NOISE IN FIBER OPTIC COMMUNICATION LINKS

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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 report the role of noise in optical communications, and how it can limit the performance of optical communications systems, will be examined. The origins of noise in the various optical and analog electronic components will be discussed, and a methodology for a "noise budget" will be proposed. The ramifications of 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. Many of the types of noise we will be dealing with may be approximated as "white" and/or "Gaussian," which permits mathematical simplification without any loss of rigor, to the extent that the approximations are valid. In keeping with the theme of this report, absolute optical power values, data rate, and frequency-dependent effects will not be discussed at length.

1. Introduction

Noise is defined as the deviation from an ideal signal, and is usually associated with random processes. By definition it corrupts the information content and fidelity of the signal, particularly at low levels. In our case, we will be dealing with voltage noise, current noise, and optical intensity noise. Noise can be classified in a number of ways.

- Intrinsic or Extrinsic – where does the noise come from?
- Random or Coherent – is the noise periodic, or correlated in any way with the signal?
- Additive or Multiplicative – how do various noise components contribute to the total?
- Stationary – is the noise statistic independent of time?
- Ergodic – does *m* samples from one device yield the same statistics as one sample each from *m* devices?

There are many more ways to classify noise, including more explicit descriptions such as the distribution functions. Exceptions to our definition of noise would be distortion due to limiting in electronics, nonlinear effects in the electro-optics, and interaction between laser chirp and fiber dispersion in general. These topics are outside the scope of this short report. It is assumed the reader is familiar with the standard deviation of a random probability distribution function (PDF), usually represented by the Greek letter sigma "σ." In the case of most noise types, the PDF is Gaussian, and σ (RMS) can be used to explicitly describe the Gaussian PDF.

2. BER, SNR, and Noise Budget

Before the different noise contributions are discussed, the overarching issues of bit-error- rate (BER) and how it relates to noise is discussed. Signal-to-noise ratio (SNR) and the concept of a noise budget are then introduced.

2.1 Bit-Error Ratio and the Q-Function

One of the major system-level requirements that drive the design of optical links is the bit-error-rate (BER). The worst-case BER of the physical layer (PHY) hardware will have ramifications upstream in the error correction, flow control, and ultimate performance of the system at the application level. If the native BER of the optical PHY is poor, no amount of gigabit transmission, forward-error correction, or other signal processing techniques will be helpful. The BER requirements of some example applications are summarized first two columns of the table below.

Optical Link Application	Max. PHY BER requirement	Minimum inferred Q requirement	Optical SNR $\sigma_0 = 0$ "shot noise limit" SNR = Q^2	Optical SNR $\sigma_0 = \sigma_1$ "thermal noise limit" SNR = $4Q^2$
Telecom	10^{-9}	6.00	36:1 (15.6 dB)	144:1 (21.6 dB)
Datacom	10^{-12}	7.05	50:1 (17.0 dB)	199:1 (23.0 dB)
Typical operation	$\sim10^{-15}$	7.95	63:1 (18.0 dB)	253:1 (24.0 dB)

It is easy to see that very small changes of the SNR (on the order of a dB) can cause very large changes in the BER, of three orders of magnitude. This is one of the reasons for the legendary touchiness of high-speed optical PHYs that are beyond the end-of-life or are operating at the limits of their specifications. The last row in the table is to illustrate the typical BER of an optical PHY that is operated with very short optical fiber, i.e. minimal loss and dispersion. At this BER, a gigabit link on the average of 1 error every 11.6 days, and presents difficulty to verify performance in a reasonable amount of time with confidence (enough errors recorded to yield meaningful statistics).

Assuming that there is equal probability of transmitting a "1" or a "0" the BER is defined as

BER = (½) Probability(0 detected, given 1 transmitted) + (½) Probability(1 detected, given 0 transmitted)

The BER can be expressed in terms of the dimensionless parameter Q parameter[1]

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \qquad \text{where} \qquad Q \equiv \frac{I_1 - I_0}{s_1 + s_0}$$

I_1 is the optical intensity and s_1 is the standard deviation of the optical noise PDF of at level "1," and I_2 and s_2 are for a "0" level. Now, implicit in the above equation are several assumptions: (i) on-off-keying is used, (ii) pulse-code modulation is used, (iii) there is equal probability of 1s and 0s to be transmitted, (iv) the PDFs are Gaussian, and (v) the decision threshold is optimally placed between the 1 and 0 average values. Unfortunately, there is not room to discuss these issues in detail and the practical issues in setting the optimum decision point. Values of Q corresponding to a given BER requirement are listed in the third column of the table.

2.2 Signal-to-Noise Ratio (SNR)

There is no universal definition of SNR, but for this report a convention will be adopted to for electrical and optical SNRs. The reason for this is to eliminate a common source of confusion, and to ultimately enable the addition of noise distributions from different sources on an apples-to-apples basis. The optical SNR (oSNR) and electrical SNR (eSNR) are defined as

$$oSNR \equiv \frac{Average\ Signal\ Power}{Optical\ Noise\ Power} = \frac{I_{optical\ signal}}{s_{optical\ signal}}$$

$$eSNR \equiv \frac{Average\ Signal\ Voltage}{RMS\ Noise\ Voltage} = \frac{V_{electrical\ signal}}{s_{electrical\ signal}}$$

An example of the eSNR would be with respect to the signal and noise at the input of the digital decision circuit (DDC). It is important to make a distinction between electrical and optical SNRs. To convert an eSNR to an oSNR-like value, the power-equivalent SNR value is calculated:

$$oSNR \equiv \frac{Average\ Signal\ Power}{Electrical\ Noise\ Power} = \frac{\left(V_{electrical\ signal}\right)^2}{\left(s_{electrical\ signal}\right)^2}$$

One must also be careful when making measurements where a voltage represents an optical signal. In this case

$$oSNR \equiv \frac{Average\ Signal\ Power}{Optical\ Noise\ Power} = \frac{\left(Voltage \propto I_{optical\ signal}\right)}{s_{voltage \propto optical\ signal}}$$

and it is a common mistake to square the denominator, using the variance instead of the RMS value.

