DesignCon 2016

100 Gb/s Serial Transmission over Copper using Duo-binary Signaling

Joris Van Kerrebrouck, Ghent University
joris.vankerrebrouck@intec.ugent.be

Jan De Geest, FCI
jan.degeest@fci.com

Renato Vaernewyck, Ghent University
renato.vaernewyck@intec.ugent.be

Michael Fogg, FCI
mike.fogg@fci.com

Guy Torfs, Ghent University
guy.torfs@intec.ugent.be

Timothy De Keulenaer, Ghent University
timothy.dekeulenaer@intec.ugent.be

Ramses Pierco, Ghent University
ramses.pierco@intec.ugent.be

Arno Vyncke, Ghent University
arno.vyncke@intec.ugent.be

Madhumitha Rengarajan, FCI
madhumitha.rengarajan@fci.com

Johan Bauwelinck, Ghent University
johan.bauwelinck@intec.ugent.be

Abstract

At last year's DesignCon we presented duo-binary signaling as an alternative for PAM4 for data rates of 56 Gb/s and higher over copper. This paper explores the feasibility of using duo-binary signaling for 100 Gb/s serial transmission over copper. It includes an in-depth comparison between duo-binary and other signaling schemes regarding the acceptable channel loss, the tolerable crosstalk and jitter and the power consumption for serial data rates up to 100 Gb/s, and we study what the channel requirements are to be able to use duo-binary signaling for 100 Gb/s serial transmission over copper.

Authors Biography

Joris Van Kerrebrouck was born in Ghent, Belgium in 1989. He received the master degree in applied electrical engineering from Ghent University, Belgium, in 2014. In 2014, he joined the INTEC Design laboratory part of the department of information technology at Ghent University, where he pursues the PhD. degree, working on high speed electrical transceivers. His current fields of interest are high-speed SiGe BiCMOS analog circuits and systems.

Timothy De Keulenaer is a Postdoctoral Researcher at INTEC. He was born in Mortsel, Belgium, in 1987. He received the bachelor and master degree in applied electronics from Ghent University, Ghent, Belgium, in 2008 and 2010 respectively and has from then on been working at the INTEC Design laboratory part of the department of information technology at Ghent University. There he received the PhD degree in applied electrical engineering in June 2015. His research focuses on high speed integrated circuit design and signal integrity aspects for backplane communication and is currently working on the development of a duo-binary transceiver chipset aiming at serial data rates up to 112Gbps as part of the BiFAST project.

Jan De Geest is a Senior Staff R&D Signal Integrity Engineer at FCI. He received the degree in electrical engineering from the University of Ghent, Belgium in 1994 and the degree in supplementary studies in aerospace techniques from the University of Brussels, Belgium in 1995. From September 1995 to December 1999 he worked as a research assistant at the Department of Information Technology (INTEC) of the University of Ghent, where he received the PhD degree in electrical engineering in 2000. Since January 2000 he has been working for FCI. His work focuses on the design, modeling and optimization of high-speed connectors and interconnection links.

Ramses Pierco is a Postdoctoral Researcher at INTEC. He received the master degree in applied electrical engineering from Ghent University, Belgium in 2010 and has from then

on been working at the INTEC Design laboratory part of the department of information technology at Ghent University. There he received the PhD degree in applied electrical engineering in 2015. His research is focused on analog high speed integrated circuit design and is currently working on the development of a duo-binary transceiver chipset aiming at serial data rates up to 112Gbps as part of the BiFAST project.

Renato Vaernewyck was born in Waregem, Belgium, in 1987. He received the M.S. and Ph.D. degree in electrical engineering from Ghent University, Ghent, Belgium, in 2010 and 2014 respectively. He has been a research assistant in the INTEC Design Laboratory part of the department of information technology at Ghent University, since 2010. His research focuses on high-speed, high-frequency (opto-)electronic circuits and systems. He is currently working on the development of a duo-binary transceiver chipset aiming at serial data rates up to 112Gbps as part of the BiFAST project.

Arno Vyncke is a Doctoral Researcher at INTEC. He received the master degree in applied electrical engineering from Ghent University, Belgium in 2010 and is pursuing the PhD. degree within the INTEC Design group part of the department of information technology at Ghent University. His current fields of interest are high-speed mixed signal designs, clock and data recovery systems and backplane communication and he is currently working on the development of a duo-binary transceiver chipset aiming at serial data rates up to 112Gbps as part of the BiFAST project.

Guy Torfs received the M.S. and Ph.D. degree in electrical engineering from Ghent University, Belgium in 2007 and 2012 respectively. From 2007 on, he has been working at the INTEC Design laboratory associated with imec and part of the department of information technology at Ghent University. His research focuses on high-speed mixed signal designs for fiber-optic and backplane communication systems, including equalization circuits and clock and data recovery systems.

Johan Bauwelinck was born in Sint-Niklaas, Belgium, in 1977. He received the Ph.D. degree in applied sciences, electronics from Ghent University, Belgium in 2005. Since Oct. 2009, he is a professor in the INTEC department at the same university and since 2014 he is leading the INTEC Design group. He also became a guest professor at iMinds in the same year and in November 2014, the Design group was awarded the 3rd bi-annual Greentouch 1000x award together with Bell Labs/Alcatel-Lucent and Orange Labs. His research focuses on high-speed, high-frequency (opto-)electronic circuits and systems, and their applications on chip and board level, including transmitter and receiver analog front-ends for wireless, wired and fiber-optic communication or instrumentation systems. He co-authored more than 150 publications and 10 patents in the field of high-speed electronics and fiber-optic communication.

1 Introduction

Standards groups like the OIF CEI-56G-VSR/MR and the IEEE P802.3bs 400 GbE have recently adopted NRZ and PAM4 for serial data rates at 50 Gb/s and 56 Gb/s [1, 2]. Although the 400 GbE is currently achieved using 8 lanes running at 50 Gb/s, a solution using 4 lanes running at 100 Gb/s would be preferred by the industry. However, no solutions for 100 Gb/s serial transmission over copper exist on the market today. At last year's DesignCon we presented duo-binary (DB) signaling as an alternative for PAM4 for data rates of 50 Gb/s and higher over copper. This paper explores the feasibility of using DB signaling for 100 Gb/s serial transmission over copper.

The paper starts with an in-depth comparison between DB and other signaling schemes regarding the acceptable channel loss, the tolerable crosstalk and jitter and the power consumption for serial data rates up to 100 Gb/s. We look at the limitations of the different solutions that are currently on the market and highlight where DB signaling offers a distinct advantage. The specific challenges and implementation issues that the different signaling schemes will face when moving towards 100 Gb/s are also considered. Power efficient design is a very important requirement from the industry and is addressed in detail here.

At DesignCon 2015 we demonstrated error-free transmission (without forward-error-correction) at 56 Gb/s over a state-of-the-art backplane demonstrator using a custom DB chipset [3]. The original design of the DB transmitter has been revised, such that it's now capable of running at data rates of 100 Gb/s and higher. The challenges and potential solutions from an implementation point of view for achieving these speeds with DB signaling are explained.

New measurements are presented using this improved chipset at serial speeds leading up to 100 Gb/s over a variety of copper channels. Using this chipset we can determine the maximum achievable date rate as a function of the total interconnection length (or loss) for cables and different types of backplane architectures. From these experiments, we can then study what the required channel performance is to be able to successfully use DB signaling for 100 Gb/s serial transmission over copper.

To conclude, an outline of future work will be given.

