. In a WDM-PON, each ONU is served by a dedicated set of wavelength channels to communicate with the OLT. Each individual ONU can enjoy a dedicated bandwidth, which is also scalable according to its own need. Thus, the system capacity and the network flexibility could be greatly enhanced. However, with conventional PON architectures, which have limited protection feature, any component or fiber failure would lead to huge loss of data or even business. Therefore, the issue of network survivability [8, 9] has aroused more attention over the recent years. Subscribers are now requesting high-availability services and connections. Thus, protection measures to enhance the network survivability are highly desirable to provide resilience against failures, for instance, in the cases of possible catastrophic events such as fires or flooding.

Fault management is one of the well-known crucial aspects in network management. Most of the conventional approaches of fault management rely on diagnosis in higher layers [10, 11], based on the status reports collected from various checkpoints on the managed optical network. However, such high-level fault diagnosis would impose excessive overhead in network signaling as well as in the network management system (NMS). Yet there is no guarantee that higher layers can provide recovery from faults in the physical layer. Therefore, in order to facilitate effective and prompt network protection and restoration, it is highly desirable to perform network survivability measures in the optical layer. This can be achieved by simple fiber link or equipment duplication with protection switching or some other intelligent schemes with minimal resource duplication or reservation for protection. For PON applications, equipment failure at either OLT or ONU can be easily remedied by having a backup unit in the controlled environment. However, for any fiber cut, it would take a relatively long time to perform the repair. Therefore, it is highly desirable to have survivable PON architectures with protection switching against any fiber cut.

In this chapter, several considerations in designing survivable network architectures for PONs will be discussed. Besides, several feasible protection schemes and architectures for both the conventional PONs and WDM-PONs will be reviewed.

## 6.2 CONSIDERATIONS OF PROTECTION IN PASSIVE OPTICAL NETWORKS

The following considerations are useful when designing survivable network architectures or other protection schemes for PONs.

### 6.2.1 Protection or Restoration

In fault management of optical networks, there are two common approaches to assure the network survivability, namely preplanned protection and dynamic restoration. Preplanned protection aims to incorporate protection lightpath at the network design stage and automatic protection switching can be readily performed to the designated protection lightpath, once any network failure is detected. The traffic restoration time can be kept very short. On the contrary, dynamic restoration would search for the spare lightpaths or network resources for restoring the disrupted traffic only after the occurrence of network failures. Although the amount of spare resources can be preallocated, the traffic restoration time may be long as it depends on the dynamic rerouting of the disrupted traffic. For most of the PON applications, as the network topology is quite regular, such as tree or ring, preplanned protection schemes are usually adopted to enhance the network survivability with short traffic restoration time. Besides, protections on the optical layer should have quick restoration time in order to minimize the disturbance to the upper layers, which usually rely on some timeout features for fault detection. Upper-layer restoration often involves routing table topology recalculation and slow convergence time. Improper handing of restoration time among different layers can cause network instability.

### 6.2.2 Network Topology

There are two common network topologies for PONs, namely tree and ring. In a tree topology, the optical signal sent from the OLT is split at the RN and delivered to the designated ONUs via the respective distribution fibers. For ring topologies, the OLT is connected to multiple access nodes (ANs) via single or double fiber rings. Each AN comprises an optical add-drop multiplexer (OADM) or simply an optical power splitter, to which multiple ONUs are further connected, either in a star or ring topology. In addition to ring and tree topologies, there are some other topologies such as bus and star-ring. When the protection network architecture is designed, the network topology definitely determines the paths or connections between the OLT and the ONUs and thus influences how the protection lightpath or fiber should be duplicated or incorporated, when appropriate. For instance, in a PON with tree topology, any fiber cut in the distribution fiber will make the affected ONU unreachable from the OLT. However, in a PON with ring topology, any fiber cut in the fiber ring will isolate all of the downstream ANs beyond the cut position along that ring, if no additional protection ring is incorporated.

## 6.2.3 Network Type

Conventional PONs usually support one (for video) or two (for data and video) downstream optical carriers, as well as one upstream optical carrier. These optical carriers are time-shared among all ONUs. In order to enable the delivery of higher capacity services to the subscribers and enhance the flexibility for network upgrade, PONs using WDM techniques, namely WDM-PONs, have recently emerged and have aroused much research interests. In WDM-PONs, each ONU is served by a set of dedicated and distinct wavelength channels to communicate with the OLT. The ranging problem in conventional time-shared PONs is also alleviated, as all upstream wavelengths are multiplexed at the RN without any signal collision. Each individual ONU enjoys dedicated bandwidth, which is readily scalable according to its own needs. Protection in a PON is usually achieved by lightpath diversity with fiber link duplication and switching. As WDM-PONs offer one more dimension for the optical channels, lightpath diversity can be much more flexibly realized by adopting wavelength routing on existing network architectures. Hence, excessive fiber-link duplications could be avoided.

## 6.2.4 Resources To Be Protected

In general, there are two major kinds of network resources which have to be protected in PONs, namely fiber links and active component or equipment. Both of them affect the availability of the wavelength channels running on the network. As fiber links are laid outside plant, they are more vulnerable to environmental conditions and it takes much more time to repair the fiber, whenever a fiber cut occurs. Moreover, any fiber cut may stop all wavelength channels traversing over it. Thus, alternate lightpath or redundant protection fibers in either $1 + 1$ or 1:1 protection scheme are usually preplanned to achieve lightpath diversity. For active component or equipment, such as the optical transceivers and optical switches residing at OLT or ONUs, they are easily protected by colocated backup units in $1{:}N$ or even $1 + 1$ protection scheme. In addition to fiber links and active components, the passive wavelength multiplexer at the RN in WDM-PONs may also need to be protected. If the spectral property of the WDM multiplexer is temperature-sensitive, such as conventional array waveguide grating (AWG), changes in the environmental temperature at the RN may possibly induce misalignment between the optical carriers and the transmission passband of the WDM multiplexer. This may induce excessive filtering and power loss to the optical carriers. Therefore, athermal WDM multiplexer, such as athermal AWG or thin-film-based WDM multiplexers, should be employed at the RN.

### 6.2.5 Single or Multiple Failures

Most of the existing efforts in network protection focus on the scenarios of a single failure at a time. In most cases, the occurrence of failure in a fiber link or a piece of network equipment is statistically independent in a network. Moreover, the mean time between failures is generally much longer than the mean time to repair a single failure. However, a single failure, such as a fiber cut, may sometimes lead to failure in multiple logical connections. Recently, there are also some research efforts on studying network protection under multiple failures.