2.3 Noise Limits

One fundamental design limit would be for the noise at the "0" level to be negligible compared to the noise at the "1" level. This would be for an ideal noiseless detector and is called the "shot noise limit" for reasons that will be made clear in a later section. It represents a formidable goal to which practical PHY designs can be compared to, and comparing the actual SNR to this value is a useful figures-of-merit in some applications. In this case, we can approximate $\sigma_0 = 0$ the relationship of BER to SNR becomes

$$Q \equiv \frac{I_1 - I_0}{s_1 + s_0} \cong \frac{I_1 - I_0}{s_1} = \frac{Voltage\ swing\ at\ DDC\ input}{Voltage\ noise\ at\ DDC\ input} = eSNR$$

because the DDC is an electronic device. Convert the eSNR to oSNR so it can be referred to the optical domain

$$oSNR = Q^2.$$

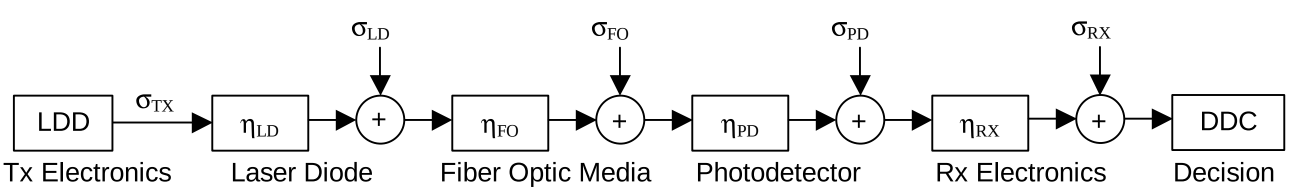
Another important case is when noise dominates the optical system, such that it is independent of the optical signal and $\sigma_0 = \sigma_1$. In this case,

$$oSNR = 4Q^2$$

and it is called the "thermal noise limit." Typical systems that do not suffer external impairments operate usually in between these two limits. Ratiometric and decibel values for these oSNRs are listed in the final two columns of the table.

2.4 Noise Budget

Below is a schematic of an optical PHY with the signal path going from left to right, showing the transmitter (TX) laser diode driver (LDD) electronics and its associated noise output σ_{TX}. Multiplicative scale factors appear in the boxes and additive noise terms are represented by the circles for the laser diode (LD), fiber optics (FO), photodetector (PD), and receiver electronics (RX). The end result is presented as a voltage to the input of the digital decision circuit (DDC).



h_{LD} is the laser diode slope efficiency in mW/mA, $h_{FO} = 10^{-0.1(dB\ Loss)}$ is the total attenuation of the fiber optic media, h_{PD} is the photodiode conversion efficiency in mA/mW, and h_{RX} is the preamplifier gain in V/A. All of the coupling coefficients and scale factors are lumped into these four constants, and their frequency dependence has been neglected, which is a major simplification.

With a few exceptions, all of the noise sources are assumed to be Gaussian. The sum of two or more Gaussian PDFs yields a third Gaussian PDF, whose variance will equal the sum of the variance of the summed PDFs. For the simple BER model adopted here, we can therefore expand the noise terms for the "1" and "0" levels

$$s_1 = \sqrt{\sum s_1^{\,2}} = \sqrt{\left(s_{1,laser}\right)^2 + \left(s_{1,fiber}\right)^2 + \left(s_{1,\det ector}\right)^2 + \left(s_{1,receiver}\right)^2 + \ldots}$$

$$s_0 = \sqrt{\sum s_0^{\,2}} = \sqrt{\left(s_{0,laser}\right)^2 + \left(s_{0,fiber}\right)^2 + \left(s_{0,\det ector}\right)^2 + \left(s_{0,receiver}\right)^2 + \ldots}$$

In this manner, the various Gaussian noise contributions with the appropriate scale factors can be concatenated using a root-sum-square summation. The non-Gaussian noise sources are added in to the noise budget later.

The end-user of an optical module does not care about noise statistics or device physics, but is interested in the minimum optical signal power he needs to achieve the system-level BER requirement. This is the other major parameter specifying an optical data link from the user's viewpoint, and sets the technology constraints for the Rx. This minimum optical power, sometimes called the "sensitivity," allows him to select the cable type, construction method, length, number of splices, etcetera, for a given installation by use of an "optical power budget" or "loss budget." Implicit in the optical power budget are various "power penalties" associated with timing jitter, inter-symbol interference, vertical eye closure, laser degradation, and a host other factors. For example, there is a power penalty associated with duty-cycle distortion, which is the symmetry of "101" versus "010" data. Rather than factor this into the noise budget, it is customary to allocate this to the optical power budget, and appears as a small loss value. It would be equal to the amount of signal increase needed to overcome a given impairment, and restore the SNR to its original value and maintain BER.

