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A Power Efficient Modulation Technique for High-Speed Communication over Wired Channels

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***Abstract*—High speed communication systems play an important role in the development of advanced networks. The optimum design of these communication links under bandwidth and power constraints needs the use of efficient approaches. In this paper, a novel power efficient modulation scheme is introduced. For this purpose, the modulator at the transmitter uses simple and effective pulse shaping functions to change the amplitude and width of the transmitter pulse. Using this simple method, a high power efficient transceiver structure, with the same performance as typical NRZ signaling, can be designed. Our results show that not only we can reduce the power consumption by more than 10% without loosing the performance but also the probability of error is improved in the presence of jitter and interference.**

Keywords: Low Power, High Speed, Pulse Shaping, Eye Diagram.

I. Introduction

Providing an efficient and reliable infrastructure is a crucial need for the development of Information Communication Technologies (ICT). High speed wired communication systems form a very important part of this infrastructure. In fact, today's multi-Gbps wired communication links, including chip-to-chip and system-to-system communication links, are the fundamental backbone of the exchanging of information in the world wide data communication networks. Accordingly, the low power design of the essential elements of high speed communication links is very important in moving toward energy efficient ICTs. In addition, low power high speed communication systems are of great importance in the development of the next generation of communication systems where the requirement of portability plays a crucial role; and consequently, power consumption is becoming a limiting factor in the amount of functionality that can be placed on portable devices [1], [2], [5].

Wired communication systems use a variety of media, including Twisted pair wire, Coaxial cable and Microstrip on printed circuit board, for carrying information. In high speed digital communication systems, these channels are recognized as bandwidth and power limited channels. The propagation of a signal along these channels are limited by two factors including conductor loss and dielectric loss, resulting in the generation of severe ISI in these systems. The presence of random impairments (e.g. noise, interference and jitter) and the variations at different levels (system and communication link variations) of the communication system are other factors that limit the performance of these communication systems. Therefore, the design of a power efficient communication system requires effective approaches to adaptively minimize the effect of these limitations and increase the efficiency of the system [3], [4], [5], [6].

For this purpose, there are different techniques at different levels, which can be applied at transmitter and receiver, to achieve power efficiency [2], [5]. An optimal low power design of communication systems, embodies optimization of the power consumption at all levels of design flow. From system level design perspective and in the absence of the usage of complex algorithms (due to real-time requirements in high speed communication systems) the low power design of the physical layer of high speed communication systems includes all methodologies and techniques which the power consumption can be saved while the exchanging of a known amount of information in a certain amount of time and with a specific quality is achievable [1]. Adaptive channel equalization [4], [7], [8], [9] (by compensating channel attenuation) and adaptive power efficient modulation methods [1], [5] are two well known techniques to achieve power efficiency in high-speed communication systems.

In this paper, a novel power efficient modulation scheme for data communication over high speed channels is introduced. In this method, the modulator at the transmitter uses simple and effective adaptive pulse shaping functions to change the amplitude and width of the transmitter pulse. For this purpose, an eye monitoring system along with a feedback channel can be utilized to adapt the parameters of the system based on the variations of the channel or system. Using this simple method, a high power efficient transceiver structure, with the same performance as typical NRZ signaling, can be designed. Such a technique, transfers the complexity of the system to the transmitter; therefore, the structure of the receiver is simplified which is very important factor in high communication links.

Our simulation results, on a real backplane channel, show that not only we can reduce the power consumption by more than 10% without loosing the performance but also the probability of error is improved in the presence of jitter and interference. This technique can be used in the design of the internal circuits of a vraiety of systems from backplane routers to mobile/portable devices. Therefore, it can play an important role in moving toward energy efficient ICTs.

The rest of this paper is organized as follows. First, the general block diagram and the characteristics of the system

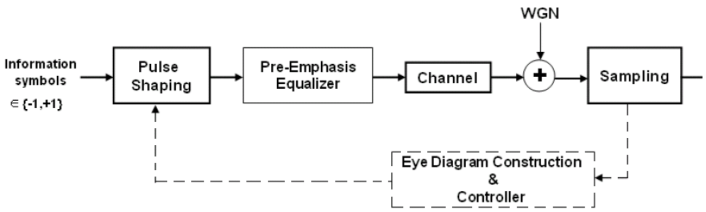


Fig. 1. The general block diagram of the system.

are described. Then, the main idea is examined by defining an optimization problem to determine the optimal parameters of the transmitted pulse. Next, the application of the power efficient modulation scheme on a real backplane channel is demonstrated. Finally, conclusion summarizes the main results of the paper.

