

Minimizing the Effect of Cross Phase Modulation in WDM Optical Transmission System

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ABSTRACT

Multilevel line coding scheme such as Novel optical line code is applied to combat the effect of cross phase modulation in a single segment dispersive optical link. The analysis is carried out for an intensity modulated direct detection WDM system with various linecoding techniques like NRZ and novel optical order-1 code. Results are numerically evaluated in terms of bit error rate and power penalty at a BER of 10^{-9} . Results show that there is an improvement in system performance by 1.89 dB in terms of input power.

Key words: XPM, SPM, linecoding, dispersion, multichannel, optical novel code.

I. INTRODUCTION

Dense wavelength division multiplexing (DWDM) is very promising for future optical fiber communication with its huge channel capacity and link distance. But the phenomenon like dispersion, self phase modulation (SPM), cross phase modulation (XPM) and four waves mixing (FWM) impose limitation on the communication range, number of channels, bit rate and the performance [1-3]. SPM is caused due to the amplitude variations of a channel itself. While XPM is a nonlinear phase effect due to optical pulses in neighboring channels in WDM systems. In a dispersive fiber, the input pulses get broaden as it travel across the fiber length causing inter-symbol interference (ISI) at the receiver. The varied power level of the neighboring channels worsens the effects of XPM. Careful design of the dispersion map (often called *dispersion management*) which allows large local dispersion but limits the total average dispersion to be below a certain level is found to be very effective to combat FWM, SPM and XPM induced degradations. Line coding is an approach to reduce the effect of dispersion by reducing the signal bandwidth [4]. Multilevel Novel line-codes are found effective in reducing signal bandwidth and thereby reducing the dispersion. It is highly desirable to quantify the effectiveness of line coding in combating effect of XPM.

One line coding scheme is considered here, viz; Novel line-coding. Bit error rate (BER) performance results are evaluated at a bit rate of 10Gb/s with and without line coding schemes. Power penalty due to XPM and effectiveness of line

coding schemes in minimizing the effect of XPM are evaluated at a BER of 10^{-9} . Computer simulation is also carried out to evaluate the eye-closer penalty and to verify the analytical results.

In this paper, an analytical approach is presented to evaluate the bit error rate (BER) of a WDM system with single mode fiber using line codes in order to minimize the effect of XPM.

II. SYSTEM BLOCK DIAGRAM WITH LINE CODER

A WDM system with optical line coding is shown in Figure 1. In Referring to Figure 1, the pump channel generates a time varying intensity signal λ_1 , while the probe generates a constant intensity continuous wave (CW) wave signal λ_2 . Then they are multiplexed and transmitted through two channels of a fiber. At the receiver, both signals are demultiplexed and compared to the original condition as in the transmitter. Both pump channel and probe channel signals experience amplitude variation. The amplitude variation in the pump channel is due to the SPM. On the other hand, the amplitude variations in the probe channel are caused by the XPM from the pump channel. This is because the signal in the probe has a constant intensity, which eliminates the effects of SPM. The operation of intensity modulation direct detection (IM-DD) is simple as depicted in Figure 1.

At the transmitter, the information signal is passed through a line coder that incorporates the appropriate line coding schemes. The transmitted field from the laser is coupled to the fiber. At the receiver, the optical signal is directly detected by one or more photodiodes to obtain base-band electric currents. Since the generated current is low, the electrical front end should comprise of a wideband, low-noise amplifier, able to provide sufficient gain to drive the clock recovery circuit and the threshold comparator. Upon amplification, the base-band current is sampled in the middle of each bit interval to obtain the decision variable. The decision variable is then compared with a threshold to estimate the transmitted bit. The received signal is decoded to retrieve the output data.

