A Survivable WDM-PON Architecture With Centralized Alternate-Path Protection Switching for Traffic Restoration

Xiaofeng Sun, Chun-Kit Chan, *Senior Member, IEEE*, and Lian Kuan Chen, *Senior Member, IEEE*

***Abstract*—In this letter, we propose and demonstrate a survivable wavelength-division-multiplexed passive optical network with simple optical network units. By employing our proposed alternate-path switching scheme, the affected traffic can be restored promptly under fiber feeder and distribution fiber link failures as well as the failure at the remote node, simultaneously.**

***Index Terms*—Passive optical network (PON), protection and restoration, wavelength-division multiplexing (WDM).**

I. Introduction

WAVELENGTH-DIVISION-MULTIPLEXED passive optical networks (WDM-PONs) [1] are promising to enhance the penetration of WDM technology further toward the subscriber side and enable the delivery of higher capacity services to the subscribers. Thus, reliable and survivable access network architectures are highly desirable. The ITU-T recommendation on PONs (G.983.1) [2] has suggested four possible fiber duplication and protection switching scenarios for asynchronous transfer mode (ATM)-PONs. However, if the same methodology is applied to WDM-PONs, all in-service wavelength channels may be momentarily interrupted due to any protection switching against even only one distribution fiber failure. Recently, we have proposed a WDM-PON network architecture [3] to provide protection against fiber link failure between the remote node (RN) and the optical network units (ONUs). By interconnecting two adjacent ONUs by a piece of fiber, the affected bidirectional traffic could be rerouted via the adjacent ONU; thus, the optical line terminal (OLT) was transparent to such fiber failure. However, it required optical switches installed at each ONU to perform protection switching.

In this letter, we propose and investigate a survivable WDM-PON with simple ONUs and a pair of AWGs at the RN. By utilizing the spectral periodicity of the AWG at the RN, a novel wavelength assignment plan is proposed and a simple alternate-path switching scheme is employed for protection against both feeder and distribution fiber link failures, as well as the AWG failure at the RN simultaneously. The protection of wavelength paths can be achieved independently and more flexibly.

Manuscript received September 21, 2005; revised December 16, 2005. This work was supported in part by a grant from the Research Grants Council of Hong Kong SAR, China (Project CUHK4216/03E).

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Digital Object Identifier 10.1109/LPT.2006.870135

II. Network Topology and Wavelength Assignment

Fig. 1(a) shows our proposed WDM-PON architecture with N ONUs, where $N = 8$, for example. At the OLT, the downstream signals are multiplexed through an $N \times 2$ AWG and routed either to the AWG_1 in the RN through feeder fiber F_1 or to the AWG_2 through feeder fiber F_2. The ONUs with odd indexes are connected to the first $N/2$ output ports of the AWG_1 and the AWG_2 via 2×2 couplers; while those with even indexes are connected to the last $N/2$ output ports of the AWG_1 and the AWG_2, as shown in Fig. 1(a). Fig. 1(c) illustrates the proposed wavelength assignment plan. For index $i = 1, \ldots, (N/2)$, the wavebands $A(\lambda_i)$ and $B(\lambda_{N/2+i})$ in the blue band (the wavelengths in blue band are underlined) are allocated for the downstream and the upstream wavelength channels of the ONUs with odd indexes (ONU_{2i-1}), respectively, while the wavebands $C(\lambda_{N+i})$ and $D(\lambda_{3N/2+i})$ in the red band (the wavelengths in red band are not underlined) are for the downstream and the upstream wavelength channels of the ONUs with even indexes (ONU_{2i}), respectively. In addition, the free-spectral range (FSR_2) of AWG_1 and AWG_2 at the RN is half of the FSR_1 of the AWG at the OLT. The wavelength λ_i is separated from λ_{N+i} by one FSR_1 of the AWG at the OLT, while the downstream and the upstream wavelengths assigned to each ONU are separated by half of the FSR_1. Under normal operation, each downstream wavelength originated from the OLT is destined for its respective ONUs through either the AWG_1 or AWG_2 at the RN. In contrast, the upstream wavelengths are duplicated by 2×2 couplers at each ONU and traverse toward the OLT via both AWGs at the RN, as illustrated in Fig. 1(a).

