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Time-Domain Pre-Distortion Technique Using Raised Cosine Shaping for High-Speed Serial Signaling

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Abstract:
In this paper the innovative time-domain pre-distortion method is proposed. This method (PWM-RC) uses raised-cosine (RC) pulse shaping and pulse-width modulation (PWM) scheme to achieve better output channel data response. The conventional pre-distortion methods based on finite impulse response (FIR) filtering are not compatible with modern low-power CMOS design. Existing perspective time-domain pre-distortion methods show many high frequency harmonic components in the pre-emphasized signal. It can cause more system crosstalk susceptibility, where the additional pre-emphasis boosted the undesirable high frequency components. The proposed method reduces the content of higher harmonic components at the pre-emphasized output signal and ISI (inter-symbol interference) effects. Advantageous properties of the PWM scheme such as high channel loss compensation are preserved. Finally, the simulation results realized in MathCAD and ADS Agilent Development Studio are introduced.

INTRODUCTION

The optimum signaling rate of a high-speed interconnect system is strongly dependent on many factors such as interconnect topologies, length, board and packaging technologies [1]. The channel characteristics are different for each of systems and play critical role for the range estimation of the operating data rates of modern communication systems such as graphics, computing or networking systems. 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. All these issues can cause significant problems in signal integrity and timing. These impacts dominate at multi-Gb/s speeds where the unwanted signal distortion can cause that signal energy is spread over multiple bit positions, a phenomenon known as intersymbol interference (ISI) [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 mitigate the channel attenuation and consequently to increase the data rates [4].

The transmitter equalization filter is commonly realized as finite impulse response (FIR) filters [5], [6], [7]. Various types of equalizers are also commercially available [8], [9]. The purpose of this operation is to increase (decrease for de-emphasis [10]) amplitude for the first bit after a logic transition relative to successive bits. However, the conventional FIR pre-emphasis techniques for recent CMOS technology trends are mainly restricted by its supply voltage, which will decrease according to CMOS scaling [2]. A time-domain pre-emphasis method does not change the pulse amplitude as for the conventional FIR pre-emphasis, but a timing resolution is used to signal pre-distortion [11], [12]. This method is able to better adapt to current requirements in CMOS technology trends where higher switching speeds and lower supply voltage dominate. In this paper, the research is primarily focused on the analysis and development of effective transmitter pre-distortion method for PCB channels where ISI and crosstalk noise are dominant factors of losses. This paper shows a modified signaling scheme to minimize these factors. Current time-domain pre-distortion methods use conventional rectangular pulse. This causes that many undesirable high frequency harmonic components are contained in a pre-distorted signal at the transmitter output. Such a system is very susceptible to crosstalk noise.

SIGNALING SCHEMES

An innovative PWM method is proposed in [12] and is applied to the coaxial cable loss equalization and simple single PCB trace equalization. It provides an alternative to the FIR pre-emphasis which is still commonly used in high-speed interconnect systems. The proposed time-domain pre-distortion method in [12] has the advantage for modern low-voltage CMOS devices where the maximum voltage swing is pushed markedly below 1.0V and the implementation of the pre-distortion methods based on pulse amplitude shaping can be a problem. The first part of the paper shows both PWM and PWM-RC signaling schemes, all presented simulations have been created in MathCAD and Agilent Advanced Design Studio

(ADS). The PWM pre-emphasis provides higher maximum loss compensation (24 dB) than the commonly used 2-tap FIR filter (18 dB), because its transfer function is able to adapt very well to the copper channel, see simulation results in Agilent ADS studio [13]. However, the crosstalk susceptibility of conventional PWM can cause additional high-frequency content in equalized data stream. Thus, the loss compensation can be significantly reduced. The proposed PWM-RC method reduces ISI, see section Eye diagram analysis and additional high-frequency noise, see section Frequency domain analysis.

