A Novel Optical-Path Supervisory Scheme for Optical Cross Connects in All-Optical Transport Networks

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***Abstract*—We propose and demonstrate a novel and effective supervisory scheme to monitor the optical-path routing at the optical cross connects in all-optical transport networks. Any error in optical-path routing due to failure in the cross connect can be detected without tapping off the power at the data wavelengths, and no dedicated monitoring light source is required. The scheme supports in-service surveillance. It can facilitate the network management in the optical layer of all-optical and reconfigurable transport networks.**

***Index Terms*—Fault detection, optical cross connects, optical networks, wavelength routing.**

I. Introduction

OPTICAL cross connects (OXC's) [1] are one of the most critical enabling technologies that, together with other network elements, offer scalability, high throughput, and multiaccess capability in all-optical wavelength routing networks. Through the OXC's, wavelength channels from various sources are routed to their respective destinations in accordance to the prescribed switch settings registered in a routing control module residing at these devices. These settings define the optical paths for different wavelength channels from different input fibers and will be reconfigured by the network configuration management prior to each data transmission.

While the transmission of the signaling control is tightly controlled and corruption in the messages is highly unlikely, a partial or complete failure, or malfunction in the optical switches in OXC's [2], [3] will route streams of data to completely wrong destinations and lead to data loss. It is, therefore, of immense interest to develop a surveillance scheme at each OXC such that any routing failure can be detected at the earliest possible stage.

Optical-path management schemes based on a pilot tone [2] and a supervisory channel [4] were previously proposed, but these schemes sacrificed data transparency and privacy, thus are intrusive in nature. In this letter, we propose a novel and nonintrusive surveillance scheme for monitoring the wavelength-routing status at OXC's. The OXC's we considered are the types without wavelength conversions. The basic principle of operation is to assign each input fiber of the OXC with a unique identification (ID), which will be detected and processed immediately at each output port without tapping off any power at the data wavelengths. Thus, any failure or incorrect physical connection at the switches can be detected at once by comparing the as-detected physical connection and the switch-setting information stored in the routing control module. The detected failure will be reported to the central office at once. This not only facilitates fault identification, but also alerts the network configuration management such that network downtime and data loss can be kept at a minimum.

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II. Proposed Surveillance Scheme for OXC

Fig. 1 shows the proposed surveillance scheme for an $N \times N$ OXC, which can be formed by a total of $2N$ (N incoming and N outgoing) $1 \times M$ arrayed waveguide gratings (AWG) interconnected by M banks of $N \times N$ optical space switches, assuming that there are M data wavelengths ($\lambda_1, \cdots, \lambda_M$) carried on each input fiber. Identical wavelength channels but from different input fibers will be routed by the same $N \times N$ optical switch to various output fibers in accordance to the routing assignment kept in the routing control module. We assume that there is an erbium-doped fiber amplifier (EDFA) at each input port of the OXC for gain equalization [5] and loss compensation. The free spectral range ($\mathrm{FSR_{AWG}}$) of the AWG is chosen to be less than one-half of the usable gain spectrum of the EDFA. Because of the periodicity property of the AWG, there exists both routed wavelength channels and filtered amplified spontaneous emission (ASE) located at one $\mathrm{FSR_{AWG}}$ from the corresponding routed wavelength channels at the output ports (see Fig. 1, inset 1).

A unique and distinct ID will be introduced to each input fiber. To generate the ID tag for the ith input port ($i = 1, \cdots, N$), a small portion of the ASE is looped back to the input of $\mathrm{EDFA_i}$ through a scanning Fabry–Perot filter (FPF) modulated at a distinct sinusoidal frequency f_i (~kHz) (see Fig. 1, inset 2). The loopback configuration generates lasing action and the amplifier gain is clamped [6]. The selected scanning spectral range of the FPF should span at least one $\mathrm{FSR_{AWG}}$ over a portion of the EDFA spectrum which is unoccupied by the data channels. Accordingly, for a wavelength channel at λ_k being routed by the OXC from the ith input fiber to the jth output fiber, there appears an ID tag on the jth output fiber, located at one $\mathrm{FSR_{AWG}}$ from λ_k,