III. OLT Configuration and Protection Mechanism

As shown in Fig. 1(b), the OLT consists of an $N \times 2 (N = 2^n)$ AWG and $M (M \leqq N)$ transceivers. Each transceiver, designated for a particular ONU, is associated with a 2×2 optical switch and a blue/red filter. Every two adjacent transceivers form a group and communicate with their respective ONUs, one with odd index $(2i - 1)$ and the other with even index $(2i)$, respectively. Under normal operation, the 2×2 optical switches associated with $\text{ONU}_1, \text{ONU}_2, \ldots, \text{ONU}_{N/2}$ are in cross states, while those associated with $\text{ONU}_{N/2+1}, \text{ONU}_{N/2+2}, \ldots, \text{ONU}_N$ are in bar states to balance the traffic on the AWG_1 and the AWG_2 at the RN. For ONU_{2i-1} (say ONU_1), the transmitter with downstream wavelength λ_i (say λ_1) and the receiver with upstream

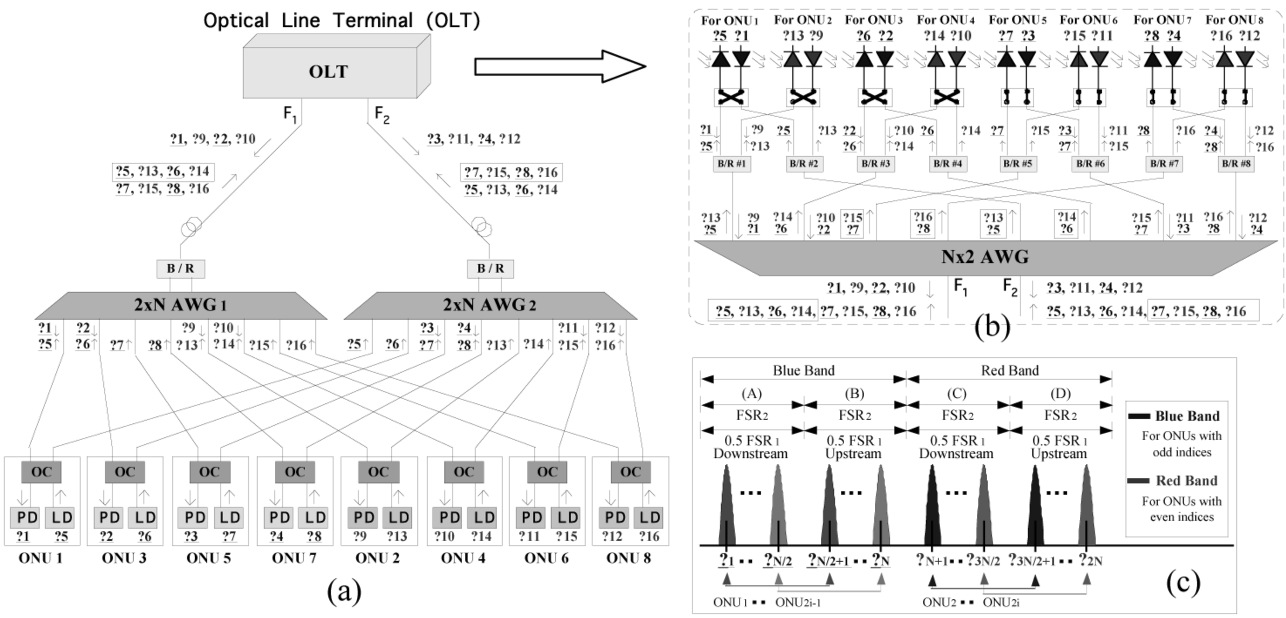

Fig. 1. (a) Proposed WDM-PON Architecture with eight ONUs; (b) OLT configuration under normal operation; (c) wavelength assignment plan. B/R: Blue/red filter; OC: 3-dB fiber coupler. Note FSR_1 stands for free-spectral range of the $N \times 2 (N = 8)$ AWG at the OLT, while FSR_2 stands for that of both 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.

