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Regular Articles

Optimizing the placement of spare amplifier cards to increase the achievable information rate resilience

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ABSTRACT

We evaluate the impact of optical amplifier failure on the achievable information rate (AIR) of a transmission link. We consider two scenarios to avoid link failure. First, we consider that after amplifier failure the optical signals are switched to a redundant passive optical line card which surpasses the damage amplifier. Second, we assume that the optical signals are switched to a redundant amplifier card. From the evolution of the AIR with the position in the link where the failure occurs we demonstrate which are the critical amplifiers that demand amplifier cards redundancy to avoid a link failure, and in which place a redundant passive optical line card is admissible. We consider polarization multiplexing (PM) quadrature amplitude modulation (QAM) constellations. To evaluate the AIR, we consider the optical amplified spontaneous emission noise and the nonlinear interference optical noise coherent, as well as the receiver thermal and shot noise sources. Results show that for the first scenario the maximum value attainable by the AIR is strongly dependent on the position of the amplifier failure on the transmission link, being the first amplifiers more critical for the performance of the link. Findings also show that a failure of the last amplifier tends to not affect the AIR. We also observe that it is possible to partially compensate the AIR decrease after an amplifier failure in the first scenario, by optimizing the gain of the remain available amplifiers on the transmission link and by optimizing the transmitter power.

1. Introduction

Optical communication transmission links provide nowadays aggregate bit-rates beyond 10 Tb/s [1]. On the basis of this achievement is the use of key technologies such as wavelength division multiplexing (WDM), optical amplification, and the implementation of coherent transmitters and receivers [1–3]. Optical amplifiers present in the optical communication systems allow to extend the reach of those systems, avoiding the use of electronic regenerators [1]. Nevertheless, amplifiers have a considerable impact on both capital expenditures (CAPEX) and operational expenditures (OPEX) of the link total cost [4,5]. This demands a careful analysis of the number and position of the amplifiers in the fiber links, and its redundancy to prevent link failures [4,5]. This due to the fact that a single amplifier failure could lead to a system service failure. In that scenario, the re-allocation of the data traffic to a different optical path and the link downtime leads to significant increase in the OPEX [6]. For instance, in [6] author shows that for the 50 node Germany network it is expected 6 Erbium-doped fiber amplifier (EDFA) failures per year. In this context, the impact and recovery of the achievable information rate (AIR) after an amplifier failure of a multi-span transmission system appears as an important topic, that will be addressed in this work. Our goal is to identify appropriates strategies to minimize amplifier cards redundancy and still avoiding link downtime.

In optical infrastructures the AIR is an important figure of merit that quantifies the performance of a transmission system. For instance, in unamplified links the AIR tends to be limited by the receiver shot and thermal noise [2,7], whereas in multi-span links the AIR tends to be limited by the optical noise [8,7]. In that sense, the AIR have been extensively studied theoretically and in simulation works [8,2,9–16,7] envisioning the performance limits of fiber based communication links. The AIR results obtained theoretically and in simulations have been applied to experimental works to enhance the performance of the transmission system [17,18]. However, the use of optical fibers as transmission medium for the signals imposes limits on the AIR of the optical infrastructure, mainly due to the Kerr effect [19,8]. In that sense several different studies were performed attempting to estimate the impact of the Kerr effect on the fiber AIR [8,20–29,13,30–32]. Nevertheless, this limiting factor for the AIR could be counter-balanced if at receiver it is implemented digital signal processing algorithms for

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nonlinear compensation (NLC) [33–35,3], or by using different techniques such as spectral inversion [36], phase-conjugated twin-wave [37], or by frequency stabilized optical signals [38].

In this work, we present a detailed analysis of the impact of an amplifier failure. Our analysis shows that a failure of an EDFA leads in general to a catastrophic loss of AIR. Nevertheless, by adding an optical path that avoids and surpasses the damaged amplifier, i.e. by adding a redundant passive optical line card, and by optimizing the optical power sent to the transmission link it is possible to recover part of the attainable AIR, avoiding a complete link failure. Finally, to attempt to recover the AIR of the transmission link after an amplifier failure, we optimize the gain of the available amplifiers. We observe that it is possible to recover at least 69% of the attainable AIR for a link length of 1000 km and at least 61% of the attainable AIR for a 2000 km transmission link, after an amplifier failure. This using a redundant passive optical line card and by optimizing only the gain of four amplifiers: the first, the previous, the following, and last one.

This paper contains five sections. In Section 2, we present the theoretical model used to evaluate the AIR. Section 3 describes the impact of an amplifier failure on the AIR. Section 4 reports the AIR assuming that the failure of an amplifier is compensated by optimizing the gain of the other optical amplifiers in the link. Finally, Section 5 summarizes the main conclusions of this paper.

