Low level Optical Signal to Noise Ratio measurement using basic statistical data from Asynchronous Amplitude Histogram Gaussian fitting.

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***Abstract*—Optical Monitoring Systems need to be less expensive if we are to create an Optical Packet Switched Network. The application presented in this paper uses low cost sampling circuits and simple Digital Signal Processing in order to acquire good approximations of the Optical Signal to Noise Ratio by using the exponential relation found between the Variance of one of the peaks in the AAH and the OSNR. The method works especially well for PSK and QPSK modulation schemes, and presents a good representation for DPSK and DQPSK systems.**

The results here presented were heuristically obtained, though some basic relation between the features used are devisable, and could lead to future analytical approaches.

***Index Terms*—Asynchronous Amplitude Histogram (AAH), Optical Signal to Noise Ratio (OSNR), Gaussian fitting, Optical Monitoring System (OMS).**

I. Introduction

Traditional Optical Monitoring Systems (OMS) have been used to monitor local impairments in local, permanent fibre links to feed the special compensation devices that make the transmission of data possible, due, in part, to their relatively high cost, but recently, efforts have been made in several investigations to develop OMS that work in a better way than the previous measurement techniques, cost less, and increase their measured parameters [1].

Previous OMS, among others, include a narrow band tunable filter which is centered at each of the channels in a Wavelength Division Multiplexing (WDM) distribution system, for measurement with an OSA (Optical Spectrum Analyzer), but this method poses a time restriction, due to the need of fine tuning the filter in use for each and every channel in the WDM system, which can probe to be very time consuming [2]. Another approximation to the measurement of the OSNR is via an interpolation of the noise in the proximity of the channel center, if one assumes that the in-band noise is the same as the one in its vicinity [3], this, obviously is not always the case.

Since presented, in [4] and [5], Asynchronous Amplitude Histograms (AAH), have shown tremendous potential due to their simplicity and remarkable flexibility [1], with some studies mentioning its sensitivity to varios optical fibre transmission impairment, including, crosstalk, CD [6], 1^{st} order PMD [7], OSNR monitoring, and, even BER degradation fault identification. An analysis of the relation between the AAH and the Q factor derived through the Bit Error Rate (BER) is presented in [4] and the similarity among the shape of the AAH and a Gaussian distribution is pointed out; additionally, the idea of a relation between the mean and standard deviation values of these Gaussian shapes and a possible measurement of an averaged Q factor is mentioned. Shake proposed some measurements that can be made to the AAH, that lead to an expression of the averaged Q factor, which probes to be highly correlated to the Q factor obtained from the BER method, additionally, the decision intervals for each mark and space in RZ and NRZ is evaluated for several ranges [5].

The effects that Dispersion, Noise, represented by the contribution of the an Erbium Doped Fiber Amplifier (EDFA) and crosstalk can have in the AAH's general shape are addressed in [8]. In [9], some relations between the shape of the AAH and the real behavior of the optical signal are develed, and a probabilistic analysis is made for each of the bins used in the quantization process prior to the creation of the AAH. A detailed investigation of the dependence of the averaged Q factor on the OMS parameters such as optical filter bandwidth, measurement times, among others, is presented in [10], and, an improved study in the decision intervals used to suppress the cross-points between the two Gaussian is conducted with the correlation of the averaged Q factor and the real Q factor in mind. In a later study [6], a comparison involving some values of CD is made to the different parameters that can be obtained from the AAH, via the averaged Q-factor technique, which is formally presented in the paper. A parameter that was created by a combination of the averaged Q-factor ones, is proposed, and has shown to change its magnitude with variations in the CD and OSNR. This effect can probe very useful to monitor both impairments simultaneously.

The application here presented was developed thinking in the reduced costs that would mean for the carriers to implement this type of OMS, having low quality sampling circuitry in addition to not needing high capacity for the method to work, and low complex mathematical operations that could be done even in low performance Integrated Circuits (IC), not being necessary the use of Application Specific IC (ASIC).
Parting from a noisy signal, asynchronous amplitude histograms are created and then analyzed using a basic relation between the OSNR an the variance of the peak that corresponds to the higher signal levels, that was found to have an exponential-like behavior when graphed versus OSNR; then, exponential fitting is applied to the resulting data in order to find an expression that can be used to monitor OSNR.