### 6.2.6 Automatic Protection Switching

Automatic protection switching (APS) can be realized by either centralized or distributed control. In centralized control, all protection switching are performed at the OLT, after the fault alarms are collected. The ONUs still stay connected with the OLT after the APS. On the contrary, protection switching can be performed at individual ONUs instead, to realize distributed control. In this case, protection switches are incorporated in the individual ONUs, which continuously monitor the status of their attached fiber links or components. APS will be triggered only at the affected ONU when any fault is detected. In case of any failure, the OLT does not need to perform any remedy and is transparent to such APS. However, this approach increases ONU complexity and costs.

### 6.2.7 Operation, Administration, and Management

When incorporating APS into a network, fault monitoring units have to be installed at strategic checkpoints to gather network status information. A monitoring unit can be as simple as mere optical power level monitoring to identify the possible loss of signal at a low detected optical power level. Some other novel techniques could also be employed to detect other parameters such as the presence of a particular wavelength, and the identification of a specific faulty fiber branch in a PON with tree topology [12]. The collected monitoring information has to be delivered to APS units for appropriate remedies. In some cases, a signaling channel may be needed to carry the monitoring information.

### 6.2.8 Traffic Restoration Time

Once a network failure is detected, the time period required to perform protection switching and restore the affected traffic is known as the traffic restoration time. This time period should be kept small, say less than a few tens of milliseconds [8], to reduce the amount of data loss during service disruptions. In most cases, such traffic restoration time greatly depends on the intrinsic response of the optoelectronic detection and the optical switching devices used in the APS, as well as the possible induced additional latency of the protection lightpath. Sometimes, higher-layer protocols are employed to retransmit the lost data.

### 6.2.9 Complexity

The design of survivable PON architectures should require the least amount of additional fiber link or equipment duplication to keep the complexity and cost low. For example, a backup transceiver may be employed at the OLT for 1:$N$ protection of all other working transceivers, instead of 1 + 1 protection. This backup transceiver can be of fixed wavelength or tunable wavelength, depending on the network type and requirement. In the case of WDM-PONs, alternate lightpath routing of wavelength channels may be adopted to bypass the failed fiber links and minimize the required additional fiber links for protection.

## 6.3 PROTECTION ARCHITECTURES

In this section, several survivable network architectures for both conventional PONs as well as WDM-PONs, in both tree and ring topologies, will be reviewed. As discussed in the previous sections, fiber link failure is the most frequent and critical in PONs, as it may interrupt many wavelength channels in a network. Therefore, the following architectures mainly focus on the protection of fiber links in PONs.

### 6.3.1 Conventional Passive Optical Networks

#### 6.3.1.1 Tree Topology

Most of the conventional PONs, such as A-PON (ITU-T G.983.1) [1, 2], B-PON (ITU-T G.983.3) [1–4], EPON (IEEE 802.3ah) [5], and G-PON (ITU-T G.984) [6, 7], adopt a tree topology to provide point-to-multipoint connections. An optical power splitter is employed to split the received optical signal at the RN to all outgoing distribution fibers. Figure 6.1 shows the four protection architectures with different levels of protection, as suggested by ITU-T G..983.1 [1]. Basically, they are duplicating the fiber links and/or the components for protection.

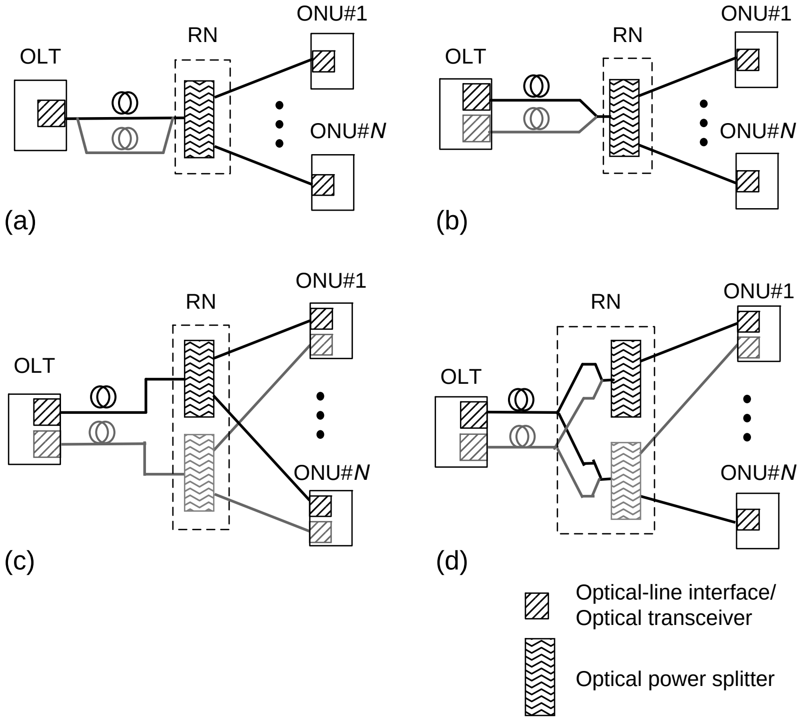


**Figure 6.1** Protection switching architectures suggested by ITU-T G.983.1.

Figure 6.1 (a) duplicates the feeder fiber between the OLT and the RN only. Only the feeder fiber is protected. Figure 6.1 (b) doubles the optical transceivers at the OLT and also duplicates the feeder fiber between the OLT and the RN. Protection switching is done by switching the data to the backup optical transceiver at the OLT. This can reduce the cost of duplicating the optical transceivers at the ONUs. Figure 6.1 (c) doubles the optical transceivers not only at the OLT but also at the ONUs. In addition, the optical power splitter at the RN is also duplicated. Hot standby circuits are placed at the OLT and the ONUs, enabling hitless switching by switching to the backup facilities in the event of a failure of fiber or equipment. Figure 6.1 (d) is similar to Fig. 6.1 (c) except that an additional optical power splitter circuit is incorporated at the RN to cope with the case that not all ONUs have duplicated optical transceivers, due to some system constraints.

In addition to these four suggested protection switching architectures, several 1:$N$ protection schemes for OLT [13–16] were also proposed, where one backup OLT interface was employed to protect all or a group of the working OLT interfaces. Figure 6.2 shows an example [14] of using an optical-splitting circuit at the RN to enable the backup OLT interface to perform the 1:*N* protection. This could alternatively be done by employing a switching circuit inside the OLT [16], instead.

