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PERFORMANCE EVALUATION OF A NOISY OPTICALLY AMPLIFIED LINK

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ABSTRACT

The physics of noise in optical communication links is of great interest in the design of fiber optic communication systems. In this paper the role of noise in optical communications, and how it can limit the performance of optical communications systems, will be examined. The signal- to- noise ratio SNR are of fundamental importance and considerable effort will be spent attempting to bound the SNR requirement for a given set of system requirements. In this paper, we calculate the evolution of noise along optically amplified link in presence of nonlinear interaction between signal and amplified spontaneous emission and amplifier saturation with attenuation of the fiber. The obtained results show the great effect of the distributed and lumped amplifications on the gain.

I. INTRODUCTION

An important goal of a long-haul optical fiber system is to transmit the highest data throughput over the longest distance without signal regeneration. Given constraints on the bandwidth imposed by optical amplifiers and ultimately by the fiber itself, it is important to maximize spectral efficiency, measured in bit/s/Hz. But given constraints on signal power imposed by fiber nonlinearity, it is also important to maximize power (or SNR) efficiency, i.e., to minimize the required average transmitted energy per bit (or the required signal-to-noise ratio per bit).

Optical fibers became the choice of medium for data transmission; the electronic regenerator did the job for inline amplification of signals [1]. The electronic regenerator has many disadvantages. Among them, the most serious one is that it has to be synchronized with the data. Optical amplifiers can be divided into two classes: optical amplifiers (OFA) and semiconductor optical fiber amplifiers (SOAs). The former has tended to dominate conventional system amplifications such as in-line amplification used to compensate for fiber losses [2]-[3]. SOA is characterized by extremely strong non-linearity, low power, high operation rate, and small size as compared to erbium doped fiber amplifiers (EDFAs) and Raman optical amplifiers [4]. One of principal reasons the optical amplifier was so detested was that its overall noise characteristic was far from ideal, significantly reducing its usefulness [5]. Therefore, when the erbium doped fiber amplifier (EDFA), which has a much improved noise characteristics and polarization insensitivity, was introduced, the optical telecommunication industry immediately responded with enthusiasm.

The noise performance of an optical amplifier is characterized by its noise factor (F) or, equivalently, the noise figure NF. The noise factor is defined as the ratio of input signal-to-noise ratio (SNR_{in}) to the output signal-to-noise ratio (SNR_{out}) while the noise figure is the noise factor expressed in dB.

II. NOISE SOURCES IN THE PHOTO-DETECTION PROCESS

The amplifier noise figure can be measured either optically or electrically [6]. The optical method involves accurately measuring the input and output signal powers along with the amplified spontaneous emission spectral profile. This method is tolerant to measurement-system non-idealities

and is often used to characterize optical amplifiers for long-haul digital communication systems. In the real world, however, the end of the optical amplification is always accompanied by a photo detection process. The optical method is based on a presumably fixed relation between the electrical noise after photo detection and the spectral characteristics of the amplified output.
In the electrical method, on the other hand, the pho-to current noise is measured on an electrical spectrum analyzer and is often preferred when characterizing optical amplifiers for analog optical communications. Because it measures the photocurrent noise at the receiver, it is the most direct way of measuring the noise figure. For this reason, we will concentrate our analysis on the noise-figure measurement by using the electrical method with an idealized setup. In this regard, we will first review the various types of noises that are always, or commonly, found in the photo detection process of amplified optical signals.
One common noise, which is always present in electronic circuits, is thermal noise, also known as the Johnson or Nyquist noise. Thermal noise arises because the electrons behave like molecules at temperature T_{fc}, where T_{fc} is the temperature in Kelvin [7]. The variance in thermal noise current, a2h, within the given electronic bandwidth B_e is given by

