Inherent Transmission Capacity Penalty of Burst-Mode Receiver for Optical Multiaccess Networks

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***Abstract*— We have performed a mathematical analysis to derive the inherent transmission capacity penalty of burst-mode optical receivers due to the finite holding time constant τ_f of the adaptive threshold control circuit. The fundmental degradation of the system depends on a decay parameter k. For capacity penalty calculation, we propose a criterion that $k \leq 0.25$ for encoded data. The transmission capacity penalty β of the network is given by $\beta = 1/(1 + \mathrm{kN/m} \cdot \ln \alpha_N)$, where N is the number of bits in one packet, α_N is the dynamic range of the receiver, and m is the maximum number of consecutive "0"s in the data pattern. When the data stream is encoded with 4B5B or 5B6B, the capacity penalty is about 12% for ATM packets (424 bits) independent of the bit-rate.**

I. Introduction

FUTURE broadband optical multiaccess networks probably require fast packet switching to support multimedia applications. As the bit rate increases to beyond what electronic processing can comfortably handle, it is increasingly desirable to reduce the amount of regenerative electronic processing at each node. Recent advances in Erbium-doped fiber amplifiers provides an impetus to investigate the feasibility of all-optical multiaccess networks. Such all-optical systems may include passive optical network (PON), LAN, MAN and other computer networks [1].

One of the important building blocks of these all-optical multiaccess networks is burst-mode receivers [2], [3]. Since any node can use a designated time slot to send a packet to some other nodes, the amplitude and phase of the received packets can be quite different from packet to packet due to different fiber attenuation and dispersion. This problem becomes especially serious in supercomputer interconnect because of the short burst length of data. Conventional optical receivers are unsuitable for this kind of applications because of the AC-coupling in the receiver and the fixed threshold level. By employing DC-coupling with adaptive threshold control [2], [3], burst-mode optical receivers can surmount this problem. The threshold and phase alignment can be established in the receiver using a few preamble bits in the beginning of a burst.

Figure 1 shows the circuit model of a burst-mode receiver. The model is based on [3]. It is very similar to the conventional receiver, except that the detection threshold has to vary with the instantaneous peak amplitude of the incoming packet. Ref. [3] demonstrated a technique in which the threshold V_{th} is determined by a peak detector circuit using a sample-and-hold mechanism.

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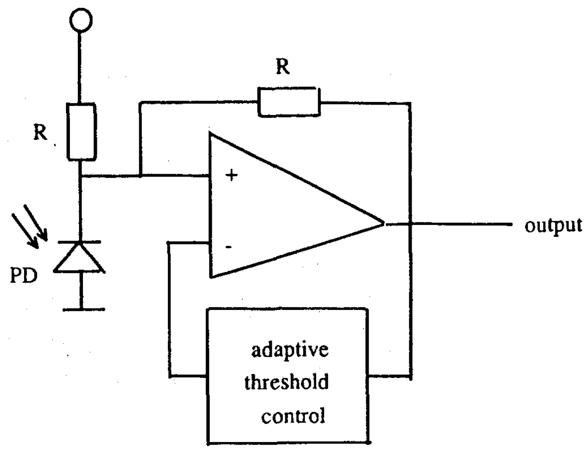

Fig. 1. Schematics of a burst-mode receiver.

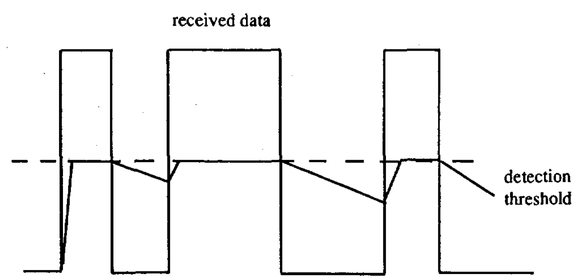

Fig. 2. The threshold of a burst-mode receiver varies accordingto the incoming data pattern. The dashed lines and solid lines arethe thresholds for the conventional and burst-mode receivers respectively.

It is important to reduce the gap time between two consecutive packets to increase the transmission efficiency. This can be achieved by reducing the holding time constant of the adaptive threshold control circuit. However, there is a fundamental conflict between the reduction of the holding time constant and the BER performance of the transmission. This is because long strings of "0"s and "1"s inevitably will occur in the data pattern. When a small holding time constant τ_f is used in the adaptive threshold control circuit, the gap time can be reduced but these consecutive "0"s in the data pattern will cause BER degradations since the threshold level continuously changes according to the incoming data pattern as shown in Fig. 2.

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In this paper we analyze the inherent tranmission capacity penalty of burst-mode optical receiver due to the holding time constant τ_f of the adaptive threshold control circuit. We show that the fundmental degradation of the system depends on a decay parameter $k = t_0/\tau_f$, where t_0 is the time-interval of maximum number of consecutive "0"s that may occur in the data pattern. We also show that there is a tradeoff between the transmission capacity penalty and the power penalty of the system.

For transmission capacity penalty calculation, we propose a criterion $k \leq 0.25$ for encoded data. For this value of k, the capacity penalty β of the network is given by $\beta = 1/(1 + \text{kN/m} \cdot \ln \alpha_N)$, where N is the number of bits in one packet, α_N is the dynamic range of the receiver, and m is the maximum number of consecutive "0"s in the data pattern. The corresponding power penalty of the system is 1 dB. When the data stream is encoded with 4B5B or 5B6B, the capacity penalty for the network is about 5% for $N = 1$ Kbit and 12% for ATM packets (424 bits) independent of the bit-rate.

II. BER Performance of Burst-Mode Receivers

In general, the BER performance of burst-mode receivers are affected by both the adaptive threshold control circuit and the carrier recovery circuit. In this paper we are only concerned about the effect of the adaptive threshold control circuit in the burst-mode receiver. Fig. 2 shows the variation of V_{th} of a burst-mode receiver versus the packet amplitude. The threshold for the burst-mode receiver $V_{\text{th}}[N,t]$ can be represented by a Markov process

$$V_{\text{th}}[N,t] = \begin{cases} V_{\text{th}}[N-1,T]\exp(-t/\tau_f) & a(N) = \text{"0"} \\ V_{\text{th}}[N-1,T] + \{\frac{V_1}{2} - V_{\text{th}}[N-1,T]\} & \\ (1-\exp(-t/\tau_r)) & a(N) = \text{"1"} \end{cases} \tag{1}$$

where $V_{\text{th}}[N,t]$ is the threshold voltage at time t in the N-th bit-interval, t is measured with respect to the start of each bit-interval, i.e., $0 \leq t \leq T$, T is the bit-interval, $a(N)$ is the symbol ("0" or "1") for the N-th bit, τ_f and τ_r are the holding (discharge) time and rising time constant of the adaptive threshold control circuit, and V_1 is the voltage level for "1". The voltage level for "0" is taken to be zero for simplicity.

It is well known that for a conventional optical receiver, the BER is

$$P_e = P(0)P(1 \mid 0) + P(1)P(0 \mid 1), \tag{2}$$

where $P(0), P(1)$ are the probability of logic "0" and "1" respectively, $P(1|0)$ is the probability of "1" when a "0" is transmitted and $P(0|1)$ is the probability of "0" when a "1" is transmitted. In an optical network employing burst-mode receivers, ideally, the error performance of a burst-mode receiver should be the same as a conventional receiver once the connection between two nodes is established. However, because of the finite rising time and holding time constant of the adaptive threshold control circuit, the threshold level is not constant but fluctuate around the ideal V_{th} according to the incoming data pattern as shown in Fig. 2, thus causing a degradation in the BER performance.

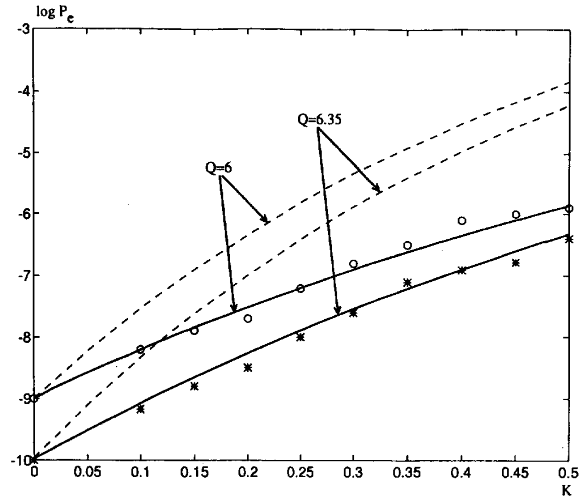

Fig. 3. BER performance of burst-mode receiver versus the decay parameter k. The dashed lines are the upper bounds computed from (4) and the solid lines are the result from the simulation experiment.

For the adaptive threshold control circuit, usually $\tau_f \gg \tau_r$, so the error probablity of the receiver caused by τ_r is small and can be neglected. The worst case occurs at the time when a large number of consecutive "0"s appear in the data pattern of the packet. In this case, the BER P_e of the symbols occurring immediately after the consecutive "0"s is given by:

$$P_e = \int_{V_{\text{th}}[N,T]}^{\infty} \frac{1}{\sqrt{2\pi}\sigma} \exp(-(V - V_0)^2/2\sigma^2)dV, \tag{3}$$

where σ is the r.m.s. noise in the receiver, t_0 is the time duration of the consecutive "0"s, and V_0 is the voltage for logic "0". For a maximum of m consecutive "0"s in the encoded signal, $t_0 = m/B$, where B is the bit rate of the network. When the system has a good optical extinction ratio and a large signal to noise ratio (SNR),

$$\begin{aligned} P_e &= \frac{1}{\sqrt{\pi}} \int_{Q\exp(-t_0/\tau_f)/\sqrt{2}}^{\infty} \exp(-x^2)dx \\ &\approx \exp(t_0/\tau_f) \frac{\exp[-(Q\exp(-t_0/\tau_f))^2/2]}{\sqrt{2\pi}Q}, \end{aligned} \tag{4}$$

where Q is the average SNR at the detector. For a BER of 10^{-9}, $Q \approx 6$ for a conventional receiver.

III. Transmission Capacity Penalty

Let us define a decay parameter $k = t_0/\tau_f$. P_e obviously depends on k as shown in Eqt. (4). From Eqt. (4) one can compute the P_e versus k. The result is shown by the dashed curves in Fig. 3. It can be seen that for a power penalty of 1 dB or less (which corresponds to $P_e \approx 10^{-7}$), k should be less than 0.11.

However, if one uses this value of k to compute the transmission capacity penalty, the result is only an upper bound for the capacity penalty. This is because P_e defined above is the BER of those symbols occurring immediately after a

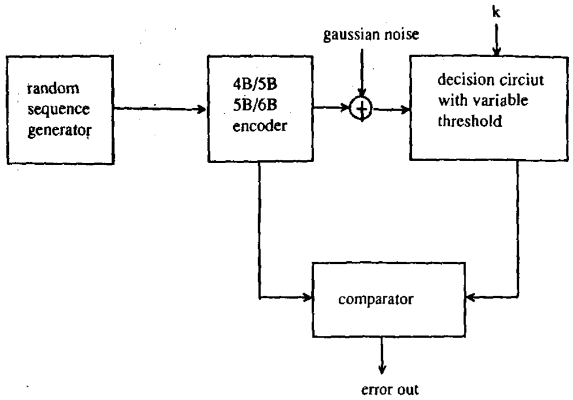

Fig. 4. Simulation experiment for burst-mode receiver with different decay parameter k.

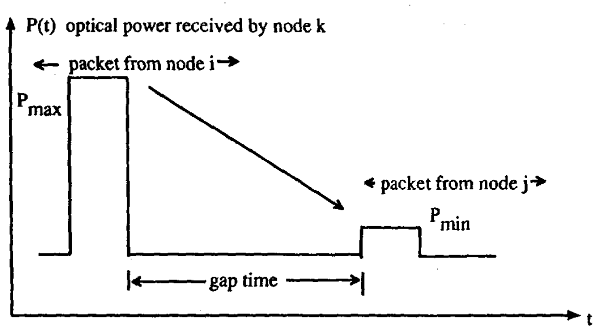

Fig. 5. The worst case for threshold shifting of a burst-mode receiver.

long string (m) of "0"s in the data pattern, and is not the conventional BER.