II. General System Description

Fig.1 shows the general block diagram of our system. In this system, the pulse shaping module (digital modulator) adaptively changes the amplitude and the width of the transmitted pulse to achieve desired eye opening and, also, higher power efficiency. The adaptive control of the pulse parameters are based on the monitoring of Eye Diagram (ED) opening at the receiver and feeding back appropriate control signals; note that considering the fact that wired channels are slowly varying channels, this controller could periodically work. Fig.2 shows the characteristics of a real backplane channel, used in this system. In this paper, the main focus is on achieving higher power efficiency using simple and effective modulation schemes. Examples of eye diagram monitoring structures have been proposed in [10], [11].

For this purpose, we first investigate the relationship between the Vertical Eye Opening (VEO) and Horizontal Eye Opening (HEO) with the amplitude of the transmitted pulse. Fig.3 indicates this relationship as the amplitude of the transmitted pulse varies from 1-5 volts; (signal bandwidths B are 3GHz and 6GHz, respectively). As we expected, the VEO is a linear function of the amplitude of the transmitted pulse; however, the HEO is not a function of transmitted pulse amplitude. Also, note that by the increase of information bandwidth the VEO and HEO are decreased, due to the increase of channel attenuation.

III. Pulse Parameter Optimization

Lets consider three different pulses shown in Fig.4(a). Considering Fig.4(b), it is clear that the more narrow pulses experience less distortions as they pass through a ISI-limited dispersive channel. Fig.4(c-e) show the ED of a typical NRZ signaling over our backplane channel when the pulse shaping functions are pulses shown in Fig.4(a).

Table.I indicates that the VEO is a function of the pulse amplitude and the HEO increases by decreasing pulse width; also, the power of the pulse increases from pulse1 to pulse3. To investigate the robustness against sampling jitter, we define Jitter Tolerance JT (in percentage) as the opening of ED at

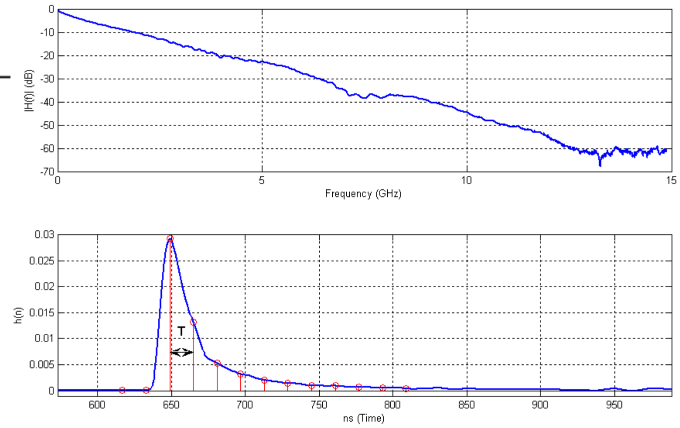


Fig. 2. The characteristics of the backplane channel in frequency and time ($T = \frac{1}{B} = 166.67ps$).

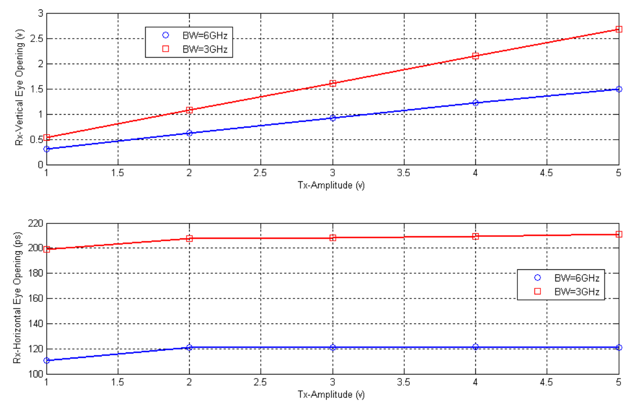


Fig. 3. VEO and HEO vs. pulse-amplitude.

the 90% of its amplitude peak divided by the pulse width T. Table.I expresses the improvement of jitter tolerance by increasing the pulse amplitude and decreaing the pulse width.

