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Signaling Optimization Techniques to Reduce Jitter and Crosstalk Susceptibility

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***Abstract*—In this paper the optimization methods to reduce undesirable effects in time-domain pre-emphasis techniques are described. In the first case the application of data-dependent method for pulse-width modulated (PWM) pre-emphasis to reduce additional jitter at output data stream is shown. Consequently, new signaling scheme based on using of raised cosine approximation to crosstalk reduction is proposed and analyzed. The time-domain pre-distortion method provides an alternative to FIR (finite impulse response) pre-emphasis with advantages in the light of developments in modern CMOS scaling. The PWM pre-emphasis method is able to compensate higher channel losses than the conventional FIR method. However additional high-frequency noise which is typical for strong amount of PWM pre-emphasis can caused system crosstalk susceptibility. Our research is primary focused on optimization of the conventional PWM scheme to reduce harmonic high frequency component. It can be solution for system where near-end crosstalk is problem. Finally, simulation results in MathCAD and Agilent ADS environment are shown.**

***Index Terms*—pre-emphasis, raised cosine, data-dependent, copper interconnect, pulse-width modulation**

I. INTRODUCTION

TODAY'S high-speed multi-core microprocessors and memory interfaces require ever-increasing interconnect bandwidth for modern applications such as computing and graphic systems, networking and other high-speed systems. In these cases higher switching speeds and the voltages provided on supply rails are going down. As data rates are increasing, their susceptibility to damage is more critical. It is caused by the nonideal aspects of transmission lines, such as crosstalks and losses as well as energy dissipation caused by reflections and radiation [1], [2]. This leads to increase in the jitter that degrades the timing margin as well as a distortion in the signal levels is the main cause of voltage margin degradation of the inter-chip signaling link [3]. In such severe environments, sophisticated pulse-shaping techniques such as equalization or pre-emphasis (equalization at the transmitter is often called transmitter pre-emphasis to reflect the effect of the filter operation), need to be employed to increase the data rates [4]. Equalization is a circuit technique that reduces the ISI-induced timing jitter and voltage margin loss by compensating for nonideal aspects, in particular the loss of interconnects at high speed [5]. In this case a high-speed serial communications for data transmission over the channel is used. This principle is often based on the use of device knows as SERDES (serializer / deserializer) which form data format into the serial stream, details in [6]. It provides ability to easier equalization techniques implementation. The transmission channel can take the form of a microstrip on a printed circuit board (PCB), or some form of connector/cable assembly for inter-PCB communication. The analyzed transmission channel which is representative of today's high-speed computing and networking systems is shown in Fig. 1. These systems have several channel parts with different lengths, and number of additional components as packages and connectors. In this case the channel performance at multi-gigahertz frequencies is strongly affected by using low cost package and PCB technologies and secondary sources such as via discontinuities. The transmission channels based on the FR4 dielectric are typically characterized by high slopes at frequencies above 1 GHz, see Fig. 1.

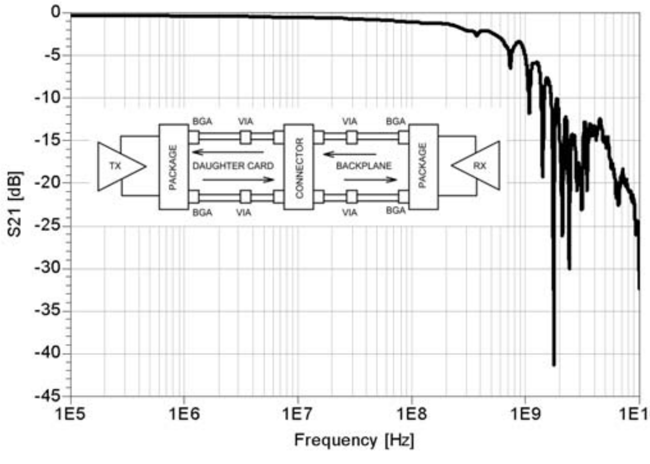

Fig. 1. Typical frequency response of longer FR4 transmission channel.

The channel has a low-pass transfer function, and therefore the high frequency (HF) components are attenuated more than the low frequency (LF) ones. Our area of study is limited to electronic circuits for high speed serial links over

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copper interconnects. In this paper, we analyze, implement and test techniques to increase the data rate of communication over copper channels. In high-speed data communication over a PCB backplane, dielectric losses, conductor losses and the effect of roughness cause inter-symbol interferences (ISI), decreasing the eye opening and thus limiting the bit rate at which data can still be reliably detected at the receiver side. As the transmission line bandwidth decreases, the tendency is for the input pulses to spread or disperse in time at the output. This pulse spreading gives rise to each received output pulse interfering with the next received pulses. When a string of 2PAM modulated bits is transmitted over the PCB transmission channel using the pattern generator, we obtain the result shown in Fig. 2 where the signal output from transmitter and channel output are compared. All the tails of the separate pulse responses are summed up. Clearly, the channel response is severely distorted by ISI. For more lossy channels and higher HF components it is no longer possible to simply place a threshold at 0V and decide whether the measured signal is above or below it [4].