In order to obtain a more precise value for k, we performed the following simulation experiment as shown in Fig. 4. A pseudo-random binary sequence is first generated. The sequence goes through a 4B5B encoder and Gaussian noise is added. From the resulting waveform, we use the Markov relation of (1) to determine the instantaneous decision threshold. This threshold is used to determine the bit value of the noise-added sequence. By comparing the output sequence with the original input, we obtain the BER. The solid curves in Fig. 3 show the simulation results for the BER degradation versus k. It is seen that for a power penalty of 1 dB, k should be less than 0.25. The curves for $Q = 6$ and 6.35 correspond to input BER of 10^{-9} and 10^{-10} respectively. One can also interpret the tradeoff between the capacity penalty and the power penalty from these curves. A small capacity penalty implies a large power penalty and vice versa.

Fig. 5 shows two packets transferred from node i and node j to node k. The worst case of threshold change is when the first packet has a maximum received power and the second packet has the minimum, which requires a maximum discharge time for the adaptive threshold control circuit to reestablish the new threshold level. The maximum discharge time Δt_N is related to the maximum and minimum voltage amplitude $V_{\text{th max}}$ and $V_{\text{th min}}$ of the incoming data by

$$V_{\text{th min}} = V_{\text{th max}} \exp(-\Delta t_N/\tau_f). \tag{5}$$

Thus, the gap time t_g between two packets should be

$$t_g \geq \Delta t_N = \tau_f \ln \alpha_N, \tag{6}$$

where α_N is the dynamic range of the receiver. The channel utilization of the network is defined as:

$$\begin{aligned} \text{channel utilization} &\, \frac{= \text{packet length}}{\text{gap time} + \text{packet length}} \\ &= \frac{1}{1 + m \ln \alpha_N / kN}, \end{aligned} \tag{7}$$

where N is the number of bits in one packet. Alternatively, the capacity penalty β is:

$$\beta = 1 - \text{channel utilization} = \frac{1}{1 + kN/m \ln \alpha_N}, \tag{8}$$

Eq. (8) can be used to calculate the information transmission efficiency of the network. When the length of the packet and the dynamic range of the receiver are given, the capacity penalty is directly determined by the number of consecutive "0"s in the packet.

As an example, let the bit rate of the network be 1 Gb/s and the data pattern be 4B5B or 5B6B encoded. Let the packet length be 1 kbit and the dynamic range of receiver be 20 dB. For a typical 4B5B or 5B6B data format (such as that produced by an Am7968 IC), the number of consective "0"s is three. Under the condition that the power penalty be ≤ 1 dB at a BER of 10^{-9}, $\tau_f = t_0/k = 12$ ns, $t_g = \tau_f \ln \alpha_N = 55$ ns and the capacity penalty is about 5%. For ATM packets, the capacity penalty is about 12% independent of the bit-rate.

IV. Discussions

Fig. 2 shows that the decay rate of the threshold depends on τ_f. When a very long string of 0's occurs in the data pattern or gap time, the threshold would be completely discharged which could make the receiver output oscillate. This problem has been solved in [3] by offseting the threshold to force the receiver to a well-defined zero output, but it results in an extra power penalty. We have not considered this complication in this simple analysis.

Fig. 3 clearly shows that the decay parameter $k = t_0/\tau_f$ determines the power and capacity penalty of a burst-mode optical receiver. By increasing τ_f, the power penalty can be reduced but a large gap time would be required causing degradations in the information transmission efficiency of the network. For fixed-size packets (say ATM), this difficulty can be resolved by counting the number of bits in a packet, and a "reset" signal can be used to accelerate the discharge time of the peak detector. However, by using this method, the burst-mode receiver will not be compatible with conventional receivers and also a high performance burst-mode clock extraction circuit is needed. For variable-size packets, there does not seem to exist any satisfactory solution to eliminate the capacity penalty for the network.

In conclusion, we have analyzed the transmission capacity penalty of burst-mode optical receivers versus the holding time constant τ_f of the adaptive threshold control circuit. For a power penalty less than 1 dB at a BER of 10^{-9}, the decay parameter k should be smaller than 0.25. When the data stream is encoded with 4B5B or 5B6B, the capacity penalty can be as high as 12% for ATM packets independent of the bit-rate.

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