# An optical-path supervisory scheme for optical cross-connects using pilot-tones

E. Kong, F. Tong, K.-P. Ho, L.-K. Chen, and C.-K. Chan[1],
Department of Information Engineering, The Chinese University of Hong Kong, Shatin, Hong Kong
[1]Department of Electrical Engineering, City University of Hong Kong, Kowloon Tong, Hong Kong

All-optical WDMA transport networks depend critically on the functioning of the optical cross-connects (OXCs) [1] that are responsible for routing wavelength channels to their respective destinations. Failure of the optical switches in OXCs will route the channels to the wrong destinations, degrading the network performance. Fault detection in channel add-drop and routing is thus of vital significance [2,3]. We propose an optical-path supervisory scheme for OXCs by imposing pilot tones onto input wavelength channels as channel identifications (IDs). Using RF pilot tones to supervise wavelength channels along their optical paths was suggested previously in [4], where crosstalk among pilot tones in Erbium doped fiber amplifiers (EDFAs) was also measured.

Figure 1 shows our proposed optical-path supervisory scheme. The ID is formed by superimposing a frequency tone $f_i$ using an optical modulator on all wavelength channels carried by fiber $i$. On the output side, the ID on each wavelength channel will be detected by tapping a small fraction of the optical signals from each output fiber. The tapped outputs are connected to a tuneable photoreceiver through an optical switch as shown. Each output fiber is selected in turn, and wavelength channels in each fiber will then be selected by the scanning fiber Fabry-Perot filter. By comparing the detected physical connections with the switch settings, any error in routing can immediately be detected. Finally, EDFAs are placed at the output ports to eliminate the IDs through gain saturation, so new IDs can be added at the input port of the next OXC.

Our supervisory scheme is limited by the EDFA gain characteristics. If complete gain saturation does not occur, the IDs will not be eliminated, and residual amplitudes will accumulate. The residual ID amplitudes can be estimated using the modulation index $m$ ($m$<<1) imposed on wavelength channels. The signal together with the ID is given by $1/2[P_o+ P_1d_1(t)]\cdot[1+m\sin(2\pi f_1t+\phi_1)]$, where $[P_o + P_1d_1(t)]$ describes the ON-OFF modulation of the input data. Through gain saturation, the sinusoidal modulation of the ID will be reduced by a factor of $r$ ($r << 1$) by the optical amplifier, which is defined as the ratio of the output optical modulation index to the input optical modulation index. Traversing $N$ stages of OXC, the total modulation can be approximated by:

$$\frac{1}{2}[P_o + P_1 d_1(t)]\cdot[1 + m\cdot\sin(2\pi f_N t + \phi_N) + m\cdot\sum_{j=2}^{N} r^{j-1}\cdot\sin(2\pi f_{j-1}t + \phi_{j-1})]$$

where the first and the second sinusoidal terms describing the modulation of the current and the sum of previous IDs, respectively. We have dropped all terms describing beatings, which contain multiple orders of $m$.

Two worst case scenarios can be observed when setting the decision threshold at $m/2$ and assuming the frequencies and the phases of the previous channel IDs are identical. First, the amplitude of all accumulated previous IDs of frequency $f_k$ is larger than that of the current ID of frequency $f_i$ ($f_i \neq f_k$), corresponding to $m\sum_{j=2}^{N} r^{j-1} > m/2$. Second, the amplitude of the current ID of frequency $f_i$ is cancelled by the accumulated IDs of the same frequency but with phase difference of $\pi$, $m - m\sum_{j=2}^{N} r^{j-1} < m/2$. For both cases the expression simplifies to $(r-r^N)/(1-r) <1/2$, which gives $r <1/3$ for large $N$. Therefore, as long as $r$ is smaller than 1/3, our path-supervisory scheme can be applied with an infinite number of cascaded OXCs.

Figure 2 shows our experimental setup consisting of a thermally stabilized $16 \times 16$ AWG (channel spacing of 100 GHz) to simulate the OXC. An intensity-modulated optical data channel (1 Gbps, $2^{15}$-1 NRZ PRBS) at $\lambda$=1546.7 nm is imposed with an ID via a Mach-Zehnder modulator with a cosine wave of $f_1$ =100 Hz before feeding into input port #1 of the AWG. Two EDFAs with optical gain of 17 dB each are placed at port #6 which is the output port of the data channel. The first EDFA acts as a limiting amplifier for the second, saturating all incoming channels such that the ID in each routed wavelength channel is much reduced. In our experiment, a 5% tap is used to connect each output port to a photoreceiver through an $8 \times 1$ optical switch (coupling loss of 0.3 dB, switching time of 300 ms) followed by a scanning Fabry-Perot filter as shown. In order to simulate the cascade of two OXCs, the output port #6 is looped back to input port #2 but with a new ID of $f_2$ =90 Hz. The inset of Figure 2 shows the resultant frequency spectra of the IDs ($f_1$ =100 Hz, $f_2$ =90 Hz) with data signal. The detected power at $f_2$ was at least 7 dB stronger than that at $f_1$, showing that the current ID can easily be distinguished from the previous ID.

Figure 3 shows measurements of the optical modulation index ratio, $r$, versus $f$ for two different input modulation amplitudes, indicating that $f$ is best limited to several hundred Hz as predicted by the lifetime of the EDFA. It should be noted that the ID with the smaller input amplitudes generates a significantly smaller value in $r$, which can be explained by the failure of the EDFA to saturate the lower portion of a large signal.