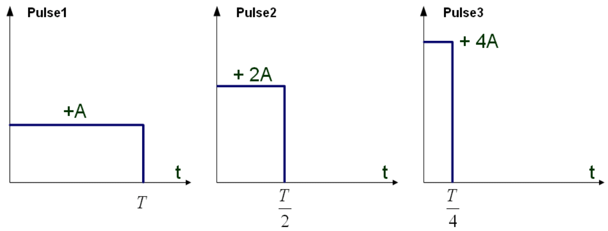
Now the question is: Can we find an optimum pulse amplitude and pulse width so that we can achieve power efficiency without loosing the performance? To examine this idea, first, lets model the communication channel by a low-pass RC filter with transfer function $H(s) = \frac{1}{1+RCs}$ (Fig.5). Assuming the input signal $V_i(t)$ is the pulse with amplitude a and duration τ, then output voltage $V_o(t)$ (Fig.5) is:

$$V_o(t) = a(1 - e^{-\frac{t}{RC}})(u(t) - u(t-\tau)) + V_\tau e^{-\frac{t-\tau}{RC}} u(t-\tau) \quad (1)$$

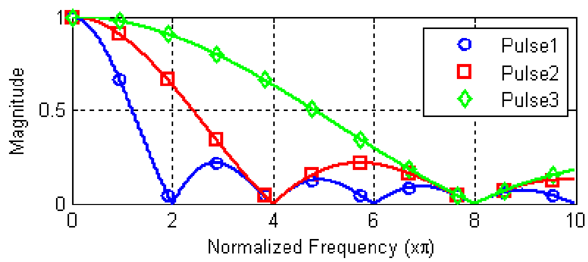
where $u(t)$ is the unit step function. The shaded area in Fig.5 indicates an equivalent measure for the amount of ISI which

TABLE I
The parameters of different pulses shown in Fig.4(a).

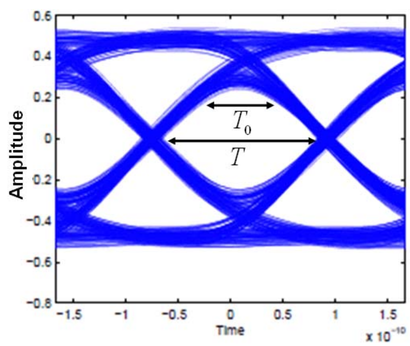
Pulse Parameters	Power	VEO	HEO	Jitter Tolerance
Pulse1	1w	0.46v	146.8ps	2.74%
Pulse2	2w	0.62v	152.4ps	3.19%
Pulse3	4w	0.66v	154.8ps	6.05%



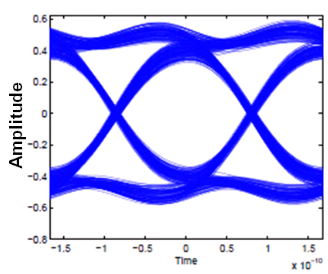
(a) Three different Pulses in Table.I (A=1).



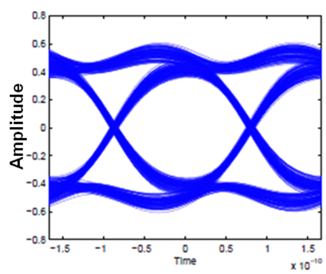
(b) The frequency response of pulses in Table.I.



(c) Pulse1 ED.



(d) Pulse2 ED.



(e) Pulse3 ED.

Fig. 4. The characteristics of different pulses and the Eye Digram (ED) of a NRZ signaling using these pulses ($JT = \frac{T_0}{T} \times 100\%$).

is defined by:

$$ISI = \int_{\tau}^{+\infty} V_\tau e^{-\frac{t-\tau}{RC}} dt = RCa(1 - e^{-\frac{\tau}{RC}}) \qquad (2)$$

The error E is also defined by:

$$E = A - a + ae^{-\frac{\tau}{RC}} \qquad (3)$$

where A is the amplitude of the pulse with duration T. Now, the optimization problem below is defined to determine the optimum values of a and τ, such that the ISI is minimized and other constraints are satisfied:

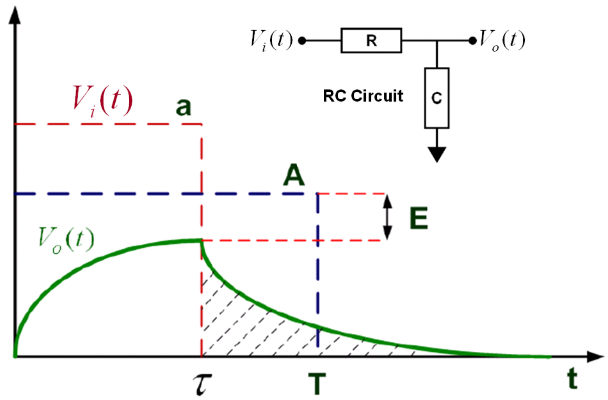


Fig. 5. The input and output of the RC circuit.

