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Research Paper

Performance Monitoring of Optical Fibre Communication Systems with Gaussian Approximation and the Non-Central Chi-Squared Distribution Methods

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ABSTRACT: *The optical performance monitoring of fibre communication systems is carried out in this paper. Simple continuous mode receiver bit error rate (BER) models for on-off keying non-return-to-zero (OOK NRZ) are presented for a PIN photodiode based receiver and an optically preamplified receiver. Sampling histograms are obtained from the OOK NRZ signal accompanied by amplified spontaneous emission noise by employing known probability density functions. Statistical moments are extracted from the histograms and employed in estimating the BER by assuming different statistical approaches such as the Gaussian approximation and the non-central chi-squared distribution. An investigation of how the BER can be estimated from samples taken from the optical data stream is then carried out. The results show how the number of samples employed affects the obtained BER. Furthermore, an estimate of the number of samples required to obtain an acceptable measure of the BER is investigated.*

KEYWORDS: *Optical performance monitoring, Sampling histograms, Statistical moments, Gaussian approximation, Non-central chi-squared distribution*

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I. INTRODUCTION

There has been vast advancement in the field of optical communication since the introduction of economic optical fibre channels in the 1980’s. This is due to the unending demand for more communication capacity, which is further triggered by the invention and expansion of the Internet. Nowadays, communication speed of around 40Gb/s has been achieved and there are prospects of accomplishing transmission speeds of 100Gb/s and beyond in the nearest future to cater for the insatiable desire for more communication bandwidth. Also, the use of repeaters for maintaining signal strength gradually became less attractive due to its high cost of procurement, enhancement and maintenance. Erbium-doped fibre amplifiers (EDFAs); which were then introduced to mitigate these unfavourable effects also have their own shortcoming in form of amplified spontaneous emission (ASE) noise [1]. For optimal system performance, the bit error rate (BER) is expected to be at a minimal level but impairments such as ASE noise, crosstalk, self-phase and cross phase modulation, polarization mode dispersion (PMD), chromatic dispersion (CD), Raman and Brillion scattering, etc., degrades the system performance by increasing the BER more than the acceptable value. As a result of these impairments, monitoring in optical fibre communication systems becomes highly essential. Effective monitoring ensures adherence to system specifications allows for real-time assessment and enhances overall system performance [1, 2]. Monitoring of quality of service (QoS) and BER at the Synchronous optical networking/Synchronous digital hierarchy (SONET/SDH) layer is known as performance monitoring. Though, various interpretations have been given to optical performance monitoring (OPM) since the early 1990s, it can simply be described as the physical layer monitoring of signal quality [2].

II. OPTICAL PERFORMANCE MONITORING (OPM)

Due to the significant capacity expansion in optical fibre communication brought about by the introduction of Dense Wavelength Division Multiplexing (DWDM) [3], there is need for a monitoring technique (i.e. OPM) for an effective management of the network [4]. OPM is required in tasks such as signal health, channel recognition, amplifier control, etc., and it regulates high capacity optical transport, switching systems, physical layers imperfection, and link level recovery. As recommended in the OPM reference model in [2], OPM has many uses which can be grouped into 3 layers. The layers are the Wavelength Division Multiplexing (WDM) channel or transport layer (i.e. first layer), the channel quality layer or optical signal (i.e. second layer) and the protocol performance layer (i.e. third layer). Physical attributes like the wavelength, CD, power, spectral OSNR, etc. are resolved in the first layer. Note that at present, potentials of OPM are limited to the first layer though it is utilised in some aspects of the second layer as well. Evaluation of some statistical attributes of the signal such as the Q-factor, histograms, eye distortion takes place in the second layer. Figure 1 describes the OPM reference model.

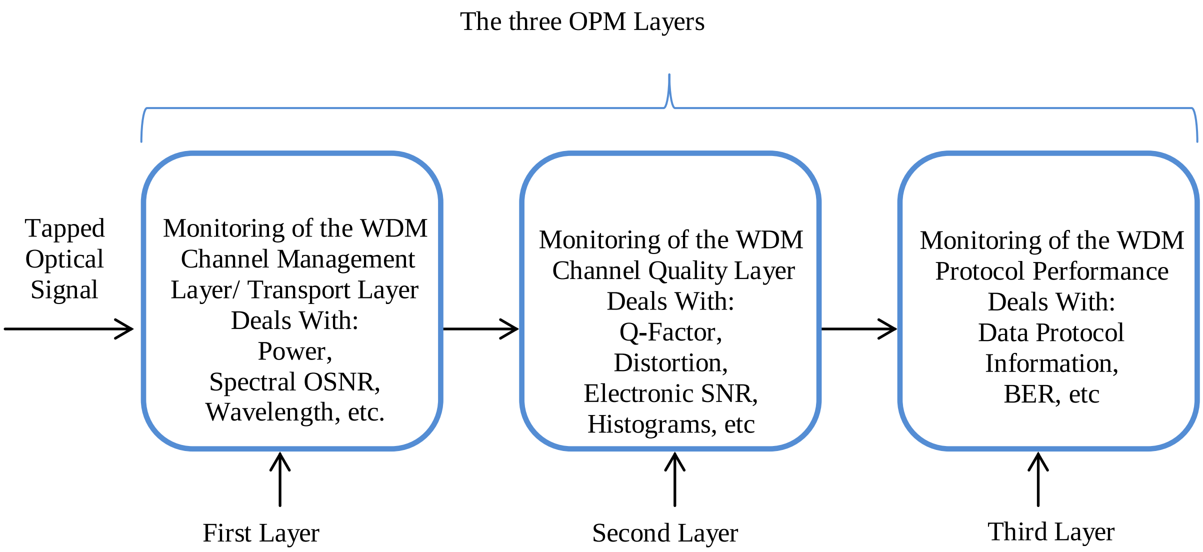

Figure 1: The OPM Reference Model [2]

