Demonstration of a Single-Fiber Self-Healing CWDM Metro Access Ring Network With Unidirectional OADM

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***Abstract*—A simple and effective coarse wavelength-division-multiplexing metro access network architecture with unidirectional optical add–drop multiplexer (OADM) for automatic optical protection in a hub/access-node single-fiber ring is proposed and experimentally demonstrated. This physical-ring/logical-star architecture greatly simplifies the design compared with previous works requiring bidirectional OADM.**

***Index Terms*—Networks, protection, wavelength-division multiplexing (WDM).**

I. Introduction

RECENTLY, hub/access-node ring architecture has emerged as a promising approach for wavelength-division-multiplexing (WDM) metro-access ring networks. The traffic from the access nodes (ANs) is transmitted/received to/from a hub, and the hub is responsible for controlling and exchanging the traffic between the ANs and the higher layer network. Multiple optical transceivers, each of a distinct wavelength, are resided at the hub; while each of them serves the point-to-point communication between the hub and the designated AN. Hence, this effectively forms a physical-ring/logical-star architecture. Conventionally, dual rings have been employed for protection against fiber failure [1], [2]. Nevertheless, a single-fiber bidirectional self-healing ring [3], [4] has recently been emerging, for reducing the required amount of fiber by half. However, they were mostly based on the specially designed bidirectional add–drop multiplexer (BADM) [3], [4], which made the network design complicated. In this letter, we propose and experimentally demonstrate a simple and effective coarse wavelength-division-multiplexing (CWDM) hub/access-node single-fiber ring network architecture with automatic protection against any fiber failure. It utilizes the commercially available low-cost thin-film unidirectional optical add–drop multiplexer (OADM), instead of BADM, at each AN. As a result, the network design is greatly simplified and thus becomes more cost-effective.

Manuscript received July 26, 2005; revised August 31, 2005. This work was supported in part by a research grant from the Research Grants Council of Hong Kong SAR, China (Project CUHK4216/03E).

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Digital Object Identifier 10.1109/LPT.2005.860400

II. Proposed Network Architecture and Protection Principle

In [3] and [4], the multiple wavelength channels are divided into two groups: one for the working channels and the other for the protection channels (or carrying the low priority traffic without protection). They are counterpropagating in clockwise (CW) and counterclockwise (CCW) directions, respectively, toward the destined AN, in which a specially designed BADM is used. If the working channel fails due to fiber cut, the traffic will be switched to the protection channel automatically, thus assuring the survivability of the system. However, the ring network can also be viewed from another perspective, which provides two different paths for the same connection between the hub and any AN. Thus, one path can be assigned as the working path and the other as the protection path. Under normal operation, these two different paths carry the same traffic for the connection and the destined AN retrieves the traffic from the working path. However, in case of fiber failure in the working path, the AN can switch to the protection path to retrieve the same traffic. With this optical path diversity, fast traffic restoration can be achieved.

Fig. 1(a) shows the proposed CWDM metro access network architecture with protection function. It consists of one hub and N ANs (here, $N = 4$ for simplicity) distributed around a single-fiber ring. At the hub, it includes N pairs of CWDM transmitters (Tx) and receivers (Rx), one CWDM multiplexer/demultiplexer (MUX/DMUX), and one 1×2 50/50 fiber coupler. Each pair of Tx and Rx corresponds to one AN, responsible for the downstream and the upstream traffic respectively. For each Tx or Rx, a distinct wavelength is assigned. For instance, Tx2d at the hub with the wavelength λ_{2d} is designated for transmitting the downstream communication with AN2; while Rx2u with the wavelength λ_{2u} is for receiving the upstream traffic from AN2. The hub is connected to the ring via the 1×2 50/50 fiber coupler. The ANs are labeled in ascending order along the CW direction on the ring network.

