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Theoretical and experimental studies of the influence of the number of crosstalk signals on the penalty caused by incoherent optical crosstalk

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I. INTRODUCTION

Incoherent optical crosstalk, i.e. the crosstalk type where the crosstalk signals have the same wavelength as the wanted signal but all signals are uncorrelated, is one of the most detrimental phenomena in optical networks and has therefore been the subject of many studies, e.g. [1]-[3]. Most of these have focused on situations with many crosstalk signals, and Gaussian statistics have been used as an approximation to the statistics of the receiver process in order to find the crosstalk penalty. However, a few recent theoretical investigations [4],[5] have used more accurate statistics and have shown for PIN receivers that the penalty caused by a given total crosstalk power increases when this power is distributed among an increasing number of crosstalk signals. This phenomenon is not predicted by the Gaussian models.

To continue the investigations of how the number of crosstalk signals affects the incoherent crosstalk penalty, we have calculated the incoherent crosstalk penalty as a function of the total crosstalk power and the number of crosstalk signals for both PIN and optically preamplified receivers. Furthermore, we have verified the theoretical results experimentally. To our knowledge, neither calculations of the penalty for preamplified receivers nor experimental verifications of the influence of the number of crosstalk signals have been reported before. The calculated penalties are compared to the penalties obtained using the Gaussian approximation, and the difference is smaller than ¼ dB when the total crosstalk power does not exceed a level 24 dB below the power of the wanted signal and 6 or more crosstalk signals exist. We have also discovered that the penalty in dB in the case of a preamplified receiver is approximately twice the penalty for the PIN case. A network consequence of our results is that if the allowed crosstalk penalty is 1 dB, up to 3 dB more total crosstalk power can be tolerated in small networks with only 1 crosstalk signal compared to larger networks with many crosstalk signals.

II. THEORY

We consider a situation where a wanted signal with a mean power of P_s is disturbed by N independent crosstalk signals each having a mean power of XP_s/N . The total crosstalk power is thus XP_s and X is denoted "total relative crosstalk power". Both the wanted signal and the crosstalk signals are assumed to have a mark density of 0.5 and extinction ratio e , where e is defined as the optical power in the "1"-level divided by the optical power in the "0"-level. In order to investigate the worst case with maximum crosstalk influence all signals are assumed to have identical polarization states. Because of the presence of crosstalk, the total received power at time t , $P(t)$, is a random variable even if it is known whether the wanted signal is "0" or "1". $P(t)$ can be written:

$$P(t) = P_s \left| \delta(t) + \sum_{i=1}^N A_i(t) e^{j\theta_i(t)} \right|^2$$

Here $\delta(t)$ is the amplitude of the wanted signal at time t and is either $\sqrt{2/(1+e)}$ or $\sqrt{2e/(1+e)}$ depending on whether the signal is "0" or "1". $A_i(t)$, $i \in \{1, \dots, N\}$ is a random variable representing the amplitude of the i th crosstalk signal at time t . It takes the value $\sqrt{2X/(N(1+e))}$ or $\sqrt{2eX/(N(1+e))}$ with equal probability. $\theta_i(t)$, $i \in \{1, \dots, N\}$ is the difference between the phase of the i th crosstalk signal and the wanted signal at time t . This random variable is uniformly distributed in $[0; 2\pi]$. The $2N$ random variables $A_i(t)$ and $\theta_i(t)$ are mutually independent and also independent of $\delta(t)$.

Fig. 1 shows the probability density function (pdf) of $P(t)$ when the wanted signal is "1" and 1, 2, 4, 6 and an infinite number of crosstalk signals exist. The Gaussian pdf used in the Gaussian approximation is also shown. Mean and variance of this Gaussian are chosen to the mean and the variance of $P(t)$ when an infinite number of crosstalk signals exist.

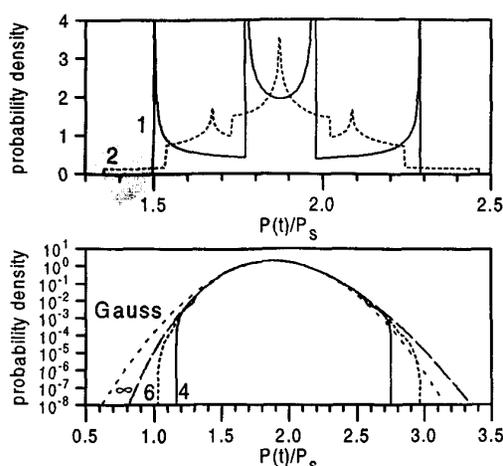


Fig. 1. pdf for $P(t)/P_s$ when the wanted signal is "1". The numbers next to the curves are the number of crosstalk signals. "Gauss": see text. The total relative crosstalk power is -20 dB, and the extinction ratio is 12 dB.

