A Model of an Optical Communication System

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The basic principles that underlie the analysis and design of well established digital communication systems [1] are adapted to optical communication systems.

1. Introduction

In the design of communication systems for transmitting information through physical channels, it is convenient to construct mathematical models that reflect the most important characteristics of the transmission medium. Then, the mathematical model for the channel is used in the design of the channel modulator at the transmitter and the demodulator at the receiver. In the case of optical communication systems a model may also help to analyze the laser performance as the characteristics of the output light cannot be measured directly; only the detected electrical signal is a measurable quantity.

2. Elements of an Optical Communication System

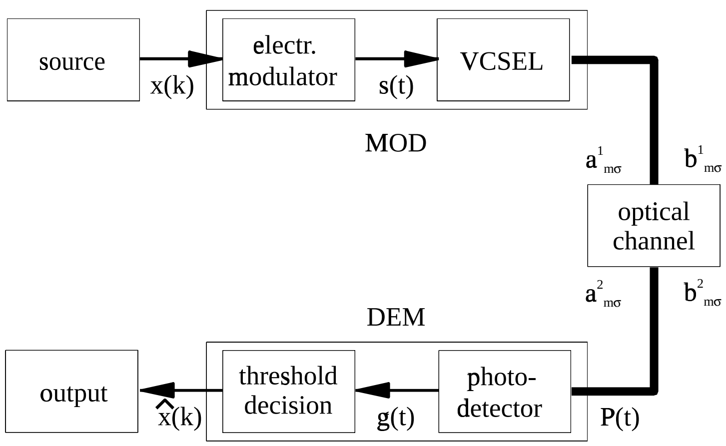

Fig. 1. Basic elements of a digital optical communication system.

Fig. 1 illustrates the functional diagram and the basic elements of a digital optical communication system employing a vertical-cavity surface emitting laser (VCSEL). The information source output $x(k)$ is a digital signal that is discrete in time and often has two output characters. This binary sequence is passed to the digital modulator MOD, which serves as the interface to the optical channel. Since the communication channel is capable of transmitting electromagnetic signals, the primary purpose of the modulator is to map the binary information sequence first into the electrical signal $s(t)$ and afterwards into the optical signal.

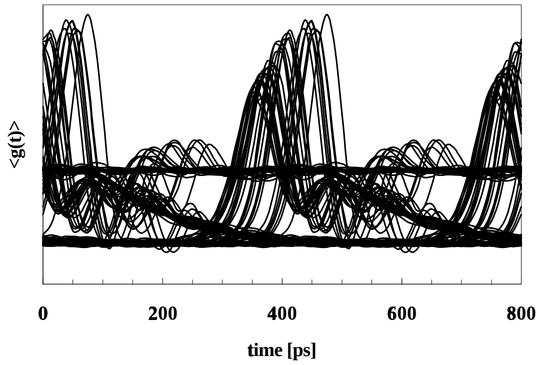

Fig. 2. Eye diagram of a 2.5 Gb/s PRBS 7. The output signal of the VCSEL suffers from the strong relaxation oscillation and the pattern dependence of the turn-on delay.

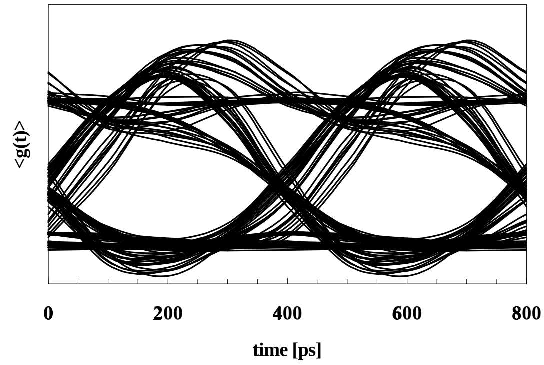

Fig. 3. A narrowband demodulator suppresses the relaxation oscillations shown in the left picture. Still there is the dependence of the turn-on delay on the transmitted pattern.

