Sādhanā, Vol. 17, Parts 3 & 4, September 1992, pp. 467–471. © Printed in India.

Noise considerations in the design of long haul lightwave communication systems

R P JINDAL

AT & T Bell Laboratories, 67 Whippany Road, Whippany, NJ 07981, USA

Abstract. Magnitude of the signal relative to noise determines the ultimate quality of all information transmission. In a lightwave system, there are several fundamental and nonfundamental noise mechanisms that govern the system performance. In this paper, concepts related to these issues will be developed and a review of the current status of this rapidly evolving field will be given.

Keywords. Noise; lightwave; long haul communication.

1. Introduction

Lightwave communication has put virtually unlimited bandwidths at our disposal. This enormous bandwidth coupled with the highest propagation speed over extremely low loss glass fibres makes this the technology of choice for our communication needs. Although lightwave continues to find new applications based on its diverse merits, one of its greatest impacts has been on providing cheap and reliable long distance communication. It is also probably the single most demanding application where its low noise features are put to the utmost test. There are several sources that limit its noise performance.

The first fundamental limit imposed on the performance arises from the quantized nature of the signal carrier itself which in this case is light. This is generally referred to as the shot noise limit. In optoelectronic components, in addition to photon statistics, additional sources of noise further limit the performance. These sources include spontaneous emission, quantized nature of charge and thermal vibrations of the crystal lattice. Other sources of noise which are not fundamental and yet may limit the system performance include the carrier multiplication noise, laser excess noise and hot carrier effects in sub-micrometre dimension electronic devices. Before looking at these topics in detail, let us review a simple lightwave system.

2. Lightwave system background

In its simplest form (direct detection scheme), digital lightwave communication consists of coding the input signal into a string of "0's" and "1's" (both equally likely for maximum information transfer rate) and sending this string optically. Using an optical source such as a light-emitting diode or a laser diode, an optical pulse is transmitted for a

"1" and nothing is transmitted for a "0" (or vice versa). This string of optical pulses travels over a transmission medium such as an optical fibre. At the destination, these pulses are converted into an electrical signal by a photo detector. This electrical signal is amplified by low noise electronics and shaped into pulses and decoded to reconstruct the message. For transmission over long distances, one may need to amplify the signal on the way to compensate for fibre propagation losses. This amplification is achieved typically via the electronic route or by direct amplification in the optical domain. We shall first look at the noise associated with the signal carrier, i.e. light, and then examine the noise mechanisms associated with some of the major components that are used in such a generic system.

3. Quantum photon statistics

Following the direct detection scheme outlined above, let us look at the transmitting end of the system where the light signal is being generated. The signal carrier noise deals with fluctuation in the pulse generation process itself. When we wish to launch an optical pulse we turn the light source (a light emitting diode or a laser diode) "on" for the duration of the pulse and then turn it "off". During this time a certain number of photons (quanta of light) are launched on to the optical fibre. The average number of photons launched depends upon the intensity of light generated. The problem, however, is that this number is not constant but fluctuates about this mean value governed by the quantum properties of the photon system. This is referred to as the shot noise of the light signal. It is therefore entirely possible that during such an optical pulse time slot where we need to transmit a pulse, no photon gets launched on the fibre at all. This results in a signal transmission error. Following Smith & Personick (1980, p. 136) we find that for the simple on/off key (OOK) coding scheme described above we need to transmit at least 10 photons per bit on an average in order to keep the probability of error below 10^{-9}. This places a limit on the ultimate sensitivity of a lightwave communication system. It should be noted that this quantum limit is a function of the coding scheme employed.

By specially arranging the photon states in a light beam it is possible to suppress these number fluctuations. This is known as *squeezed* light; e.g. Slusher & Yurke (1990). This can be achieved in several ways but the net result is that one can go below the 10 photon limit discussed above for the OOK scheme. However, *squeezed* light is very sensitive to losses in the system and hence not of practical importance, at least at the present time. Further, under the constant power constraint this results in only a factor of 2 improvement in the channel capacity of the medium. It turns out that current lightwave systems have yet to attain the 10 photon limit. The reason for this is the extra noise generated by other components of the system. Next we shall examine the noise in these individual components.

