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Published in:
Journal of Physics: Conference Series

Link to article, DOI:
[10.1088/1742-6596/274/1/012012](https://doi.org/10.1088/1742-6596/274/1/012012)

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Amaya, F., Cárdenas, A., & Tafur Monroy, I. (2011). Modeling the video distribution link in the Next Generation Optical Access Networks. *Journal of Physics: Conference Series*, 274(1), 012012. <https://doi.org/10.1088/1742-6596/274/1/012012>

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2011 J. Phys.: Conf. Ser. 274 012012

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Modeling the video distribution link in the Next Generation Optical Access Networks

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Abstract. In this work we present a model for the design and optimization of the video distribution link in the next generation optical access network. We analyze the video distribution performance in a SCM-WDM link, including the noise, the distortion and the fiber optic nonlinearities. Additionally, we consider in the model the effect of distributed Raman amplification, used to extend the capacity and the reach of the optical link. In the model, we use the nonlinear Schrödinger equation with the purpose to obtain capacity limitations and design constraints of the next generation optical access networks.

1. Introduction

The increase of users connected to the Internet and the high demand for Web sites with features resources such as audio and video clips to encourage users to spend more time online and publish their own content on different servers to be visited by other users, has even begun to compromise the capacity of transmission media such as high capacity optical fibers.

In optical communication systems, the capacity has increased a million times (Mbps to Tbps) in the last 30 years [1]. This situation of increased demand for bandwidth is not only present in the transport networks, in the last mile link is one of the biggest problems today [2], [3]. The growth in consumption of bandwidth for access networks has been about 10000 times in the last 20 years [1].

Figure 1 shows in the upper part of the horizontal line, the bandwidth consumption estimated in both the downstream and the upstream for different services. It is important to note that the bandwidth requirements for most services are greater for the downstream. Below the horizontal line, it is shown some different access technologies and their capacity. The technologies xDSL and HFC used in access, with 64.5% and 20.6% of subscribers worldwide, respectively [4], do not meet the demands of some of the services.

The need to provide higher bandwidth in the long-term, and the challenges that such need imply on access networks, has led operators to seek new solutions. One of those solutions is becoming notorious worldwide: It is the increasing use of fiber to the user (FTTx). This access reached 12.67% of broadband access in the second quarter of 2009, growing by 2.9% with reference to the first quarter of that year [4]. Two alternative architectures that use fiber access network are PON (Passive Optical Network) and P2P (Point-to-Point), PON being more reliable and less expensive to use no active elements in the outside plant.

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An interesting aspect of the PON architecture is that it can use the video distribution scheme SCM (Subcarrier Multiplexing), similar to technology used in the HFC (Hybrid Fiber Coaxial) currently used by cable operators to provide triple play services. Additionally, the transmission of digital video using SCM, with modulations such as M-QAM (Quadrature Amplitude Modulation) and QPSK (Quadrature Phase Shift Keying), offers greater flexibility and needs less bandwidth compared to the transmission of video using a digital carrier [5]. Another application of the use of SCM is in the transmission of RF signals in the technology of Radio over Fiber (RoF), reducing complexity and lowering costs of installing base stations [6], providing wireless communications support through optical fiber.

Upgrade alternatives for PON to next generation, has raised the use of WDM (Wavelength Division Multiplexing) to increase the capacity [7] and the use of optical amplification to extend range.

The use of WDM increases operating costs and therefore have developed techniques to reduce the cost of WDM sources used in the premises of end users [8], [6]. As the use of optical amplification in the access network, it can integrate the access network and metro network, reducing complexity and installation costs [2]. Additionally, the optical amplification of moving from a passive outside plant active external plant, so the challenge is how to increase the range of passive optical fiber maintaining the outside plant.

It is expected that next-generation optical access networks video transmission in SCM (Subcarrier Multiplexing) are used for their advantages of flexibility and low bandwidth consumption [5]. In this case, the access architecture based on SCM-WDM for the distribution of information in conjunction with optical amplification, provide high bandwidth, flexibility and scalability and long range.

