Evaluation of BER Performance in the Presence of ASE Noise using Cascaded Optical Fibre Amplifiers

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Abstract

For accurate prediction of the bit-error rate (BER) performance in cascaded optical amplifiers, it is germane to calculate the BER at the input and output of every optical amplifier in cascade. This was implemented by considering two cases: first, a simulation of the BER calculator with all noises (thermal receiver and shot noises) to help determine what happens if specific receivers are used and secondly, a simulation is implemented with only optical beat noises. The fibre length was calculated from the total loss (taking a value for attenuation in dB/km and a value for the allocation of loss to the other components). For both noise cases, the Q-factor with penalty due to dispersion was calculated and the values were the same together with the total amplified spontaneous emission power spectral density output (ASE PSDout) (W/Hz) in one polarization state. Results obtained showed that much improved Q (Q-factor with no penalty), Q-pen (Q-factor with penalty) and BERapp (BER with penalty) input with beat noises only which include spontaneous-spontaneous beat noise and signal spontaneous beat noise. However, a worst-case situation was detected with all noises included.

Keywords: BER performance, ASE noise, Optical fibre, Cascaded amplifiers.

1. Introduction

Optical amplifiers operate on the principle of stimulated emission of injection laser diodes with a shorter lifetime as compared to spontaneous emission by light emitting diodes. The aforementioned process relies on collision of input photons and excited state electrons. In the upper level of concern, electron charge densities are often negligible at thermal equilibrium. It is notable that other than stimulate an emission an input photon would be absorbed. Two energy levels namely valence band and conduction band play important roles in how optical amplifiers work [1,6]. At thermal equilibrium, a system with a lower energy level has more electrons than one at upper energy level which is expected for semiconductor materials at room temperature. Optical amplification can be achieved by creating a non-equilibrium distribution of atoms hence, the population inversion of higher energy level greater than the lower energy level ($N_2 > N_1$). This is attained through the use of external energy source known as 'pumping'. A popular procedure used for pumping entails the use of intense radiation from an optical tube or high radio frequency field. Current is injected into the semiconductor via the pump to provide excess of electrons in the conduction band (population inversion) [2]. Recombination of electron is created in the conduction band with hole in the valence band, when an incident photon is fired externally into the amplifier. This causes emission of a second identical photon (simulated emission) for a long gain medium. It implies that the output signal is an exact replica of the input photon as they both have similar properties (frequency, phase, direction and polarization). Propagation of these photons in the semiconductor, causes a process of spontaneous emission which takes place repeatedly and effectually thereby creating avalanche multiplication and the input signal (incident photon) is amplified. Semiconductor optical amplifiers (SOAs) amplifies input photons and are assigned optical gains. Optical material gain depends absolutely on the operating conditions and basic device composition.

Though, the amplifier gain expresses the relationship between the output and input optical

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power. It is necessary to consider noise generation causes within the amplifier due to electron presence in the higher energy state that spontaneously recombines with a hole in the lower energy state which is termed as spontaneous emission. Spontaneous emission causes the emitted photon to have equal energy between the electron and hole. Spontaneous emission generated photons propagated in the amplifier experiences gain through simulated emission. This amplification of spontaneous emitted photons is called amplified spontaneous emission (ASE), It removes amplifier gain that should be accessible to the signal. ASE is a noise mechanism which is related to the incident photon and is a random process. [2, 9].

Active fibre amplifiers and semiconductor amplifiers (SOAs) are two classes of optical amplifiers deploy in fibre-based systems. Due to their unique features such as high output saturation power, high gain, polarization insensitivity, and long excited state life time that reduces crosstalk effects, fibre-based amplifiers have progressed more rapidly in the deployment phase. Not ideally compatible for the 1.31μm fibre optics transmission window, fibre-based amplifiers have been efficiently used in the 1.55 μm fibre optics transmission window but [3, 5]. State-of-the-art applications in SOAs have led to astounding improvements in saturation power, gain, crosstalk rejection and polarization sensitivity. SOAs have distinctive capabilities that make their application in optical networks so attractive: these devices are not complex and can be integrated with semiconductor devices, their flat gain bandwidth ranges over a relatively wide wavelength that allows them to concurrently amplify signals of different wavelengths, switching of gain at high speed to provide modulation function is achievable, and monitored current to provide simultaneous amplification and detection. Moving forward, there has been projected interest in semiconductor amplifier studies by their ability to operate in the 1.3µm fibre optics transmission window. Hence, semiconductor optical amplifiers is growing as an interesting area of research and offer a complementary optical amplification to fibre-based amplifiers [3, 4].