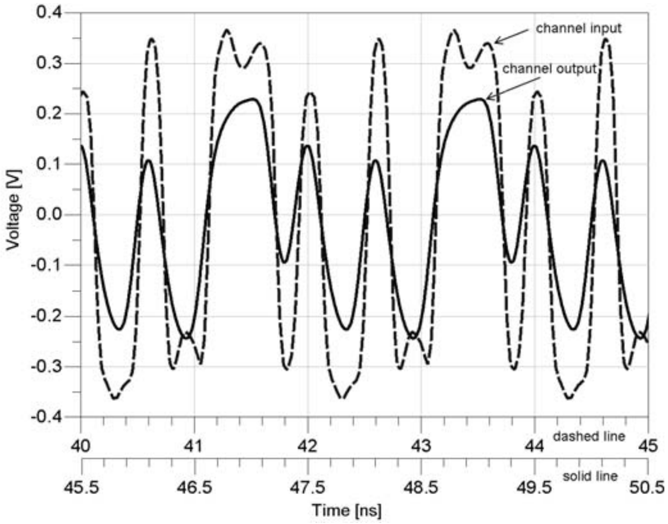

Fig. 2. Simulated response of single differential PCB transmission pair

The output of the channel is connected to a receiver. One of the main parameter, receiver sensitivity can be used to calculate a transmitted voltage swing. The signaling power can be expressed as [7]

$$P_{SIGNALING} = \frac{V_{DD} \cdot V_{RX}}{Z_0 \cdot H(f)} \tag{1}$$

where V_{DD} is I/O supply voltage, V_{RX} represents receiver sensitivity, $H(f)$ is channel frequency response, the transmitted swing is defined as $V_{TX} = V_{RX} / H(f)$.

The expression shows that the minimum transmitted signal swing depends on the receiver sensitivity and the channel's frequency response [8]. In our case, the signal swing requirement assumes inter-symbol interferences (ISI) compensation by equalization techniques such as pre-emphasis at the transmitter. Ideally for minimum bit error rate (BER) which is typically 10^{-9}- 10^{-14}.

In this paper the time-domain pre-emphasis techniques are modified to achieve better compensation of undesirable effects described above. In the first case some adaptability is shown for time-domain pre-emphasis method based on pulse-width modulated signaling scheme [9], [10]. The idea of data dependent time-domain pre-emphasis was firstly described in [11]. The simulation results of application of this method for advanced communication channel by using own designed models in MathCAD and ADS Agilent are presented. Consequently the signaling scheme for time-domain pre-emphasis based on raised cosine approximation is proposed. It is shown that crosstalk susceptibility is more reduced and higher loss compensation for higher order channel can be achieved.

II. ANALYSIS OF PRE-EMPHASIS FILTERS

A. PWM Signaling Scheme

In Fig. 3, the output voltage waveforms for both 2-tap FIR signaling and the PWM signaling are shown. Transmitter output is normalized to +/- 1V. Transmission channel model has a monotonically decreasing transfer function. It corresponds approximately with PCB loss model for single trace. The current channel losses are adjusted using the typical bandwidth parameter BW_{3dB}. Actual channel losses BW_{3dB} = 0.35 GHz corresponds with the 70 cm long PCB trace. A similar result is shown for 25m long coaxial cable in [12].

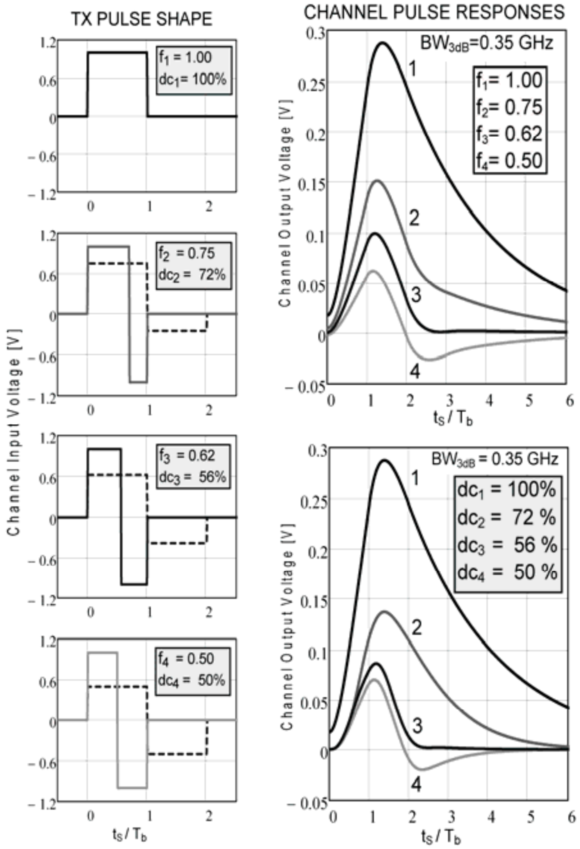

Fig. 3. TX pulse shapes (T_S = 200 ps) of FIR filter (dashed line) and PWM filter (solid line) and simulated channel pulse responses for transmission line bandwidth BW_{3dB} = 0.35 GHz.