In [17], protection of the distribution fibers was achieved by serially interconnecting the ONUs, as shown in Fig. 6.3. At each ONU, an optical switch (OSW) was employed for protection switching purpose. Half of the received downstream signal at the ONU (say $ONU_2$ in Fig. 6.3) was tapped off and fed to the OSW residing at the previous connected ONU (say $ONU_1$ in Fig. 6.3), via a piece of interconnection fiber. Therefore, if the distribution fiber for $ONU_1$ was broken, $ONU_1$ could still receive the downstream signal via $ONU_2$ and $OSW_1$ in protection state. Thus, the distribution fiber for $ONU_2$ and the interconnection fiber for both $ONU_1$ and $ONU_2$ served as the protection path for $ONU_1$, at the expense of installing the additional inter-ONU interconnection fibers.

In [18], two distribution fibers, one for working and the other one for protection, were designated for each ONU. The protection distribution fiber was looped back to one of the input ports of the optical star coupler at the RN. A protection feeder fiber was also installed, connecting the OLT and one of the output ports of the optical star coupler at the RN. In case of any cut at the distribution fiber, the optical switch at the ONU would switch to the protection distribution fiber, while the OLT would switch to the protection feeder fiber, as the same time. Thus, both the feeder and the distribution fibers could be protected at the expense of two distribution fibers per ONU and simultaneous protection switching at both the OLT and the affected ONU (Fig. 6.4). Moreover, the switching at the OLT would induce a hit to all the ONUs on the same PON.

In [19], the coarse WDM (CWDM) technology was employed to provide protection of the feeder fiber among two PONs, as shown in Fig. 6.5. The feeder

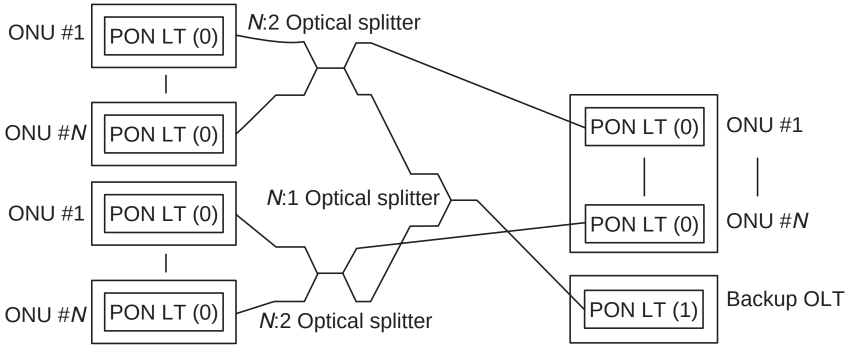


**Figure 6.2** A 1:*N* protection scheme at OLT [14]. LT: Line Terminal.

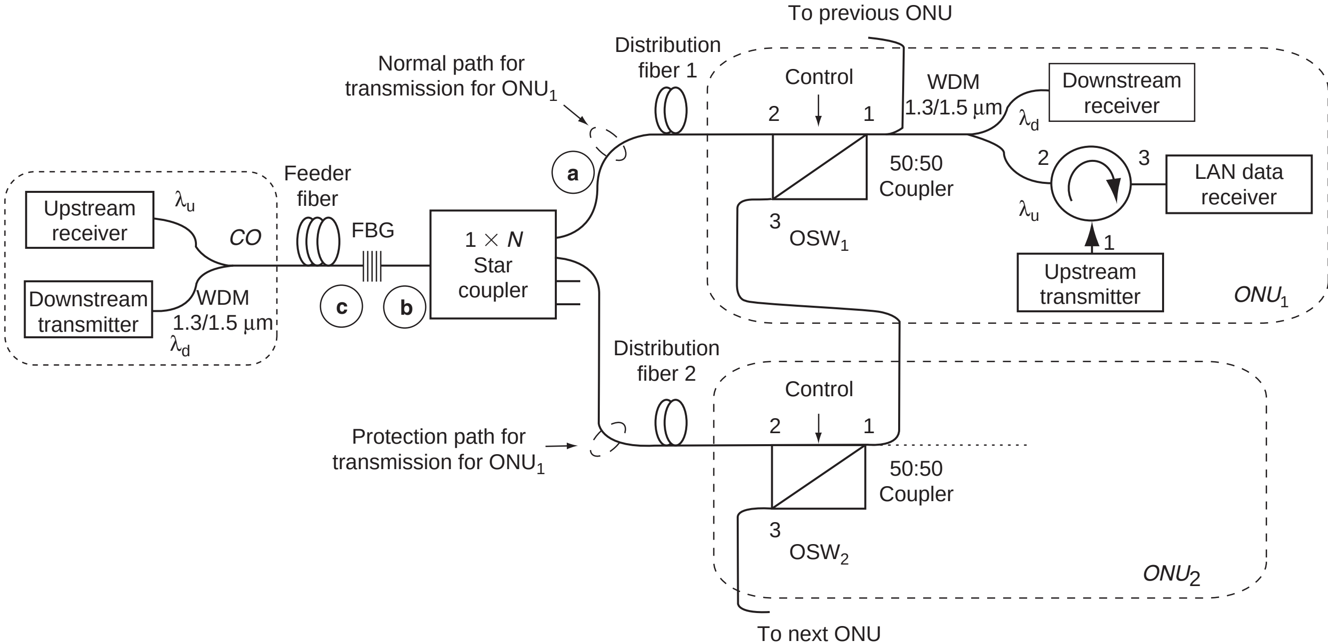


**Figure 6.3** A PON architecture with protection of distribution fibers by interconnecting ONUs with protection switching [17]. OSW: optical switch, FBG: fiber Bragg gratings, $\lambda_d$: downstream wavelength, $\lambda_u$: upstream wavelength.

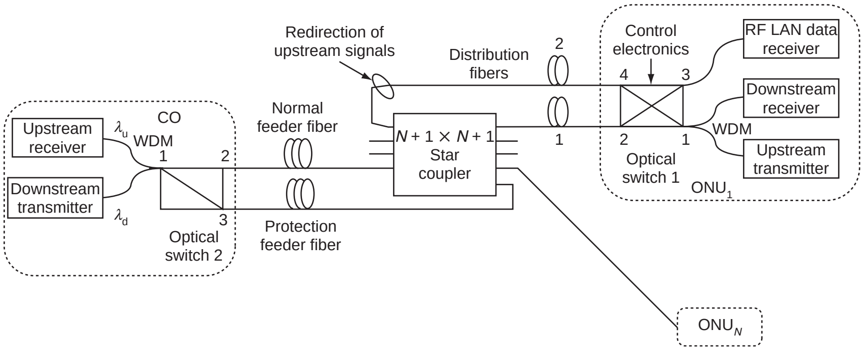


**Figure 6.4** A PON architecture with protection of both feeder and distribution fibers by an additional loopback distribution fiber with protection switching [18]. $\lambda_d$: downstream wavelength, $\lambda_u$: upstream wavelength.