More attention is given to the Q-factor consideration in the second layer since it is related to the BER [2, 5]. Though most monitoring options are focussed on monitoring one impairment at a time, multiple parameter physical-layer monitoring is achievable as suggested in [5] for OSNR and PMD monitoring using polarization-assisted techniques, PMD and GVD monitoring using enhanced RF power analysis/eye pattern analysis and wavelength, power, and path monitoring using frequency-modulated pilot tones [5]. In the physical layer, measurement of the average power, V-Curve (Q factor)/Bit error rate (BER), Chromatic dispersion, Eye diagram, Amplitude histograms, Optical spectrum, Amplitude power spectrum and the Pulse/Bit Shape can be made for OPM [6, 7]

III. OPTICAL SAMPLING

Optical sampling can be described as a process in which samples of an optical signal are tapped from the communication link and transferred to a monitoring system (e.g. BER monitoring system) where they are observed and processed [7,8]. Optical sampling can be employed for various tasks such as waveform description. From this waveform description, histograms can be obtained; through which the BER can be estimated. Note that electrical and optical sampling techniques gives similar result but the former has some shortcomings like limited bandwidth (i.e. cannot handle very high speed communication). This limited bandwidth causes ringing due to its inability to match the impedance. This shortcoming is absent in an all-optical sampling system which has the capability of handling wider bandwidths without unfavourable resultant effects. Optical sampling is required basically because electronic sampling of information signals becomes costly (or even unattainable) at very high bit rates thereby making is almost impossible for any form of electrical measurement [9]. At these high bit rates, amplitude histograms (i.e. generated from optical sampling) can be used to estimate the BER of an optical signal contaminated by ASE noise [7, 10]. Amplitude histograms can be obtained from optical sampling which can either be synchronous or asynchronous [11]. The asynchronous all-optical sampling technique does not depend on the bit-rate and electronic clock recovery is not necessary. Nevertheless, it has the shortcoming of having some forms of inaccuracy and defects since the sampled data has to transit between the sampled 1’s and 0’s [12]. For the synchronous all-optical sampling technique, it is possible for the CD and PMD to be measured, processed and interpreted. It is dependent on the system bit rate in contrast to the asynchronous all-optical sampling technique [3, 13].

3.1 Amplitude Histograms and Statistical Moments

Figure 2 shows a description of possible amplitude histograms that can be obtained from optical sampling;

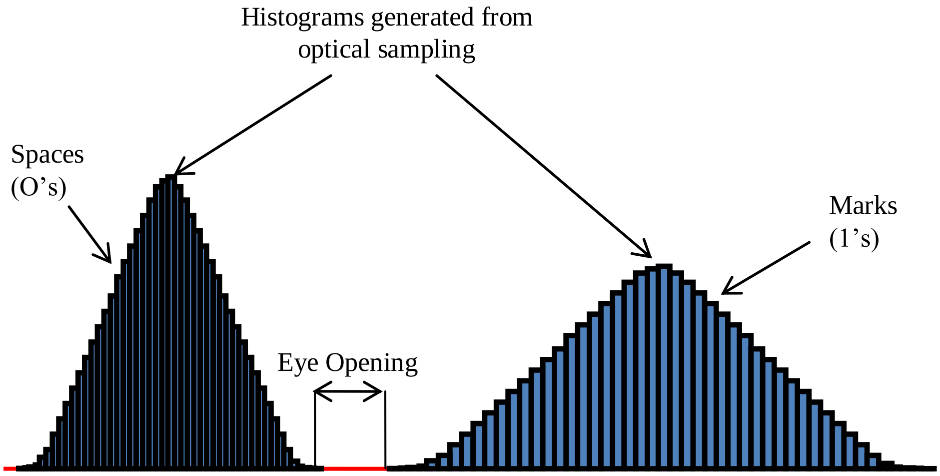

Figure 2: A description of possible amplitude histograms that can be obtained from optical sampling

The BER can be evaluated from amplitude histograms which are generated from random samples [13]. Definitive information about the tails of amplitude histograms cannot be directly obtained but statistical moments obtained from the histograms can be used to estimate an approximation of the probability distributions. The approximation can then be used to estimate the BER [13, 14].

IV. RECEIVER MODELLING FOR BER IN THE PRESENCE OF ASE NOISE

An optical receiver is designed such that it photodetects and demodulates the optical signal with an acceptable BER. In an optical receiver, the optical signal (including ASE noise and crosstalk) can be filtered optically to reduce the amount of the ASE noise and crosstalk. After the filtering, it is photodetected, amplified and filtered electrically. The output is then transferred to the decision circuit where a decision threshold is used to determine the transmitted bits. In most cases, a phase lock loop (PLL) is employed in a continuous mode receiver. Note that an AC coupled receiver is frequently used and in instances where the ASE noise gets too much, an offset circuit is required [15].

4.1 Gaussian Approximation

The Gaussian approximation (GA) is considered in this section. The first part deals with the design/modelling of the approximation from system parameters while the second part deals with how it is monitored by employing amplitude histograms.