2. BER Calculator in a Cascaded Amplifier Model

Investigation of BER performance in a network of cascaded optical amplifiers require that BER calculations at each amplifier input and output are implemented. To achieve this, two conditions were considered. Initially, BER calculator with all noises comprising receiver thermal and shot noises were simulated in MATLAB to verify its values using specific receivers and simulations were also carried out with only optical beat noises. Secondly, fibre attenuation in dB/km or total loss was calculated due to signal propagation through fibre length taking losses inherent in fibre components into consideration. Calculated Q-factor with penalty because of dispersion for both noise situations appear consistent and follows same pattern with the total ASE PSDout (W/Hz) in one polarization state. Assuming beat noises only which comprised of spontaneous- spontaneous beat noise and signal spontaneous beat noise, a better Q (no penalty), Qpen (Q-factor with penalty) and BERapp (with penalty) was obtained while a worst-case scenario was observed with all noises included. The disparity observed was due to the addition of the variance of the shot and thermal noises in the noise current standard deviations for 1 and 0 components that are signal independent (the thermal and spontaneous-spontaneous beat noise) and components that are signal dependent (the signal-spontaneous beat noise and the signal part of the shot noise). For beat noises, only the thermal and shot noises are neglected. Hence, we have the lowest (best) BERapp input value.

3. Investigation of Signal Propagation in Cascaded Amplifiers

1. As the signal travels along its route, the OSNR deteriorates because the ASE noise increases across the amplifiers. A decrease in OSNR in the amplifier at any point will have a similar effect on the average transmitted power. Equation (1) below illustrate that OSNR is inversely proportional to ASE noise as the signal propagates through the amplifier.

$$OSNR = \frac{P_{av}}{2N_0 B_{OSNR}} \qquad (1)$$

However, the average transmitted power may vary but in every increase in the amplifier input power there is subsequent increase in the amplified spontaneous emission noise.

2.
$$OSNR_n = \frac{G^n L^{n-1} P_{inOA1}}{(\sum_{i=1}^{n} (LG)^{i-1}) m_t (NFG-1) h\nu B_{OSNR}} \qquad (2)$$

We were able to verify equation (2) assuming a case with identical amplifiers and span losses. For cases when gain equal to loss, gain exceeds loss and loss exceeds gain, the same OSNR output was obtained from the OSNR calculator in equation (1). Figure 1 shows variation of OSNR with number of cascaded optical amplifiers. It was observed that the impact of loss and gain to the OSNR is minimal as compared to that of the ASE PSD noises. OSNR worsen due to increase in ASE PSD [8, 9].

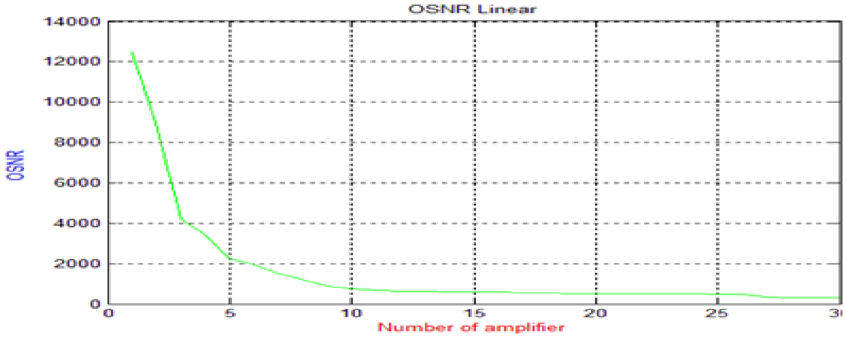

Fig. 1: OSNRout against number of amplifiers

3. For constant noise figures and adjusting the loss of each section to be the same as any other section and adjusting the gains between high gain and low gain will achieve the same OSNR as obtained above. The plot of OSNR output against number of amplifier cascade gives the results shown in figure 1. Repeating the same process but adjusting the noise figure and section loss will yield OSNR outputs that reduces with increase in amplifier number which is evident between amplifier one to five after which there is random variations and finally reduces towards zero from twenty-five and thirty. This is shown in figure 2 below.