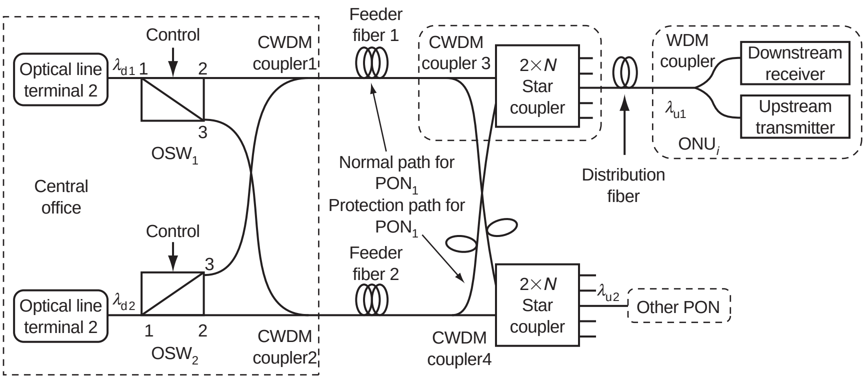


**Figure 6.5** Protection of feeder fibers in two PONs using CWDM technology [19]. OSW: optical switch, $\lambda_d$: downstream wavelength, $\lambda_u$: upstream wavelength.

fibers of both PONs were cross-connected via the optical switches attached to each OLT, while the two RNs were also cross-connected as shown in Fig. 6.5. By employing CWDM technology, $PON_1$ could offer its feeder fiber as the protection path for $PON_2$, and vice versa, by means of optical multiplexing of one's working signals and the protected signals from the other PON, on the same feeder fiber, without any interference. The protection switching was performed at the OLT only.

#### 6.3.1.2 Ring Topology

Conventionally, network protection schemes for ring-type PONs are similar to the SONET self-healing rings (SHRs) [20], in which duplicated protection fibers are employed to provide redundant paths, and line or path protection switching is incorporated at both the OLT and the access nodes. There are three common approaches [21–25] for optical ring protection, namely two-fiber unidirectional path-switched ring (UPSR), four-fiber bidirectional line-switched ring (BLSR/4), and two-fiber bidirectional line-switched ring (BLSR/2). UPSR is essentially a $1 + 1$ dedicated protection ring; while BLSR/2 and BLSR/4 are 1:1 shared protection rings. Figure 6.6 illustrates these protection switching operations of shared protection rings [25].

In [26], a star-ring architecture for a subcarrier-multiplexed PON was proposed. As shown in Fig. 6.7, multiple feeder fibers were employed in a star topology and each of them was connected to an RN. Every two adjacent RNs were interconnected via a ring network, on which multiple ONUs were connected. Protection switches and circuits were incorporated in the RN, as shown in the inset of Fig. 6.7, such that the two attached rings on both its sides could be combined to form a larger ring, when the feeder fiber connected to the RN failed. Thus, the failed feeder fiber could be isolated. In this scenario, the network was reconfigured such that the affected ONUs would still be in connection with the CO via the two neighboring working RNs.

### 6.3.2 WDM Passive Optical Networks

#### 6.3.2.1 Tree Topology

In a WDM-PON with a tree topology, each ONU is designated with a dedicated set of wavelengths for both the downstream and the upstream channels. Therefore, a wavelength multiplexer is employed at the RN for wavelength routing, and different distribution fibers are carrying the respective set of wavelengths destined for their attached ONUs. Due to the similar tree topology as in conventional PONs, the protection switching architectures proposed in ITU-T G.983.1, as shown in Fig. 6.1, could also be employed for WDM-PONs, except that the optical power splitter at the RN has to be replaced by a wavelength multiplexer. However, these approaches incur excessive fiber duplication and protection switching for network protection. Figure 6.8 shows an example of WDM-PON with feeder fiber duplication [27], where a separate pair of protection feeder fibers were needed.

On the other hand, by utilizing the additional feature of wavelength routing in the AWGs employed in the WDM-PONs, lightpath diversity could be realized with higher flexibility and the amount of fiber duplication could also be reduced.

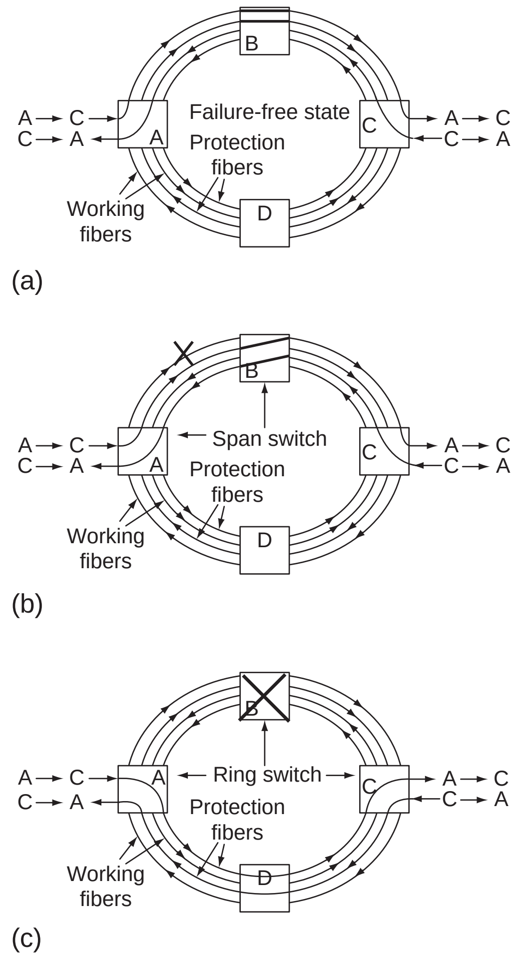


**Figure 6.6** An example of a four-fiber shared rings in (a) normal operation; (b) span switching; and (c) ring switching [25].

With the recent much aroused research interests in the enabling technologies for WDM-PONs, several interesting and feasible survivable architectures for WDM-PONs in tree topology have been proposed.

