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Optimization of WDM lightwave systems (BAC) design using error control coding

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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 noise in the optical amplifiers is the major source of noise in it. The property of erbium doped fiber amplifier is nearly ideal for application in lightwave long haul transmission. We investigate performance of error correcting codes in such systems in presence of stimulated Raman scattering and amplified spontaneous emission noise with asymmetric channel statistics. Performance of some best known concatenated coding schemes is reported.
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Keywords: Binary asymmetric channel (BAC); Stimulated Raman scattering (SRS); Amplified spontaneous emission (ASE); Erbium doped fiber amplifier (EDFA); Bit error rate (BER); Wavelength division multiplexing (WDM); Concatenated error coding (CEC)

1. 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 to 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 large SNR differential between the channels in WDM systems [4]. This is undesirable because it will cause low SNR and system impairments in unequalized WDM systems having cascade of EDFAs [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 [5]. Its spectrum is 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 the self beat of ASE power within the optical band of the receiver and the signal-spontaneous component from the beats between the signal and the ASE. The signal-spontaneous beat usually dominates in practical systems so that SNR is approximated by [5]

$$\mathrm{SNR} = \frac{I_{\mathrm{p}} B_{\mathrm{o}}}{I_{\mathrm{ASE}} B_{\mathrm{e}}}, \tag{1}$$

where I_{p} and I_{ASE} are average photocurrents due to signal power ASE noise, respectively and B_{o} and B_{e} are optical and electrical bandwidths at the receiver, respectively. The ASE noise power is [5]

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$$P_{\mathrm{ASE}} = M h \upsilon n_{\mathrm{sp}} B_{\mathrm{o}}(G - 1), \tag{2}$$

where M is the number of EDFAs which is given as L/L_{a}, where L is the fiber link length and L_{a} is the amplifier spacing, $h\upsilon$ is the photon energy, n_{sp} is the amplifier emission noise factor, and G is the amplifier gain equals $e^{\alpha L_{\mathrm{a}}}$, under the assumption that the gain of each amplifier is equal to the loss between two amplifiers, where α is 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 $m = B_{\mathrm{o}}/B_{\mathrm{e}}$ 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.

2. 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 the variance of noise effecting bit ‘0’ and bit ‘1’ are the same. In other words the noise is stationary. Such systems are modeled as 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 results in variance of noise affecting bit ‘1’ to be more compared to 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) does not turn out to the same generally.

Under such circumstances the channel modeled more suitably as that of a binary asymmetric channel (BAC) as shown in Fig. 1. It is worth mentioning here that this is closely 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 technologies called asymmetric error correcting coding technology have been proposed for such channels [10–13].

Very few reports exist to the best of our knowledge wherein error correcting coding technologies has been proposed to counter the nonlinear effects in BAC of the type encountered in lightwave communication systems. Further this is an area of the active research [14,15]. In the case of optical on-off keying (OOK) modulation scheme, the signal bit is either zero or one. Bit one is usually transmitted with signal energy of $2E_{\mathrm{s}}$. Let the N channel WDM system be operating in 1.5 µm window with a uniform spacing of 30 GHz 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 $g = 7 \times 10^{-14}$ m/W with its slope of $dg/df = 4.67 \times 10^{-25}$ m/W/Hz. We have taken thermal noise current of 100 nA and shot noise current of 10 nA in our calculations. The single mode fiber is assumed to have loss coefficient of 0.2 dB/km with effective link length of 21.7 km, excess input coupling noise factor of 2 and core effective area of 50 µm^2. We assumed the bit rate of 10 Gbs, $B_{\mathrm{e}} = 5$ GHz and $B_{\mathrm{o}} = 90$ Å [6]. As per the theory given in [2] and Fig. 2, with amplifier spacing of 40 km, for SRS depletion to be less than 1 dB, the maximum channels a system can accommodate is 131 at 100 km distance while it is only 14 at 1000 km distance.

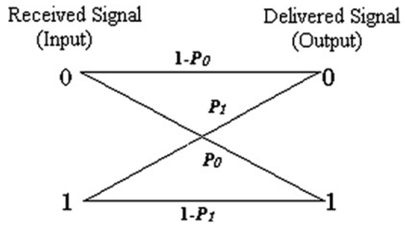

Fig. 1. Model of binary asymmetric channel.

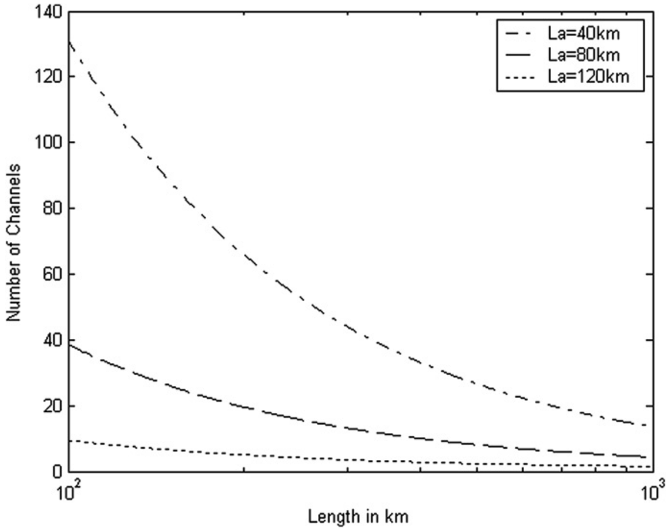

Fig. 2. Maximum number of channels that can be accommodated so that SRS depletion is less than 1 dB.

