MODELING ADAPTIVE TECHNIQUES IN HIGH-SPEED COMMUNICATION SYSTEMS

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ABSTRACT

One of the major problems with any transmission media used for digital communications in High-Speed SerDes (serializer / deserializer) devices is inter-symbol interference, ISI for short. This paper gives an overview of the causes of ISI and its effect on the reception quality of digital data. The available techniques for limitation of ISI, particularly equalization, including transmitter pre-emphasis and receiver equalization are discussed and modeled. A comparison between analog and digital implementations of equalization techniques with a commercial equalizer by Maxim will be presented along with the advantages of both methods.

1. INTRODUCTION

At present, the high-frequency interconnections play the most significant role in many commonly used systems for high-speed data transmission. With the increasing signal speed and decreasing feature size of modern high-speed integrated circuits, the interconnection effects associated with parasitic capacitances, resistances and inductances and their effects on the delay, crosstalk and distortion become the major factors limiting performance of microelectronic systems [1]. When transmitting the very high-speed multi-gigabit per second serial data across a transmission line (transmission channel), the low-pass filtering nature of the line will cause inter-symbol interference that can lead to degraded system bit-error-rates (BERs). When the channel bandwidth gets lower, the effect of ISI becomes higher on both the amplitude and duration of the received bits, with the exception of symmetric alternating patterns, where the effect of ISI appears only on the amplitude of the received bits but no their duration. One approach towards mitigating the degraded BER is to provide some kind of equalization that will reduce the received ISI. If we could design circuits which can produce the reverse behavior of the channel frequency response to compensate the effects, the signal will be restored. The pre-emphasis and equalization technique have been proven to be an effective way to produce such effects and a correct design to eliminate these undesirable effects. Pre-emphasis is an equalization technique in which the drive current of the output driver is intentionally increased on the rising edges of the transmitted pulses in order to compensate for the limited transmission line bandwidth. Receive equalization is a function applied at the receiver that counteracts the data degradation in the long transmission line [2], [3]. This paper examines the design considerations, tradeoffs and a technique used to produce an equalization solution.

2. MODEL ANALYSIS

The basic structure of the model for the design of SERDES communication is shown in Fig. 1a. The model was created in the development environment Mathcad [4]. In order to simplify the model, let's assume that the transmission line channel could be modeled as a simple RC network, which essentially represents a low-pass filter. Furthermore, let's assume that the channel has a much smaller bandwidth than the digital signal that is being sent across it and that the digital pulses are simple gate pulses. That is, a 1 is represented by a pulse with an amplitude N_A and a duration of T_b (bit period), while a 0 is represented by a pulse with an amplitude -N_A and the same duration. In Fig. 1b is shown the response of a band-limited channel to a single pulse. As shown in Fig. 1b, the response of the channel to such a pulse involves two effects. First, the maximum amplitude the output pulse can reach is less than the original amplitude of the input pulse. Second, the output pulse becomes dispersed and its duration extends beyond *Tb*. The rising edge of the output pulse, see Fig. 1b, could be written as:

$$V_0(t) = N_A \cdot (1 - e^{-t/RC}), \quad \text{for} \quad t < T_b . \tag{1}$$

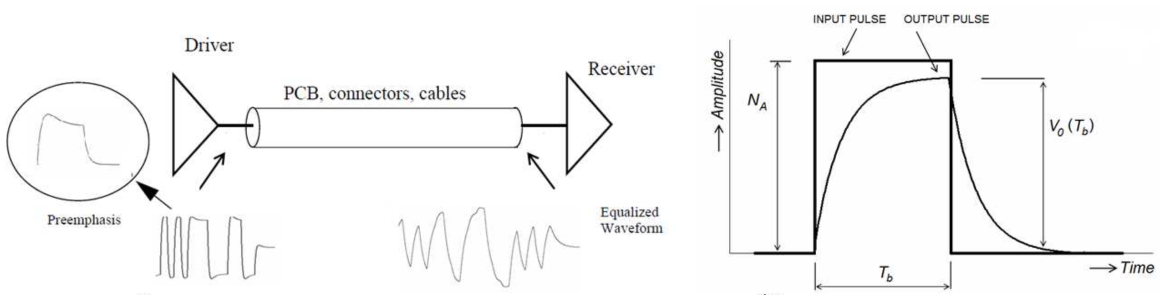
Using equation (1), the maximum voltage in the output pulse could be found by replacing t with T_b, that is:

$$V_0(T_b) = N_A \cdot (1 - e^{-T_b/RC}). \tag{2}$$

On the other hand, using equation (2), the falling edge of the output pulse could be written as:

$$V_0(t) = N_A \cdot (1 - e^{-T_b/RC})e^{-t/RC}, \ \text{for} \quad t > T_b . \tag{3}$$

As equations (1) to (3) shows, the output pulse is being spread out in time beyond its allocated time period T_b, therefore, when another pulse is sent out across the channel, the residue from the previous pulse represented by equation (3) is going to contaminate the new received pulse, and potentially mislead the front end receiver.



a) b)

Fig. 1: a) Basic communication model , b) The response of a band-limited channel.

2.1. TRANSMITTER PRE-EMPHASIS

There are numerous techniques to increase the eye opening. Of these, pre-emphasis at the transmitter side has been proven to be one of most effective techniques. The transmitter includes a feed forward equalization (FFE), see Fig. 2a, to reduce inter-symbol interference (ISI) at the receiver [1]. The FIR filter-based pre-emphasis function is used to boost the high-frequency content of the transmitted signal, thereby extending the bandwidth of the combined pre-emphasis and channel transfer functions. The following equation describes the relationships of the FFE coefficients [1].

$$H(z) = \sum_{n=0}^{N-1} C_n \cdot z^{-n} \tag{4}$$

where C_n is the tap coefficient, $z = exp\ (j2\pi f / f_s)$, the sampling frequency $f_s = 1 / T$.

The manifestation in a discrete linear equalizer is increased amplitude for the first bit after a logic transition relative to successive bits. This effect is shown in Fig. 2b for a transmitter with 10% equalization (2) and the bipolar NRZ signaling scheme is used to represent the bit stream. In this complementary signaling the N_A^+ signal represents the following bit stream: +1, +1, -1, +1, -1, +1, -1, -1, -1, +1, +1, -1, -1, -1, +1, +1, -1, -1. Each bit within the N_A^- signal is characterized with the opposite polarity of the corresponding N_A^+ bit. The reason for taking the difference between N_A^+ and N_A^- is to attempt to get rid of the noise that is common on both transmission line conductors. This kind of noise is classified as common-mode noise. The principle of creating output pulse with pre-emphasis for input pulse with 600 mV amplitude and 1ns width is shown in Fig. 2a.

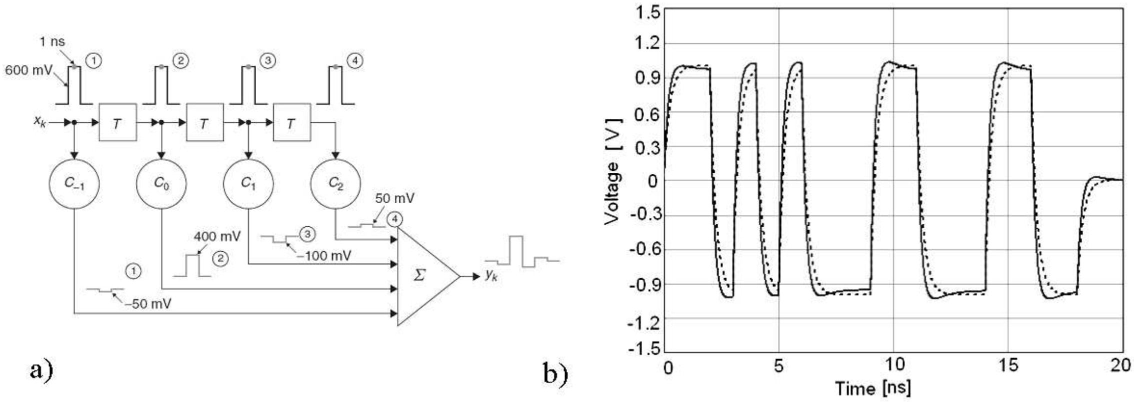


Fig. 2: a) Transmitter equalization filter operation , b) Transmitter output bit stream with (solid line) and without (dashed line) pre-emphasis.