II. Materials and Methods

In the following paragraphs, a basic explanation of the less demanding stages is presented, after that the important stages in the AAH process are analyzed.

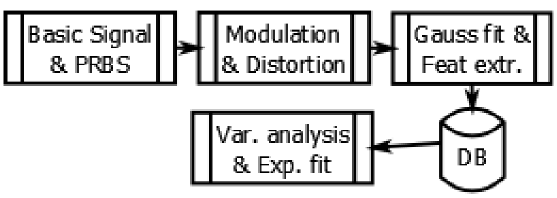

Fig. 1. Flow Chart of the scripts used to develop the method

Having in mind that the commonly used light sources in the real optical networks, are physical devices, and consequently, imperfect, a pure sinusoidal light source should not be used for the simulations since it will have different responses to distortions. The first block of Fig. 1, uses a basic signal created using reverse-engineering from real lasers' spectrums, following the proportionality of the central frequency and its sidebands, this artificially created spectrum is then transformed into the time domain, being the real part of this result, the basic sinusoidal input for the system as shown on Fig. 2 a), that for our case has 200 samples.

The Pseudo Random Binary Sequence (PRBS) is created using a uniformly distributed random integers algorithm with a length of 5000 bits. For the modulation Stage, we used PSK, DPSK, QPSK and DQPSK (the two las ones with a $pi/4$ phase offset) obtained through the concatenation of phase changed basic signals like the one in Fig. 2 a). Distortion was carried out by adding White Gaussian Noise in different levels

$$\Delta_{noise} = (n_0 + \alpha n_{inc}, n_0 + (\alpha + 1)n_{inc}),$$

where Δ_{noise} is the interval that contains the noise levels used, and the vector containing each value would be $\mathbf{n}_{levels} = \{n_0 + \alpha n_{inc}\}$, α varies between $0 \rightarrow 5$, n_0 and n_{inc} are the initial noise level and the increment between levels respectively, both valued 5.

A. AAH

AAH owes its name to the difference in the clock used for the sampling of the amplitude of the incoming optical or electrical signal, which in contrast to synchronous amplitude histograms, is not necessarily the same or a direct multiple of the system clock this means that AAH may be acquired by sampling the optical signal at an arbitrary rate in the electrical [8] or optical domain [5].

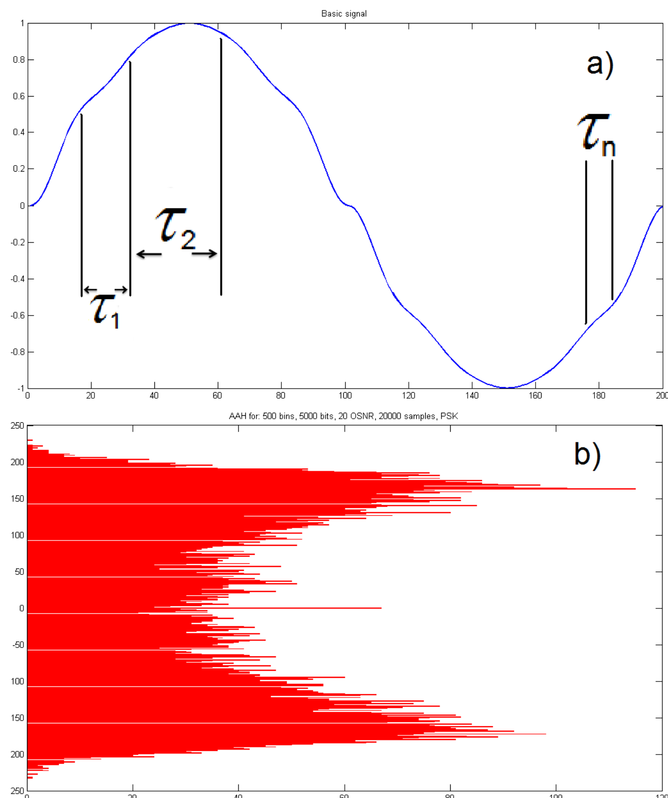

Fig. 2. a) Basic Signal b) Example AAH for 500 bins, 5000 bits, 20dB OSNR, 20000 samples and PSK modulation

