Inter-Wavelength Transfer of Digital Lightpath Labels Induced by Stimulated Raman Scattering

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Abstract: WDM systems using digital lightpath labels can experience modulation transfer among wavelengths due to stimulated Raman scattering (SRS), creating label replicas. We present pump-probe measurements of 10.24 Gb/s OOK and DPSK transmission to assess the system effects.

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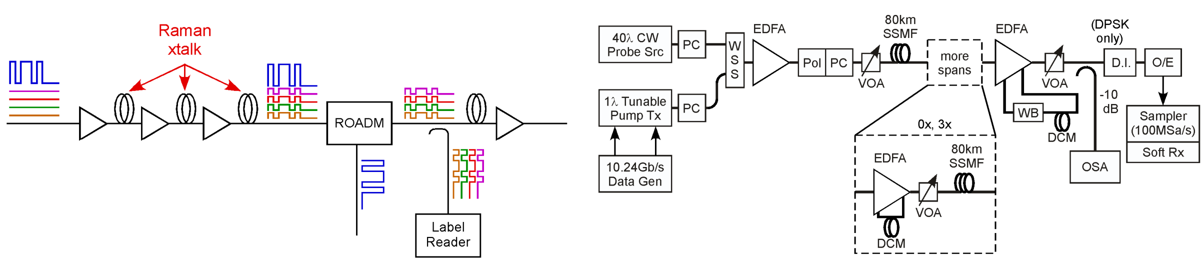
Introduction

To detect, diagnose, and localize routing faults in dynamic wavelength-routed networks, we have recently introduced digital lightpath labels based on a binary coding method we call LightLabel[1,2]. LightLabel encoding adjusts the average power of the optical signal by choosing codewords from a complementary constant-weight (CCW) code, to define the chips of a CDMA (code-division multiple access) signature. The resulting CDMA frames carry a general label message that can be detected by a slow (~10MHz) photoreceiver which is shared among multiple wavelengths (λs), leading to low-cost label readers that can be deployed ubiquitously throughout the network. Originally developed for on-off keying (OOK) systems [2], the method has recently been demonstrated in a differential phase-shift keying (DPSK) system [3], using a shared delay interferometer to minimize cost.

LightLabel (LL) shares some characteristics with labelling by overmodulation with analog pilot tones [4,5], but it does not require an additional modulator and completely eliminates label-to-payload crosstalk in an ideal linear transmission channel. The low data rate of the label provides tolerance to most fiber impairments, such as chromatic dispersion and polarization-mode dispersion, and the CDMA layer provides effective rejection of inter-label crosstalk in a linear channel. However, stimulated Raman scattering (SRS) in transmission fiber can effectively transfer a λ's unique CDMA signature to other λs, creating label replicas which may persist after the original lightpath has been dropped.

The lightpath tracing function of LL can be made quite tolerant to these label replicas by using a unique signature for each new lightpath. (With signature lengths of 200-400 chips, the number of distinct signatures available is ample.) However, if the LL reader is also required to confirm the complete extinction of the dropped channel, label replicas can cause significant errors in estimating the extinction.

This paper presents the first measurements of SRS-induced label replicas in a digital lightpath labelling system operating at 10.24Gb/s. Pump-probe experiments were carried out for OOK and DPSK modulation in a system with 40 λ channels. For OOK modulation, partial-band label readers were evaluated as a means to reduce errors in the drop extinction estimates.



a) b)

Fig. 1. a) SRS-induced modulation transfer creates replicas of a digital lightpath label on co-propagating wavelengths. These replicas can persist after the labeled wavelength has been dropped, causing errors in the estimation of drop channel leakage. b) Setup for label replica measurement. PC is a polarization controller, Pol is a polarizer, D.I. is a (shared) delay interferometer, WSS is a wavelength-selective switch, and WB is a wavelength blocker.

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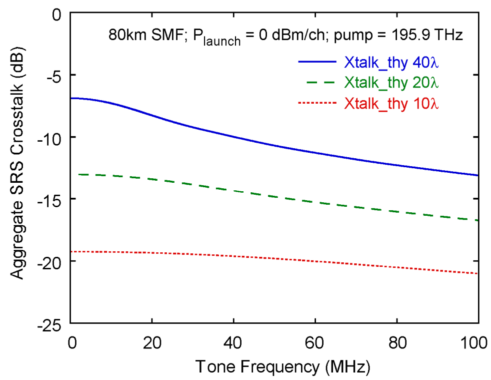

Fig. 2. Calculated SRS crosstalk of a 40-channel WDM system at 100 GHz spacing, transmitted through 80 km of SMF.

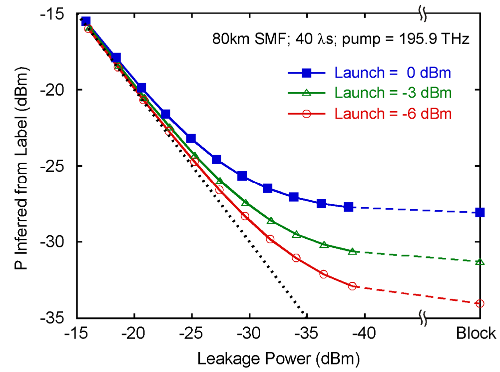

Fig. 3. Leakage power inferred from label amplitude vs. OSA reference measurement, for various fiber launch powers.

Theory and Experiments

The label replicas arise because SRS transfers energy from short λs to longer λs, with more energy transfer when the optical power is high, resulting in a transfer of amplitude modulation from each λ to all others. When a labelled λ is dropped, the label replicas on other λs continue to propagate in the line, where they will be read by downstream label readers, as illustrated in Fig. 1a. This is the digital version of the 'ghost tones' discussed in [5]. It could be mitigated by the optical allpass filters introduced in [6], but for best effectiveness, that strategy requires lighting λs in a pre-planned order, which may not be practical for dynamic WDM mesh networks. A frequency-domain theory of SRS modulation transfer in WDM links, based on a triangular Raman gain profile, was developed by Phillips and Ott [7]. In Fig. 2, we have applied that theory to an 80-km span of standard single-mode fiber (dispersion = 17 ps/nm/km, effective area = 80 μm^2, Raman gain coefficient = $5x10^{-15}$ m/W/THz) carrying 40 λs at 100 GHz spacing. Aligned polarizations (worst case) have been assumed. To first order, the crosstalk scales linearly with the number of spans traversed, although polarization wander and saturation effects could reduce it somewhat. Modulation transfer decreases at high frequencies due to walk-off, and we could adjust the LL codes to achieve higher chip rates, but the label reader cost and the coding overhead would increase significantly. Using a band-filtered label reader, in which only 10 or 20 λs reach the photodetector simultaneously, might be more practical. This approach is explored experimentally below. It is important to note that no SRS-induced modulation transfer is predicted for DPSK systems which have no amplitude modulation.

Fig. 1b illustrates the experimental setup for label replica measurements. A single λ at 195.9 THz is modulated with an LL-coded data stream at 10.24 Gb/s. As in [2], there are 1024 bits per CCW codeword, 1 word per chip, and the code weight is W=440. Unlike [2], the signatures for OOK measurements have been dilated in a process similar to Manchester coding to suppress low-frequency content and eliminate crosstalk due to cross-gain modulation (XGM) in the EDFAs. The resulting signatures are 400 chips long and the frame rate is 25 kframes/s for each λ. This code is designed to support up to 80 λs. Since LL-DPSK does not suffer from XGM, we used the 200-chip random signatures of [3] (label message rate of 50Kframes/s per λ) for our DPSK measurements.

The labelled λ is combined with 39 CW waves, with equal powers and aligned polarizations, then launched into an 80 km span of standard single-mode fiber. For some experiments, a total of four 80-km spans are used. Nominally-matched dispersion compensation modules (DCMs) are included in each span. The EDFA receiver preamplifier has a wavelength blocker (WB) in its midstage to emulate the dropping of the signal λ with a controlled amount of leakage. The WB also levels residual gain tilt (as ROADMs do in actual networks) and serves as a variable bandpass filter when band-filtered LL operation is emulated. After optoelectronic conversion with 7.5 GHz analog bandwidth, the received waveform is sampled and frames are resolved with a signature-matched CDMA software decoder. The average amplitude of the detected frames before decision is used as the measure of label strength. In the absence of label replicas, label amplitude would be directly proportional to the residual optical power of the partially dropped λ. In the present experiments, the WB is adjusted to vary the residual (leakage) power of the test channel while the CW probe λs are held constant. This emulates the imperfect drop of a single λ in a ROADM. An optical spectrum analyzer (OSA) provides the reference measurement to quantify the errors induced by SRS-induced label replicas.

Experimental Results

Figure 3 shows the power inferred from label amplitude versus the direct OSA measurement, after a single 80-

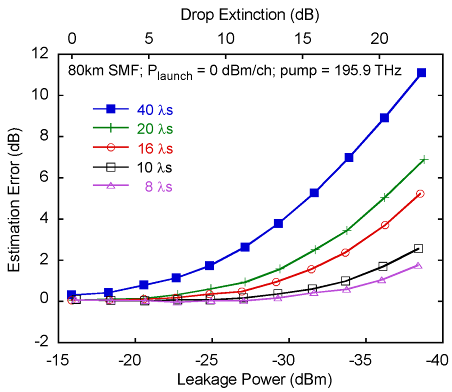

Fig. 4. Error in estimating leakage power after λ drop for a single 80-km span with 8,10,16,20,and 40 channels.

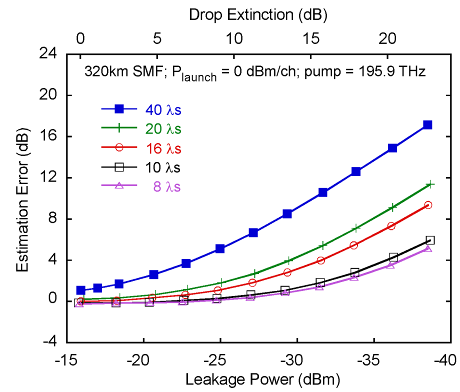

Fig. 5. Error in estimating leakage power after λ drop for 4 spans of 80km with 8,10,16,20,and 40 channels.

km span, at three levels of launch power. The power condition marked 'block' indicates a blocked setting of the WB, in which the leakage power is <-60 dBm. As the leakage power is reduced, the label amplitude decreases, saturating at a level representing the sum of all label replicas. As predicted by theory, a 3dB increase in launch power brings ~3 dB increase in the modulation transfer. The straight line in Fig. 3 indicates an ideal measurement. In Fig. 4, this ideal-case line has been subtracted from the label amplitude result to show the error incurred when estimating drop channel leakage. The launch power was 0 dBm in all cases, and the five curves represent banded label readers with 8, 10, 16, and 20 λs, as well as a full-spectrum reader shared among 40 λs. The full-spectrum reader shows an error of 2.2 dB for leakage power of -26 dBm (drop extinction ~10 dB). In contrast, banded readers shared among 8 or 10 λs show errors <0.2 dB at 10 dB extinction for this single span.

The strength of the label replicas induced for transmission through N spans should be approximately N times that of a single span, though fluctuating polarization alignment of different λs may cause some variation. In Fig. 5, we show the measured errors in a 4-span experiment. Curve fitting indicates that the aggregate replica strength is 3.3-4.4 times the single-span values.

Fortunately, LL-DPSK is largely immune to SRS-induced label replication. This is demonstrated in the measurements of Fig. 6, for a single span and 4-span transmission link using DPSK. For drop extinction up to >20dB, the accuracy of the leakage power estimate remains within ±0.2 dB.

Summary and Acknowledgements

We have measured the formation of label replicas in WDM transmission systems using digital lightpath labeling. After transmission of an OOK modulated signal through 320 km of SMF, the replicas induced by SRS in a 40-channel system were found to introduce errors up to 17 dB in the estimate of drop λ extinction. Errors could be reduced below 1 dB at 10 dB extinction by using a banded label reader. Label replicas are substantially absent when DPSK modulation is used, so the drop extinction can be measured with good accuracy.

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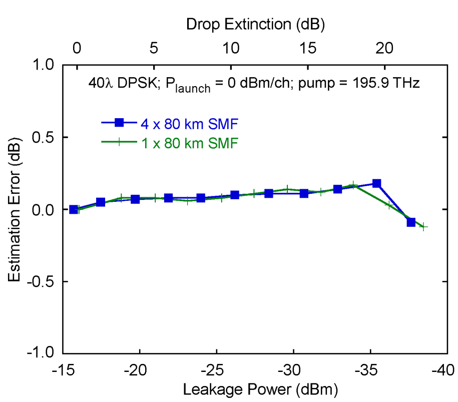

Fig. 6. Error in estimating leakage power after λ drop for DSPK transmission of 40 wavelength channels.

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