Novel Network Architectures for Survivable WDM Passive Optical Networks

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Abstract
In this paper, several considerations in designing survivable WDM-PONs will be discussed. Several feasible protection schemes and architectures for automatic traffic restoration upon any fiber cut in WDM-PONs will be reviewed.

Introduction

Over the past decade, passive optical networks (PONs) have emerged as an attractive and promising approach to deliver broadband services to a large number of subscribers. With the recent availability of the low-cost optical components, PONs using wavelength division multiplexing (WDM) technique have emerged as the next generation optical access networks. 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 [1] has attracted more attention over the recent few years. Subscribers are now requesting high-availability services and connections. Thus, the networks should provide resilience against failures, for instance, in case of possible catastrophic events such as fire or flooding.

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. In order to facilitate effective and prompt network protection and restoration, it is desirable to perform network survivability measures in the optical layer. For PON applications, equipment failure at either optical line terminal (OLT) or optical network unit (ONU) can be easily remedied by having a backup unit in the controlled environment. However, in case of any fiber cut, it would take a relatively long time to perform the repair. Therefore, survivable network architectures with protection switching are highly desirable to protect the WDM-PONs against any fiber cut.

In this paper, several considerations in designing survivable network architectures for WDM-PONs will be discussed. In addition, several feasible protection schemes and architectures for WDM-PONs will be reviewed.

Design Considerations for WDM-PON Protection Architectures

In WDM-PONs, the fiber links are laid outside plant, thus are more vulnerable to environmental conditions. Whenever a fiber cut occurs, all wavelength channels traversing on that fiber would be interrupted and it takes much more time to repair the fiber. Conventional protection measures against fiber cut in PONs are usually achieved by 1+1 lightpath diversity with fiber link duplication and automatic protection switching (APS). As WDM-PONs offer one more dimension for the optical channels, lightpath diversity can be much more flexibly realized by adopting alternate lightpath routing of the wavelength channels on the existing network architectures, so as to by-pass the failed fiber links and to minimize the required additional fiber links for protection. Such lightpath diversity greatly depends on the network topology, which actually determines the physical paths or connections between the OLT and the ONUs. As the network topology of WDM-PONs is quite regular, such as tree or ring, pre-planned protection schemes are usually adopted to enhance the network survivability with short traffic restoration time. Protections on the optical layer could realize short restoration time, say less than a few tens of milliseconds, 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 protection switching, as well as the possible induced additional latency of the protection lightpath.

When incorporating APS into the 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

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particular wavelength, etc. The collected monitoring information has to be delivered to the APS units for appropriate remedies. In some cases, a signaling channel may be needed to carry the monitoring information. Besides, 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. APS will be triggered only at the affected ONU when any fault is detected. In case of any fiber failure, the OLT does not need to perform any remedy and is transparent to such APS. However, this approach increases the complexity and cost of the ONUs.

In general, the design of survivable WDM-PON architectures should require the least amount of additional fiber link or equipment duplication to keep the complexity and cost low, while the affected traffic can be restored promptly.

Novel Survivable Architectures for WDM-PONs

In this section, several survivable network architectures for WDM-PONs, in both tree and ring topologies, for fiber link protection, will be reviewed.

(a) WDM-PONs with Tree Topology

In a WDM-PON with a tree topology, a wavelength multiplexer is employed at the remote node (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 could also be employed for WDM-PONs, as shown in Fig. 1. However, these approaches incur excessive resource duplication for network protection. The work in [2] is an example of WDM-PON with feeder fiber duplication, where a separate pair of protection feeder fibers was needed.

On the other hand, by utilizing the additional feature of wavelength routing in the arrayed waveguide gratings (AWGs) employed at the RN in the WDM-PONs, lightpath diversity could be realized with higher flexibility. In [3], 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 periodic spectral property of the AWG and with proper wavelength assignment.