Mapping the electrical signal into an optical signal can be favorably done by modulating the intensity of a VCSEL with the laser drive current. Turn-on delay and relaxation oscillations are responsible for the intrinsic distortions of the VCSEL, especially for bias-free modulation (see pp. 48–51). Fig. 2 shows an example of an measured eye diagram of the detected electrical signal for 2.5 Gb/s PRBS 7 (pseudo random bit sequence with $2^7 - 1$ different patterns) modulation and a broadband (10 GHz) demodulator. Fortunately the strong relaxation oscillations can be suppressed by using a narrowband (2 GHz) detector as indicated in Fig. 3, but there is still the dependence of the turn-on delay on the transmitted pattern.

The communication channel is the physical medium used to send the signal from the transmitter to the receiver. The essential feature is that the transmitted signal is corrupted in a random manner by a variety of possible mechanisms.

The light signal is treated in a classical manner with normalized modal baseband amplitudes $a^j_{m\sigma}(t)$, which have a magnitude equal to the square root of the optical power and a phase equal to a selected observable such as the electric field [2]. If at some reference plane the reflected waves are characterized by a normalized amplitude $b^j_{m\sigma}(t)$, the net power flowing into port j is

$$P^j(t) = \sum_{m\sigma} \left(|a^j_{m\sigma}(t)|^2 - |b^j_{m\sigma}(t)|^2 \right) \quad , \tag{1}$$

where m is the mode index and σ is the polarization index.

Noise and distortions of the semiconductor laser signal are altered considerably due to the interaction of the laser with the optical channel. The influence of partition noise [3] is important if the channel exhibits material dispersion or if the transmission loss is wavelength-dependent. An interaction with the active medium of the laser occurs if some light is reflected from the channel back to the laser yielding noise and distortions [4]. Forward transmission interferences may occur between different fiber modes (modal noise effects) yielding, also, noise and distortions with respect to the transmitted optical power.

At the receiving end of the digital communication system, the demodulator DEM processes the transmitted waveforms corrupted by the channel and reduces the waveforms to a sequence of numbers $\hat{x}(k)$ that represent estimates of the transmitted data symbols $x(k)$.

A measure of how well the demodulator performs is the frequency with which errors occur in the detected sequence. More precisely, the average probability of a bit error at the output of the demodulator is a measure of the overall system performance. In general, the probability of error is a function of the code characteristics, the types of waveforms used to transmit the information over the channel, the transmitter power, the characteristics of the channel, i.e. the amount of noise, the nature of interference, etc., and the method of demodulation. Some items will be discussed in more detail in the following section.

3. Detection Errors due to Noise

In the previous section light is treated in a completely classical manner; describing the detection of light there is no necessity to deal with quantization of the electromagnetic fields, only the interaction of the classical field and matter has to be quantized [5].

When light, having a deterministic variation of intensity over space and time, is incident on a photodetector, the fluctuations of the photocounts obey a Poisson statistics. In most problems of real interest, however, the light wave incident on the photosurface has stochastic attributes. Any stochastic fluctuations of the classical intensity $P(t)$ do influence the statistical properties of the photon generation process. According to this, the relationship between the variance of the detected electrical signal $\sigma_g^2(t)$ and the averaged received optical power $\alpha\langle P^{ref}(t)\rangle$ has a physical interpretation. The variance consists of three distinct terms:

$$\sigma_g^2(t) = \langle \delta g(t)^2 \rangle = \sigma_{receiver}^2 + \alpha\sigma_{shot}^2(t) + \alpha^2\sigma_{excess}^2(t) \quad . \tag{2}$$

The first term represents the receiver noise, the second can be interpreted as representing the effects of pure Poisson noise introduced by the random interaction of light and matter, also called shot noise. The third term, because it is proportional to the variance of the fluctuations of the incident intensity, is the classically expected result in the absence of any noise associated with the interaction of light and matter (excess fluctuations).

Fig. 4 shows the dependence of the bit error rate (BER) on the averaged received optical power $\alpha\langle P^{ref}(t)\rangle$ with different weighting of receiver, shot and excess noise. Strong classical light fluctuations result in a bit error floor, the performance of the demodulator cannot be improved by increasing the transmitted optical power. In accordance with the simulated BERs, Fig. 4 d) presents a measured BER curve. Excess noise, as a result of strong modal noise created in the optical channel, dominates the BER for power levels above -24 dBm.

