BER Performance of Digital Optical Burst-Mode Receiver in TDMA All Optical Multiaccess Network

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We have extended our previously proposed theoretical model for burst-mode receivers to compute the BER performance for both unencoded (NRZ) and coded (mBnB) signals under adaptive threshold variation. The theoretical model agrees well with the simulation results and provides a natural explanation for the observed power penalty of previously reported burst-mode receivers.

I. INTRODUCTION

RECENTLY there is a lot of interest in high bit-rate burst-mode receivers [1]–[4]. These receivers are intended for the future broadband all optical multiaccess and multimedia networks in which various nodes communicate with one another via short bursts (or packets) of data. It is important to understand the system performance of such receivers since they are considerably different from conventional receivers [3]. A previous attempt [2] only gave an understanding of the BER penalty due to the length of the preamble field of the packet.

It was recently shown [3] that the decay time constant of the adaptive threshold control circuit in the receiver can contribute significantly to the system penalty. However, the previous framework only provides: 1) an upper bound of the BER performance for random data sequence under additive gaussian white noise, and 2) the exact BER performance for random data sequence encoded into a line code (e.g., 4B5B or 5B6B). In this paper we provide a more complete framework for the computation of BER penalty, which can be applied to unencoded NRZ data as well as line coded data. The theoretical model can be used to explain the observed power penalty of previously reported burst-mode receivers [5]. We believe this is the first attempt to quantitatively explain the observed power penalty.

II. MODEL AND ANALYSIS

We define the BER of a burst-mode receiver as

$$P_e = P(0)P_{e0} + P(1)P_{e1}, \tag{1}$$

where $P(0), P(1)$ are the probabilities of "0's" and "1's" appearing in the data pattern, P_{e0} and P_{e1} are the error probabilities caused by "1's" and "0's" in the burst-mode receiver.

We shall use the same burst-mode receiver model as that of [1] or [3]. A peak detection circuit is employed by the

receiver to detect the amplitude of the incoming signal for adaptively setting the detection threshold. It is understood that the holding time constant of the peak detection circuit (τ_f) is much larger than the rising time constant (τ_r), i.e., $\tau_f \gg \tau_r$. Assuming $\tau_r < 1/B$, where B is the bit rate of the data link, the BER caused by erroneous "0's" should be the same as that of the conventional receivers. That is, $P_{e1} = P_{e1c}$, where the subscript c denotes the BER of a conventional receiver.

However, $P_{e0} \neq P_{e0c}$. This is because the detection threshold depends on the holding time constant τ_f of the peak detection circuit. When there is a large number of consecutive "0's" in the input data, the threshold will decay rapidly, reducing the signal-to-noise ratio (SNR) of the receiver [3]. Thus, a power penalty is introduced, i.e., $P_{e0} > P_{e0c}$.

The threshold of a burst-mode receiver is determined by a Markov process $V_{th}[m, t]$ [3], where m is the relative position of the bit under consideration in a sequence of consecutive "0's", and t is the time reference within the bit interval. For a long string of consecutive "0's" appearing in the input signal, the average threshold for the m-th bit is given by

$$\bar{V}_{th}[m] = \frac{1}{T} \int_{(m-1)T}^{mT} V_{th}[m, t]dt = \frac{(e^{-(m-1)K} - e^{-mK})V_c}{K}, \tag{2}$$

where $K = \frac{T}{\tau_f}$, and V_c is the optimal threshold for a conventional receiver. The decay parameter K has been redefined. It is related to the decay parameter k introduced in [3] by the relation $k = M \times K$, where M is the maximum number of consecutive "0's" in an encoded data pattern.

If we assume the network operates with a good extinction ratio, i.e., $V_{on} \gg V_{off}$, *then* the Q-factor of the m-th bit in a consecutive string of "0's" is

$$Q[m] = \frac{\bar{V}_{th}[m] - V_{off}}{\sigma_0} = \frac{(e^{-(m-1)K} - e^{-mK}) \times Q_c}{K}, \tag{3}$$

where Q_c and $Q[m]$ are the Q-factors for conventional and burst-mode *receivers* respectively, and σ_0 is the RMS noise voltage for "0's".

For a pseudo-random input signal with $N = 2^n - 1$, where N is the length of the pseudo-random number sequence (PRNS), the ratio of "0"-bits contained in strings of i consecutive "0's" relative to N is $\frac{1}{2^{i+1}}$. The average BER can thus be expressed as

$$P_e = P(1)P_{e1} + P(0)P_{e0} = P(1)P_{e1} + \sum_{i=1}^{n} \frac{1}{2^{i+1}} \frac{1}{i} \sum_{j=1}^{i} P_{e0j}, \tag{4}$$
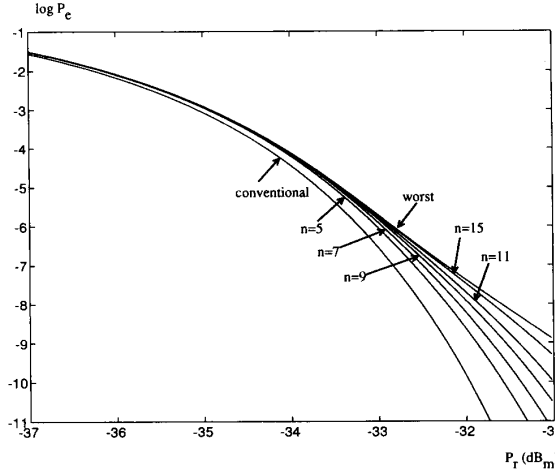
Fig. 1.   BER versus received power for unencoded NRZ signal $N = 2^n - 1$. The decay parameter $K = 0.05$.

