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Role of amplifiers gain on the achievable information rate of M-ary PSK and QAM constellations

Nuno A. Silva [a,b,*], Armando N. Pinto [a,b]

[a] Department of Electronics, Telecommunications and Informatics, University of Aveiro, 3810-193 Aveiro, Portugal
[b] Instituto de Telecomunicações, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

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ABSTRACT

The impact of optical amplification on the achievable information rate (AIR) is evaluated, considering continuous and discrete modulation formats. The theoretical model for the AIR considers the optical amplification noise, the nonlinear optical noise, and the coherent receiver shot and thermal noise sources. Two different scenarios for the AIR are analyzed. First, we admit that the gain of each optical amplifier under or over compensate the previous fiber span loss. After that, we consider the case where we remove optical amplifiers from the transmission link. Results show that for the first scenario, when we under or over compensate the span loss the AIR tends to decrease. Nevertheless, for low cardinality constellations the AIR is not primarily limited by the gain of the optical amplifiers. In the second scenario, results show that it is possible to remove amplification stages from the end to the beginning of the transmission link without decreasing the AIR. We observe that for a polarization multiplexing (PM) 4-PSK constellation the plateau of 4 bits/symbol is preserved even if we remove the last two amplifiers from the transmission link.

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1. Introduction

The continuous increase of Internet traffic demands transmission systems with high values of information rate [1]. Advanced modulation formats with coherent detection are an effective way to increase the fiber information rate [2,3]. Nevertheless, high cardinality constellations demands high values of signal-to-noise ratio (SNR) [4,5]. In this context, the detailed analysis of the impact of the amplifiers gain on the achievable information rate (AIR) of a dense wavelength-division-multiplexed (DWDM) transmission system with lumped amplification appears an important topic that will be addressed in this work. Our goal is to identify appropriate regimes for which the trade-off between amplifiers gain and optical SNR maximizes the system AIR.

The notion of channel capacity was introduced by Claude Shannon in his seminal work in 1948 [6]. In that work, Shannon derived the capacity for a linear, band-limited and additive white Gaussian noise channel. The extension of Shannon's theory for a fiber based optical channel faces several difficulties, mainly due to fiber nonlinearities [5]. The fiber nonlinearities leads to signals distortion, since they experience refractive index variations that change both in time and frequency domain [7]. The absence of an analytic solution for the nonlinear Schrödinger equation that describes the propagation of optical signals in fibers with arbitrary shapes and amplitude levels [7,5] gave rise to several attempts to evaluate the impact of the Kerr nonlinearity on the fiber capacity limit [8–21]. The Gaussian noise (GN) model [10] provides a way to evaluate the impact of fiber nonlinearities on the channel capacity through the quantification of the nonlinear noise due to signal-to-signal interaction in the fiber, mediated by the Kerr effect. This interaction is also known as nonlinear interaction [10]. The GN model has been extensively validated by simulations [22,23] and experiments [24,25]. The signal-to-signal interaction can (in principle) be equalized at the coherent receiver applying digital signal processing (DSP) techniques [26–28]. However, its implementation in commercial devices is very limited [29,30]. The evaluation of the fiber AIR in a DWDM architecture for an unconstrained modulation format was investigated in [8]. Subsequent studies extended that work in order to consider discrete modulation techniques [4,14,31–33]. All of that studies were performed assuming that the optical amplifiers fully compensate the fiber loss. Nevertheless, the amount of optical gain impacts severely the linear and nonlinear optical noise generated over the communication link [10]. Furthermore, the energy consumption of a transmission link is also strongly affected by the number of optical amplifiers [34].

Our analysis shows that it is possible to decrease the optical

* Corresponding author at: Department of Electronics, Telecommunications and Informatics, University of Aveiro, 3810-193 Aveiro, Portugal
E-mail address: nasilva@av.it.pt (N.A. Silva).

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gain of the amplifiers present in the transmission link without decreasing the AIR, for low cardinality constellations (up to 8-PSK or 8-QAM). Moreover, we observe that it is possible to remove optical amplifiers from the end to the beginning of the transmission link without decreasing the AIR. The obtained results can guide the implementation of optimum AIR and energy efficient optical transmission links.