The optimum coefficients settings, duty-cycle (*dc*) for PWM method and coefficient *f* for FIR method, are strongly dependent on the channel characteristics, see Fig. 3. In this case the optimal coefficients are $f = 0.62$ and $dc = 56\ \%$ for FIR pre-distortion and PWM pre-distortion, respectively. The PWM pulse shape is similar to Manchester code for *dc* parameter setting to 50 %. However, the Manchester code has fixed amplitude at 50 % without a tunable duty-cycle [12]. A duty-cycle of 100 % corresponds to transmission of a normal polar NRZ data signaling without pre-distortion. In [13] the symmetrical impulse response for the channel where dielectric losses dominated is shown. The measured results and advanced simulation model shows that this channel has nonsymmetrical pulse response see Fig. 3. The PWM pulse p_{pwm}(t) is defined as follows, see Fig. 3.

$$p_{pwm}(t) = \left\{ \begin{array}{cc} 0 & t < 0 \\ 1 & 0 \le t < dc \cdot T_b \\ -1 & dc \cdot T_b \le t < T_b \\ 0 & T_b \le t \end{array} \right\}, \tag{2}$$

where *dc* denotes the duty-cycle ($0.5 < dc < 1$ fits best to PCB backplanes) and T_b again represents the symbol period ($T_b = 200$ ps).

The time-domain pre-distortion method described above has the advantage of only one coefficient settings to achieve optimal pre-emphasis level. Thus it can be very simplified implementation process of adaptive duty-cycle settings for control algorithms which are widely used for receiver equalization. A sign-sign block least mean squares (LMS) algorithm can be used as shown in [14]. From Fig. 3 it is clearly seen that replacing FIR pre-distortion with PWM pre-distortion, when amplitude resolution requirements are replaced with timing resolution requirements, can be beneficial for future low voltage CMOS technologies where stringent noise margins can reduce the usable voltage amplitude for pre-distortion level settings. It is obvious that optimal pulse shaping (coefficient setting) for analyzed channel is accompanied by a reduction of signal amplitude. It should be noted that the minimum transmitted signal swing clearly depends on the receiver sensitivity and channel frequency response. This is shown in [7] where reduction in receiver sensitivity from 100 mV to 25 mV changed the minimum required transmitter signal swing from 600 mV to 200 mV while the same BER is maintained.

B. PWM-RC Signaling Scheme

The conventional PWM scheme based on rectangular pulse shaping has many harmonic high-frequency components [12]. It can cause problems in practical implementation of this method in real communication systems, e.g. PCI Express based ones. A method proposed in this work uses a raised cosine pulse scheme to reduce crosstalk noise. The combination of PWM pre-distortion technique and appropriate pulse shaping method can provide an effective reduction of high-frequency components of the pulses. This preserves the beneficial properties of time-domain pre-distortion technique and consequently the crosstalk susceptibility as a main disadvantage of PWM scheme can be reduced. The raised cosine signaling is the process when the waveform of transmitted pulses is changed in order to achieve better signal adaptation to the band-limited channel. The raised-cosine filtering is widely used in digital modulation techniques to effectively suppress ISI. In this thesis the PWM-RC scheme is introduced for the first time. In the frequency domain, a function is defined in MathCAD formulation as

$$G_{RC}(f) = \left\{ \begin{array}{cc} 1 & \left| f \cdot T_b \right| < \frac{1-\beta_S}{2} \\ \frac{1}{2} \cdot \left\{ 1 - \sin\left[\frac{\pi}{\beta_S} \left(\left| f \cdot T_b \right| - \frac{1}{2} \right) \right] \right\} & \frac{1-\beta_S}{2} \le \left| f \cdot T_b \right| \le \frac{1+\beta_S}{2} \\ 0 & \left| f \cdot T_b \right| \ge \frac{1+\beta_S}{2} \end{array} \right\}. \tag{3}$$

The raised cosine pulse transform function is shown in Fig. 4. The parameter β_S (pulse roll-off parameter) is varied from 0.1 to 1.0. It controls the smoothness and the bandwidth, see β_S variation in Fig. 4. The frequency on the x axis is normalized according to the current bit period T_b to easily identify bandwidth variations.

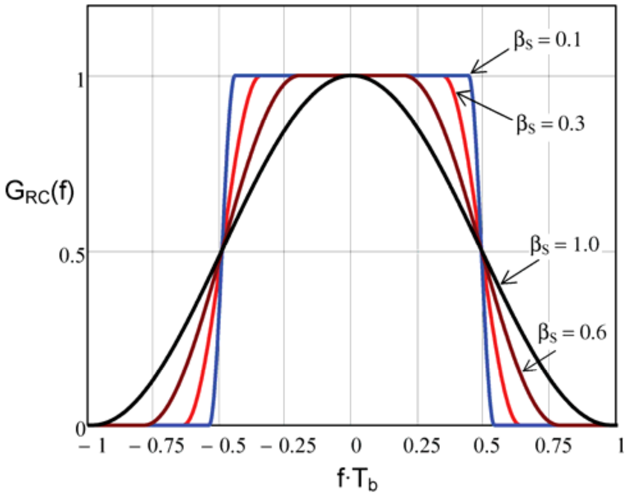

Fig. 4. Spectral analysis of raised cosine function.