2 Duo-binary signaling

DB signaling is an alternative for the omnipresent NRZ and PAM4 signaling schemes which was first proposed by Lender in 1963 [4], evolved in the following decades [5, 6] and still receives a lot of interest to date albeit more in the optical world [7-9]. When using DB two subsequent bits of a NRZ stream are combined into a three-level symbol (1,0 or -1), following the function $1 + z^{-1}$, with the same symbol rate as the initial NRZ bit rate. Since certain three-level symbols can't be followed directly by certain other three-level symbols (e.g. a 1 can never be followed by a -1), the bandwidth of the signal is reduced as shown in Figure 1.
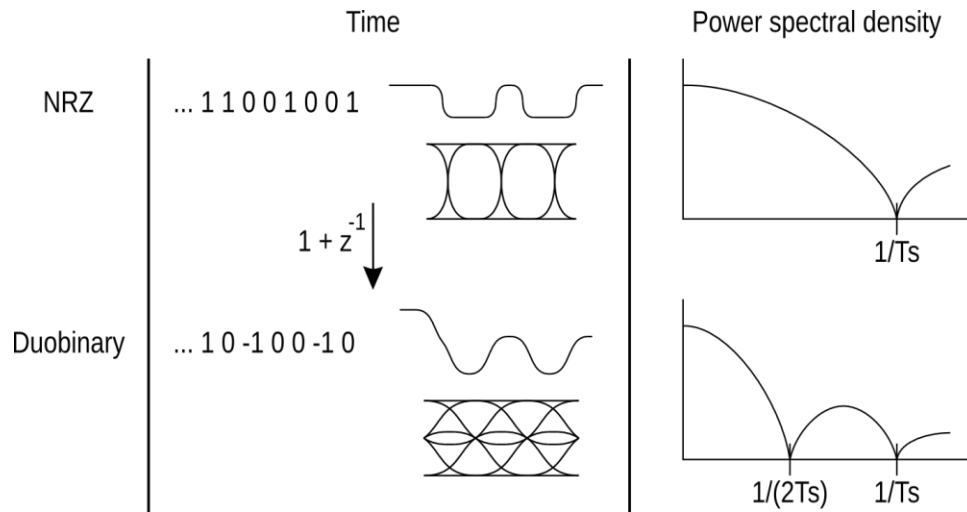
Figure 1: DB signal created from NRZ (bit period of Ts): waveform, eye diagram and spectrum.

The reduction of signal bandwidth for DB signaling comes at the cost of an extra level and thus half the vertical eye opening at the receiver. However, for backplane channels and cables of which the amplitude response inevitably rolls off as a function of frequency and which will have dips or so called suck-outs in the transfer function (due to e.g. via hole stubs, ground resonances, imperfect cable shielding, etc.), the use of a multi-level signaling scheme can result in overall larger eye opening at the receiver compared to NRZ. This is dependent on the channel frequency response in combination with the desired data rate as will be discussed further in section 2.1.
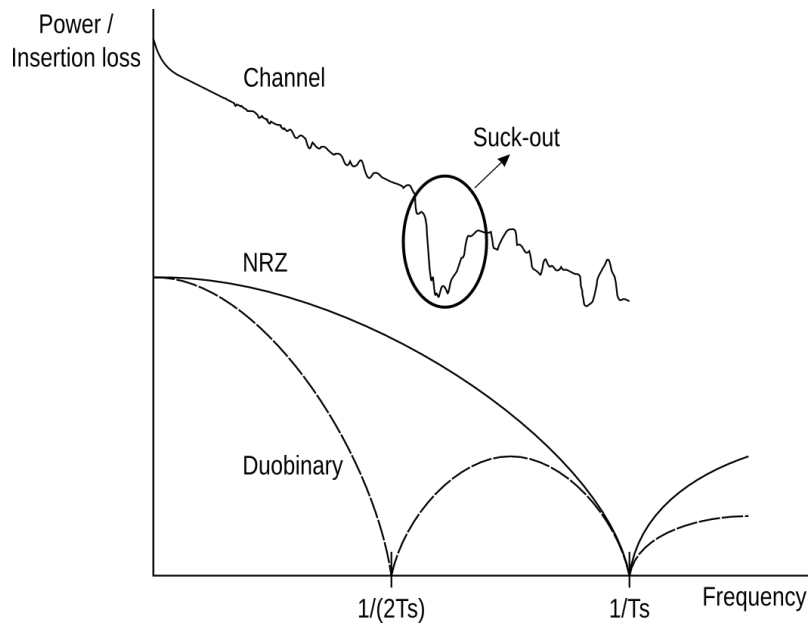
Figure 2: Typical insertion loss profile of a backplane/cable channel together with the power spectral density of NRZ and DB, with a bit duration of Ts.

From the power spectral density (PSD) shown in Figure 2, it is clear that the larger part of the DB signal is confined below 1/(2Ts), with Ts being the bit duration. This PSD corresponds closely to the one of PAM4 where four amplitude levels are required at half the bit rate. With a channel insertion loss as shown in Figure 2, it is hard if not impossible to equalize the transmission channel at frequencies far above 1/(2Ts) for NRZ. Because of this it will be necessary to shift to more complex modulation formats like DB and PAM4.

Since DB has a vertical eye height which is half of that of a NRZ signal, it will be twice as susceptible to crosstalk (not taking into account the extra bandwidth requirements for NRZ). This is nonetheless better than PAM4 which is three times as susceptible to crosstalk compared to NRZ.

2.1   Nyquist, channel loss and CPSD

A measure often used when comparing different modulation formats is the Nyquist frequency which corresponds to the channel bandwidth (considering a perfect brick-wall filter) for which no inter symbol interference (ISI) occurs. For NRZ and PAM4 this corresponds to 1/(2Ts) and 1/(4Ts) respectively. In the case of DB the Nyquist frequency is 1/(2Ts) (an infinite series of DB zeros requires the 1/(2Ts) frequency, although this frequency component itself can be infinitely small), while practically (and as suggested by the PSD) the DB signal can have a much smaller channel bandwidth without seeing significant ISI.

For DB the Nyquist frequency is often defined as 1/(3Ts) [10], as this corresponds to the largest frequency commonly present in a DB signal with a non-zero amplitude caused by the symbol sequence 100100… (or -100-100…) as shown in Figure 3.
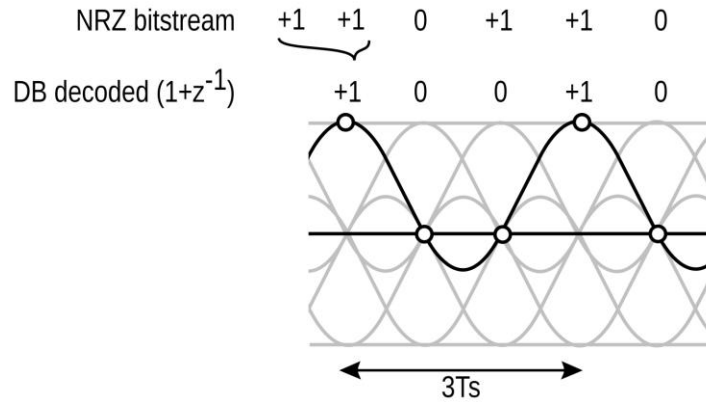

Figure 3: DB data stream with highest frequency component (with non-zero amplitude) highlighted.

By using the Nyquist frequency together with the channel loss and assuming a channel with a linear loss characteristic (as shown in Figure 2) without much ripple or suck-outs, the amount of channel loss (expressed in dB/GHz) for which a certain modulation will result in a higher vertical eye height can be calculated. This calculation can easily be done for NRZ and PAM4 taking into account the 9.54 dB penalty for PAM4 (eye height divided by the amplitude of the highest frequency component).

$$\text{Channel loss} = \frac{9.54 \text{ dB}}{f_{Nyq,NRZ} - f_{Nyq,PAM4}}$$

For a 100 Gb/s transmission this means that as soon as a channel has a loss in excess of 0.38 dB/GHz, PAM4 will be the optimal choice regarding vertical eye height compared to NRZ. For DB signaling things are a bit different as the highest frequency component in the DB stream isn't going rail-to-rail and the vertical eye height is three quarters of the amplitude of the highest frequency component. Because of this DB only has a 2.5 dB penalty compared to NRZ.

$$\text{Channel loss} = \frac{2.5 \text{ dB}}{f_{Nyq,NRZ} - f_{Nyq,DB}}$$

When a 100 Gb/s transmission is again considered, channels with a channel loss larger than 0.15 dB/GHz will lead to the largest vertical eye height by using DB instead of NRZ. A similar equation as before can be derived for calculating the channel loss at which PAM4 will have a larger vertical eye opening than DB.

$$\text{Channel loss} = \frac{9.54\,\text{dB} - 2.5\,\text{dB}}{f_{\text{Nyq,DB}} - f_{\text{Nyq,PAM4}}}$$

From the previous formula follows that a 100 Gb/s transmission will have a larger vertical eye height in case of PAM4 instead of DB whenever the channel loss is larger than 0.84 dB/GHz (or 42 dB at 50 GHz).