2.2. RECEIVER EQUALIZER

There are generally four categories of receiver equalizers for over Gbps data transmissions [1], [3], [5], [6]. It is passive equalizer, active equalizer using split-path amplifier, active equalizer with discrete-time FIR filter or continuous-time FIR filter. Furthermore we will focus on the first type of this equalizer. Just a passive compensation network is a part of the integrated circuits below. Commercially available integrated circuits of equalizers by Maxim are for example: MAX3784, MAX3785, MAX3787 [5], [6] and can work until 12,5 Gbps in case of MAX3787. Based on the model of the passive filter in [5] was designed adequate model in Mathcad. The passive compensation network including the bridged-T network with some bypassing to get the mid-band and high-band portions of the spectrum. It helps to pass with less and no attenuation respectively. An ideal limiting amplifier was used in the simulation to restore the signal amplitude. Finally the transmission channel in the model is represented by the PCB differential transmission line pair (transmission channel) with length l = 0.381m.

Into account are taken the characteristic parameters of the transmission line at reference frequency 1 GHz, see [1].

2.3. SIMULATIONS RESULTS

The advantages of the techniques for reducing inter-symbol interference are shown in the following figure. To facilitate analyses, the bits can be superimposed to create a single plot from which all of the signaling specifications can be checked. A good plot results when the waveform is plotted for one clock period before and half one after, are captured. Superimposing all of the bits the builds an eye diagram. In Fig. 3a is shown transmission channel output without any of the equalization techniques described above. The maximum eye height is about 300 mV and the timing jitter is about 50% of a bit period. Fig. 3b shows the output eye pattern when 10% pre-emphasis is induced onto the input signal. You can see the significant improvements in the output eye pattern with pre-emphasis. The eye opening has been increased by about 75%, whereas the timing jitter has been reduced by 50%.

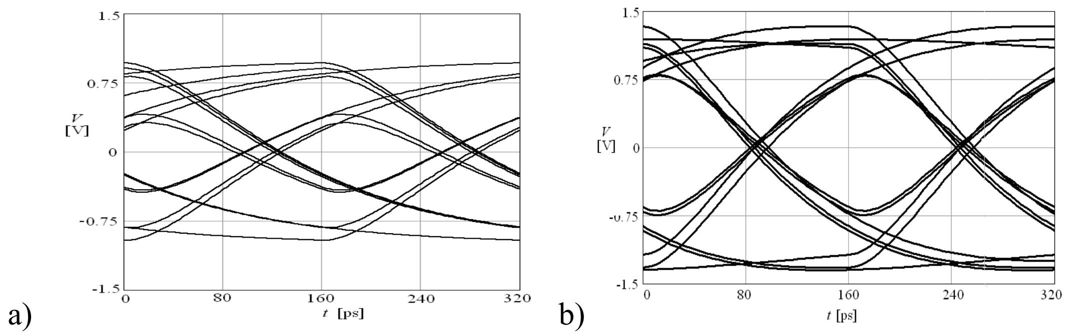


Fig. 3: Eye diagram a) output of transmission channel without any equalization techniques, b) Output channel with 10% pre-emphasis.

In Fig. 4a can be seen as both equalization schemes helped to reduce the output rise times and fall times significantly. As can be seen from the time delay plot in Fig. 4b, the passive equalizer induces a much smaller spreading of the time delays as a function of frequency than without the equalizer.