For roll-off parameter values close to zero a rectangular shape in the frequency domain is obtained. Extremes are $\beta_S = 0$ and $\beta_S = 1$. In the first case for rectangular shape ($\beta_S = 0$), a significant ripples can cause that neighboring bits will interfere with the current bit. This effect becomes more pronounced for low values of the β_S parameter. The impulse response is defined as

$$h(t, \beta_S) = \operatorname{sinc}\left(\frac{\pi \cdot t}{T_b} \right) \cdot \frac{\cos\left(\frac{\pi \cdot t \cdot \beta_S}{T_b} \right)}{1 - \left(\frac{4 \cdot \beta_S \cdot t}{T_b} \right)^2}. \tag{4}$$

It is clearly seen in the time-domain pulse analysis in Fig. 5 where the impulse response (inverse Fourier transform) is shown. The second case (β_S = 1) shows double bandwidth occupation but the impulse response shows more ripple reduction.

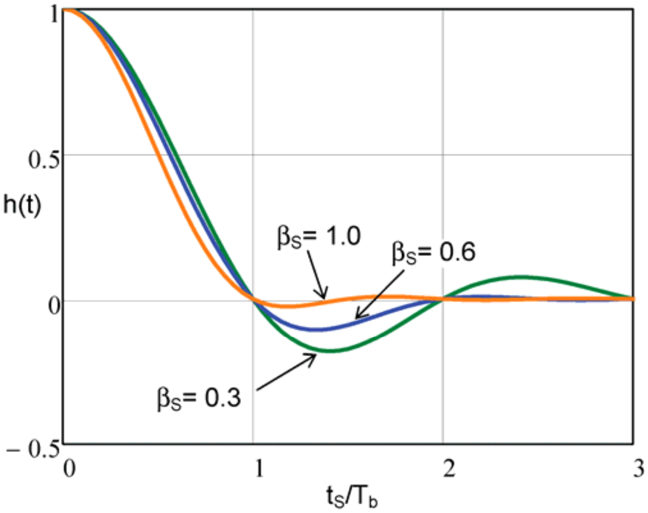

Fig. 5. Raised cosine impulse response.

The proposed PWM-RC scheme which is described below still used only one coefficient *dc* to achieve the required value (amount) of pre-emphasis, compare (2) and (5). Experimental pulse shaping results normalized to unity peak realized in MathCAD according to (5) is shown in Fig. 6 for weak (left) and strong (right) pre-emphasis.

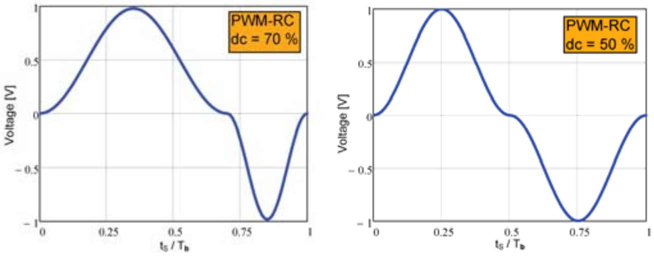

Fig. 6. Raised cosine impulse response.

For the proposed PWM-RC method the pulse shaping in the time-domain is defined as

$$s_{RC}(t)=s_1(t)-s_2(t) \tag{5}$$

where

$$s_1(t)=\frac{1}{2\cdot dc\cdot T_b}\cdot\left(1-\cos\frac{2\cdot\pi\cdot t}{dc\cdot T_b}\right) \tag{6}$$

$$s_2(t)=\frac{1}{2\cdot(1-dc)\cdot T_b}\cdot\left(1-\cos\frac{2\cdot\pi\cdot(t-T_b)}{(1-dc)\cdot T_b}\right) \tag{7}$$

where interval for function $s_1(t)$ is defined as $0\le t\le dc\cdot T_b$ and for function $s_2(t)$ interval is defined as $dc\le t\le dc\cdot T_b$.

For a predefined bit sequence a pulse shaping is analyzed for both time-domain pre-emphasis methods, see Fig. 7. It is obvious that high-frequency signal content (data sequences with fast transitions) is less attenuated for PWM-RC pre-emphasis than for conventional PWM pre-emphasis. It means that for the same channel properties the less amount of pre-emphasis can be used in the case of PWM-RC method. This significantly reduces the additional high-frequency signal content that is caused by using the pre-distortion methods.

