Author(s): S. B. Sun and M. S. Leeson

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SPECTRUM-SLICED WDM SYSTEMS WITH OPTICAL PREAMPLIFIERS

S. B. Sun and M. S. Leeson

School of Engineering

University of Warwick

Coventry

CV4 7AL

UK

Email: {s.sun.1; m.s.leeson}@warwick.ac.uk

Tel: +44 24 7652 3908

Fax: +44 24 7652 2129

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Abstract - The effect of dispersion on a spectrum-sliced WDM (SS-WDM) system with an optical preamplifier receiver is investigated for the first time. A theoretical model based on the statistics of both the incoherent source emission and the fiber dispersion is developed and used to obtain the bit error rate (BER). This model improves understanding of the spectral slicing method in a realistic situation where dispersion significantly impacts the transmission prior to arrival at the optical preamplifier. The optically preamplified receiver delivers a system of 2.5Gbps with at least twice the transmission capacity of a one with a pin diode receiver. This arises because the optimum slice width is decreased to ~0.3 nm allowing over 110 WDM channels. As a further benefit, a sensitivity improvement of 8.75 dB offers a superior power budget in comparison with the pin diode receiver, and the power efficiency can be improved by over 8dB. The results are obtained using the saddlepoint approximation and compared to the customary Gaussian approximation. The latter is found to be reasonably accurate in predicting the optimum bandwidth but conservative in sensitivity predictions.

Keywords: Spectrum-sliced WDM, Dispersion, Optical Preamplifier.

1. Introduction

High capacity wavelength division multiplexed (WDM) systems have been considered as an ultimate solution for long distance core networks. This technology is now also available for broadband access networks, such as WDM passive optical networks (PON), to satisfy the constantly increasing need for speed [1]. However, in the context of access networks, using a conventional WDM source comprised of fixed wavelength lasers for different channels is cumbersome and expensive due to the large number of optical network units (ONUs) located in individual homes. This key problem is alleviated by introducing spectrum sliced WDM (SS-WDM) as a lower complexity and cost alternative [2] [3], which enables the realization of a colorless transmitter thus removing the burden of operating and administrating wavelengths with a consequential reduction in inventory cost.

In SS-WDM, individually modulated spectral slices of a cheap broadband noise-like source are employed in the highly cost-sensitive ONUs. Previous research has proved that SS-WDMcan provide access applications with sustained bit rates of up to 10Gbps by employing semiconductor optical amplifier (SOA) based noise reduction [4] [5], forward error correction (FEC) [6] and supercontinuum sources [7]. However, as the slice width obtained from the broadband source via filtering cannot be as narrow as laser linewidths, this method includes the inherent limitation from beat noise via square-law photo-detection [8]. The beat noise remains at the decision with a level that depends on the ratio of the optical bandwidth to the bit rate, which is usually denoted by ***m***. Beat noise increases with decreasing *m*, producing a power penalty to maintain the signal to noise ratio (SNR) that favors large values of *m*.

Due to the wide wavelength range of the light source, SS-WDM systems employing conventional single-mode fibers are highly susceptibility to chromatic dispersion [9]. The dispersion induced intersymbol interference (ISI) increases with increasing ***m***, producing a power penalty to prevent a drop in the SNR. In addition, since the SOA-based noise suppression is achieved by an elaborate balancing the between numerous frequency components of light, It has been experimentally demonstrated that such high correlation is vulnerable to frequency-dependent dispersion [10], which means the beat noise is an issue for all types of optical links. Therefore, for a basic SS-WDM system, there is a tradeoff in slice width between increasing the signal-to-excess optical noise ratio and reducing dispersion-induced ISI. The result is an optimum slice width that minimizes the sensitivity for a given bit error rate (BER).

Optical amplifiers are routinely used for effectively improving the sensitivity of optical receivers by preamplifying the optical signal before it arrives at the photodetector [11]. Normally the receiver sensitivity can be improved by 10-20dB using an erbium doped fiber amplifier (EDFA) as an optical preamplifier [12]. Hence, the power budget can be improved without changing other system configurations. However, the amplified signal is noisier than the input signal because of contamination by the incoherent nature of amplified spontaneous emission (ASE). In SS systems, such additional noise will have some beating effects with the noise-like signal. In a thorough system evaluation, it is important to include all sources of power penalty as well as the performance enhancement.

This paper numerically investigates the effect of dispersion on an optically preamplified SS system for the first time. Both Gaussian and saddlepoint approximations are employed whose utility and applicability are analyzed under the assumptions in this paper. The optimum slice widths are determined based on the maximization of the receiver sensitivity. First, an improved theoretical model for assessing the dispersion effects in SS systems is developed in Section 2. Section 3 proceeds to further investigation of the optically preamplified receiver. In Section 4, numerical results are presented and compared with previous analysis and experiments; the optimum bandwidth is also calculated. Finally, conclusions are drawn in Section 5.

2. Modeling SS Systems with Dispersion

Figure 1 shows a schematic diagram of a spectrum sliced WDM system where a broadband ASE source is first filtered into small spectrum fractions. One slice of light has power spectral density (PSD) $P(\Omega)$, centered on Ω_0 and with bandwidth B_o. On-off keyed (OOK) data $s(t)$ modulate the slice and the signal is conveyed by a suitable optical fiber, of length z and linear dispersion parameter β_2. At the receiver, an optical band pass filter and an ideal square law detector are used. An integrator measures the energy in the decision interval, and compares it to a threshold that is optimized using the probability density functions (pdfs) of the received signal and noise.