Fig. 2.   BER versus the decay parameter K for unencoded data $N = 2^n - 1$ at the same Q. ($Q = 6$ response to BER $= 10^{-9}$ for conventional receiver).

where

$$P_{e0j} = \int_{V_{th}[j]}^{\infty} \frac{1}{\sqrt{2\pi}\sigma} \exp(-(V - V_{off})^2/2\sigma^2)dV$$

$$= \frac{\exp(-Q^2[j]/2)}{\sqrt{2\pi}Q[j]}. \tag{5}$$

In Fig. 1 is shown the BER P_e versus the optical received power P_r for unencoded NRZ data. In this figure, we assume that the bit rate B of the data link is 1 Gb/s, the input impedance and the noise figure F_n of the pre-amplifier are 1 KΩ and 1.7 dB, and the responsivity R of the photo-detector is 1 A/W. The BER performance of the receiver depends on the length of the PRNS N. For $N = 2^{15} - 1$ and $K = 0.05$, the power penalty is 1 dB at a BER of 10^{-9}. In Fig. 2 is shown the BER versus the decay parameter K for the same PRNS. For $N = 2^n - 1$ ($n = 5, 7, 9, 11, 15$), the required K values are 0.08, 0.06, 0.053, 0.05, and 0.048 respectively at a BER $= 10^{-9}$ and a power penalty of ≤ 1 dB . This means that a short pseudo-random length of unencoded NRZ signal can reduce τ_f of the receiver and thus the capacity penalty of the network. From Fig. 1, the BER performance will approach the worst case when $n \geq 15$. In Figs. 1 and 2, it is shown that because of the strong improbability of long strings of zeros, the BER for unencoded data does not diverge for a nonzero decay parameter as the maximum length of zeros goes to the infinite because of the strong improbability of long strings of zeros.

For a typical 4B5B or 5B6B encoded data format (such as that provided by Am 7968 IC from AMD), statistical distributions for consecutive "0"s are obtained by simulation and results are shown in Table I. The BER for these encoded data is

$$P_e = P(1)P_{e1} + P_1 P_{e01} + P_2 \sum_{i=1}^{2} P_{e0i}/2 + P_3 \sum_{i=1}^{3} P_{e0i}/3, \tag{6}$$

Fig. 3 shows P_e versus the received power P_r for 4B5B or 5B6B encoded data. It is shown that for these two data *formats*, 4B5B has a slightly better BER performance. The
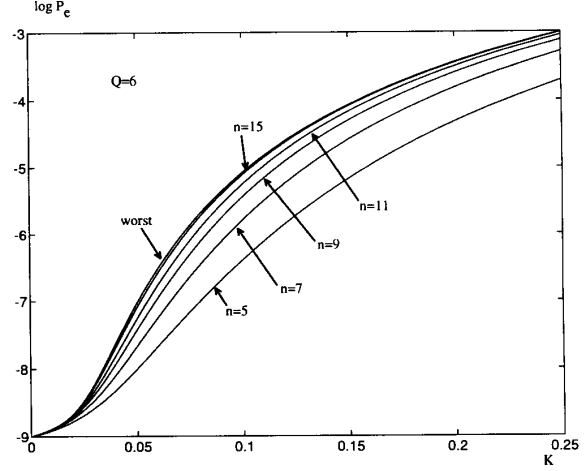
TABLE I
THE DISTRIBUTION OF CONSECUTIVE "0's" IN ENCODED 4B5B AND 5B6B DATA

ratio "0"s in data	4B5B	5B6B
P_1("0")	0.21	0.18
P_2("00")	0.079	0.071
P_3("000")	0.008	0.02

relationship between the decay parameter K and P_e is shown in Fig. 4. Here, we compare the simulation results shown in [3] with the present theoretical results for different data *formats* under the same SNR ($Q = 6$ which corresponds to a BER of 10^{-9} for conventional receivers). The theoretical curves agree with the simulation results very well. In the simulation, we use $N = 2^{23} - 1$ pseudo-random signal generator to produce an unencoded NRZ data stream, thus the simulation result approaches the upper boundary.

We can use the above equations to evaluate the power penalty versus K and the results are shown in Fig. 5. For a power penalty of 1 dB at a BER of 10^{-9}, K must be ≤ 0.05, 0.1, and 0.12 for *unencoded* data (PRNS $N = 2^7 - 1$), 4B5B and 5B6B respectively. The decay parameter k for the 4B5B encoded data is $k = mK = 0.3$ (since $m = 3$) which agrees with the result shown in Ref. [3]. We can also use Fig. 5 to predict the K parameter from the power penalty of a recently published burst-mode receiver [5]. K should be ≈ 0.06 for a penalty of 1.5 dB (PRNS $N = 2^9 - 1$).

