BIT-ERROR-RATE OF AN SCM/WDMA OPTICAL NETWORK EMPLOYING POLARIZATION SCRAMBLING UNDER OPTICAL BEAT INTERFERENCE

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I. INTRODUCTION

A mixed analytical-numerical technique is used to calculate the average bit-error-rate (BER) for a two-user per channel subcarrier multiplexed wavelength division multiple access (SCM/WDMA) optical network. The network is subject to optical beat interference (OBI)[1-5]. The BER is found through elaborate simulation and numerical computation. It is shown that the system performance is severely degraded by OBI, even at very low subcarrier bit rates (e.g., 50 Mbps), when polarization scrambling is not used. However, the network can support much higher subcarrier bit rates (up to 500 Mbps/channel) with sufficiently high polarization scrambling rates (about 100 GHz). Using Dense WDMA, the network is shown to support more than 150 Gbps total throughput.

II. OBI EFFECTS ON SCM/WDMA NETWORKS

A two-user per optical channel SCM/WDMA system was simulated using MATLAB with the subcarrier center frequencies f_1 and f_2 separated by twice the electronic filter bandwidth, under the assumption of f_2 being the larger. The first subcarrier was centered at 4 GHz. Both subcarriers were PSK-modulated at an equal rate of $\boldsymbol{R_b}$ bps. The electronic BPF bandwidth $\boldsymbol{B}$ was equal to the subcarrier modulation bit rate $\boldsymbol{R_b}$. The PSK modulated subcarriers intensity modulated two lasers whose frequencies were assumed to fluctuate uniformly in a range $\boldsymbol{R}$ of 50 GHz. Both users had an equal laser intensity modulation index value of $\sqrt{2}$. With this setup, we evaluated the average carrier-to-interference ratio (CIR) and average probability of error $\boldsymbol{P(e)}$ for the first user.

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Figure 1 shows the CIR as a function of the simultaneous optical carrier frequency separation. It can be seen from this figure that there is a sharp drop in the CIR when the carrier separation $F_x = |f_1 - f_2|$ satisfies:

$$|F_x - f_1| < B/2 \qquad (1)$$

This demonstrates how serious OBI can be when the optical carriers get too close to one another.

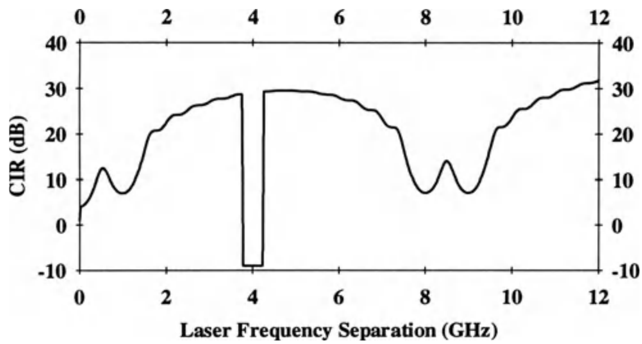

Figure 1. *CIR* as function of optical carrier separation with no polarization scrambling

Figure 2 shows the CIR averaged over all possible optical carrier separations. In this figure, the CIR is plotted versus the subcarrier bit rate to test the achievable network capacity under OBI. As Figure 2 shows, the CIR becomes very poor at subcarrier bit rates higher than about 150 Mb/s.

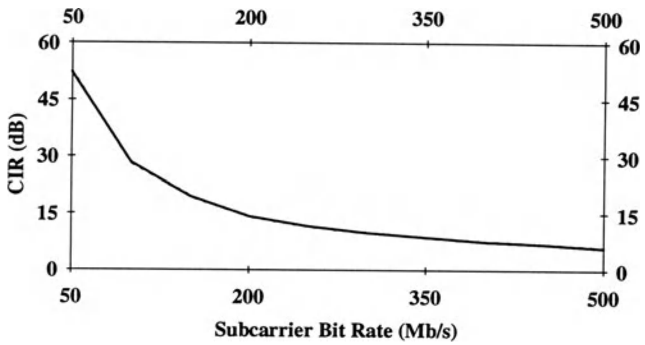

Figure 2. *CIR* averaged over optical carrier separation with no polarization scrambling

Figure 3 shows the simulation result for the system average probability of error $P(e)$. As can be seen from the figure, the probability of error does not fall below 10^{-3} even at bit rates as low as 50 Mb/s. Furthermore, there is almost a linear increase in $P(e)$ at bit rates higher than about 200 Mb/s.

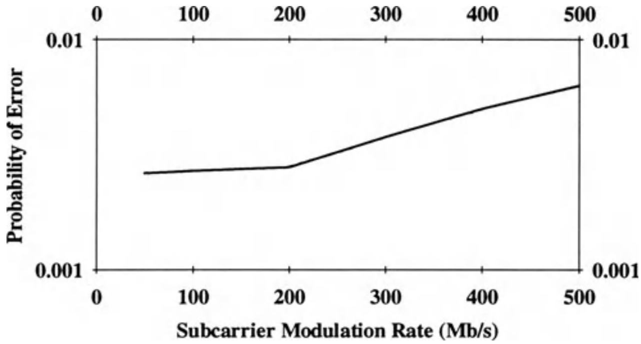

Figure 3. Probability of error with no polarization scrambling

It can be seen from the above figures and the above discussions that the network performance under OBI is not acceptable. In the next section, we demonstrate how polarization scrambling can bring significant improvements to the network performance and throughput. Polarization scrambling will be shown to support network throughputs as high as 150 Gb/s.