PWM Scheme

In Fig. 1, the output voltage waveforms for both 2-tap FIR signaling and the PWM signaling are shown. Transmitter output is normalized to +/- 1 V. Transmission channel model has a monotonically decreasing transfer function. It corresponds approximately with the PCB loss model for a single trace. The current channel losses are adjusted using the typical bandwidth parameter BW_{3dB}. Actual channel losses $BW_{3dB} = 0.35$ GHz correspond with the 70 cm long PCB trace. A similar result is shown for 25 m long coaxial cable in [12]. The optimum duty-cycle settings are strongly dependent on the channel characteristics, see Fig. 1. 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 a Manchester code for duty-cycle (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 [14] the symmetrical impulse response for the channel where dielectric losses dominated is shown. The measured results and advanced simulation model show that this channel has a nonsymmetrical pulse response, see Fig. 1.

The coefficients for FIR pulses time domain simulations are rewritten according to [12] as $c_1 = f$, $c_2 = f\text{-}1$ with $f \in \{0.5...1\}$, resulting in one coefficient f that can be used to control the pre-distortion level and T_b represents the symbol period ($T_b = 200$ ps). The FIR pulse definition is described in detail in [13]. The conventional PWM pulse $p_{pwm}(t)$ is defined as follows, see Fig. 1

$$p_{pwm}(t) = \begin{Bmatrix} 0 & t < 0 \\ 1 & 0 \le t < dc \cdot T_b \\ -1 & dc \cdot T_b \le t < T_b \\ 0 & T_b \le t \end{Bmatrix}, \qquad (1)$$

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).

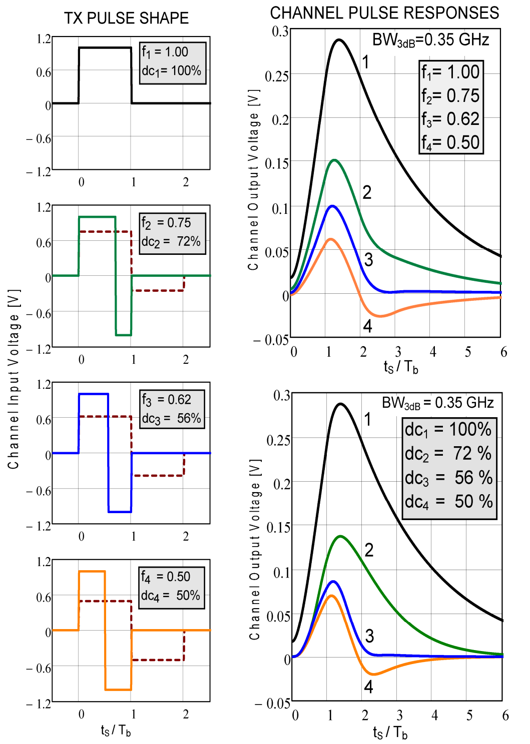

Fig. 1: TX pulse shapes ($T_S = 200$ ps) of FIR filter (dashed line) and PWM filter (solid line) and simulated channel pulse responses for transmission line bandwidth $BW_{3dB} = 0.35$ GHz.

The 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 [15]. From Fig. 1 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 the 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 [1] 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.

PWM-RC Scheme

The conventional PWM scheme based on rectangular pulse shaping has many high-frequency harmonic 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 paper the PWM-RC scheme is introduced for the first time. 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 (1) and (2). Experimental pulse shaping results normalized to unity peak realized in MathCAD according to (2) is shown in Fig. 2. For the proposed PWM-RC method the pulse shaping in the time-domain is defined as

$$s_{RC}(t) = s_1(t) - s_2(t), \qquad (2)$$

where

$$s_1(t) = \frac{1}{2 \cdot dc \cdot T_b} \cdot \left(1 - \cos\frac{2 \cdot \pi \cdot t}{dc \cdot T_b}\right), \qquad (3)$$

$$s_2(t) = \frac{1}{2 \cdot (dc-1) \cdot T_b} \cdot \left(1 - \cos\frac{2 \cdot \pi \cdot (t - T_b)}{(dc-1) \cdot T_b}\right), \qquad (4)$$

for defined border $0 \leq t \leq dc \cdot T_b$ in the case of s_1, $dc \cdot T_b \leq t \leq T_b$ in the case of s_2.