In [28], a self-protected WDM-PON architecture with the idea of group protection of ONUs was proposed to protect against any failure at the distribution fibers. Two adjacent ONUs were grouped and their corresponding downstream and upstream wavelengths were connected to the OLT via the same output port of the AWG at the RN. This was achieved by utilizing the

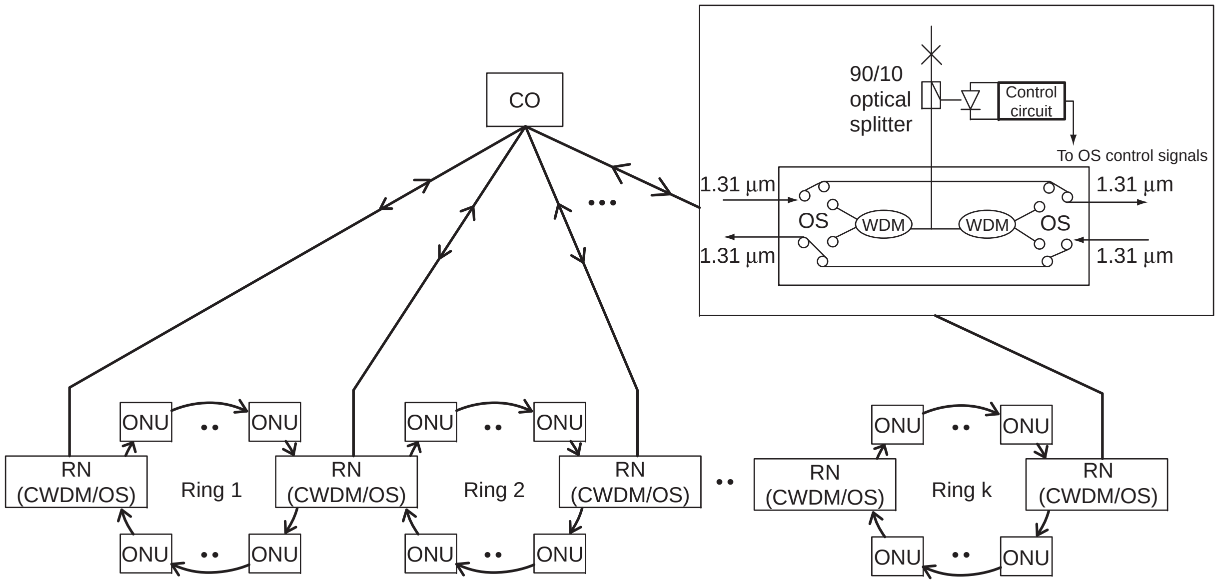


**Figure 6.7** A modified star-ring PON with protection capability [26]. Inset shows the structure of the RN to illustrate the protection mode. OS: optical switch.

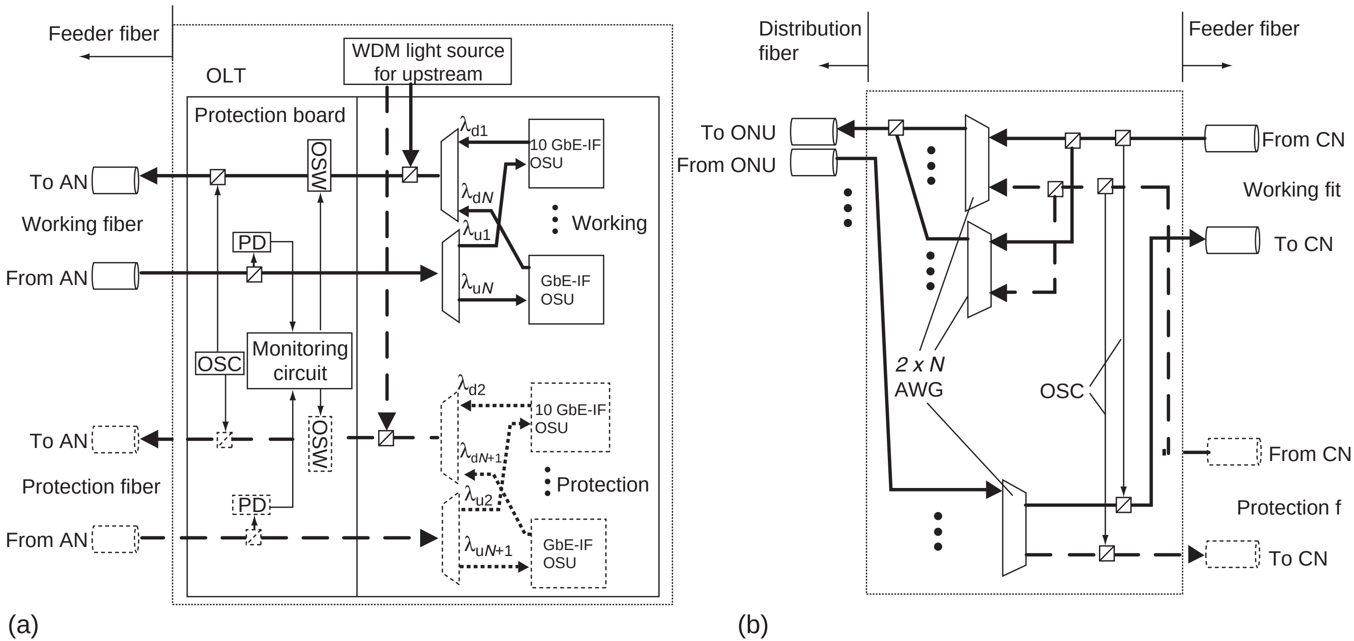


**Figure 6.8** The structure of (a) the OLT and (b) RN of a WDM-PON with duplicated fiber feeders for protection [27]. AN: access node, CN: central node, OSC: optical supervisory channel, PD: photodiode, OSW: optical switch.

