# Signaling Technique Using Inverse Exponential Function for High-Speed On-Chip Interconnects

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*Abstract:* In modern digital systems where advanced miniaturization is used, on-chip interconnects are becoming more incompatible with existing signaling methods to overcome signal distortion caused by natural low-pass effect of transmission lines. Current requirements for signal pre-emphasis driver at transceiver side are logically similar to the general requirements for low-power voltage digital systems. High efficiency of signal pre-emphasis together with a minimum voltage swing during signal emphasizing and still lower power dissipation are the main features of modern signaling methods. In this paper a novel pulse shaping method based on the use of an inverse exponential function that has smaller distortion than conventional raised-cosine pulse is introduced together with advanced channel modeling. Thus, a robust pulse pre-emphasis method using combination of amplitude emphasis and time-domain emphasis is proposed. Analysis clearly shows that proposed pulse shaping method due to the spectral efficiency can increase the transmission bandwidth of low cost wire channel.

*Key-Words:* pre-emphasis, high-speed interconnects, raised-cosine, exponential function, transmission

## 1 Introduction

Since development in Information Communication Technologies (ICT) is still in progress an efficient design of high-speed transmission lines and optimized signal modulation techniques based on the use of digital signal processing are needed to ensure reliable communication in current and future modern multi-Gbps wired communication systems. These problems are relevant for chip-to-chip links and also for inter-system communication links. Great emphasis is placed on development of the next generation of low-power communication systems [1-3]. High-speed I/O serial interconnect standards like PCI-Express, USB or Serial ATA show good reliability for high transmission rate where low voltage swing and common-mode noise immunity are achieved. However, there are still problems during system integration due to the natural low-pass effects of transmission lines. Thus, resistive losses, reflections, interferences and crosstalk between differential pairs can occur, resulting in the generation of multiple inter-symbol interferences (ISI) in these systems [4-6].

As an effective solution modern pre-emphasis and equalization methods are used. The pre-emphasis technique (commonly used at transmitter side) is an effective way to improve signal integrity in cases where signal is affected by channel discrepancy as vias, line delay or impedance mismatch. In many cases, it is possible to overcome the low-pass effect of transmission lines by using this method. However the requirements for power efficient communication involve development of new effective aproaches to minimize the effect of the limitations described above. Pulse shaping plays crucial role in spectral shaping in the modern wire/wireless communication to reduce the spectral bandwidth. Recently introduced signal shaping adaptive techniques can be used to replace a conventional signaling method with the same or higher efficiency of the system during the high-speed data transferring [7-9].

In this paper, a novel power efficient adaptive modulation scheme to overcome real transmission channel limitations is introduced together with related findings from the own previously published papers dealing with this issues [10], [11]. In these papers, it has been shown that optimized signal shaping based on application of raised cosine scheme can help solve problems with additional HF signal content and the performance of signaling method is maintained. However, the lossy channel properties show better adaptation to the pulses whose definition is based on the use of inverse exponential functions. Conventional amplitude pre-emphasis techniques are based on overdrives the transmit side of interconnect

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with a voltage pulse higher than the signal swing [12]. Thus, additional power is required. This method is becoming less effective in cases when lower voltage levels for signaling are used in modern low-voltage CMOS logic [13] because there is a relationship between the amplitude of pre-emphasis and channel losses together with signal properties. The decisive factor is the amount of high-frequency signal components to be compensated. Simply put, the higher channel low-pass effect together with the increasing data rate requires a higher amount of pre-emphasis (more additional power) to improve signal quality at the channel output. Using feedback from the receiver side known as adaptive channel equalization [14-16] and adaptive power efficient modulation methods [2], [8] two powerful techniques to achieve optimal signaling at the transmitter side can be obtained and combined. It is obvious that for accurate estimation of signal shaping and its modulation a feedback from receiver side is necessary.

