An Effective Noise Figure for the Backhaul Section of a Deep Reach Optical Access Network

D P Shea†, J E Mitchell†, A Lord‡ and R P Davey‡

† University College London, ‡ BT

Abstract: Deep Reach Optical Access Systems offer a feasible solution for optical fibre access networks. To simplify the design of such networks the established architecture of the back haul section including fibre and optical amplifiers can be modelled as an effective optical amplifier with an effective noise figure.

1. Introduction

Deep Reach Optical Access Networks (DROAN) are currently one of many solutions under study to remove the bandwidth bottle neck in the access network. Optical access networks have for a long time been unfeasible due to the associated expense of optical components and installation. Deep reach optical access networks over come these short falls by extending the range, reach and capacity of the shared fibre infrastructure of current passive optical networks (PONs) [1] through the introduction of technologies used currently in core and long haul networks e.g. optical amplifiers and forward error correction (FEC). Optical amplification is used in the backhaul section of the DROAN to provide sufficient gain to ensure a signal at the receiver after large attenuation due to transmission through the backhaul fibre. The infrastructure of the backhaul section has been firmly established and therefore it would be favourable, to model it as an effective single optical amplifier with equivalent parameters to the actual components. As a design tool this would allow lengthy calculation associated with the backhaul section to be simplified while achieving accurate results. In this paper we complete the first stage of defining a backhaul equivalent optical amplifier; calculation of an effective noise figure.

2. Deep Reach Optical Access Networks and ASE Propagation

A DROAN architecture is shown in Figure 1. The backhaul section begins after the last passive optical split with an optical pre-amplifier, followed by a booster optical amplifier situated at a location equivalent to the existing local exchange site. A 90 km G.652 fibre connects OA_B and OA_C, attenuating the signal and optical noise by 34 dB (0.35 dB/km with 2.5 dB excess loss)

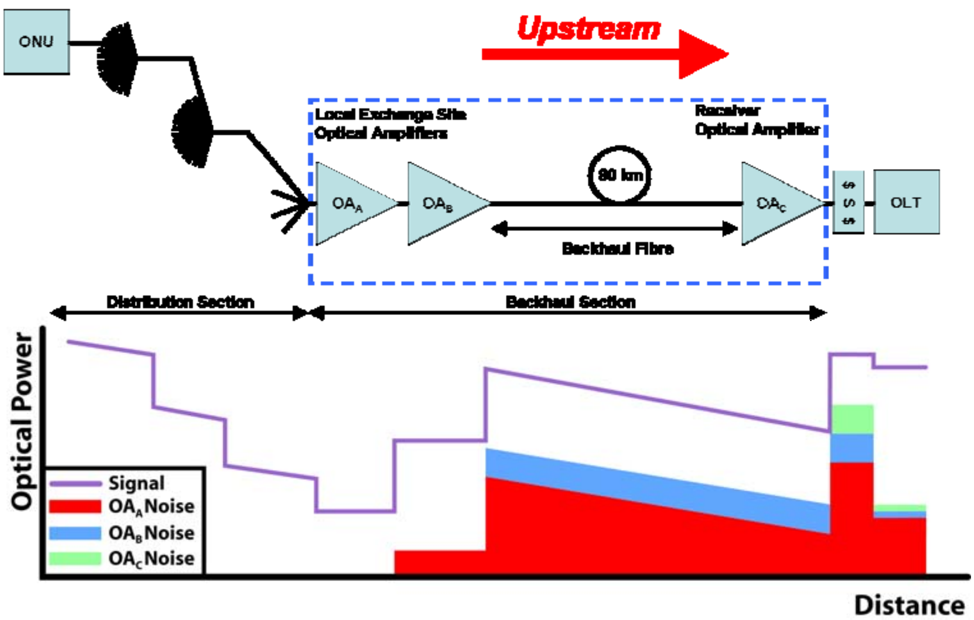

Figure 1: Propagation of the Optical Signal and Optical Noise through the Deep Reach Optical Access Network

Transmission in the upstream direction begins with an optical signal transmitted from the Optical Network Unit (ONU) in the customer premises. Losses due to fibre and passive optical splits present in a distribution section with reach 10 km and 1024 split, attenuate the transmitted signal to approximately -36 dBm at the input to the backhaul section/optical pre-amplifier. The optical amplification process provides gain for the signal but also has the undesired effect of adding optical noise to the signal, known as Amplified Spontaneous Emission. Therefore the booster amplifier, OA_B, amplifies both the amplified signal and optical noise from OA_A. OA_B also generates ASE, which is attenuated by the backhaul fibre, along with the amplified signal and amplified ASE from OA_A. A third stage of optical amplification, OA_C, is positioned before the receiver which adds more ASE as well as amplifying signal and ASE from the previous stages. ASE generated by OA_A is amplified by OA_B and OA_C, as it propagates along the backhaul fibre. Therefore OA_A provides the majority of the optical noise present at the receiver which is shown diagrammatically in Figure 1. It can therefore be stated that the effective noise figure of the backhaul section will be strongly dependent on the noise figure of OA_A.