$$\sigma_{th}^2[A^2] = \frac{4k_B T_k B_e}{R} , \quad (1)$$

Where: K_B: The Boltzmann constant and R is the matched load resistor.
The shot noise in a photo detection circuit can be thought of as being generated by the random arrival time of the electrons that make up the photocurrent [8]. Although the shot noise has Poisson statistics, Poisson statistics can be well approximated by Gaussian statistics for large < n >.
Therefore, the variance in the photocurrent due to shot noise is given in terms of optical power as:

$$\sigma_{sn}^2[A^2] = 2q\Re < P > B_e \quad (2)$$

This shot noise becomes important when the signal power is very low. Since this shot noise is due to the quantum nature of photons, the shot-noise-limited optical source is referred to as the quantum-limited source. Central to the understanding of the optical-amplifier noise figure are the two beat noises. Suppose we are given an amplifier with a signal gain G and an optical input power Ps. Further suppose that the amplifier output is filtered by a narrow optical band pass filter with bandwidth B_O centered on the signal wavelength. The amplifier output power is then composed of an amplified signal GP_S and an unwanted amplified spontaneous emission (ASE) P_{ASE}

$$P_{out}[W] = GP_s + P_{ASE} \quad (3)$$

The noise power can be written as:

$$P_{ASE}[W] = 2\rho_{ASE} B_o , \quad (4)$$

Where:
ρ_{ASE}: The noise power spectral density (W/Hz) in a single polarization.
The presence of ASE accompanies three kinds of noises, the ASE shot noise, the signal-spontaneous beat noise, and the spontaneous-spontaneous beat noise. The shot noise is, as discussed previously, fundamental to the quantum nature of photons, and the ASE has the same kind of contribution to the shot noise as does the signal output. The signal-spontaneous beat noise is due to the interference between the amplified signal and the ASE. On the other hand, the spontaneous-spontaneous beat noise can be considered as the intensity noise of the ASE itself.
We assume the noise power spectral density is constant within the optical bandwidth B_O of an ideal rectangular filter. When integrated over the electrical filter bandwidth B_e, the variance in the photocurrent due to the signal-spontaneous beat noise is given by [6]

$$\sigma_{s-ASE}^2[A^2] = 4R^2 GP_s \rho_{ASE} B_e . \quad (5)$$

The spontaneous-spontaneous beat noise similarly arises due to the beating between the different ASE components. Integrated over the electronic bandwidth, the variance in the noise current due to the spontaneous-spontaneous beat noise is given by:

$$\sigma^2_{ASE-ASE}[A^2] - 2R^2\rho^2_{ASE}B_e(2B_o - B_e) \qquad (6)$$

There are other types of noises, but the above-mentioned ones are those that are the most important for characterizing the optical amplifier noise figure.

III. The Optical Amplifier Measurments

i) noise figure

An ideal laser source with an appropriate signal wavelength, line width, and power is directly connected to an ideal detector. The connection is assumed to be lossless, and the optical source is assumed to be shot-noise limited. The optical detector is assumed to be ideal in that all the excess noises are absent and the quantum efficiency of the detector is unity ($\eta = 1$). Since thermal and shot noises are independent statistical processes, the noise variances add algebraically as

$$\sigma^2_{in}[A^2] = \sigma^2_{th} + \sigma^2_{sn} \qquad (7)$$

The thermal noise contribution can be easily subtracted from the measurement because thermal noise is constant for a given load resistance at fixed temperature. Therefore, under the assumption of a shot-noise-limited source, the SNR_{in} is given by

$$SNR_{in} = \frac{I_s^2}{\sigma^2_{sn}} = \frac{(RP_s)^2}{2qRP_sB_e} = \frac{P_s}{2hvB_e}\ . \qquad (8)$$

The optimum bandwidth of the electrical filter following the photodiode is determined by the measurement time interval T:

$$B_e[Hz] = \frac{1}{2T}\ . \qquad (9)$$

Therefore, the ideal input signal-to-noise ratio equals the mean input photon number:

$$SNR_{in} = \frac{P_sT}{hv} = \langle n \rangle \qquad (10)$$

The output noise current consists of several components: namely, the thermal noise, the shot noise of the amplified signal and the ASE, the signal-spontaneous beat noise, and the spontaneous-spontaneous beat noise. Again, all these noises are statistically independent of each other, and the variance of the total noise current is given as:

$$\sigma^2_{out}[A^2] = \sigma^2_{th} + \sigma^2_{sn} + \sigma^2_{s-ASE} + \sigma^2_{ASE-ASE}\ . \qquad (11)$$