3. Noise Contribution from the Transmitter

The electronics that drives the laser or modulator will have some finite noise present, due to semiconductor noise, thermal (Johnson) noise, and external sources.

3.1 Transmitter Electronics Random Noise

Laser diode driver (LDD) electronics have a small current noise associated with the DC drive current. With the appropriate AC-coupling, this noise would be observed to be zero-mean, Gaussian PDF, which is white up to the specified bandwidth. An LDD specified to have a given I_{RMS} noise current over a given bandwidth, has its noise converted to optical noise by the laser, and therefore multiplied by the coefficient η_{LD}.

(equivalent optical noise at PD input) $= s_{TX} = h_{LD}\, h_{FO}\, I_{RMS}$

Note that the current noise is not squared due to the electro-optic conversion. The worst-case noise transfer is for lossless fiber, so h_{FO} is often set to unity.

$$s_{1,TX} = s_{0,TX} = h_{LD}\, I_{RMS}$$

Sometimes the supplier specifies the performance to have I_{RMS} in terms of $uA/Hz^{1/2}$, or alternately $dBA/Hz^{1/2}$. Then is would have to be multiplied by the square root of the bandwidth.

$$s_{1,TX} = s_{0,TX} = h_{LD}\, I_{RMS}\, B^{1/2}$$

If an external modulator is used, or the laser is biased below threshold to transmit a "0" bit, this noise component would be absent from s_0 and only contribute to s_1. However, if the laser's operating point is higher, such that both "0" and "1" are above threshold, this noise will be present in both s_1 and s_0 summations.

3.2 Transmitter Electronics Periodic Noise

If a spectrum analyzer is used to look at what appears to be white Gaussian noise, there will often be periodic content noted. This non-random noise components need to be separated from the random components and will be added later because the sources are myriad and not deterministic in the design sense. At the last step of the calculation, an "unallocated" noise margin will be added for the non-random noise in the link, which is dependent on the art of electronics: shielding, bypassing, signal integrity, grounding, baseline wander, power filtering trees, and other layout-related items. The power supply rejection ratio (PSRR) of laser driver ICs is sometimes specified, which describes the output's immunity from V_{cc} noise.

3.3 Low Frequency (servo effects)

There is often a servo circuit which will control the laser diode DC operating current, to achieve a given optical power output. This is done to stabilize the operation over the perturbations of aging, temperature, and supply voltage. The type and design of the servo, frequency response, delay, and damping characteristics will determine the degree of noise reduction below the frequency response of the servo. Fortunately for our calculations, AC-coupling will effectively mask this noise, and this can be neglected for properly-designed laser diode drivers.

3.4 1/f Noise

This phenomenon is evident in many physical systems, including lasers and electronics, but its origin is not well understood. This is the dominant noise at very low frequencies. Again, AC-coupled electronics eliminates this contribution from our calculations also.

3.5 Comment

The use of AC-coupling in the Rx electronic path as mentioned, and is necessary for its high-pass filtering properties. On the Tx side, AC-coupling is also highly encouraged. This is to avoid static biasing the laser to an unsafe power level in the event of certain system fault modes. When AC-coupling is performed, the quality, physical size, and parasitic behavior of the capacitor should be considered. Too small of a value can induce baseline wander for long strings of 1s and 0s, and will be evidenced as pattern-dependent timing jitter. Additionally, after the AC-coupling capacitors, there should be a slight DC bias offset between the first differential pair of transistors. If the Tx input is static or open, the AC-coupling capacitors will discharge after a few RC time constants, and noise can cause random switching (chatter). This slight bias offset will provide some immunity, at the expense of higher duty cycle distortion and resultant horizontal eye closure.

4. Noise Contribution from the Laser

The laser has very interesting physics and noise contributions. The classic text on the subject is by Petermann[2]

4.1 Relative Intensity Noise (RIN)

RIN is a number that aggregates the noise contributions that can be contributed to the laser diode, and is a major specification and cost driver of lasers. Contributions to RIN include quantum effects, thermal fluctuations, acoustic disturbances, and so on. RIN is defined as the ratio of variance of the intensity fluctuations about the average to the square of the instantaneous optical intensity. In other words, the mean squared noise power divided by the optical intensity squared. The level of RIN noise increases with the square root of link Rx bandwidth *B*

$$RIN \equiv \frac{s^2}{I^2}$$

RIN has the units of dBW/Hz, or sometimes pW/Hz. To calculate the noise contribution at the output of the laser

$$s = I \sqrt{RIN \cdot B}$$

This assumes that RIN is white, i.e. constant with respect to frequency. Actually the RIN rises as it approaches the relaxation oscillation peak, which would need to be accounted for in a more rigorous analysis. To get the oSNR contribution referenced to the input of the PD, the scale factors must be added

$$s_1 = h_{FO} \, I_1 \sqrt{RIN \cdot B}$$

$$s_0 = h_{FO}\, I_0 \sqrt{RIN \cdot B}$$

RIN-dominated optical links will have a SNR that is not changed by attenuation in the PHY, i.e. fiber loss reduces the signal as well as the noise by the same amount. The fiber transmission coefficient is often placed at it's worst case value of unity. Sometimes this is referred to as "multiplicative" noise. Often the "0" term can be neglected due to the low light level. Generally, the RIN number drops with I^2, which means the RMS noise will be proportional to the average laser operating power as shown. However, at lower bias levels, the RIN drops proportional to I^3, which means that σ can scale as $I^{3/2}$ at the lower laser power levels. A practical discussion of RIN and its measurement and control is suggested reading.[3]