periodic spectral property of the AWG and with proper wavelength assignment. The two ONUs in the same group were connected by a piece of protection fiber and a pair of protection switches were incorporated into each ONU for signal rerouting. In case of a fiber cut between a particular ONU and the RN, the protection switches in the ONUs in the same group would be triggered via simple power monitoring at the modules M1 and M2, as illustrated in Fig. 6.9. Both the affected downstream and upstream wavelengths would be rerouted to its adjacent ONU before being routed back to the OLT via the same AWG output port. The normal traffic on the adjacent ONU was not affected while the OLT could still keep its connection with the affected ONU. In this way, the two ONUs in the same group protected each other and the OLT was transparent to such fiber failure. An improved version [29] which greatly reduced the number of optical couplers needed at the RN by means of a novel wavelength assignment was also proposed. These two architectures performed protection switching at the ONU side. This might increase the complexity at the ONUs. In [30, 31], centrally controlled WDM-PON survivable architectures were proposed to have all the protection switching performed at the OLT. This could greatly facilitate the control and management of all the protection switching and help to keep the ONUs simple. The protection switching in [30] was performed by a 2×2 OSW connecting the fiber feeders, thus having the possibility of inducing service interruption to all in-service wavelength channels during the short switching period. In [31], as shown in Fig. 6.10, multiple 2×2 OSWs were employed at the OLT to perform protection switching at the wavelength channel level. The wavelength assignment plan for both the downstream and the upstream wavelength channels was depicted in Fig. 6.10 (c), utilizing the cyclic spectral properties of the AWGs employed at the OLT and the RN. Therefore, any toggling of the switching state of any OSW at the OLT would activate the protection path by alternate wavelength routing between the OLT and the respective ONU. Whenever the feeder fiber or the distribution fiber connected to a particular ONU was broken and caused service outage, the respective protection switches for those affected ONUs at the OLT would have their switching states automatically toggled. Therefore, the affected wavelengths would be routed via their designated protection paths, without affecting any other in-service wavelength channels. All protection switching were performed at the OLT only. In [32], a novel WDM-PON architecture with protection of both the feeder fibers and distribution fibers were proposed, as shown in Fig. 6.11. Both the RN and the distribution fibers were duplicated. The wavelength channels for a destined ONU were copied and routed simultaneously in two different lightpaths, one for normal operation and the other for protection purpose, to achieve lightpath diversity. When a fiber cut occurred, the OSW at the ONU would be triggered to redirect the disrupted signals to the protection path.

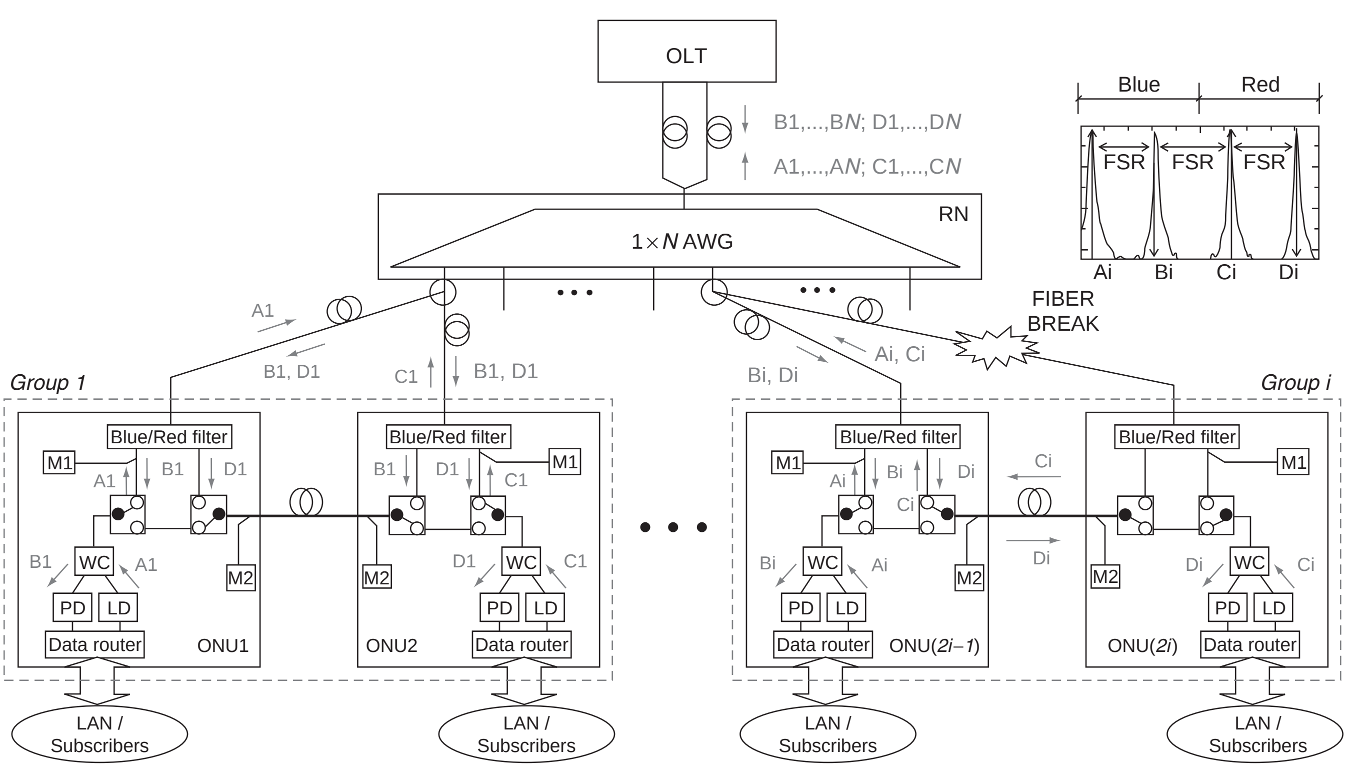


**Figure 6.9** Self-protected network architecture for WDM-PON. LD1–4: laser diode; PD1–4: PIN photodiode; WC: WDM coupler; M1&M2: optical power monitors; {A*i*, C*i*} for $i \in \{1, \ldots, N\}$: upstream wavelengths; {B*i*, D*i*} for $i \in \{1, \ldots, N\}$: downstream wavelengths. Inset shows the spectral response of one of the output ports of the AWG. FSR: free-spectral range of the AWG [28].