wavelength $\lambda_{N/2+i}$ (say λ_5), both of which are in the blue band, are connected to the respective blue-band ports of the two blue/red filters (say B/R#1 and B/R#2) in the same group, respectively, as depicted in Fig. 1(b) and (c). Similarly, for ONU_{2i} (say ONU_2), the transmitter with downstream wavelength λ_{N+i} (say λ_9) and the receiver with upstream wavelength $\lambda_{3N/2+i}$ (say λ_{13}), both of which are in the red band, are connected to the respective red-band ports of the two blue/red filters (say B/R#1 and B/R#2) in the same group, respectively. In general, the combined port of the B/R#$(2i-1)$ (say B/R#1) and that of the B/R#$(2i)$ (say B/R#2) are connected to the ith (say first) and the $(N/2+i)$th (say fifth) input ports of the $N \times 2$ (say 8×2) AWG, respectively. The spectral transmission peaks of the two output ports of the AWG are spaced by half of its FSR_1, and each of them are connected to the either feeder fiber F_1 or F_2. The downstream wavelengths for the first $N/2$ ONUs (ONU_1 to $\mathrm{ONU}_{N/2}$) will be propagating through AWG_1 at the RN, while those for the last $N/2$ ONUs ($\mathrm{ONU}_{N/2+1}$ to ONU_N) will be propagating through AWG_2 at the RN. At the RN, each of the feeder fibers F_1 and F_2 are connected to a blue/red filter, which is connected to input ports of $2 \times N \mathrm{AWG}_1$ and AWG_2, respectively. The spectral transmission peaks of those input ports are spaced by half of its FSR_2. Thus, the wavelengths in the blue band will be transmitted to the first $N/2$ output ports, while those in the red band will be transmitted to the last $N/2$ output ports. Since the FSR_2 of the AWGs in the RN is half of the FSR_1 of the AWG at the OLT, the downstream and the upstream wavelengths for each ONU will be transmitted through the same output port of the AWGs at the RN. At each ONU, the upstream will be sent out via both AWG_1 and AWG_2, thus, two copies of the upstream wavelengths originating from all ONUs will reach the $N \times 2$ AWG, where they are demultiplexed and routed toward the transceivers at the OLT, via the respective blue/red filters and 2×2 optical switches. One of the copies of the upstream wavelengths traverses through the path which the corresponding downstream wavelength passes would reach their respective upstream receivers; while the other copy of the upstream wavelengths would reach the transmitters where they would be blocked by the built-in optical isolators of all transmitters at the OLT. Fig. 1(a) and (b) illustrates the flow of the downstream and the upstream wavelengths under normal operation.

In case of any fiber cut, the monitor units incorporated before the receivers at the affected ONUs will detect the loss of upstream signals. Such conditions will trigger all the 2×2 optical switches associated with the transceivers designated for the affected ONUs at the OLT to toggle their switching states automatically. As a result, all the blocked downstream wavelengths can be routed to the affected ONUs through the other AWG at the RN along the other available path; while all the respective upstream receivers at the OLT can still receive a copy of the upstream wavelengths. Fig. 2 illustrates the flow of the downstream and the upstream wavelengths when the fiber between RN and ONU_1 is broken, as an example. Under this condition, the downstream wavelength for $\mathrm{ONU}_1(\lambda_1)$ could not reach ONU_1 via the AWG_1. Thus, the protection switching at the OLT reroutes λ_1 to go along the AWG_2 and reach the downstream receiver at ONU_1. At the same time, the upstream wavelength λ_5 from ONU_1 would reach the respective upstream receiver at the OLT via a different path, as illustrated in Fig. 2. In the same way, feeder fiber failure and AWG failure at the RN can be also protected. For example, if feeder fiber F_2 is broken or AWG_2 fails, the four 2×2 switches for ONU_5 to ONU_8 at the OLT will be automatically toggled to cross state so that the affected wavelengths will be rerouted in the alternate path, via AWG_1 and F_1. In order to further ensure the availability of protection path, an extra monitor unit can be incorporated before the isolator in each transmitter at the OLT. The received power of nonworking upstream will be monitored so that the failure of protection path can be corrected in time. With this proposed protection mecha-