The previous calculation of the channel loss at which DB presents the optimal modulation format isn't entirely correct. Firstly, as mentioned before, the actual Nyquist of DB is 1/(2Ts) and secondly, DB can be created by using the lossy characteristic of the channel [11] which will result in a larger eye height at the receiver than suggested by the previous derivation. To understand this last reason the transmitter (Tx) – channel – receiver (Rx) chain is given for a 100 Gb/s data transmission using PAM4 and DB in Figure 4.
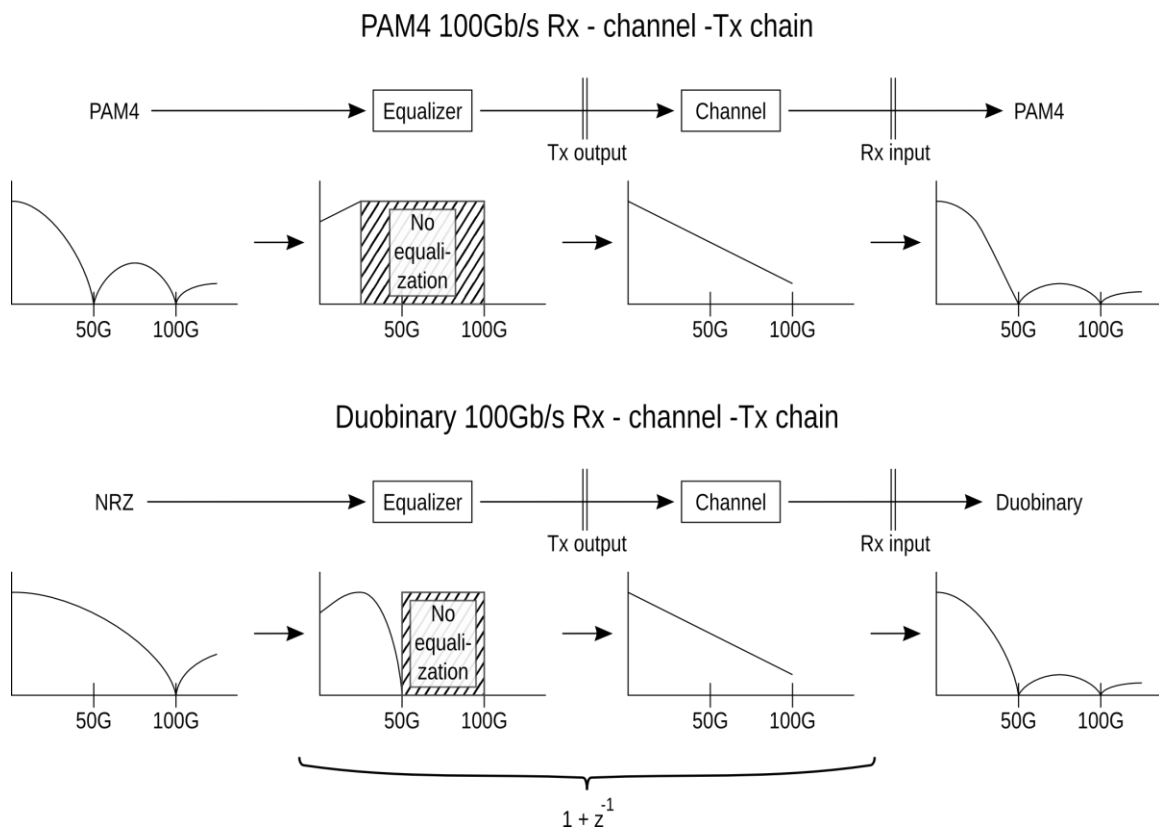

Figure 4: PAM4 and DB 100 Gb/s transmission chain.

The main difference between a PAM4 and a DB transmission chain lies in the difference between the in- and output modulation in case of DB since the equalizer and the channel response are actually used to create the DB signal at the Rx input. This has as a result that the ideal equalizer characteristic of a DB transmission isn't the inverse of the

channel characteristic as is the case for NRZ and PAM4. However, the previous calculation of the eye height at the Rx is entirely based on the equalizer having the inverse function of the channel. Since this isn't valid anymore for DB we need to find another way of determining the vertical eye opening at the Rx.

In a real-life transmission system the main limiting factor in creating larger eye heights is the amplitude that can be delivered at the Tx. Depending on the modulation format, the channel response (determined by the equalizer at the Tx) up to the Tx output will look different and it is the DC value (the channel ideally has no loss at DC) of this channel response which will determine the signal strength at the Rx input.
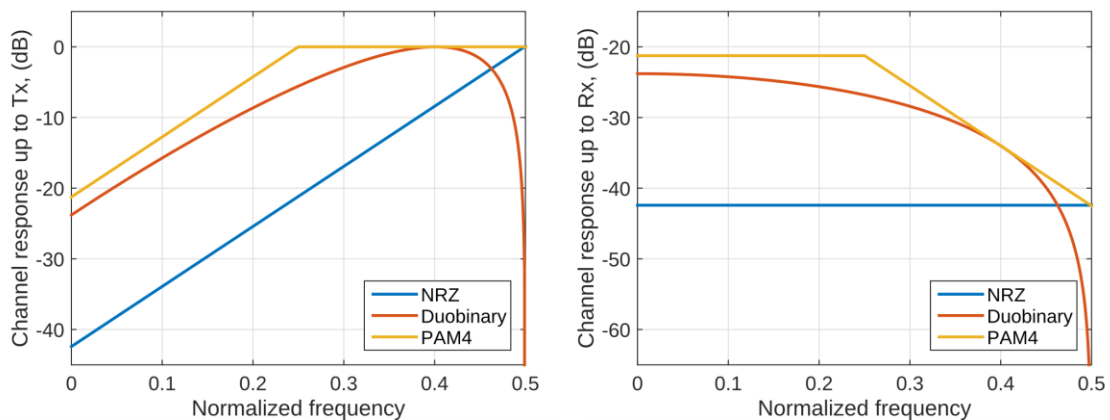

Figure 5: Channel response (equalizer at the Tx) for NRZ, DB and PAM4 up to the Tx output and Rx input for a channel loss of 0.85 dB/GHz with a 100 Gb/s transmission.

In Figure 5 the channel response up to the Tx and Rx for a 100 Gb/s signal with a channel loss of 0.85 dB/GHz (which is above the earlier determined 0.84 dB/GHz) is shown. The channel response of a DB and PAM4 signal show significant differences at the Tx output since DB needs to be equalized up to $1/(2Ts)$ and the equalization isn't the inverse of the channel. By checking the DC value of either the channel response at the Tx or Rx (no DC loss in the channel), the amplitude of the received signal can be read. When comparing DB and PAM4 signaling, a 100 Gb/s transmission with a channel loss of 0.85 dB/GHz is still better off with DB (taking into account the 9.54 dB – 6.02 dB = 3.52 dB penalty for PAM4 compared to DB) while the previously used calculation led to a channel loss of 0.84 dB/GHz as the crossover point. With this more realistic method, the crossover channel loss is determined at 0.91 dB/GHz for a 100 Gb/s transmission.