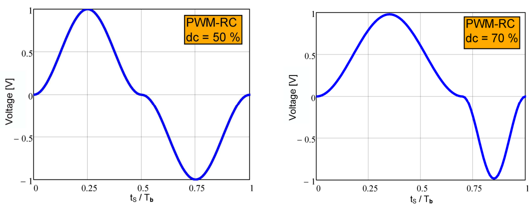

Fig. 2: PWM-RC pulse shaping.

FREQUENCY DOMAIN ANALYSIS

The spectrum of PWM pulse is more boosted at higher frequencies above Nyquist frequency (0.5 on the x axis) approximately for *dc* values from 65 % or less. It can be important factor for higher performance to compensate more lossy channels [12], [13]. The main disadvantage of the PWM method proposed in [12] is that the output pre-distorted signal has many high frequency harmonic components, especially if low-frequency pattern is transmitted. This situation is critical with increasing level (amount) of pre-emphasis. Furthermore, it is necessary to take into consideration that for practical implementations optimal duty cycle coefficients for more lossy channel are just located about strong pre-emphasis level between 50 % and 60 %. In Fig. 3 the frequency spectrum analysis for both conventional PWM and proposed PWM-RC pre-distortion methods is shown. In this case a strong pre-emphasis level (*dc* = 56 %) is chosen. It is clearly demonstrated that for proposed PWM-RC pulse the high-frequency harmonic components are more attenuated. It can be an important factor to suppress high-frequency harmonic content in a conventional PWM scheme and also a potential crosstalk noise. Both signal pulses have T_b = 200 ps.

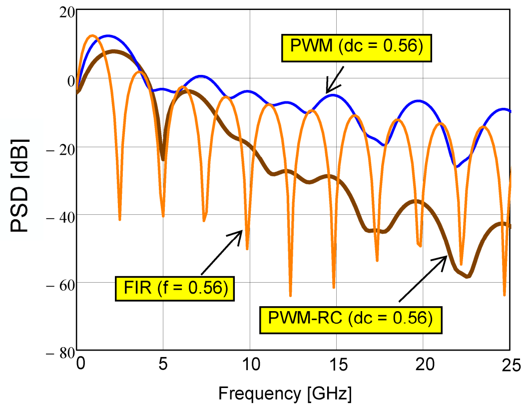

Fig. 3: Pre-emphasis pulse spectrum analysis.

The PWM pulse definition (1) is used to calculate the spectrum of the PWM filter by taking the Fourier transform, similarly as in [12]. Now for the proposed PWM-RC pre-emphasis the frequency domain transfer function can be calculated according to (5) by taking (1) and raised cosine pulse definition in [16] (where β_S parameter is a measure of the excess bandwidth of the filter) into account. The frequency transfer function response for the PWM-RC filter can be calculated as follows

$$H_{PWM-RC}(\omega) = \frac{P_{pwm}(\omega)}{G_{RC}(\omega)}. \qquad (5)$$

In Fig. 4 the PWM-RC filter transfer function for various duty cycle coefficients setting is shown. In this case, the pulse roll-off parameter β_S is set to 0.4. The proposed PWM-RC scheme is capable of higher loss compensation around Nyquist frequency (0.5 on the x axis). For example, the gain 10 dB of PWM-RC equalizer corresponds with value 0.6 on the x axis, see Fig. 4. The conventional PWM filter shows the same gain value but for the value 0.8 on the x axis. The proposed method allows not only to set the optimal pre-emphasis level by changing the duty cycle but the β_S parameter can be used to adjust the optimal equalization characteristic according to current channel losses. It is obvious that the Nyquist frequency varies according to the actual data transmission rate. For lower data rates the β_S parameter can be set to a higher value. In this case high frequency noise and crosstalk, which can degrade performance in real systems, are effectively reduced because high frequency boost is tempered. For higher data rates it is possible to achieve higher channel loss compensation because the amount of equalization around the Nyquist frequency can be effectively adjusted depending on where current high slopes in channel frequency response occur.

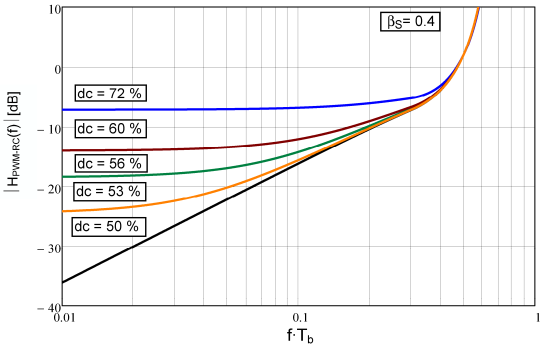

Fig. 4: Calculated magnitude of PWM-RC filter transfer function (β_S = 0.4).