$$\min_{a,\tau} \frac{aRC}{u}(1 - e^{-\frac{\tau}{RC}}) \quad s.t. \begin{cases} \frac{A-a+ae^{-\frac{\tau}{RC}}}{v} \leq \epsilon \\ \tau - T \leq 0 \\ \tau \geq \rho T \\ A - a \leq 0 \end{cases} \qquad (4)$$

where ϵ is the permissible error to guarantee desirable link probability, ρ is a positive real number ($\rho < 1$) and u and v are normalization factors. By defining $\alpha = \frac{aRC}{u}$, $\beta = \frac{\tau}{RC}$, $\gamma = \frac{ARC}{u}$ and $\epsilon_0 = \left(\frac{ARC}{u} - \frac{\epsilon v RC}{u}\right)$, and also, by introducing new variables $x_1 = \log(\alpha)$ and $x_2 = \log(1 - e^{-\beta})$, an equivalent linear optimization problem can be defined as:

$$\min_{x_1,x_2} x_1 + x_2 \quad s.t. \begin{cases} x_1 + x_2 \geq \log(\epsilon_0) \\ x_2 \leq \log\left(1 - \frac{1}{e}\right) \\ x_2 \geq \log\left(1 - e^{-\rho}\right) \\ x_1 \geq \log(\gamma) \end{cases} \qquad (5)$$

This is an LP problem which is solved using CVX package [12]. Knowing x_1 and x_2, the optimum pulse parameters are computed as:

$$a_{opt} = \frac{ue^{x_1}}{RC} \quad \text{and} \quad \tau_{opt} = -RC\log(1 - e^{x_2}) \qquad (6)$$

Among these, we are interested in solutions which minimize the power of the transmitted pulse, also. Table.II expresses the optimization parameters and relative measurement quantities (in a comparison with a typical NRZ pulse with amplitude $A = 1$ and duration $T = 0.1592ns$). Quantities including Relative Amplitude (*RAMP*), Relative Pulse Width (*RPW*), Relative Power (*RPOW*), Relative ISI (*RISI*), and Relative Error (*RE*) are the relative value of the corresponding quantity in a pulse with amplitude a_{opt} and width τ_{opt} to the pulse with amplitude A and width T. This table represents that: 1) there is a trade-off between the ISI and Error, that is, the more the ISI is, the less the error is, and 2) power efficiency is achievable, but it depends on the amount of tolerable error (i.e. the maximum error that designers are prepared to accept). Therefore, based on the characteristics of the filter/channel (which is subject

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TABLE II
OPTIMIZATION PARAMETERS AND RELATIVE QUANTITIES(PARTIAL RESULTS).

Optimization Parameters	RAmp	RPW	RPow	RISI	RE
$(RC = \frac{T}{2}, \rho = 0.6, \epsilon = 0.6)$	1.1734	0.6525	0.8985	0.9891	1.0695
$(RC = \frac{T}{2}, \rho = 0.8, \epsilon = 0.6)$	1.0127	0.8105	0.8312	0.9396	1.3857
$(RC = T, \rho = 0.8, \epsilon = 0.66)$	1.0710	0.8209	0.9415	0.9487	1.0882
$(RC = T, \rho = 0.8, \epsilon = 0.7)$	1.0322	0.8152	0.8686	0.9103	1.1541
$(RC = 2T, \rho = 0.8, \epsilon = 0.5)$	1.0892	0.8224	0.9756	0.9332	1.0433
$(RC = 2T, \rho = 0.6, \epsilon = 0.6)$	1.1159	0.6489	0.8081	0.7858	1.1389

TABLE III
THE PARAMETERS OF DIFFERENT PULSES WITH DIFFERENT AMPLITUDES AND WIDTHS.

Pulse Number	Amplitude	Duration	Power
Pulse1	1v	$\frac{3}{4}T$	0.75w
Pulse2	1.1547v	$\frac{3}{4}T$	1w
Pulse3	1.1274v	$\frac{3}{4}T$	.9533w
Pulse4	1.1v	$\frac{3}{4}T$	0.9075w

to change), it is possible to adaptively use power efficient pulses (pulses with $RPow < 1$), while obtaining enough link reliability (or eye opening), simultaneously. Darker rows in Table.II indicate the possible pulse amplitudes and pulse widths which not only minimize the ISI (with approximately the same error as the typical NRZ signaling) but also the power of the transmitted pulses are lower.

IV. POWER EFFICIENT MODULATION: PERFORMANCE EVALUATION

To examine this idea in a real scenario, we made a comparison between two different cases: 1) a typical NRZ-BPSK signaling using pulses with amplitude $A = 1$ and duration $T = 166.67ps$ (i.e. $B = 6GHz$) and 2) NRZ-BPSK signaling using pulses with amplitude $a_{opt}(> A)$ and pulse width τ_{opt} $(< T)$. The communication system considered here is the system shown in Fig.1 with different pulse shaping functions, represented in Table.III. To evaluate the performance of these two communication systems at low BER, 10^8 bits are modulated and passed through the communication channel. This process is repeated for 100 times and BER is measured at the receiver in different SNRs.

Fig.6 shows the BER for different pulses, indicating the fact that pulses with higher amplitudes and lower pulse widths can improve the performance of high-speed communication links. By comparing different modulation schemes, it is clear that power efficient modulation schemes with the same performance as the typical NRZ signaling method are achievable; this is, also, indicated in Fig.7. That is, it is possible to get the same BER as the typical NRZ signaling, but with lower power consumption per each pulse; pulse-3 and pulse-4 are two examples of such pulses. This power efficiency is a large gain in high-speed communication systems where data rates are very high. For example, using pulse-4 it is possible to get 10% power efficency. This gain can be increased in higher SNRs (which is the case in Multi-Gbps communication systems).

Fig.8.(b-c) show the ED of two different modulation schemes shown in Fig.8.(a). Also, Table.IV compares the VEO

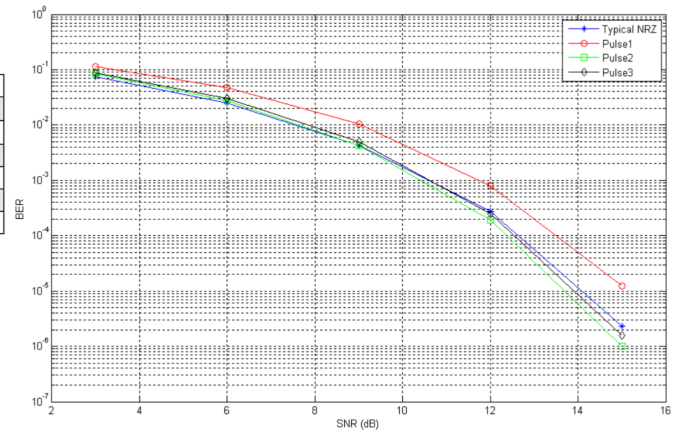


Fig. 6. BER vs. SNR (dB) for pulses in Table.III.

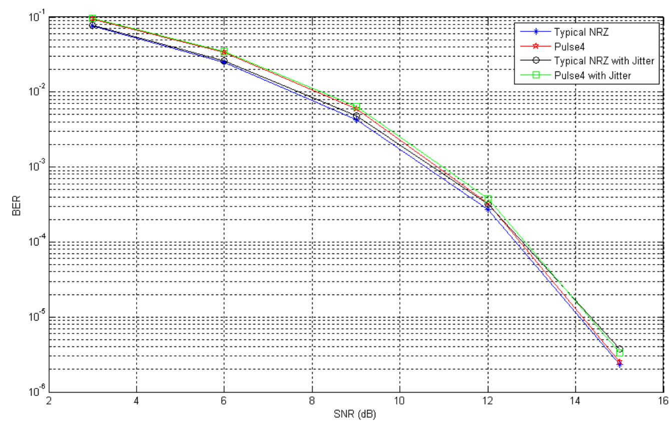
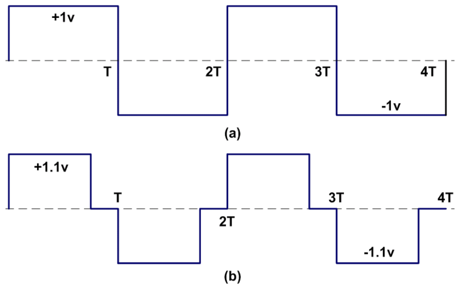


Fig. 7. BER vs. SNR (dB) for pulse 4 in Table.III (in the presence of 6.25% jitter.)