4.2 Mode-Partition Noise (MPN) In Fabry-Perot Lasers

MPN is found in multi-longitudinal mode laser diodes (i.e. Fabry-Perot lasers). These types of lasers have, in the optical frequency domain, multiple lasing lines that are closely spaced. The frequency difference between adjacent lasing lines would be $Df = c/2nL$, where c is the speed of light ($c = 3 \times 10^8$ m/sec) and n is the refractive index of the laser of InGaAs/InGaAsP which is in the range of 3.3 to 3.7 depending on the molar fraction. Assuming that $n = 3.5$ and the laser cavity length $L = 0.5$ mm, results in a free spectral range of $\Delta f = 85$ GHz. Aside from RIN, the time average of the optical power in all the lasing modes is constant with time. However, if we to observe the power in only one of the lasing modes (perhaps with a spectrometer) the time average of its optical power would vary wildly, and could be said to have an additional noise component.

Another way of saying this is the RIN of the laser's output, measured as a whole, has some nominal value. But if some highly wavelength-selective device inadvertently isolates a single longitudinal mode from the spectrum, the RIN will be much greater than the nominal value. For observation frequencies below 500 MHz, the noise can be above -30 dB. This power fluctuation between the various laser modes, even though the total power is constant, leads to a contribution to intersymbol interference. For non-DFB lasers,

$$s = \frac{K}{\sqrt{2}}\left(1 - e^{-(pt/T)^2}\right)$$

where K is the mode partition factor (0 < K < 1) and T is the symbol time, and τ is the dispersion time. Typical lasers have a K value in the range of 0.25 to 0.6, but K = 0.8 will be used for the purposes of this analysis[4]. τ is found by $\tau = DL\Delta\lambda$, and D is the fiber dispersion coefficient (usually in picoseconds/km•nm), L is the fiber length, and $\Delta\lambda$ is the RMS spectral width of the envelope of the laser lines, i.e. the total laser spectrum.

Fabry-Perot lasers are not used in long-distance high data rate optical links, because of this noise. Mode-Partition Noise In DFB/DBR Lasers can also occur for cases of incomplete side-mode suppression ratio (SMSR). It is possible that when SMSR < 20 dB, mode hopping occurs, which is observed as noise. This effect can be controlled by specifying SMSR requirements when DFB lasers are employed.

4.3 Quantum Noise

Laser quantum (shot) noise, which is a component of RIN, arises from the quantum nature of the injected carriers and emitted photons of the laser diode. For frequencies <100 MHz, these components are below –60 dB. In an incoherent emitter such as a LED, or a laser operating below the threshold, the laser quantum noise arises from spontaneous emission only. In the normal operating mode of a laser, there is the spontaneous emission, plus another term that is the spontaneous emission beating with the lasing optical field.

4.4 Modification of Quantum Noise by Relaxation Oscillation (RO)

It was originally assumed that the RIN value is independent of the frequency of observation. The white noise spectrum will be modified by and look somewhat like the transfer function of the laser as a function of frequency, increasing and peaking at the RO frequency. In practice, the RO frequency increases, proportional to the square root of the average laser power $I^{1/2}$. The net effect is that the noise peak flattens out and moves toward higher frequencies at higher average laser power values. For systems operating well below the RO frequency, this should not be a first-order concern.

4.5 Laser 1/f Noise

Laser 1/f noise can dominate the RIN below 100 kHz[5]. Fortunately, AC-coupling in the downstream electronics will filter out these effects.

4.6 Conversion of Phase Noise to Amplitude Noise

Lasers also exhibit phase noise in the optical domain. This could be converted to amplitude noise by Fabry-Perot cavities in single-mode PHYs. However, this would be only due to a poor transmitter design, poor component design, cracked fiber or splice, or air gap in a connector and will be neglected in this analysis. It is not generally an issue in multimode fiber, that have different mechanisms for these same defects to produce noise.

4.7 Optical Feedback Effects

Lasers can be highly susceptible to light that gets reflected back into the laser cavity. This can come from scattering in splices, mated optical connectors, scattering from dirt and fiber imperfections, and Rayleigh scattering from the fiber itself [6]. There are also Fresnel reflections from the first and last fiber endface, each contributing roughly 4% backreflection. An optical isolator (or two) are used in conjunction with high-performance lasers to keep fiber backreflection from returning to the laser cavity.

4.8 Comment

Some analyses include laser noise terms that arises from other than the above major contributors. Some of those are:

- Nonlinearity: This is not a true noise, and outside the scope of this report. Through proper circuit design, component selection, and possibly compensation, this can be reduced to negligible levels.
- Distortion: This is not a true noise, and is outside the scope of this report. This can also be dealt with through proper circuit design.
- Signal Integrity: This is not a true noise, and is outside the scope of this report. Again, this is controlled by correct application of transmission lines, terminations, and layout dressing.
- Laser Kinks: This is often associated with mode hopping, and is of concern with Fabry-Perot lasers and low-quality DFB lasers.
- Mode Hopping: This is due to gain competition in homogeneously broadened gain media, and is of concern with Fabry-Perot lasers.
- Relaxation Oscillation: This results from an exchange of energy between the carrier population and the photon population, and damps out rapidly. If the RO frequency were within the passband of the electronics, since it is uncorrelated with the signal, it would appear as noise. Lasers are specified with a high RO frequency compared to the transmission data rate.
- Self-Pulsation: This is a dynamic instability often associated with CD-quality Fabry-Perot laser diodes. It can often be an indicator of damage to the laser diode. If the SP frequency were within the passband of the electronics, it would appear as noise, since it is uncorrelated with the signal.