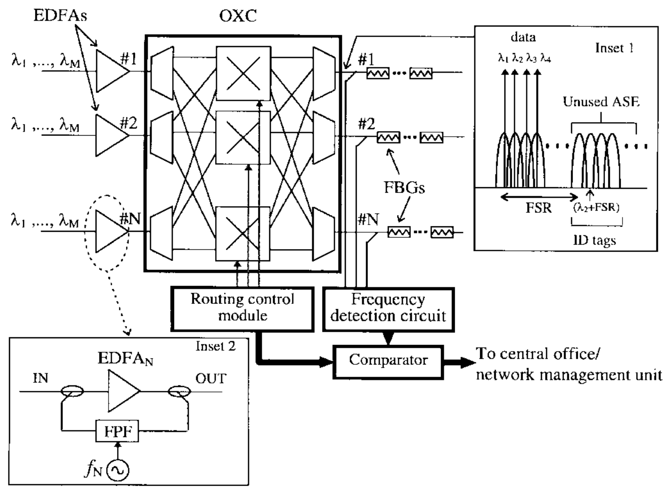

Fig. 1. Proposed optical-path supervisory scheme for an OXC in an all-optical transport network. In this scheme, both routed data channels and filtered ASE (located at one $\mathrm{FSR}_{\mathrm{AWG}}$ form the corresponding routed data channel) emerge from the output ports (inset 1). Inset 2 illustrates how a channel ID can be generated.

(e.g., $\lambda_{\mathrm{ID}\text{-}k} = \lambda_k + \mathrm{FSR}_{\mathrm{AWG}}$; $k = 1, \cdots, M$), and represented by periodic pulses that correspond to the power fluctuation at $\lambda_{\mathrm{ID}\text{-}k}$ with an frequency of f_i. Such power fluctuation at $\lambda_{\mathrm{ID}\text{-}k}$ is due to the periodic scanning lasing at the ith input port. Thus, there will be M ID tags on each output fiber, each signifying the input fiber in which the corresponding data channel is routed from. Note that the ID's for different wavelength channels will not be mixed up because no two data channels of identical wavelengths will be routed to the same output port.

On each output fiber, fiber Bragg gratings (FBG) with center wavelengths at $\lambda_{\mathrm{FBG}\text{-}k} = \lambda_{\mathrm{ID}\text{-}k}$ (for $k = 1, \cdots, M$) are used to drop the ID tags through circulators. The ID tags can be either demultiplexed [7], or scanned by an FPF before being detected by photodiodes. A frequency detection circuit is then used to recover the frequency of the detected pulses at each ID tag. For instance, a recovered frequency f_r (for $r = 1, \cdots, N$) of the detected pulses at $\lambda_{\mathrm{ID\text{-}k}}$ indicates that the wavelength channel λ_k has been routed from the rth input fiber. By comparing the as-detected physical connection with the prescribed switch settings stored in the routing control module, any failure or error in routing can immediately be detected. Finally, a broad-band rejection filter is to be placed after all the FBG's on each output fiber to eliminate the ID's, and new ID's will be generated at the input ports in the next OXC.

III. Experimental Results

Fig. 2 shows our experimental setup. In our experiment, a thermally stabilized 16 $\times$ 16 AWG with a channel spacing of 100 GHz, an $\mathrm{FSR}_{\mathrm{AWG}}$ of 12.8 nm and a 3-dB full-width of 0.4 nm in a loopback configuration is used to simulate the OXC. Two EDFA's (EDFA_1 and EDFA_3) with similar gain outputs are placed at the input ports 1 and 3 of the AWG, respectively. Output ports 4 and 6, which correspond to the routing of two different data channels but of identical

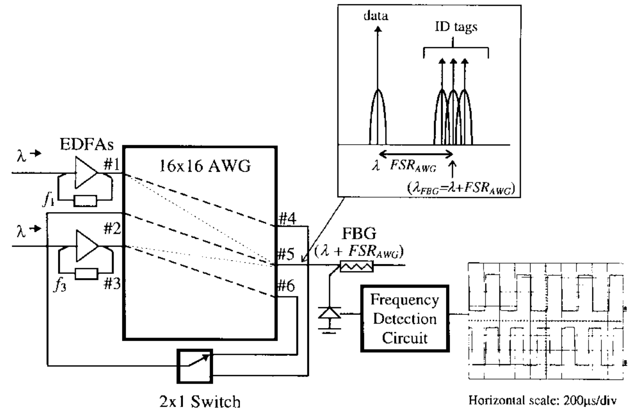

Fig. 2. Experimental setup. The inset shows the detected and recovered channel ID at output fiber #5 when the 2 $\times$ 1 switch input is connected to output fiber #4 (upper trace, $f_1 = 2.5$ kHz) and #6 (lower trace, 3 kHz). The horizontal scale: 200 μs/div.