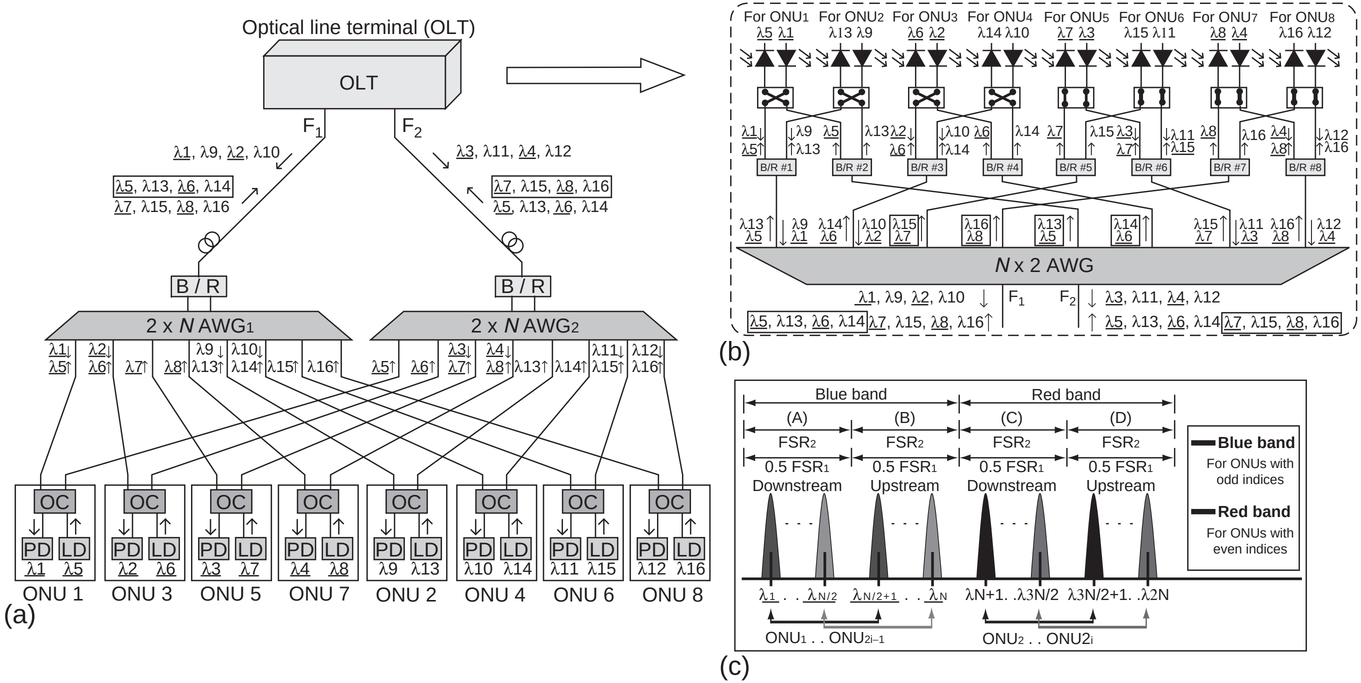


**Figure 6.10** (a) A WDM-PON survivable architecture with eight ONUs and centralized protection switching control; (b) OLT configuration under normal operation; (c) wavelength assignment plan. B/R: blue/red filter; OC: 3-dB fiber coupler; LD: laser diode; PD: photodiode. Note: FSR1 stands for free-spectral range of the $N \times 2$ ($N = 8$) AWG at the OLT while FSR2 stands for that of both AWG1 and AWG2 at the RN. The wavelengths quoted in boxes are the working upstream wavelengths. The wavelengths in blue band are underlined but those in red band are not [31].

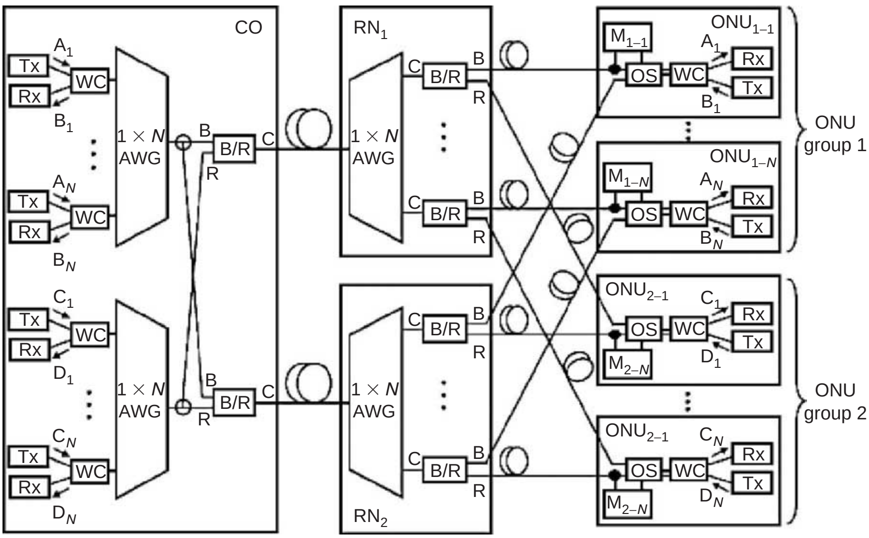


**Figure 6.11** A WDM-PON architecture with self-protection capability against both feeder fiber and distribution fiber failures [32]. WC: wavelength coupler, B/R: blue/red filter, OS: optical switch, M: power monitoring modules.

Besides, there were some other survivable network architectures proposed, such as broadcast-and-select WDM-PON with an ONU group protection [33], star-ring WDM-PON with interconnected ONUs via an additional fiber ring [34], WDM-PON with 1:*N* protected OLT with tunable transceivers [35], and WDM-PON with waveband filters for protection [36].

### 6.3.2.2 Ring Topology

In WDM-PONs with ring topology, the OLT is connected to multiple ANs via single or double fiber rings. Each AN comprises an OADM or simply an optical power splitter, to which multiple ONUs are further connected either in star or ring topologies [37, 38]. Similar to conventional PONs with the ring topology, protection is achieved by means of self-healing rings [20]. Duplicated protection fiber rings are employed to provide redundant paths; and line or path protection switching is incorporated at both the OLT and the ANs. Several interesting WDM self-healing access ring networks have been recently reported [39–46]. In [39], a dense-WDM self-healing ring network, with a unidirectional

OADM, which was based on acousto-optic switches, at each network node, was proposed. In [40], optical filters and OSWs were employed at ANs for wavelength dropping and protection switching respectively. In [40, 41], an AWG add-drop filter was employed as the OADM and a loopback circuit was implemented to provide protection switching at each AN. However, these approaches still required two working fiber paths to support both protection as well as bi-directional transmission. In [42–46], single-fiber bidirectional SHR (Self Healing Ring) networks were also reported. This could further reduce the system cost and increase the fiber efficiency in SHR networks. In [47], an interesting star-ring-bus dense-WDM subcarrier-multiplexed network, with simple protection switching at the ANs was proposed. However, extensive fiber connections were required in the proposed network architecture.

In [45], a simple single-fiber CWDM optical access ring network with unidirectional OADMs incorporated in the ANs was demonstrated, as shown in Fig. 6.12. The downstream wavelength channels were power-split and sent along the ring network in both counter-propagating directions. A 2×2 OSW and a pair of low-cost CWDM OADM was employed at each AN, as illustrated in Fig. 6.12 (b). When a fiber cut along the ring network was detected, by means of signal-loss detection, the OSWs at the affected ANs would be triggered to toggle their switching states such that they could still communicate with the OLT via the input fiber in another propagation direction. In [46], a single-fiber bi-directional self-healing optical access ring networks with bidirectional OADM was demonstrated. The idea was to apply the same OLT architecture and alternate path switching scheme as in [31] to achieve self-healing function in a single-fiber optical access ring.