5. Noise Contribution from the Medium

The fiber can have its own sources of noise, which would appear at the receiver. Noise sources in the transmission medium are often controlled by design rules, and upon careful examination can be often neglected.

5.1 Modal Noise

For multimode fiber, the light is carried by numerous modes in the core of the fiber. If a coherent optical source is used, there will be interference between the modes, observed to the naked eye as “speckle.” Although power is coupling back and forth between the individual, modes, the net num of all of the modes’ power is constant.

However, if a portion of the speckle was obscured, for example by opaque dust on a connector, an offset-core connector, or certain types of attenuators, a large amount of noise will be observed[7]. This is because there is not a full spatial integration of all of the speckles on the photodetector[8]. Correct photodetector design makes sure all of the light is gathered in a fashion to avoid mode-selective loss (MSL).

When buying multimode fiber attenuators for laboratory of field use, care must be taken to make sure the attenuator does not employ a technique that induces MSL. Asymmetric spatial filtering in active and passive optical components can also contribute to this effect. A common way to eliminate modal noise is to use an incoherent source, such as an LED, where speed permits. Where diode lasers are used in multimode fiber, typically the high-coherence FB/DBR lasers are not used. This type of noise is included in the power budget as a separate power penalty of 0.1 to 1 dB, and is not part of this calculation.

5.2 Polarization

There will be dispersion between the eigenstates-of-polarization (ESOP), called polarization-mode dispersion (PMD). The physics of this dispersion follow Maxwellian statistics. PMD is accounted for as a separate entry in the timing budget, or as a power penalty in the loss budget, and is generally not an issue at data rates $\leq$ 2.5 Gbps.

There is no polarization noise per se in multimode optical fiber due to the averaging of a large number of modes. However, in single-mode optical fiber, there are two ESOP modes, which can in effect have modal noise as energy is exchanged between the ESOPs. This phenomenon would be greatly enhanced if there were a polarization-selective element in the optical train, such as an optical isolator (which contain polarizers) in front of the photodetector. In this situation, special polarization-insensitive isolators would be demanded. It is worth mentioning that most devices have a finite polarization dependency, this is often specified as polarization-dependent loss (PDL), which has become an important parameter to specify.

5.3 Phase Noise

Temperature fluctuations create constantly changing phase noise in optical fibers. This is generally an issue important to interferometric fiber optic sensors, but not optical communication. However as before, phase noise can be converted to amplitude noise under the right conditions, such as poor component design, damaged connector, fiber or splice.

5.4 Acoustic Noise

It is possible to have mechanical or acoustic vibrations generate noise-like effects through various transduction effects. For example, undersea cables experience sea-noise due to the hydrostatic pressures encountered.[9] Other sources of this type of noise would be air gaps in fiber connectors or damaged fiber that can cause microphonic effects to occur. This type of noise can be neglected in properly designed systems.

5.5 Optical Amplifier Noise

If optical amplifiers are used in the system, they have additive and multiplicative noise components that must be taken into consideration. This is beyond the scope of this report, but is important in long-haul transmission.

5.6 Comment

An interesting but important phenomenon is known as “bandwidth collapse” for multimode fiber. It would seem that certain multimode fiber types can have extremely poor bandwidth when used with diode lasers. Even though the fiber passed bandwidth testing using LED or overfilled launch, certain pathological fiber reacted poorly to laser transmitters, with their lower NA (more restricted angular launching conditions). While a detailed discussion is well beyond the scope of this report, it is a fairly recent development and still the subject of technical debate.

6. Noise Contribution from Photodetector

The sources of noise contribution of a photodetector[10] may be classified into intrinsic and extrinsic: Intrinsic noise arises from fundamental physical effects, and extrinsic-sourced noise comes from the surrounding environment. All detectors are square-law detectors.

6.1 Quantum Shot Noise

Shot noise is sometimes called quantum noise, and results from the discrete electronic charge of electrons or other carriers as they pass across a potential barrier. For example, photons that generate electron-hole pairs in a PIN photodiode produce a photocurrent which that has random fluctuations about its mean value. The 2-sided PSD is

$$S(w) = q\,(i_{AVG} + i_D)\,|H(w)|^2$$

Where q is the electron charge, i_{AVG} is the average photocurrent, and i_D is the dark current of the photodiode. H(ω) is the Fourier transform of the impulse response of the electron-hole recombination, and may be considered unity for our frequency range of interest. This yields a uniform PSD

$$S(w) = q\,(i_{AVG} + i_D)$$

And the contribution due to the optical received power can be found using the photodetector responsivity h_{PD}

$$S(w) = q\,h_{PD}\,I$$

and is proportional to the optical power received. The shot-noise current may be found by

$$\left\langle i^2(t) - i^2{}_{AVG} \right\rangle \equiv s^2 = \int_{bandwith} S(w)dw = \int q h_{PD} I\, dw = 2 q h_{PD}\, I\, B$$