1) Creation of the AAH: As the signal comes into the OMS it is sampled, on average, four times per cycle. By adding a uniformly distributed random integer to each of the sampling times created in the original signal vector we simulate the low performance of the sampling circuit, as shown in Fig. 2 where the different τ mean the different sampling periods. After the samples are taken they are quantized in 500 bins, for the creation of the histogram, when enough samples are acquired (20000 for this case), the processing can continue.
Note, though this sampling frequency is in fact higher than the system frequency, this method could be operational with lower sampling frequencies as long as the randomness of the clock is guaranteed and enough samples are taken, leading to

a series of data that correctly represents, the only reason we used this sampling frequency was because the mere generation of the PRBS and the modulation process for 5000 bits, could take hours in our computational system.

An analogy to the different levels in the signal can be made trough Fig. 3, where we can see that each sample of an eye diagram would fit into one quantization bin for the AAH case. It is important to know, however, that eye diagrams require synchronization for their creation, while AAH strength of representation is precisely in the lack of that requirement.

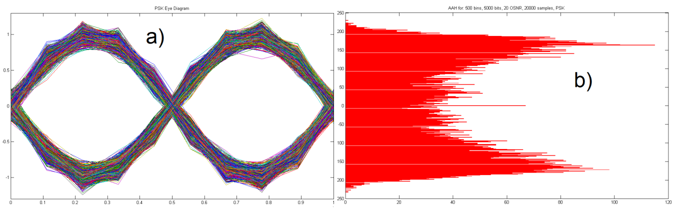

Fig. 3. Comparison between a) eye diagram and b) AAH.

B. Gaussian Fitting of the AAH

In order to make the fit of the AAH, we first filtered the AAH using a moving weighted average filter, as seen in light green lines on Fig. 4, and, based on the peaks' amplitudes and the Normal distribution expression (1), by matching the amplitude of the peak to the coefficient that accompanies the e in expression (1), and then clearing σ, to obtain the standard deviation.

$$f_{(x)} = \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-\mu)^2 / 2\sigma^2} \tag{1}$$

Where σ and μ denotes the standard deviation and mean respectively, being the mean the maximum value of each of the peaks in Fig. 4.

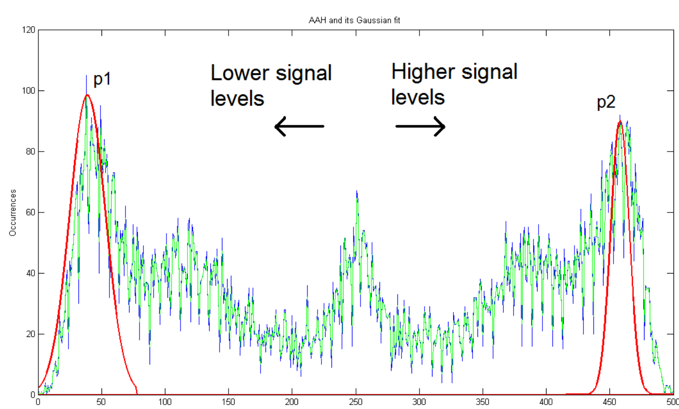

Fig. 4. Normal AAH (blue), Treated AAH (Light-green), Gaussian fits (Red)

Having the standard deviation, the height of the Gaussian maximum, and the distance from the peak to the nearest maximum/minimum signal amplitude, it is posible to form the Gaussian fit shown in Fig. 4. From the characteristics that are used to describe the Gaussian fit we extracted characteristics such as the value of the means and the variances and created a DataBase (DB in Fig. 1) consisting of 50 observations for each combination.

C. Variance Analysis

We then created a summarization of all the records, for each noise level ($\mathbf{n}_{levels}$) and each modulation, by simply averaging the different fields explained in section II-B. The variance of the 2^{nd} peak was noted to have slight variations according to the noise level used. Previously it has been shown that the second, or rightmost peak is more influenced to noise than the lower due to the impact of signal-ASE noise beat which occurs predominantly at high signal levels [1]. The behavior shown in Fig. 5. Note the loss of OSNR variation when the variance approaches 400 and higher values due to the peaks in the AHH broadening more and more, a major difficult for the AAH method, although an alternate approach to this problem is presented in section III.

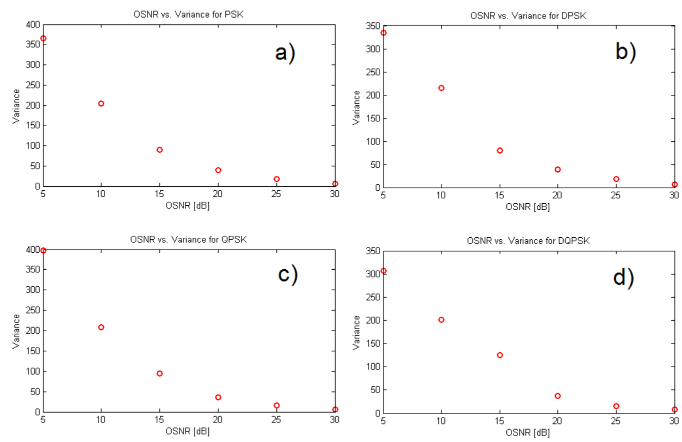

Fig. 5. Variance vs. OSNR of the summarization of the DB for a) PSK, b) DPSK, c) QPSK, d) DQPSK

Then, we have to find an expression that represents these data.

D. Exponential fitting

The parameters we changed through the iterations, in order to find the most suitable representation for the data from the DB, correspond to the coefficient A, and the value B of expression (2) whose final values are presented on section III:

$$V = Ae^{(-B)x} \tag{2}$$

where x is the OSNR. For the A parameter the possible values were in the range $[500, 1500]$ with resolution of 1, and for the B parameter the range was $[1/40, 1/5]$ with a resolution of $1/2000$.

E. Objective function

In the process of determining the best fit for each modulation, several error functions were used, each of them showing a special characteristic in the representation of the averaged data points, the analysis of each of them is shown in the following paragraphs. It is important to say that there are uncountable objective functions and the ones presented here are not the only ones that can show good results while working in optical systems or any other system that requires SNR measurement.

Another approach, would be to combine several objective functions and make them work by intervals, this would make the method more robust without adding too much complexity to the deployment, but increasing the research needed to estimate this objective functions and the method in which one or another would enter in the analysis of a signal.

1) 2^{nd} Norm: When minimizing the expression 3, we obtained a very good performance for PSK and QPSK modulations, but their differential variants showed held representation errors too large to be ignored.

$$E_{norm} = \sqrt{\sum_{n=1}^{N} \left(x^t{}_n - x^p{}_n\right)^2} \tag{3}$$

Where, $x^t{}_n$ refers to the n^{th} element of the theoretical (summarized DB) value for the variance, while $x^p{}_n$ is the n^{th} element of the practical (Exponential fitting) value of the variance, and N is the number of noise levels.

2) Standard Error (STDERR): The expression for standard error (4) proved a to be a good fit for most of the high values of OSNR, but was very imprecise for low OSNR:

$$E_{stderr} = \frac{1}{N} \sum_{n=1}^{N} \left| \frac{x^t{}_n - x^p{}_n}{x^t{}_n} \right| \tag{4}$$

3) Mean Square Error (MSE): 5 was the one in which the approximated values were in general the closest to the summarization ones, but did not offer a significant performance in any modulation or noise level, except for the first one (5dB) in most modulations, and for the QPSK modulation format:

$$E_{mse} = \frac{1}{N} \sum_{n=1}^{N} \left(x^t{}_n - x^p{}_n\right)^2 \tag{5}$$

4) Weighted Mean Square Error (WMSE): Was the one we selected as the final and definitive objective function since, we could weight the contributions of each noise level to the error, and thus, could control the behavior of the approximation curve, increasing the precision [11] for one or other OSNR level:

$$E_{wmse} = \frac{1}{|\mathbf{w}|} \sum_{n=1}^{N} w_n \left(x^t{}_n - x^p{}_n\right)^2 \tag{6}$$

where w_n corresponds to the n^{th} element of the weights vector, and $|\mathbf{w}|$ its absolute value.

III. Results and Further Analysis

The final results are condensed in Figs. 6 and 7, where we used the WMSE (6) to give more importance to the error contributed by the lower OSNR values, since those are the ones in which we would be more interested in measuring.