In this paper we introduce a distributed Raman amplification in the access network, in order to extend the scope of SCM PON toward next generation optical access networks. The use of Raman amplification introduces noise ASE (Amplified Spontaneous Emission) and increases the effect of nonlinearities. This should be taken into account when designing such networks.

The paper is organized as follows: Section II describes the main impairments in the design of a SCM-WDM link, including the distortion, the noise level introduced by the system and the nonlinearities of the fiber optic. In Section III we present the proposed design methodology. We present simulation results for EPON and GPON with different video modulation formats. Finally, the conclusions are presented.

2. Fiber optic impairments

The fiber optic impairments considered in the model of distribution of video in an optical access network are the nonlinearities, the nonlinear distortion and the noise.

The main fiber optic nonlinearities that affect the performance of an optical link are: stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), self phase modulation (SPM), cross phase modulation (XPM), and the four-wave mixing (FWM) effect. SBS can be minimized and there exists commercial transmitters that minimize this effect at optical powers up to 20 dBm [5]. The FWM effect must be considered in DWDM for closer spacing wavelengths or when the dispersion value is close to zero.

We consider the effects SPM, SRS and XPM calculating the nonlinear crosstalk over a wavelength transporting video SCM due to a wavelength transporting a digital baseband signal. The nonlinear crosstalk is calculated with the following equation [9]:

$$XT = \frac{m_{BB}^2}{m_{SCM}^2} P_{NL}(z) \quad (1)$$

where m_{BB} is the modulation index of the baseband signal, m_{SCM} is the modulation index of the SCM video channels and $P_{NL}(z)$ is the normalized power crosstalk. The value of m_{BB} with NRZ codification, a data bit rate R_b , an electrical bandwidth B_e , in a frequency f , is [10]:

$$m_{BB} = \sqrt{\frac{4B_e}{R_b} \frac{\sin(\pi f / R_b)}{\pi f / R_b}}. \quad (2)$$

The crosstalk power is obtained with the coupled nonlinear Schrödinger equation (CNLSE), to calculate the effect of the nonlinearities between two wavelengths with electrical field envelopes $A_1(z,t)$ and $A_2(z,t)$ [11]:

$$\frac{\partial A_1}{\partial z} + \frac{\alpha_1}{2} A_1 + i \frac{\beta_{21}}{2} \frac{\partial^2 A_1}{\partial t^2} = i \gamma_1 (|A_1|^2 + 2|A_2|^2) A_1 - \frac{g_1}{2} |A_1|^2 A_2, \quad (3)$$

$$\frac{\partial A_2}{\partial z} + \frac{\alpha_2}{2} A_2 + i \frac{\beta_{22}}{2} \frac{\partial^2 A_2}{\partial t^2} = i \gamma_2 (|A_2|^2 + 2|A_1|^2) A_2 - \frac{g_2}{2} |A_2|^2 A_1, \quad (4)$$

where α_i is the attenuation coefficient, β_{2i} is the second order dispersive coefficient, γ_i is the nonlinear coefficient and g_i is the Raman gain coefficient between both wavelengths. We assume wavelength 1 is continuous wave (CW) and the wavelength 2 transports an RF tone. The normalized power crosstalk $P_{NL}(z)$ is the power at the end of the fiber in wavelength 1,

$$P_1(z) = |A_1(z)|^2, \quad (5)$$

normalized with respect to the power at the end of fiber in wavelength 1, when both wavelengths are CW [12].

In order to extend the reach of the optical link, optical amplification may be employed, and the two main alternatives are EDFA and distributed Raman amplification. The optical gain and the ASE noise are the main parameters of optical amplifiers.

