Channel Error Estimation in Next Generation Optical Networks

STAMATIOS V. KARTALOPOULOS
Williams Professor in Telecommunications Networking
ECE Department, TCOM graduate program
The University of Oklahoma
4502 E. 41st Street, Tulsa, OK 74135, USA

Abstract: - The next generation optical network demands unprecedented performance due to ultra-high aggregate bandwidth and the many channels transported by a single fiber. In dense wavelength division multiplexing (DWDM) networks, optical channels travel for hundreds of kilometers and thus they suffer from attenuation, noise, jitter, dispersion and other degradations due to photon-matter interactions. Among the well-established link layer performance parameters that determine channel performance are bit error rate (BER), Q-factor, received signal power and signal to noise ratio (SNR). To date, BER and signal power are the only two parameters that are monitored in-service using error detected codes (EDC) and signal power meters, respectively. However, typical EDC codes have a limited error detection capability and require several information frames (or packets) to estimate BER and thus they are time consuming. In this paper we present a statistical estimation method, which in short intervals and in-service estimates BER, SNR, Q-factor and average power at each optical channel. Our method lends itself to VLSI implementation to estimate in real-time the aforementioned performance parameters so that proactive.

Key-Words: - Optical channel performance estimation, Optical Noise, BER

1 Introduction

Noise in communications channels is generated by many mechanisms. However, what is important is the relative amount of power noise with respect to the power of signal, or signal-to-noise ratio (SNR) [1-3]. Noise can be electrical (generated by electronic devices and by metal conductors) and optical (generated by photon-matter linear and nonlinear interactions, impurities and imperfections). Cross-talk, dispersion, polarization dispersion loss, four-wave-mixing, cross-phase modulation, modulation instability and inter-symbol interference, are among the noise sources as a result of photon-matter and photon-photon interactions in fiber communications [4]. In addition to these degradations, jitter and wander is generated by laser chirp and by optical amplifiers that further degrade channel performance.

In general, the quality of signal impacts both service and network. For example, quality of service, link length, service protection, channel re-assignment, bandwidth utilization, traffic balancing, topology, network reliability, cost, and more all are related to quality of signal and channel performance. BER, Q-factor, and SNR are three key channel performance parameters, a good estimation of which accurately defines whether the channel and the link perform as expected. Although sophisticated error detecting and correcting (EDC) codes monitor each signal, EDCs have a limited error detection capability, require several frames (or packets) and thus long intervals to estimate and act promptly whenever severe degradation is encountered.

In this paper, we present an estimation methodology that automatically and continuously estimates channel BER, SNR, and Q-factor at the receiver without service interruption. Our method is based on statistical sampling and estimates are made in very short intervals (as short as a single packet at ultra-high bit rate) and proactive remediation action may be initiated before the degradation becomes severe. We also discuss implementation of a VLSI circuit to estimate these performance parameters.

2 Bit error rate

The data signal in its evolutionary travel through the fiber arrives at the receiver contaminated with all degrading contributors. Let the contributing noise variances be:
\[ \sigma^2_{\text{ampl}} = 4R^2 \rho_{\text{ASE}} B \] (for optical amplifier ASE),
\[ \sigma^2_{\text{RCVR}} = 4kTB/R_L \] (for receiver),
\[ \sigma^2_{\text{dark}} = 2e_i B \] (for dark current),
\[ \sigma^2_{\text{filter}} = 4gR^2 \rho_{\text{ASE}}^2 B^2 \] (for filter), and
\[ \sigma^2_{\text{RIN}} = 4gR^2 \rho_{\text{RIN}} B \] (for relative intensity noise),

where \( \rho_{\text{ASE}} \) is the spectral density of optical amplifier ASE, \( g \) is the ratio \( \Delta \nu/B \), \( \Delta \nu \) is the optical filter bandwidth, \( B \) is the receiver bandwidth, and \( n_{\text{RIN}} \) is the relative intensity noise (RIN) factor. Then, the variance of the noise current per bit at the output of the receiver is:

\[ \sigma^2_{\text{N,photon}} = 2(\eta P_R/h\nu)^2 \sigma^2_T \]

where \( h \) is the Planck’s constant, \( \nu \) is the frequency, \( P_R \) is the incident power per bit, and \( \sigma_T \) is the total variance of all contributing photonic and electronic noise variances, \( \sigma^2_T = \sum \sigma^2_i \).

