Optical WDM Systems with Binary Pulse Position Modulation and Coding on Binary Asymmetric Channel

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Abstract: In a binary asymmetric channel (BAC) it may be necessary to correct only those errors which result from incorrect transmission of one of the two code elements. In optical fiber multichannel systems, the optical amplifiers are critical components and Amplified Spontaneous Emission (ASE) noise in the optical amplifiers is the major source of noise in it. In this paper performance of single as well as concatenated error correcting codes in such systems in presence of Stimulated Raman Scattering and Amplified Spontaneous Emission noises (ASE, ASE-Signal beat and ASE-ASE beat) with asymmetric channel statistics with Binary Pulse Position (BPPM) modulation scheme is reported. The error probability performances have been evaluated and compared between un-coded OOK, coded BAC with OOK and coded BPPM systems. The coded BPPM is found to be more efficient and has a better error rate than others.

Index terms: Binary Asymmetric Channel (BAC), Binary Pulse Position Modulation (BPPM), Stimulated Raman Scattering (SRS), Amplified Spontaneous Emission (ASE), Erbium Doped Fiber Amplifier (EDFA), Bit Error Rate (BER), Wavelength Division Multiplexing (WDM), Concatenated Error Coding.

I. INTRODUCTION

Single mode optical fiber with its enormous bandwidth provides attractive option for transferring digital data at high bit rate to longer distances and to exploit this bandwidth fully, WDM schemes are accommodated. Among all the nonlinearities, the SRS effect causes the spectral gain to be wavelength dependent with longer wavelengths having higher gain [1]-[3]. Optically amplified systems employing EDFA have revolutionized the long distance communication. The margin or difference between the received Signal to Noise Ratio (SNR) and the SNR required to maintain given BER is important for the design and operation of optical amplifier transmission systems. The EDFA gain spectrum is wavelength dependant while the link loss between the amplifiers is wavelength independent and this will result in severe SNR differential among the channels in WDM systems [4]. This is undesirable because it will result in low SNR for systems with higher number of channels [4]. Also the optical amplification is obtained at the expense of the noise added to the output signal. In a chain of repeater amplifiers, ASE noise generated in each amplifier will accumulate and be further amplified by the succeeding amplifiers. The accumulated ASE noise is proportional to the gain of each amplifier and the number of amplifiers in the chain [5]. Its spectrum is same as that of the broad spectrum of the spontaneous emission modified by the gain profile of the amplifier chain. The wideband WDM systems cannot accommodate narrow optical filters to attenuate unwanted ASE noise. The detected noise at the receiver due to ASE consists of a spontaneous-spontaneous component, which is a self beat
noise of ASE within the optical band of the receiver and a signal-spontaneous component from the beats between the signal and the ASE. The signal-spontaneous beat is usually dominates in practical systems so that SNR is approximated by \[ (1) \]

\[
\text{SNR} = \frac{I_p \cdot B_0}{I_{\text{ASE}} \cdot B_E}
\]

where \( I_p \) and \( I_{\text{ASE}} \) are average photocurrents due to signal power ASE noise respectively and \( B_0 \) and \( B_E \) are optical and electrical bandwidths at the receiver respectively. The noise power of ASE is \[ (2) \]

\[
P_{\text{ASE}} = mhvn_{sp}B_0(G-1)
\]

where \( m \) is number of EDFAs which is given as \( L/L_A \) where \( L \) is fiber link length and \( L_A \) is amplifier spacing, \( h \) is photon energy, \( n_{sp} \) is amplifier emission noise factor and \( G \) is amplifier gain equals \( e^{\alpha L_A} \), under the assumption that the gain of each amplifier is equal to the loss between two amplifiers, where \( \alpha \) as loss coefficient of the fiber. The application of the central limit theorem to the sum of independent random variables for large value of system parameter \( M = \frac{B_0}{B_E} \) yields Gaussian approximation for both symbols [6]. In this paper we study the performance enhancement with coding applied to multichannel optical communication systems in presence of both SRS and ASE noise.

II. ANALYSIS

In most of the electrical communication systems, the probabilities of the crossover from bit ‘1’ (ON state) to ‘0’ (OFF state) and vice-versa are the same. This is because of the variance of noise effecting bit ‘0’ and bit ‘1’ are same. In other words the noise is stationary. Such systems are modeled as

Fig.1: Model of Binary Asymmetric Channel

Fig.2: Maximum number of channels that can be accommodated so that SRS depletion is less than 1 dB.