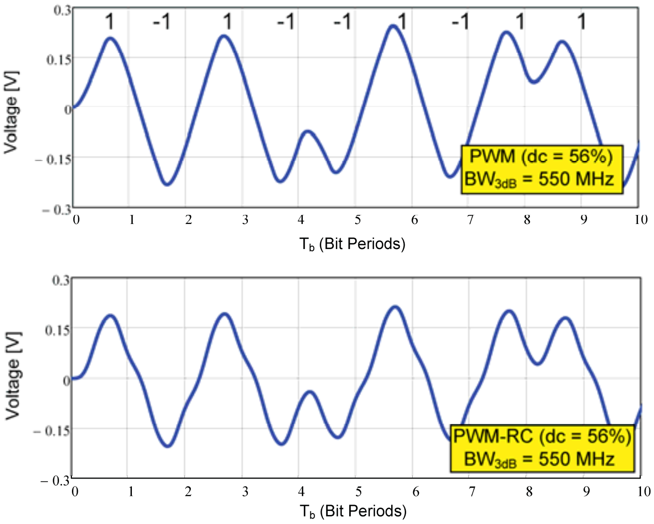

Fig. 7. Data bit sequences over band-limited channel..

III. SIMULATION RESULTS

A. *Crosstalk Analysis*

For the experimental measurements two types of 30 cm long backplanes created within diploma thesis [15] was used, see Fig. 8. The first backplane prototype was designed with relatively large distance between transmission lines, *d* = 6 mm.

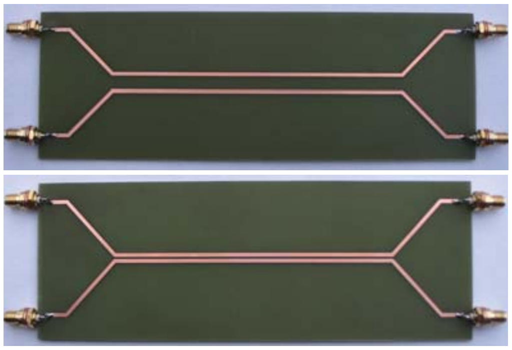

Fig. 8. Two analyzed backplane prototypes (taken from [15]).

In this case the microstrip conductor and dielectric losses are dominant factors that must be taken into account. The second backplane prototype is designed with significant distance reduction between transmission lines, *d* = 0.5 mm. In this case a significant crosstalk effect which should be taken into account in real communication systems occurs. Eye diagram results example is shown in Fig. 9 for channel input and output data if transmitter signal pre-distortion is enabled. In this case coupling length is about 20 cm. The simulations results realized in MathCAD show significant increase in crosstalk for relatively long coupling lengths (this corresponds with realized backplane prototypes measurements) and decreasing in aggressor distance. The aggressor represents separated single ended circuit.

Fig. 9. Experimental backplane measueremnts.

It is obvious the optimal pre-emphasis level setting is able to improve eye diagram opening, see Fig. 3. Other additional increase in the amount of pre-emphasis can cause eye diagram closure. In this case a Xilinx Virtex IV development kit is used to generate 3.125 Gbps data rate, see Fig. 9. The amount of pre-emphasis is fully programmable and is expressed in dB. This is the most common way of specifying the effect at the transmitter. There are two ways to emphasis the signal. In the first case pre-emphasis can be calculated as additive to the smaller voltage. In the second case to reflect the fact that equalization can be performed as a reduction in voltage amplitude the term de-emphasis is used [16]. The resulting effect of compensation for channel loss is identical for both methods.

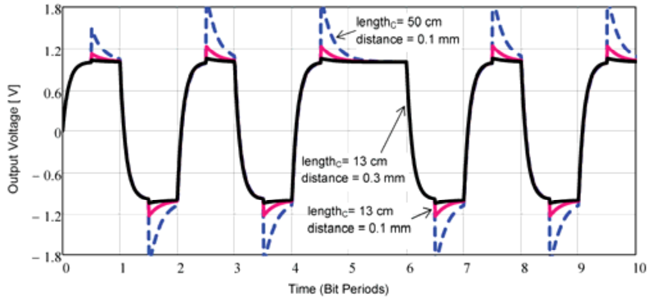

Fig. 10. Crosstalk variations for various defined parameters of transmission lines (MathCad simulation).

Signal degradation factors described above can cause significant ISI and crosstalk. The important factor for PCB pre-distortion technique design is crosstalk noise. The conventional pulse shaping scheme based on the square wave approaches can induce higher frequency content onto a signal. This situation is shown in Fig. 10. It can be determined that crosstalk occurs along the raising and falling edges. From the simulations in MathCAD development environment it is possible to expect that smaller rise-times would produce more crosstalk. Two parameters, coupling length (*length*$_C$) and isolation distance (*distance*), are varied. Note the significant reduction in the peak crosstalk for larger isolation distance.

B. *Adaptive PWM Scheme*

The method of pulse width modulated pre-emphasis technique described above is able to compensate a 1-st order channels which can be modeled as a lowpass filter with different slopes, depending on the frequency where the current losses just dominate. The pre-emphasis techniques for higher-order channels are commonly realized as multitap filters. It means that the number of taps of conventional FIR filters is increased according to complexity of the channel transfer function. In this case both circuit complexity and power consumption are increasing.

A very effective approach using the concept of adaptive PWM pre-emphasis technique based on data dependency to compensate for deterministic jitter, in particular, data-dependent jitter (DDJ), is shown in [11]. The method is based on the fact that the amount of timing jitter which is induced in data sequence is strongly dependent on the current bits but also on the previously transmitted ones, see Fig. 11.