The EDFA optical gain may be easily included in the calculations. However, for the distributed Raman amplifier case, the optical gain is distributed along the optical fiber. For M pump signals, in order to include the Raman gain over the two wavelengths, we use the equivalent fiber loss approach, replacing in the CNLSE the attenuation coefficient α_i by the equivalent fiber loss [9], [13]:

$$\alpha_i(z) = \frac{1}{P_{av,i}(z)} \frac{dP_{av,i}(z)}{dz}, \quad i=1,2, \quad (6)$$

where $P_{av,i}(z)$ is the average optical signal power and is obtained resolving the following set of equations:

$$\frac{dP_{av,i}(z)}{dz} = -\alpha_i P_{av,i}(z) + \sum_{k=1}^M g_{ik} P_{av,i}(z) P_k(z), \quad i=1,2; k=1..M, \quad (7)$$

$$\pm \frac{dP_k^\pm(z)}{dz} = -\alpha_k P_k^\pm(z) + \sum_{l \neq k} g_{lk} P_k^\pm(z) P_l(z), \quad k=1..M, \quad (8)$$

where the sign '+' is for co-propagating pump and the sign '-' is for counter-propagating pump. The ASE power produced by the distributed Raman amplifier is calculated with the following equation [14]:

$$\frac{dP_{ASE,i}(z)}{dz} = -\alpha_i P_{ASE,i}(z) + \sum_{k=1}^M g_{ik} P_k(z) (P_{ASE,i}(z) + 2h\nu_i B_o F_T), \quad i=1,2; k=1..M, \quad (9)$$

where h is the Plank constant, ν_i is the optical frequency, B_o is the optical bandwidth and F_T is a temperature dependent factor [14].

The ASE power of an EDFA amplifier is [13]:

$$P_{ASE,i} = h\nu_i F_a G B_o, \quad i=1,2, \quad (10)$$

where F_a is the figure noise of the EDFA and G is the EDFA gain.

The ASE noise beats with the signal in the receiver, generating the signal-spontaneous beat noise and the spontaneous-spontaneous beat noise.

The CNLD is solved using the split-step Fourier transform method (SSF) [11] and equations (7), (8) and (9) are solved using the Rounge Kuta algorithm [7].

The main nonlinear distortion source considered is the clipping noise and this increases with the number of RF channels and it depends on the modulation index employed [15]. The carrier to nonlinear distortion ratio CNLD may be calculated using the modified Saleh's formula [15]:

$$CNLD = \sqrt{2\pi} (1 + 6\mu^2) \mu^{-3} \exp(1/2\mu^2), \quad (11)$$

where μ is the root-mean-squared (RMS) overall optical modulation index (OMI).

In the total standard noise calculation we consider the shot noise, thermal noise, relative intensity noise (RIN), signal-spontaneous beat noise and spontaneous-spontaneous beat noise, using the following equations [13]:

$$\sigma_{sh}^2 = 2qRP_0 B_e, \quad (12)$$

$$\sigma_{th}^2 = i_{th}^2 B_e, \quad (13)$$

$$\sigma_{rin}^2 = (RP_0)^2 B_e \cdot RIN, \quad (14)$$

$$\sigma_{S-ASE}^2 = 4R^2 S_{ASE} P_0 B_e, \quad (15)$$

$$\sigma_{ASE-ASE}^2 = 4(RS_{ASE})^2 B_o B_e, \quad (16)$$

where q is the electron charge, R is the photodetector responsivity, P_0 is the photodetector optical received power, i_{th} is the thermal current, and RIN is the relative intensity noise of the laser. When EDFA and distributed Raman amplification are employed in the optical link, the power spectral density S_{ASE} of ASE noise is obtained using the following equation:

$$S_{ASE} = (P_{ASE_EDFA} L_s + P_{ASE_Raman}) / B_o, \quad (17)$$

when P_{ASE_EDFA} is the ASE power generated by the EDFA (equation 10), P_{ASE_Raman} is the ASE power of the Raman amplification at the end of the fiber (equation 9) and L_s is the loss or gain from the EDFA output to the photodetector input (if loss $L_s < 1$, if gain $L_s > 1$).

