Analytical Upstream Modelling of Amplified 10Gbit/s, x1024 Split, 100 km SuperPONs

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Abstract: We describe an analytical model for upstream transmission in a 10 Gbit/s, x1024 split, 100 km SuperPON and investigate the optical amplification parameters required for successful system operation with two stages of optical amplification and Forward Error Correction.

1. Introduction

Passive optical networks are an emerging technology aimed at replacing the current copper access network with a shared fibre network offering much greater capacity. Current PON standards define a maximum physical reach of 20 km, maximum of 64 customers with data rates not exceeding 2.5 Gbit/s, shared between all users [1]. Super Passive Optical Networks have been studied in the past [2] but we feel that optical technologies have matured to a point where the SuperPON principle is now a feasible concept for modern access networks. SuperPONs use optical amplifiers and other technologies such as Forward Error Correction (FEC) to increase the range, number of customers and data rate so that the network has greater performance and is cheaper on a per user basis.

In this paper we investigate analytically the parameters of optical amplifiers required to ensure that a SuperPON with a reach of 100 km, 1024 users and a data rate of 10 Gbit/s is feasible in the upstream direction. Additional difficulties are present in the upstream direction because high power transmitters, used in the downstream direction, cannot be justified in the customer premises equipment on grounds of cost.

Section 2 gives a full description of the analytical model developed for the study of the upstream transmission. Section 3 is focused on the influence of the optical amplifiers on the total system performance with the conclusions of the study given in Section 4.

2. Analytical Model

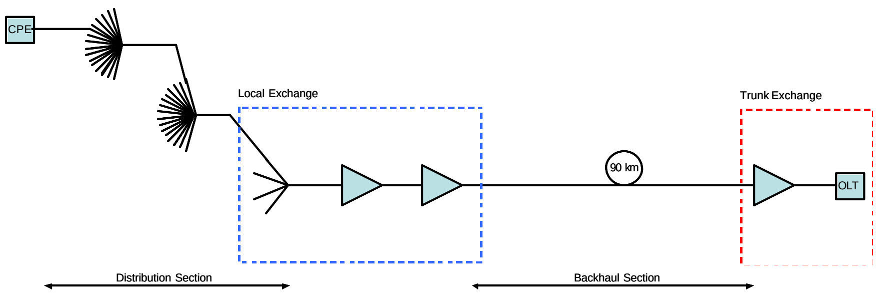


Figure 2.1 10 Gbit/s, x1024 Split, 100 km SuperPON Infrastructure

Figure 2.1 depicts the SuperPON upstream architecture defined by the analytical model. The distribution side of the SuperPON network runs from the CPE into the Local Exchange and ends after the final distributed split point. Earlier simulations [3] used a single lumped 1024 way split, however this is unrealistic due to the random distribution of customers in the access network. Therefore the distribution section is divided into three parts each containing a length of fibre (3 km, 3km and 4km) and a split (x16, x16 and x4) resulting in total length of 10 km and a split of 1024. A loss only model for the fibre is assumed, with the loss of the fibre being calculated by multiplying the fibre attenuation coefficient, α by the fibre length.

Situated in the Local Exchange, after the distribution section, is the first optical amplification stage. Amplification is required at this point to overcome split and fibre loss in the distribution section. Optical amplifiers are modelled using a fixed gain system where the gain and noise figure are assumed to be scalar constants, no saturation effects are taken into account. Gain is modelled by multiplying the signal and noise components (if any) by a linear gain.

Amplified Spontaneous Emission (ASE) Noise generated internally within the amplifier is represented by Equation 1 [4].

$$P_{ASE}(W) = 2n_{sp}hn(G-1)B_o \qquad \textbf{Equation 1}$$

Where: n_{sp}- Population inversion factor, B_o- Optical Bandwidth

Total ASE Noise is calculated by the sum of the ASE contributions from the individual amplifiers multiplied by any gain and loss encountered in the transmission path. B_o represents the optical bandwidth of the system and can be adjusted to reduce the amount of spontaneous noise in the system, equivalent to adding ideal optical filtering to the infrastructure. The optical bandwidth is initially set to 20 nm, a value secured in previous work [3].

The backhaul section of the SuperPON architecture consists of a 90 km fibre connecting the output of the Local Exchange amplification stage to the receiver optical amplifier located in a Trunk Exchange. Amplification and ASE generation at the receiver amplifier is performed by the same method as described previously for the Local Exchange optical amplifiers.

A receiver with sensitivity of –20 dBm at BER = 10^{-10}, is located after the receiver optical amplifier. At the receiver the extinction ratio is used to separate the average signal power into powers for 1's and 0's respectively. Noise variances and standard deviations due to a square law detector are calculated and used to calculate the system Q and BER giving an assessment of the system performance [5][6]. Table 2.1 contains a summary of the main parameters in the upstream analytical model.

Parameter	*Value*	*Units*
TX Power	4	dBm
Wavelength	1550	nm
Extinction Ratio	10	dB
CPE Loss	0.5	dB
a	0.35	dB/km
Distribution Fibre Length	10	km
Distribution Fibre Loss	3.5	dB
Split Level 1 (x16)	14	dB
Split Level 2 (x16)	14	dB
Split Level 3 (x4)	7.3	dB
All amplifer Noise Figures	6	dB
Local Exchange IN Loss	1	dB
Local Exchange OUT Loss	1	dB
Backhaul Fibre Length	90	km
Backhaul Fibre Loss	31.5	dB
Trunk Exchange Loss	1.5	dB
Receiver Sensitivity (@ 10e-10)	-20	dBm

Table 2.1 SuperPON Analytical Model Parameters

3. Optical Amplification

3.1 Local Exchange Amplifiers

A pair of optical amplifiers is situated in the Local Exchange building to boost the signal power after the split and fibre loss of the distribution section to ensure a strong enough signal is present for transmission along the backhaul section of the SuperPON.

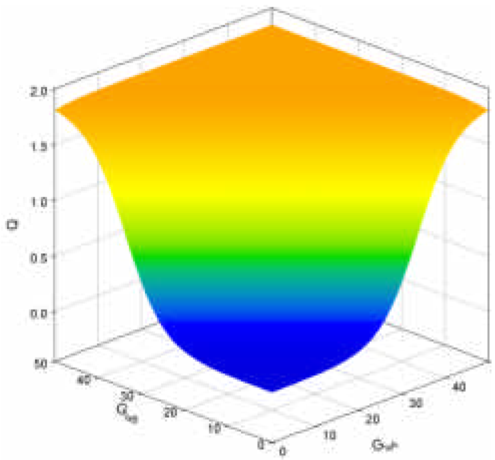


Figure 3.1 3D Surface Plot of Q against the Gain of both of the Local Exchange Amplifiers G_{lxA} and G_{lxB}

The analytical upstream model described in the previous section was used to assess the impact of these optical amplifiers on the overall system performance, measured by Q. The gains of both amplifiers were varied from 0 to 50 dB. A surface plot was created from the results of the model which is shown in Figure 3.1. It can be seen from the symmetrical nature of Figure 3.1 that Q is equally dependant on the gain of each amplifier. In fact the symmetry of Figure 3.1 shows that when gain saturation is not present, the amplifier pair may be considered as a single amplifier with gain equal to the sum of the independent gains.

$$TotalASE = 2hnB_o[n_{spA}G_AG_B - n_{spA}G_B + n_{spB}G_B - n_{spB}] \qquad \textbf{Equation 2}$$

Equation 2 represents the total ASE noise generated by the amplifier pair. Amplifier A has a greater contribution to the total optical noise in the system because any ASE it generates is amplified by Amplifier B in addition to its own gain. Therefore ensuring the Amplifier A has a low noise figure can reduce the total spontaneous noise in the system.

3.2 Receiver Amplifier

The second amplification stage in the SuperPON is the receiver amplifier which provides gain for the signal prior to detection. To understand how the receiver amplifier affects the overall performance of the SuperPON the analytical model was used to calculate the system Q for a range of receiver amplifier gains. Since the performance of the SuperPON depends heavily on the gain of the amplifier pair at the Local Exchange, the gain of these amplifiers was also taken into account. This was done by using the total gain from both Local Exchange amplifiers as the second variable, allowing a 3D contour plot of Q verses the Receiver Amplifier gain and Local Exchange site gain, as shown in Figure 3.2.