Fig. 1(b) illustrates the structure of AN2, for example. It consists of one 2×2 optical switch, one unidirectional CWDM OADM, and a pair of Rx and Tx, which are named as Rx2d and Tx2u, and are matched to the Tx2d and Rx2u at the hub, respectively. This OADM is responsible to add channel λ_{2u} and to drop channel λ_{2d} at AN2. The channel add–drop is performed via commercially available low cost CWDM three-port thin film filters (TFFs). For a specific CWDM wavelength, it can be dropped from Port 1 to Port 3 or added from Port 3 to Port 1. For other wavelengths, they can pass between Port 1 and

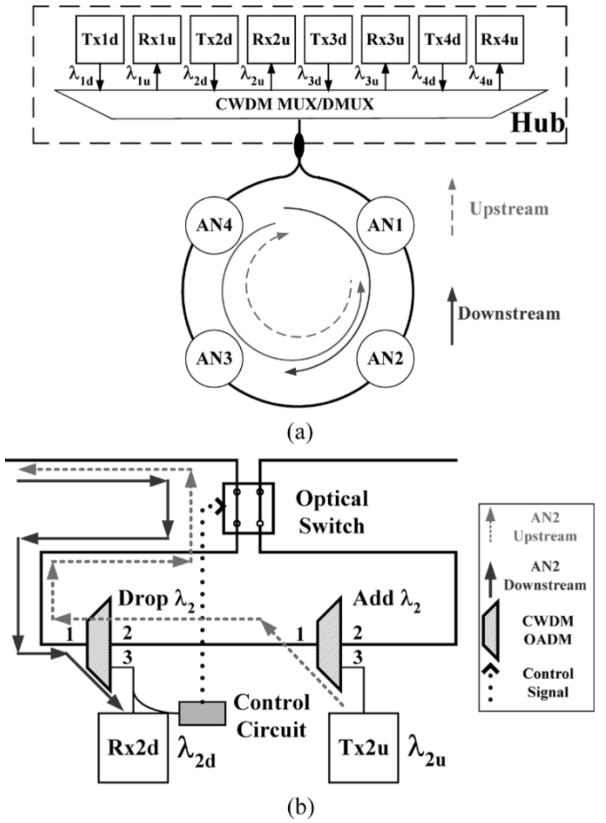

Fig. 1. (a) Proposed network architecture. (b) Structure of AN2 in the normal state: solid and dashed arrows show the routing paths of the downstream and upstream traffic of AN2, respectively; both of the traffic for AN2 will pass through the left-hand fiber, so AN2 can receive/send data from/to the hub through the CCW/CW direction.

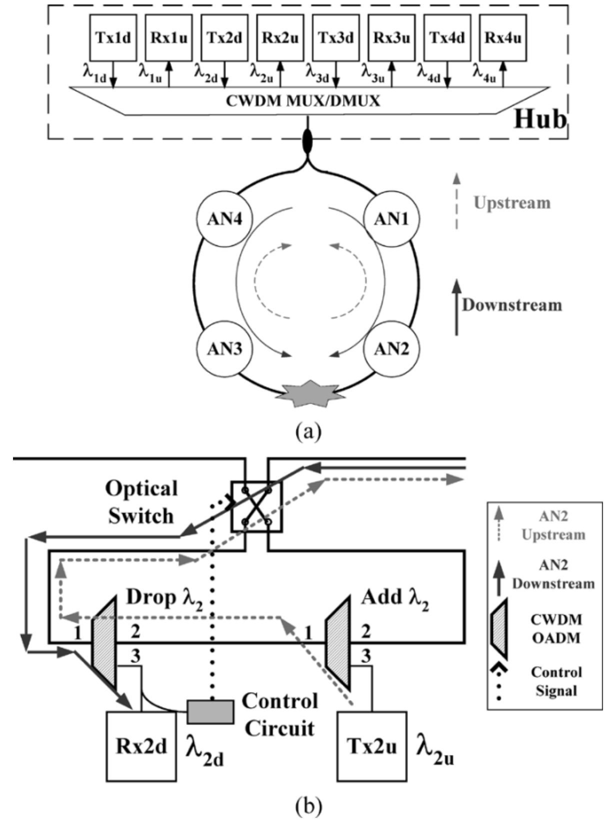

Fig. 2. (a) Network structure in case of fiber cut between AN2 and AN3. (b) Structure of AN2 in the protection state: solid and dashed arrows show the routing paths of the downstream and upstream traffic of AN2, respectively; both of the traffic for AN2 will pass through the right-hand fiber, so AN2 can still communicate with the hub via the other direction of the ring without interrupting other in-service data streams.

