Concatenated Error Control Coding Applied to WDM Optical Communication Systems for Performance Enhancement

H.S. Mruthyunjaya\textsuperscript{a}, G. Umesh\textsuperscript{b}, M. Sathish Kumar\textsuperscript{a},

\textsuperscript{a}Reader, Department of Electronics & Communication Engineering, Manipal Institute of Technology, Manipal, India.
\textsuperscript{b}Professor, Department of Physics, National Institute of Technology Karnataka, Surathkal, India.
Tel.: 91-0820-2924821; Fax.: 91-0820-2571071; E-mail: hsmhgd@yahoo.com

Abstract: Long haul incoherent optical multichannel communication systems employing $N \times N$ Wavelength Division Multiplexing (WDM) in presence of Stimulated Raman Scattering (SRS) and other receiver noises including channel and Amplified Spontaneous Emission (ASE) beat noises is analyzed. Concatenated error control coding techniques are employed to counter system degradation due to these limiting factors. It is shown that the Bit Error Rate (BER) of the order of 10^{-9} can be achieved for large values of $N$ (=270) at link length of 200km without crossing SRS threshold of 1dB. Also power penalty due to multiplexer crosstalk effectively comes down from 5.5dB to 0.14dB for a 64 channel WDM system.

Index Terms: Wavelength Division Multiplexing (WDM), Stimulated Raman Scattering (SRS), Amplified Spontaneous Emission (ASE), Bit Error Rate (BER), Concatenated Error control coding, channel beat noise.

I. INTRODUCTION

Single mode optical fiber with its enormous bandwidth provides attractive option for transferring digital data at high bit rate to longer distances. To exploit this bandwidth fully, WDM schemes are accommodated. Among the nonlinearities, the SRS effect causes the spectral gain to be wavelength dependent with longer wavelengths having higher gain [1]-[3]. When signal power is more than 2mW per channel, the nonlinear fiber interaction will cause significant SRS and results in severe signal-to-noise ratio (SNR) differential among many WDM channels after propagating long distances [4]–[6]. The crosstalk variance of SRS in WDM system is found to be Gaussian [7].

As mentioned in [1], using triangular Raman gain profile and neglecting the fiber dispersion effects, for SRS power penalty to be not more than 1dB, the maximum power $P_{\text{max}}$ at distance $L$ for $N$ channel system should be

$$P_{\text{max}} = \frac{875 \times 10^{24} \cdot A_{\text{eff}} \cdot (1 - 10^{-0.1}) \cdot 10^{-0.02L}}{\Delta f \cdot L_{\text{eff}} \cdot N(N-1)}$$

(1)

where effective fiber length, with fiber loss coefficient of 0.2dB/km, is defined as

$$L_{\text{eff}} = \frac{(1 - e^{-0.2L})}{0.2}$$

(2)
and $A_{\text{eff}}$ is effective fiber core area and $\Delta f$ is frequency spacing.

Crosstalk in optical network systems can be classified as either heterodyne, between signals at different wavelengths, or homodyne, between signals at the same nominal wavelength. Homodyne crosstalk can be further subdivided into coherent crosstalk, between phase correlated signals, and incoherent crosstalk, between signals which are not phase correlated. Several studies have been reported in the literature, addressing different crosstalk contributions in optical networks [8]-[14]. Studies in [8] show that incoherent crosstalk may cause fluctuation of signal power because it can be a coherent combination of crosstalk contributions. The results in [11] revealed that when the crosstalk power exceeds a critical value, the error rate due to this can dominate all other affects inducing errors, and lead to poorer BER. The crosstalk must be less than -34dB for $16 \times 16$ system to keep the power penalty below 1dB at BER of $10^{-9}$ [14]. Along with SRS, we have considered receiver shot and thermal noises. In this work we propose to introduce redundancy in the transmitted data bits by employing error control coding techniques and show considerable improvement in the system performance.