This paper contains six sections. In Section 2, we present the theoretical model used to model a multispan fiber communication system with variable gain per amplifier. Section 3 describes the impact of amplifiers gain on the AIR of a polarization multiplexing (PM) Gaussian constellation. Section 4 reports the role of under and over fiber loss compensation on the AIR of a PM M-ary phase-shift keying (PSK) constellation and a PM M-ary quadrature amplitude modulation (QAM) constellation. In Section 5, we discuss the impact on the AIR of removing amplifiers from the transmission link, for PM Gaussian, PM M-ary PSK and PM M-ary QAM constellations. Finally, Section 6 summarizes the main conclusions of this paper.

2. Transmission link model

In this section, we present the theoretical formalism used to model the multispan fiber communication system. A generic optical transmission system is shown in Fig. 1.

In Fig. 1 the transmitter side is composed by N_{ch} modulated DWDM channels with optical power P_{TX_i}, with $i = 1, \ldots, N_{\text{ch}}$. All the channels are multiplexed and sent to a dispersion uncompensated transmission link, composed by N_s spans. Each span comprises a transmission fiber with length L_j and an Erbium-doped fiber amplifier (EDFA). In Fig. 1, $P^{(j)}_{\text{TX}_i}$ is the optical power of the channel i at the input of the j-th span. At the end of the transmission link, the optical channels are demultiplexed, and detected using a coherent receiver. The optical power of a given channel at receiver side in Fig. 1 is given by [10]

$$P_{\text{RX}_i} = P_{\text{TX}_i} \prod_{j=1}^{N_s} a_j \Gamma_j, \tag{1}$$

where a_j is the linear fiber loss of the j-th fiber span, and Γ_j is the linear gain of the j-th amplifier, given respectively by

$$a_j = \exp\left\{ -\alpha_j L_j \right\} \tag{2a}$$

$$\Gamma_j = \exp\left\{ \eta_j \alpha_j L_j \right\}, \tag{2b}$$

where $\eta_j \geq 0$ is the percentage of power loss compensation of the j-th amplifier. For $\eta_j = 100\%$ we have $P^{(j)}_{\text{TX}} = P^{(j+1)}_{\text{TX}}$. Moreover, if $\eta_j < 100\%$ we operate in an under amplification regime with $P^{(j)}_{\text{TX}} > P^{(j+1)}_{\text{TX}}$, and if $\eta_j > 100\%$ we operate in an over amplification regime with $P^{(j)}_{\text{TX}} < P^{(j+1)}_{\text{TX}}$.

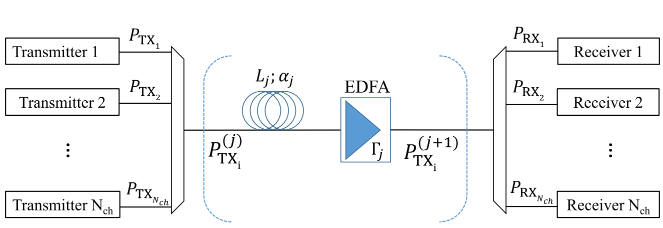

Fig. 1. Block diagram representing the multispan DWDM communication system. The system is composed by N_{ch} channels, and N_s spans. Each span comprises a fiber and an EDFA. Details of the diagram are present in the text.