The signal current after the photo detector in a bit time *T* can be expressed as [13]:

$$I = \frac{1}{2T}\int_0^T [x^2(t) + y^2(t) + \tilde{x}^2(t) + \tilde{y}^2(t)]\,dt + I_n \tag{1}$$

In (1), $x(t), y(t)$ $\tilde{x}(t)$ and $\tilde{y}(t)$ are four independent identically distributed baseband Gaussian processes corresponding to two orthogonal phases and polarizations. Each of these has variance σ^2 and bandwidth $B_o/2$. The receiver thermal noise current is represented by I_n, which is assumed to be a zero-mean Gaussian random process. For the mathematical convenience, a large extinction ratio (r_e>>20dB) is assumed, so that the received optical signal only presents in the "ON" state and is well modeled by a chi squared pdf [12]. Since the closed form expression for the combined signal and noise distribution is difficult to manipulate numerically, it is common to approximate all pdfs by Gaussians, with appropriate means and variances [13]. Although it produces a reasonably accurate estimate of the BER, this Gaussian approximation (GA) proves conservative when *m* is small. Here, the saddlepoint approximation [13], which is extremely accurate for all *m* values and is based on the true pdf via its moment generating function (mgf), is utilized in addition to the GA.

2.1 Gaussian Approximation

In single mode fiber, the SS signal operating at a wavelength of 1550 nm suffers particularly from linear chromatic dispersion [14] because of the range of frequencies present in the slice. Here, the statistical analysis of the dispersion effects is based on the approach taken by Pendock and Sampson [15] and O'Reilly and Da Rocha [16]. It is assumed that $P(\Omega)$ is intensity modulated by a Gaussian pulse shape $s(t)=exp(-t^2/2T_0^2)$, where T_0 is the e^{-1} half-width. For OOK transmission with dispersion, considering only 010 and 101 covers the worst situation, and the modulation envelopes are $s_{010}{}^2=exp(-t^2/T_0^2)$ and $s_{101}{}^2=[\, exp(-(t-T)^2/2T_0^2) + exp(-(t+T)^2/2T_0^2)]^2$.

Since the slice coherence time is substantially shorter than the bit period, the detected signal mean power after the transmission through a fiber can be written as the convolution:

$$\langle p_{010/101}(t)\rangle = s_{010/101}(t) * f_1(t) \tag{2}$$

In (2), $\langle p_{010/101}(t)\rangle$ is the ensemble mean and $f_1(t)$ is the inverse Fourier transform

$$F_1(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} P(\Omega)\exp\left[-j\omega\beta_2 z(\Omega-\Omega_0)\right]d\Omega \tag{3}$$

where ω is the angular baseband electrical frequency. For analytical tractability, a Gaussian form of the PSD is assumed

$$P(\Omega) = \exp\left(-\left\{\Omega T/\sqrt{2\pi}\, m\right\}^2\right) \quad (4)$$

The degree of dispersion is commonly depicted by the normalized distance z/L_D, where the dispersion length, $L_D = T^2/(12\,|\beta_2|)$, is the distance at which the rms pulse width of a Gaussian pulse increases by a factor of $\sqrt{2}$ from its initial width. Therefore, it is possible to derive the analytical expression of the mean output current as:

$$\left\langle I(t)_{010} \right\rangle = 2\sigma^2 \operatorname{erf}\left\{\frac{\Delta T}{2}\right\} \quad (5)$$

$$\left\langle I(t)_{101} \right\rangle = 2\sigma^2 \left[\operatorname{erf}\left\{\frac{3\Delta T}{2}\right\} - \operatorname{erf}\left\{\frac{\Delta T}{2}\right\} + 2\exp\left\{-\frac{T^2}{T_o^2}\right\}\operatorname{erf}\left\{\frac{\Delta T}{2}\right\}\right] \quad (6)$$

where $\Delta = \sqrt{ac/(a+c)}$, $a = 1/T_0^2$ and $c = T^2/2m^2\beta_2^2 z^2 \pi$.

The mean signal photocurrent in the ON-state in one polarization is found from [12]

$$\sigma^2 = \overline{N}_p \eta q R_b \quad (7)$$

where η is the quantum efficiency of the photodetector, q is the electron charge and R_b is the bit rate, and $\overline{N}_p$ is the mean number of photons per bit. From [14], the variance of the received power can be evaluated from

$$\left\langle v_{010/101}(t) \right\rangle = s^2{}_{010/101}(t) \otimes f_2(t) \quad (8)$$

where $f_2(t)$ is the inverse Fourier transform obtained by replacing $P(\Omega)$ with $P^2(\Omega)$ in (3). Therefore, the variance of the SS-OOK signal can be derived as:

$$\left\langle v(t)_{010}^2 \right\rangle = \frac{2\sigma^4}{m}\operatorname{erf}\left\{\frac{T}{2}\sqrt{\frac{2ac}{2a+c}}\right\} + \sigma_g^2 \tag{9}$$

$$\left\langle v(t)_{101}^2 \right\rangle = \sigma_g^2 \tag{10}$$

where σ_g is the variance of the thermal noise, given by $\sigma_g^2 = 8\pi V_T C_T q B_e^2$ for receiver electrical bandwidth B_e, receiver effective noise capacitance C_T and thermal potential V_T. By using the GA, the BER can be evaluated in terms of the decision point SNR, $Q = [(I_{010}-I_{101})/(v_{010}+v_{101})]$, as:

$$P_e \approx \frac{1}{\sqrt{2\pi}Q}\exp\left(-\frac{Q^2}{2}\right) \tag{11}$$

Based on the equations above, it is thus possible to derive the receiver sensitivity as a function of m in the presence of dispersion. There is an expected BER floor above 10^{-9} when m is less than a certain value, due to the performance limitation of the GA in the tail of the density, which is heavy-tailed compared to that arising with coherent systems.