The spontaneous emission noise factor of each EDFA is assumed to be constant. The amplifier gain bandwidth is assumed to be 25 nm 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]. 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 asymmetric Gaussian densities [17]. The BER performance is evaluated based on Q-factor given by

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_0 + \sigma_1}, \tag{3}$$

where $\mu_{1,0}$ is mean value of 1/0 bit and $\sigma_{1,0}$ is the standard deviation [18]. 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 [16]. The Gaussian approximation of ASE noise distribution has mean of mP_{ASE} and $mP_{\mathrm{ASE}} + 2E_{\mathrm{s}}$, during 0/1 bit respectively. Similarly the variances are mP_{ASE}^2 and $mP_{\mathrm{ASE}}^2 + 4E_{\mathrm{s}}$, respectively.

To maintain BER of 10^{-9} the receiver needs at least 0.6 µW of power [19]. Hence to compensate for fiber attenuations [20], we may have to place an EDFA at least for every 10 km link length. Figure 3 shows the number of EDFAs versus Q-factor

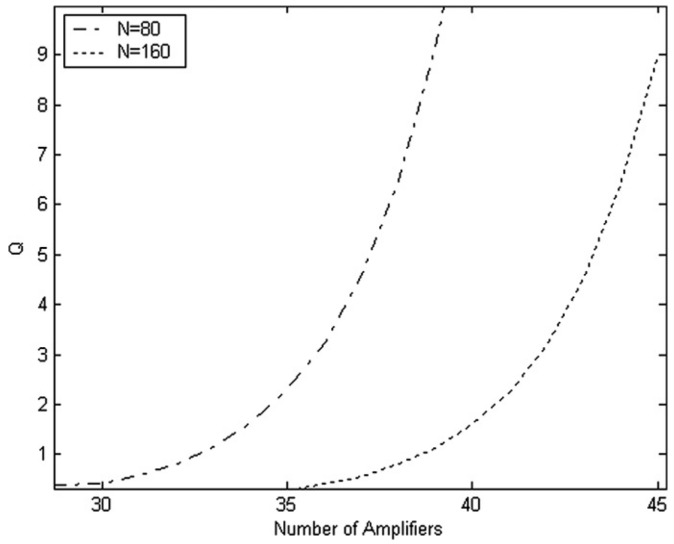

Fig. 3. Dependance of Q-factor on number of amplifiers.

for 300 km, 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 EDFAs for 80 and 160 channels, respectively.

3. Results

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 a cost of increasing overhead. A concatenated code is one that 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. We have shown performance with concatenated scheme of RS(255,254) and BCH(255,215) coding with different configurations [7] as shown in Figs. 4 and 5.

We have compared the performances between three configurations of concatenated coding schemes applied on BAC. As shown in Figs. 4 and 5, the best performance can be achieved with RS-RS coding (concatenation of two RS codes in series). The 80 channel WDM system of link length 1000 km with RS-RS coding studied herein becomes one of the best possible combination as shown in Figs. 4 and 5.

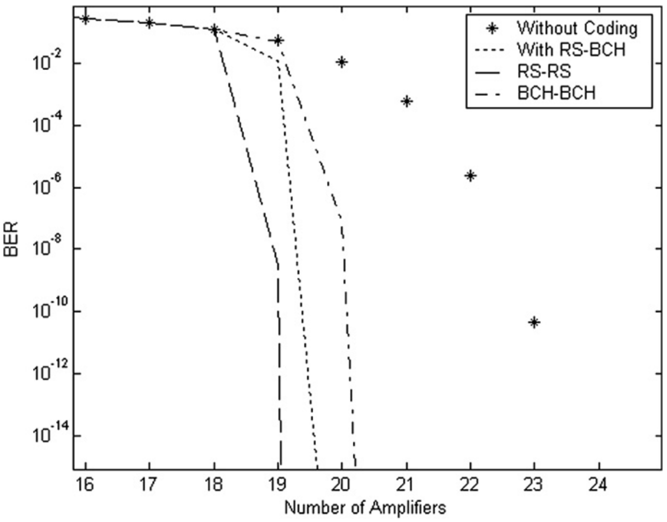

Fig. 4. BER performance with and without concatenated coding techniques.

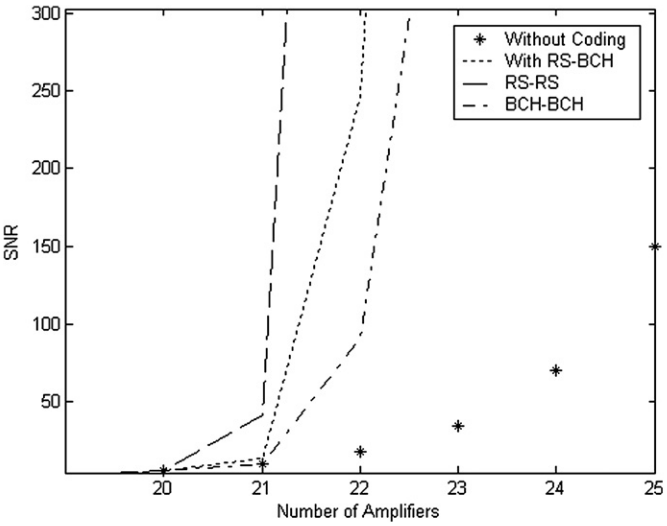

Fig. 5. SNR performance with and without concatenated coding techniques.

4. Conclusions

In this paper, we proposed the use of concatenated error control coding techniques applied to WDM optical systems on a BAC, which is affected by ASE noise. We evaluated the performances with adoption of thee possible combinations of concatenation of codes namely RS-RS, RS-BCH, and BCH-BCH. We feel that the techniques discussed in this paper will be of considerable use in optical WDM systems.

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