Fig.3: Dependance of Q-factor on Number of Amplifiers.
Binary Symmetric Channel (BSC) and error correcting codes for BSCs have been studied extensively [7]. In optically amplified Lightwave communication systems, the shot and ASE noise affects bit ‘1’ more severely compared to bit ‘0’. This will result in variance of noise affecting bit ‘1’ to be more compared to that of variance of noise affecting bit ‘0’. Consequently, even after appropriately selecting the detection threshold, probability of error in bit ‘1’ \( P_1 \) and probability of error in bit ‘0’ \( P_0 \) are not equal.

In such circumstances it is better to model the channel as a Binary Asymmetric Channel (BAC) as shown in Fig.1. It is worth mentioning here that this is closely resembles the Z channel wherein either \( P_0 \) or \( P_1 \) is zero [8], [9]. In such cases, conventional error correcting coding technologies may result in under utilization of the codes capacity. Special error correcting coding techniques called asymmetric error correcting coding technology have been proposed for such channels [10]-[13].

To the best of our knowledge very few reports exist on the use of error correcting coding technologies to counter the nonlinear effects in BAC of the type encountered in Lightwave communication systems. Further this is an area of the active research as reported in [14], [15]. In [16] application of error correcting codes on BAC has been reported, but without using Binary Pulse position Modulation and Concatenated coding techniques as highlighted in sections 3 and 4 respectively. Also, in [16] the presence of ASE beat noise powers (refer section 1 above) were not taken into consideration.

Bit one is usually transmitted with signal energy of \( 2E_s \). Let an \( N \) channel WDM system be operating in 1.5µm window with a uniform spacing of 30GHz between the wavelengths. Let bits 0’s and 1’s be equally likely. Let all channels fall within the triangular Raman gain profile of coefficient \( g = 7x10^{14} \) m/w and a slope of \( dg/df = 4.67x10^{-25} \) m/W/Hz. The thermal noise current of 100nA and shot noise current of 10nA is considered in calculations. The single mode fiber is assumed to have loss coefficient of 0.2dB/km with effective link length of 21.7km, excess input coupling noise factor of 2 and core effective area of 50µm². We assumed the bit rate of 10Gbs, \( B_s = 5GHz \) and \( B_0 = 90Å \) [6]. As per the theory given in [2] and Fig.2, with amplifier spacing of 40km, for SRS depletion to be less than 1dB, the maximum channels a system can accommodate is 131 at 100km distance while it is only 14 at 1000km distance.

The spontaneous emission noise factor of each EDFA is assumed to be constant. The amplifier gain bandwidth is assumed to be 25nm in 1.5 µm window. The amplifier can be modeled as a linear optical field amplifier together with a source of Gaussian noise over the bandwidth of interest [6], [16 - 17]. Though the most accurate theoretical model for ASE noise is asymmetric Chi-square model, because of more convenient properties of Gaussian distributions, the ASE noise is approximated as a symmetric Gaussian densities [18]. The BER performance is evaluated based on \( Q \)-factor given by

\[
Q = \frac{\mu_1 - \mu_0}{\sigma_0 + \sigma_1}
\]

(3)

where \( \mu_{1,0} \) is mean value of 1/0 bit and \( \sigma_{1,0} \) is the standard deviation [19]. The mean and variance of the channel output is a function of the system parameter \( m \) and hence the \( Q \)-factor also depends on \( m \) in addition to the SNR [17]. The Gaussian approximation of ASE noise distribution is having mean value of \( MP_{ASE} \) and \( MP_{ASE} + 2E_s \) during 0/1 bit respectively. Similarly the variances are \( MP_{ASE}^2 \) and \( MP_{ASE}^2 + 4E_s \) respectively.
Fig. 4.: Performance enhancement using Hamming and Convolution coding for $M = 0.5$.

Fig. 5.: Performance enhancement using Hamming and Convolution coding for $M = 5$.

Fig. 6.: BER as a function of SNR with BPPM plus coding and without coding for $M = 0.5$.

Fig. 7.: BER as a function of SNR with BPPM plus coding and without coding for $M = 5$. 
In order to maintain a BER of $10^{-9}$ the receiver needs at least 0.6µW of power [20]. Hence to compensate for fiber attenuations [21], we may have to place an EDFA at least for every 10km link length. Fig.3 is shows number of EDFAs versus $Q$-factor for 300km, 80 and 160 channel WDM systems in presence of SRS. The required BER of $10^{-9}$ (corresponding to $Q = 6$) is achieved with 37 and 44 EDFA’s for 80 and 160 channels respectively.