4.1.1 Design/Modelling from System Parameters

The BER (i.e. assuming no other impairment is accounted for apart from ASE noise) can then be estimated using the GA. The BER (i.e. considering the probability density function's (pdf's) for the 1's and 0's) is shown below [15];

$$
\begin{aligned}
BER &= P(1|0)P(0) + P(0|1)P(1) \\
&= \frac{1}{2}\left\{\frac{1}{2}\operatorname{erfc}\left(\frac{i_D - i_0}{\sigma_0\sqrt{2}}\right) + \frac{1}{2}\operatorname{erfc}\left(\frac{i_1 - i_D}{\sigma_1\sqrt{2}}\right)\right\}
\end{aligned} \qquad (1)
$$

where P (1|0) = Probability of receiving a "1" when a "O" is transmitted, P (0) = Probability of transmitting a "0", P (0|1) = Probability of receiving a "0" when a "1" is transmitted, P (1) = Probability of transmitting a "1", erfc () = is used for Gaussian statistics to estimate the area in the tail of a Gaussian distribution, i_D = decision threshold, σ_0^2 and σ_1^2 denote the variances for 0 and 1 and i_0 and i_1 denote the noise free currents for the transmitted "0" and "1" [15, 16]. At the sampling particular moment, if the value of the current falls below the decision threshold, a zero is received and when it falls above it, a one is received. Also, an 'optimal' threshold exists and it is given as;

$$
i_{Dopt} = \frac{\sigma_1 i_0 + \sigma_0 i_1}{\sigma_1 + \sigma_0} \qquad (2)
$$

This 'optimal' decision threshold traditionally gives the lowest BER value and with the threshold, the BER can be expressed for low values and high values of Q respectively as;

$$BER = \frac{1}{2}\,\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right) \quad (3)$$

Where $$Q = \frac{i_1 - i_0}{\sigma_1 + \sigma_0} \quad (4)$$

Conventionally, to get a BER of 10^{-9} (i.e. appropriate for lab experiment use), the Q value must be approximately 6 and it must be approximately 7 (i.e. specifically 7.034) to get a BER of 10^{-12} (i.e. appropriate for commercial purposes) [15]. When the responsivity is multiplied by the power in a "1", the current in a "1" is obtained and when the responsivity is multiplied by the power in a "0", the current in a "0" is obtained. The ratio of the power in a "1" to the power in a "0" is the extinction ratio(i.e. $r = P_1/P_0$). The current in a "1" and "0" is given as;

$$i_1 = RP_1 = \frac{2r}{r+1}RP_{av} \quad (5)$$

$$i_0 = RP_0 = \frac{2}{r+1}RP_{av} \quad (6)$$

The noise current standard deviation can be obtained by summing respective individual noise constituents is given for the 1's and 0's respectively as;

$$\sigma_1 = \sqrt{\sigma_{s1-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{sh,1}^2 + \sigma_{th}^2} \quad (7)$$

$$\sigma_0 = \sqrt{\sigma_{s0-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{sh,0}^2 + \sigma_{th}^2} \quad (8)$$

Note that 's-sp', 'sp-sp', 'sh' and 'th' represents signal-spontaneous beat noise, spontaneous-spontaneous beat noise, shot noise and receiver thermal noise respectively [9]. The shot noise for the 1's and 0's respectively is given as;

$$\sigma_{sh,1}^2 = 2qR\left(P_1 + m_t N_0 B_{opt}\right)B_e \quad (9)$$

$$\sigma_{sh,0}^2 = 2qR\left(P_0 + m_t N_0 B_{opt}\right)B_e \quad (10)$$

where q represents the electronic charge, m_t represents the number of polarisation states, N_0 is the single polarisation state ASE power spectral density (ASE PSD), B_{opt} is the optical bandwidth and B_e is the electrical bandwidth [15]. The signal-spontaneous beat noise for the 1's and 0's respectively is given by;

$$\sigma_{s1-sp}^2 = 4R^2 P_1 N_0 B_e \quad (11)$$

$$\sigma_{s0-sp}^2 = 4R^2 P_0 N_0 B_e \quad (12)$$

and the spontaneous-spontaneous beat noise is also given as;

$$\sigma_{sp-sp}^2 = 2m_t R^2 N_0^2 B_{opt} B_e\left(1 - \frac{B_e}{2B_{opt}}\right) \quad (13)$$

4.1.2 Monitoring by employing amplitude histograms

Amplitude histograms can be employed in estimating the BER by assuming the GA. In this case, the cumulative distribution function (cdf); obtained by integrating the area under the pdf curve (area must be one) is interpolated with samples of the optical stream (i.e. random numbers as employed in this project) to generate amplitude histograms. Moments can then be obtained from the histograms. Note that for the GA, only the first two moments (e.g. mean and variance) are required. This process is carried out separately for the 1's and 0's. The formulas for estimating the first two moments from amplitude histograms are shown below;

$$\text{Mean}, \mu = \frac{1}{n}\sum_{i=1}^{n} f_i x_i \quad (14)$$

$$\text{Variance}, \sigma^2 = \frac{1}{n}\sum_{i=1}^{n} f_i (x_i - \mu)^2 \quad (15)$$

where n refers to the number of samples, f_i refers to the frequency (number of samples) in i'th bin, and x_i refers to the i'th bin mark. The standard deviation can be obtained from the variance as shown below;

$$\text{Standard Deviation}, \sigma = \sqrt{\text{Variance}} = \sqrt{\sigma^2} \quad (16)$$

After the first two moments have been obtained for the 1's and 0's, the Q factor is then calculated by employing the equations (3) and (4).