The proposed signaling method uses pulse shaping based on inverse exponential functions with adaptive changeable pulse width, amplitude and slope. Thus, better results in comparison with raised-cosine signaling [17] are shown. The pulse shaping and width can be adjusted according to channel characteristic. It means that both pre-emphasis methods as pulse width modulation [2], [7] and pulse shaping [18], [19] are combined together. Thus, the main disadvantage of the signal shaping methods reported before, [7], [20], [21], where additional undesirable high-frequency signal content can cause synchronization problem due to the near-end crosstalk occurring at the transceiver signal output, is minimized. In addition, our published analysis takes into account real channel disturbances as in [22]. It can help to adapt the proposed signaling method for real applications.

The rest of the paper is organized as follows. First, the measurement results of real channels together with appropriate channel model are shown and discussed. Then, the main idea is examined and an optimization problem to determine the optimal parameters of the transmitted pulse is defined. Next, the application of the proposed signaling scheme on a real backplane channel is demonstrated. Finally, conclusion summarizes the main results of the paper.

## 2 Channel Properties

For performance tests of variable signaling methods a professional development board DS25BR100EVK from Texas Instruments was used [23]. Thus, the performance of low-voltage differential signaling (LVDS) single channel buffers can be analyzed. Available are transmit pre-emphasis (PE) [24] and receive equalization (EQ), details see in [25], [26] example of their performance testing. The evaluation kit consists of three separate FR4 striplines (14 cm, 71cm and 106 cm in length). It allows the use of this board for tests of both conventional and innovative signaling techniques. Thus, signal conditioning features (pre-emphasis and equalization) can be simply compared. Based on the measured results of channels responses an appropriate communication chain in Agilent ADS development environment (hereinafter ADS) was created. Measured transfer functions of all three available channels are shown in Fig. 1.

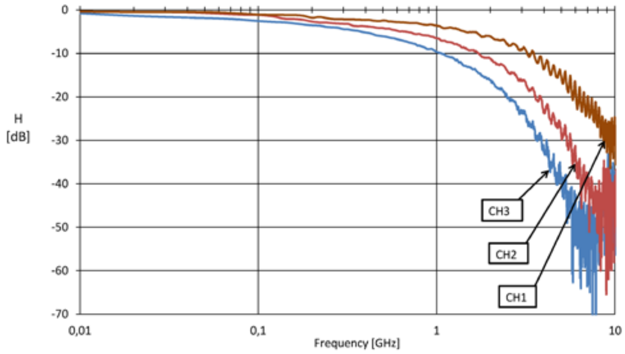


Fig.1 Transfer functions of real transmission channels

The general functional diagram of proposed/ modeled communication chain which will be analyzed through ADS is shown in Fig.2. The system consist of a pulse shaping part which ensures adaptive changes of the amplitude and edge shaping in order to achieve optimal eye opening and higher power efficiency. The pre-emphasis module provides precise adjustment of transmitted pulse width and its appropriate digital modulation. Thus, the signal can be precisely adapted according to the behavior of the transmission channel due to the feedback from the monitoring of eye diagram opening at the receiver. Moreover, the real backplane channels are slowly varying and so it isn’t necessary full real-time eye diagram monitoring.

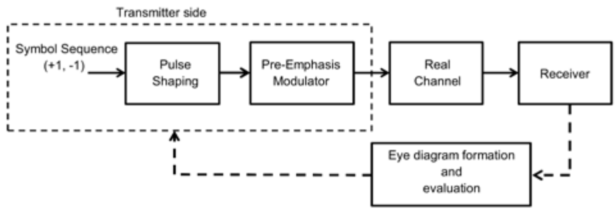


Fig.2 Simple schematic of proposed/modeled communication chain

Based on the real transmission channel measurements two main impact findings are obvious from the output eye diagrams. These are pulse amplitude and pulse width. In the first case eye width and eye height are analyzed together with increasing bit rate. Fig.3 shows that eye height decreases non-linearly with higher slopes and the eye width parameter has an exponential decreasing tendency with higher slopes and the eye width parameter has exponential decreasing tendency during increasing bit rate. The performance test was calculated in ADS where the real channel transfer function was used. In this case a conventional bipolar signaling with rectangular pulses was used. The pulse amplitude corresponds to the value ±1V and pulse width corresponds with bit period $T_b$.