The SNR is the ratio of the mean square value of the generated current by the receiver to the total noise variance in the photocurrent. In this case, the target SNR, based on a minimum power and minimum number of photons required to detect a “1” bit (of a period \( \tau_c \)), may be approximated by:

\[ \text{SNR} = (\eta P_R/h\nu)^2 / \left[ (e^2 \eta P_R/h\nu + e_i + 2kT/R_L)B + (\eta P_R/h\nu)^2 \sigma^2_{\text{N,ph}} + (\eta P_R/h\nu)^2 \tau_c B \right] \]

Finally, if the receiver has a trans-impedance amplifier (TIA), then the power spectral density of the TIA input noise is:

\[ \text{psd}_{\text{TIA}} = (I_v/R)^2/2n_{\text{TIA}} \]

where \( I_v \) is the input referred noise current of the TIA, the factor 2 appears because of the two sided spectral density, and \( n_{\text{TIA}} \) is the noise bandwidth of the TIA defined as

\[ n_{\text{TIA}} = (1/2\pi)S|\text{Fo}(\omega)|^2d\omega, \]

where the integral \( S \) is from 0 to infinity.

As a result of noise and jitter, the signal is degraded such that some logic “1” or “0” are corrupted and they are read as logic “0” or “1”, respectively. However, a received bit in error is a random process and therefore it is treated with probabilities and statistics. Typically, the estimated probability for error is denoted as \( P'(\varepsilon) \), and when the sample is large, then the estimate is almost equal to the actual. In communication channels, an upper limit of \( P'(\varepsilon) \) is set to a specified level \( \gamma \), \( \gamma = 10^N \), where \( N \) may vary from 6 to 24, depending on application. If errors are considered to be Poisson random, and for a very large sample, the probability that \( N \) or more errors will occur in \( n \) transmitted bits is expressed by

\[ \Sigma P_n(k) = \sum (np)^k/k! e^{-np}, \]

where the sum is calculated from \( k = N+1 \) to \( n \), and we have used \( p^k/n^k = (np)^k/k! e^{-np} \).

### 3 Estimation of BER, Q and SNR

A qualitative measure of the quality and integrity of the received signal is the “eye-diagram” [5-9], which reveals on the aggregate all characteristics of the signal such as jitter, rise and fall time, ringing, side-tones, asymmetry (skew and kurtosis), overshoot and undershoot, and amplitude tilt, Figure 1.

![Eye-diagrams](image)

**Figure 1: Eye-diagrams**

Based on the expected pulse distortion, a minimum current threshold for a logic 1, \( I_{1,\text{min}} \), and a maximum current threshold for a logic 0, \( I_{0,\text{max}} \) are determined as well as the sampling point between 0.5T and 0.6T (to account for jitter), Then, the eye opening is defined as \( E_{\text{eye}} = I_{1,\text{min}} - I_{0,\text{max}} \).

Noise and jitter are random effects, most likely with a Gaussian distribution. If the standard deviation for logic “1” is \( \sigma_1 \) and for logic “0” is \( \sigma_0 \), their corresponding average values are \( \mu_1 \) and \( \mu_0 \), then the quality factor or Q-factor is defined as

\[ Q = E_{\text{eye}} / \sqrt{\text{var}(\sigma_0^2 - \sigma_1^2)} = |\mu_1 - \mu_0| / (\sigma_1 + \sigma_0). \]

In addition, the bit error rate (BER) is defined as

\[ \text{BER} = \frac{1}{2} \text{erfc} \left( \frac{Q}{\text{sqrt}(2)} \right), \quad \text{or} \quad \text{BER} = \left( \exp(-Q^2/2) / \left( \text{Q sqrt}(2\pi) \right) \right). \]
If the sum of all degrading factors act on the signal, then from the maximum peak-to-peak eye, \( E_{\text{max}} \), and the eye opening, \( E_{\text{eye}} \), the signal degradation is expressed as

\[
\Delta S/N = 20 \log \left[ \frac{E_{\text{max}}}{E_{\text{eye}}} \right].
\]