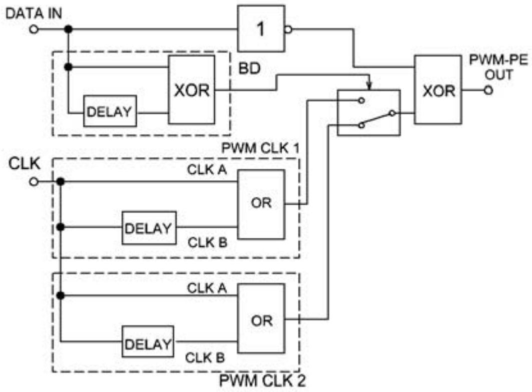

Fig. 11. PWM signal generation circuit.

This means that a specific data sequence of previous bits changes the output amplitude and also the ISI can be very different. The same reasoning can be applied to the amount of pre-emphasis for the specific data sequence. In this case it is necessary to distinguish the data sequences with slow transitions where strong pre-emphasis is applied and the data sequences with fast transitions (high frequency data pattern, e.g. 0101) where weak pre-emphasis is applied. Such a changing duty cycle procedure is implemented by using BD (Bit Detect) circuits as shown in Fig. 11. For the long data sequence with bits of the same value the optimal (strong) pre-emphasis is employed adaptively. This method was implemented in Agilent ADS development environment and the real PCI-Express based higher order channel was used. Using described data-dependent PWM pre-emphasis techniques, the data-dependent ISI can be removed, subsequently an eye-diagram is improved, especially the additional HF noise for low frequency output patterns analyzed in Fig. 10 can be minimized. Conventional PWM scheme is able to achieve eye height 59.6 mV and jitter is about 20 ps. This data dependent PWM scheme is able to enlarged the eye height to 67.5 mV and jitter is minimized to 10 ps for the same conditions.

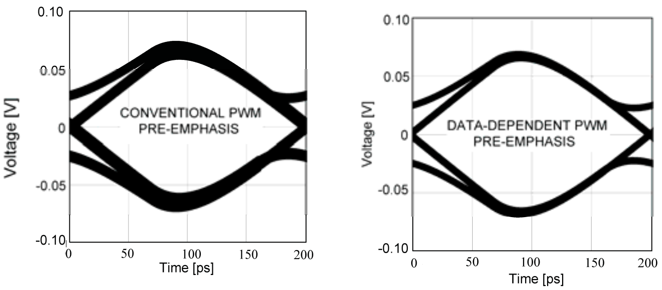

Fig. 12. Effect of data-dependent pre-emphasis.

Using a Fourier series calculation, the spectrum for all pre-emphasis techniques is analyzed, see Fig. 13 and Fig. 14 for strong and weak pre-emphasis, respectively. Concretely, $d = 56$ % for the strong pre-emphasis and $d = 75$ % for the weak pre-emphasis. In [12] it is shown that the difference between PWM and FIR pre-distortion methods is as follows. For the HF pattern there is only a difference in phase (time-shift). For the LF pattern, the behavior is different. The FIR output spectrum does not contain additional HF components whereas the PWM filter output shows the same power as for its HF pattern.

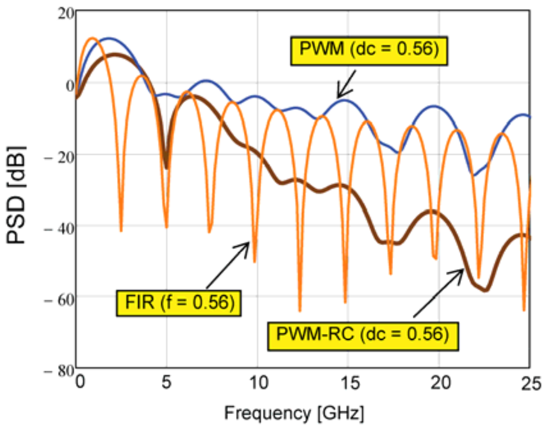

Fig. 13. Signal spectrum analysis for strong pre-emphasis.

The implemented adaptive PWM scheme can help solve this problem because a strong pre-emphasis is applied adaptively. Other possible solution is based on using a low-pass filter at the TX output and crosstalk can be effectively decreased. A similar analysis is performed in [9] where the optimal PWM duty-cycle coefficients are analyzed for a cable channel transfer function. However, the proposed PWM-RC signaling scheme is able to significantly improve the frequency spectrum especially for strong amount of pre-emphasis, compare Fig. 13 and Fig. 14.

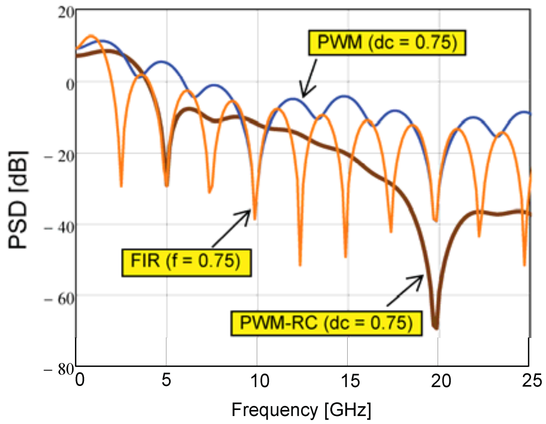

Fig. 14. Signal spectrum analysis for weak pre-emphasis.