Assuming ideal-Nyquist channels, and according with the GN model, the nonlinear noise power spectral density (PSD) at the center frequency (worst case) of the overall DWDM comb of a PM transmission link can be obtained from (41) in [10], and it is given by

$$G_{\text{NLI}}(0) = \frac{8}{27} G_{\text{TX}}^3 \sum_{j=1}^{N_s} \left(\gamma_j^2 L_{\text{eff},j}^2 \left[\prod_{k=1}^{j-1} \Gamma_k^3 a_k^3 \right] \left[\prod_{l=j}^{N_s} \Gamma_l a_l \frac{\operatorname{arcsinh}\left(\frac{\pi^2}{2} \left|\beta_{2,j}\right| \alpha_j^{-1} \left(N_{\text{ch}} B_{\text{ch}}\right)^2 \right)}{\pi \left|\beta_{2,j}\right| \alpha_j^{-1}} \right] \right), \tag{3}$$

where we assume that the channel bandwidth $B_{\text{ch}} > 25$ GHz [10]. In (3), γ_j, and $\beta_{2,j}$ are the nonlinear coefficient, and the dispersion coefficient of the j-th fiber span, respectively. In (3), $L_{\text{eff},j}$ is the effective length of the j-th fiber span given by $L_{\text{eff},j} = [1 - \exp(-\alpha_j L_j)]/\alpha_j$, and $G_{\text{TX}} = P_{\text{TX}}/R_s$ is the value of the PSD of the optical signal, with R_s representing the symbol rate, and assuming that all the N_{ch} channels send to the transmission link have the same optical power $P_{\text{TX}_i} = P_{\text{TX}}$. In (3) it is assumed that the coherent receiver does not apply DSP techniques for nonlinear equalization. Nevertheless, that could (in principle) be considered through the use of an effective nonlinear coefficient [35].

In long transmission links the accumulated loss is very high. Therefore, to compensate that optical amplifiers are used along the optical link, see Fig. 1. Optical amplifiers produces optical noise. The PSD of the amplified spontaneous emission (ASE) noise generated by the optical amplifiers at the end of the transmission link is given by [10]

$$G_{\text{ASE}} = \sum_{j=1}^{N_s} N_{F,j} (\Gamma_j - 1) h\nu \prod_{k=j+1}^{N_s} \Gamma_k a_k, \tag{4}$$

where $N_{F,j}$ is the noise figure of the j-th amplifier, h is the Planck's constant, and ν is the center frequency of the DWDM comb.

The performance of the multispan DWMD transmission system in Fig. 1 can be estimated in terms of the SNR at the decision circuit input [4,36]

$$\text{SNR} = \frac{R_D^2}{4} \frac{P_{\text{LO}} \overline{\langle P_{\text{RX}}(t) \rangle}}{\sigma_{\text{Th}}^2 + \sigma_{\text{Sh}}^2 + \sigma_{\text{LO-ASE}}^2 + \sigma_{\text{LO-NLI}}^2}, \tag{5}$$

where $R_D = q/(h\nu)$ is responsivity of each photodiode that composes the dual-polarization coherent receiver, assumed to be the same for all the photodiodes, and q is the electron charge [37]. In (5), P_{LO} is the optical power of the local oscillator, and $\overline{\langle P_{\text{RX}}(t) \rangle}$ can be written as [10]

$$\overline{\langle P_{\text{RX}}(t) \rangle} = P_{\text{RX}} R_s^{-1} B_H, \tag{6}$$

where $P_{\text{RX}}(t)$ is the overall transmitted optical power for the PM optical signal, and $B_H = \int |H_{\text{RX}}(f)|^2 df$ with $H_{\text{RX}}(f)$ being the baseband transfer function of the receiver including the adaptive equalizer if present [10,36]. Finally in (5) σ_{Th}^2, σ_{Sh}^2, $\sigma_{\text{LO-ASE}}^2$, and $\sigma_{\text{LO-NLI}}^2$ are the variances of the thermal noise, shot noise, local oscillator-ASE beat noise, and local oscillator-NLI beat noise, respectively, given by [4,36]

$$\sigma_{\text{Th}}^2 = (i_{\text{Th}})^2 B_e \tag{7a}$$

$$\sigma_{\text{Sh}}^2 = q R_D \left(P_{\text{LO}} + \overline{\langle P_{\text{RX}}(t) \rangle} \right) B_e \tag{7b}$$

$$\sigma_{\text{LO-ASE}}^2 = \frac{R_D^2}{2} P_{\text{LO}} G_{\text{ASE}} B_e \tag{7c}$$

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