This can be considered a multiplicative noise source. Shot noise actually has a Poisson PDF, but above nanoWatt levels it may be approximated as a Gaussian PDF.

$$s_{SHOT} = \sqrt{2qh_{PD}IB}$$

To get the value at the input of the photodetector, divide by the coefficient

$$s_{1,SHOT} = \left(\frac{1}{h_{PD}}\right)\sqrt{2qh_{PD}I_1B}$$

$$s_{0,SHOT} = \left(\frac{1}{h_{PD}}\right)\sqrt{2qh_{PD}I_0B}$$

6.2 Shot Noise from Dark Current

The second shot noise term is due to the finite dark current of a photodetector, and is independent of the optical received power. Dark current arises from carrier leakage paths and other imperfections in the photodetector design and manufacturing process, and is specified for PDs. It is an additive noise component, present even with no light input. Dark current can increase by a large amount at high temperatures, on the order of 10×~ 20× increase going from 25℃ to 70℃.

$$S(w) = q\,i_D$$

where q is the electronic charge $1.6\text{x}10^{-19}$ Coulomb.

$$\left\langle i^2(t) - i^2{}_{AVG} \right\rangle \equiv s^2 = \int_{bandwith} S(w)dw = \int q\, i_D dw = 2q\, i_D B$$

Thus the shot noise due to the dark current is proportional to the square root of the system bandwidth.

$$s_{DARK} = \sqrt{2q\, i_D B}$$

To refer this back to the input of the photodetector requires dividing by the photodetector efficiency.

$$s_{1,DARK} = s_{0,DARK} = \left(\frac{1}{h_{PD}} \right) \sqrt{2q\, i_D B}$$

For our example of B = 10 GHz, i_D = 10 nA, and h_{PD} = 0.9 mA/mW results in $s_{1,DARK}$ = $s_{0,DARK}$ = 6.3 nW RMS.

6.3 Avalanche Multiplication Noise

For systems that employ an avalanche photodiode (APD), the intrinsic gain provided by the APD is useful in high-sensitivity applications. The downside is the increase in cost of the APD, and there is a noise term associated with APD usage. Because avalanche amplification is a random process, the avalanche multiplication of the electron-hole pairs increases the noise of the original photo-induced carriers. In general, the noise of the photodetector is multiplied by a factor M, and the following equation replaces the shot noise contribution.

$$s_{APD}{}^2 = M^x \; s_{SHOT}{}^2$$

Where M is the avalanche gain of the APD, and x is a constant in the range of $2 < x < 3$. A similar correction is used for the dark current shot noise term. APDs require a high bias voltage and are expensive, and generally are not used in datacom or short-distance telecom PHYs.

$$s_{APD} = 0$$

6.4 Thermal Noise

Thermal noise for the photodiode itself is usually neglected, because the parasitic shunt resistance associated with a reverse-biased PN junction is very large, inducing little noise. Thermal noise of the subsequent amplification stages, particularly the first stage of amplification or transimpedance amplifier, can be important for low light levels. This having been said, the discussion of thermal noise is deferred until the receiver electronics section of this document.

$$s_{THERMAL} = 0$$

6.5 Extrinsic Optical Crosstalk

As the name implies, this would be noise (which may be somewhat correlated with the signal) that somehow impinges on the photodetector. This would be originated in the optical domain, but would be observed as noise on the received photocurrent. This noise source may usually be easily mitigated, but becomes increasingly challenging in highly integrated DWDM and parallel PHY systems.

In duplex serial PHYs that use transceivers, any laser light that fell upon the photodetector would qualify as optical crosstalk. For transceivers that use pigtails or duplex-SC receptacles this is fairly easy to design against, but some of the small form factor (SFF) modules have only a few hundred microns between the laser the photodetector. In this case, extreme care must be taken to avoid stray reflections inside the module to keep optical crosstalk to a minimum. Some duplex serial PHYs use simplex media, i.e. the same fiber supporting bi-directional traffic. In this case, optical crosstalk would be created by any backreflection in the launch/receive splitters, splices, connectors, and by Rayleigh scattering in the fiber itself.

In parallel optical fiber links, this type of crosstalk would be induced by light from a given fiber falling on a detector other than its assigned detector. In the receiver based on MT connector and standard ribbon fiber technology, the detectors must have 250 micron center-to-center spacing. This produces some challenges in these systems.

In WDM links, the wavelength muxing and demuxing filters are imperfect, letting a small amount of light from adjacent wavelengths through, which eventually find themselves on the wrong detector. This is exacerbated for higher modulation speeds (linewidth broadening), closer channel spacing (DWDM) and lower-cost filters. If the implementation uses highly integrated packaging techniques, there would be similar geometric challenges on the Rx side as the parallel fiber approach.

6.6 Extrinsic Optical Interference

This source of noise is from uncorrelated extrinsic sources that are optical in nature, and is often referred to as interference. For convenience, RF interference in the photodiode will be lumped into the Rx electronics. Through proper shielding techniques, extrinsic noise sources may often be neglected.

One major but equally correctable source is background light. Any stray light from the environment will degrade the SNR, especially at low average signal power. Fluorescent lights have a large 60 Hz component and arc lights produce their own characteristic spectra. Fortunately, most 1300/1550 nm photodetectors are “blind” to visible wavelengths, and the low-frequency cutoff of downstream electronics is well above 60 Hz. It is very easy to design the fiber receptacle to shroud the photodetector when a connector is installed.