The main advantage of the proposed PWM-RC pre-distortion method lies in its adjustable variability. A comparison of the conventional PWM pre-emphasis and FIR pre-emphasis transfer functions is shown in [12]. In this case the proposed PWM-RC method retains the same behavior for low-frequencies as the FIR filter and conventional PWM filter. The PWM scheme due to the time-varying has high-order transfer function and so effective gain of the PWM filter increases to infinity [12]**.** It can cause also additional high-frequency noise in output pre-distorted signal even if weak pre-emphasis is applied. The PWM-RC pre-emphasis technique is capable to find optimal settings for both low-frequency and high-frequency signal content and additional high frequency content can be minimized due to the adjustability at higher frequency compensation, see Fig. 5.

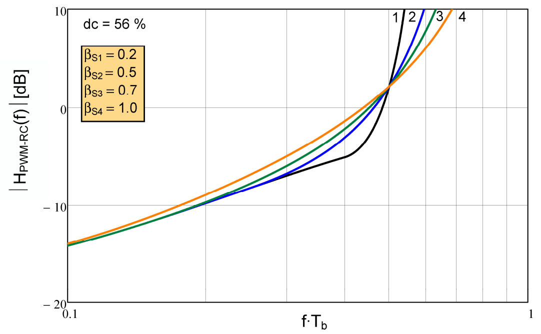

Fig. 5: Calculated high-frequency compensation settings for different values of β_S parameter.

EQUALIZED CHANNEL OUTPUT

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 reduce difference between the attenuation of low-frequency and high-frequency signal contents. This is usually called “flattening” of the magnitude of the frequency response [2]. The performance of all analyzed pre-emphasis methods for maximum loss compensation is shown in Fig. 6. It is obvious that the reduction in the loss variation for the 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_{3dB} = 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. 4), is able to decrease the overall losses to 12 dB. For BW_{3dB} = 350 MHz setting this reduction approximately triples the frequency at which the eye closes completely from 0.8 GHz to 2.5 GHz, see [1] 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.

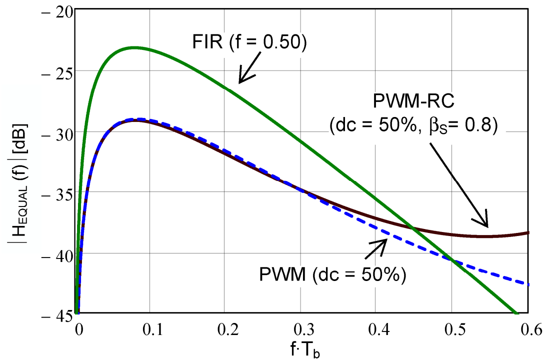

Fig. 6: Equalized first-order channel transfer function (strong pre-emphasis).

In Fig. 7 the overall loss compensation of all equalizers for various BW_{3dB} setting is shown.

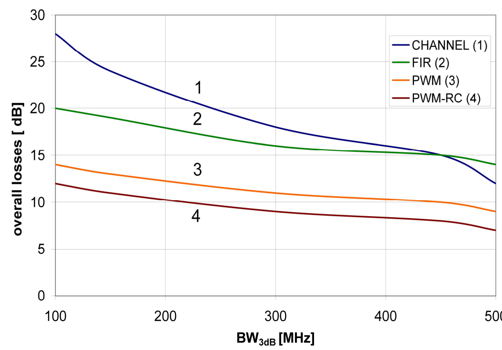

Fig. 7: Pre-emphasis techniques overall losses compensation performance analysis (1st order channel).