2.2 Saddlepoint Approximation

The saddlepoint approximation (SPA) can be used to evaluate the BER, and has been shown to be remarkably accurate in the analysis of optical transmission systems [16], [17]. When the received signal is expressed as (1), the summation is the square of $4m$

independent Gaussian variables and is thus chi-square distributed with *4m* degrees of freedom. In the presence of dispersion, the mean is nonzero hence the chi-square distribution is noncentral. The moment generating function (MGF) of dispersed SS signals, which can be interpreted as a double-sided Laplace transform of the density function, can be derived as:

$$M_{ss}(s) = \left(\frac{1}{1 - 2v^2 s} \right)^{2m} \exp\left(\frac{4mI^2 s}{1 - 2v^2 s} \right) \tag{12}$$

where v^2 and I are the variance and mean of the output current. For the thermal noise, assumed Gaussian and white with zero mean and variance σ_g^2, the MGF is well known as:

$$M_g(s) = \exp\left(\frac{s^2 \sigma_g^2}{2} \right) \tag{13}$$

Let I_{th} be the decision threshold at the receiver. The phase functions for received bit patterns 010 and 101 are:

$$\phi_{010}(s) = \ln\{M_{010}(s)\} - sI_{th} - \ln|s| \tag{14a}$$

$$\phi_{101}(s) = \ln\{M_{101}(s)\} - sI_{th} - \ln|s| \tag{14b}$$

where $M_{010}(s)$ and $M_{101}(s)$ are the respective MGFs of the received signals 010 and 101. Since the MGF of the sum of two independent variables is the product of their MGFs. When the 101 pattern occurs, the MGF is close to Gaussian in the range of applicable filter widths with only a small contribution from the tails of the out “1” pulses. However,

M_{010} contains significant contributions via the product of (12) and (13). Then the bit error probability when the sequence 010 is transmitted can be approximated by

$$P_{e-}(I_{th}) = \frac{\exp[\phi_{010}(s_1)]}{\sqrt{2\pi\phi_{010}''(s_1)}} \qquad s_1 < 0 \tag{15}$$

Similarly for 010, the bit error rate is:

$$P_{e+}(I_{th}) = \frac{\exp[\phi_{101}(s_0)]}{\sqrt{2\pi\phi_{101}''(s_0)}} \qquad s_0 > 0 \tag{16}$$

where the parameters s_0 and s_1 are the positive and negative roots of the equations $\phi_{101}'(s) = 0$ and $\phi_{010}'(s) = 0$ respectively.

By choosing a fixed BER, here 10^{-9}, it is thus possible to derive the receiver sensitivity as a function of *m* based on the equations above. The SPA has been used here to evaluate the performance of SS systems in the presence of dispersion, to give more accurate results than those in the literature.

3. Optical Preamplifier Receiver Modeling

A shared optically preamplified receiver in the access network offers a greatly improved power budget that is cost-effective by virtue of the sharing of the resource between many customers, and this option is also available to SS-WDM. A common way to characterize an optical amplifier is as an optical field amplifier with frequency-independent gain G in combination with additive noise representing spontaneous emission. The random fluctuations caused by spontaneous emissions increase almost linearly with the gain, which produces an output photocurrent $I_{sp} = 2n_{sp}(G-1)qB_o$, where n_{sp} is the spontaneous emission factor. The ASE introduces two additional beat noise terms into the total noise power. These are beating between the signal and the added ASE:

$$\sigma^2_{s-sp} = \frac{4GI_{sp}\sigma^2}{m}\,\mathrm{erf}\left\{\frac{\Delta T}{2}\right\} \tag{17}$$

and noise from beating among the spectral components of the added amplifier ASE:

$$\sigma^2_{sp-sp} = \frac{2I_{sp}}{m} \tag{18}$$

In SS systems, there is a third beat term between different frequency components of the signal, representing the autocorrelation of the signal spectrum [18]. Since the thermal noise and shot noise can be neglected when the amplifier gain is large, the total noise variance is the sum of the three beat noise components. By using the same approach as in Section 2, the means and variances of the photocurrent using the optical preamplifier receiver can be expressed as:

$$\langle I_{OPR}(t)_{010}\rangle = 2\left\{GI(t)_{010} + I_{sp}\right\} \tag{19}$$

$$\langle I_{OPR}(t)_{101}\rangle = 2\{GI(t)_{101} + I_{sp}\} \tag{20}$$

$$\langle v_{OPR}(t)^2_{010}\rangle = \frac{2}{m}\left\{\left[G\sigma^2 \operatorname{erf}\left\{\frac{T}{2}\sqrt{\frac{2ac}{2a+c}}\right\}\right]^2 + \sigma^2_{s-sp} + \sigma^2_{sp-sp}\right\} \tag{21}$$

$$\langle v_{OPR}(t)^2_{101}\rangle = \frac{2I^2_{sp}}{m} \tag{22}$$

All parameters to approximate the two pdfs are thus obtained in terms of the mean and variance of the corresponding receiver outputs. This facilitates the utilization of the GA via (11).

To obtain more accurate results, the SPA may also be applied in this case, with the inclusion of additional MGF terms for optical preamplifier ASE noise and for the beating noise from the signals and the ASE. The signal term of the MGF can be expressed as:

$$M_{S-OPR}(s)_{010} = \left(1-\frac{sv^2_{OPR-010}}{m}\right)^{-2m} \exp\left(\frac{4msI^2_{OPR-010}}{1-\frac{sv^2_{OPR-010}}{m}}\right) \tag{23a}$$

$$M_{S-OPR}(s)_{101} = \left(1-\frac{sv^2_{OPR-101}}{m}\right)^{-2m} \exp\left(\frac{4msI^2_{OPR-101}}{1-\frac{sv^2_{OPR-101}}{m}}\right) \tag{23b}$$

The signal-spontaneous and spontaneous-spontaneous beat noise term are given for both 010 and 101 by:

$$M_{Sp-OPR}(s)_{010/101} = \left(1 - {s\sigma^2_{sp-sp}}\big/{m}\right)^{-2m}\left(1 - {s\sigma^2_{s-sp}}\big/{m}\right)^{-2m} \qquad (24)$$

Since the ASE noise is independent to the signal, the MGFs of the two processes can be multiplied together, to generate the phase function:

$$\phi_{\text{OPR-010/101}}(\text{s}) = \ln[M_{S-OPR}(s)_{010/101}] + \ln[M_{Sp-OPR}(s)_{010/101}] - sI_{th} - \ln|s| \qquad (25)$$

By forming the first derivative of (25), the corresponding roots can found for use in (15) and (16) to calculate the BER.