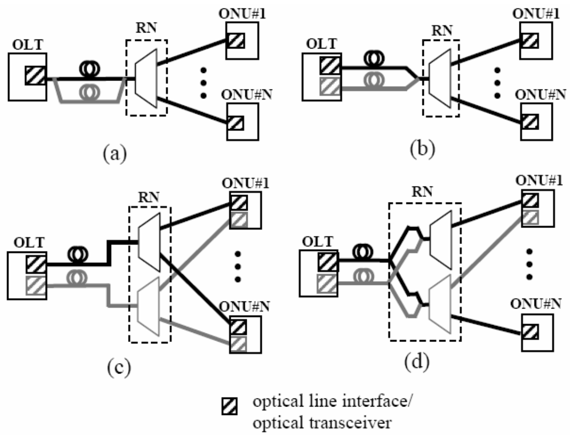

Figure 1: Protection switching architectures for WDM-PONs using the similar approaches suggested by ITU-T G.983.1.

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 re-routing. 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 ONUs. Both the affected downstream and upstream wavelengths would be re-routed 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 [4] 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 and require the fiber connection between two adjacent ONUs. In [5], a novel WDM-PON architecture with protection of both the feeder fibers and distribution fibers were proposed. Both the RN and the distribution fibers were duplicated and interconnected. 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 optical switch at the ONU would be triggered to redirect the disrupted signals to the protection path.

In [6-9], 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. In [9], multiple 2×2 optical switches were employed at the OLT to perform protection switching at the wavelength channel level, as depicted in Fig. 2. The wavelength assignment plan for both the

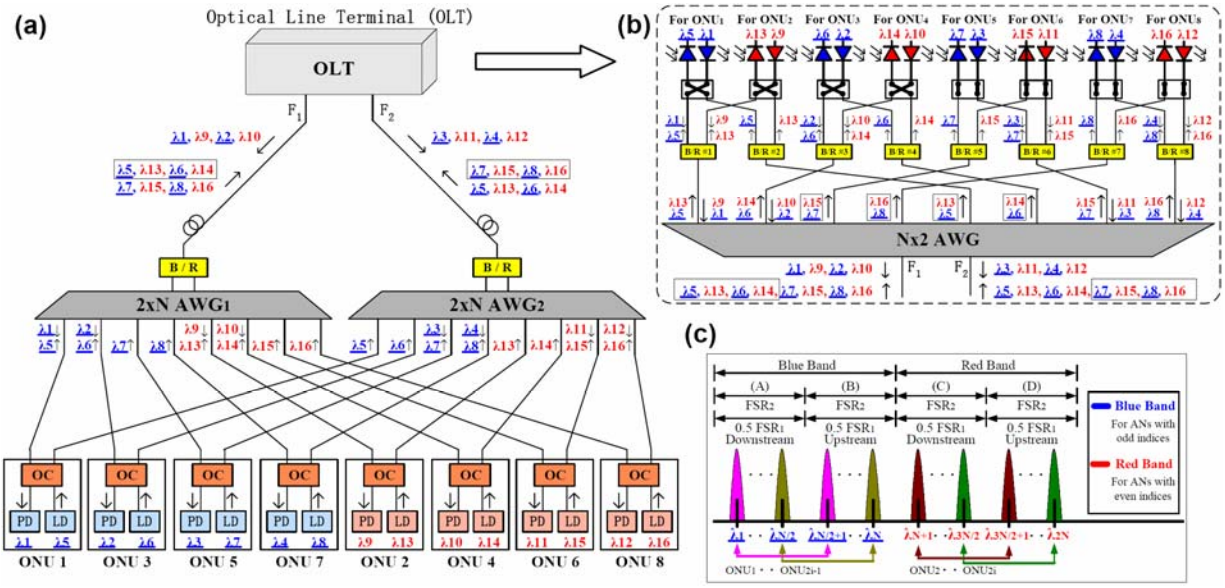

Figure 2: (a) A WDM-PON survivable architecture with eight ONUs with alternate lightpath routing; (b) OLT configuration under normal operation; (c) wavelength assignment plan. B/R: blue/red filter; OC: 3-dB fiber coupler; LD: laser diode; PD: photodiode. Note FSR_1 stands for free-spectral range of the $N\times2$ ($N=8$) AWG at the OLT; while FSR_2 stands for that of both AWG_1 and AWG_2 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 [9].

downstream and the upstream wavelength channels was depicted in Fig. 2(c), utilizing the cyclic properties of the AWGs employed at the OLT and the RN. Therefore, any toggling of the switching state of any optical switch 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.