The shot noise is composed of two parts, one due to the amplified signal and the other due to the ASE. In the usual region of operation, the ASE power is very small compared to the amplified signal power. Since shot noise is proportional to the power, shot noise associated with ASE is negligible compared to the shot noise associated with the amplified signal, we cannot neglect the shot noise as a whole. Although shot noise is usually smaller than the signal-spontaneous beat noise, shot noise can dominate over the signal-spontaneous beat noise for small gain. In that case, neglecting the shot noise leads to an erroneous result for the noise figure. Therefore, if the shot noise due' to the amplified signal and the signal-spontaneous beat noise are retained, the SNR_{out} is given by

$$SNR_{out} = \frac{I^2_{out}}{\sigma^2_{sn} + \sigma^2_{s-ASE}} = \frac{(RGP_s)^2}{2qRGP_sB_e + 4R^2GP_s\rho_{ASE}B_e}\ . \qquad (12)$$

Then, it is easy to show that the noise factor is given by

$$F = \frac{2\rho_{ASE}}{Ghv} + \frac{1}{G} , \quad (13)$$

Where the first term is the signal-spontaneous beat noise contribution and the second term is the shot-noise contribution.
In the linear operating region of an optical amplifier, the noise power is given by:

$$P_{ASE} = 2n_{sp}hv(G-1)B_o , \quad (14)$$

With Eq. (13), the noise factor reduces to

$$F = 2n_{sp}\frac{(G-1)}{G} + \frac{1}{G} . \quad (15)$$

ii) bit error rate

The current optical communication link in the world is based on an ASK (amplitude shift keying) direct detection system, also known as an intensity modulation, direct detection (IMDD) system. In this modulation format, the "1" bit and the "0" bit are designated by the presence or the absence of the signal power, respectively. In essence, the transmitter laser is turned off during the "0" bit and turned on at constant power during the "1" bit.
The BER (bit error rate) is the most important figure of merit indicating the statistical performance of a given digital communication system. It is the ratio of the bits received in error over the total number of bits received. When the "1" bit is as likely to occur as the "0" bit and the occurrence of each bit is completely independent of the past history, then the BER is given as the arithmetic average of the probability that the "1" bit is sent but the "0" bit is received and the probability that the "0" bit is sent but the "1" bit is received.
In this idealized setup, there is no chance of mistaking a "0" bit as a "1" bit because laser is completely turned off and the photon counter is ideal in that there is no misfire. However, the "1" bit can be misinterpreted as a "0" bit due to the Poisson statistics. Since the probability that n photons will be received during the time interval T is given by Eq. (16), there is a non-zero chance of receiving no photon during a one bit-period as given by:

$$p(0) = e^{-rT} = e^{-<n>} , \quad (16)$$

The BER is given as:

$$BER = \frac{1}{2}e^{-<n>} . \quad (17)$$

Then, the BER is found as an exponential function of SNR:

$$BER = \frac{1}{2}e^{-SNR} . \quad (18)$$

Therefore, for a given SNR, the bit period T can be decreased to Ts until the BER equals the preset BERS value to fully exploit the system capacity. In other words, the system capacity is given as

$$\frac{1}{T_s} = \frac{P_s}{hvln\left[\frac{1}{2BER_s}\right]} . \quad (19)$$

IV. SIMULATION RESULTS

1. System model

Table.1 Parameters for simulations

γ	Nonlinear Coefficient	1.22 W^{-1}/km
B_o	Optical filter bandwidth	42.7 GHz
λ	Wavelength	1.55 um

α	Attenuation coefficient	0.25 db/km
η_{sp}	Spontaneous emission factor	1.41

Table.1 lists the parameters used for simulations; the parameters are same as in [9]:
Attenuation in the fiber is compensated by the EDFAs and the ASE noise added to the system is given by: $\sigma^2 = 2\, h\, v\, \eta_{sp}\, B_o\, \alpha\, L_A$
Which has already been defined, the gain of each amplifier is equal to αL_A, where L_A is fiber length between each amplifier.