From the analysis above, the power budget of an SS-WDM system at a certain transmission distance can be calculated for a given bit rate, according to the optimum optical bandwidth. Considering the PSD of the broadband source, the transmitted power per channel is given by:

$$\text{P}_\text{t} = 10\log_{10}(B_o \cdot P_\Omega) \qquad (26)$$

where B_o is the slicewidth in nm, and P_Ω is the PSD over the wavelengths of interest. The available power budget can be thereafter evaluated by the difference between P_t and receiver sensitivities. When performing the system optimization, both optimum optical bandwidth and sensitivity in optimum are taken into account to work out the best power budget at a certain dispersion length.

4. Results and Discussion

This section presents numerical results to compare the performance of the system described above with and without an optical preamplifier in the presence of different dispersion levels. For practical consideration, the optical bandwidth is expressed in wavelength units and the receiver sensitivity is in power units. The simulation is applied using a data rate of R_b=2.5Gbps (STM-16) for each channel. A source of unpolarized ASE at 1550nm is considered with bandwidth of 35nm. The ideal extinction ratio (r_e>>20dB) is applied. A fourth-order Bessel-Thomson response with optimum 3dB bandwidth of B_e=0.6 R_b is used to represent the receiver noise filter [19]. C_T is 0.1pF, η is 0.7 and V_T is 26 mV. The ratio between T_0 and T is 0.275 so that little power is out of its time slot before the transmission. The group velocity dispersion parameter is taken as 17psnm^{-1}km^{-1} for conventional single-mode fiber.

As a baseline, Figure 2 shows the receiver sensitivity as functions of slice width to maintain a BER of 10^{-9}, for several transmission distances, which are normalized by z/L_D. Results from the GA and the SPA are presented, which illustrate the trade-off between excess beat noise and dispersion. When no dispersion is present, the receiver sensitivity improves as the optical bandwidth increases because of the inverse proportionality between the beat noise and B_o. However, dispersion favors smaller filter bandwidths to reduce pulse spreading. There are thus competing effects of beat noise and pulse spreading producing an optimum optical filter bandwidth for a specific bit rate and transmission distance.

Compared to the results of Arya and Jacobs [12], obtained from the pdfs, the GA can provide a convenient and sufficiently accurate estimate of the BER when the optical bandwidth is large (B_o is larger than 1nm) and the dispersion is moderate (z/L_D less than approximately 0.01), with the effect of excess noise easily included via the variance. However, when the slice width is small (B_o is smaller than 1nm), or the link distance is long such that z/L_D is greater than 0.01, the GA is highly inaccurate. Instead, the SPA approximation provides much better numerical results for the complete range of values of optical bandwidths and dispersion levels considered. For example, with a bit rate of 2.5Gbps, a FWHM slice width of 0.8nm, and no dispersion, the GA sensitivity prediction (-26.9dBm) differs by some 2dB compared with an extremely computationally intensive calculation based on the accurate pdfs (-28.9dBm) from Arya and Jacobs [12], whereas the SPA (-28.5dbm) is within 0.4dB. Moreover, the SPA has proved highly effective at obtaining agreement with measured results [13] and the results correspond well with those using a Fourier approach with chi square statistics [14]. In addition, measured results in [15] display power penalties of 1-2 dB consistent with the SPA results rather than the large penalties predicted by the GA.

Figure 3 shows the optimum receiver sensitivity and its corresponding optical bandwidth as a function of the normalized distance. The figure also illustrates the increasing penalty with greater transmission distance. To expand on this, it may be observed that when the distance is short, the power penalty is small because the reduction of optimum bandwidth decreases the dispersion effect with only a small increase in the excess beat noise. However, when the transmission distance increases, the optimum bandwidth narrows and the receiver sensitivity is significantly degraded. The increasing pulse spreading means that it is no longer possible for the decrease in optimum bandwidth to compensate for the dispersion. Using dispersion-shifted fiber would be necessary to achieve long transmission distances.

The results from Gaussian approximation are observed to be reasonably accurate in predicting the optimum bandwidth. However, they show a high deviation in sensitivity especially at long distance where the optimum optical bandwidth is small. The results from the SPA, as they are easy and accurate, are translated into system terms by considering the PSD of the broadband source. Over the wavelengths of interest (the C band of 1530 nm to 1565 nm) the PSD may be approximated by a constant value of 4 $mWnm^{-1}$ [13]. This results in an input power of ~5 dBm for the range of slice widths to maintain the BER of 10^{-9} in Figures 2 and 3, and hence a power budget of 33 dB for the 2.5 Gbps SS system using pin receiver. This restricted power budget limits the applications for the local access SS-WDM systems. Furthermore, the FWHM values translate to bandwidths of ~100 GHz enabling approximately 16 to 40 WDM channels to be accommodated. At this point, the question to be addressed is the extent of any benefits arising from the employment of an optically preamplified receiver.

Figure 4 shows the optical preamplifier receiver sensitivity using a gain of 20dB employing both the GA and the SPA. As stated above, the latter is more accurate and thus generally employed from hereon. The GA, although numerically convenient, is again proved to be conservative by showing consistency with the results of Arya and Jacobs [12] only at large slicewidths.

From the results obtained by the SPA, there are several effects evident. First, the sensitivity is improved over the *pin* receiver. Second, the optimum slice width is substantially reduced compared to the *pin* receiver being ~37GHz and thus delivering more than 110 possible WDM channels in the C band. Third, initial inspection would suggest a sensitivity gain of over 13dB but the second point must be accounted for because the power in the slice scales linearly with the FWHM. For a pin receiver, the optimum bandwidth is around 0.8 nm, whereas for the optical preamplifier receiver it is ~0.3 nm. This represents a penalty of ~4.25 dB meaning that the overall sensitivity gain is 8.75 dB. Fourth, it may be noted that even when the link is back to back the sensitivity goes up after reaching its lowest point because the ASE noise generated by the optical preamplifier in terms of (17) and (18), whose level is proportional to the slice FWHM as well as the gain, is dominant when the optical bandwidth is large. In the presence of dispersion, there is a much more rapid sensitivity change, making the correct selection of filter bandwidth crucial in these systems..