Using this method, the eye height at the Rx is more realistic, however, there are no longer easy formulas to calculate the crossover channel loss. Furthermore we are still using a bandwidth of $1/(4Ts)$ for PAM4 while typically more bandwidth is required to

cope with the fact that real-life consists of approximately rectangular pulses instead of ideal Nyquist pulses. Another way of looking at the required bandwidth is by observing the cumulative power spectral density (CPSD) which shows what percentage of the bit energy is confined below a certain frequency (see Figure 6).
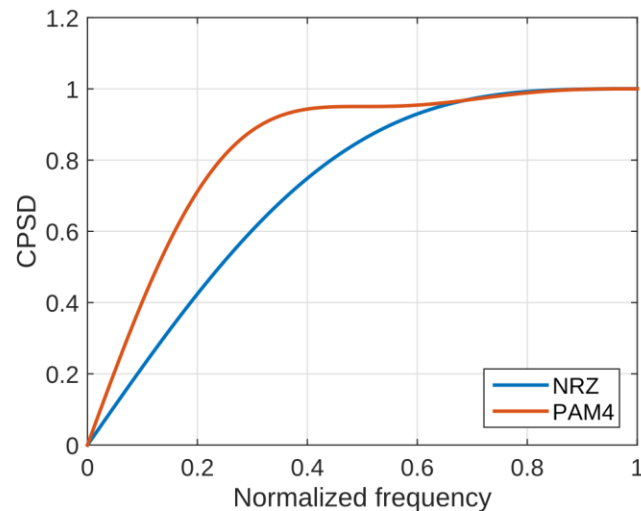

Figure 6: Cumulative power spectral density (CPSD) for NRZ and PAM4 modulation, assuming rectangular pulses.

For a bandwidth of 25% (1/4Ts) the CPSD of PAM4 amounts to 81.5%. At the same time a higher CPSD of 85% or even 90%, corresponding to respectively 0.273/Ts and 0.317/Ts, can be used to get closer to the expected ideal PAM4 waveform. However, by increasing the bandwidth spent on PAM4, the eye height at the Rx is reduced since the channel is equalized up to higher frequencies which results in a lower DC value for the channel transfer function up to the Tx output (see Figure 5). Based on the data rate and the amount of bit energy (expressed by the CPSD) a plot can be made of the channel loss for which either NRZ, DB or PAM4 will result in the largest eye height at the Rx using the previously discussed method. The result of this is shown in Figure 7.

It should be noted that if a PAM4 transmission is equalized up to 1/(2Ts), the eye height for a DB transmission will always be larger. This not only because there are only two vertical eyes for DB but also due to the absorption of some of the channel loss in the creation of the DB signal.
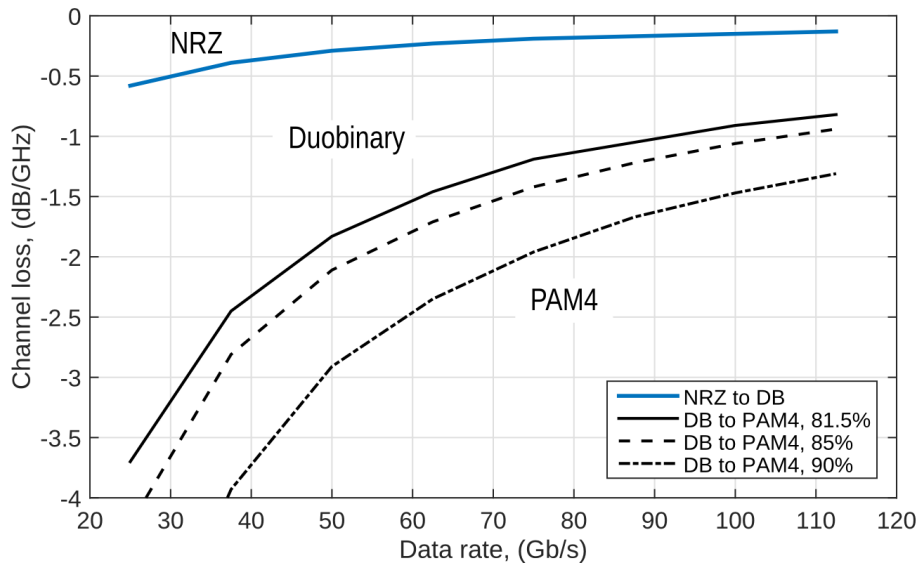
Figure 7: Division of channel loss into areas where either NRZ, DB or PAM4 will result in the largest vertical eye height depending on the data rate and the CPSD for PAM4 (81.5% corresponds to Nyquist signaling).

2.2 Jitter and CDR

The DB modulation scheme may only have three levels, while PAM4 has 4 levels. It does however require to be interpreted (and thus sampled) at the full data rate where this rate is only half in the case of PAM4. Logically this will lead to a difference in the influence of jitter on the correct demodulation of both modulation formats. To get an estimate of this influence, the horizontal eye opening of both signaling schemes needs to be evaluated (see Figure 8).
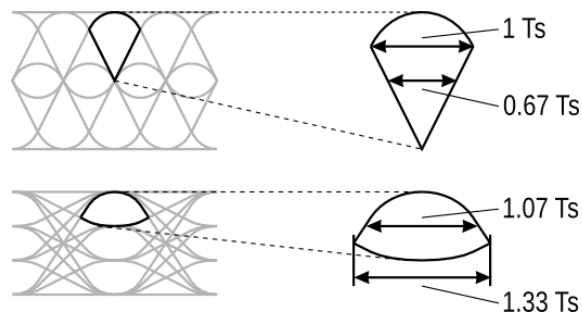

Figure 8: Comparison of horizontal eye opening in case of DB signaling (top) and PAM4 signaling (bottom) assuming Nyquist pulses.

When looking at the eye width of DB and PAM4 it is important to consider that the location with the largest horizontal eye opening doesn't correspond to the largest vertical eye opening. Therefore, two horizontal eye openings are defined in Figure 8, of

which one is the largest available eye width and the other is attributed to the level within the eye with the largest eye height. As expected the horizontal eye opening for a PAM4 signal is larger than the one of a DB signal, however, the difference between both is relatively small considering that the symbol rate of PAM4 is half of the symbol rate of DB. This is due to the crossings of the PAM4 signal which don't coincide as is the case with DB, leading to a 33% larger eye width for PAM4 when comparing the maximum eye width and a 60% larger eye width for PAM4 when comparing the level corresponding to the largest eye height. Switching the threshold for PAM4 and DB to the value which delivers the largest eye width corresponds to an eye height penalty of 41.4% for DB and 50% for PAM4.

The smaller horizontal eye opening in case of DB means that the implementation of a CDR at the Rx can tolerate less jitter. However, the implementation of this CDR also becomes less complex since all crossings coincide while in a PAM4 CDR certain crossings will need to be selected resulting in an increase in both complexity and power consumption [9].

3   Practical considerations

3.1   Tx and Rx topology

From an implementation point of view the design of a DB transceiver is a lot less complex compared to that of a PAM4 transceiver. At the Tx side it suffices to build a NRZ Tx (possibly with an equalizer) while a PAM4 Tx requires the design of a high-speed 2-bit digital-to-analog converter (DAC). It is important to note that a DB Tx does require the addition of a pre-coder which avoids error propagation at the Rx and allows simple decoding by means of a XOR gate. This pre-coding in general is easy to implement and consists in its simplest form of a flip-flop and a XOR gate.