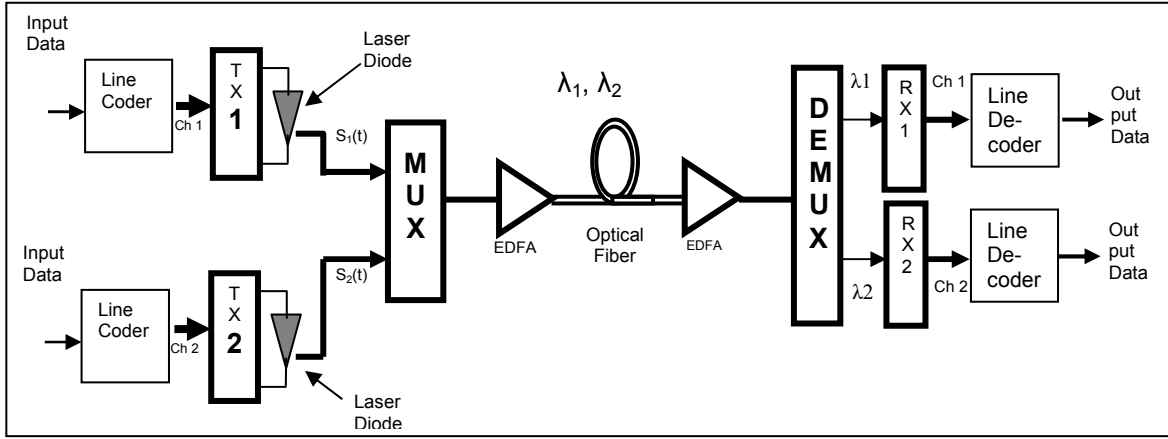


Figure 1: System Block Diagram with Line Coder

III – Coding

Optical systems by and large use NRZ modulation format. NRZ modulation is suitable for long haul systems in which the dispersion in a single mode fiber is compensated for by another fiber with negative dispersion. But novel optical line codes are more resilient to dispersion and are found superior to NRZ modulation. In NRZ, the '0' bit is simply represented by a zero voltage or current level and '1' is presented by a positive voltage or current level. Novel optical line coding is similar to conventional Miller coding with the difference being that two of them are scaled by a factor $\beta < 1$. Novel optical codes are ranging from order 1, 2, ..., n and here only order one novel optical codes are used. The first order novel code uses four waveforms $s_i(t)$ where $i = 1, 2, 3$ and 4 as shown in Figure 2. Elementary signals form two pairs with $s_1(t) = -s_4(t)$ and $s_2(t) = -s_3(t)$. Two of the elementary signals [$s_2(t)$ and $s_3(t)$] are scaled by β . Here β is chosen to be 0.5 to produce the spectral shape. Σ_1 and Σ_2 are the code states. The actual elementary order one novel coded signal will be one of $s_1(t)$ or $s_2(t)$ or their negatives [i.e., $s_4(t)$ or $s_3(t)$ respectively] depending on the sequence of the input bit stream.

IV. Analysis

XPM is a nonlinear phase effect due to optical pulses in neighbouring channels. Therefore, XPM occurs only in multi-channel systems. In a multi-channel system, the total nonlinear phase shift for the j th channel during the period of required for traveling the fiber length is described by [1],

$$\phi_j^{NL} = \frac{2\pi}{\lambda_j} n_2 L [I_j(t) + 2 \sum_{n \neq j}^M I_n(t)] \quad (1)$$

where M is the number of co-propagating channels in the fiber, λ_j is the wavelength of the j th channel and L is the