6.7 Comment

It should be noted that when the connector is removed and the dust cap is not in place, ambient light incident on the photodetector could de-assert any control signals outputs such as loss of light (LOL) indicator. While this does not affect SNR, there will be negative system consequences unless careful LOL circuit design is adhered to.

7. Noise Contribution from Receiver

The design of the receiver electronics has a large effect on the ultimate performance of the optical link. Unfortunately, space does not permit delving into all of the intricacies of the noise performance of high-frequency semiconductors and circuits[11]. We will forgo the frequency-dependence, and review the main contributors to receiver noise.

7.1 Johnson Noise

Johnson, or thermal, or Nyquist noise arises from thermally induced random fluctuations of electron motion at temperatures above absolute zero. Thermal noise is additive, and has a Gaussian PDF with a zero mean, and a PSD which may be approximated as uniform. From quantum theory, the PSD of thermal noise is given by:

$$S(w) \;=\; \hbar w\left(\frac{1}{2}+\frac{1}{e^{\hbar w/kT}-1}\right) \;\cong\; kT \qquad \text{for} \qquad kT >> \hbar w$$

where $\hbar$ is Planck’s constant divided by 2π, and k = Boltzmann’s constant, approximately 1.38×10^{-23} J/°K. For reasonable temperatures and frequencies < 1 THz, the PSD of thermal noise power may be approximated as constant and proportional to Kelvin temperature. Taking the inverse Fourier Transform of the PSD yields the autocorrelation function $R(t)$of the thermal noise, which is an impulse function:

$$\Im^{-1}\{S(w)\} \;=\; R(t) \;=\; \Im^{-1}\{kT\} \;=\; kT\,d(t)$$

The average power σ^2 is calculated by integrating the PSD over some bandwidth, or alternately from *R(0)*

$$s^2 = \int_{bandwith} kTdw = 2kTB$$

where the integral is zero outside of a bandwidth *B*, and the factor 2 comes from using the 2-sided PSD. The noise current may be computed from the noise power by using Ohm's law $P = I^2R$, and adding another factor of two, to because 50% of the noise power generated by an equivalent current source contributes to the measurable noise power *2kTB*:

$$\left\langle i^2(t) \right\rangle = s^2 = 4\frac{kTB}{R}$$

The mean value of the noise current is zero $\left\langle i(t) \right\rangle = 0$ and the standard deviation of the Gaussian PSD is

$$i_{RMS} \equiv \sqrt{\left\langle i^2(t) \right\rangle} = s = 2\sqrt{\frac{kTB}{R}}$$

for a given resistance *R* at an absolute temperature *T*, measured over a bandwidth *B*. Note that the noise varies with the square root of bandwidth. R could be the feedback resistor value of a transimpedance amplifier, for example. Similarly, the noise voltage is described by:

$$\left\langle v(t) \right\rangle = 0 \qquad \text{and} \qquad \left\langle v^2(t) \right\rangle = s^2 = 4kTRB$$

$$v_{RMS} \equiv \sqrt{\left\langle v^2(t) \right\rangle} = s = 2\sqrt{kTRB}$$

Thermal noise, being additive, is observed whether or not the signal is present. Therefore, it tends to dominate the shot noise at low optical power levels. To refer the Johnson noise back to the input of the PD, we need to divide by the conversion coefficients of the amplifier and photodetector.

$$s_{1,JOHN} = s_{0,JOHN} = \left(\frac{1}{h_{PD}}\right)\left(\frac{1}{h_{RX}}\right)2\sqrt{kTRB}$$

As the temperature increases from 25C to 85 C, one would expect about $(360/310)^{1/2}$ ~ 10% more noise voltage or current.

7.2 Excess Amplifier Noise

Any subsequent amplification stages before the DDC would need to have its input-referred noise specification converted to the appropriate power-equivalent σ value. For an amplifier with a given input-referred excess noise voltage specification V_{RMS}, the noise contribution relative to the input of the PD is given by

$$s_{1,AMP} = s_{0,AMP} = \left(\frac{1}{h_{PD}}\right)\left(\frac{1}{h_{RX}}\right)V_{RMS}$$

Noise could also be specified as a power spectral density, with the dependence on the square root of the bandwidth like the Tx noise. Amplifier noise is additive noise, being present whether or not there was an optical input. Since it is reduced by a factor of h_{RX}, it is easy to see that the early stages in the Rx amplifier chain have the most impact on total electronic noise. Sources of this type of noise include junction or channel thermal noise, junction or channel leakage-generated shot noise, flicker (1/f) noise, and thermal fluctuations in the drain or collector circuit.

7.3 External Noise Sources[12]

In transceivers, electrical crosstalk can come from the transmitter electronics, especially the high-frequency current loop that drives the laser. Shielding of the photodiode and first stages of the receiver will increase immunity to noise and parasitic oscillation. If a receiver is susceptible to electromagnetic emissions or electrostatic discharge, these can appear as noise and would have to be taken out of the SNR budget. Careful layout, shielding, and design can minimize the external noise sources on the receiver electronics.

Power supplies must be effectively isolated, from the glitches on the V_{cc} line, but from the transmitter's V_{cc} line also. Several layers of "Pi" networks using ferrites and high-quality capacitors are necessary, along with correct ground plane and V_{cc} plane layout. Like in the Tx electronics, the PSRR is an important specification in Rx electronics.