Port 2 without any restraint. Under normal operation, the 2×2 optical switch is set in bar state. Thus, AN2 can receive/send data from/to the hub through the CCW/CW direction. For other wavelength channels that are not destined to AN2, they can just pass through AN2 from either direction.

Fig. 2 illustrates the protection mechanism of the proposed network architecture, in which a fiber failure occurs between AN2 and AN3, for example. In this case, the control circuit [5] at AN2 as well as all subsequent ANs in the CCW direction (e.g., AN1) detects the loss of the downstream signal from the CCW direction. This automatically triggers its optical switch to change from bar state to cross state. Hence, AN2 as well as all affected ANs (say AN1) can still communicate with the hub via the CW direction of the ring without interrupting other in-service data streams. AN3 and AN4 remain unaffected. Consequently, the affected traffic due to the fiber failure are promptly restored and, thus, this assures the survivability of the proposed network.

III. Experiments

The experimental setup was similar to Fig. 1 except that it only includes one hub and three ANs: AN1, AN2, and AN3, in ascending order along the CW direction on the ring network. The lengths of single-mode fiber spans between the hub and AN1, AN1 and AN2, AN2 and AN3, AN3 and the hub are 8.8, 6.6, 1.0, and 8.8 km, respectively. Six commercial CWDM Gigabit Ethernet (GbE) small form pluggable (SFP) transceivers were used for the demonstration. In principle, the wavelengths can be assigned freely. In our experiment, we adopted the following allocation plan. AN1 was assigned with 1590 and 1510 nm for the downstream and the upstream, respectively. Similarly, AN2 was assigned with 1610 (downstream) and 1530 nm (upstream); while AN3 was assigned with 1570 (downstream) and 1490 nm (upstream). The optical switches used at the ANs were commercially available optomechanical switches, and their switching times (including the response time of the control circuit) were measured to be 5 (at AN1), 3 (at AN2), and 8 ms (at AN3), respectively. The discrepancy in the switching time was due to the variance in the product performance. However, the switching times for all of the switches were below 10 ms. To simulate the fiber cut scenario, the fiber link between AN2 and AN3 was intentionally disconnected. With our proposed automatic protection scheme described above, the affected AN1 and AN2 could automatically restore their traffic.

With this setup, we measured the bit-error-rate (BER) performance using 1.25-Gb/s $2^{23}-1$ pseudorandom binary sequence data for both upstream and downstream traffic of AN1 and AN2 in normal and protection modes, and the measurement results were depicted in Fig. 3. Here, the 1.25-Gb/s data was used to represent the data rate of GbE signal. In all cases, the measured receiver sensitivities varied from -28.0 to -26.5 dBm and the induced power penalties were negligible (<0.5 dB), which were attributed to the chromatic dispersion of the fiber. It showed that

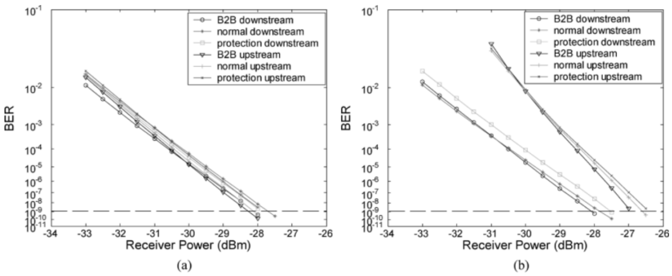

Fig. 3. BER measurements under normal and protection modes: (a) AN1; (b) AN2.