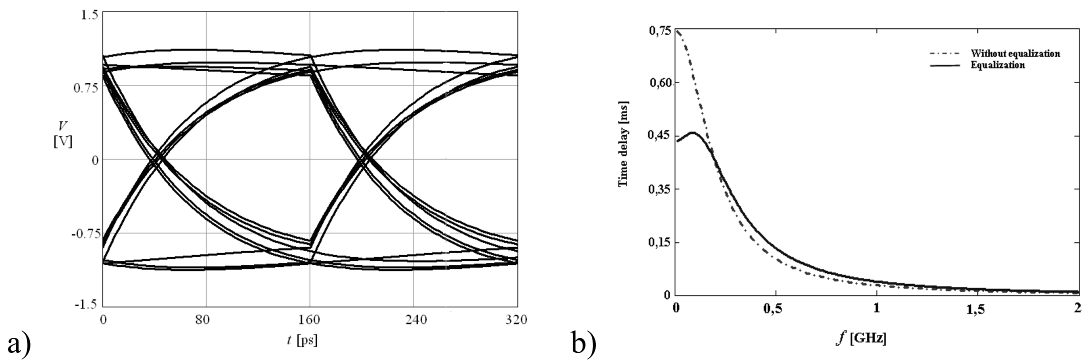


Fig. 4: a) Eye diagram of the receiver input with 10% pre-emphasis and RLC equalizer by Maxim, b) Overall time delay response.

Another important factor for examination of the quality of received data is to compare the BER with and without equalization techniques enabled. In Fig. 5a we can see how the combination of both equalization techniques produces some dramatic improvements in the output BER relative to the case in which no equalization is implemented into the system. Achieved BER is in the worst case better than 10^{-13} with both pre-emphasis and equalization enabled. Fig. 5b shows a comparison of the proposed model with practical results and measurements [5], [6]. It is clear that the proposed model estimates the overall lower error rates of data transmission because it is not possible to include all real parasitic effects in the analysis model. However, it is evident very good accuracy of the estimate jitter with increasing data rate.

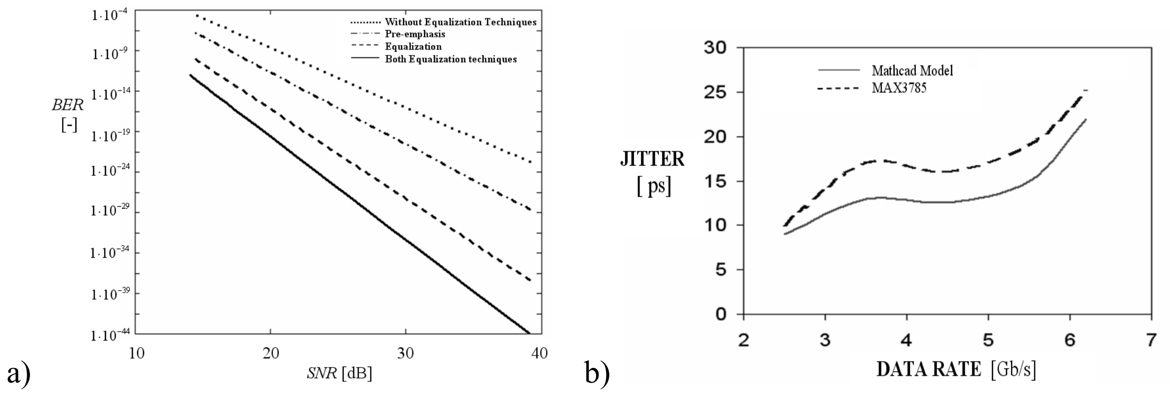


Fig. 5: a) Achieved BER for different cases, b) Accuracy of the model in comparison with practical measurements.

3. CONCLUSION

In this paper the general channel models are developed with the extensive experimental data. It is possible with very good accuracy to predict real phenomena in high-speed communications. It is obvious that for high-speed communication across a transmission line, the low-pass filtering nature of the line will cause inter-symbol interference that can lead to degraded system bit-error-rates (BER). One approach towards mitigating the degraded BER is to provide some kind of equalization described in the article above that will reduce the received inter-symbol interference.

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