Based on the eye-diagram and assuming that \( E_{\text{max}} \) corresponds to the received signal plus noise \( (E_S + E_N) \), and also that \( E_{\text{eye}} \) corresponds to signal minus noise \( (E_S - E_N) \), then the signal to noise ratio relation is derived as (where \( \rho^* = \frac{E_{\text{max}}}{E_{\text{eye}}} \)),

\[
\text{SNR} = \frac{E_S}{E_N} = \left( \frac{\rho^* + 1}{\rho^* - 1} \right).
\]

### 4 Error estimation from sampled pulses

The aforementioned statistical relationships may be used to estimate performance parameters from sampling received pulses. To accomplish this, each bit period at the receiver is sampled and sample values above a threshold are recorded as “one” and below it as “zero”. These samples are grouped and stored in memory locations from where the sample frequency of occurrence per group establishes a virtual histogram, Figure 2. From this histogram, the statistical parameters \( \mu, \sigma^2 \) and \( \sigma, I_{1\text{,min}}, I_{0\text{,max}}, E_{\text{eye}}, \) and \( E_{\text{max}} \) are calculated.

\[ E_{\text{eye}} = (E_{1\text{,mean}} - k_1\sigma_1) - (E_{0\text{,mean}} + k_0\sigma_0), \]

where \( k_0 = 1, 2, \) or \( 3 \), and \( E_{0\text{,mean}} \) is the mean value for logic “0”. In addition, from the estimated peak value \( V_p \) and \( \text{BER} \), the standard deviation of noise is calculated from

\[
\text{BER} = \frac{1}{2} \{ 1 - \text{erf}(V_p/[2\sigma_n \sqrt{2}]) \}.
\]

Finally, from the measured input power, from the noise characteristics at the receiver, and the estimated SNR value, the noise figure is calculated from

\[
\text{NF} = \Psi/k_{T_0}d/f_{\text{OSNR}}.
\]

The method described above lends itself to circuit integration. For example, sample and hold, analog to digital conversion, grouping and memory storing, frequency of occurrence calculation, and virtual histograms from which \( \sigma, \mu, Q, \text{BER}, \text{SNR} \), and other parameters are calculated are all well-established functions that can be implemented with integrated circuits and/or algorithms (firmware/software). The detail description of such implementation is the subject of another publication. However, in this paper it is important to demonstrate the performance of the method.

### 6 Performance of the BER estimation method

Optical channels typically transport data at 2.5, 10 or 40 Gbps. Because of the statistical nature of the method, few thousands samples will suffice. At 10 Gbps, 10,000 contiguous samples correspond to 1 \( \mu \)s interval only. However, 1 \( \mu \)s is an extremely short interval for most applications for which 1 msec would be sufficient. Thus, because errors are random, sampling may be taken one every 1000 bits. Thus, in 1 msec 10,000 samples are obtained to construct an uncompromised virtual histogram from which channel performance parameters, BER, Q, and SNR are calculated at lower execution speed.

### 7 Proactive channel reassignment during severe degradation

If we assume that each optical channel is monitored with the outlined BER statistical method. Assume also that there is a performance threshold below which the channel is declared severely degraded. Then, if the receiver is capable to
communicates to the transmitter the received performance parameters, as soon as the threshold is approached, the transmitter reassigns the channel to another that performs better so that service continues uninterrupted. We call this “proactive reassignment”.

8 Conclusion

In this paper, we presented an estimation methodology that automatically estimates channel BER, SNR, and the Q-factor at the receiver without service interruption. Our method is based on statistical sampling and therefore performance parameter estimates are made in very short intervals from virtual histograms. As a result, a proactive remediation action may be initiated before the degradation becomes severe. In addition, we have discussed methods for relaxing sampling so that parameter estimation may be automated with standard integrated circuits.

Further work is under way to automate the process of optimizing the channel assignment and re-assignment of optical channels. In addition, work continues on another front; analyze the histogram characteristics and identify and localize the degradation cause.

References: