Real-time Detection of a 40 Gbps Intradyne Channel in the Presence of Multiple Received WDM Channels

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Abstract: We characterize a single-ended intradyne receiver's performance when multiple channels are received without optical demultiplexing. A 40Gb/s dual-polarization QPSK channel is recovered from 16 interfering channels with less than 2dB OSNR penalty at $1\text{x}10^{-3}$ BER.

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1. Introduction

Carriers have long recognized the advantages of reconfigurable optical networks. The ability to remotely rearrange wavelength connections enables a network to meet new traffic demands quickly and efficiently. Reconfigurable Optical Add/Drop Multiplexers (ROADMs) are already widely deployed in large optical networks, as they permit each wavelength channel to be routed independently through a node. Wavelengths intended to terminate within the node are routed to a demultiplexer that filters each wavelength and then sends the resulting signal to an optical receiver. A "colorless" drop path has the advantage that any wavelength can be routed to any receiver. When the drop path is not colorless, a transponder cannot be tuned to an arbitrary wavelength without manual reconnection, regardless of whether or not the transponder's laser is tunable. A colored drop path makes it less practical to deploy transponders in anticipation of need, as well as prohibits applications such as bandwidth-on-demand and 1:N protection against transponder failures. Unfortunately, reconfigurable optical demultiplexers, whether constructed of tunable filters or wavelength-selective switches (WSS), are far more expensive than fixed demultiplexers, which are typically constructed of waveguide grating routers and optical interleavers [1].

Optical demultiplexing, however, is not strictly necessary when coherent reception is used. In the 1980s a great deal of research focused on using coherent heterodyne detection to separate transmitted WDM signals at the receiver (see, for example, [2-3]). The wavelength of interest is selected by tuning a local oscillator (LO) and filtering the resulting signal electronically. Heterodyne detection offered the advantage of reducing interference, as the LO-signal product could be placed at an intermediate frequency (IF) to minimize interference from other channels. Unfortunately, minimizing the amount of interference at the IF also limits the spectral efficiency of the system, as the wavelengths must be sufficiently spaced so that only one channel has an optical frequency at $f_{opt}=f_{LO} \pm \text{IF}$.

Recently coherent detection has enjoyed a resurgence in popularity, largely due to the development of the digital demodulation process for both heterodyne [4] and intradyne reception. [5] Unlike heterodyne detection, intradyne detection does not use an IF, but downconverts the received signal to baseband. The interference in this band is not due to the LO beating with other channels (those mixing products are out-of-band) but is due to each of the channels mixing with itself. Although balanced detection can suppress this interference [2], balanced receivers are more complicated and costly than single-ended receivers. In this work we describe the performance of a 40Gbps intradyne single-ended receiver that is presented with the signal-under-test and up to sixteen adjacent WDM channels. Although this technique might not enable detection of one channel in the presence of the full C-band, it could still be used to significantly reduce the number of tunable components required in a colorless demultiplexer.

2. Experimental Demonstration

We demonstrate the practicality of using coherent detection to distinguish between multiple wavelength channels impinging on a receiver. Our WDM signals were modulated at 40-Gbps using dual-polarization, quadrature-phase-shift-keying (DP-QPSK) with a 2^{31} -1 PRBS and separated by 50 GHz. The signal under test (at 193.40 THz) was generated and received using two production-grade Nortel eDC40G transceivers, previously described in [5]. The coherent receiver uses four single-ended (not balanced) detectors to receive the four signal components that are orthogonal in optical phase and polarization. The signals are digitized and then processed in real-time using a custom ASIC. As shown in Figure 1, the odd and even interfering signals were separately modulated with 40Gbps DP-QPSK, transmitted through decorrelating fiber, and then combined with the signal channel in a WSS. Noise loading (to vary the channels' optical signal-to-noise ratio (OSNR)) was provided by the filtered amplified spontaneous emission from an optical amplifier. A WSS was used to select which channels would reach the receiver input of tunable transceiver #2. From one to seventeen channels were transmitted through the WSS to the receiver, and as can be seen from the optical spectrum shown in the inset of Fig. 1, the channels had equal power. The interfering channels were placed on either side of the signal under test.

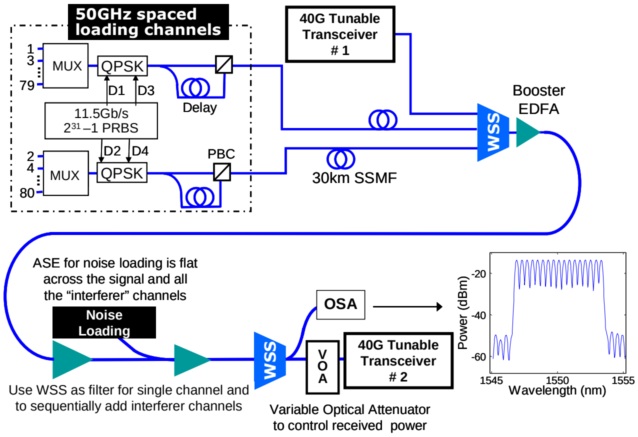

Figure 1: Experimental set-up. Inset: Optical spectrum at receiver with 17 channels.

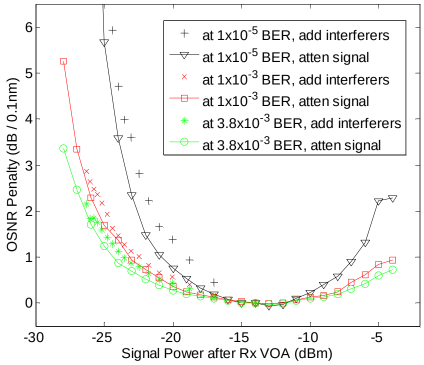

Figure 2: OSNR penalty vs. Signal Power for constant combined power as interferers are added (markers), versus simply attenuating the signal at the receiver in the absence of adjacent channels (markers and lines to guide the eye).

Equation 1 provides a simplified formula of the ratio of the signal to the noise and interference at the receiver:

$$S/(N+I) \approx P_{LO}P_{signal}/(\rho N_{rec'r} + P_{LO}P_{ASE} + \eta(P_{LO} + \sum_{m=1,M} P_m) + \gamma \sum_{m=1,M} P_m P_m) \quad (1)$$

where S, N and I are the electrical signal, noise and interference power at each of the receiver's photodiodes, M is the total number of channels at the receiver, P_{LO}, P_m and P_{ASE} are the optical power in the LO, the m^{th} wavelength channel, and the amplified spontaneous emission in the signal channel, respectively. We refer to ΣP_m as the combined-channel power at the receiver, and P_{signal} as the signal power. $N_{rec'r}$ is the receiver noise, ρ accounts for coupling loss, η translates the shot noise and includes both coupling and bandwidth factors, while γ accounts for the modulation of each channel spreading its spectrum. Terms that would be due to the LO beating with the interfering channels or interfering channels mixing with other channels are assumed to be outside the electronic bandwidth of the circuit.

We characterized three modes of operation for the combined-channel power level (ΣP_m) at the receiver as the number of channels M presented to the receiver increases: (1) P_{signal} kept constant, such that ΣP_m will increase with M, assuming the interferers have equal power to the signal; (2) ΣP_m kept constant; or (3) P_{signal} adjusted for optimum performance (i.e. minimum bit-error-ratio, BER). When P_{signal} is kept fixed and additional channels are presented to the receiver, the dominant impairment is due to each interfering channel beating with itself ($\Sigma P_m P_m$).

3. Results

When ΣP_m is kept constant, P_{signal} drops as interferers are added, and there is the potential for both receiver noise and interference noise to contribute to the penalty. For this case of constant ΣP_m we investigated the relative importance of the receiver noise and interference noise by measuring the receiver's OSNR sensitivity with only the signal-under-test for decreasing P_{signal}, as shown in Fig. 2, where we define the OSNR penalty relative to the OSNR sensitivity at -14dBm signal power. These results are overlaid with the OSNR penalties determined from BER curves taken with constant ΣP_m as the number of interferers was increased. Figure 2 indicates that receiver noise becomes the primary source of impairment as the number of interferers presented to the receiver increases for constant combined-channel power (ΣP_m). Figure 2 also includes data taken on a single channel at powers above -14 dBm. At power levels above -10 dBm the penalty is primarily due to signal-signal beat noise.

We investigated how the optimal signal power at the receiver varies with the number of interfering channels. Fig. 3 presents the measured BER vs. received power for various channel counts. At each channel count the received OSNR was adjusted first so that the BER was $\approx 1\text{x}10^{-3}$ for a combined power after the VOA of -9dBm. Then the received power was varied and BER's were measured. From Eqn. 1, we expect the optimal power to the receiver to occur when the interference caused by the interfering channels is equal to the fixed noise from sources independent of M. Assuming equal powers of all the channels at the receiver, the optimal power actually decreases as the number of interfering channels increases, and it is best to attenuate the combined-channel power at the input to the receiver, as shown in Fig. 4. Equation 1 predicts that the optimal combined-channel power should increase as $\sqrt{M}$, and optimal signal power should decrease as $1/\sqrt{M}$. Indeed, Fig. 4 shows that a $1/\sqrt{M}$ curve referenced to -14dBm for M = 1 is a very good fit of the measured optimum signal power.

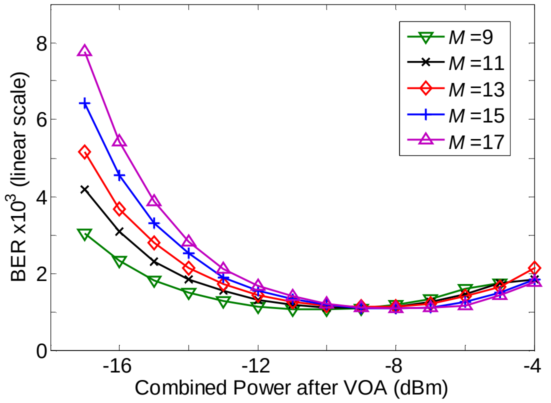

Figure 3: The BER vs. the combined power after the VOA. For each channel count the noise loading was set to give a BER = 10^{-3} at -9dBm combined power after the VOA.

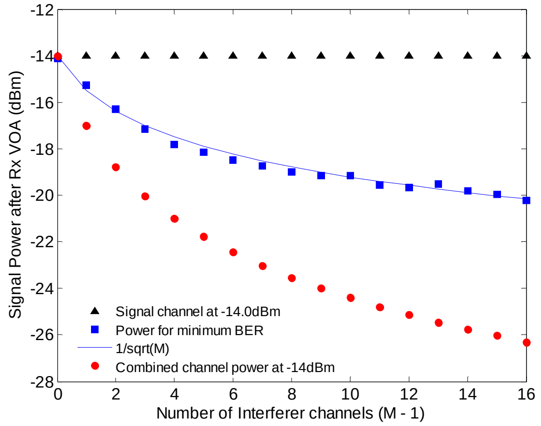

Figure 4: Comparison of optimal signal power (P_{signal}) after receiver VOA with power at receiver when signal is held constant, or combined power is held constant. The BER curves in Fig. 5 correspond to the blue squares.

Figure 5 shows BER curves taken with the combined-channel power optimized for odd M from 1 to 17. From these it can be seen that the OSNR penalty at BER=10^{-3} with M=17 is less than 2 dB. Figure 6 shows the OSNR penalties derived from BER curves for the three cases of the combined-channel power at the receiver, and for 0 to 16 interfering WDM channels. The OSNR penalty in the presence of 16 interferers is less than 2dB when the signal power is optimized, which is 1dB less than for constant combined channel power. For the case where the signal power is held constant, the larger penalty is due to interferer-interferer beat noise as M increases.

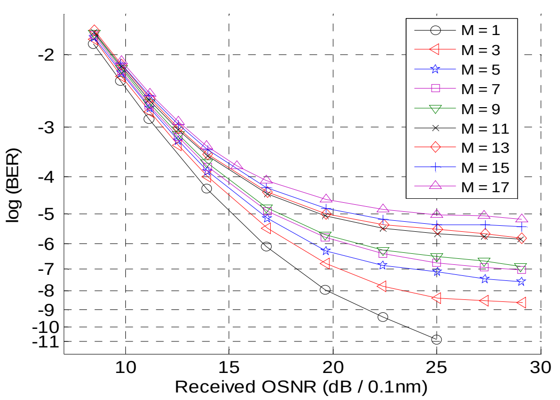

Figure 5: BER curves for the signal-under-test with 0 to 16 interferers (M = 1 to 17) for the case of optimal signal power.

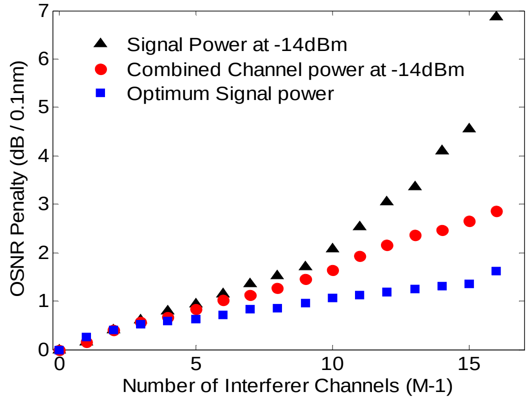

Figure 6: OSNR penalties, referenced to 1×10^{-3} BER for the three cases of the combined-channel power at the receiver, for 0 to 16 interfering WDM channels.

4. Conclusion

A single-ended intradyne coherent receiver with real-time digital signal processing has been used to detect, without optical demultiplexing, a single 40Gb/s dual-polarization QPSK channel from 17 WDM channels with less than 2dB OSNR penalty at 1×10^{-3} BER. This result illustrates that coherent receivers could be used in a reconfigurable network to significantly reduce the number of tunable components required in a colorless demultiplexer.

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