The carrier to standard noises ratio may be expressed with the equation:

$$CN = \frac{\overline{i_0^2}}{\sigma_{sh}^2 + \sigma_{th}^2 + \sigma_{rin}^2 + \sigma_{S-ASE}^2 + \sigma_{ASE-ASE}^2}, \quad (18)$$

where the mean square value of the current at the output of the photodetector is:

$$\overline{i_0^2} = R^2 P_0^2 m_{SCM}^2 / 2, \quad (19)$$

We use the carrier to noise ratio (CNR) as performance quality measure including the main impairments [9]:

$$CNR = (CN^{-1} + CNLD^{-1} + XT)^{-1}, \quad (20)$$

where CN is the carrier to standard noise sources ratio (equation 18), $CNLD$ is the carrier to nonlinear distortion ratio (equation 11) and XT (equation 1).

3. Simulation results

The transport of video using SCM imposes a high CNR requirement. The main nonlinear impairment in PON is the SRS crosstalk in the optical carrier of the SCM video signal at 1550 nm caused by the digital baseband signal at 1490 nm. The first part of this section presents simulation results for a standardized PON and the second part presents a PON with distributed Raman amplification.

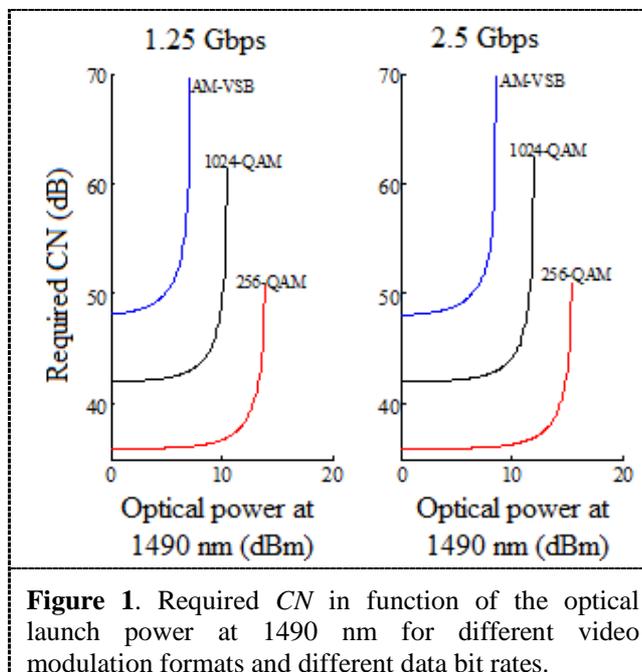
3.1.1. Simulation results for the standardized PON

The maximum value of CNR of the video signal is limited by the SRS crosstalk and this depends on the optical launch power and the data bit rate at 1490 nm. In order to guarantee the CNR value of the video signal, the optical power at 1550 nm must be increased. The required CNR value depends on the video modulation format as is presented in table 1.

Table 1. Required CNR for different video modulation formats.

Video format		Required CNR
Analogical video	AM-VSB	48 dB
	1024-QAM	42 dB
Digital video	256-QAM	36 dB

Figure 1 presents the required CN (carrier to standard noise sources ratio) for different video formats, for data bit rates at 1490 nm of 1.25 and 2.5 Gbps.



When the required CN value is increased, the required power at 1550 is increased also. The required CN value increases with the optical power at 1490 nm. We observe a maximum optical launch power at 1490 nm, depending on the video modulation format and the data bit rate at 1490 nm. For analogical video (AM-VSB) and digital video (QAM) with higher symbol rate, the required CN is higher because the required CNR is higher also. In table 2 is shown the maximum launch power at 1490 nm, obtained from figure 1.