2. Distributed Amplification

In distributed amplifications the signal traveling through the fiber is amplified throughout the fiber. It can also be assumed as a system with very small incremental lengths between amplifiers and having a large number of amplifiers.

3. Lumped Amplifications

Lumped amplification is practically implemented in long haul fiber optical communication links. Each amplifier is placed at distances from about 40 to 100 kilometers for 10 Gbps systems. The gain of each amplifier is equal the loss in the span between the EDFAs.

4. Average Power Definition

The average power traveling through the filter is given as follows:

$$P_{av} = (1/{}^{L}{}_{A}) \int P_o e^{-\alpha z}\, dz = (1-e^{-\alpha L}{}_{A}) / {}^{\alpha L}{}_{A} \qquad (20)$$

Where P_o is the launched power and P_{av} is the average power traveling through the fiber. In order to maintain the average received power almost equal to that of launched power distributed amplification in terms of powers traveling through the fiber.

5. Optical link performance

The optical link performances are affected by four-wave mixing (FWM), modulation instability (MI), and parametric gain. Their impact on amplifier noise has been studied theoretically and experimentally [10]-[11].
We describe OA by means of semi classical noise-model [12], in which we now also include the effects of PG on the amplified spontaneous emission (ASE). We focus on the erbium doped fiber amplifier (EDFA's) and take into account the effective spectral gain shape and the saturation, treating cascading amplifiers in a self-consistent description.

6. Numerical results

Fiber link length:2500km, amplifier spacing 50 km, signal power 1mw after each OA, the fiber dispersion parameter β_2 = -1 ps^2/km, the nonlinear coefficient of the fiber γ = 1.22 $W^{-1}km^{-1}$, and the power attenuation coefficient α = 0.22 dB/km.
Fig. 1 and fig.2 show the variations of the average optical power with different link lengths and power attenuation coefficients. From figures, it is clear that the average power decreases with increasing of link lengths and power attenuation coefficients.
Fig.3 shows the variations of the noise power spectral density with wavelengths for different power attenuation coefficients. Fig. 4 shows the effect of frequency on the noise power spectral density with different power attenuation coefficients.
Fig. 5 shows the parametric gain of the probe signal, for a 2500-km fiber link, with 50 km amplifier span, in anomalous and normal dispersion.
The peak for the anomalous regime is reduced. The peak at 57 and 80 GHz, known as sideband instability effect [13], are due to the periodic variation of the power signal that acts as a sort of phase-

grating. If the OA spacing is randomly changed by 10%, the peak structure damps out, however still at constant total power.

In Fig.6, an unfiltered link with OA's has the output optical spectra for different OA's are of the same long. It is noted that the shift of the ASE peak to longer wavelength with increasing OA's number (for long and deeply saturated amplifiers the gain always moves to longer wavelengths with substantial amplification up to 1620).

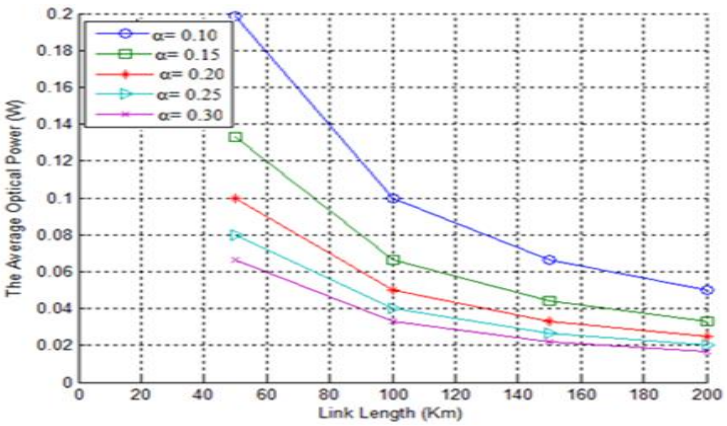

Fig.1 The average power versus Link length with different power attenuation coefficients.