C. *Eye Diagram Analysis*

The effect of adjusting the *dc* parameter of the PWM filter and *f* parameter of the FIR filter is shown in Fig. 15 where all described pre-emphasis method are compared. The model of the communication system for PWM and PWM-RC pre-emphasis methods was created in MathCAD and has not been published in any paper yet. The simulated pulse shaping for PWM method corresponds very well with the measured results [12].

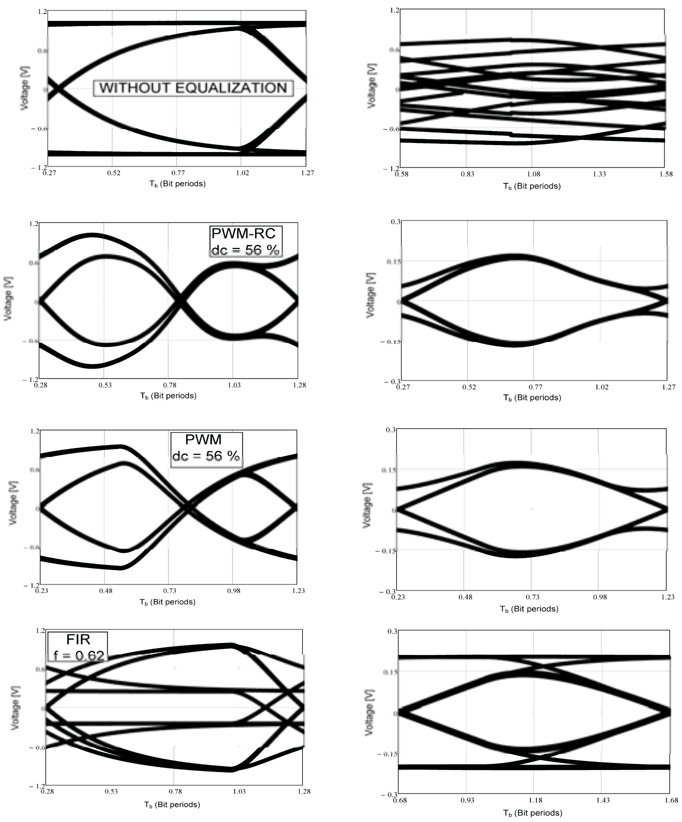

Fig. 15. Eye diagram performance analysis.

The left and right edges in the eye diagrams correspond to the symbol edges. For all analyzed methods an optimal coefficient settings were selected according to the analysis in Fig. 3. The optimal value of pre-emphasis is strongly dependent on current channel losses, see eye diagrams where over-emphasis are shown [17], [18]. The channel response without any pre-emphasis technique is also shown. Note that the time scale is the same for all eyes and one bit period is intercepted. Note how the proposed PWM-RC method minimizes ISI while the maximum eye opening is maintained, compare PWM and PWM-RC channel output eye diagrams.

D. Crosstalk Susceptibility and Loss Compensation

Among the various noise factors, the dominant one for backplane is the crosstalk noise, specially the near end crosstalk (NEXT) at the connectors. The proposed method significantly reduces harmonic high frequency components of pre-emphasized data signal, see Fig. 16 where random bit sequence is analyzed for both conventional PWM pre-emphasis and proposed PWM-RC pre-emphasis.

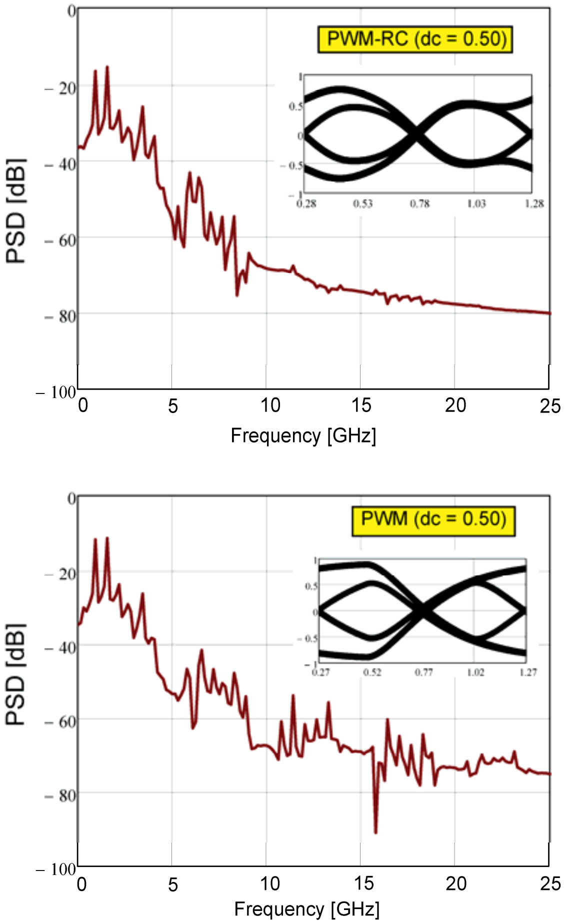

Fig. 16. Crosstalk susceptibility analysis.