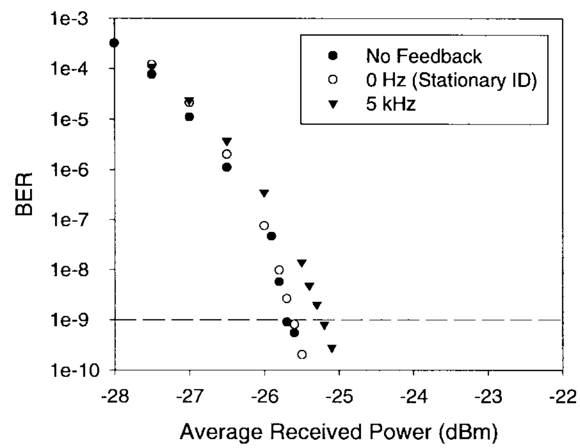

Fig. 3. BER performance of the data channel with and without the proposed supervisory scheme. The data channel is externally modulated by a 1-Gb/s $2^{15}-1$ NRZ PRBS and the channel ID is set at 5 kHz.

wavelength at $\lambda = 1546.7$ nm from input ports 1 and 3, are looped back to input port 2 through a 2 $\times$ 1 optical switch (insertion loss $=$ 0.3 dB and switching time $=$ $\sim$300 ms). The resultant configuration can route the data channel λ, from either input port 1 or 3 to output port 5, depending on the state of the 2 $\times$ 1 optical switch. This configuration also generates three neighboring ID's at output port 5, two originating from one input EDFA and one from the other, which allows us to study the worst-case scenario of the neighboring ID tags. An FBG with a center wavelength of $\lambda_{\mathrm{FBG}} = \lambda_{\mathrm{ID}} = 1559.5$ nm (one $\mathrm{FSR}_{\mathrm{AWG}}$ away from λ), a power reflectivity of 54 dB and a 3-dB full-width of 1 nm, is placed at the output port 5 for reflecting the power at λ_{ID} (ID).

To generate the channel ID, a small portion from each of the amplifiers' outputs (through a 95:5 coupler) is fed back to its input (through a 50:50 coupler). A tunable FPF of finesse 100 with a 3-dB bandwidth of 0.7 nm is placed in between the couplers at each input fiber 1 and 3. By applying a sinusoidal voltage of 0.4 V (peak-to-peak) at 2.5 kHz to the FPF at input port 1 and an identical voltage at 3 kHz to the FPF at input port 3, we thus obtain the ID's for the input ports 1 and 3, respectively.

A simple detection circuit is implemented after the photodiode and is used to recover the fluctuation frequency of the power reflected from the FBG, which is the ID for the data channel. Inset in Fig. 2 shows the recovered waveforms of the detected ID when the 2×1 switch is in two different states. The frequency of the pulse pattern changes from 2.5 to 3 kHz when the 2×1 switch's input is changed from output port 4 to port 6, and vice versa. This shows our scheme can effectively detect the routing status at the OXC.

BER measurements were also performed for the data channel at λ, externally modulated by a 1-Gb/s $2^{15}-1$ nonreturn-to-zero (NRZ) pseudorandom bit sequence (PRBS) data stream, for a channel ID frequency of 5 kHz. The results are displayed in Fig. 3, showing that there is no observable power penalty arising from the FPF. Since the scanning range used in our experiment is close to the falling edge of the amplifier gain spectrum, we observed a gain dependence on the amplifier spectrum, causing the data's eye-pattern "breathing" at the same rate of the scanning frequency. This feature eventually limits the range of usable bandwidth and thus the number of data channels operated under this supervisory scheme. For better operation, the scanning range for the channel ID's should be chosen within the flatter gain (unused ASE) spectrum to avoid the gain dependence effect.

IV. SUMMARY

We have proposed and demonstrated the principle of operation of a novel and effective supervisory scheme to monitor the optical-path routing at the optical cross connects in all-optical transport networks. Any error in optical-path routing due to failure in the cross connect can be detected without tapping off the power at the data wavelengths, and no dedicated monitoring light source is required. The scheme supports in-service surveillance. It can facilitate the network management in the optical layer of all-optical and reconfigurable transport networks.

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