4. Light sources

With the above qualifications, the lower noise limit for all light sources including laser diodes (see Van der Ziel 1970, p. 119) is quantum shot noise. However, noise levels orders of magnitude above the shot noise have been experimentally observed by Jackel & Guekos (1977). This is due to noise from other mechanisms that degrade the system performance further. These include spontaneous emission fluctuations, mode partition noise, feedback noise and low frequency noise. As the name implies, the spontaneous emission noise results from the spontaneous emission of a photon in the lasing system. Treating light as a wave phenomenon, this produces both phase and amplitude fluctuations in the light output as this photon adds incoherently to the laser output. The phase fluctuation adds to the finite laser line width. The amplitude fluctuation produces fluctuations in the total intensity of the emitted light even at a constant bias. Spontaneous emission has further effects on the lasing medium in terms of carrier population and refractive index enhancing the system disorder. Intensity noise is also enhanced when one measures these fluctuations in a single mode of a multimode laser. This is referred to as the mode partition noise and results from the optical power switching back and forth between various lasing modes. Feedback noise generally refers to the instability that results when one tries to reduce the laser line width by, for example, an external cavity. These fluctuations tend to be both stochastic and chaotic in nature. Other forms of noise including $1/f$ have also been observed in laser diodes. These fluctuations also tend to originate from both random and chaotic sources.

5. Photo detectors

Photo detectors can be classified into either the photovoltaic category (non-ohmic type) or the photoconductive category (ohmic type). Most of these are two terminal devices and hence broadly fall under the classification of photodiodes as opposed to phototransistors. Their purpose, as the name implies, is to detect light by producing an electrical output in response to an optical input. Photovoltaic devices with unity amplification deliver one current carrier (for 100% efficiency) per incident photon and are generically called PINs. Photovoltaic devices with gain produce a large number of carriers per incident photon and are generically called Avalanche Photo-Detectors (APDs). Photovoltaic devices exhibit, among others, leakage current shot noise, generation recombination (GR) noise and $1/f$ noise. In addition, APDs also exhibit excess shot noise associated with the carrier multiplication process. Technologically this is the most challenging of the mechanisms to eliminate since it arises from the fundamental quantized nature of charge and randomness of transport across the device.

Good PINs exhibit near-ideal noise performance for both short wavelength detection ($\lambda = 0{\cdot}8\,\mu$m) and long wavelength ($\lambda = 1{\cdot}3\,\mu$m $- 1{\cdot}55\,\mu$m). However, to diminish the effect of noise generated by the following electronics, it is desirable to have some gain during the detection process itself. This is provided by the APDs. As described by Schinke *et al* (1980, p. 63), at short wavelength, silicon APDs with electron initialed avalanche multiplication, having nearly ideal noise performance have been realized. At long wavelengths, where the bandgap of silicon rules out pure silicon devices, the noise performance is marginal. This is due to a fundamental device issue that materials with a smaller bandgap sensitive to the longer wavelength have nearly equal hole-to-electron ionization rates. This increases the uncertainty in the multiplication process thus increasing the carrier multiplication noise of the device. Several methods have been suggested to get around this problem. One method given by Capasso *et al* (1983) attempts to artificially tailor the ionization by device structure engineering. Alternatively, photodetector device structures that inherently use the equal ionization rate and still produce very small excess noise have also been proposed by Hollenhorst (1986) and Jindal (1987a).

Photoconductive detectors provide an alternative to their photovoltaic cousins and have been employed typically for long wavelength applications. Dominant noise sources in these detectors, as described by Van der Ziel (1976, p. 146), are generation-recombination noise, $1/f$ noise and thermal noise. Of these, the one that cannot be suppressed conventionally is the GR noise.

A means of tackling the limiting noise in the above devices i.e. excess shot noise in APDs and GR noise in case of photoconductive detectors is provided by noninstantaneous multiplication. In this technique, as proposed by Jindal (1990), one trades off speed for noise, effectively producing noiseless amplification.

6. Electronic amplification

Once the optical signal has been detected, it needs to be amplified before it can be shaped into a pulse and processed digitally. This is done by the analog front end that follows the detector. The analog front end typically consists of a low noise preamplifier and a high adjustable gain post amplifier. Once the signal has passed through this stage, it does not suffer any further deterioration in the signal to noise (S/N) ratio. The noise performance of the front end electronics is limited by several fundamental noise mechanisms. These include the shot noise generated by the discrete nature of electronic charge, thermal noise associated with the random motion of the crystal lattice, supershot noise exhibited by certain avalanche processes, hot carrier noise generated by charge carriers under extremely high electric fields and surface and bulk $1/f$ noise. The relative importance of each noise mechanism is determined by the technology used to fabricate these circuits e.g. Jindal (1987b). For systems operating at 1 gigabit/s and below, silicon MOS technology has demonstrated the required performance, e.g. Jindal (1987c), to meet the system specifications. For higher bit rates demanding low noise performance, compound semiconductor technologies such as GaAs MESFET technology tend to be the choice. As technologies advance, several trends are becoming clear. First, the performance of every technology is improving with time. This is being pushed in part by finer lithography and low temperature processing which is making all technologies faster. As device dimensions shrink, the electric field in these devices also increases. This results in hot carrier effects, a term implying charge carriers with energies well above the thermal energy of lattice. These hot carrier effects not only raise reliability issues but also produce excess noise problems. However, as shown by Jindal (1985), with the application of a fundamental understanding of the device behaviour these effects can be tamed. The net result is that with time the performance of silicon-based electronics is improving and covering higher and higher bit rate systems.