III. DISCUSSION

In the above analysis, we have evaluated the BER performance of the burst-mode receiver without considering the effect of *accumulated CW* optical power (or extinction ratio) *from unmodulated optical sources* in the optical bus. In reality, all transmitters have some residual CW optical power coupled into the fiber even when they are not transmitting due to
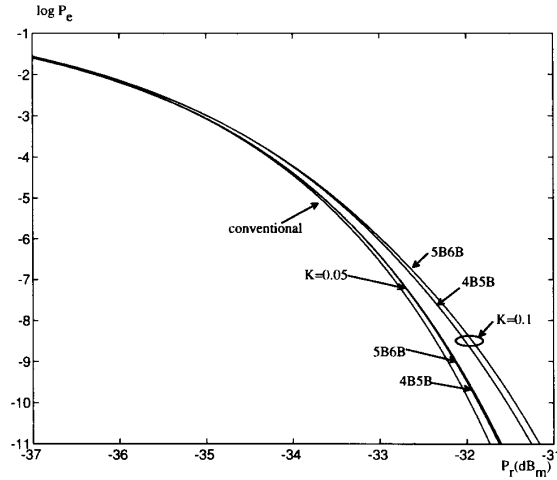
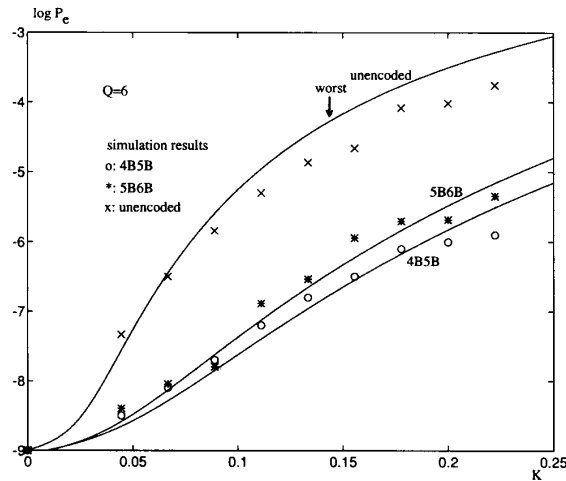Fig. 3. BER versus received power for 4B5B and 5B6B encoded data. The decay parameter $K = 0.05$ and 0.1.

Fig. 5. Power penalty versus the decay parameter K for unencoded and encoded data when $Q = 6$.

Fig. 4. BER versus the decay parameter K. The comparison of simulation results and theoretical model (solid line) for different data format with the same Q.

the extinction ratio. All these residual *CW powers* from different nodes will accumulate and could seriously degrade the performance of the receiver. The extinction ratio $\alpha = V_{off}/V_{on}$ of the receiver changes with the amplitude of the input and the worst case is when the input is at its minimum. In this case, $Q[m, \alpha]$ is:

$$Q[m, \alpha] = Q_c \times \left(\frac{1 + \alpha}{1 - \alpha} \times \frac{e^{-(m-1)K} - e^{-mK}}{K} - \frac{2\alpha}{1 - \alpha} \right). \tag{7}$$

The power penalty of a burst-mode receiver relative to the conventional receiver due to the extinction ratio can be obtained by using (4) and (6). For the same extinction ratio α, the power penalty for encoded data is less than unencoded
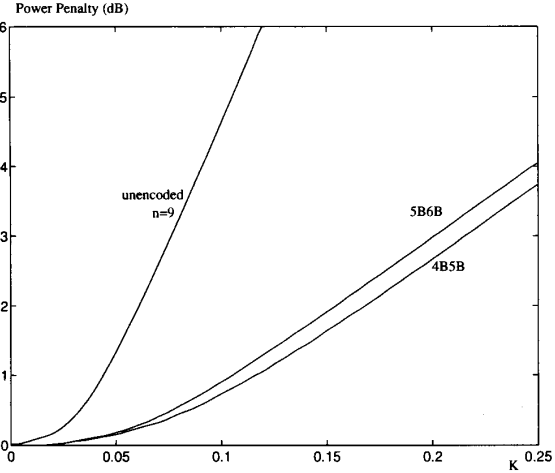
data. When α is 0.1, the power penalty is 1.2, 1.4, and 2.1 dB for 4B5B, 5B6B, and unencoded data, respectively. The BER performance will be greatly degraded by a large extinction ratio. A solution to reduce this power penalty is to use a dark-level compensator subcircuit to automatically measure and subtract out the signal due to background light [4].

In conclusion, we have proposed a more complete theoretical model for the BER penalty calculation of digital optical burst-mode receivers employed in a multiaccess TDMA network. This model can be applied to unencoded (NRZ) data as well as line coded (mBnB) data. The theoretical results agree well with the simulation results and *the model* can be used to explain the observed power penalty of previously reported burst-mode receivers [5].

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