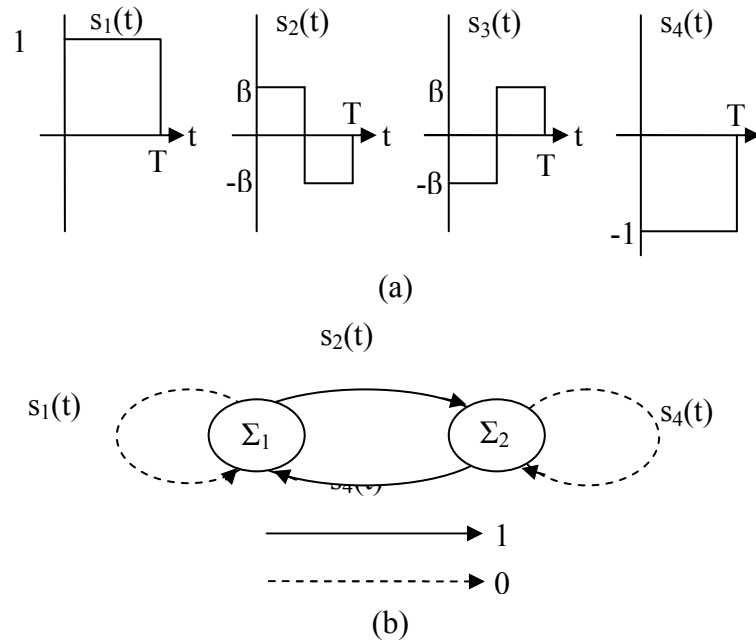


Figure 2: (a) Elementary Signals and (b) Code State Diagram for Order one Novel Line Code

length of the fiber. n_2 is nonlinear refractive index ($n_2 \approx 2.6 \times 10^{-20} \text{ m}^2/\text{W}$). $I(t)$ is the optical intensity of the propagating signal of the particular channel. The first term is responsible for self-phase modulation (SPM) and the second term is for XPM. Equation (1) might lead to a speculation that the effect of XPM could be at least twice as significant as that of SPM. To investigate the effect of XPM alone, SPM and XPM part from Equation (1) must be separated. A pump-probe approach with $M = 2$ helps isolate the effect of XPM [2]. The total XPM induced IM

of probe channel at fiber output is the sum of the XPM induced IM along the fiber with length L is given by [4]:

$$P_{\text{xpm}}(\omega) = 2\gamma_1 P_1(0) P_2(\omega) \exp(-\alpha L) \exp(-j\omega L/v_{g1}).$$

$$\left\{ \frac{1}{a^2 + (b+q)^2} [a \sin(bL) - (b+q) \cos(bL) + a \sin(qL) + (b+q) \cos(qL)] \exp(-\alpha L) \right. \\ \left. - \frac{1}{a^2 + (b-q)^2} [a \sin(bL) - (b-q) \cos(bL) + -a \sin(qL) + (b-q) \cos(qL)] \exp(-\alpha L) \right\} \quad (2)$$

Here $a = \alpha - j\omega d_{12}$, $b = \omega^2 D \lambda_1^2 / (4\pi c)$ and $q = \omega^2 D \lambda_2^2 / (4\pi c)$. α is the attenuation constant, ω is the angular frequency, D is the dispersion of the fiber ($D = 17$ ps/km-nm), λ is the wave length, d_{12} is the walk-off length, γ_1 is the nonlinear coupling coefficient of the optical signal with $\gamma_1 = (2n_2\pi)/(\lambda_1 A_{\text{eff}})$. A_{eff} is the effective core area of the fiber ($A_{\text{eff}} = 5.28 \times 10^{-11} \text{ m}^2$), v_{g1} is the group velocity of channel-1 and c is the velocity of light. In a nonzero dispersion region $d_{12} \approx D_1 \Delta\lambda_{12}$ where $\Delta\lambda_{12} = \lambda_1 - \lambda_2$ is the wavelength separation between channel 1 and channel 2.