3. Effective Noise Figure Calculation

The backhaul section contains a total of three optical amplifiers with attenuation between OA_B and OA_C as shown in Figure 2. For simplicity it shall be assumed that each of the optical amplifiers has identical parameters.

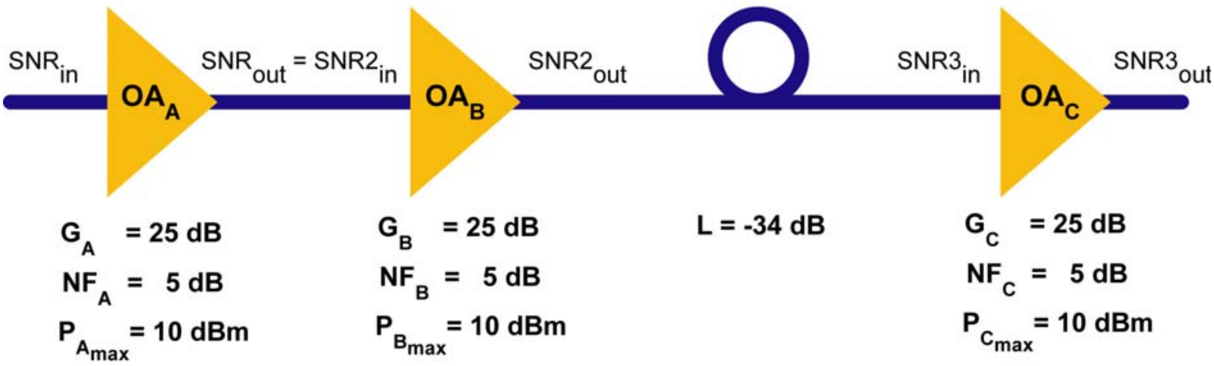

Figure 2: Backhaul section parameters

The noise figure of an optical amplifier is defined as follows [2]:

$$F_{Effective} = \frac{SNR_{IN}}{SNR_{OUT}} \qquad \textbf{Equation 1}$$

This is denoted as the effective noise figure to differentiate from the intrinsic noise figure supplied in optical amplifier datasheets. Using equation 1 to calculate the noise figure of OA_A will provide a result approximately equal to the intrinsic noise figure. However, this is not true for OA_B as the input signal to OA_B contains ASE from OA_A unlike the ASE-free signal into OA_A. Therefore the noise figure calculated for OA_B, OA_C and any further subsequent amplification stages calculated using equation 1 gives the effective noise figure of the optical amplifier. This is a measure of how the optical amplifiers contribution to the optical beat noise degrades the SNR.

At the input to the backhaul section the optical signal does not contain any ASE as no optical amplifiers are present before this point. The only noise contribution which is present at this point is shot noise; therefore it is assumed that the input signal to noise ratio, SNR_{in} is shot noise limited, in line with previous work. Beyond the input of the first optical amplifier ASE is present giving rise to optical beat noise terms. The SNR is then calculated using equation 3, dividing the amplified signal by the sum of the noise variances given by equations 4 through 6 [3].

$$SNR_{IN} = \frac{s^2}{\sigma^2_{shot\_in}} \qquad \textbf{Equation 2}$$

$$SNR_{OUT} = \frac{s^2}{\sigma^2_{shot} + \sigma^2_{sig-spon} + \sigma^2_{spon-spon}}$$ **Equation 3**

Equation 4

where:

$$\sigma^2_{shot} = 2eB_e[s + n_{ASE}]$$ **Equation 5**

$$\sigma^2_{sig-spon} = 4B_e s n_{ASE}$$ **Equation 6**

$$\sigma^2_{spon-spon} = 2(2B_o - B_e)B_e n^2_{ASE}$$ **Equation 7**

and:

s_i = Optical signal power after the *i*th optical amplifier

$n_{ASE\,i}$ = Optical noise power after the *i*th optical amplifier

B_o = Optical Bandwidth

B_e = Electrical Bandwidth of noise-less receiver

e = Elementary charge

Each optical amplifier adds gain to the optical signal, s_{i-1} and n_{ASEi-1} from the previous optical amplifier as well as the ASE it generates internally to form n_{ASEi}. The equations representing s_i and n_{ASEi} after the third optical amplifier, i.e. at the output of the backhaul section are:

$$s_3 = G_3 L G_2 G_1 P$$ **Equation 8**

$$n_{ASE_3} = 2h\nu G_3 L G_2 [G_1 n_{sp1} + n_{sp2}] + 2h\nu G_3 n_{sp3}$$ **Equation 9**