Figure 5 shows the optimum bandwidth of the optical preamplifier receiver versus normalized distance at different optical preamplifier gains, again obtained from the SPA. As shown by the graph, when the gain increases, the rapid changes at low z/L_D values disappear, which means that the optical bandwidth range required to operate at the optimum is narrowed along the various transmission distances. It is suggested that when the preamplifier gain is carefully chosen (more than 15dB), the optically preamplified receiver offers compensation for the effect of dispersion within spectral slicing systems. This implies that the optimum bandwidth can be restrained between 0.2nm and 0.6nm, which provides a relative steady number of channels regardless of the transmission distance.

Figure 6 predicts the available power budget under the configuration of optimum *m* with 2.5Gbps bit rate per channel. As the transmission distance is increased, the power budget decreases. The plot indicates that the SS-WDM with an optical preamplifier receiver possessing a 20dB gain is capable to offer up to 45dB of power budget, which is at least an 8dB improvement to that of using a *pin* receiver. It is also seen that the system with an optical preamplifier receiver is less susceptible to dispersion since there is only 0.8dB power budget degradation from zero-dispersion to z/L_D=0.04 in which range *pin* receiver system drops by some 6 dB. Therefore, the advantages of an optical preamplifier receiver to provide higher power efficiency and to mitigate the effects of beat noise and dispersion are confirmed.

5. Conclusion

The receiver sensitivity of optical preamplifier in a SS-WDM system employing a single-mode optical fiber has been determined via the GA and the SPA. There is an optimum bandwidth per channel for a normalized distance due to the competing effects of dispersion and excess beat noise. An optically preamplified receiver offers significant benefits to SS systems operating over a few tens of kilometers. The transmission capacity is at least doubled by virtue of the significantly decreased optimum slicing filter width allowing in excess of 110 WDM channels in contrast to less than 40 channels for a *pin* receiver. Furthermore, there is an 8.75 dB improvement in the receiver sensitivity for the 2.5 Gbps system considered. Since the power launched in the system to keep the BER at a certain level is reduced, the power budget is improved over 8dB accordingly. Nevertheless, fiber dispersion is still a significant issue for SS-WDM whether an optical preamplifier receiver is applied or not. The degradation on the receiver sensitivity due to dispersion forms the limitation to transmission distance as a result of the noise like nature of the source. Further research and appropriate design are thus needed to ameliorate system performance degradation.

6. REFERENCES

[1] C. H. Lee, “Fiber to the home using a PON infrastructure,” J. Lightw. Technol., Dec. 2006, vol. 24, no. 12, pp. 4568–4583.

[2] J. M. Senior, M. R. Handley, M. S. Leeson. Developments in wavelength division multiple access networking, IEEE Commun. Mag. 36; 1998, 28-36.

[3] L. G. Kazovsky, W.-T. Shaw, D. Gutierrez, N. Cheng, and S.-W. Wong, “Next-generation optical access networks,” J.Lightwave Technol., Nov. 2007, vol.25, no. 11, pp.3428-3442.

[4] A.D. McCoy; P. Horak; B.C. Thomsen; M. Ibsen; M.R. Mokhtar; D.J. Richardson, "Improving signal quality in a spectrum-sliced WDM system using SOA-based noise reduction," Photonics Technology Letters, IEEE , vol.17, no.1, pp.241-243, Jan. 2005.

[5] A. D. McCoy, M. Ibsen, P. Horak, B. C. Thomsen, and D. J. Richardson, "Feasibility Study of SOA-Based Noise Suppression for Spectral Amplitude Coded OCDMA," J. Lightwave Technol. 25, 394-401 (2007)

[6] S. Kaneko, J. Kani, K. Iwatsuki, A. Ohki, M. Sugo, and S. Kamei, "Scalability of Spectrum-Sliced DWDM Transmission and Its Expansion Using Forward Error Correction," J. Lightwave Technol. 24, 1295- (2006).

[7] J.H. Lee; C.H. Kim; Y.-G. Han; S.B. Lee, "WDM-Based Passive Optical Network Upstream Transmission at 1.25 Gb/s Using Fabry-Perot Laser Diodes Injected With Spectrum-Sliced, Depolarized, Continuous-Wave Supercontinuum Source," Photonics Technology Letters, IEEE , vol.18, no.20, pp.2108-2110, Oct. 2006

[8] J. S. Lee, Y. C. Chung, and D.J. DiGiovanni. Spectrum-sliced fiber amplifier light source for multichannel WDM applications. IEEE Photon. Technol. Lett. 5; 1993, 1458-1461.

[9] G. P. Agrawal. Fiber-Optic Communication Systems. Wiley, New York; 2002.

[10] Hoon Kim; Sangho Kim; Seongtaek Hwang; Yunje Oh, "Impact of dispersion, PMD, and PDL on the performance of spectrum-sliced incoherent light sources using gain-saturated semiconductor optical amplifiers," Lightwave Technology, Journal of , vol.24, no.2, pp. 775-785, Feb. 2006

[11] E. Desurvire. Erbium Doped Fiber Amplifiers. Wiley, New York; 1994.

[12] V. Arya and I. Jacobs. Optical preamplifier receiver for spectrum-sliced WDM. J. Lightwave Technol., 15; 1997, 576–583.

[13] M. S. Leeson. Performance analysis of direct detection spectrally sliced receivers using fabry-perot filters. J. Lightwave Technol. 18; 2000, 13–25.

[14] V. Wongpaibool. Effect of dispersion on SS-WDM systems. MS thesis, Virginia Polytechnic Institute and State University; 1997.

[15] G. R. Pendock and D. D. Sampson. Transmission performance of high bit rate spectrum-sliced WDM systems. J. Lightwave Technol. 14; 1996, 2141–2148.

[16] J.J. O'Reilly, J.R.F. Da Rocha. Improved error probability evaluation methods for direct detection optical communication systems. IEEE Trans. Inform Theory; 1987, 33, 839-848.

[17] S. L. Danielsen, B. Mikkelsen, T. Durhuus, C. Joergensen and K. Stubkjaer. Detailed noise statistics for an optically preamplified direct detection receiver. J.