At the Rx the simplest possible DB Rx consists of a wide-band low noise amplifier (LNA) followed by two comparators with a different threshold level (determined by the two DB eyes) and a XOR gate which gives a NRZ output stream. For a PAM4 Rx one possible implementation is to have three comparators followed by decoding logic which is similar to a 2-bit flash analog-to-digital converter (ADC).
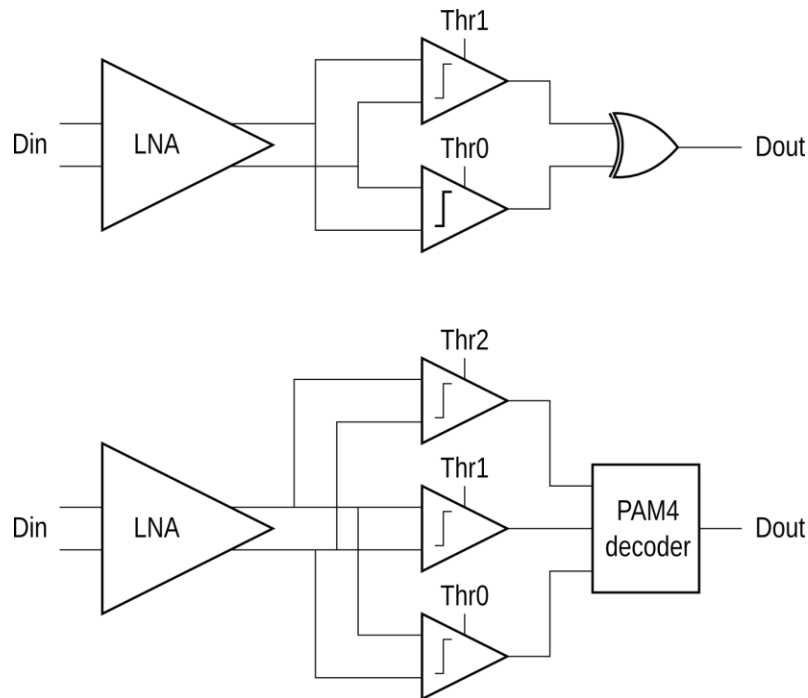
Figure 9: Possible implementation for a DB Rx (top) and a PAM4 Rx (bottom).

Figure 9 clarifies that a DB Rx will have a lower complexity in decoding the NRZ bit-stream. Furthermore the implementation of a CDR at the Rx is less complex since the eye crossings for a DB signal coincide in contrast to a PAM4 signal as was shown in Figure 8. For DB signaling this means that the design of a CDR can be as simple as that of a NRZ CDR [12] while the design of a PAM4 CDR will first require the selection of the appropriate crossings requiring additional logic and thus an increased power consumption.

3.2 Power consumption

Comparing the power consumption of different modulation formats is no easy thing as each scheme requires a different set of Tx and/or Rx subblocks or at least a variation of these subblocks. Moreover the speed requirement of the different blocks can change with the modulation format which can potentially have a large impact on the power consumption.

Despite this, efforts have been made to make an estimation of the power consumption based on for instance a "unit energy" constraint at the Tx emphasis filter [13]. However, the only way to get an honest comparison is by actually designing a chipset in the same technology (or, if possible, using similar off the shelf components) for each modulation format for the same data rate and the same communication channel. Exactly this has been done in the past for a data rate of 10 Gb/s [11, 14] and a data rate of 20 Gb/s [12].

The conclusion from these two papers is that for the channels under consideration, DB provides an alternative with lower power consumption than PAM4, while providing larger eye heights. In [12] a 20 Gb/s transmission across a 40-cm Rogers channel and a 10-cm FR4 channel leads to a 20% and a 71% lower power consumption respectively in case of DB, with roughly twice the eye height of PAM4 at the Rx across a channel with a loss of 1 dB/GHz. It is reasonable to expect the same kind of result if this effort were to be repeated for 100 Gb/s transmissions.

3.3   Cable channels for 100 Gb/s

Where up to now the choice of modulation format was largely determined by the complexity of the modulation scheme and the attributed power consumption (which is the reason why NRZ is used for data rates up to 50 Gb/s), future higher data rates will cause the modulation to be dictated by the transmission medium (i.e. NRZ will in many cases no longer be a viable/reasonable option). Measurements have been performed on a number of existing high-speed cable links, likely to be used in future 100 Gb/s communication, to determine their respective channel loss. This information is shown in Figure 10 and can be used to get to know which modulation format will result in the largest vertical eye height at a certain data rate.
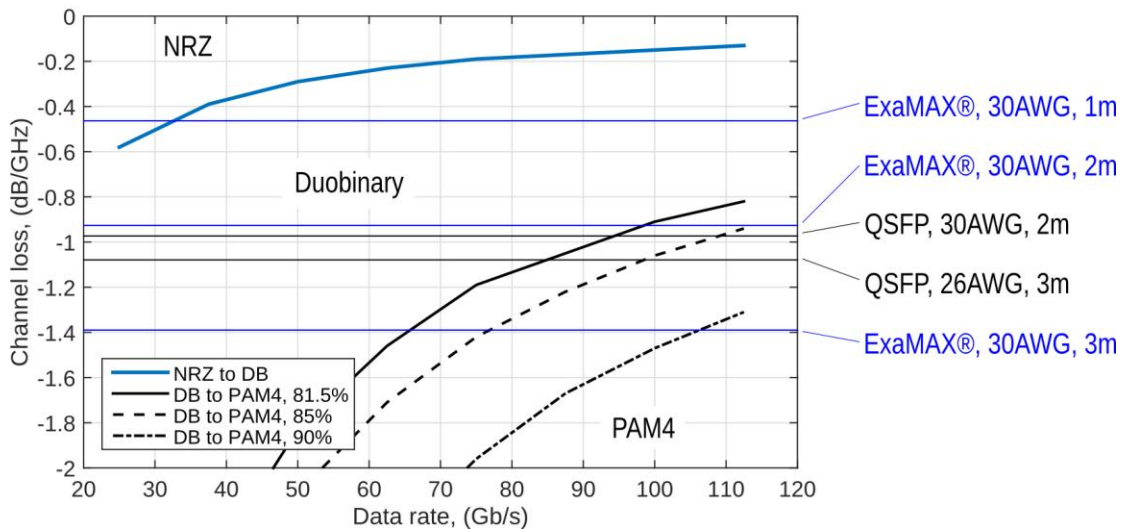

Figure 10: Division of channel loss into areas where either NRZ, DB or PAM4 will result in the largest vertical eye height together with the channel loss of several high-speed cable links.

Although the use of PAM4 for 100 Gb/s communication will result in a larger vertical eye opening for several, likely to be used, channels when moving to 100 Gb/s, the increase in complexity compared to NRZ and DB still needs to be justified. Subsequently it is only

when the eye height becomes small compared to the noise that the transition to PAM4 is desirable. The actual eye height at the Rx is shown in Table 1 for 100 Gb/s communication with either NRZ, DB and PAM4 together with the maximum possible SNR (eye height divided by the peak-to-peak thermal noise voltage assuming a 100Ω differential channel with a bandwidth of 1/(2Ts), 1/(3Ts) and 1/(4Ts) for NRZ, DB and PAM4 respectively and assuming room temperature) at a differential voltage swing of 1Vpp at the Tx.

In theory an SNR larger than 0 dB at the Rx should be enough for successful transmission, however, the noise figure of the Rx LNA together with the addition of other noise sources will lead to a more realistic required SNR of at least 10 dB. When applying this to table 1 it follows that NRZ drops out as a contender for all channels longer than 2m. Both DB and PAM4 then remain as a possible solution with the added advantage for DB of having a lower complexity which is expected to lead to a lower power consumption.

Eye height (mV) / SNR (dB)	ExaMAX®, 30AWG, 1m	ExaMAX®, 30AWG, 2m	ExaMAX®, 30AWG, 3m	QSFP, 30AWG, 2m	QSFP, 26AWG, 3m
NRZ	70.16 / 35.8	4.85 / 12.6	<1 / <0	3.75 / 10.4	2.02 / 4.98
Duo-binary	169.5 / 48.2	22.49 / 30.7	2.33 / 11.0	18.18 / 28.8	10.85 / 24.4
PAM4, 81.5%	88.08 / 43.8	23.10 / 32.2	6.10 / 20.6	20.29 / 31.0	14.89 / 28.4
PAM4, 85%	77.93 / 42.3	18.07 / 29.6	4.22 / 17.0	15.69 / 28.4	11.19 / 25.5
PAM4, 90%	61.65 / 39.7	11.30 / 24.9	2.09 / 10.3	9.59 / 23.5	6.47 / 20.1

Table 1: Eye height and SNR of the eye at the Rx for a 100 Gb/s data rate using NRZ, DB or PAM4 over several cable channels.