In order to determine the bit error probability and the receiver sensitivity, which is the total received optical average power that gives an error probability of 10^{-9} , the pdf of the input voltage to the decision circuit of the receiver is calculated. Since we study incoherent crosstalk, the vast majority of the spectrum of $P(t)$ falls within the bandwidth of the electrical amplifiers in the receiver. Consequently, the photocurrent proportional to $P(t)$ will be amplified but not significantly distorted in the electrical amplifiers. Therefore we assume that the input voltage to the decision circuit is the sum of a signal part $HP(t)$, where H is a constant, and a zero mean Gaussian noise with variance $a+bP(t)$. a is the power of the signal independent noise generated in the receiver (thermal noise, for optically preamplified receivers also spontaneous-spontaneous beat noise and shot noise from the spontaneous emission) and $bP(t)$ is the power of the signal dependent noise (signal shot noise, for optically preamplified receivers also signal-spontaneous emission beat noise).

Fig. 2 shows the calculated crosstalk penalty as a function of the total relative crosstalk power and the number of crosstalk signals for both a PIN receiver and an optically preamplified receiver whose dominant receiver noise contribution is signal spontaneous beat noise. It is clear from fig. 2 that the penalty increases when a given amount of total crosstalk power is distributed among a larger number of crosstalk signals. As an example we see that a total relative crosstalk power of -20 dB distributed over 1, 6 and an infinite number of crosstalk signals gives penalties of 1.1 dB, 2.1 dB or 2.7 dB, respectively, in

the PIN case. In the case of an optically preamplified receiver, the penalties are approximately two times higher (namely 1.9 dB, 3.8 dB and 5.0 dB), and fig. 2 shows that this relation between PIN receiver penalty and preamplified receiver penalty is **general**.

Fig. 2 can also be used to determine how much total relative crosstalk power that can be tolerated if the penalty must be smaller than, say, 1 dB. In the PIN case, the tolerable amount of total relative crosstalk power decreases from -20.4 dB in the case of 1 crosstalk signal to -23.3 dB in the case of an infinite number of crosstalk signals. This shows that up to 3 dB more crosstalk power can be tolerated in small networks with only 1 crosstalk signal than in larger networks with many crosstalk signals.

The curves called "Gauss" on fig. 2 show the penalties calculated using the Gaussian pdf's from the Gaussian approximation instead of the exact pdf's. The Gaussian approximation is seen to give results which are accurate within $\frac{1}{4}$ dB if 6 or more crosstalk signals exist and if the total relative crosstalk power is smaller than -24 dB.

III. EXPERIMENTS

In order to verify the theoretical results, the incoherent crosstalk penalty has been measured in the set-up shown on fig. 3: CW light from a DFB laser (wavelength 1555 nm, linewidth 48 MHz) is modulated with a 5 Gbit/s $2^{31}-1$ PRBS in a Mach-Zehnder modulator and then split into a crosstalk part and wanted signal part. The former is further split into 6 crosstalk signals whose powers are controlled by attenuators. After decorrelation in delay lines consisting of 0.5, 1, 2, 3, 4 and 23 km of dispersion shifted fiber, the crosstalk signals and the wanted signal are combined again, and a small fraction of the combined signal is coupled into a polarization analyzer. The rest is attenuated in an attenuator that controls the total power into the PIN or the optically preamplified receiver. A bit error rate test set connected to the receiver measures the bit error rate. Identical polarization states of all signals arriving at the receiver input are obtained using the polarization analyzer and the polarization controllers.

The measured incoherent crosstalk penalties for different values of total relative crosstalk power distributed on 1, 2, 4 and 6 crosstalk signals with equal powers are shown on fig. 2 for both a PIN and an optically preamplified receiver. The agreement between the theoretical predictions and the measurements is very good.

