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Signal Tracking and Performance Monitoring In Multi-Wavelength Optical Networks

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ABSTRACT – We propose and demonstrate a new technique for unambiguous in-service signal tracking in optical networks in which each optical carrier is individually tagged with a unique FSK-modulated pilot tone that can be easily monitored via low-speed detectors.

INTRODUCTION – Using dense wavelength-division multiplexing (WDM) and high-performance erbium-doped fiber amplifiers (EDFA), fiberoptic communication systems are now capable of transmitting many multi-Gb/s wavelength channels over distances of several thousand km's without requiring electrical regeneration of the signals [1–2]. It is expected that these optically-amplified point-to-point transmission systems will soon evolve into all-optical networks that employ reconfigurable wavelength routers and fast optical cross-connects [3–4]. Operation of such all-optical networks will be substantially different from present communication networks, and hence, will require new techniques for managing and controlling the flow of a large number of optical carriers through the network [3]. For example, it would be desirable to monitor continuously the proper routing of the various optical carriers through the network without converting the high-speed information data into electrical signals. In this paper we propose and demonstrate a novel scheme for unambiguous carrier identification in multi-wavelength optical networks that allows end-to-end signal tracking as well as in-service performance monitoring and fault location.

SIGNAL IDENTIFICATION – To distinguish the various optical carriers from each other, we propose to tag each individual carrier entering the network with a unique low-speed identifier signal, as shown in Fig. 1. This is achieved by modulating a low-frequency pilot tone between 10 kHz and 1 MHz onto each carrier, using amplitude modulation, such that the tone frequencies are below the bandwidth of the high-frequency payload, but high enough to not be effected by the slow gain dynamics in the EDFA's [4]. We use a different tone frequency for each optical wavelength, as proposed in [4], and furthermore, we encode a unique digital signal onto the tone using frequency-shift keying (FSK), as indicated in Fig. 1 (b). For example, this digital information may contain the complete optical routing information for the carrier, i.e., its origin, destination, and designated path.

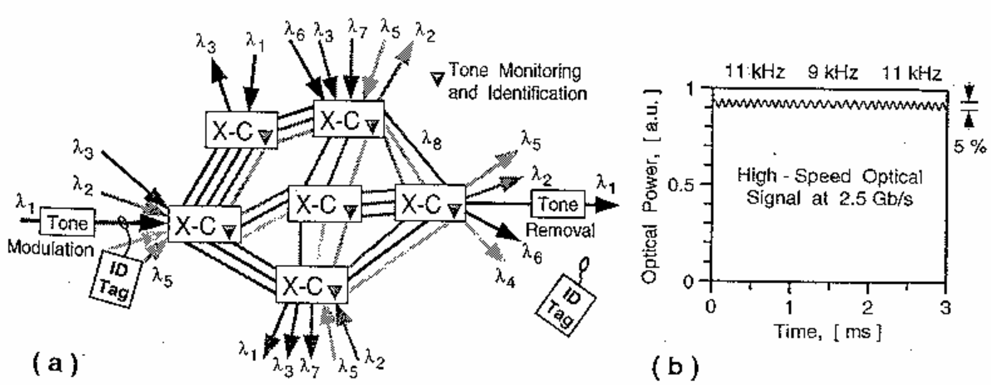

Fig. 1. *Proposed carrier identification in multi-wavelength optical networks using FSK-modulated pilot tones as unique identifiers (left). The right diagram shows a 10 kHz pilot tone with ± 1 kHz frequency excursions modulated onto an optical carrier using 5% peak-to-peak amplitude variations*

The frequencies of the tones and the low-speed digital information carried by them can easily be monitored at various points in the network using optical taps and inexpensive low-speed detectors followed by narrow-band electrical filters. These monitor detectors then allow unambiguous identification of all optical carriers in the network, even when several carriers are multiplexed. Hence, they permit continuous tracking of the proper optical routing through the network.

Fig. 2 depicts the experimental setup for the identification of two multiplexed optical signals at 1.5465 µm and 1.5481 µm wavelength. The two carriers are modulated here with different pilot tones at 10 kHz and 12 kHz, respectively, which are FSK-modulated at a rate of 100 b/s with frequency excursions of ±500 Hz. The 10-kHz tone carries a pseudo-random bit sequence (PRBS) of length 2^7-1 and the 12-kHz tone a periodic "0101" pattern. Furthermore, both optical carriers are modulated with a 2.5-Gb/s PRBS of length $2^{15}-1$ using high-speed lithium niobate Mach-Zehnder modulators. The 10-kHz tone is generated here by modulating the injection current to the semiconductor laser source such that it produces peak-to-peak intensity variations of 5% in the laser output. The 12-kHz pilot tone is generated by an interferometric lithium niobate modulator which is intentionally operated at the maximum of its sinusoidal modulation curve for minimal insertion loss. The modulator is driven by an FSK-modulated 6-kHz signal with ±250 Hz frequency excursions and produces frequency-doubled intensity modulation at 12 kHz with peak-to-peak power variations of 5%. The multiplexed optical carriers are then monitored by a single low-speed detector, which is connected to two narrow-band electrical filters tuned to 9.5 kHz and 12.5 kHz, respectively. Both filters exhibit a 3-dB (10-dB) bandwidth of 600 Hz (2.7 kHz).