III. SCM/WDMA PERFORMANCE WITH POLARIZATION SCRAMBLING

To reduce the OBI level at the output of the electronic BPF, we propose using polarization scrambling. In this process, the laser field is passed through a controllable refractive index material like $LiNbO_3$. The control signal is a high-rate pseudonoise sequence capable of shifting the input field phase by $\pm\pi/2$ radians.

To study the effect of polarization scrambling on the CIR, the system was simulated using MATLAB. The same parameters as in section II were used, with the subcarrier bit rate assuming values of 250 and 500 Mb/s. Figure 4 shows the resulting CIR. Significant improvements in the CIR are achieved at high PN rates. Shown also in the same graph is the threshold CIR value needed in the case of Gaussian OBI to obtain a 10^{-9} error probability. It can be shown that the OBI does become Gaussian for PN rates required to achieve these threshold CIR values.

$P(e)$ is shown in Figure 5 in the case of a 500 Mb/s subcarrier bit rate. For PN rates less than 60 GHz, the OBI was not found to be Gaussian and the probability of error was found by numerically computing the electronic detector decision variable, comparing it to zero, and finding the proportion of times in which it is negative.

When the PN rate exceeds 60 GHz, the OBI becomes Gaussian, and we can integrate over its pdf to find $P(e)$. The OBI pdf is totally determined by its variance estimated by the variance of the equivalent Gaussian random variable. A numerical search algorithm using least squares minimization was used to determine the variance value that best fits the simulated values of the OBI characteristic function.

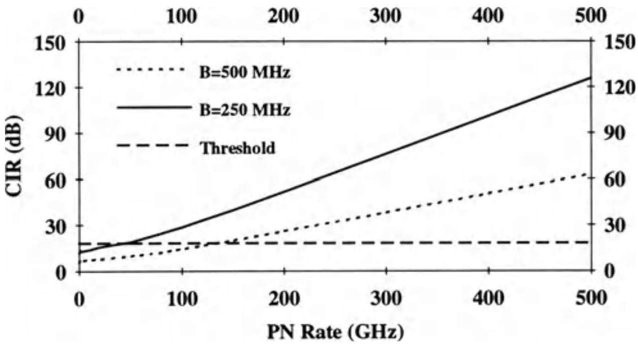

Figure 4. *CIR* with polarization scrambling. Threshold of *CIR*=18 is shown

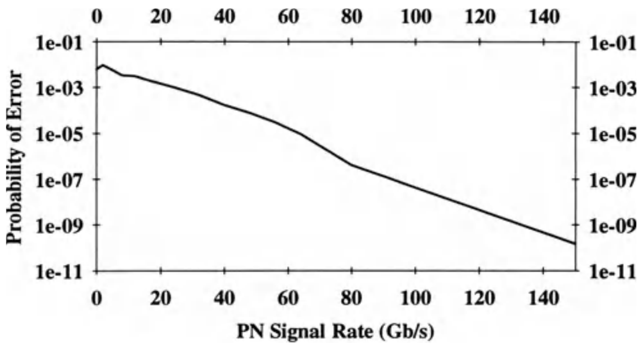

Figure 5. Probability of error with polarization scrambling

With this in mind, $P(e)$ can be calculated from:

$$P(e)=\frac{1}{\sqrt{2\pi\sigma_{obi}^2}}\int_{-\infty}^{-m_1T_b/4} e^{-x^2/2\sigma_{obi}^2}\,dx \qquad (2)$$

Note that, T_b is the bit duration, m_1 is the first user intensity modulation index, and $m_1T_b/4$ is the signal term of the PSK matched filter receiver output. The last result can be written in terms of the complementary error function in the form:

$$P(e)=\frac{1}{2}\text{erfc}\left[\frac{m_1T_b}{4\sigma_{obi}\sqrt{2}}\right] \qquad (3)$$

As can be seen from Figure 5, the probability of error decreases almost linearly with the increase in the PN polarization scrambling rate.

It is possible at PN rates around 100 GHz to achieve a 10^{-9} error probability with two subcarrier each transmitting at 500 Mb/s. This makes the throughput of each optical channel equal to 1 Gb/s. With a laser frequency uncertainty range of 50 GHz and a polarization scrambling rate of 100 GHz, optical channels can be allocated at about 200 GHz spacing. Assuming a total fiber bandwidth of about 30 THz, 150 optical channels can be supported. This results in a total network throughput of 150 Gb/s.

IV. CONCLUSIONS

Polarization scrambling using PN signals has been demonstrated to significantly improve SCM/WDMA networks performance against OBI. A network throughput as high as 150 Gb/s was shown to be achievable with two subcarriers per optical channel. Although the results indicate that high-rate PN signals are needed, it should be emphasized that this is true only in the worst case of identical field polarizations. When field polarizations are different and varying with time, the required PN signal rates are drastically reduced, resulting in practically implementable polarization scrambling.

The network BER at high PN rates was estimated using a mixed analytical-numerical technique. This technique is based on least squares fitting of the output decision variable characteristic function to a Gaussian characteristic function. Excellent fitting was observed.

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