Substituting Equations 9 and 10 into the noise component Equations 4 through 7 and Equation 4, subsequently forms SNR_{out3}, the signal to noise ratio for output of the system. The effective noise figure can then be found by using the SNR_{in} and SNR_{out3} in equation 1.

$$F_{Backhaul} = \frac{SNR_{IN}}{SNR_{OUT3}}$$ **Equation 10**

4. Comparison with Long Haul Effective Noise Figure Approximation

When using the Deep Reach optical Access Network parameters as shown in Figure 1, the equation developed in the previous section gives an effective system noise figure of 6.29 dB. This value disagrees with the approximation of effective noise figure for optical amplifier cascades in long haul transmission, given below, which gives a value of 5.5 dB [4].

$$F'_{Cascade} = NF_1 + \frac{NF_2}{G_1} + \frac{NF_3}{G_1 G_2 L}$$ **Equation 11**

However, Equation 12 was developed under the assumption that the system is purely signal-spontaneous noise limited with no other noise terms included [4]. The more comprehensive effective noise figure developed here does not use this assumption and hence incorporates all noise terms.

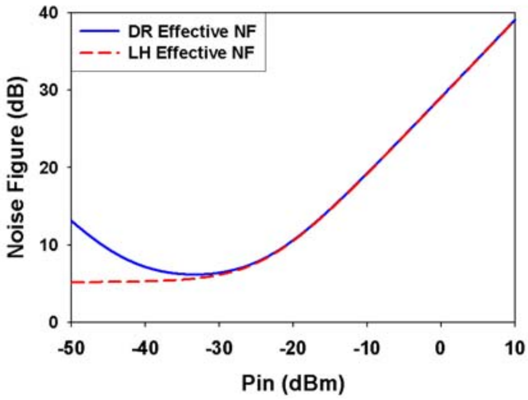

Figure 3: Effective Noise Figure for Deep Reach Optical Access Networks (DR) compared with Effective Noise figure for Long Haul Systems (LH) with varying optical input power

As can be seen from Figure 3 the long haul approximation does agree with the result of the previous section until the backhaul section input power decreases below -30 dBm. Long haul networks are deigned to be signal-spontaneous noise limited through the use of narrow optical filters and costly transmitters with accurately defined signal wavelengths. Deep reach optical access networks aim to provide a cost effective solution for optical access network and therefore are unable to use costly transmitters meaning that narrow filters cannot be used to ensure that the spontaneous-spontaneous noise contribution is insignificant. In addition optical amplifiers in a deep reach optical access networks are not uniformly or optimally positioned as in long haul networks giving rise to conditions i.e. large backhaul fibre loss and low initial input power, where the spontaneous-spontaneous noise ceases to be insignificant. As the spontaneous-spontaneous noise increases the effective noise figure deviates progressively further from the effective noise figure approximation for a long haul system.

5. Conclusion

We have calculated a value for the effective noise figure for the backhaul section of a Deep Reach Optical Access Network. This agrees with existing work for signal-spontaneous limited amplifier chains in long haul networks. However, the Deep Reach Optical Access Network effective noise figure differs from the long haul network when the input power is low and backhaul loss is high which would be the case for a large split (>1024) with a long back haul fibre (+90km). Due to cost limitations on the ONU transmitters narrow filters cannot be used to limit the spontaneous-spontaneous noise therefore the effective noise figure calculation presented in this paper should be used as it takes into account all noise contributions. The approximation for a long haul system is invalid due to its assumption of a purely signal spontaneous noise limit.

6. References.

[1] "General characteristics for Gigabit-Capable Passive Optical Networks (GPON))", ITU-T Recommendation G984.1, 2003

[2] D.M.Baney, P.Gallion, R.S.Tucker, "Theory and Measurement Techniques for the Noise Figure of Optical Amplifiers". Optical Fibre Technology 6, 122-154, 2000

[3] N.A.Olsson, "Lightwave Systems with Optical Amplifiers", Journal of Lightwave Technology, Vol. 7, No. 7, July 1989

[4] P.C.Becker, N.A.Olsson, J.R.Simpson, "Erbium-Doped Fibre Amplifiers Fundamentals and Technology", pp 234, Academic Press, 1997