The verification of proposed PWM-RC method is performed by using two type channel models. In the first case, the band-limited channel ($BW_{3\mathrm{dB}} = 0.35$ GHz) with first order transfer function is used. This channel has a monotonously increasing attenuation with frequency. The maximum loss compensation (strong pre-emphasis, $dc = 50$ %) is selected. The decisive factor for the performance of the proposed equalizer is how the overall swing is reduced in order to achieve the reduction in minimum-to-maximum loss for the system. In other words, how the equalizer is able to reduced difference between attenuation of low-frequency signal content and high-frequency signal content. This is usually called "flattening" of the magnitude of the frequency response [4]. In [13] better performance of the PWM filter for equalization of 1st order cable channel transfer function (approximately corresponds to channel transfer function of theoretical channel [19], [20]) is shown. The performance of all analyzed pre-emphasis methods for maximum loss compensation is shown in Fig. 17, where the overall loss compensation of all equalizers for various $BW_{3\mathrm{dB}}$ setting is shown.

It is obvious that the reduction in the loss variation for FIR filter (note that f_N is at 0.5 on the x-axis) is only approximately 7 dB improved compared with a transmission channel loss at the same $BW_{3\mathrm{dB}} = 100$ MHz. The conventional PWM method reduces overall losses to 14 dB. The proposed PWM-RC method due to the possibility of high frequency loss compensation adjustment (see Fig. 3.5a) is able to decrease the overall losses to 12 dB. For $BW_{3\mathrm{dB}} = 350$ MHz setting this reduction approximately triples the frequency at which the eye closes completely from 0.8 GHz to 2.5 GHz, see Chapter 2 where 6 dB limitation is described. In the case of conventional PWM filter the reduction in the loss variation allows only shifting the frequency at which the eye closes completely from 0.8 GHz to 1.8 GHz.

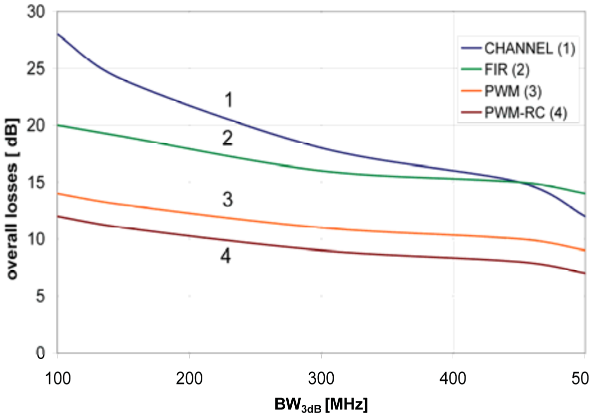

Fig. 17. PWM signal generation circuit.

Similarly, the equalized transfer function of PCB channel with higher-order transfer function was performed. The proposed PWM-RC method significantly improves the equalized transfer function by increasing high-frequency loss compensation, see Fig. 18. For more complex channel transfer function it is necessary to consider filters with multitap coefficients. However, the proposed equalization method due to its adjustability is able to better equalize real PCB channel discontinuities that come from the vias, connectors and packages used in the design of PCB transmission channel.

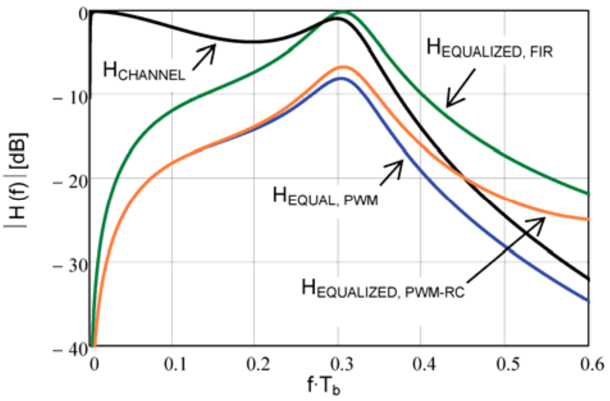

Fig. 18. Equalized higher order channel transfer function (strong pre-emphasis).

IV. CONCLUSION

A perspective digital pre-emphasis technique based on the pulse-width modulation (PWM) is analysed in detail. The PWM method does not tune the pulse amplitude (as with FIR pre-emphasis), but uses a timing resolution. This corresponds well for today and the future low voltage high-speed CMOS processes. However, the conventional PWM scheme shows more high frequency harmonic components if the data signal is strong pre-emphasized. It can cause system crosstalk susceptibility. Two methods to improve the quality of pre-emphasized signal are described. This methods is able to improve the output signal quality and an additional HF noise which is generated by the PWM filter can be minimized. Especially second method based on PWM-RC signaling scheme shows great potential for high-order channel equalization. Future work will be focused on practical experimental measurements.

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