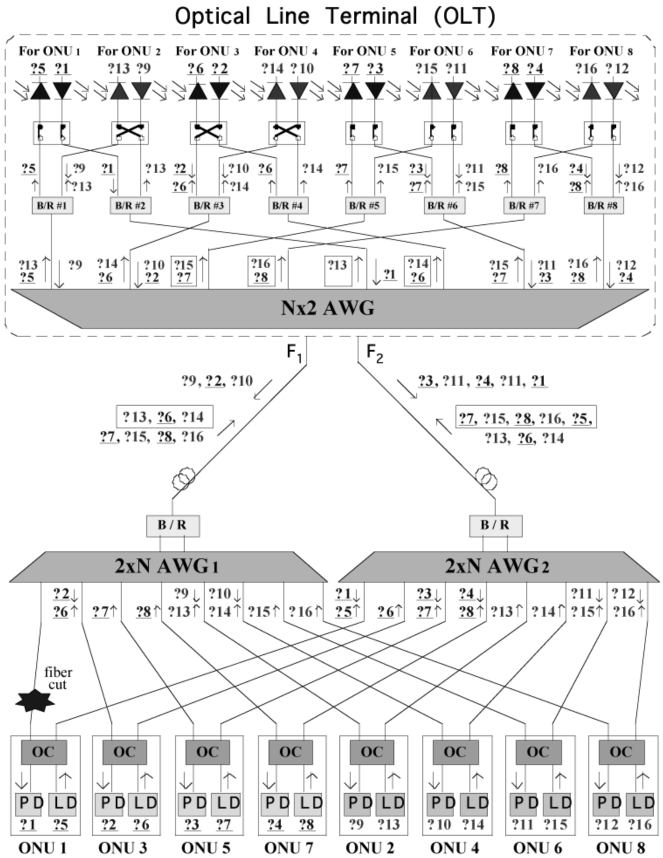

Fig. 2. OLT configuration under distribution fiber link failure ($N = 8$). B/R: Blue/red filter; OC: 3-dB fiber coupler. The wavelengths quoted in boxes are the working upstream wavelengths. The wavelengths in blue band are underlined but those in red band are not.

nism, a fast restoration of fiber failures and AWG failure at the RN can be achieved and all protection switching operations are performed at the OLT only. All the in-service wavelength channels unaffected by the fiber failure will be undisturbed by the protection switching. In regard to system power budget, each wavelength traverses one optical switch (1 dB), two AWGs (at 5 dB), two blue/red filters (at 1 dB), one fiber coupler (3 dB), and about 20-km standard single-mode fiber (SMF) (0.2 dB/km at 1550 nm), thus, the loss budget is about 20 dB.

IV. Experiment Results

The transmission performance and the protection switching of our proposed network were experimentally investigated, using the setup similar to Fig. 1. ONU_1 has been implemented to demonstrate the operation principle. We used 2.5-Gb/s directly modulated DFB laser diodes at the OLT and ONUs. A 16×16 AWG, with 100-GHz channel spacing and an FSR_1 of 12.8 nm, was used at the OLT. It was also connected to two 1×16 AWGs, with 50-GHz channel spacing and an FSR_2 of 6.4 nm, at the RN via a pair of 22-km standard SMFs, as the feeder fibers. The optical spectra of the AWGs in the OLT. The blue/red filters used at the OLT and RN had 18-nm passband at both red and blue bands. Each transceiver at the OLT was

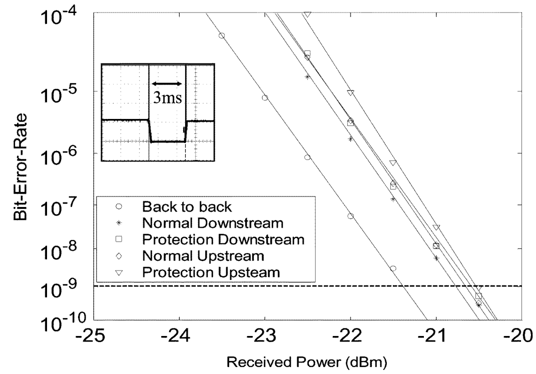

Fig. 3. BER measurement of the 2.5-Gb/s downstream wavelengths for both the normal and the protection modes. Inset shows the switching time measurement under the protection mode.