3.4 OIF 56G standardization

Recently the OIF CEI-56G-XSR/VSR/MR as well as IEEE 802.3bs have adopted PAM4 for serial data rates at and above 50 Gb/s. This means that a 400GbE link can be achieved by using 8 lanes where the preferred industry solution would be to have 4 lanes running at 100 Gb/s. In Figure 11 the channel loss defined in the 56 Gb/s OIF standard [1] are applied to the previously defined areas in which NRZ, DB or PAM4 give the maximum eye height.
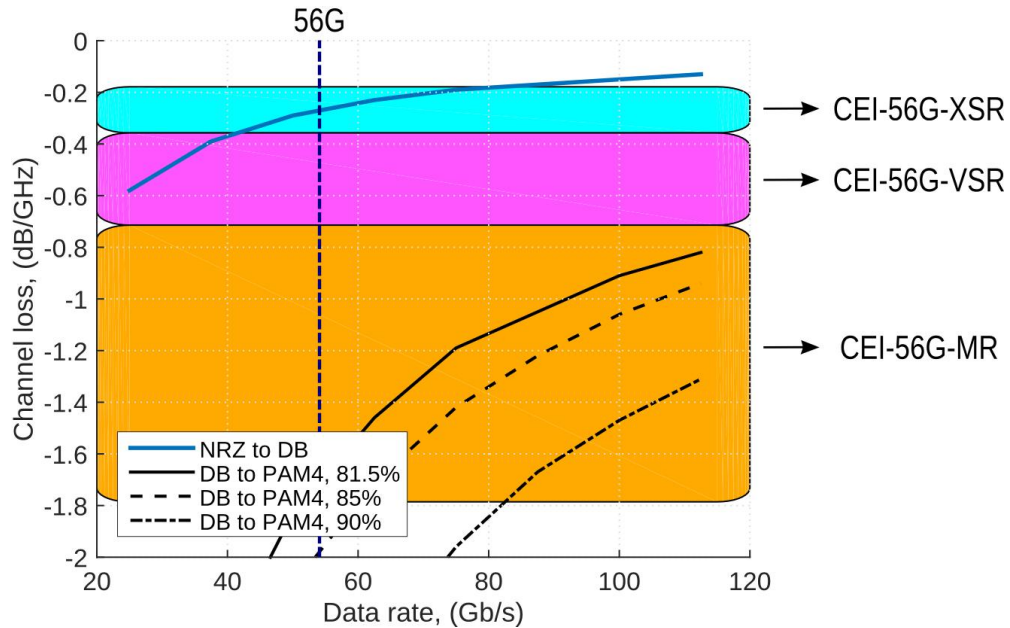

Figure 11: Division of channel loss into areas where either NRZ, DB or PAM4 will result in the largest vertical eye height, together with the channel loss defined in the OIF 56 Gb/s standard.

From Figure 11 it follows that DB will result in the largest eye height for 100 Gb/s transmission across a channel as defined in the current CEI-56G-XSR and CEI-56G-VSR standards. In comparison to NRZ, DB has a higher complexity at the Rx (the Tx is almost identical), however, this is countered by the additional amount of amplification required at the Rx in case of NRZ. Compared to PAM4 DB has a lower complexity and needs less amplification resulting in a significantly lower power consumption. Because of this DB is an ideal candidate for providing 100 Gb/s transmission across channels as defined in CEI-56G-XSR and CEI-56G-VSR.

3.5 Suck-out

In the previous estimation of the eye height at the Rx only the channel loss was taken into account. Another important phenomenon in real-life channels is the presence of a suck-out or resonance in the channel response due to e.g. via hole stubs, ground resonances, imperfect cable shielding, etc. As an example the measured transfer function for a QSFP connection with a 26AWG cable of three meters is shown in Figure 12.

The measurement shown in Figure 12 has a suck-out around 28.5 GHz with an average loss of 15 dB and a width of 0.35 GHz. In order to get an idea what the effect will be on the DB eye at the Rx, simulations have been performed for a 100 Gb/s transmission. In this simulation the equalizer is based on measurements performed on a real-life equalizer previously presented [3] to have a more realistic result. In Figure 12 the eye at the Rx for different suck-out frequencies is shown for a suck-out width of 0.35 GHz and a suck-out depth of 15 dB in an ideal channel having a channel loss of 1 dB/GHz.
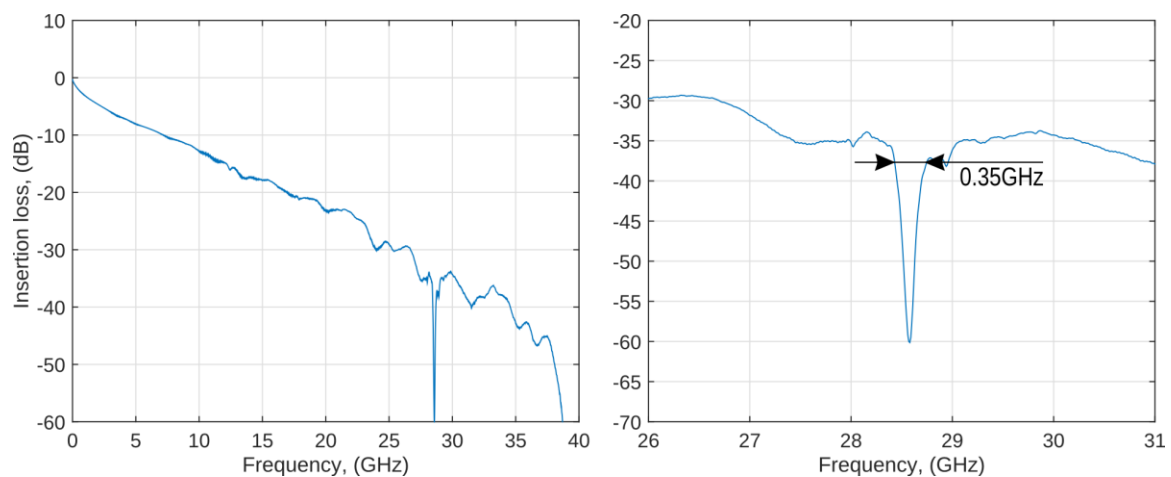

Figure 12: Insertion loss for a 26AWG, 3m QSFP cable channel (left) with suck-out around 28.5 GHz (right).