Lightwave Technol.; 1995, 13, 977-981.

[18] G.-H. Duan and E. Georgiev. Non-white photodetection noise at the output of an optical amplifier: Theory and Experiment. IEEE J. Quantum Electronics; 2001, 37 1008-1014.

[19] M. Leeson, "Determination of the optimum electrical bandwidth for spectral slicing," *Optical and Quantum Electronics,* vol. 38, pp. 667-673, 2006

[20] J.-H. Han, J.-S. Lee, T.-Y, Yun, H.-K. Kim, C.-H. Lee, and S.-Y. Shin. 2.5 Gbit/s transmission of spectrum-sliced fibre amplifier light source over 200 km of dispersion-shifted fibre. Electron. Lett.; 1995, 31, 989-990.

7. Figure Captions

Figure 1: Model of the optically preamplified spectrally sliced system receiver

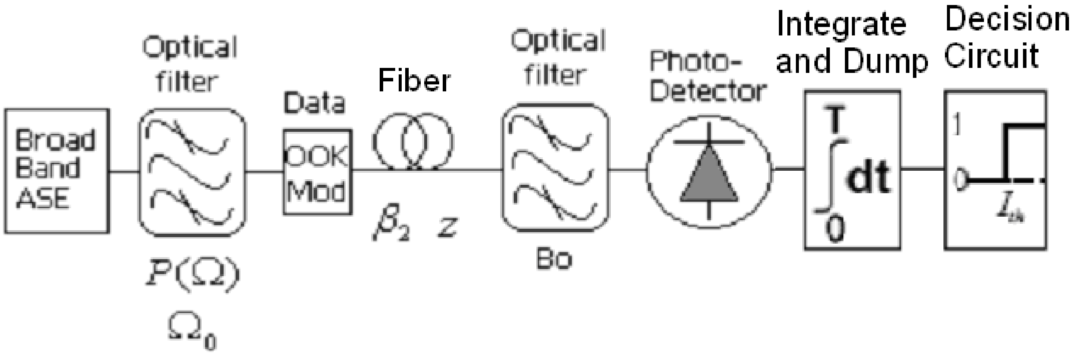
Figure 2: Optimum *pin* receiver sensitivity and the corresponding optical bandwidth versus z/L_D at $P_e = 10^{-9}$, using the GA and the SPA.

Figure 3: Sensitivity of SS OOK for *pin* receiver at $P_e = 10^{-9}$, $R_b = 2.5$Gbps as a function of slice width in the presence of dispersion, using the GA and the SPA.

Figure 4: Sensitivity of SS OOK for optical preamplifier receiver at $P_e = 10^{-9,}$ Gain = 20dB, in the presence of dispersion, using the GA and the SPA.

Figure 5: Optimum bandwidth of the optical preamplifier receiver versus z/L_D at different optical preamplifier gains.

Figure 6: System power budget against transmission distance for both optical preamplifier receiver and *pin* receiver.