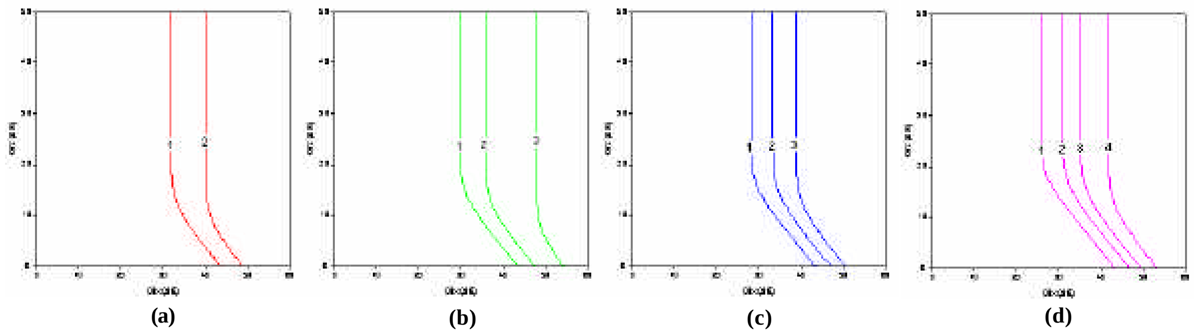


Figure 3.2 Contour Plots of Q against the Receiver Amplifier Gain (G_{rx}) and the Combined Gain of the Local Exchange Amplifier Pair (G_{lx}) with 20 nm (a), 10 nm (b), 5 nm (c), 2 nm (d) Optical Bandwidths

An interesting feature of all plots in Figure 3.2 is that once the gain of the receiver amplifier is above a certain point Q becomes independent of G_{rx}. In addition it can be seen from Figure 3.2 that the value of the gain at which Q becomes independent of the receiver amplifier gain increases with decreasing optical bandwidth. To provide an explanation of these features of Figure 3.2 the analytical model was used to generate plots of the noise contributions at the receiver with G_{lx} and G_{rx} set as variables, as shown in Figure 3.3. Each plot is a surface plot viewed along the z-axis; hence a dominant noise contribution at specific values of G_{lx} and G_{rx} will be clearly visible. Initial analytical calculations were carried out with a 20 nm optical bandwidth as shown in Figure 3.3(a). If G_{rx} is below 15 dB the summation of the amplified spontaneous noise from the Local Exchange amplifiers and the internally generated spontaneous noise from the receiver amplifier is insignificant relative to the thermal noise. Reducing the optical bandwidth attenuates the spontaneous-spontaneous beat noise contribution to the total noise at the receiver. At high gains the system becomes signal spontaneous noise limited. However, at low gains the contribution of thermal noise increases and therefore the value of G_{rx} required for the system to become beat noise limited and independent of the receiver amplifier increases.