Consider a system with chain of in-line amplifiers and assuming that the gain of each amplifier exactly equals the loss between two amplifiers. Following the analysis given in [15], for SRS degradation to be less than 1dB at BER of $10^{-9}$ with amplifier excess noise factor of 1.4, the maximum power to be fed in is

$$P_m = \frac{8.8145 \times 10^{15}}{N \cdot (N-1) \cdot \Delta f \cdot L_e} (3)$$

where effective fiber length

$$L_e = \frac{(1-e^{0.2L_A}) \cdot L}{0.2 \cdot L_A} (4)$$

and $L_A$ is Amplifier spacing. Here we have assumed effective fiber core area of 50 $\mu$m$^2$.

II. SYSTEM CONSIDERATIONS

Consider an intensity-modulation and direct detection (IMDD) $N$ channel equally spaced WDM system operating in 1.5µm window with $M$ number of Amplifiers. Let bits 0’s and 1’s to 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 100nA and shot noise current of 10nA in our calculations. The single mode fiber is assumed to have loss coefficient of 0.2dB/km with effective link length of
21.7km, core effective area of 50µm^2. The input power per channel \( P \) is taken as 1mW.

As shown in Fig.1, the minimum power required by a PIN receiver is 0.6µW for BER to be \( 10^{-9} \) for 16 x 16 WDM systems in the absence of noise. In presence of SRS, the receiver needs around 3.75µW and obviously the SRS dominates the contribution to degradation of system performance. As shown in Fig.2, in order to have power penalty due to SRS less than 1dB, the maximum value of \( N \) with channel spacing \( df = 30 \text{GHz} \) is around 120 and this value decreases with increase in channel spacing.

Interchannel crosstalk arises when an interfering signal comes from a neighboring channel that operates at a different wavelength and can be possibly removed by the demultiplexer at the receiver end. The intrachannel crosstalk is more severe as it falls completely within the receiver bandwidth. Such severe degradation is due to beat noise caused by the interference of crosstalk light. The studies on beat noise have already been reported in [14], [17]. As reported in [18], the impact of same wavelength crosstalk as small as -20 dB imposes a 3 dB power penalty. If the average intrachannel crosstalk power is a fraction \( \varepsilon \) of the average signal power \( P \) then power penalty is defined as

\[
PP = -10\log(1 - \varepsilon)
\]

and factor \( \varepsilon \) is

\[
\varepsilon = \sum_{i=1}^{N} \varepsilon_i
\]

where \( \varepsilon_i \) is crosstalk power contributed by each channel of a WDM system. The factor \( \varepsilon \) is proportional to multiplexer crosstalk \( R \) given by [14]

\[
\varepsilon = R(N-1)Q^2
\]

As shown in Fig.3, for power penalty due to beat noise to be less than 1dB, the multiplexer crosstalk must be less than -33, -39 and -42dB for number of channels of 16, 64 and 128 respectively. The Fig.4 indicates the maximum number channels can be accommodated with respect to the fiber link length in presence of ASE noise and SRS degradation limited to 1dB.

The transmitted signal power, channel bandwidth and power spectral density of receiver noise are the key parameters which determine the signal energy per bit to noise power density ratio (SNR). The performance of single-mode fiber optic systems has been mainly determined by BER impairments. Usually practical modulation schemes puts limit on the value of SNR and don’t provide acceptable data.
quality. The acceptable one of the option for maintaining data quality for particular SNR is concatenated error correcting coding. In this paper we show that the dispersion limited systems employed with a single- and multiple- error correcting codes can be more effective. Studies have been conducted in [19]-[21] and demonstrated in [21] that error correction can produce BER reductions equivalent to an 18 dB increase in optical source power.

The error detection and correction codes uses 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 [23], [24]. 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. Here (k/n) is the code rate. The error detecting and correcting capabilities of a code word is determined using minimum distance between the code words [24]. The addition of redundant bits influences on faster rate of transmission, which means more bandwidth.