In [47, 48], an interesting protected optical star-shaped ring network was proposed, as shown in Fig. 6.13. The physical network topology was star-shaped, but the logical connections of all nodes, in form of wavelength paths, were actually in a ring topology, as shown in Fig. 6.13 (b). It was realized by the optical foldback at the AWG employed at the OLT and the wavelength routing properties of the AWG device. Another set of backup wavelength paths are also designated for protection against any fiber link failure. This set of backup wavelength paths can be activated by switching the fiber connections at the designated input ports of the AWG. When a fiber or a network node failed, the protection switch at the OLT would be reconfigured to activate the backup wavelength paths, so as to bypass the failed nodes or link.

## 6.4 SUMMARY

With the fast-growing deployments of PONs in both enterprise and residential areas, high network availability should be assured to all subscribers. Therefore,

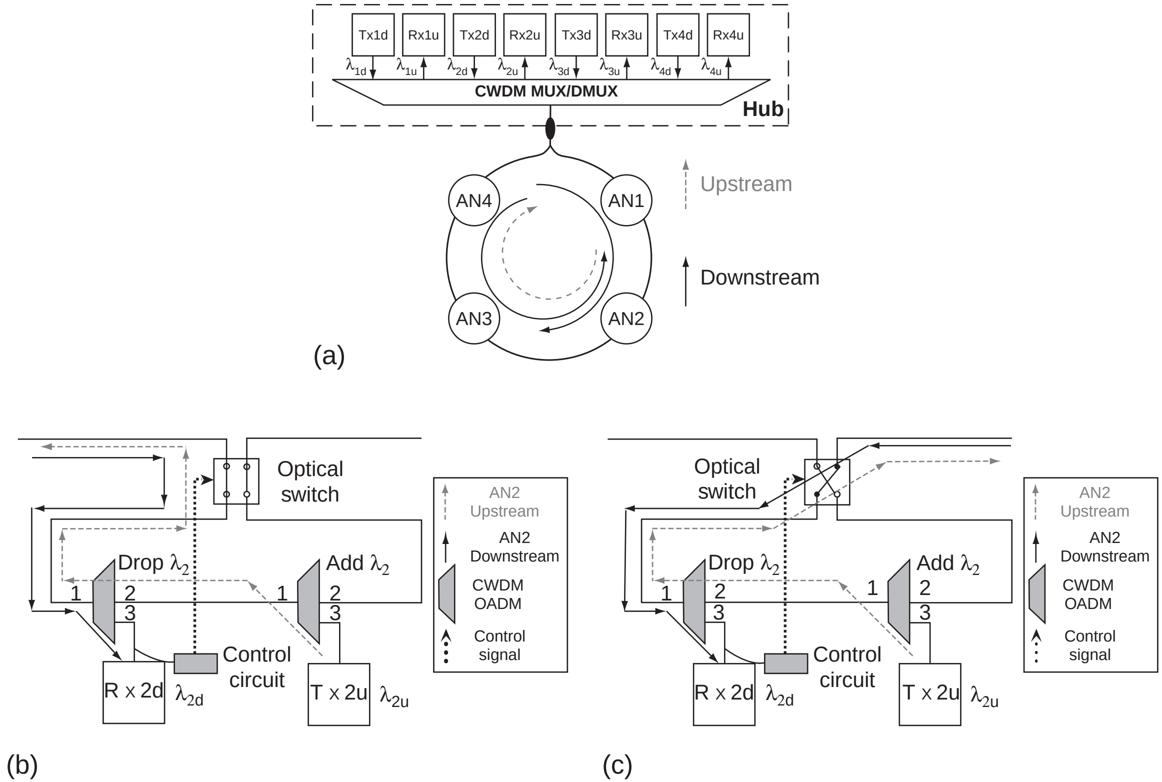


**Figure 6.12** (a) A single-fiber CWDM optical access ring network; (b) & (c) the structure of AN2 in (b) normal state and (c) protection state when there was a fiber cut between AN2 and AN3 [45]. AN: access node, Tx: transmitter, Rx: receiver.

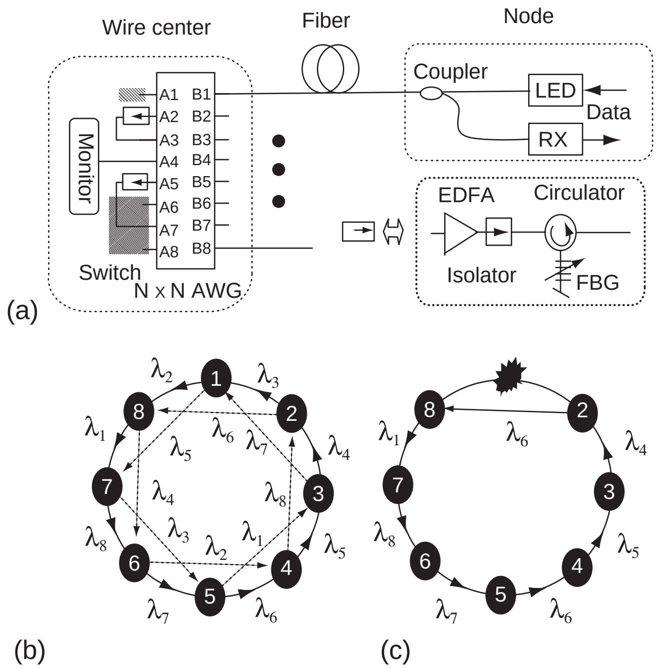


**Figure 6.13** (a) A protected optical star-shaped ring network; (b) lightpath diagram, dotted lines were the designated protection paths; (c) the protection lightpath was adopted when node 1 failed [47]. FBG: fiber Bragg gratings.

the issue of network survivability has aroused much attention recently. It is highly desirable to have flexible and robust survivable network architectures as well as protection switching schemes in the optical layer to provide good resilience against any failure of fibers or network equipment. Several important design considerations of protection in PONs have been discussed and some of the recently proposed survivable network architectures for both conventional PONs and WDM-PONs have been reviewed. In most of these schemes, the critical optical components are the OSWs to enhance the protection switching. Hence, optical-switching technologies [49] with low-cost and fast-switching responses would be very crucial and of high practical importance to enable wide deployments of the survivable PONs. Typical protection switching time should be kept below a few tens of milliseconds, say 50 ms, to reduce the amount of data loss during traffic restoration.

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