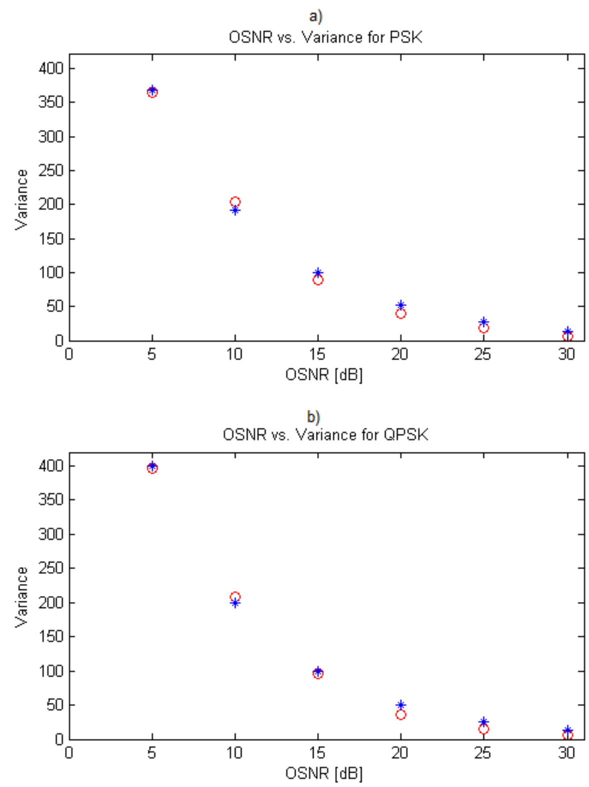

Fig. 6. Variance vs. OSNR (red circles) and the corresponding fit (blue stars) for a) PSK, b) QPSK

We can see that the results are very accurate and precise for PSK an QPSK systems, while the error in DPSK and DQPSK is not great.

Table I shows the final heuristical approximation to the optimal values, which are to be replaced on (2).

TABLE I
CONDENSED RESULTS

Modulation	A	B
PSK	710	546.0355
DPSK	625	504.7139
QPSK	801	583.9974
DQPSK	520	437.6294

A. Proposed OMS

Fig. 8 shows a diagram of the simple OMS that would be implemented if this method was adopted.

1) Received signal block: In this block the original signal from the channel is received as shown in Fig. 8 a) (The distorted signal is not shown for didactic purposes).

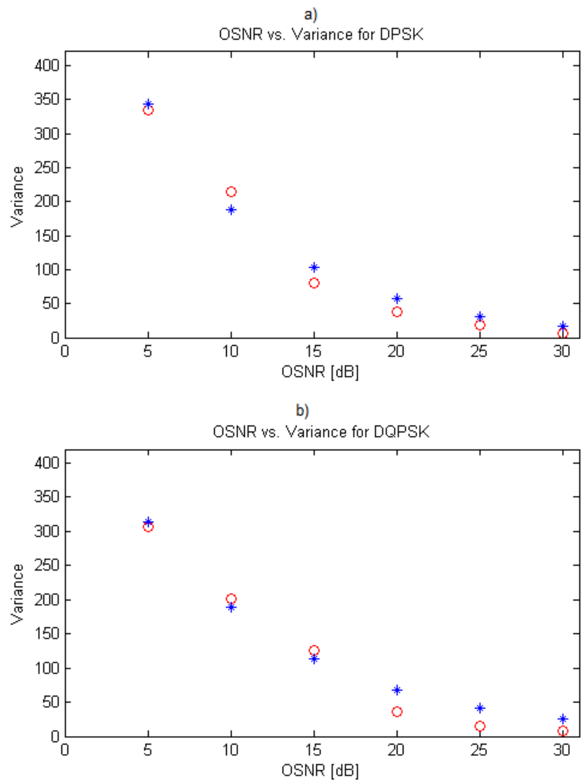

Fig. 7. Variance vs. OSNR (red circles) and the corresponding fit (blue stars) for a) DPSK, b) DQPSK

2) Sampling circuit: The original signal is asynchronously sampled, where the green dots in Fig. 8 b) are the different samples taken at different intervals.