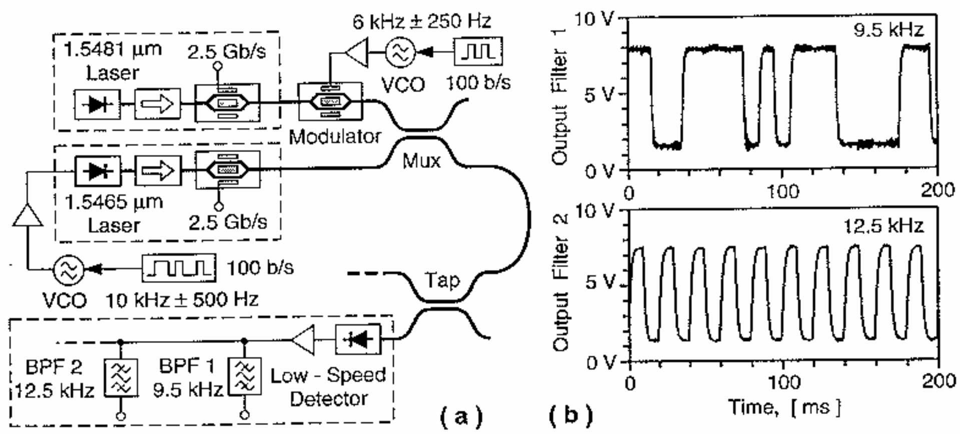

Fig. 2. *Monitoring of a 10 kHz and 12 kHz pilot tone modulated onto two wavelength-multiplexed 2.5 Gb/s optical carriers: (a), experimental setup; (b), demodulated tones at 9.5 kHz and 12.5 kHz (BPF, bandpass filter).*

Fig. 2 (b) shows the demodulated digital information carried by the pilot tones. Both signals are recovered with high fidelity, although we observe some crosstalk of less than 5% between the two signals as well as constant offsets in both signals due to the incomplete electrical filtering. The average optical power of both wavelength channels at the monitor detector is about 10 µW each. Their relative powers may differ by up to a factor of 10 before one of the 100-b/s signals cannot be recovered anymore (Using longer bit patterns for the 2.5-Gb/s high-speed modulation, e.g., a $2^{31}-1$ PRBS, also generates additional noise on the demodulated signals of less than 10%). We find that the magnitudes of the demodulated signals are proportional to the optical powers in the two wavelength channels.

The tones can thus be used to monitor the relative optical powers of several multiplexed carriers, which is very useful, for example, for adjusting the gain of the optical amplifiers (EDFA's) in the network to the (varying) number of optical carriers and their relative intensities. For this application, however, we would employ slightly broader electrical filters that pass the entire bandwidth of each FSK-modulated tone, thus generating a continuous electrical signal which allows fast response to changes in the optical powers.

TONE REMOVAL AND REPLACEMENT – If it is desired, we may remove the pilot tones from the optical carriers when they exit the network. Furthermore, we may have to refresh the tones occasionally within the network, or alternatively, we may need to change the tone frequencies, for example, when the wavelength of the optical carrier is changed in a wavelength converter. Likewise, the digital information carried by the tones may have to be replaced when the carrier is re-routed along an alternate path. Fig. 3 shows our experimental setup for removing and replacing the pilot tone using an in-line optical modulator. Here, we assume that the optical wavelength channels are demultiplexed into separate fibers such that only one carrier is present at the modulator. Such demultiplexing is not necessary if we use a wavelength-selective modulator, e.g., a polarization-independent acousto-optic mode converter [5]. In Fig. 3 we use a feedback technique to remove the original 10-kHz tone from the 2.5-Gb/s optical carrier, i.e., we detect the tone after the modulator and feed the amplified, filtered, and inverted signal back to the modulator, which is biased here in the linear portion of the modulation curve.