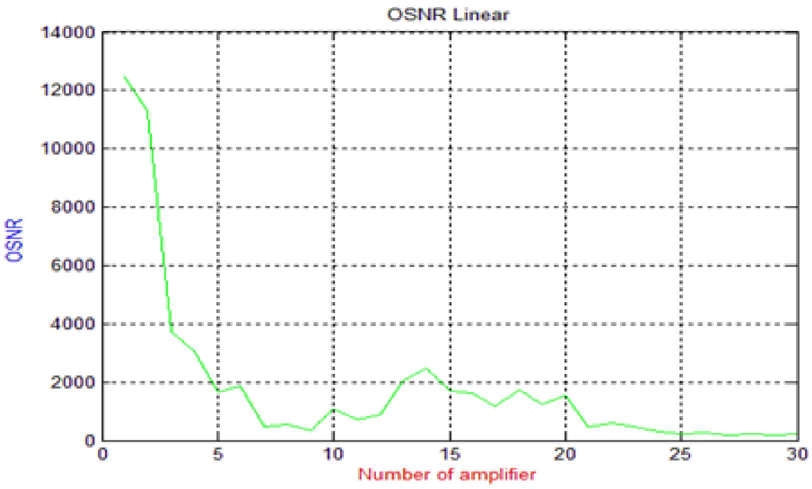

Fig. 2: OSNRout against number of amplifiers

4. Repeating 3 but with gain fixed and loss alternating between high and low loss will give us same results as obtained when the section loss and noise figure was changed.
5. Repeating 3 but with gain and loss fixed and with alternating high and low noise figure (NF) gives us the same OSNR as the previous [8, 9].
6. System A and B have the same transmit power, same received power, same section losses, same amplifiers but the only difference is that systems A goes Tx-G1-loss1-G2-loss2-...Gj-lossj-Rx whilst system B goes Tx-loss1-G1-loss2-G2-...lossj-Gj-Rx [8, 9].

From the equation (1)

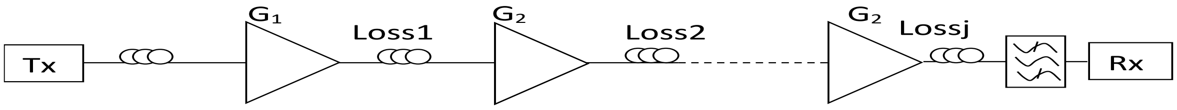

Fig. 3: System A

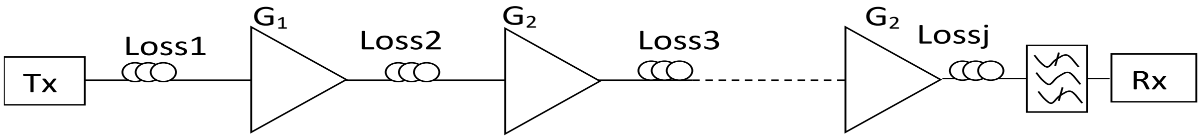

Fig. 4: System B

System A provides a better OSNR than system B. This is as a result of high input power entering each amplifier stages in the system while for system B, we have the worst case for the OSNR as a result of the lower input power entering the amplifier stages. System A gives the best OSNR but it is not practical because high input power entering the amplifier is not a guarantee that we can send bits across great distances as high input power creates impairments and nonlinearities. There is cost implication due to mounting of amplifiers and it is very expensive [8, 9].

4. Discussions and Results

Bit Error Rate (BER) is the probability that an error may occur in a bit of a pulse train, i.e., a “1” bit turns into a “0” bit or vice versa. A target BER for a commercial fibre system is 10^{-12}, while it is 10^{-9} for laboratory experiment. Mathematically, under the assumption of Gaussian noise statistics in the electrical domain, BER at optimal threshold is given by:

$$BER = \frac{1}{2}\, erfc\left(\frac{Q}{\sqrt{2}}\right)$$

Sometimes the BER can be useful for high Q, BERapp = $\frac{\exp\left(-\frac{Q^2}{2}\right)}{\sqrt{2\pi}Q}$

Where $Q = \frac{i_1 - i_0}{\sigma_1 + \sigma_0}$

A Matlab program was used to calculate the Q and BER values, and to generate the BER curves. At constant OSNR of13dB (varying ASE PSD), a BER floor occurred at approximately 10^{-12} and 10^{-9} figure 6. BER floor did not occur when ASE PSD was fixed at 1e-17 (see figure 5).