4.1.3 Limitation of the Gaussian Approximation

Although the GA is acceptable, it becomes less effective when the optimum threshold required at the decision circuit is to be determined. In fact, the pdfs of the binary signals contaminated by the beat noise (i.e. signal-spontaneous and spontaneous-spontaneous beat noises) introduced by the ASE produced by the EDFA have been established to be non-Gaussian. The signal-spontaneous beat noises have been theoretically established to be Gaussian but when an input signal is present, the EDFA's observed output is a combination ofsignal-spontaneous and spontaneous-spontaneous beat noises. Due to this reason, the pdf is determined on the basis of the combined beat noises (i.e. since it is the observed output) and not the signal-spontaneous beat noise alone. Due to this understanding and considering the fact that there is no definite confirmation of this non-Gaussian attribute, a correlation of real system pdf's with theoretical Gaussian and non-Gaussian pdf's was carried out to establish the non-Gaussian attribute of the real system by Chan and Conradi. It was then established that real systems are non-Gaussian [15, 16, 17].

4.2 NCCS Distribution

In the NCCS distribution approach, the BER is first evaluated from system parameters before it is estimated from experimental amplitude histograms. Note that monitoring (BER estimation from amplitude histograms) with the NCCS distribution approach follows the same procedure as in the GA approach. Marcuse and Azizoglu in [18] derived theoretical expressions for the mean and the variance of a non-central chi square distribution as shown below;

$$\text{Mean}, \mu = MN_o + E = Mm_tN_oB_e + P_1 \quad (17)$$

$$\text{Variance}, \sigma^2 = MN_o^2 + 2EN_o = Mm_tN_o^2B_e^2 + 2P_1N_0B_e \quad (18)$$

Theoretical expressions (i.e. employing the non-central chi square distribution) have been formulated by Marcuse and Azizoglu in [18] for the pdfs of signal-spontaneous and spontaneous-spontaneous beat noises for the "1"s and "0"s. These pdf's were analysed and modified in Chan and Conradi [17] for the 1's and 0's respectively as;

$$f_1(y) = \frac{1}{(\frac{P_{ASE}B_e}{m_t\ B_o})}\left(\frac{x}{P_1}\right)^{\frac{Mm_t-1}{2}}.\exp\left(-\frac{x+P_1}{\left(\frac{P_{ASE}B_e}{m_t\ B_o}\right)}\right)I_{Mm_t-1}\left(\frac{2\sqrt{xP_1}}{\left(\frac{P_{ASE}B_e}{m_t\ B_o}\right)}\right) \quad (19)$$

$$f_0(y) = \frac{1}{(\frac{P_{ASE}B_e}{m_t\ B_o})}\left(\frac{x}{P_0}\right)^{\frac{Mm_t-1}{2}}.\exp\left(-\frac{x+P_0}{\left(\frac{P_{ASE}B_e}{m_t\ B_o}\right)}\right)I_{Mm_t-1}\left(\frac{2\sqrt{xP_0}}{\left(\frac{P_{ASE}B_e}{m_t\ B_o}\right)}\right) \quad (20)$$

where $f_1(y)$ and $f_0(y)$ refers to the pdf's for the 1's and 0's respectively over the interval x, $m_t = 1$ or2 depending on the state of polarisation, P_{ASE} refers to ASE power,B_e refers to the electrical bandwidth,B_o refers to the optical bandwidth and G refers to the gain of the amplifier, where P_1 and P_0 represents the EDFA's input signal power for transmitted 1's and 0's respectively [17] and;

$$P_{ASE} = m_tN_{sp}hv(G-1)B_o \quad (21)$$

where G represents the EDFA gain, m_t represents the observed degree of polarisation and can either be 1 or 2, $I_{Mm_t-1}(.)$ represents the modified Bessel function where $Mm_t - 1$ denotes the order, $B_e = \frac{1}{T}$, T represents the symbol time, B_o represents the double sided corresponding bandwidth of the noise and $M = \frac{B_o}{B_e}$ [18].

V. RESULTS AND DISCUSSION

This section shows the results obtained from the mathematical/computational analysis**.** Table 1 shows some standard parameters employed in the computations. These values were obtained from [9]. Other useful parameters not included in Table 1 are given in the discussion.

Table 1: Standard parameters used for the simulation

Parameters	Values
Optical Bandpass Filter Bandwidth (B_o)	B_e * M
Electrical noise Bandwidth (B_e)	R_b * 0.5
Bit Rate (R_b)	10×10^{-9}Gb/s
OSNR Bandwidth (B_{OSNR})	1.25×10^{10}GHz
Electric Charge (q)	1.60×10^{-19}C
Quantum Efficiency (η)	0.9
Signal Wavelength (λ)	1.55μm

5.1.1 PIN photodiode based receiver

For the PIN photodiode based receiver considered, the noise is predominantly thermal noise and it is assumed to be Gaussian and signal independent. Figure 3 shows the relationship between BER and the average signal power.

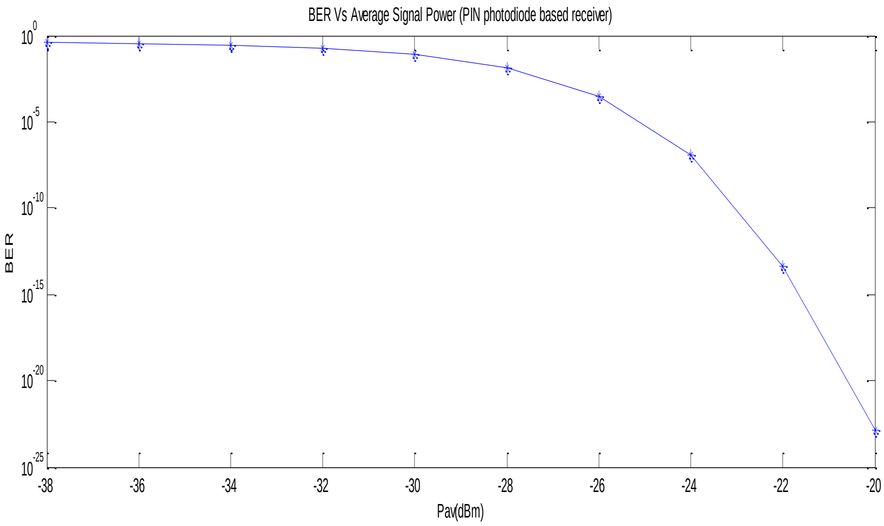

Figure 3: BER vs Signal Power (Noise predominantly thermal noise)

Figure 3 shows a plot of BER curves for the different input power and constant OSNR. As shown in the figure, for a fixed OSNR, the BER values will gradually decrease with an increase in input power.

5.1.2 Optically preamplified receiver design (assuming Gaussian Approximation)

Given that signal power, P = -36dBm, extinction ratio, r = 10dB, OSNR = 12.78dB, mean, μ = $4.5671 \times 10^{-07}$and 4.5671×10^{-08}, standard deviation, σ = 4.2309×10^{-08} and 1.6308×10^{-08} for the transmitted 1's and 0's respectively. Note that in the GA, the transmitted power is used as the mean. The pdfs of the transmitted 1's and 0's are then obtained by using system parameters as shown in figure 4.

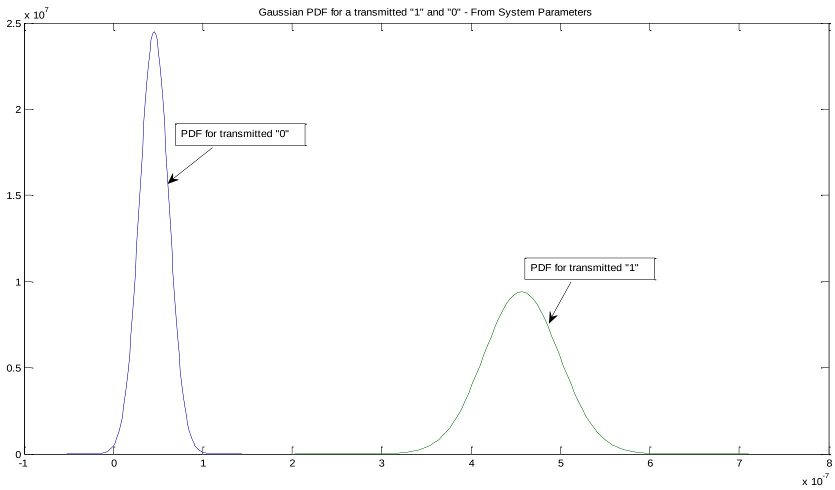

Figure 4: Gaussian PDFs for a transmitted "1" and "0"

By employing equations (3) and (4) and the parameters given above, a theoretical BER of 2.8663×10^{-10} is obtained for the GA.

5.1.3 Optically preamplified receiver design (assuming NCCS distribution)

In the GA pdfs, BER models were produced with an initial knowledge of the first two moments (mean and variance). For the NCCS distribution, the means and standard deviations for the transmitted 1's and 0's have to be estimated from the pdf. Given that signal power, P = -36dBm, extinction ratio, r = 10dB and OSNR = 18.9419dB. The pdfs of the transmitted 1's and 0's are then obtained by using system parameters as shown in figure 5.

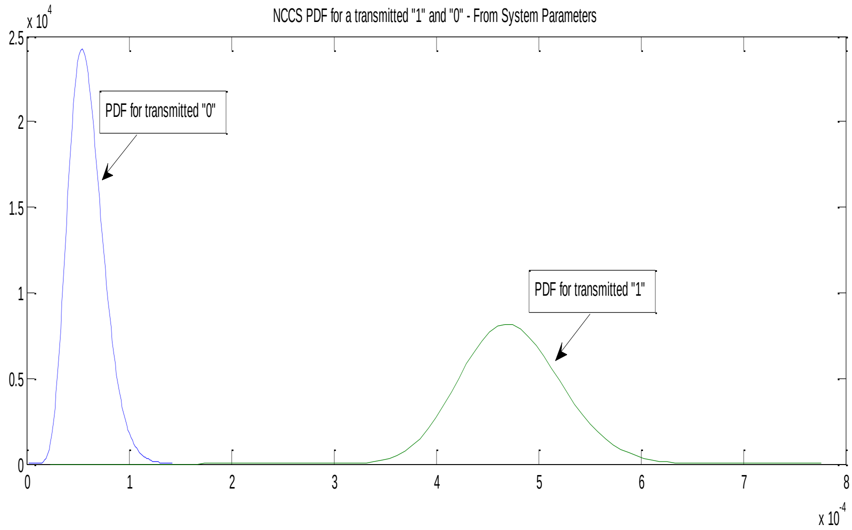

Figure 5: NCCS PDFs for a transmitted "1" and"0"

The theoretical means and variances can be obtained by employing equations (17) and (18). These means and variances can then be employed in estimating the BER is a theoretical BER of 1.3377×10^{-10} is obtained for the NCCS distribution. The BER obtained from the NCCS distribution is different from that obtained from the GA as established by Chan and Conradi in [17].