As shown in Figure 13 both the eye height and eye width are reduced by the addition of a suck-out at both 30 GHz and 20 GHz. The addition of a suck-out at 40 GHz has little effect as expected since frequencies above 1/(3Ts) shouldn't add significant ISI for DB. For 40 GHz, 30 GHz and 20 GHz a reduction of the eye height of respectively 4.8%, 16.7% and 40.5% is simulated. Due to the shape of the PSD of the DB scheme, a suck-out at lower frequencies will result in a larger reduction of bit energy and a corresponding larger reduction in eye height.
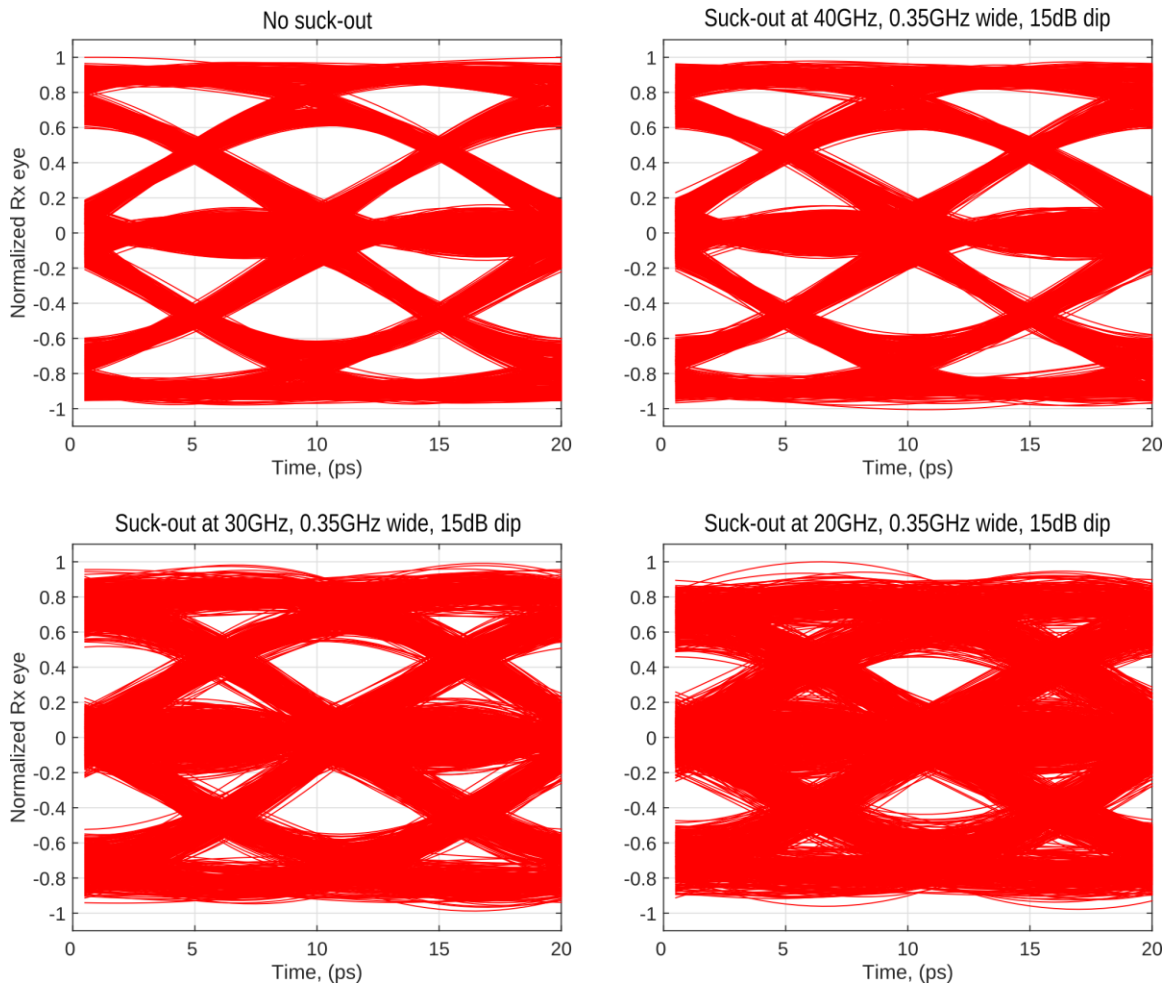
Figure 13: Simulated DB eye at the Rx for 100 Gb/s and a channel loss of 1 dB/GHz at different suck-out frequencies. Suck-out depth is 15 dB and suck-out width is 0.35 GHz.

Another important factor, next to the frequency, is the width of the suck-out (the depth typically has little influence as long this is above 10 dB). Variation of the suck-out width from 0.35 GHz to 1.4 GHz at different center frequencies gives the simulation eye at the Rx as shown in Figure 14. It is clear that the width of the suck-out isn't of much importance as long as the suck-out occurs past the 1/(3Ts) frequency.
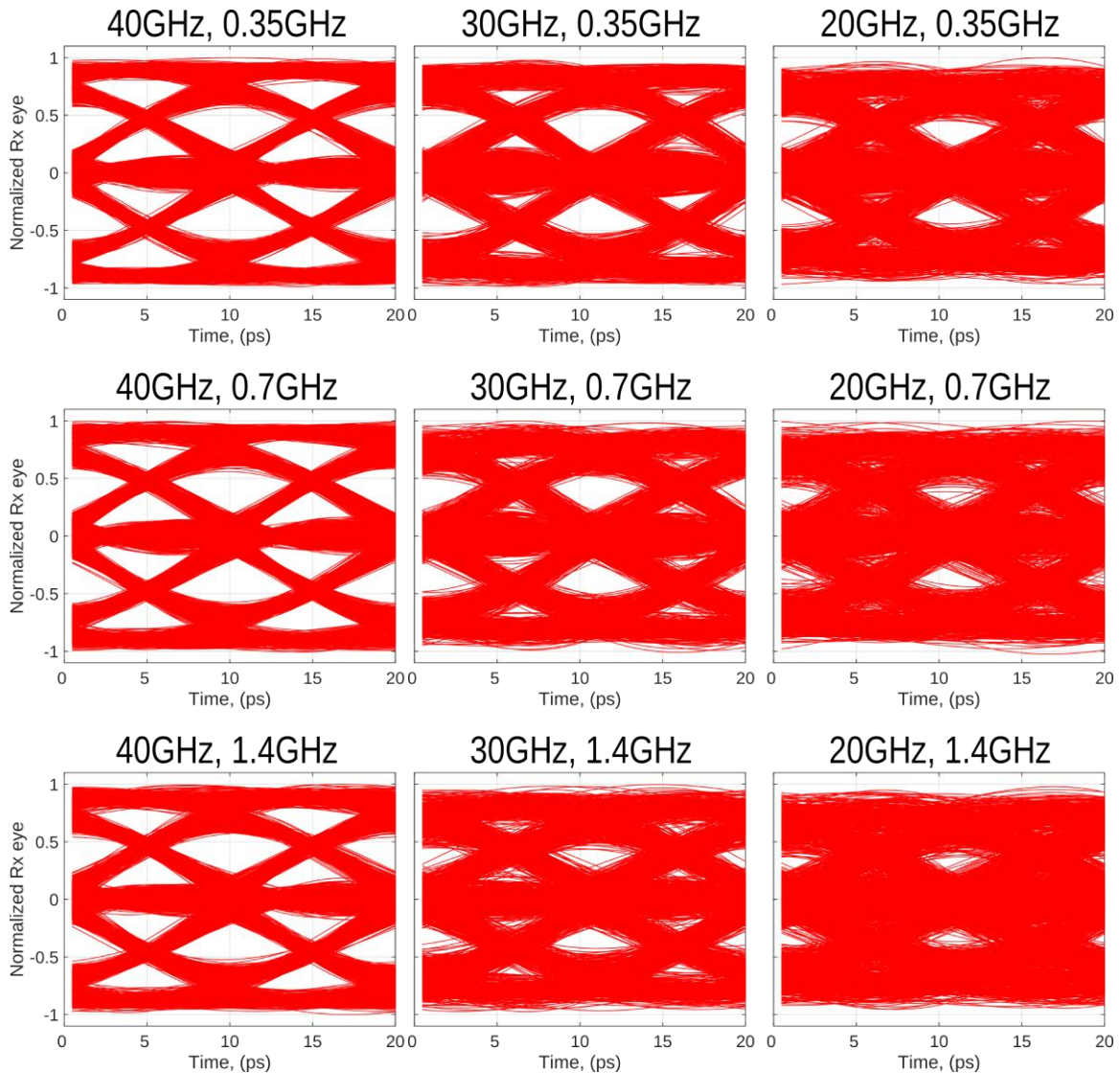
Figure 14: Simulated DB eye at the Rx for 100 Gb/s and a channel loss of 1 dB/GHz for different suck-out frequencies and different suck-out widths.