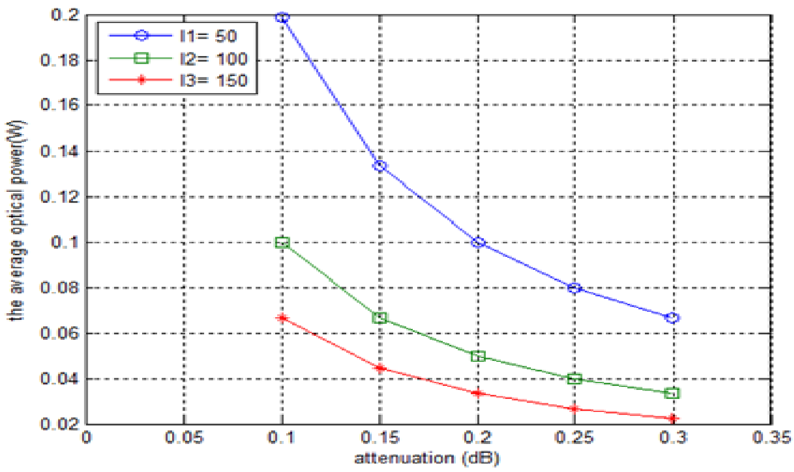

Fig.2 The average power versus power attenuation coefficients.

(dB/km) with different link lengths.

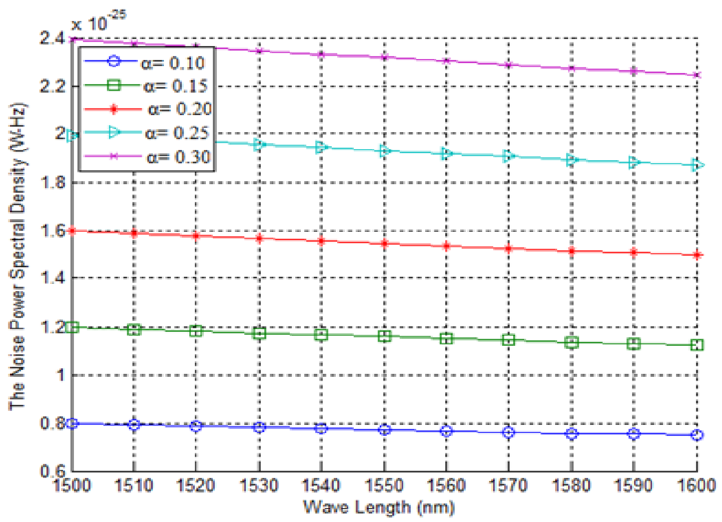

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Fig.3 The noise power spectral density versus wavelength (nm).

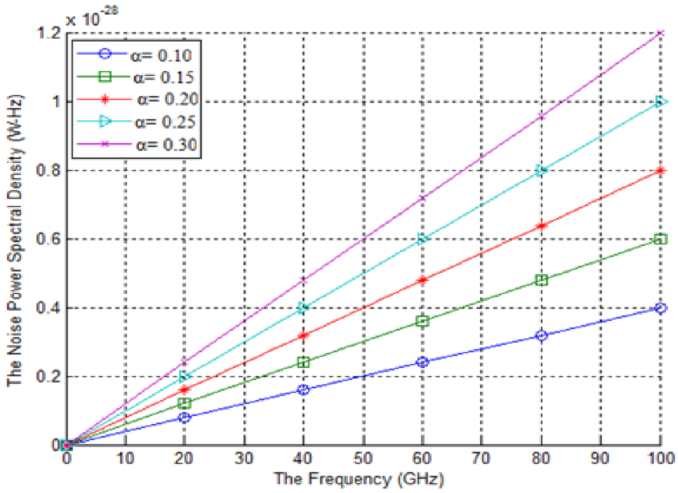

Fig.4 The noise power spectral density versus frequency (GHz).