Applying Line Coding Schemes: The output signal with NRZ coding can be expressed as:

$$P_2(z, \omega) = P_2(0, \omega) \cos(qz) \exp(-\alpha z) \exp(-j\omega z/v_{g2}) \quad (3)$$

where subscript 2 indicates the channel-2 or pump channel, $P_2(0, \omega)$ is the power spectrum of the pump channel at $z = 0$, v_{g2} is the group velocity of channel-2, $q = (\omega^2 D \lambda_2) / (4\pi c)$ with D is the fiber dispersion coefficient, λ_2 is the wavelength of the pump signal, α is the attenuation coefficient of the fiber ($\alpha = 0.21$ dB/km) and c is the speed of light. The input power of a system with Novel coding is expressed as:

$$P_2(0, \omega) = G_i(\omega/2\pi) \cos(qz) \exp(-\alpha z) \exp(-j\omega z/v_{g2}) \quad (4)$$

where $G_i(\omega/2\pi)$ is the power spectrum of the i th channel and is defined as [6]:

$$G_i(f) = \frac{1}{T} |S_1(f)|^2 \cos^2(\pi f T) + \frac{1}{T} |S_2(f)|^2 \sin^2(\pi f T) \\ + j \frac{1}{T} S_1(f) S_2^*(f) \sin(2\pi f T) \quad \dots\dots\dots (5)$$

where $S_1(f)$ and $S_2(f)$ are the Fourier transforms of the order one Novel line coded elementary signals $s_1(t)$ and $s_2(t)$ respectively. $T/2$ is the rectangular pulse duration.

V. RESULTS AND DISCUSSIONS

Standard parameters are used to evaluate the performance results. The bit pattern used is PRBS 512 bits, wave length of first channel $\lambda_1 = 1550$ nm, channel separation = 50 nm. According to Equation (2), the

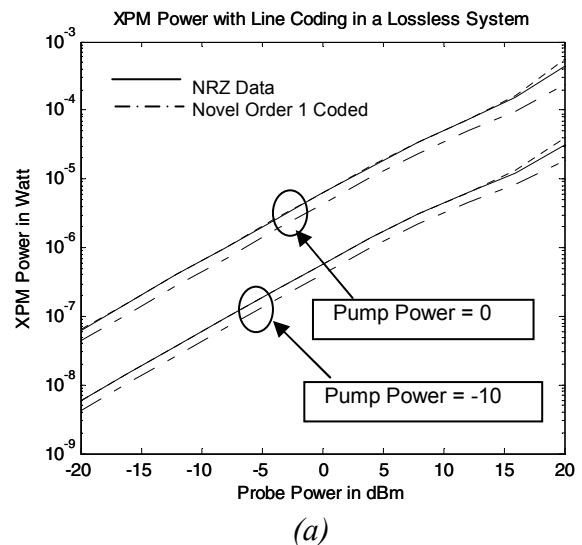
XPM induced power depends on factors such as probe power, pump power, distance, channel separation, bit rate, etc. Here only varied input power and link length is considered.

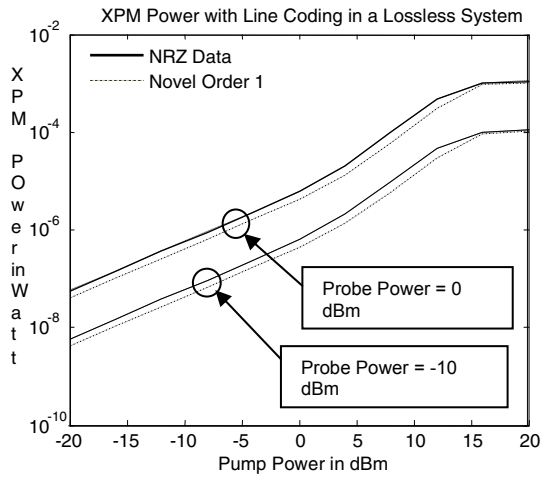
Figure 3 shows the effect of the application of line coding scheme in a DWDM system with bit rate of 10 GHz, channel spacing of 50 GHz and fiber length of 100 km. It shows XPM Power with and without line coding for different pump and probe powers. It unveils a very important finding that the XPM induced power is less for Novel line coded scheme. Novel line coding are applied in this simulation. It is evident from the plot that comparing the NRZ scheme, the Novel Order one coding scheme shows a remarkable reduction of XPM induced power.