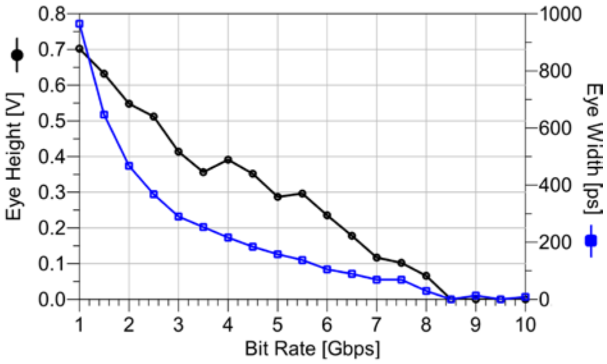


Fig.3 Output eye diagram analysis, conventional pulse

The situation is somewhat different in case of increasing signal amplitude together with appropriate decreasing in pulse width to maintain the same pulse power, see Fig. 4

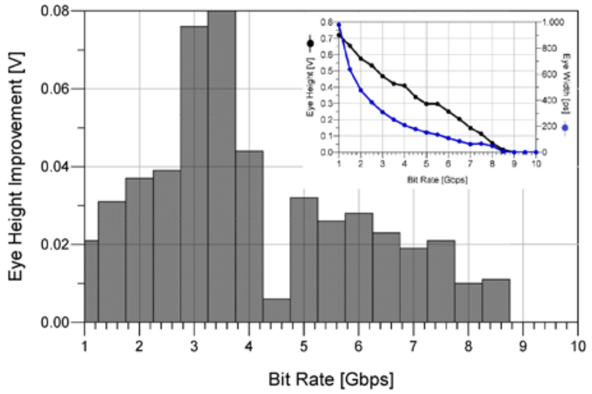


Fig.4 Histogram of eye height improvement

It is obvious that the decreasing tendency of eye width parameter remains the same as in the previous case. However, more important is the fact that eye height parameter can be improved and higher bit rates over the same channel can be achieved or the same bit rates with better signal quality. In this case, the pulse amplitude $A \neq A_{opt}$ and bit period $T_b \neq T_{bopt}$. Note that the histogram in Fig.4 is unbalanced. The best values are achieved about 3 Gbps bit rate, which is nominal value of test board [23].

A communication channel is most often characterized as an idealized low-pass filter with a transfer function defined as

$$H(s)=\frac{2\pi BW}{s+2\pi BW} \qquad (1)$$

where $BW$ is the typical 3 dB bandwidth parameter which controls the losss of transmission lines. It fully agrees with a low-pass RC filter transfer function.

For our analysis, we consider extended channel model where additional parameters according to real assumptions as driver impedance, load capacitance, propagation delay and source reflection coefficient are supplemented based on the findings in [27], [28] and real channel measurement. Thus, the channel transfer function is defined as

$$H_{REAL}(s)=\frac{H(s)\frac{2}{CZ_0}}{s+\frac{1}{CZ_0}}+\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4 \qquad (2)$$

where $\Gamma$ represents the reflection from the load to the source and is defined as

$$\Gamma_n=\rho_S{}^n H(s)^{2n} e^{-s2nt_d}\frac{\frac{2}{CZ_0}\left(\frac{1}{CZ_0}-s\right)^n}{\left(s+\frac{1}{CZ_0}\right)^{n+1}} \qquad (3)$$

where $C$ is load capacitance, $Z_0$ is characteristic impedance of transmission line, $t_d$ is one-way time delay, $\rho_S$ is source reflection coefficient defined as $\rho_S=\left(R_D-Z_0\right)/\left(R_D+Z_0\right)$ and finally $n$ is the number of reflections from the load to the source.

## 3 Pulse-width pre-emphasis

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. We consider that the input voltage pulse $V_{inp}(t)$ is defined by amplitude $A$ and duration $T_b$. The output voltage impulse can be described as

$$V_{out}(t)=A\left(1-e^{-2\pi BW_2 t}\right)\left(u(t)-u(t-T_b)\right)+ \\ +V_{T_b}e^{-2\pi BW_2(t-T_b)}u(t-T_b) \qquad (4)$$

where $u(t)$ is the unit step function and $BW_2$ is a parameter forming the pulse rise time.

Thus, a single pulse with exponentially shaped rising/falling edge can be obtained. Note the enormous increase in pulse width after passing through the lossy channel. The amount of ISI is defined based on last term in the previous equation.

$$ISI=\int_{T_b}^{+\infty}V_{T_b}e^{-2\pi BW_2(t-T_b)}dt=\frac{A}{2\pi BW_2}\left(1-e^{-2\pi BW_2 T_b}\right) \qquad (5)$$

In Fig. 5 two output pulses passed through the transmission channel defined by eq. (2) and (3) are compared. It is obvious that the optimized pulse width ($T_{bopt}$) with appropriate increase in amplitude ($A_{opt}$) improve signal jitter performance and eye opening. Both optimized parameters have been calculated in ADS by using advanced parametric analysis and are shown in Table I.

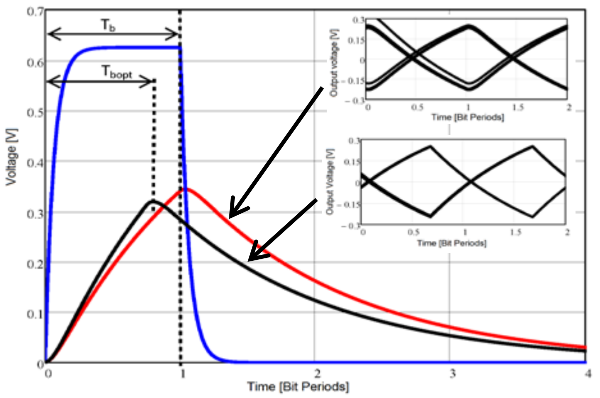


Fig.5 Output eye diagram analysis, optimized pulse

However, from Table I, it is clearly seen that both optimal parameters $A_{opt}$ and $T_{bopt}$ for measured channel CH1 in Fig. 1 are not changed in the same way with increasing bit rate. The variation of $A_{opt}$ has a linear character and the $T_{bopt}$ is exponential. Hence the pulse shaped according to optimal parameters in Table I for higher bit rates is not more power efficient than conventional pulse for the same bit rate. One of the possible solutions lies in the use of non-conventional pulse shaping based on the more sophisticated pulse definition, more details in the next section.

Table 1 Optimized pulse parameters

| | Channel Output | | Optimized pulse parameters | | |
|---|---|---|---|---|---|
| Bit Rate | Eye Height | Eye Width | $A_{opt}$ | $T_{bopt}$ | $T_b$ Percentage |
| [ Gb/s ] | [ V ] | [ ps ] | [ V ] | [ ps ] | [%] |
| 1 | 0,67 | 1000 | 0,96 | 1000 | 100,0 |
| 2 | 0,58 | 465 | 1,02 | 476,2 | 95,2 |
| 3 | 0,46 | 310 | 1,05 | 314,5 | 94,4 |
| 4 | 0,41 | 218 | 1,05 | 232,6 | 93,0 |
| 5 | 0,30 | 163 | 1,08 | 183,5 | 91,8 |
| 6 | 0,23 | 114 | 1,10 | 149,3 | 89,6 |
| 7 | 0,14 | 79 | 1,12 | 123,5 | 86,5 |
| 8 | 0,07 | 69 | 1,15 | 107,3 | 85,8 |

## 4 Signal shaping analysis

Based on the measuring kit and analysis described above and the results presented in [10], [11] a modified pulse is proposed. The most commonly used Nyquist pulse is the raised-cosine pulse [17]. In [10], [11] pulse shaping based on cosine functions is successfully applied in high-speed signaling communication through real lossy transmission channels. Thus, more variants of signal conditioning are applicable to improve signal integrity through the lossy channels. As can be shown in Fig. 5 pulses at the output of the transmission channel are spread over several symbol periods with exponential character. The proposed signal pulse uses a flipped-exponential function, firstly published in [19]. Our invention lies in adaptation of this function to the pulse shaping filter which uses time-domain and amplitude pre-emphasis. Thus, a novel pulse shaping is achieved. Our assumptions are based on the similar functionality as in the case of equalizers used in high-speed communication signaling where equalizer transfer function is ideally inverse to transmission channel response. Thus, the conventional raised-cosine pulse shaping is replaced. As will be shown below, this causes better pulse adaptation to pass through the lossy transmission channel. Together with optimized adaptive pulse shaping a better performance is achieved compared to the conventional pulse [18], [19], [29]. The modified pulse is defined in time-domain as

$$s_{\exp}(t) = A_{OPT}\,\mathrm{sinc}\left(\frac{\pi t}{T_b}\right)\left[\frac{4\beta_x t\pi z_1 + 2\beta_x^2 z_2 - \beta_x^2}{4\pi^2 t^2 + \beta_x^2}\right] \quad (6)$$

where

$$z_1(t) = \sin\left(\pi\alpha_x \frac{t}{T_b}\right) \quad \text{and} \quad z_2(t) = \cos\left(\pi\alpha_x \frac{t}{T_b}\right) \quad (7)$$

The key pulse parameter which establishes an inverse exponential function is $\beta_x$. The modification of our proposed pulse shaping lies in two parameters. The first parameter $A_{OPT}$ is adaptively changed together with parameter $\beta_x$ which is defined as

$$\beta_x = \frac{\ln 2}{\alpha_x B_x} \quad (8)$$

where $B_x$ variable is set similarly according to analysis described above in section pulse-width pre-emphasis. The maximum value $B_x = 1/(2T_b)$ but optimal value will be lower, $B_{xopt} = 1/T_{bopt}$. The variable $\alpha_x$ is represented as in the case of raised cosine pulse roll-off factor.

In Fig. 6 are shown all the analyzed pulses. It is obvious that the magnitudes of the two largest side lobes of the pulses based on the flipped-exponential function are smaller than the magnitudes of the two largest side lobes of the conventional raised-cosine pulse. If we compare both pulses based on the based on the flipped-exponential function, we can see additional better performance for optimized exponential pulse where magnitudes of two largest side lobes have still decreasing tendency. Moreover, notice the difference in pulse shaping of optimized exponential pulse where steeper transition is evident. This reduces pulse width and minimizes the pulse spreading due to the channel ISI effect.

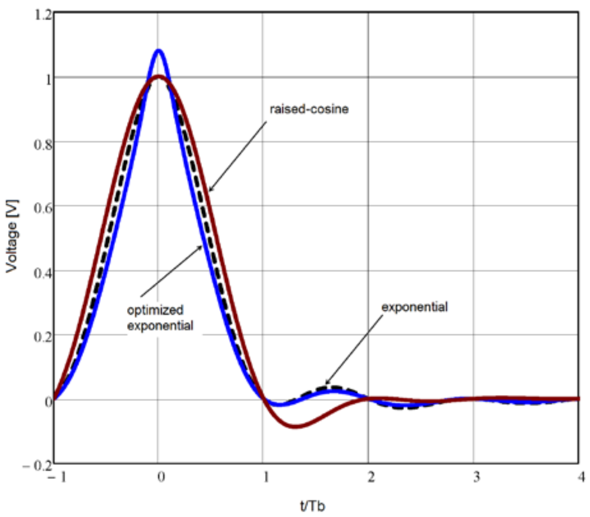


Fig.6 Impulse responses of all compared pulses

The parameter $\beta_x$ can be adjusted by changing two variables. Both of the parameters are swept linearly. However the response of $\beta_x$ is different for each of them. Increasing value of the first variable $\alpha_x$ causes an exponential decreasing of $\beta_x$. Increasing value of the second variable $T_b$ shows linear increasing of $\beta_x$. This situation is shown in Fig.7.

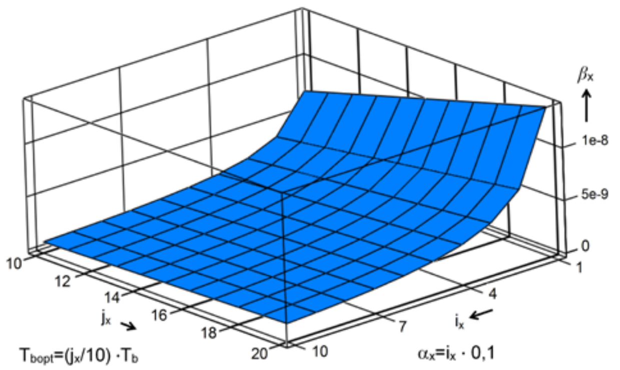


Fig.7 Dependence of $\beta_x$ when variables $\alpha_x$ and $T_{bopt}$ are linearly swept.

For optimal setting of both parameters, it is necessary to analyze their impact on output signal. In Fig. 8 it is shown the impulse response and output eye diagram of proposed pulse during the $\alpha_x$ variation. It is obvious that appropriate $\alpha_x$ setting can improve jitter and eye opening. In this case transmission channel with small losses was used. Optimal $\alpha_x$ value lies approximately in the middle of range ($\alpha_x = 0.60$). Two possible extremes of $\alpha_x$ are 0 and 1 but in this case eye diagram shows strong ISI. Very low value of $\alpha_x$ can cause significant ISI between symbols and additional signal jitter as well higher $\alpha_x$ values. The second variable $T_b$ shows additional jitter during variation. The situation is clearly shown in Fig. 9. As in the previous case, an optimal eye opening is strongly dependent on accurate setting of variables.

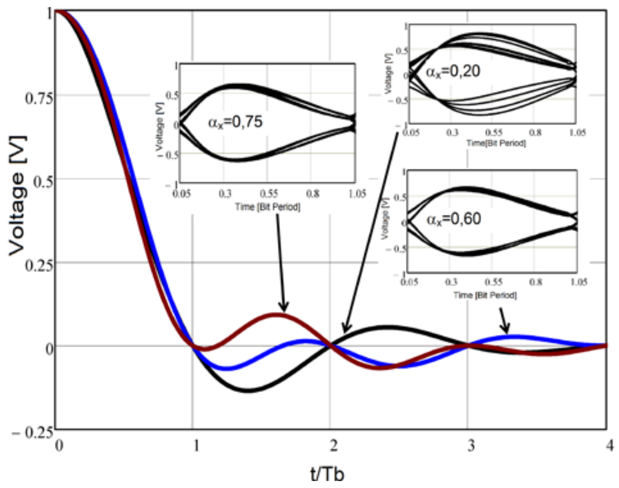


Fig.8 Impulse response and eye diagram performance for various $\alpha_x$.

Both variables complement each other due to the different response of $\beta_x$ parameter on variation each of them, see Fig. 7. The optimal setting process for $\beta_x$ parameter includes two main steps. Firstly, the optimal value of $\alpha_x$ variable is found with a set maximum value of $B_x$. The next step involves adjusting of variables $T_b$ to achieve jitter reduction.

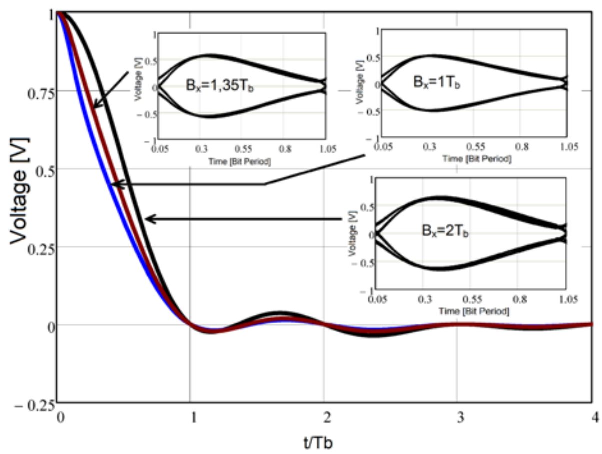


Fig.9 Impulse response and eye diagram performance for various $T_b$.

Very important is the analysis of pulses susceptibility to system errors. In this case a BER analysis is performed for several values of variable $\alpha_x$. The BER was analyzed for SNR = 15 dB. Below in Table II, Table III and Table IV are shown results of error probabilities for all analyzed pulses. Note that the error rates are better (smaller) for all $\alpha_x$ variations and timing offsets of the proposed exponential-optimized pulse.

Table 2 BER analysis, raised cosine

| $\alpha_x$ | $t/T_b$ | $t/T_b \pm 0.05$ | $t/T_b \pm 0.1$ | $t/T_b \pm 0.2$ | $t/T_b \pm 0.25$ |
|---|---|---|---|---|---|
| 0.25 | 3.33E-07 | 5.51E-07 | 1.48E-06 | 2.37E-05 | 9.71E-05 |
| 0.55 | 4.93E-08 | 1.07E-07 | 2.29E-07 | 2.45E-06 | 1.64E-05 |
| 0.65 | 4.99E-08 | 5.03E-08 | 9.94E-08 | 1.40E-06 | 6.94E-06 |

Table 3 BER analysis, exponential

| $\alpha_x$ | $t/T_b$ | $t/T_b \pm 0.05$ | $t/T_b \pm 0.1$ | $t/T_b \pm 0.2$ | $t/T_b \pm 0.25$ |
|---|---|---|---|---|---|
| 0.25 | 2.55E-07 | 3.82E-07 | 1.03E-06 | 1.55E-05 | 6.50E-05 |
| 0.55 | 6.05E-08 | 6.63E-08 | 9.10E-08 | 1.62E-06 | 7.70E-06 |
| 0.65 | 2.09E-08 | 2.65E-08 | 4.98E-08 | 1.16E-06 | 6.66E-06 |

Table 4 BER analysis, exponential-optimized

| $\alpha_x$ | $t/T_b$ | $t/T_b \pm 0.05$ | $t/T_b \pm 0.1$ | $t/T_b \pm 0.2$ | $t/T_b \pm 0.25$ |
|---|---|---|---|---|---|
| 0.25 | 2.35E-07 | 3.70E-07 | 9.92E-07 | 1.41E-05 | 5.79E-05 |
| 0.55 | 2.08E-08 | 2.34E-08 | 5.79E-08 | 1.09E-06 | 6.02E-06 |
| 0.65 | 1.32E-08 | 1.53E-08 | 2.89E-08 | 4.00E-07 | 5.99E-06 |

Eye diagram outputs of all analyzed pulses are shown in Fig. 10. The conventional raised-cosine pulse shows more ISI predisposition than pulses based on the flipped-exponential function. This may cause former eye closing during the increasing channel losses. Better immunity to ISI shows flipped-exponential variants of pulses. This confirms our consideration that pulses based on flipped-exponential functions can be less degraded by the channel itself. However residual signal jitter is reduced if exponential-optimized pulse is used.