7.4 Comment

As mentioned earlier, when the optical power to the Rx input drops below a certain value, the LOL indicator is asserted. There has been some controversy as to whether or not the output of a post-amplifier should be squelched (held to a static value) during LOL. For very low SNR situations, the minute amount of signal present can cause downstream system problems, if the deserializer can recognize a valid data character.

7. Example of PHY

All numbers are calculated with B = 10 GHz, h_{LD} = 0.5 W/A, h_{FO} = 1, h_{PD} = 0.9 A>W, h_{RX} = 1000 V/A, $q = 1.6\text{x}10^{-19}$ Coulomb, and $k = 1.38\times10^{-23}$ J/°K.

	"1" bit σ_1 contribution	Watts RMS	"0" bit σ_0 contribution	Watts RMS
§3.1 Tx Circuit (1uA RMS spec)	$h_{LD}\, h_{FO}\, I_{RMS}$	5.00×10^{-7}	$h_{LD}\, h_{FO}\, I_{RMS}$	0
§4.1 Laser RIN (-145db/Hz spec)	$h_{FO}\ I_1 \sqrt{RIN \cdot B}$	0.0056 I_1	$h_{FO}\ I_0 \sqrt{RIN \cdot B}$	0.0056 I_0
§4.2 Mode-Partition Noise	Neglected	0	None	0
§5.2 Fiber Modal Noise	In the optical loss budget	0	None	0
§5.2 Fiber Other Noise	Negligible of controlled	0	None	0
§6.1 Shot Noise	$\left(\frac{1}{h_{PD}}\right)\sqrt{2qh_{PD}I_1B}$	$5\text{x}10^{-7}\ \sqrt{I_1}$	$\left(\frac{1}{h_{PD}}\right)\sqrt{2qh_{PD}I_0B}$	$5\text{x}10^{-7}\ \sqrt{I_0}$
§6.2 Dark Current Noise (10 nA i_D spec)	$\left(\frac{1}{h_{PD}}\right)\sqrt{2q\, i_D B}$	$6.30\text{x}10^{-9}$	$\left(\frac{1}{h_{PD}}\right)\sqrt{2q\, i_D B}$	$6.30\text{x}10^{-9}$
§6.2 APD Noise Multiplication	Not used	0	Not used	0
§7.1 Johnson Noise (T= 300K) (R=h_{PD} =1000Ω)	$\left(\frac{1}{h_{PD}}\right)\left(\frac{1}{h_{RX}}\right)2\sqrt{kTRB}$	$4.55\text{x}10^{-7}$	$\left(\frac{1}{h_{PD}}\right)\left(\frac{1}{h_{RX}}\right)2\sqrt{kTRB}$	$4.55\text{x}10^{-7}$
§7.2 Amplifier Noise (Not included)	$\left(\frac{1}{h_{PD}}\right)\left(\frac{1}{h_{RX}}\right)V_{RMS}$	0	$\left(\frac{1}{h_{PD}}\right)\left(\frac{1}{h_{RX}}\right)V_{RMS}$	0

The square sum of the squares in the columns for our example as described in the report are computed

$$\sigma_1^2 = 4.57\times10^{-13} + 3.60\times10^{-9} I_1 + 3.16\times10^{-5} I_1^2$$

$$\sigma_0^2 = 2.07\times10^{-13} + 3.60\times10^{-9} I_0 + 3.16\times10^{-5} I_0^2 \sim 2.07\times10^{-13}$$ if we let = 0.5, I_O approach zero.

By doing this we are neglecting the shot noise and RIN noise contributions at the "0" bit. We have defined *DI* to be the signal swing, or $I_1 - I_0$ modulation. Rearranging the oSNR calculation and solving for "1" noise variance

$$Q^2 = \frac{I_1 - I_0}{s_1 + s_0} \approx \frac{\Delta I}{s_1 + s_0} \qquad \Rightarrow \qquad \left(\frac{I_1}{Q^2} - s_0\right)^2 = s_1^{\ 2}$$

Which permits the following equality to be made

$$[\,(1/Q^2)I_1 - 4.55\times10^{-7}\,]^2 = \sigma_1^2 = 4.57\times10^{-13} + 3.60\times10^{-9} I_1 + 3.16\times10^{-5} I_1^2$$

Which is a quadratic equation that we can solve for I_1. Gathering terms, the resulting quadratic equation is

$$3.73\times10^{-4} I_1^2 + 1.47\times10^{-8} I_1 - 2.50\times10^{-13} = 0$$

where we have taken Q = 7.05 from the requirements table at the beginning of the report. The resulting solution is

$$DI = 1.97\times10^{-5} \pm 3.25\times10^{-5} \quad \text{Watts}$$

Throwing out the negative solution, which is a non sequiter, leaves us with the final solution

$$DI_{MINIMUM} = 1.97\times10^{-5} + 3.25\times10^{-5} = 52.2 \text{ microWatts } (-12.8 \text{ dBm})$$

Which would be the minimum optical power required at the receiver to meet the 10^{-12} BER. This does not include excess amplifier noise in the receiver, nor unallocated noise margin for non-Gaussian sources. A similar exercise would be performed for nonzero I_0 values.

9. Conclusion

A methodology was proposed which permits the easy organization and calculation of the myriad noise contributions in optical PHYs. For an example of a hypothetical 13 Gbps system (requiring 10 GHz bandwidth) using a DFB laser it was shown that the minimum detectable power to achieve a 10^{-12} BER is 52 microWatts.

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