incorporated with one 2×2 optical switch to reroute the wavelength under the protection mode. Under this configuration, the optical power of the upstream signals from the ONU_1 to the OLT was monitored. Fiber link failures were simulated by disconnecting the fiber connections. The bit-error-rate (BER) performance under both the normal and the protection path was measured and is depicted in Fig. 3. In all cases, the measured receiver sensitivities at BER $= 10^{-9}$ were very close to each other. The small induced power penalty (<0.5 dB) compared to the back-to-back measurement was due to chromatic dispersion of the directly modulated wavelength channels.

The switching time in case of the simulated fiber cut was also at the monitoring unit in OLT, and was measured to be about 3 ms, which was determined by the switching response of the optomechanical switch employed in the experiment. This corresponded to the network traffic restoration time achieved.

V. Conclusion

We have proposed and experimentally investigated a survivable WDM-PON. By incorporating optical switches and filters into the OLT, and by duplicating the AWG in the RN, full protection against fiber feeder and distribution fiber link failures as well as the AWG failure in the RN can be achieved simultaneously. With the proposed alternate-path switching scheme, the protection switching is performed at the OLT only and all the wavelength channels unaffected by the fiber failure will be transparent to the protection switching. In addition, the ONU is kept simple without any optical switches. The complexity at the OLT is justified by easy centralized network management and cost-sharing among all subscribers.

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Comments and Corrections

Corrections to "Estimating Intensity Fluctuations in High Repetition Rate Pulse Trains Generated Using the Temporal Talbot Effect"

Dominik Pudo and Lawrence R. Chen

In the above paper [1], equation (3) contained an error. The correct equation is shown below:

$$o_k(t) = \frac{1}{m} H_0 \sum_{q=0}^{m-1} \sum_{p=-\infty}^{\infty} e^{j\left(2\pi p \frac{q}{m} + sq^2 \frac{\pi}{m}\right)} \cdot a_k(t - p \cdot T/m), \quad k = 0, \ldots, m-1. \quad (3)$$

In addition, the correct e-mail address for D. Pudo is dpudo@photonics.ece.mcgill.ca.

References

[1] D. Pudo and L. R. Chen, "Estimating intensity fluctuations in high repetition rate pulse trains generated using the temporal Talbot effect," *IEEE Photon. Technol. Lett.*, vol. 18, no. 5, pp. 658–660, Mar. 1, 2006.

Manuscript received February 16, 2006.
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Digital Object Identifier 10.1109/LPT.2006.872194

Erratum to "A Survivable WDM-PON Architecture With Centralized Alternate-Path Protection Switching for Traffic Restoration"