Hamming codes are a class of block codes characterized by generating polynomial $g(x) = x^8 + x^4 + x^3 + x^2 + 1$ and for every (n, k) code word $GH^T = 0$, where $G$ is k x n generator matrix and $H$ is parity check matrix. When message ‘r’ is received, the decoder computes error syndrome $s = rH^T$. The implementation is done using dividing circuit employing shift registers [23], [24]. These codes have minimum distance of 3 and hence capable of correcting all single errors and detecting all combinations of two errors (and less) within a block. The Reed-Soloman (RS) codes operate on multiple bits rather than individual bits. For an RS (n, k) code, a block of ‘k’ symbols are expanded to ‘n’ symbols by adding (n-k) redundant symbols. For ‘t’ error correcting RS code, parity check size $(n-k) = 2t$ symbols and minimum distance is $(2t + 1)$ symbols. The RS codes provide a wide range of code rates and efficient decoding techniques are available [24]. The Golay code is formed by adding an overall parity bit to the (n, k) code [23]. It is more powerful than Hamming code. However, decoder is more complex and requires more bandwidth [23]. A convolution encoder operates on the incoming message sequence continuously in a serial manner and is generated by passing the message sequence through shift registers consisting of ‘m’ stages of k-bit each and ‘n’ modulo-2 adders [23]. The Bose-Chadhuri-Hocquenghem (BCH) codes are class of block codes providing large selection of block lengths, code rates and error correcting capability [24].

A concatenated code is one that uses two levels of coding, an inner code and outer code, to achieve the desired error performance [23]. A simple concatenated code is formed from two codes $(n_1,k_1)$ and $(n_2,k_2)$ or $(n_1,k_1)$ and $(n_1,k_2)$ or $(n_1,k_1)^2$. The minimum distance and coding gain of concatenated code is the product of the minimum distance and coding gain of the individual codes respectively.

IV. RESULTS AND DISCUSSIONS

Figures 5 to 12 shows improvement in system performance after employing concatenated error correcting coding techniques. We have used a bit rate of 10G bits/sec, thermal noise current of 100nA, shot noise current of 10nA, channel spacing of 30GHz for uncoded system and 50GHz for coded system in our calculations. Fig.5 shows SNR performance and comparison is made between all the above said coding techniques. The BER of $10^{-9}$ is achieved with $Q = 6$ without coding while using BCH+RS codes it is possible to achieve same BER with $Q = 2.33$ as shown in Fig.6. As shown in Fig.7, the power penalty due to channel beat noise reduces for a particular value of multiplexer cross talk value. At multiplexer cross talk of -35dB, the BCH+RS codes reduces the power
penalty from 5.5dB to 0.14dB at BER of \(10^{-9}\) and \(N = 64\).

As shown in Fig.8, with multiplexer cross talk of -35dB, by employing BCH+RS coding BER of as low as \(10^{-7}\) can be achieved even with 1000 channels. Fig.9 show performance curves after employing BCH+BCH codes. As shown in Fig.10 the BER of \(10^{-9}\) can be achieved with \(N = 250\) at 200km distance with BCH+RS coding. The power available at 200km length for 100 channels has effectively increased from -71.5dB to -64dB with BCH+RS codes as shown in Fig.11.

\[\text{Fig.5: BER performance with different codes}\]

\[\text{Fig.6: BER variations with Q factor}\]

\[\text{V. CONCLUSIONS}\]

In this paper we have shown the enhancement of system performance by applying various type of concatenated error correcting codes to a WDM system. The BCH+BCH codes are expected to give the best result than other codes. Fig.12 shows performance enhancement after employing error correcting codes in presence of both SRS and channel beat noise with above said parameters. Without coding BER of \(10^{-9}\)
can be achieved at the maximum of 90 channels while with coding it can be achieved beyond 100 channels. In other words the power penalty for 100 channels reduces from 2.6dB to 0.7dB with coding in presence of both SRS and channel beat noise.

REFERENCES