Table 2. Maximum launch power at 1490 nm.

Video modulation format	Maximum optical launch power at 1490 nm	
	with 1.25 Gbps	with 2.5 Gbps
AM-VSB	5 dBm	7 dBm
1024-QAM	8 dBm	10 dBm
256-QAM	12 dBm	13 dBm

The maximum launch power at 1490 nm may be higher with lower symbol rates in the modulation format and increasing the data bit rate.

We use equation (20) to find optimal parameters in the design of PON. The optimization parameters are obtained running several iterations of equation (20), in order to calculate the received optical power at 1550 nm P_0 , which maximizes CNR at a target value. Figure 2 displays the values of the optimal optical received power at 1550 nm for different target CNR values for several data bit rates at 1490 nm. We observe a maximum CNR depending on the data bit rate at 1490 nm, and the maximum increases with the bit rate in agree with the results of Kim [16].

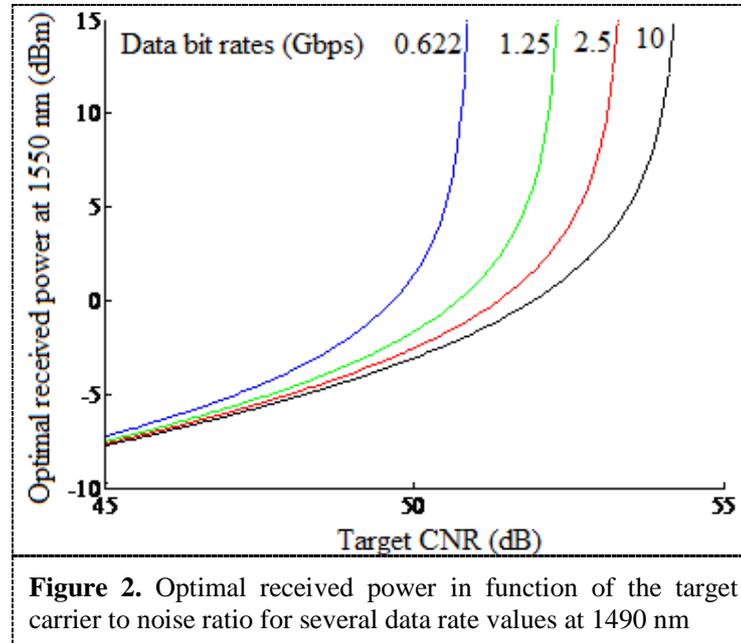


Figure 2. Optimal received power in function of the target carrier to noise ratio for several data rate values at 1490 nm

Table 3 presents the optimal received power P_0 , and the optimal modulation index of the video channels m_{SCM} values, for several standardized types of PON. A maximum optical power of 5 dBm at the input of the EDFA is considered.

Table 3. Optimal received power at 1550 nm P_0 , for several standardized types of PON.

Modulation format	Data bit rate at 1490 nm	P_0 (dBm) at 1550 nm	Optimized m_{SCM} (%)
AM-VSB	0.622 Gbps	-3.92 dBm	3.54
	1.25 Gbps	-4.66 dBm	3.54
	2.5 Gbps	-4.98 dBm	3.54
	10 Gbps	-5.20 dBm	3.54
1024-QAM	0.622 Gbps	-9.69 dBm	3.89
	1.25 Gbps	-9.79 dBm	3.89
	2.5 Gbps	-9.84 dBm	3.89
	10 Gbps	-9.87 dBm	3.89
256-QAM	0.622 Gbps	-13.89 dBm	4.31
	1.25 Gbps	-13.90 dBm	4.31
	2.5 Gbps	-13.91 dBm	4.31
	10 Gbps	-13.92 dBm	4.31

The optimal launch optical power at 1550 nm may be calculated with the optimal received power P_0 , using the following equation:

$$P_s = P_0 + \alpha L + 10 \log_{10} N_u + 3.5 \tag{20}$$

where N_u is the number of ONUs or split ratio, α is the fiber attenuation and the splice losses, and the value of 3.5 dB includes the connector, WDM and excess loss of the splitter in a standardized PON.