Broad
Band
ASE
Optical
filter
$P(\Omega)$
Ω_0
Data
OOK
Mod
Fiber
β_2 z
Optical
filter
Bo
Photo-
Detector
Integrate
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T
dt
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1
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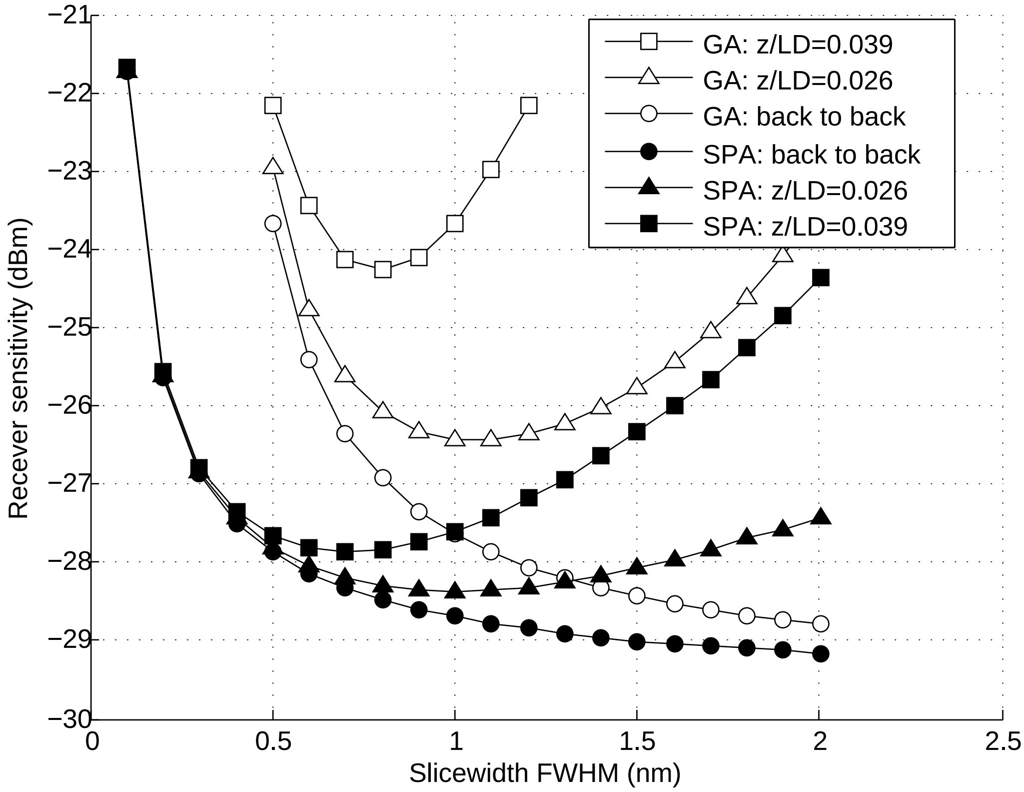
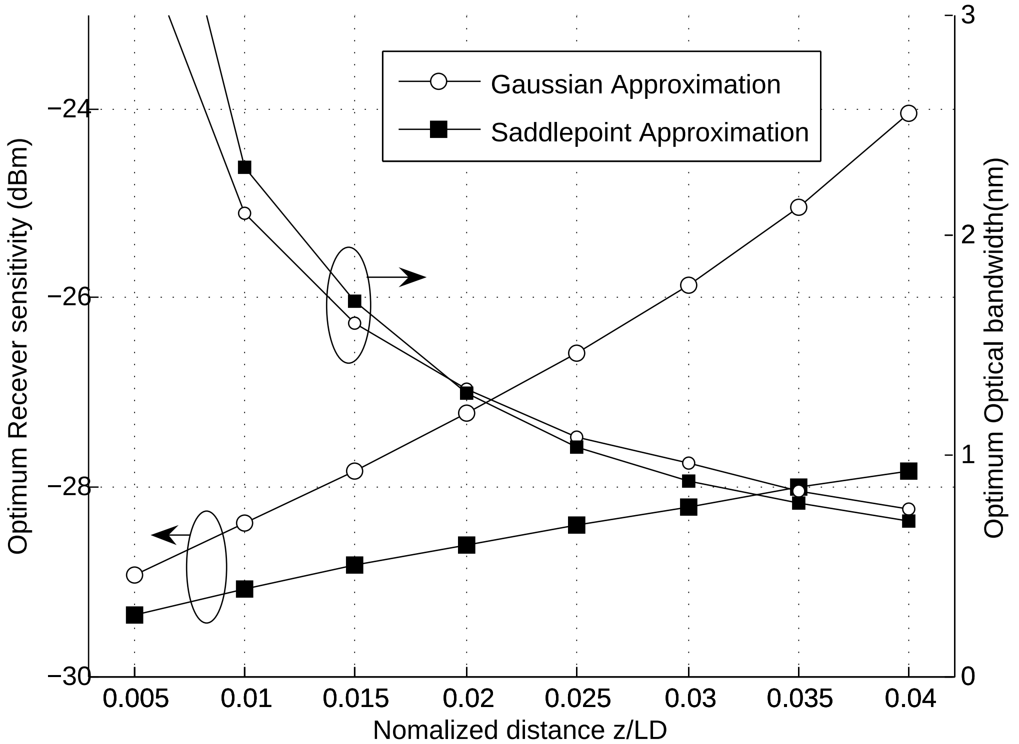
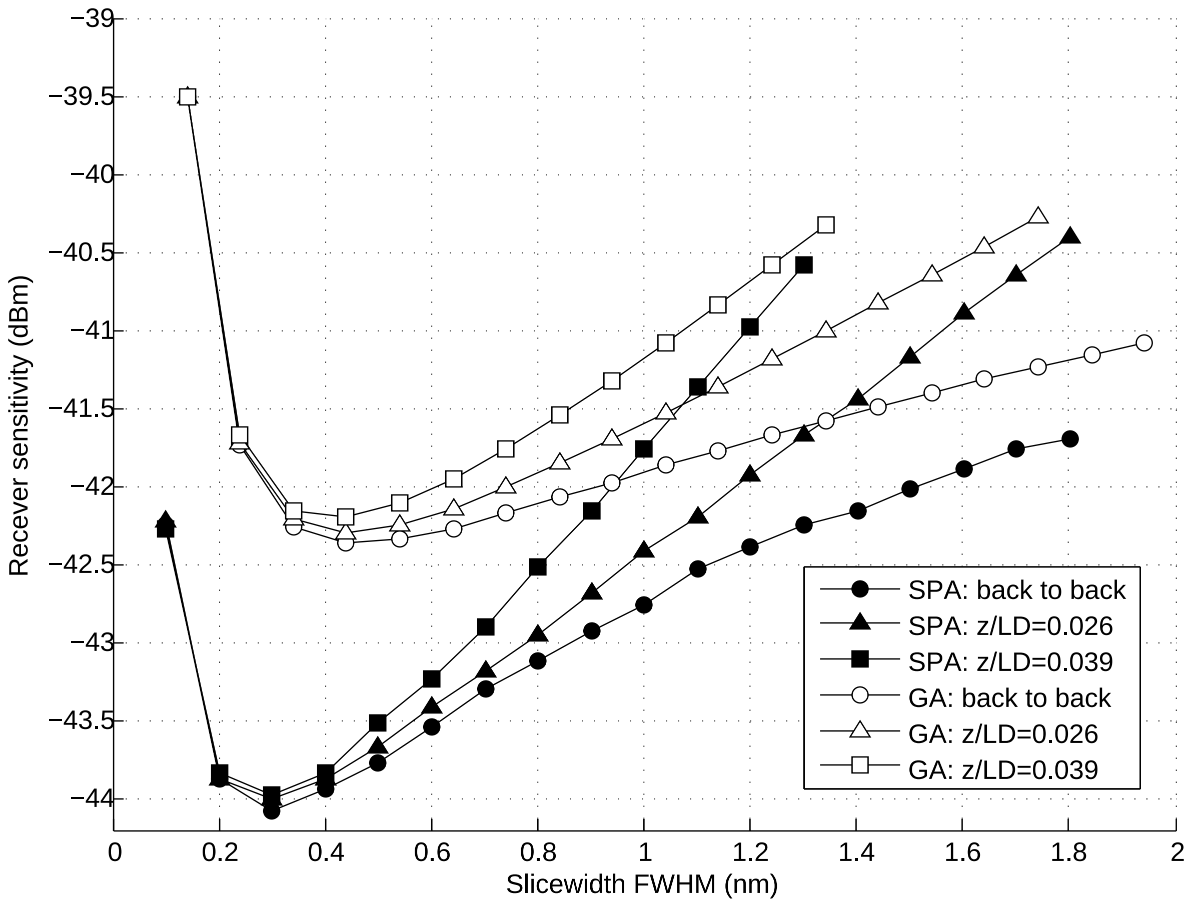
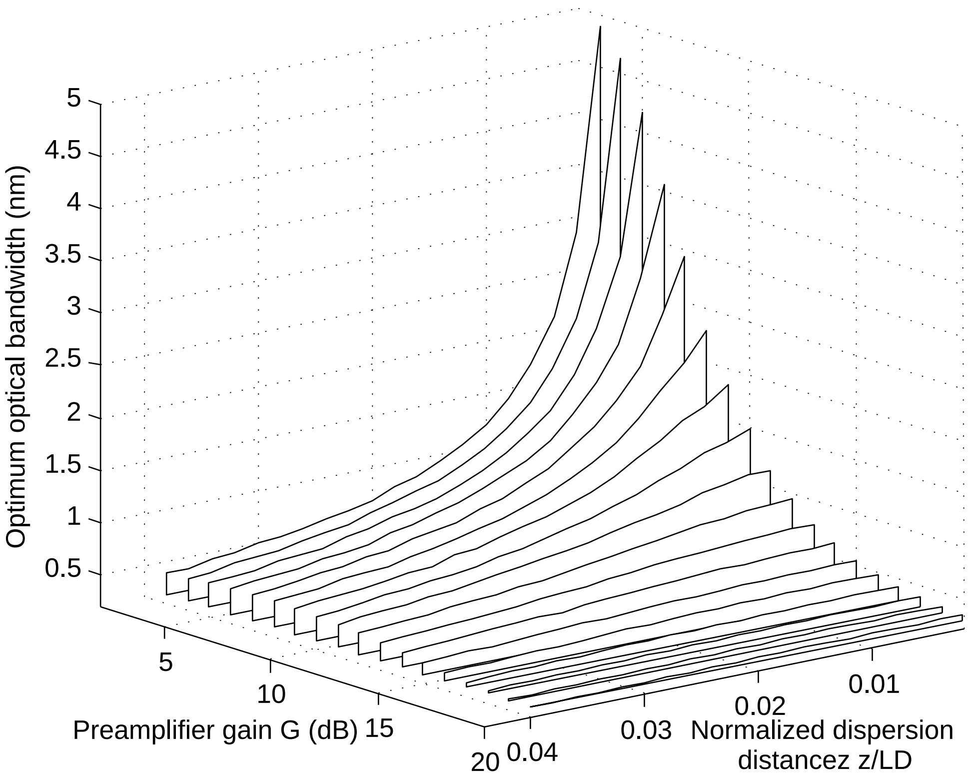