III. PERFORMANCE WITH BINARY PULSE POSITION MODULATION

In OOK system, the signal bit ‘1’ and bit ‘0’ is transmitted with a pulse of positive amplitude and pulse of zero amplitude respectively. The receiver decides the received bit as ‘0’ or ‘1’ depending on whether the photon count is less or greater than the threshold respectively. Thus in OOK systems, it is necessary to determine the optimum detection threshold by searching the cross over point of the two conditional density functions associated with bit ‘0’ and bit ‘1’. In this section the usage of an alternative modulation technique called Binary Pulse Position Modulation (BPPM) is reported wherein the data detection does not require a ‘search’ of the optimum threshold. In BPPM system, a bit interval is divided into two time slots [22]-[26]. Bit ‘0’ is represented by transmitting a sequence of zero pulses in the first half and optical pulse of normalized intensity ‘1’ in the second half. For transmitting bit ‘1’, this is done in the reverse order. In this case, the detector decides in favor of bit ‘1’ if the photon count is above threshold as before. This system eliminates necessity to determine the optimum threshold, which is required to be done in OOK systems.

IV. CONCATENATED ERROR CONTROL CODING

In addition to the modulation formats, error correction techniques are considered as a promising way to improve the performance...
of existing optical systems. The error detection and correction codes use redundant or parity bits which are added to the data bits. In block codes the source data are segmented into blocks of ‘k’ data bits and each block represents one of $2^k$ distinct messages [7]. The encoder transforms each ‘k’ bit data into larger block of ‘n’ bits, referred as $(n, k)$ code word with $(n-k)$ bits as redundant or parity bits. The error detecting and correcting capabilities of a code word is determined using minimum distance between the code words and coding gain [7].

Code concatenation has been widely used in wireless communication and can also be used in optical communication systems to improve the error correction capability at the cost of increasing overhead. A concatenated code uses two levels of coding, an inner code and an outer code, to achieve the desired error performance [7]. A simple concatenated code is formed from two codes $(n_1, k_1)$ and $(n_2, k_2)$ or $(n_1, k_1)$ and $(n_1, k_2)$. The minimum distance and coding gain of concatenated code is the product of the minimum distance and coding gain of the individual codes respectively. One of the most popular concatenated coding systems uses a Viterbi-decoded convolution inner code and a RS outer code [27]. The two separate coders are interconnected with an interleaver at the transmitter side and deinterleaver in between the decoders at the receiver side [27]. The performance with and without BPPM with single as well as concatenated scheme of Hamming (31, 26), RS (255,254), ½ rate Convolution coding [7] in different configurations is reported.

V. RESULTS AND DISCUSSIONS

The performance enhancement using RS – convolution and Hamming – RS concatenated error control coding techniques, with BPPM, in presence of above mentioned system impairments has been investigated. The error probability performance using Hamming (31, 26) and rate ½ convolution coding technique on BAC is investigated and plotted in Figs. 4 and 5 for $M$ equal to 0.5 and 5 respectively. From Fig. 4 at $M = 0.5$, at BER of $10^{-9}$, the effective improvement in SNR with Hamming coding technique when compared to that without coding amounts to 20 (i.e. the BER of $10^{-9}$ is possible to achieve with SNR of 20 with coding instead of 40 in absence of coding). Similarly, from Fig. 5, this enhancement amounts to 34 at $M = 5$. With adoption of ½ rate convolution coding techniques, the enhancement in effect is 15 and 28 for $M$ values of 0.5 and 5 respectively as shown in Figs. 4 and 5.

Error probability for BPPM has been obtained and the results have been compared to the performance of the corresponding OOK coded/un-coded systems. The superior performance of the proposed method can be clearly observed. As shown in Fig. 6 for $M = 0.5$, BER of $10^{-9}$ can be achieved at SNR of 13 and 9 with Hamming coding and Convolution coding techniques along with BPPM when compared to un-coded OOK systems. Similarly they are 24 and 19 respectively as shown in Fig. 7 for $M = 5$.

The BER curves with BPPM and concatenated coding techniques are plotted in Figs. 8 and 9 for $M = 0.5$ and 5 respectively. Here only two types of concatenation are considered just as an example. BER of $10^{-9}$ with RS - Convolution concatenation coding is obtained at SNR of 6.5 with $M = 0.5$ while it is 16 with $M = 5$ from Fig. 8. From Fig. 9, same BER is obtained at SNR of 5.5 and 14 respectively with Hamming - RS concatenation codes.

The error probability performances have been evaluated and compared between un-coded OOK, coded BAC with OOK and coded BPPM systems. The concatenated error control coded system with BPPM is more efficient and has a better error rate than others.
VI. CONCLUSIONS

In this paper, the use of concatenated error control coding techniques applied to WDM optical systems on BAC, which is effected by SRS, ASE, ASE-ASE beat and ASE-signal beat noises is proposed. Study on the performances with single error control coding with BPPM modulation scheme instead of OOK is done. Also, the adoption of two possible combinations of concatenation of codes namely Hamming – RS and RS - ½ rate Convolution code, with BPPM technique, is reported. The author feel that the techniques discussed in this paper will be of considerable use in optical WDM systems.

REFERENCES