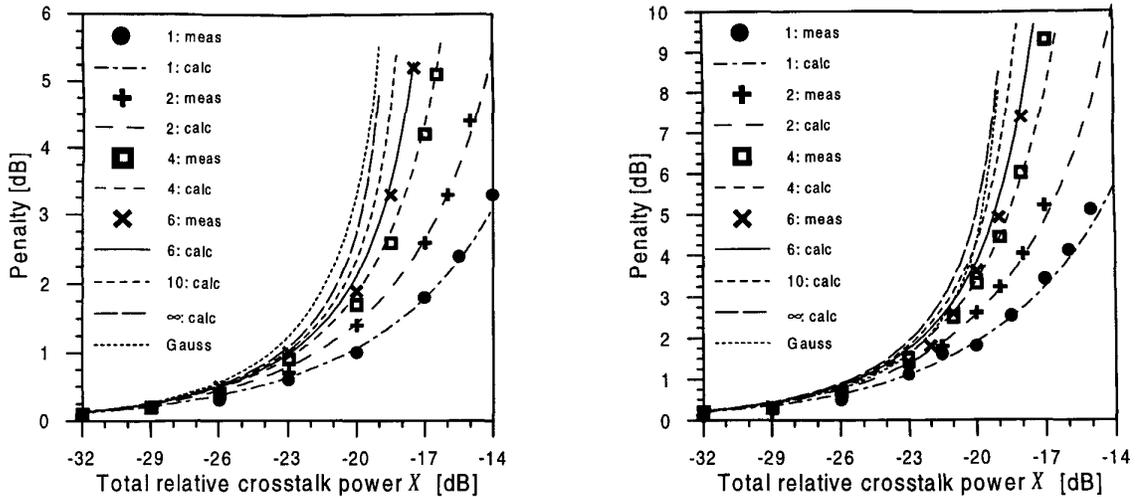


Fig. 2. Calculated and measured incoherent crosstalk penalty for a PIN receiver (to the left) and an optically preamplified receiver (to the right) as a function of the total relative crosstalk power with the number of crosstalk signals as parameter. Gauss: See text. The extinction ratio is 11.7 dB in the PIN case and 12.0 dB in the optically preamplified case.

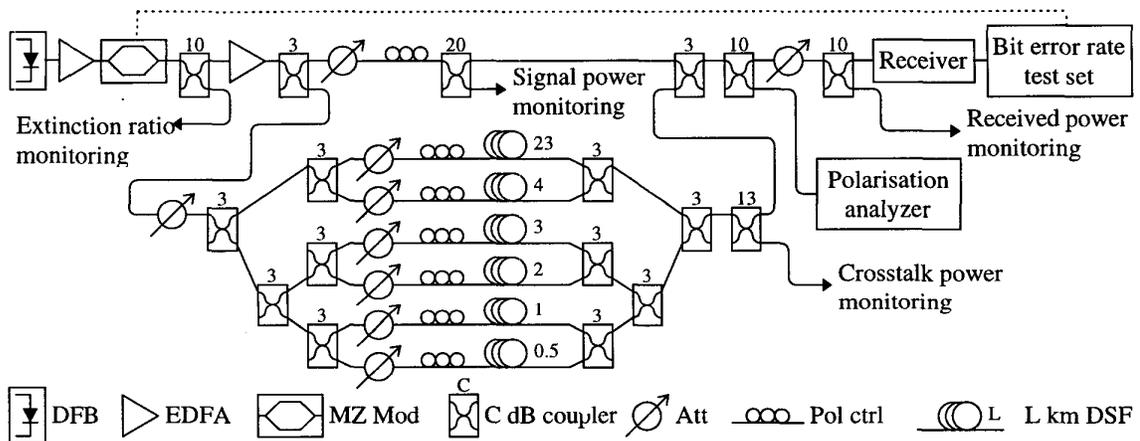


Fig. 3. Set-up for measurements of incoherent crosstalk penalty. DFB: DFB laser; EDFA: Erbium Doped Fibre Amplifier; MZ Mod: Mach-Zehnder modulator; Att: Attenuator; Pol ctrl: Polarization controller; DSF: Dispersion shifted fibre.

IV. CONCLUSION

The penalty caused by incoherent crosstalk has been calculated and measured for both PIN and optically preamplified receivers. Measured and calculated penalties agree excellently, and they show that the penalty is not only a function of the total crosstalk power but also of the number of crosstalk signals among which the power is distributed. As an example, the penalty caused by a total relative crosstalk power of -20 dB increases in the preamplified case from 2 dB to 4 dB when 6 instead of 1 crosstalk signals exist. As to the relation between the penalty in the PIN and the preamplified case, a

rule of thumb is derived: The penalty in dB in the preamplified case is two times the penalty in the PIN case. Finally, the penalty calculations based on the exact pdf of the received optical power show that the often used Gaussian approximation is accurate within ¼ dB if 6 or more crosstalk signals having a total relative power smaller than -24 dB exist.

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