Figure 4 shows the effect of the application of line coding scheme in a DWDM system with parameters as of Figure 2. It shows that the BER caused by XPM with for different probe powers for NRZ data and Novel Order 1 code. It shows that Novel Order 1 code could successfully reduce the BER caused by XPM induced power.

Figure 5 shows the allowable probe power at different distances applying line codes. It is evident that with Novel Order 1 code, the allowable probe power can be increased for the same BER. It is evident that the improvement is not the same for all the combinations of power.

The allowable probe power for NRZ and novel code is almost the same for different distances. It is also evident from Figure 4 that at higher distances like 150 km the required probe power is more and there is no difference in required probe power at lower pump power. As the pump power is increased, the effect of the application of line coding becomes evident. The maximum improvement is 1.89 dB at 100 km with pump power 16 dBm. This improvement is the main finding of this study.





(b)

Figure 3: XPM Power with line coding, (a) analytical result for pump power = -10 and 0 dBm and (b) simulated result for probe power = -10 and 0 dBm with fiber length = 100 km, bit rate = 10 GHz and channel spacing = 50 GHz.

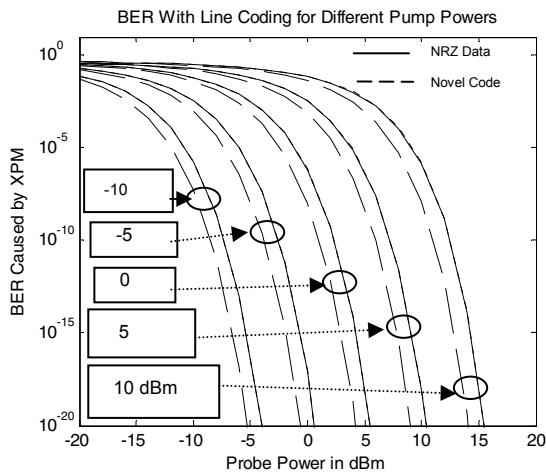


Figure 4: Plot of BER caused by XPM with NRZ data and Novel Order 1 Code for pump power -10, -5, 0, 5 and 10 dBm for 100 km fiber.

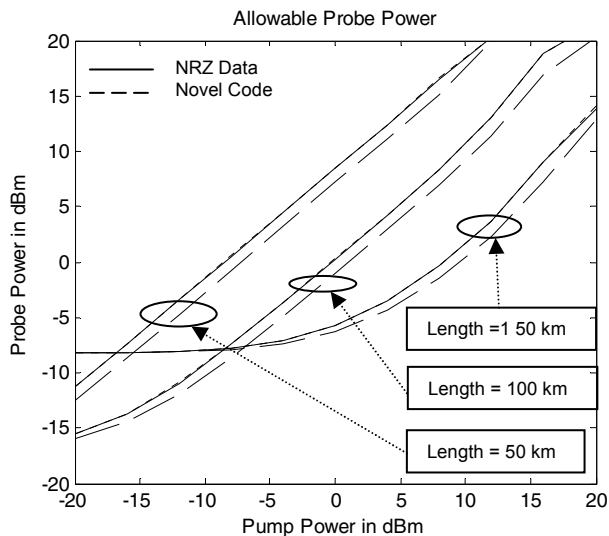


Figure 5: Plot of allowable probe power for BER of 10^{-9} at 50, 100 and 150 km

VI. CONCLUSION

An analytical approach is presented to evaluate the effectiveness of optical line coding scheme with Novel Optical Line codes in minimizing the effect of XPM in a dense WDM transmission system over a single mode fiber. Results are evaluated in terms of BER and power penalty at a BER of 10^{-9} . It is found that there is an improvement of 1.89 dB in allowable input power due to line coding scheme in presence of XPM. Line coding combined with other measures to combat the nonlinear effects of optical fiber proves to be an effective approach in supporting future bandwidth requirements.

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