BER measurements were also taken for the data channel using an ID at $V_{pp}$ = 0.5 V and $f$=100 Hz for three cases: (1) direct transmission through AWG without ID, (2) transmission through AWG with one ID, and (3) loop back configuration with two IDs. A small degradation of ~0.2 dB in receiver sensitivity was observed at a BER of $10^{-9}$ with and without ID, but no degradation was found between the cases of single and dual IDs.

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System penalty variation as a function of $V_{pp}$ was also studied for a range of $0.3 < V_{pp} < 1.0$ V (corresponding to $0.010 < r < 0.012$) at a BER of $10^{-9}$ (see inset, Fig. 4). The increase in power penalty is owed to the increase in residual amplitudes of the ID.

In summary, a real-time optical-path surveillance scheme for OXCs is proposed and demonstrated. The scheme is based on imposing RF pilot tones that serve as channel IDs to each wavelength channel inputted to the OXC. Optical-routing error can then be detected by comparing the ID with the stored routing information.

**References:**

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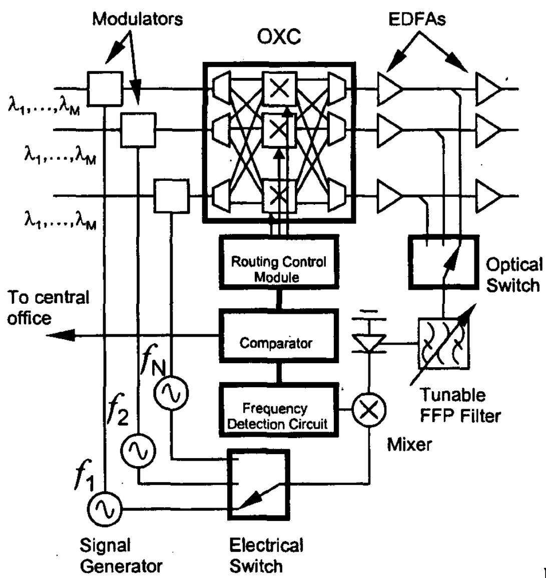


Fig. 1. Proposed optical-path supervisory scheme.

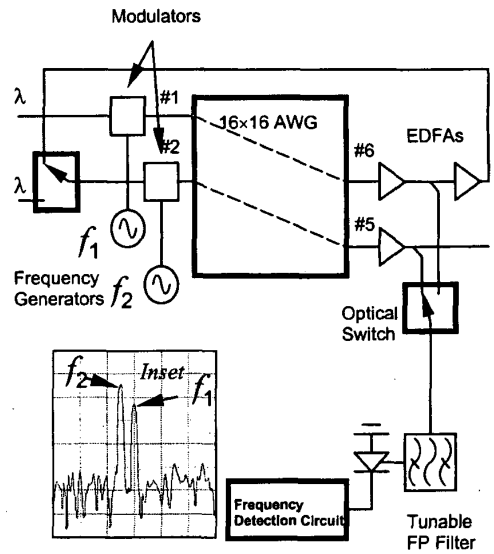


Fig. 2. Experimental setup. The inset shows the spectra measured at output fiber #5 for $f_1$ =100 Hz, $f_2$ =90 Hz, $V_{pp}$ =0.5V ($r$ =0.011). The power at the current ID ($f_2$) is ~7dB higher than the previous ID ($f_1$). Horizontal scale is 20 Hz/div, while the vertical scale is 10 dB/div.

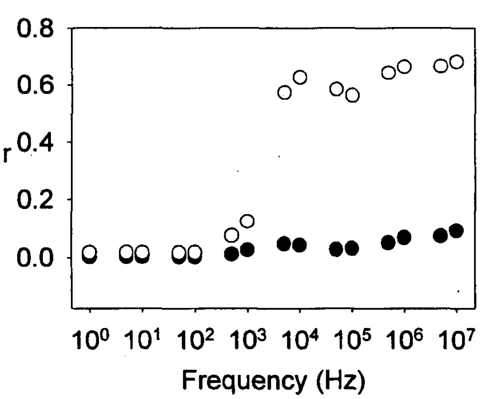


Fig. 3. The optical modulation index ratio, $r$, versus frequency plot for two input modulation amplitudes of 0.1 (●) and 0.8 (○).

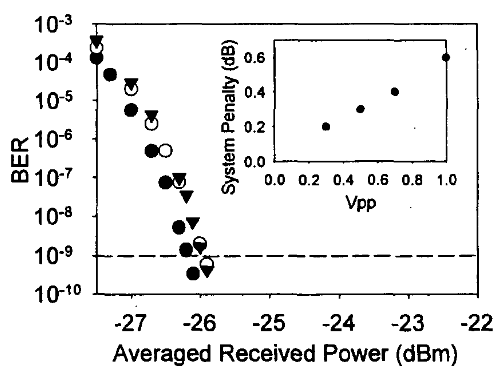


Fig. 4. BER measurements for (●) direct transmission through OXC without ID, (○) transmission through OXC with one ID, and (▼) loop back configuration with two IDs. We used external modulated 1-Gb/s $2^{15}$-1 NRZ PRBS at λ=1546.7 nm as the data channel and the channel ID is set at 100 Hz. System penalty for various values of $V_{pp}$ is shown in the inset.