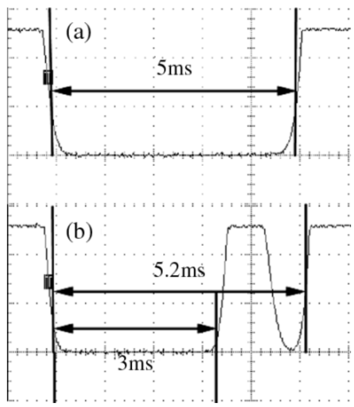

Fig. 4. Measured protection characteristics by monitoring the received power of the downstream signals: (a) AN1; (b) AN2.

Rayleigh backscattering and channel crosstalk had negligible system degradation. The discrepancy in the BER slopes of the upstream and the downstream data may be attributed to the different performance of the respective receivers. By monitoring the received power of the downstream signal at AN1 and AN2, we have also measured the restoration times in case of the simulated fiber cut, and the results are shown in Fig. 4. The measured restoration times were about 5 (at AN1) and 5.2 ms (at AN2), respectively. The restoration time curve of AN2 is more complicated than that of AN1, implying the restoration procedure of AN2: At first, the AN2 will detect the signal power drop and change its switching state (switching time: 3 ms) to obtain the traffic from another direction, as indicated in Fig. 4(b). At the same time, AN1 will also change its own switching state to react to the fiber cut, causing a temporary traffic interrupt. Since the switching time of AN1 is larger than that of AN2, AN2 will be influenced by this interrupt, showing another signal power drop on the curve, until the switch state of AN1 becomes stable. For a larger ring network which involves more ANs, the transients might become more complicated and cause the oscillations of the switching states. To solve this problem, a wait period could be added to the control circuit at each AN such that its switching can be completed at the time instant when all relevant switching transients from other affected ANs have ceased. This wait period at each AN could be determined by subtracting its intrinsic switching time from the maximum switching time among all ANs. The signal propagation time between the ANs would be negligible as it is usually much shorter than 1 ms for metro-access applications. Consequently, traffic restoration of the whole system could be achieved with a total restoration time no more than the maximum switching time among all ANs.

IV. Discussion

In such a single-fiber ring network with bidirectional transmission, Rayleigh backscattering induced crosstalk might degrade the system performance. The induced crosstalk can be divided into interband crosstalk and intraband crosstalk. When the counterpropagating signals are of different wavelengths, interband crosstalk exists. However, with our proposed scheme, this crosstalk can be readily filtered out by the in-line WDM devices. When the wavelengths of the counterpropagating signals are the same, it will cause intraband crosstalk, but this situation will not occur in this scheme. For the upstream traffic, it will choose only one path from the AN to the hub; for the downstream traffic, the traffic from both directions will terminate on the same OADM (one is dropped and the other is blocked by this OADM). As a result, the Rayleigh backscattering have practically no effect on the performance of the system, as observed in our experiment. This is indeed an advantage of our proposed architecture.

Without the optical amplification, the power budgets of the GbE transceivers used in the experiment are above 26 dB. The insertion losses of the CWDM MUX/DMUX and the 1×2 fiber coupler are about 1 and 3.2 dB, respectively. When the signal passes through each AN, it will suffer from about 1-dB power loss, due to the in-line TFF and the optical switch. We assume the total ring length is 20 km. Since the fiber loss over the entire CWDM wavelength range (except the wavelengths residing near the water peak) is no more than 0.5 dB/km, the transmission loss budget will be up to 10 dB. Thus, the proposed network can support 12 ANs.

V. Summary

We have proposed and demonstrated a simple and effective CWDM metro access network architecture using unidirectional OADMs for optical protection in a hub/access-node single-fiber ring. The transmission characteristics using 1.25-Gb/s CWDM transceivers and fast automatic protection against fiber failure have been experimentally demonstrated and characterized. This physical-ring/logical-star architecture provides greater simplicity over previous designs requiring bidirectional ADM. This CWDM metro access network architecture is data rate transparent and can be readily extended for application in multiwavelength 10-GbE single-fiber ring networks.

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