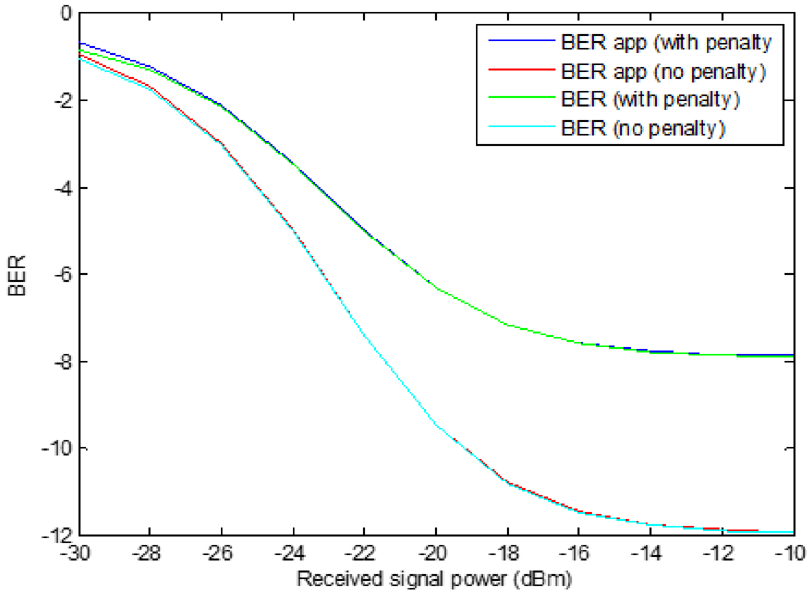

Fig. 5: BER curve at constant OSNR (13 dB)

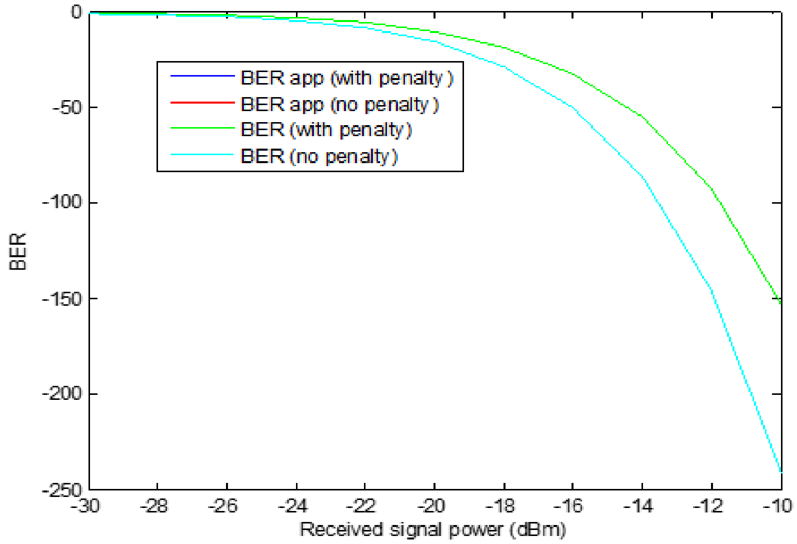

Fig. 6: BER curve at Fixed ASE PSD (1E-17)

5. Conclusion

BER calculation across cascaded optical amplifiers is significant for efficient optical network design and evaluation of optical network system performance. The Q-factor is a vital optical network parameter that gives a qualitative description of the receiver performance via the signal-to-noise ratio (OSNR). The Q-factor is used to verify the minimum OSNR needed to achieve a particular BER for a given signal. System performance of optical networks can be monitored within the amplifier cascade network through measuring the optical signal-to noise ratio (OSNR) and bit error rate (BER) for the investigation of performance degradation due to amplified spontaneous emission noise. The gain of the amplifier cascade should exceed losses to obtain better receiver performance. Here, we observed that when amplifier loss exceeds gain the OSNR of the amplifier cascade is far worse than conditions when gain exceeds the loss. Although the signal increases almost linearly, the OSNR does not improve. In a best-case scenario, the OSNR would remain constant as the signal progresses down the amplifier cascade.

In this investigation, we neglected polarization dependent loss and gain, optical amplifier saturation, polarization mode dispersion (PMD), gain dynamics and crosstalk as their presence leads to spectral broadening, impairments and nonlinearities which further reduces the maximum length of the propagation path.

The dynamic range of the receiver sets the maximum and minimum power range of the receiver. For optical power above $3\,dBm$ propagating through the fibre will incur further nonlinearity penalties. The addition of amplifier noise across the cascade will cause the noise monitoring sensitivity requirement to evolve through the network.

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