Besides, there were some other survivable network architectures proposed, such as broadcast-and-select WDM-PON with a ONU group protection [10], WDM-PON with 1:N protected OLT with tunable transceivers [11], WDM-PON with waveband filters for protection [12], and using N×N AWG at the RN [13], etc.

(b) WDM-PONs with Ring Topology

In WDM-PONs with ring topology [14], the OLT is connected to multiple access nodes (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. Similar to conventional PONs with the ring topology, protection is achieved by means of self-healing rings (SHRs). 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.

In [15], 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 [16], optical filters and optical switches were employed at access nodes for wavelength dropping and protection switching respectively. In [16, 17], an AWG add-drop filter was employed as the OADM and a loop back circuit was implemented to provide protection switching at each access node. However, these approaches still require two working fiber paths to support both protection as well as bi-directional transmission. In [18-22], single-fiber bi-directional SHR networks were also reported. This could further reduce the system cost and increase the fiber efficiency.

In [21], a simple single-fiber CWDM optical access ring network with unidirectional OADMs incorporated in the ANs was demonstrated, as shown in Fig. 3. The downstream wavelength channels were power-split and sent along the ring network in both counter-propagating directions. A 2×2 optical switch and a pair of low-cost CWDM OADM was employed at each AN, as shown in Fig. 3(b). When a fiber cut along the ring network was detected, by means of signal loss detection, the optical switches 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, as illustrated in Fig. 3(c). In [22], a single-fiber bi-directional self-healing optical access ring networks with bi-directional OADM was demonstrated. The idea was to apply the same OLT architecture and alternate path switching scheme as in [9] to achieve self-healing function in a single-fiber optical access ring.

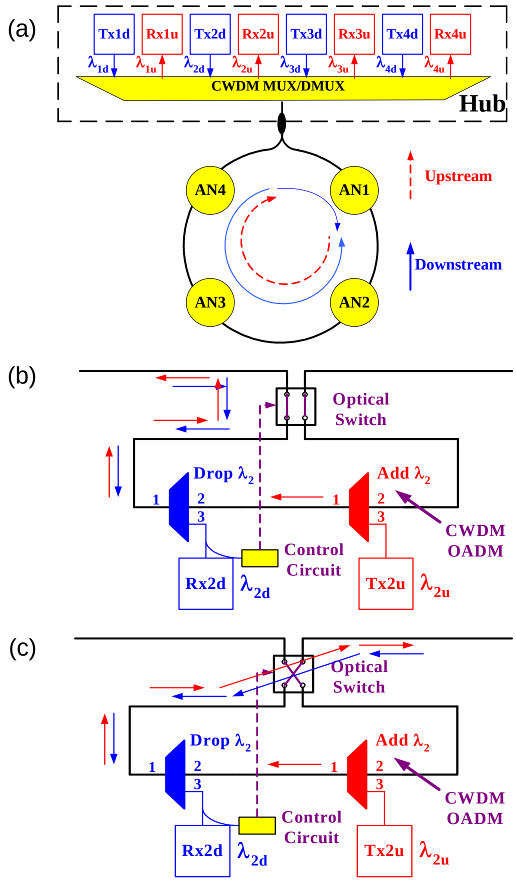

Figure 3: (a) A single-fiber CWDM optical access ring network; (b)&(c) the structure of access node AN2 in (b) normal state; (c) protection state when there was a fiber cut between AN2 and AN3 [21] .

In [23, 24], an interesting protected optical star-shaped ring network was proposed. 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. 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 designated for protection and can be activated by switching the fiber connections at the designated input ports of the AWG, in case of any fiber failure. When a fiber or a network node failed, the protection switch at the OLT would be re-configured to activate the backup wavelength paths, so as to bypass the failed nodes or link.

Summary

With the fast growing deployments of PONs for providing high capacity data and video access in both enterprise and residential services, high network availability should be assured to all subscribers. Therefore, the issue of network survivability has received 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 WDM-PONs have been discussed and some of the recently proposed survivable network architectures for WDM-PONs have been reviewed.

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