4. Conclusions

The simplest mathematical model for a communication channel is the additive noise channel, illustrated in the equation

$$g(t) = \alpha s(t) + n_{receiver}(t) \quad . \tag{3}$$

If the noise is introduced primarily by electronic components and amplifiers at the receiver, it may be characterized as thermal noise. This type of noise is characterized statistically as a Gaussian noise process. Channel attenuation is easily incorporated in the attenuation factor α.

The additive gaussian noise channel does not adequately characterize many of the optical channels encountered in practice. A more accurate model has been presented in this text. The

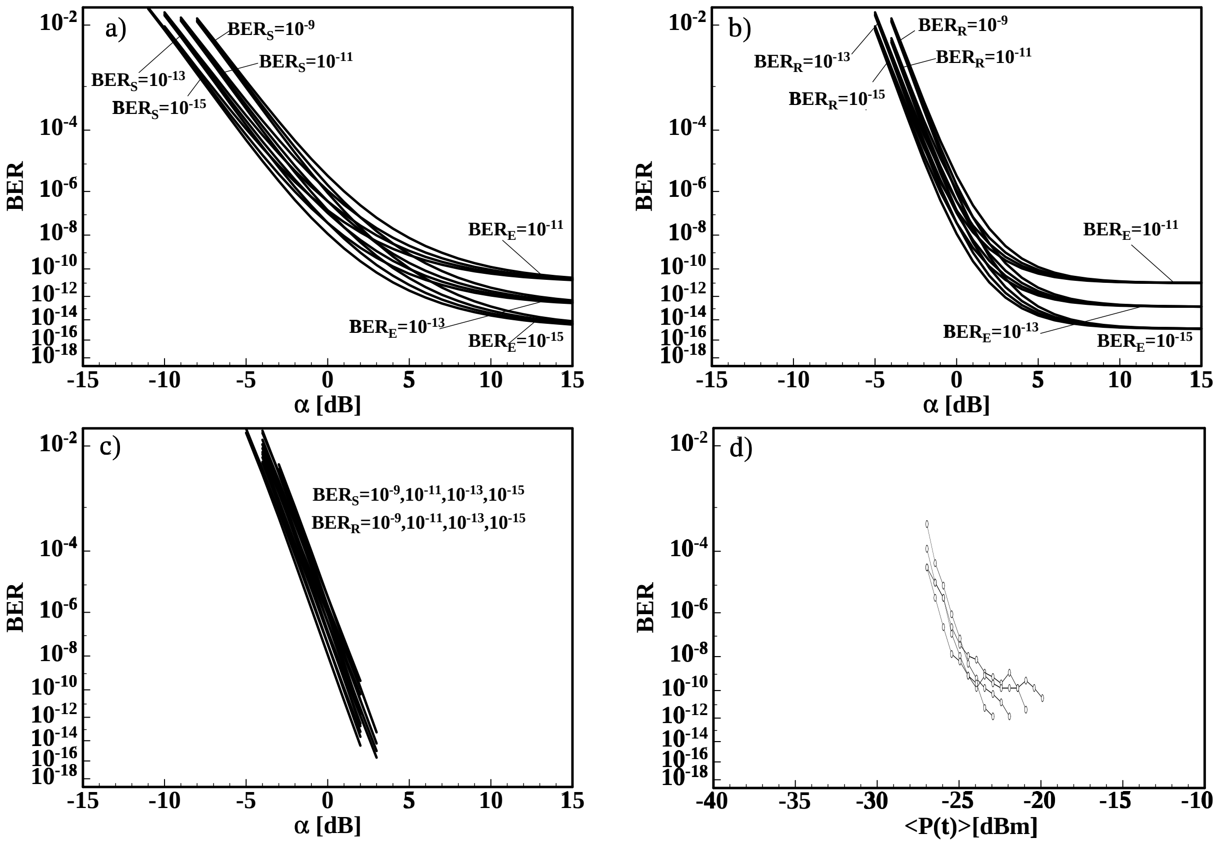

Fig. 4. Dependence of the BER on the received light intensity: a) to c) simulation of different weighting (reference $\alpha = 0$ dB) of receiver noise (R), shot noise (S) and excess noise (E); d) measurement.

statistics of shot noise and excess noise depend on the averaged received optical power, i.e. on the optical attenuation factor α. Linear filters may describe bandwidth limits, relaxation oscillations and the turn-on delay of the laser.

References

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