5.2 Generation of experimental amplitude histograms

As earlier stated, amplitude histograms are obtained from random numbers (which represent the optical stream). This random numbers are interpolated with the cdf of the distribution obtained by integrating the area under the pdf curve over a specified interval. For the histogram generation, 100 random samples are employed unless otherwise stated.

5.2.1 Generating histograms by assuming the NCCS distribution

The NCCS distribution is employed and experimental amplitude histograms are generated for the transmitted 1's and 0's as shown in figure as shown in figures 6.

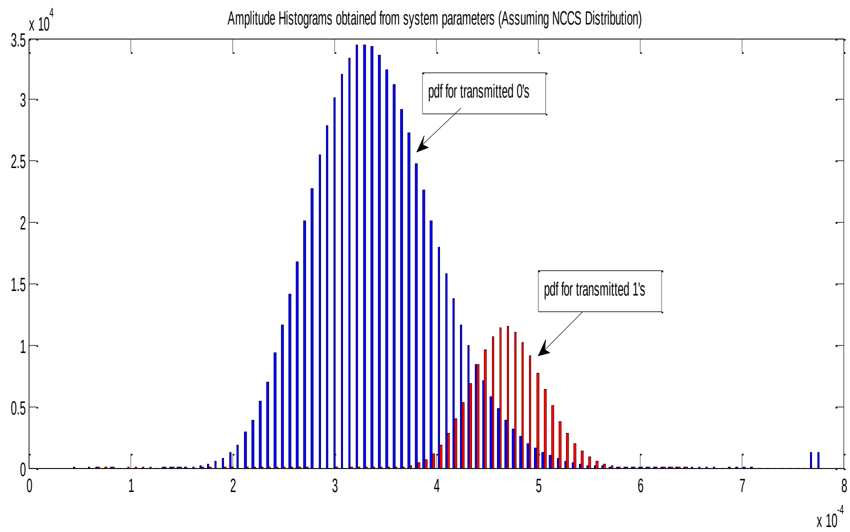

Figure 6: NCCS PDFs for a transmitted "1" and "0" obtained from amplitude histograms

5.2.2 Extracting statistical moments from amplitude histograms

Moments are extracted from experimental histograms as discussed in section 4.1.2. The NCCS distribution only employs the first two moments. The equations used in the determination of these moments are shown below

$$\text{First moment (Mean)}, \mu = E(X) \quad (22)$$

$$\text{Second moment (Variance)}, \sigma^2 = E(X-\mu)^2 \quad (23)$$

5.3 Comparison of the means and variances for Gaussian approximation and the NCCS distribution

Now from the NCCS distribution and considering the amplitude histograms in figure 6, the first two moments is obtained. Given that signal power, P = -36dBm, extinction ratio, r = 10dB and OSNR = 18.9419dB. The means for the transmitted 1's are 0's are given as 5.6956×10^{-04} and 5.8822×10^{-05} respectively and the variances for the transmitted 1's and 0's are given as 2.4266×10^{-09} and 3.1811×10^{-10} respectively. These values are different from the value obtained from the GA thereby confirming the work of Chan and Conradi where it was established that real optical systems are not Gaussian.

5.4 Estimating BER assuming samples

The BER of the system is estimated by taking the extracted statistical moments obtained from the NCCS distribution and employing it for the GA. The number of samples needed to give an acceptable measure of the BER is also estimated.

5.4.1 BER estimation assuming Gaussian approximation

In figures 7, 8, 9 and 10, different numbers of samples are employed to investigate how the BER may be estimated assuming the GA. After replacing the first two moments of the GA with the ones obtained from the amplitude histograms (i.e. from NCCS distribution) and employing equations (4) and (5), the BER can be obtained.

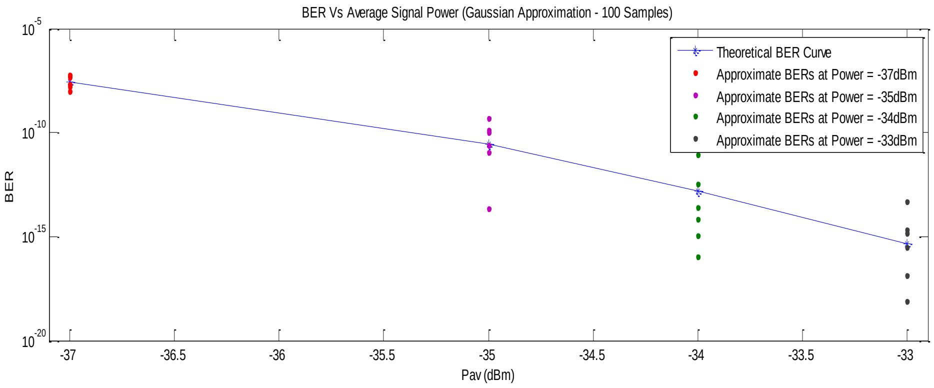

Figure 6: BER vs average signal power for the GA, G=30dB, r=10dB, 100 samples

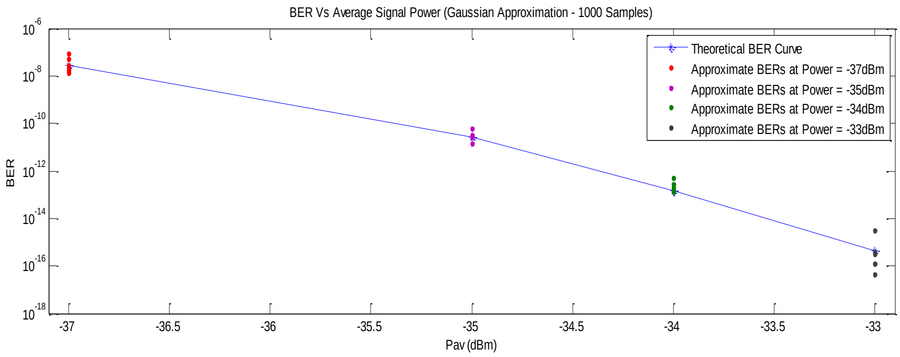

Figure 8: BER vs average signal power for the GA, G=30dB, r=10dB, 1000 samples

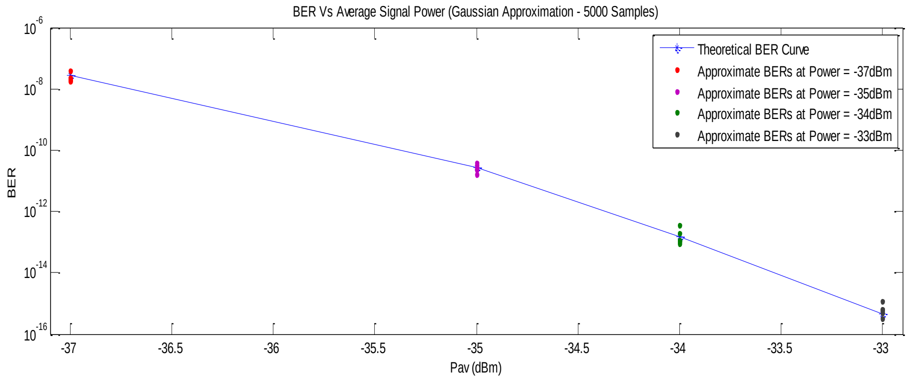

Figure 9: BER Vs average signal power for the GA, G=30dB, r=10dB, 5000 samples

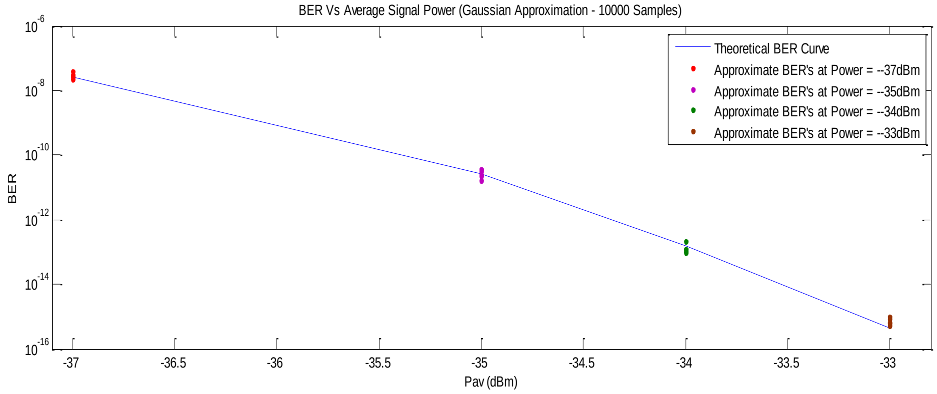

Figure 10: BER Vs average signal power for the GA, G=30dB, r=10dB, 10000 samples

In figures 7, 8, 9 and 10, the theoretical BERs were plotted against different average power values. For each average power value, simulation were repeated 6 times and various approximate BERs were obtained for each theoretical BER. A spread of these approximate BERs around the theoretical BER is noticed. Note that if the approximate BER spreads are far from the theoretical BER or sparsely distributed as noticed in figure 7, the system's performance is deemed low. A closely packed BER spread denotes acceptable system performance and it can be used to determine the acceptable number of samples. The 100 samples employed in figure 7 is not acceptable considering how far way the approximate BERs are from the theoretical BER. This spread gets close when 5000 samples (Figure 9) were employed and even closer when the numbers of samples were increased to 10000 (Figure 10). Therefore for the GA, 10000 samples are enough to get an acceptable measure of the BER. Conclusively, though more samples gives better performance, the number of samples employed should be kept at a reasonable minimum so as to reduce processing time and cost. Therefore, the least number of samples that just give an acceptable BER should be employed in an optical fibre communication system.

5.4.2 BER estimation assuming NCCS distribution

In figures 11, 12, 13 and 14, different numbers of samples are employed to investigate how the BER may be estimated assuming the NCCF distribution.

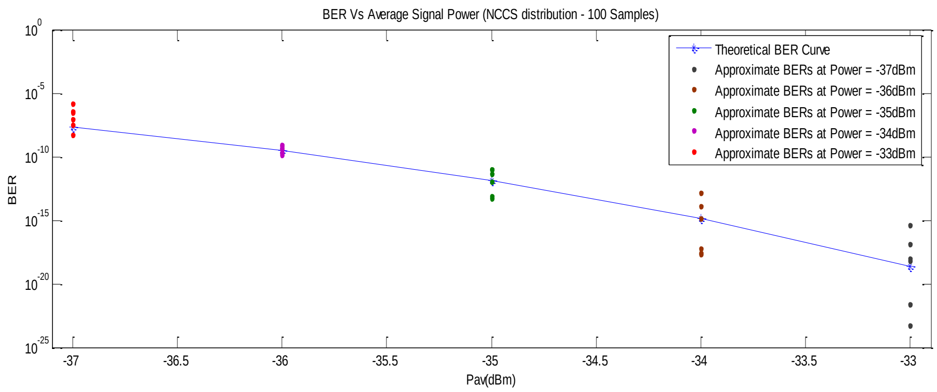

Figure 11: BER Vs average signal power for the NCCS Distribution, G=30dB, r=10dB, 100 samples