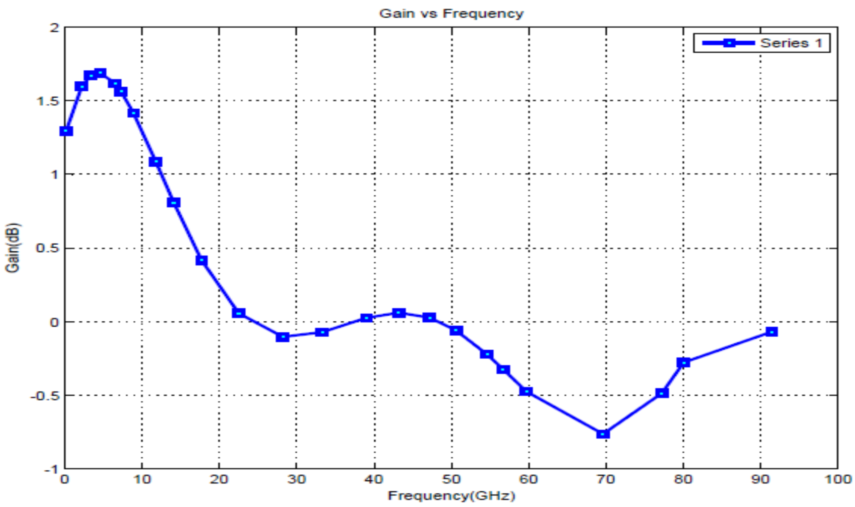

Fig. 5 Parametric gain [dB] versus frequency (GHz)

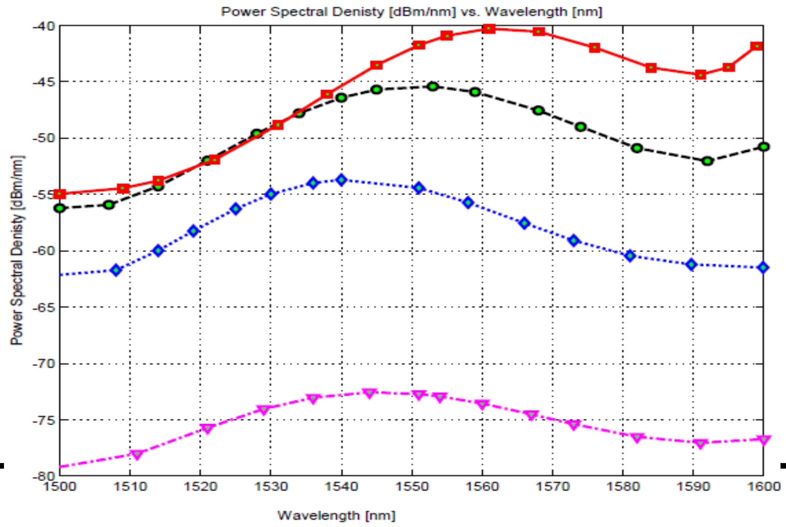

Fig.6 Output optical spectra with different OA's

V. CONCLUSIONS

In this paper, noise variance estimation of erbium doped fiber amplifier that removes the white noise assumption is described. SNR estimation indicates the reliability of the link between the transmitter and receiver. It is used for measuring the quality of the channel. Then, the system parameters are changed adaptively based on this measurement. If the measured channel quality is low, the transmitter adds some redundancy or complexity to the information bits(more powerful coding),reduces the modulation level(better Euclidean distance), or increases the spreading rate (longer spreading code) for lower data rate transmission. Results indicate that the instability effect is reduced if the OA spacing is changed by 10%. It is noted that the peak output optical spectral density for different OA's to longer wavelength with increasing OA's number.

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