7. Optical amplification

Optical amplifiers, whose concept dates back to the early seventies (as described by Personick 1973), are making their debut in the lightwave arena. Of these, the semiconductor laser amplifiers are either the Fabry–Perot type or the travelling-wave type, the difference being in the facet reflectivity. The fibre-based amplifiers are the travelling-wave type. Optical amplifiers offer a distinct advantage in that they amplify the signal in the optical domain and hence are not tied to a specific bit rate and can amplify several channels at the same time permitting wavelength division multiplexing. However, if these amplifiers are cascaded as is required for long haul applications, the lightwave system has an extremely narrow bandwidth and its span is severely dispersion-limited. The noise mechanisms in an optical amplifier can be classified into five categories. These include (1) amplified signal shot noise, (2) spontaneous emission noise, (3) signal-spontaneous beat noise, (4) spontaneous-spontaneous beat noise, and (5) amplified signal excess noise. Of these, under relatively high gain, the third and the fourth terms dominate. Of these two, the signal-spontaneous beat noise results in a fundamental 3 dB penalty in the noise performance of these amplifiers.

To get around the dispersion problem, the feasibility of soliton transmission is being currently investigated. In conventional systems, as the light pulses travel over the fibre, they suffer both attenuation and distortion. With soliton transmission, which employs small nonlinearities in the refractive index, one can essentially cancel the fibre dispersion and thus preserve the shape of these optical pulses. However, fibre attenuation is still a problem. Hence, these pulses need to be amplified, either in a distributed or lumped manner with noise issues characteristic of optical amplifiers.

8. Conclusions

Lightwave systems continue to improve in performance both in terms of speed, sensitivity and reliability. Communication networks based on this technology will dominate in the foreseeable future. As we approach the fundamental limits, these systems will fuel fundamental research leading to better devices and systems.

The author would like to thank Dr A R Hartman for his support through the documentation phase of this project.

References

Capasso F, Tsang W T, Williams G F 1983 Staircase solid state photomultipliers and avalanche photodiodes with enhanced ionization rates ratio. *IEEE Trans. Electron Devices* 30: 381–390

Hollenhorst J N 1986 Ballistic avalanche photodiodes: Ultra low noise avalanche diodes with nearly equal ionization probabilities. *Appl. Phys. Lett.* 49: 516

Jackel H, Guekos G 1977 High frequency intensity noise spectra of axial mode groups in the radiation from CW GaAlAs laser. *Opt. Quantum Electron.* 9: 233–239

Jindal R P 1985 Invited Paper. *International Electron Devices Meeting Technical Digest* 68–71

Jindal R P 1987a A scheme for ultra low noise avalanche multiplication of fiber optic signals. *IEEE Trans. Electron Devices* 34: 301–304

Jindal R P 1987b General noise considerations for Gb/s rate NMOS FET front end design for FOC systems. *IEEE Trans. Electron Devices* 34: 305–309

Jindal R P 1987c GHz band high gain low noise AGC amplifiers in fine line MOS. *IEEE J. Solid-State Circuits* 22: 512–521

Jindal R P 1990 Operating conventional electronic devices in the noninstantaneous multiplication (amplification) regime. *J. Appl. Phys.* 68: 324–327

Personick S D 1973 Applications for quantum amplifiers in simple digital optical communication systems. *Bell System Tech. J.* 52: 117–133

Schinke D P, Smith R G, Hartman A R 1980 Photodetectors. *Topics in applied physics, 39* (ed.) H Kressel (New York: Springer Verlag) chap. 3

Slusher R E, Yurke B 1990 Squeezed light for coherent communications. *IEEE J. Lightwave Technol.* LT-8: 466–477

Smith R G, Personick S D 1980 Receiver design for FOC systems. *Topics in applied physics, 39* (ed.) H Kressel (New York: Springer Verlag)

Van der Ziel A 1970 *Noise: Sources, characterization, measurement* (New Jersey: Prentice Hall)

Van der Ziel A (ed.) 1976 *Noise in measurements* (New York: John Wiley)