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A LOW COST MULTILEVEL FIBRE OPTIC TRANSMISSION SYSTEM

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ABSTRACT

The problem of designing a simple, reliable, low cost optical fibre communication system for transmitting multilevel pulse amplitude modulation (PAM) signals is investigated. The main components of the system are a single mode fibre, a semiconductor light emitting diode (LED), and a PIN diode photodetector that is modeled as an ideal photon counter. Analysis of the power requirements, and a typical application as a subscriber transmission system operating in the 1300 nm window are presented.

1.0 INTRODUCTION

It is well known that the many advantages of optical fibre communication enable it to provide a wide range of services to subscribers when used in subscriber transmission systems [1]. These systems range in complexity from the simple single optical transceiver for binary and multi-level signals to more complex lightwave systems comprising call-by-call power activation, pulse frequency modulation (PFM) of the optical pulses which carry frequency division multiplexed (FDM) video, audio and digital signals, with carrier sensing techniques [2].

In this paper, we are concerned with the design and performance evaluation of a simple optical transceiver for multilevel (PAM) signals in so far as receiver sensitivity and transmitter power requirements are concerned. Multilevel transmission is used instead of binary transmission because this is the simplest method of increasing the transmission (information) rate for a given channel bandwidth. Early lightwave communication systems utilised multimode fibres which allowed only limited information bandwidth and repeater spacing [3]. As a result of advances in technology, emphasis has shifted towards the higher bandwidth, lower loss, single mode fibre systems. As a result, the range of potential applications has increased considerably, leading to the utilisation of lightwave systems in highly competitive commercial applications.

As shown in Fig.1, the optical transceiver under consideration utilises a single mode fibre, a light-emitting diode (LED) as the source, and a PIN photodiode as the detector. This system offers the attractive features of reliability, simplicity, and low cost, when compared with the more sensitive laser diode - avalanche photodiode (APD) source - detector combination. When used in the 1300 nm and 1500 nm windows, this system is particularly appealing for the subscriber connection because it offers the additional advantage of allowing for full duplex transmission on a single fibre. In addition, the relatively short distances of the order of 5km that are encountered in subscriber loop applications somewhat limit the potential advantages of higher launched optical power from the laser diode, and higher conversion efficiency of the APD.

The rest of the paper is organised as follows. In Section II the problem under consideration is formulated. In particular we use a well known modified Gaussian distribution to approximate the tail of the Poisson distribution that models the optical received signal and shot noise statistics. Section III is devoted to the development of the procedure for computing the threshold settings at the receiver that correspond to the multilevel transmitted signal. In Section IV a power budget computation example is presented, while conclusions are presented in Section V.

2.0 PROBLEM FORMULATION

The basic elements of the optical fibre communication system discussed in this paper are shown in Fig. 1. In this model the amplifier and resistor R combination acts as a current to voltage converter. In practice this combination may be replaced by a receiving and/or equalization filter in which the receiving filter is matched to the basic pulse shape of the PAM signal.

The basic assumptions used in our analysis of the system are:

1) The LED source has a perfect extinction ratio.
2) The PIN photodiode is modeled as an ideal photon counter.
3) Poisson photoelectron fluctuations.
4) All noise sources in the photodiode are modeled as shot noise.
5) The additive thermal noise, which includes a contribution from the amplifier stage, is assumed to be Gaussian with zero mean and variance σ^2, which can also be expressed as N_σ photoelectrons.

Let N be the average number of photoelectrons generated by the PIN diode per symbol interval. Then applying the third assumption above, it is easy to see that the probability that m photoelectrons are gener-

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ated per symbol interval can be written as

$$P(m) = \frac{N^m e^{-N}}{m!} \qquad (1)$$

which is simply the probability mass function. The variance of the distribution is also N. The (average) PIN diode output current is proportional to the number of photoelectrons, and is given by

$$I = \left(\frac{N_q}{T}\right) \qquad (2)$$

where $q = 1.6 \times 10^{-19}$ C is the charge on an electron, and (1/T) is the symbol rate.

Let us assume that an L-level NRZ PAM signal is to be transmitted. Denote by $N_i (i=1,2,\ldots,L)$, the average number of photoelectrons generated per symbol interval by the PIN diode when the ith signal level is transmitted. In addition, a shot noise component N_d will also be generated in the absence of any signal. This is related to the average dark current I_d as shown in (2). In order to simplify the analysis somewhat, it is assumed that the Poisson shot noise and the Gaussian thermal noise are statistically independent. Furthermore, the Poisson distribution is approximated by a Gaussian distribution. Hence, when expressed in terms of photoelectrons, the output noise is approximately Gaussian with mean N_d and variance $N_d + N_\sigma$, where N_σ is obtained from σ^2_d. Hubbard [4] has obtained a better Gaussian approximation for the tails of the Poisson distribution, which when applied to (1) becomes

$$p(m) = \left(\frac{1}{\sqrt{2\pi N}}\right)^{\frac{1}{(1+\gamma)}} \exp\left(-\frac{\beta}{1+\gamma} - \frac{(m-n)^2}{2N(1+\gamma)}\right) \qquad (3)$$

for the positive tail. It was found that

$$\beta = \left(0.0667\mu^2 - 0.3933\mu + 0.810\right)^{-1} \qquad (4a)$$

and

$$\gamma = \left(0.0800\mu^2 - 0.230\mu + 1.26\right)^{-2} \qquad (4b)$$

where $\mu = \ln(N)$. These results apply to the negative tail also by changing the signs of β and γ. For this approximation the mean remains unchanged but the variance changes to $N(1+\gamma)$. The validity of this approximation, especially for symbol error probabilities in the range 10^{-6} to 10^{-9} (approximately 4 to 6 standard deviations away from the mean) that are normally encountered in digital lightwave communication, is illustrated in Fig.2. When Hubbard's approximation is applied to the Poisson noise, the mean value of the output noise remains unchanged but the variance becomes $N_\sigma + N_d(1+\gamma)$.

In the next section we will develop expressions for the threshold settings $K_i (i=1,2,\ldots,L-1)$ in terms of the observed signal and noise statistics, assuming non-return-to-zero (NRZ) PAM signals.

3.0 THRESHOLD SETTINGS

Let us assume that the first level of the NRZ PAM signal is associated with zero transmitted optical power. From the previous section it is seen that $N1 = N_d$. If we also assume equally likely transmitted pulses and equal conditional error probability for each received level, then the conditional error probability is the same as the (average) symbol error probability. In this case, specifying a value for the desired symbol error probability P_e enables us to obtain a quantity α_i that represents the number of standard deviations away from the mean N_i that the associated threshold setting K_i is located. In particular, because of the Gaussian approximation to the signal and noise statistics, it is well known [5] that

$$P_e = \phi\left(\frac{K_i - N_i}{\sqrt{N_\sigma + N_i(1+\gamma_i)}}\right)\delta_i \qquad (5)$$

$$\triangleq \phi(\alpha_i)\delta_i$$

where ϕ denotes the normal probability integral,

$$\delta_i = \frac{\sqrt{2\pi N_i(1+\gamma_i)}}{(2\pi N_i)^{\frac{1}{2(1+\gamma_i)}}} . e^{-\left(\frac{\beta_i}{(1+\gamma_i)}\right)} \qquad (6)$$

and β_i and γ_i are obtained from (4) by replacing μ with $\mu_i = \ln(N_i)$. The exponential scale factor in (6) is a result of Hubbard's approximation. From (5), the threshold settings that are associated with the L-level signal are

$$K_i = N_1 + \alpha_i\sqrt{N_\sigma + N_i(1+\gamma_i)}, i = 1,2,\ldots,L-1 \qquad (7)$$

where

$$N_i \begin{cases} \dfrac{I_d T}{q} & i = 1 \\ K_{i-1} + \alpha_i \sqrt{N_\sigma + N_i(1+\gamma_i)}, & 1 = 2,3,\ldots,L \end{cases}$$

(8)

The steps involved in computing the threshold settings are:

1) Compute N_1 using (8) based on the desired information rate and dark current of the PIN diode.
2) Use N_1 and the values obtained from the noise statistics to compute K_1 using (7).
3) Using the second expression on the right hand side of (8) and (7), recursively compute N_i then K_i for i starting from 2, up to L-1 for K_i and L for N_i.

These levels can be expressed in terms of currents by using (2). In addition, the threshold settings in Fig.1 are normally expressed in terms of voltages. If we assume a linear current-to-voltage converter following the PIN diode then the voltage levels are just scaled versions of the photoelectron levels that are computed in this section.

4.0 EXAMPLE CALCULATION

The data listed in Table 1 represent typical parameter values of a four-level lightwave communication system, of the type under consideration in this paper, when used as a subscriber transmission system operating at 1.31μm. We will use the data to determine the minimum average LED power required for the system to detect a four-level NRZ PAM signal.

It can be shown that if N photoelectrons on the average are generated by the PIN diode then the received optical power P_r is given by [6]

$$P_r = \frac{N}{cT\left(\dfrac{\lambda}{hv}\right)} \qquad (9)$$

where the variables (other than N) on the right hand side of (9) are explained in Table 1. If the total fibre loss (including losses for connectors and multiplex-demultiplex) and the system margin are denoted by L then the LED power is just LP_r. Now any signal above K_3 will be detected as the fourth level of the transmitted signal. Therefore by replacing N in (9) by K_3, it is easy to see that the minimum average LED power required to detect a four-level NRZ PAM signal is given by

$$P_t = \frac{LK_3}{cT\left(\dfrac{\lambda}{hv}\right)} \qquad (10)$$

From (8), $N_1 = 223$ photoelectrons. Assume that the transmission bandwidth is equal to the baud rate so that

$$N_\sigma = 140\left(\frac{\sigma T}{q}\right)^2 x10^{-12} \qquad (11)$$

$$= 558{,}036 \text{ photoelectrons}^2$$

Now $\mu_1 = 1n(N_1) \approx 5.4$, therefore from (4) $\beta_1 = 1.58$ and $\gamma_1 = 0.18$. From (5) $\phi(\alpha_1) \approx 2.02 x10^{-9}$. Using tables that approximate the normal probability integral we obtain $\alpha_1 = 5.88$. When these values are substituted into (7) we find that $K_1 = 4{,}616$ photoelectrons. Following the steps outlined in Section III we find that in terms of photoelectrons, $N_2 = 9{,}112$, $K_2 = 13{,}607$, $N_3 = 18{,}142$, $K_3 = 22{,}676$, $N_4 = 27{,}251$. Replacing N in (9) by K_3 we see that an average value of at least -32dBm optical received power is required to ensure detection of the four-level NRZ PAM signal for a symbol error rate of 10^{-9}. In practice a margin of 6dB is considered sufficient [7]. Therefore an average optical LED power of -21dBm is required for satisfactory operation. A plot of probability of symbol error versus the minimum average received optical power required for the system to detect a four-level NRZ PAM signal is given in Fig.3 for the data in Table 1 and assuming a 6dB margin.

In this paper it is assumed that no signal transmission is associated with the first level of the multilevel signal. In many cases, such as the transmission of return-to-zero (RZ) signals, it is desirable to separate the noise floor from received signal levels. For the NRZ L-level PAM case, the design procedure is modified to include the computation of the L^{th} threshold setting. Furthermore, the i^{th} transmitted level is associated with observed signals that are above K_i. In this case, an important parameter to be determined is the receiver sensitivity representing the minimum average received optical power to detect level-1 signals. This is determined by replacing N in (8) with K_1.

5.0 CONCLUSIONS

The idea of using multilevel non-return-to-zero pulse amplitude modulation signals in a simple, low cost optical transceiver comprising a LED source, single mode fibre, and PIN diode detector was investigated. The system design was based on power budget considerations only. In practice chromatic dispersion due to the single mode fibre has to be taken into account. However the system is primarily for operation in the subscriber loop where transmission distances are relatively short so that the dispersion should be within tolerable limits. The work shows the potential of this scheme for fibre optic transmission in future fibre subscriber loops.

6.0 ACKNOWLEDGEMENTS

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TABLE 1
PARAMETER VALUES FOR THE FOUR-LEVEL OPTICAL COMMUNICATION SYSTEM UNDER CONSIDERATION.

PARAMETER	VALUE
Symbol Rate (1/T)	140MSymbols
Transmission Distance	5 km
Fibre Loss and Coupling Loss	0.4dB/km
Total Loss over 5 km (L)	11dB
Led Power (avg) (P_T)	-20dBm
Wavelength (λ)	1.31μm
Quantum Efficiency (c)	0.8
Average Dark Current (I_d)	5nA
Average Thermal Current Variance (σ^2)	$2 \times 10^{-6} \mu A^2/MHz$
Conditional Probability of Error	10^{-9}
Charge of an Electron	1.6×10^{-19} C
Planck's Constant (h)	6.63×10^{-34} J s
Velocity of Light (V)	2.998×10^{-8} m/s

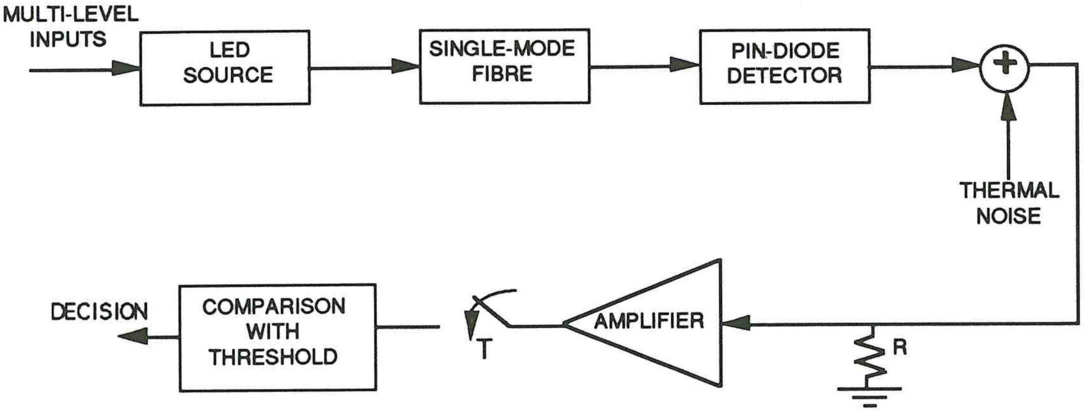

Figure 1. Digital lightwave communication system block diagram for multi-level input signals.

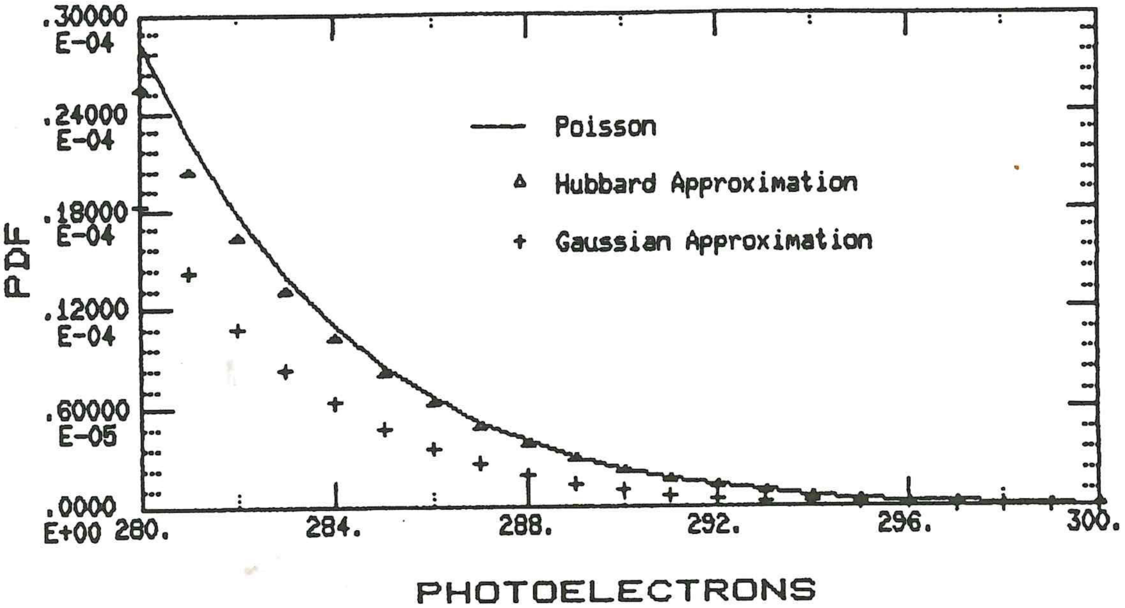

Figure 2. Comparison of the positive going tails of the Poisson and Gaussian probability density functions. (Mean = Variance = 223 for Poission distribution)

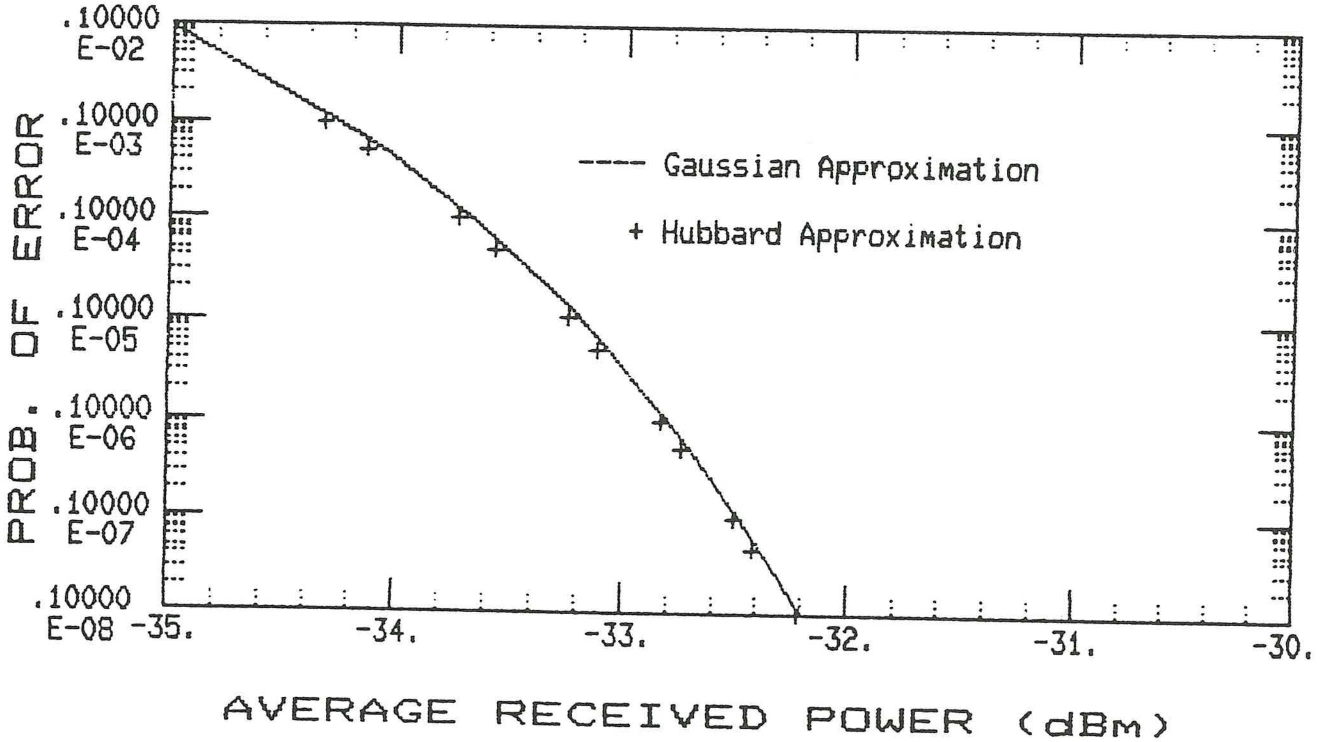

Figure 3. Probability of symbol error versus average received optical power for detecting ar-level NRZ PAM signal.