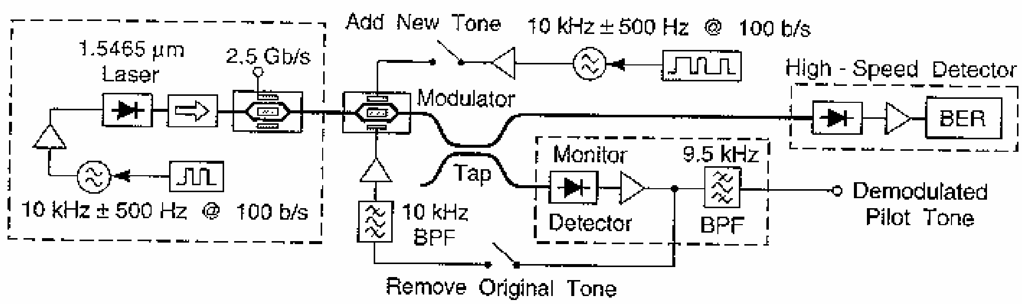

Fig. 3. *Experimental setup for removing and replacing a 10 kHz pilot tone on a 2.5 Gb/s optical carrier using an in-line modulator with electrical feedback from a monitor detector (BER, bit error rate analyzer).*

The upper diagram in Fig. 4 (a) shows the demodulated digital signal of the original 10-kHz pilot tone (carrying a 100-b/s "0101" pattern) before the feedback loop for tone removal is closed. The middle diagram displays the signal when the feedback loop, which has an overall loop gain of –12.5 (22 dB electrical), is closed. Here, the demodulated signal is reduced to less than 8% of its original magnitude, indicating that the residual peak-to-peak optical intensity modulation is less than 0.4%. Our setup in Fig. 3 also allows the addition of a new pilot tone either at the same or at a different subcarrier frequency. The new tone may simply be added to the feedback signal, or as in our experiment, it may be applied to a second set of modulator electrodes. In both cases we need to amplify the tone signal sufficiently to overcome the loop gain. The lower diagram of Fig. 4 (a) displays the demodulated signal of the added tone carrying a 100-b/s PRBS at the same subcarrier frequency as the original tone. The residual original tone causes here visible crosstalk, which may be reduced by increasing the loop gain. With an improved feedback loop we have recently achieved tone suppression with less than 0.1% residual intensity modulation.

Fig. 4 (b) shows the optical transmission penalties for removing and exchanging the pilot tone on the high-speed information carrier. As a base line, the solid circles in Fig. 4 (b) display the measured bit error rate as a function of received optical power for a 2.5-Gb/s optical carrier without a pilot tone, while the solid squares show the same measurements for a carrier modulated with a 10-kHz tone of 10% peak-to-peak optical intensity variations. The power penalty for adding the pilot tone is less than 0.15 dB, as expected for a 10% sinusoidal modulation of the eye opening. When the original 10 kHz tone is removed, using the setup of Fig. 3, the power penalty essentially disappears (open circles), yielding nearly the same values as for an unmodulated carrier. Finally, the addition of a new 10-kHz tone of 10% modulation index introduces again a 0.15 dB power penalty in the received signal (open squares). We have measured similar transmission penalties for a PRBS of length $2^{31}-1$.

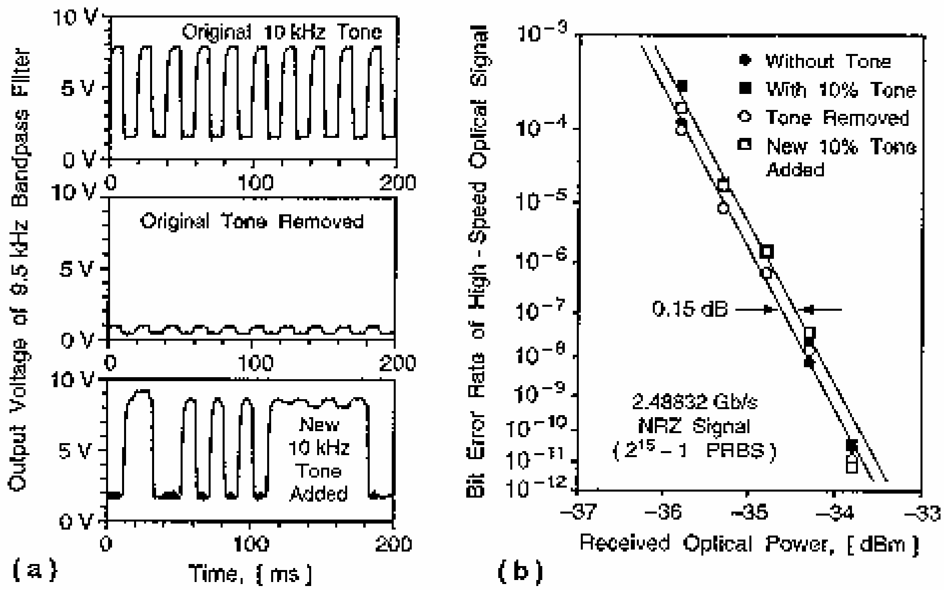

Fig. 4. *Performance and high-speed transmission penalties of tone removal and exchange: (a), demodulated signal from original pilot tone before and after tone removal (top and middle) and with newly added tone (bottom); (b), bit error rate measurements of the received 2.5-Gb/s signals with and without pilot tones of 10% peak-to-peak intensity modulation.*

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