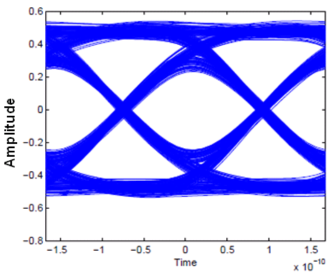
and HEO of these two modulation schemes. We can see that the performance of the pulse-4 modulation scheme is slightly better in terms of the eye opening parameters. However, using the pulse-4 modulation scheme not only more power efficiency can be obtained but also we can get better performance in the presence jitter (see Table.IV and Fig.7).

To consider a real scenario, the probability of error (P_e) of the typical-NRZ and pulse-4 signaling schemes were computed in the presence of noise, jitter and interference. For this purpose, two different cases (namely Case1 and Case2) are considered where the interference signals are the typical-NRZ and pulse-4 signaling schemes, respectively. These interferences are injected into the main communication link signal with different Signal-to-Interference Ratios (SIR).

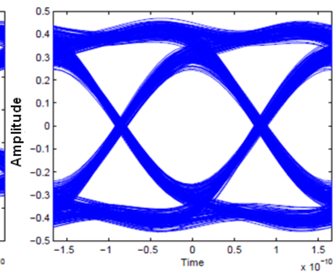
The main communication link signals are typical-NRZ and the pulse-4 signaling schemes (passed through the communication channel) with SNR=15dB, and the amount of sampling jitter is 6.25%. Table.V shows the results in this scenario. We can see that in the presence of interference the performance of the system is degraded, significantly; however, the performance of pulse-4 signalling scheme is still better. This table also indicates the fact that the performance of the system in the presence of wideband interferences (here pulse-4) is decreased



(a) Typical NRZ and Pulse 4 signaling.



(b) NRZ-BPSK ED.



(c) Pulse-4 ED

Fig. 8. The ED of two NRZ based modulation schemes.

further.

In fact, intuitively, such a technique pumps more energy into the channel capacitor (considering an equivalent low-pass RC model for the communication channel) in a smaller period of time which leads to a shorter rise time. By turning off the pulse at time $\tau < T$, the capacitor starts discharging (before charging by the next pulse) and the ISI is decreased. Consequently, the eye opening parameters are improved. This provides the opportunity to compromise between the contribution of ISI and noise/interference. Accordingly, a higher power efficient modulation scheme can be achieved. To increase the power efficiency, this technique can be combined with in a Binary Alternate Mark Inversion coding technique where logical zeros are transmitted at zero volt level and logical ones (marks) are transmitted alternatively by pulses with amplitudes $+a_{opt}$ and $-a_{opt}$ and with duration τ_{opt} (assuming having line coding schemes for synchronization). In addition, to achieve bandwidth efficiency, this signaling technique can be used in an M-ary scheme.

Finally, using an eye diagram monitoring module, this structure can also be adaptively used to determine the optimal parameters of the transmitted pulse in the presence of variations in the system or channel. In this case, a good strategy (based on the results represented if Table.II) is to start decreasing the pulse width, first, and then follow a simple control mechanism to find the power efficient's pulse amplitude and pulse width, which meets the desired eye opening (while achieving power efficiency).

TABLE IV
EYE OPENING PARAMETERS OF TWO MODULATION SCHEMES SHOWN IN FIG.8.(A).

Modulation Scheme	VEO	HEO	JT
Typical NRZ Signaling	0.450v	144 ps	24.60%
NRZ signaling using Pulse-4	0.477v	149 ps	26.04%

TABLE V
BER IN THE PRESENCE OF NOISE, JITTER AND INTERFERENCE.

P_e(Mod)	Case1:SIR=3dB	Case1:SIR=6dB	Case2:SIR=3dB	Case2:SIR=6dB
P_e(NRZ)	0.0542	0.0091	0.0839	0.0151
P_e(Pulse4)	0.0343	0.0048	0.0574	0.0084

V. CONCLUSION

In this paper, it was shown that using a simple and effective pulse shaping function, a power efficient modulation scheme, for data communication over wired channels, can be designed. This structure uses the fact that in ISI limited channels it is possible to create a trade-off between the contribution of ISI and noise/interference. Accordingly, more power efficiency can be achieved which is critical in the development of the next generation of wired/wireless communication systems and moving toward energy efficient ICTs. Furthermore, such a structure facilitates the communication over highly attenuated channels in high-speed communication links by: 1) improving the performance in the presence of jitter and interference, and 2) by transferring the complexity of the system to the transmitter side.

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