GA: z/LD=0.039
GA: z/LD=0.026
GA: back to back
SPA: back to back
SPA: z/LD=0.026
SPA: z/LD=0.039
Recever sensitivity (dBm)
Slicewidth FWHM (nm)
−21
−22
−23
−24
−25
−26
−27
−28
−29
−30
0
0.5
1
1.5
2
2.5

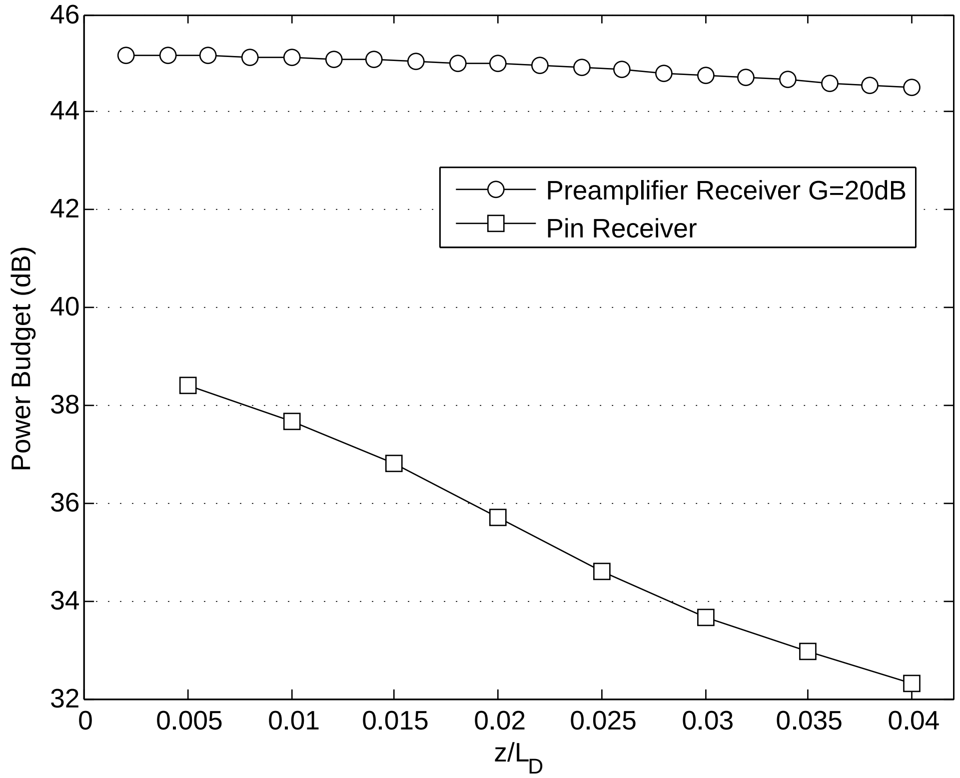


Gaussian Approximation
Saddlepoint Approximation
Optimum Recever sensitivity (dBm)
Optimum Optical bandwidth(nm)
Nomalized distance z/LD
−24
−26
−28
−30
3
2
1
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04


−39
−39.5
−40
−40.5
−41
−41.5
−42
−42.5
−43
−43.5
−44
Recever sensitivity (dBm)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Slicewidth FWHM (nm)
SPA: back to back
SPA: z/LD=0.026
SPA: z/LD=0.039
GA: back to back
GA: z/LD=0.026
GA: z/LD=0.039



Optimum optical bandwidth (nm)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
5
10
15
20
Preamplifier gain G (dB)
0.04
0.03
0.02
0.01
Normalized dispersion
distancez z/LD



46
44
42
40
38
36
34
32
Power Budget (dB)
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
z/L_D
Preamplifier Receiver G=20dB
Pin Receiver