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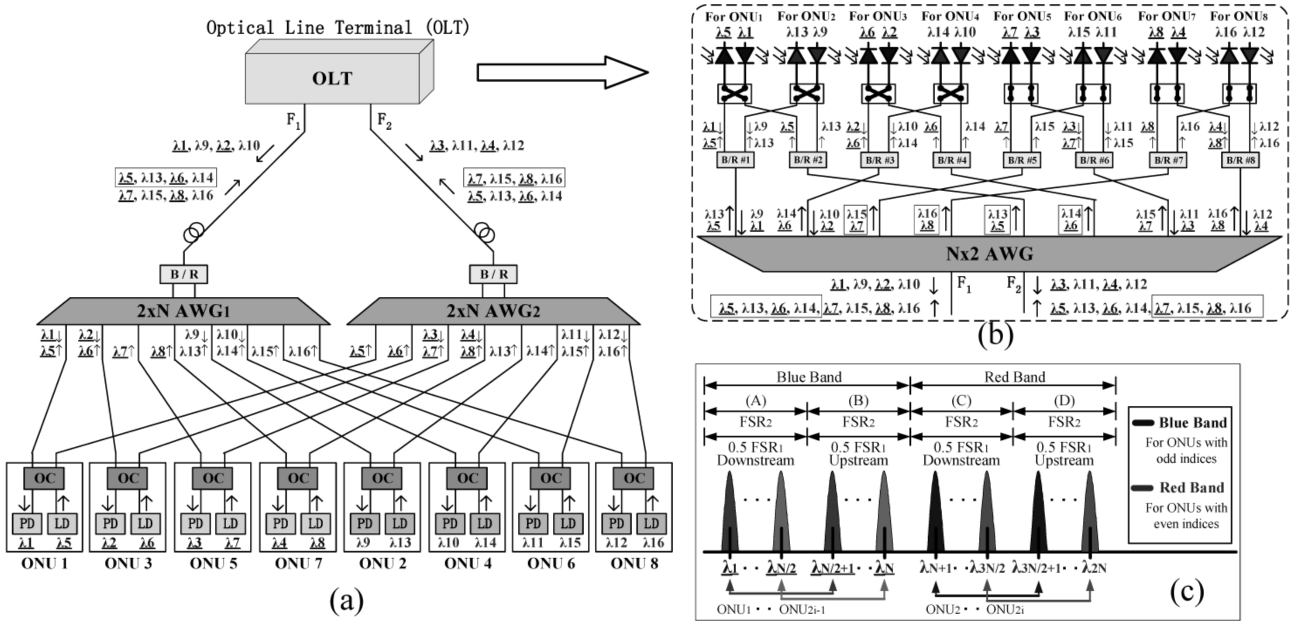
In the above paper [1], Figs. 1 and 2 were incorrect. The correct figures are shown on the next page.

figures are shown on the next page.

Manuscript received February 15, 2006.
The authors are with the Department of Information Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China (e-mail: ckchan@ie.cuhk.edu.hk).
Digital Object Identifier 10.1109/LPT.2006.872195



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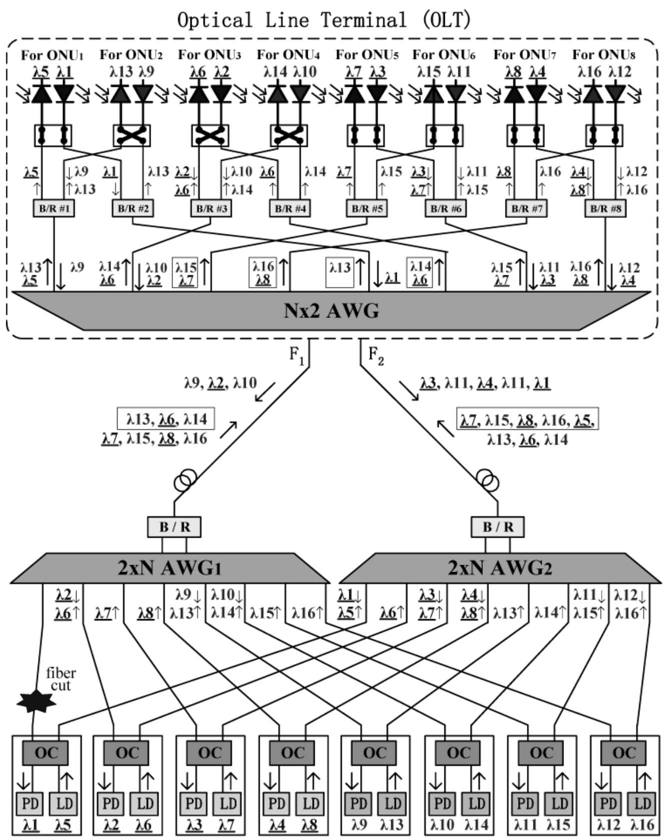

Fig. 2. OLT configuration under distribution fiber link failure $(N = 8)$. B/R: Blue/red filter; OC: 3-dB fiber coupler. The wavelengths quoted in boxes are the working upstream wavelengths. The wavelengths in blue band are underlined but those in red band are not.

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