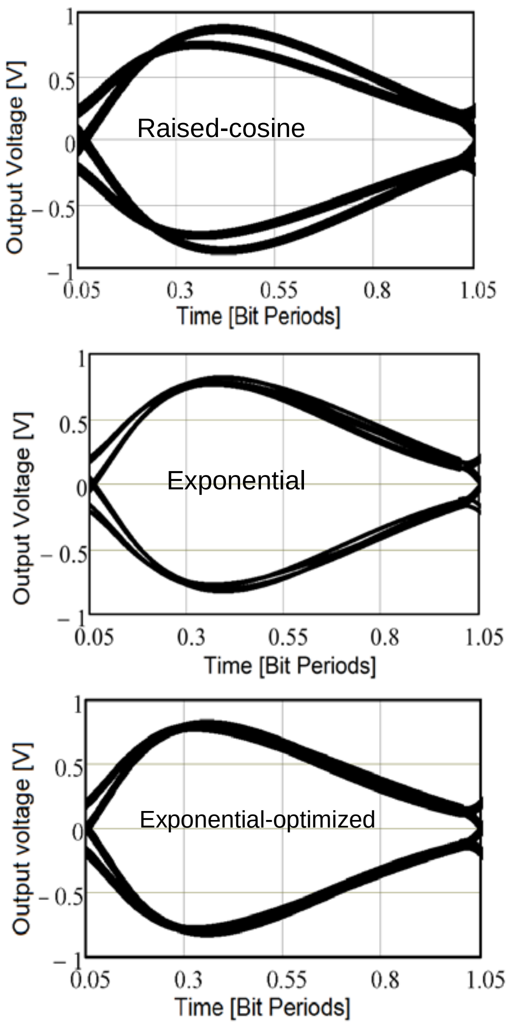


Fig.10 Eye diagram performance of all analyzed pulses

The BER results for the last set values of $\alpha_x = 0.65$ are plotted in Fig. 11. The optimal values of both variables for exponential-optimized pulse are determined as $\alpha_x = 0.65$ and $T_{bopt} = 1.75T_b$.

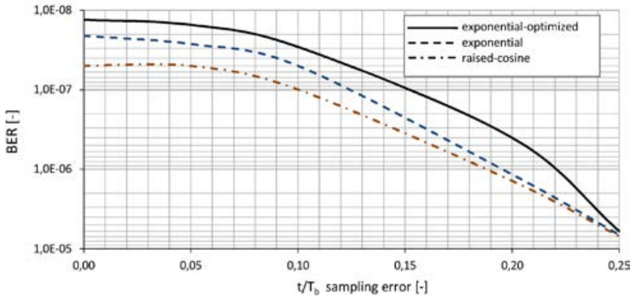


Fig.11 ISI error probability

We can see that raised cosine pulse and exponential pulse have tendency to increase BER during increasing of sampling error. Higher values of sampling errors show almost identical BER results for both pulses. Note also steep increase of BER if sampling error exceeds value ±0.10. On the other hand, exponential-optimized pulse shows a different behavior during sampling error variation. In this case the increase of the BER is gradual. As a critical value of sampling error can be marked ±0.25.

## 5 Conclusion

In this paper the novel pulse shaping was firstly introduced for high-speed chip-to-chip interconnects. The proposed pulse reflects knowledge obtained by measuring of real lossy wire channels and analysis of their impact on the passing pulses is shown in the first two sections of the paper. As it can be seen from the analysis performed above the exponential-optimized pulse is capable to better withstand channel impairments compared to conventional pulses. In other related research works detailed analyses of proposed pulse in frequency-domain will be performed. The obtained results are important for continuing research in the field of signaling methods for modern low-power high-speed communication systems. The research presented in this paper is a part of development project solved by Brno University of Technology and ABB development and research department which is focused on the development of novel protection systems that use digital process data from electronic sensors.

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