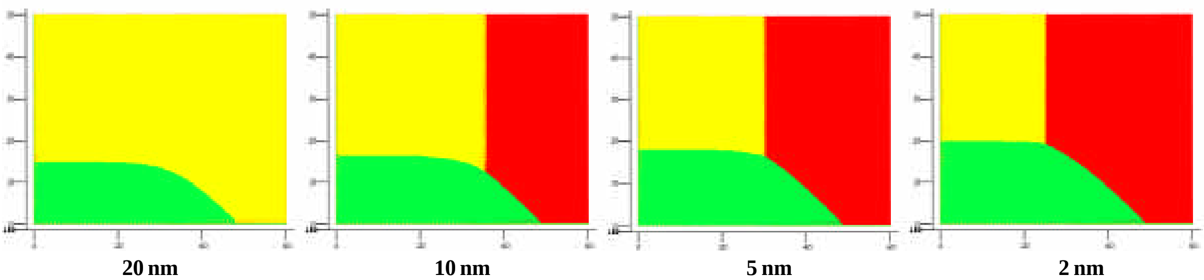
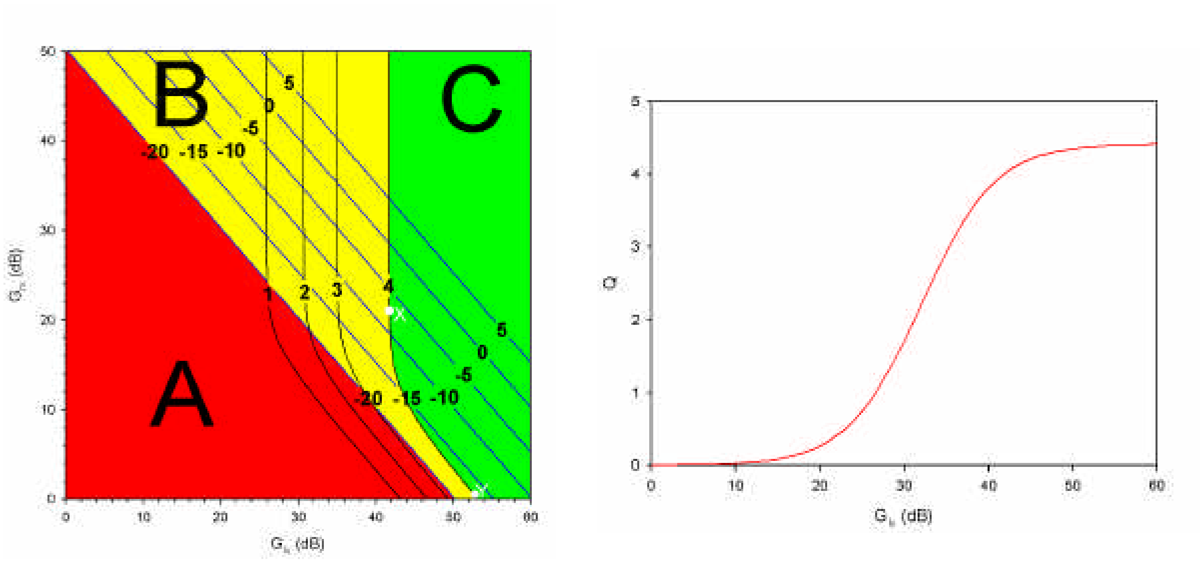


Figure 3.3 Noise Contributions for Variations in Gain of Local Exchange (x-axis) and Receiver Amplifiers (y-axis) with Different System Optical Bandwidths (Thermal Noise (Dark Grey), Signal-Spontaneous Beat Noise (Black) and Spontaneous-Spontaneous Beat Noise (Light Grey))



(a) (b)

Figure 3.4 (a) Q against the Receiver Amplifier Gain (G_{rx}) and the Combined Gain of the Local Exchange Amplifier Pair (G_{lx}) with a 2 nm Filter and Contours for the Received Signal Power Corresponding to the Optical Amplifier Gain Values. (b) Q against G_{lx} when G_{rx} = 20 dB

Upstream transmission with Q>4 (or ~8 with FEC [7]) can be achieved if the total gain of the optical amplifiers is enough to allow operation in region C on Figure 3.4(a). Region C operation requires either G_{lx} > 42 dB and G_{rx} > 20 dB (point X on Figure 3.4(a)) or G_{lx} > 53 dB and G_{rx} = 0 dB (point Y on Figure 3.4(a)). However, the latter is undesirable as it may lead to instabilities due to the large gain from the local exchange amplifiers. Figure 3.4(a) also shows that the system performance is solely dependant on G_{lx} as increases in G_{rx} above the threshold for beat noise limitation is inconsequential. Increasing G_{lx} further results in a modest increase in Q to ~4.4 at G_{lx} = 60 dB (Figure 3.4(b)). Since this is well above the FEC threshold of Q = 3.7, FEC coding gain increases Q to ~10 [7], giving an excellent system performance.

4. Conclusions

An analytical model has been created to examine various aspects of SuperPON. In this paper it has been used to study the impact of the optical amplifiers on the system performance. It has been found that for the system to operate with a satisfactory performance (Q > 3.7, the FEC threshold [7]) it must either be spontaneous-spontaneous beat noise or signal-spontaneous beat noise limited i.e. not thermal noise limited. Best performance, Q > 4 (~8 with FEC [7]) is achieved when the system is signal-spontaneous limited, possible when the receiver amplifier gain is greater than 20 dB. The role of the receiver amplifier is to provide enough gain (~20 dB) to ensure the system is signal-spontaneous limited whilst the Local Exchange amplifiers must provide a minimum of 44 dB and are responsible for the overall system performance. In addition total ASE at the receiver can be reduced by ensuring Amplifier A in the Local Exchange pair has a low noise figure.

References

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