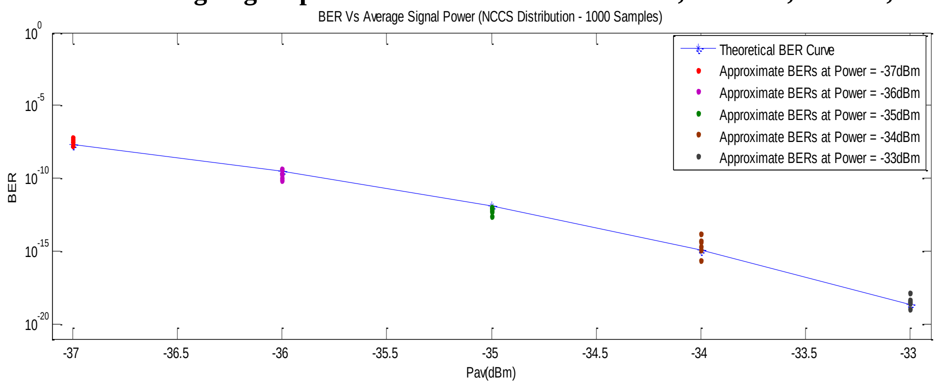

Figure 12: BER Vs average signal power for the NCCS Distribution, G=30dB, r=10dB, 1000 samples

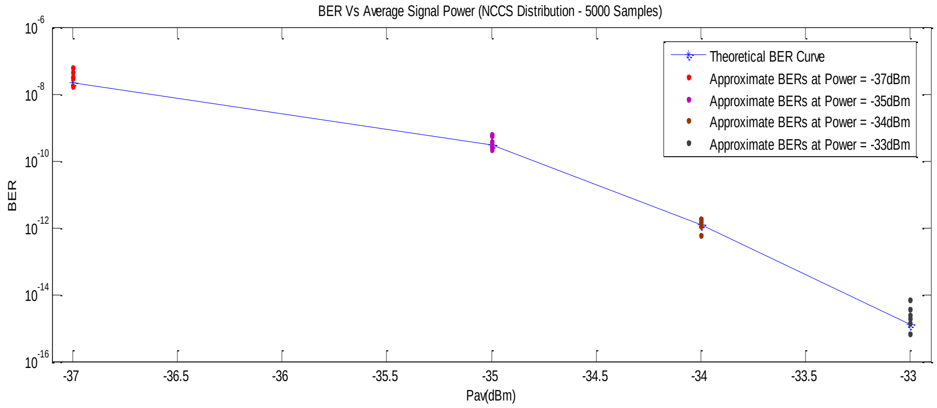

Figure 13: BER Vs average signal power for the NCCS Distribution, G=30dB, r=10dB, 5000 samples

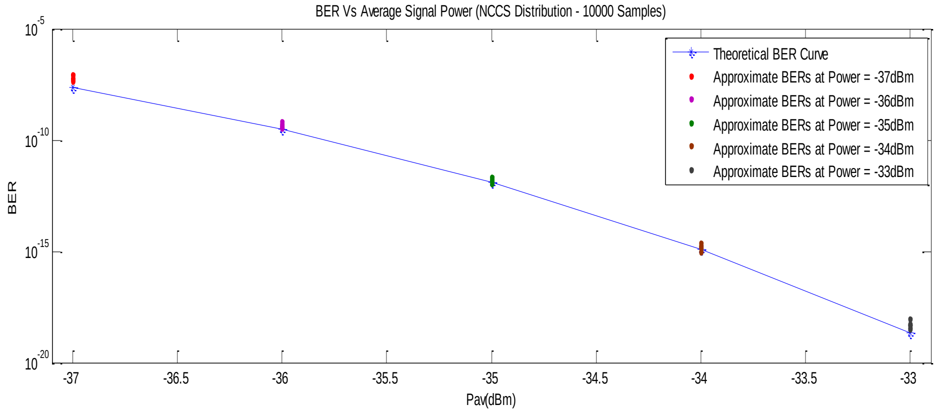

Figure 14: BER Vs average signal power for the NCCS Distribution, G=30dB, r=10dB, 10000 samples

In figures 11, 12, 13 and 14, the theoretical BERs were plotted against different average power values for the NCCS distribution. For each average power value, simulations were repeated several times and several approximate BERs were obtained for each theoretical BER in the same way as the GA. It is also noticed that as the number of samples increases, the approximate BER values move closer to the theoretical value. 10000 samples (i.e. Figure 14) are also enough to give an acceptable measure of the BER.

VI. CONCLUSION

In this paper, the GA and NCCS statistical approaches were employed in the performance monitoring of an optical fibre communication system. It was observed that even though the GA gives a fair representation of the system, the system is non-Gaussian. The NCCS distribution was observed to give a more accurate representation of the optical channel. It has also been shown that as the average signal power increases, the BER improves as well. After running simulations for different number of samples, it was also observed that as the number of samples increases, the BER estimations become more acceptable. However, there has to be a trade-off between cost and performance since it would be expensive to employ too many samples. It is therefore safe to employ the number of samples that just gives an acceptable measure of the BER.

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