2. Transmission link model

We consider a PM-transmission system with N_{ch} channels, and N_s spans, see Fig. 1b. Each span comprises an optical fiber and an EDFA. The optical power of a given channel at receiver side is given by [21,7]

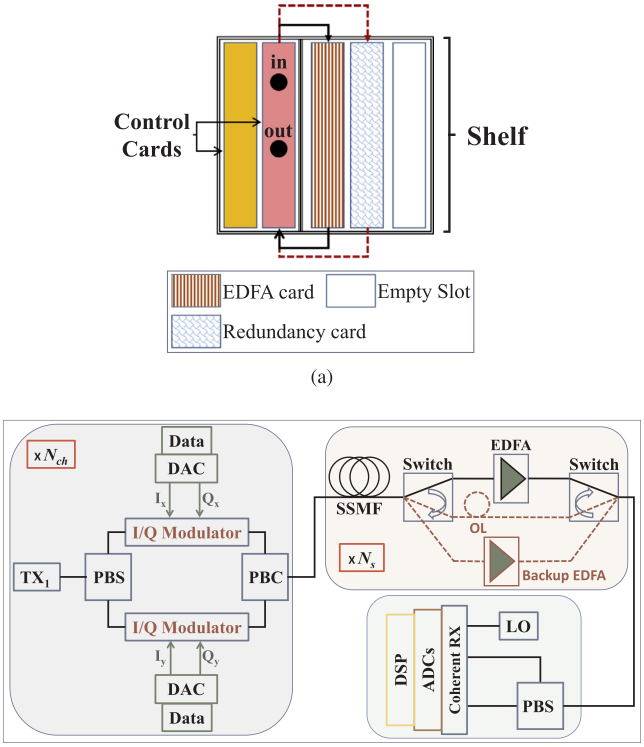
$$P_{\text{RX}_i} = P_{\text{TX}_i} \prod_{j=1}^{N_s} \exp\{(\eta_j - 1)\alpha_j L_j\}, \tag{1}$$

where P_{TX_i} is the optical power of the i channel at transmitter output, with $i = 1, \ldots, N_{\text{ch}}$, L_j is the length of the j-th fiber span, and α_j is the loss of the j-th fiber span, with $j = 1, \ldots, N_s$. In (1), η_j is the percentage of loss compensation of the j-th amplifier. If the j-th amplifier fails we have $\eta_j = 0$.

The presence of optical amplifiers in the transmission links to compensate the fiber loss leads to the generation and propagation of optical noise. The power spectral density (PSD) of the amplified spontaneous emission (ASE) noise generated by the optical amplifiers at the coherent receiver input can be written as [21]

$$G_{\text{ASE}} = \sum_{j=1}^{N_s} N_{F,j}(e^{\eta_j \alpha_j L_j} - 1) h\nu \prod_{k=j+1}^{N_s} e^{(\eta_k - 1)\alpha_k L_k}, \tag{2}$$

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 WDM comb. Usually, in a WDM scenario, uniform gain for all optical channels is an essential feature that each EDFA should provide. Typically, to achieve that goal reconfigurable gain equalizer filters are used in the EDFAs present in the links. This combined with the adjustable EDFAs pump powers leads to an almost flat gain profile, for a large range of optical channels EDFAs input powers [39,40]. We are assuming that the EDFAs have an automatic gain control system to maintain the flatness even after the failure.



(b)

Fig. 1. (a): Graphical representation of a shelf node composed by a set of network modules. In the figure we can see that in the presence of an EDFA failure the link operator can switch the data signals to a redundant card, that can be an optical line which surpasses the damage amplifier, or a secondary (backup) EDFA. (b): Schematics of the optical fiber communication system. It can be seen in the figure that when an amplifier fails the operator can overcome the failure by migrating the data traffic to the optical line (dashed line in the figure) parallel to the amplifier, or to a backup amplifier (if available), by using the switches. PBS (C): polarization beam splitter (combiner), DAC: digital-to-analogue converter, N_{ch}: number of WDM channels, SSMF: standard single mode fiber, EDFA: Erbium doped fiber amplifier, OL: optical line, N_s: number of spans, LO: local oscillator, ADCs: analogue-to-digital converters, DSP: digital signal processing.

In fiber based transmission systems the fiber nonlinearities tend to deteriorate the signal quality, leading to a decrease of the signal-to-noise ratio (SNR) at the coherent receiver output. According with the GN-model the PSD of the nonlinear interference (NLI) noise generated over the transmission link at the center of the WDM comb for an ideal-Nyquist can be written as [21]

$$G_{\text{NLI}} = \frac{8}{27} G_{\text{TX}}^3 \sum_{j=1}^{N_s} \left(\gamma_j^2 L_{\text{eff},j}^2 \left[\prod_{k=1}^{j-1} (e^{(\eta_k - 1)\alpha_k L_k})^3 \right] \left[\prod_{l=j}^{N_s} e^{(\eta_l - 1)\alpha_l L_l} \frac{\text{arcsinh}\left(\frac{\pi^2}{2} |\beta_{2,j}| \alpha_j^{-1} (N_{\text{ch}} B_{\text{ch}})^2 \right)}{\pi |\beta_{2,j}| \alpha_j^{-1}} \right] \right), \tag{3}$$

where we assume that $B_{\text{ch}} > 25$ GHz, being B_{ch} the -3 dB bandwidth of each optical signal. In (3), G_{TX} is the PSD of the optical signal, γ_j is the fiber nonlinear parameter of the j-th fiber span, and $L_{\text{eff},j}$ represents the effective length of the j-th fiber span. Moreover, in (3) $\beta_{2,j}$ is the