Similarly, the equalized transfer function of the PCB channel with a higher-order transfer function was performed. For the analysis of higher-order transfer function a simplified model of the transmission path is described in [17]. The value of parasitic via capacitances C_{VIA} is varied from 2 pF to 4 pF and the performance of all equalizers to overall loss compensation is calculated in Fig. 8. In this case the overall loss compensation is calculated as the difference between attenuation of parasitic peak and attenuation at Nyquist frequency (0.5 on the x axis). It is clearly seen that the conventional PWM method is not able to achieve the same performance as the conventional FIR method.

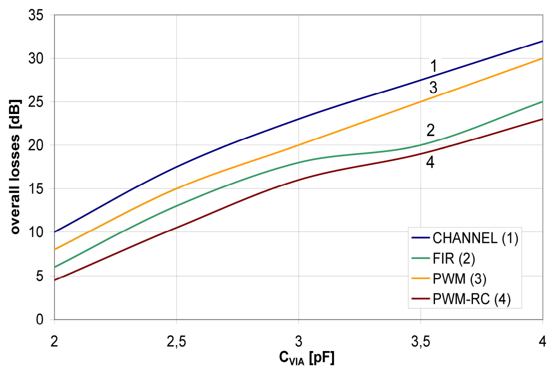

Fig. 8: Pre-emphasis techniques overall losses compensation performance analysis (higher order channel).

The proposed PWM-RC method significantly improves the equalized transfer function by increasing the high-frequency loss compensation. 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 channels.

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. 9 where all described pre-emphasis methods are compared. The models of the communication system for PWM and PWM-RC pre-emphasis methods were created in MathCAD and have not been published in any paper yet. The simulated pulse shaping for PWM method corresponds very well with the measured results [12]. The left and right edges in the eye diagrams correspond to the symbol edges. For all analyzed methods optimal coefficient settings were selected according to the analysis in Fig. 1. The optimal value of pre-emphasis is strongly dependent on current channel losses, see eye diagrams where over-emphasis are shown [13], [18]. 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 (right side diagrams).

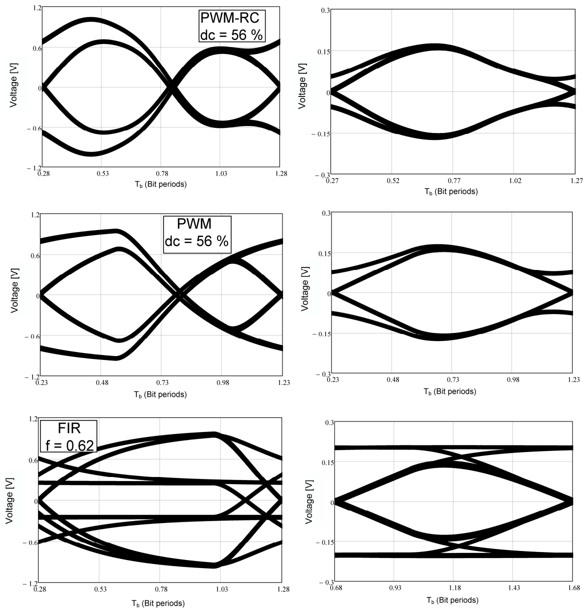

Fig. 9: Transmitter output eye diagrams at 5 Gbps (left side diagrams) and channel output eye diagrams at 5 Gbps (BW_{3dB} = 350 MHz , right side diagrams).

CONCLUSIONS

In this paper the perspective digital time-domain pre-distortion technique based on pulse-width modulation scheme and using raised cosine signaling (PWM-RC) is described. The conventional PWM method does not tune the pulse amplitude (as for FIR pre-emphasis), but instead exploits timing resolution. However, the additional content of many high-frequency harmonic components which is strongly dependent on low-frequency content in the data signal can cause problems with implementation for high-speed channels with crosstalk susceptibility. It is shown that the proposed PWM-RC scheme is capable to reduce the high-frequency content as well as to retain advantageous properties of PWM scheme. The frequency-domain analysis shows better performance of proposed method for equalization of transmission channels where the attenuation is not monotonically increasing. Additional variability to adjust high-frequency loss compensation can play a critical role for optimal pre-emphasis setting. For example, the weak pre-emphasis can be sufficient to low-frequency content compensation but the compensation for high-frequency content is not still sufficient. The solution for the conventional PWM method is to increase the amount of pre-emphasis and it also boosts high-frequency noise.

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