3) AAH: The values are then quantized and saved to a temporal storage device, where they can be counted, and the AAH graphed as in Fig. 8 c), additionally the boundaries (red vertical line) for each peak estimation are set to the middle of the histogram and the regions are labeled R1 and R2 for further reference.

4) Peak & feature extraction: In Fig. 8 d) marked with blue lines are the peaks that are found via a maximum value algorithm, and using this information, one can easily lookup the value in a table not bigger than 500 records with 10 bit precision values (approximately 5kB), and that value will be related to the real OSNR we are looking for.

Given the modular nature of this method, one could easily replace the table for another which has been created using different objective function and/or modulation schemes. Another possibility would be to use an IC that is capable of calculating the former values given it has the values in table I, which could make our OMS very flexible, and not modulation scheme dependant. The DB mentioned in Fig. 8 is not the same one as in Fig. 1.

IV. Conclusions

A basic method for extracting OSNR based in variance analysis from the gaussian fitting of AAH, has been proposed.

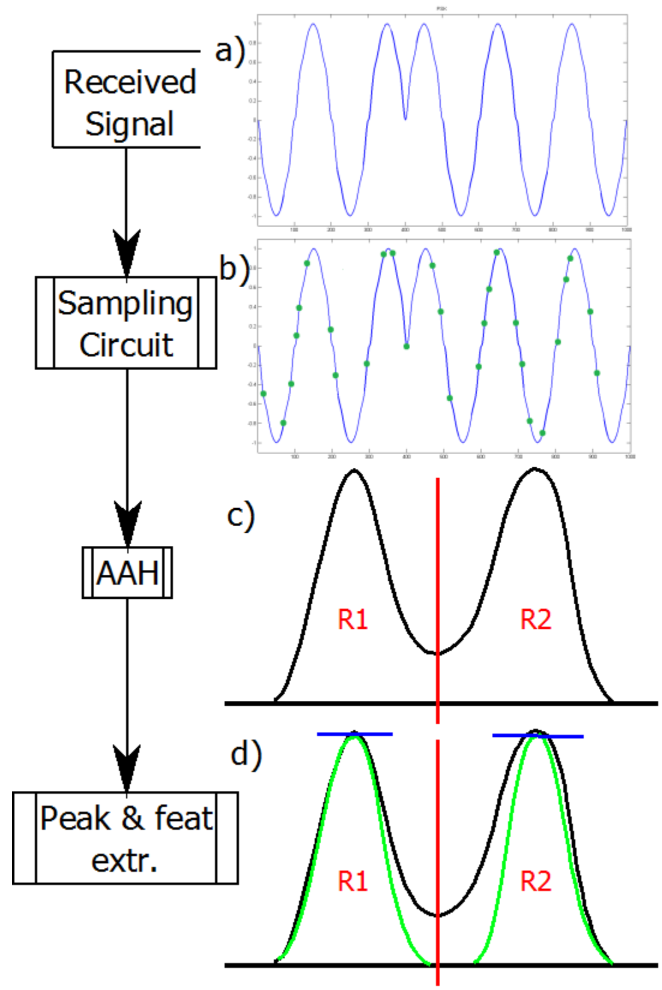

Fig. 8. Proposed OMS broken down into phases.

The objective function behavior can be easily changed by adjusting the weights in the WMSE expression [(6)], giving order to different combinations and fits for which the OMS pick the one that suits the best for each channel during its analysis. Furthermore, the objective function can be changed to other expressions that give other characteristics to the OMS, or a mixed-objective function may be created to incorporate strengths of different functions.

This method should work for higher order modulation schemes such as 16QAM, since AAH generated for this systems also have a rightmost peak representing the high values of the signal, the only one used in this method, which will undoubtedly present greater spreading as the noise level increments, prior testing has to be performed in order to find the coefficients that work for those cases though.

V. Future Work

A possible beginning point for the next research concerning this topic, would be to find an analytical explanation to the values that were heuristically found in this paper. An analysis of the representation capacities of the AAH is needed too, because there is no expression that clearly states which is the appropriated number of bins used for the quantization process.

The contribution that one objective function or the other can have to the method is very powerful, but a mixed-objective function would most likely work better, but, the switching between one another function during in-line analysis needs to be further investigated.

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