3.1.2. Simulation results for PON with Raman amplification

The SRS crosstalk at 1550 nm in the CATV frequency range for different pump schemes is presented in figure 3.

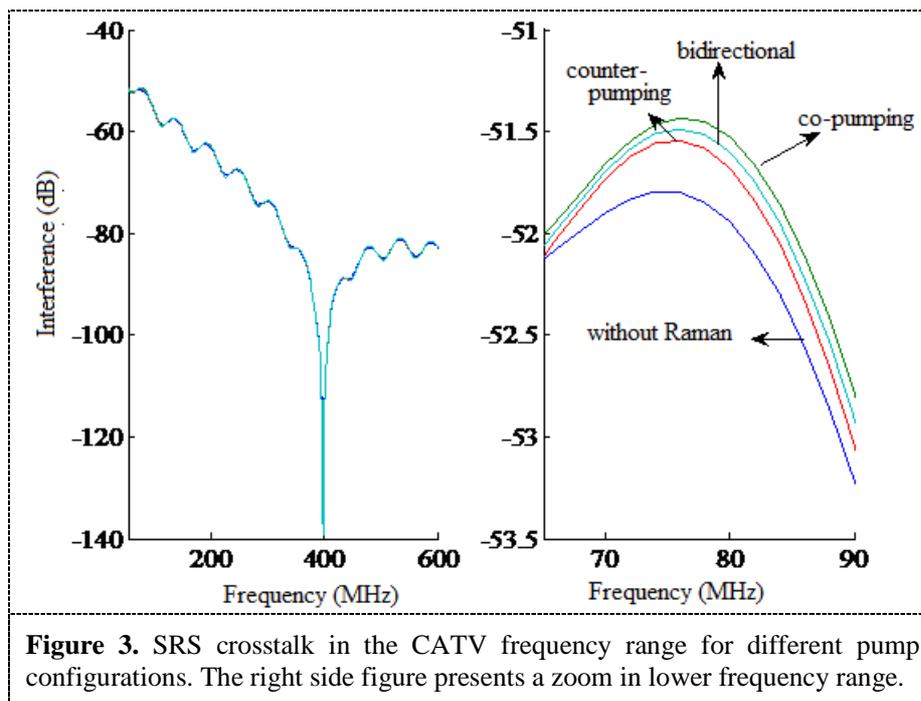


Figure 3. SRS crosstalk in the CATV frequency range for different pump configurations. The right side figure presents a zoom in lower frequency range.

The SRS crosstalk was calculated employing equation 1, considering only the SRS effect in the CNLS, with a bit rate of 1.25 Gbps of the baseband signal at 1490 nm, and a video SCM modulation index of 3.5 %. The average crosstalk interference for the different pump schemes is equal to -51.4dB, with a maximum difference of 0.3 dB. The impact of distributed Raman amplification in the SRS crosstalk is lower than 1 dB. In figure 3 the minimum value at 400 MHz is due the digital baseband modulation index (see equation 2).

4. Conclusions

In this paper, we have presented results that allow the optimization of the video overlay distribution in a PON considering the distortion, the noise and the nonlinearities. The EPON and GPON systems with several video modulation formats and several data bit rates were analyzed to determine the minimum optical launch power and the optimal modulation depth. We showed that introduce Raman amplification to extend the length of the optical access network, has effects in the link performance. In particular, the pump power needed to produce Raman Amplification limits the CNR parameter, depending on the modulation formats. In this case, by increasing the length of the fiber requires greater pumping power, which increases the noise.

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Acknowledgments

The results were obtained under the project “Modelamiento de enlaces SCM-WDM en redes tipo PON” sponsored by COLCIENCIAS (www.colciencias.gov.co).