When looking at the impact of a suck-out on the performance of a 100 Gb/s PAM4 transmission, it is expected that a suck-out past the Nyquist frequency of 1/(4Ts) will have little effect (as is the case for DB with 1/(3Ts)). However, Figure 15 demonstrates that this is not the case. Apparently a suck-out at a frequency of 30 GHz (above the PAM4 Nyquist) has a similar effect as for DB with the added benefit for DB that there are only two eyes. Because of this, a suck-out at 20 GHz with a width of 1.4 GHz results in still somewhat of an eye for DB while this is non-existent for PAM4.
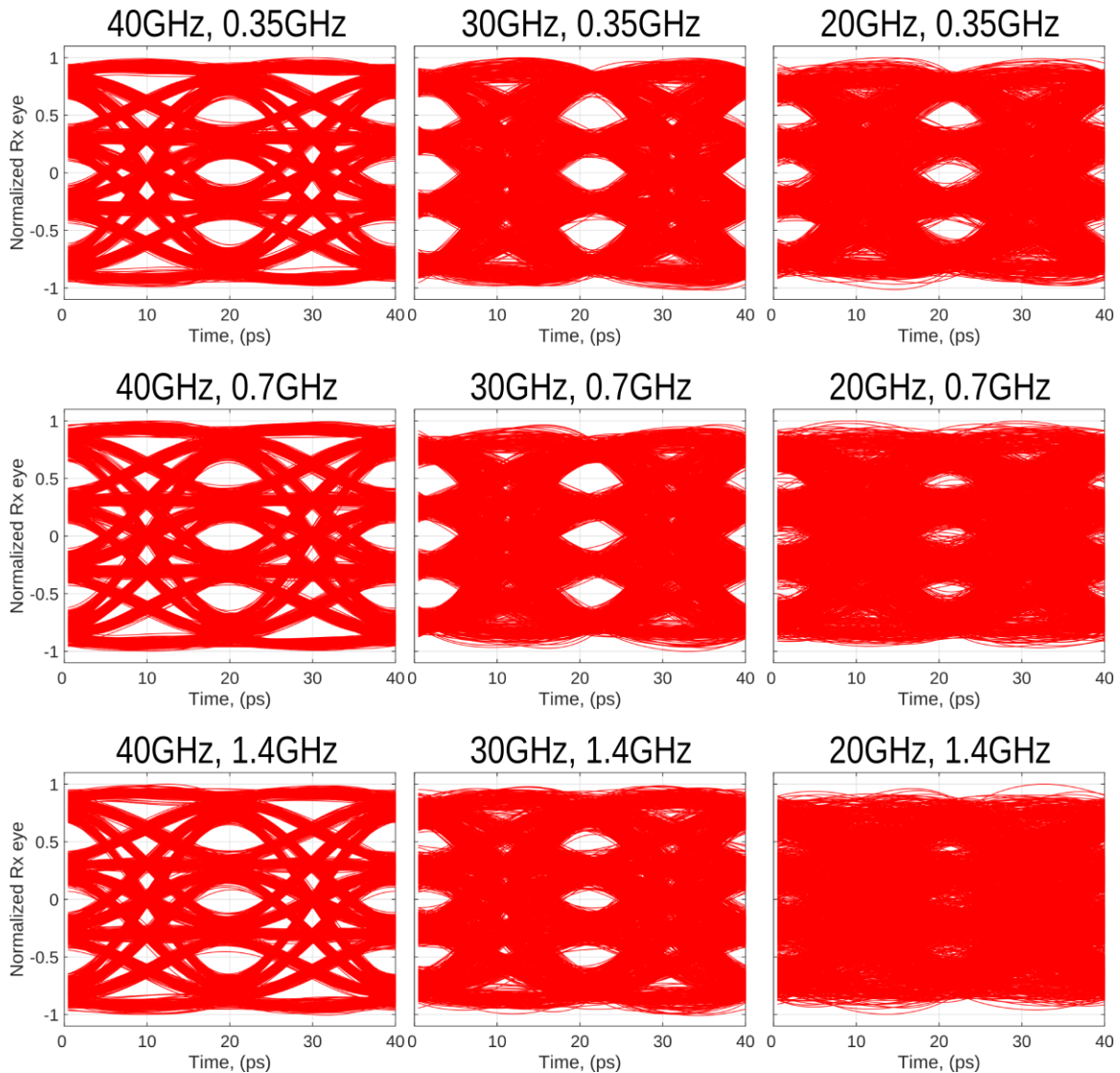
Figure 15: Simulated PAM4 eye at the Rx for 100 Gb/s and a channel loss of 1 dB/GHz for different suck-out frequencies and different suck-out widths.

An important conclusion from looking at Figure 14 and Figure 15 is that it seems that the theoretical Nyquist frequency has little to do with the influence of the suck-out on the eye at the Rx (which is mainly because Nyquist frequency is based on ideal Nyquist pulses). What is more important is the CPSD of the modulation at the suck-out frequency (a low CPSD will results in a large influence) together with the width of the suck-out (a larger suck-out width at the same frequency will take away a larger portion of the bit energy). Since DB and PAM4 have the same CPSD the influence will be similar, however, DB has the benefit of having only two eyes resulting in a larger eye height.

4   Eye-pattern and BER measurements

4.1   Measurement setup

To validate the use of DB at data rates above 50 Gb/s, testboards have been developed for an existing DB Rx chip [3] and a newly designed DB Tx chip. The goal of these testboards is to determine the maximum data rate which can be processed by the DB chipset and to determine the expected channel loss that can be compensated before using it with real-life channels. The channel in this initial testing phase will consist of high-end coaxial measurement cables (avoiding the presence of suck-outs or excessive ripple on the insertion loss). The test setup that will be used for this is shown in Figure 16 and allows inspection of the generated DB eye together with bit-error-rate (BER) measurements.
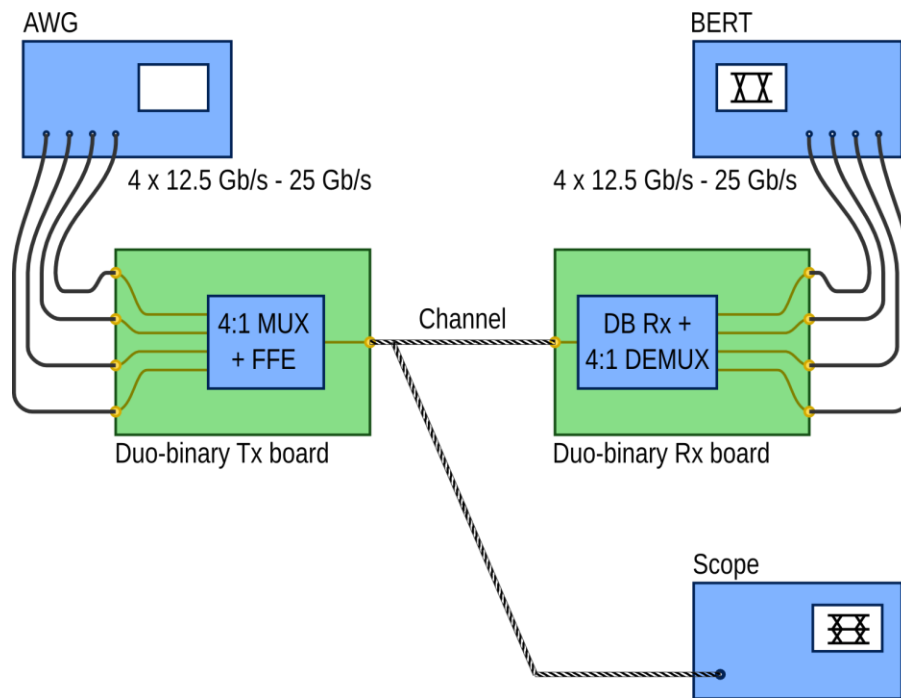

Figure 16: Measurement setup for DB Tx and Rx.

In the setup shown in Figure 16 the four-to-one multiplexer (MUX) and the feedforward equalizer (FFE) are implemented onto a single DB Tx chip. By means of the FFE and the channel response the NRZ signal coming from the multiplexer is transformed into a DB signal at the Rx. This signal is amplified and demodulated by the DB Rx chip where it is also demultiplexed (DEMUX) to four NRZ streams.

4.2 Measurements on ExaMAX® DMO connector

One of the possible future 100 Gb/s connections is the ExaMAX® DMO connector. To check the possibility to use DB across this kind of link, the insertion loss of this connector was first measured and is shown in Figure 17.
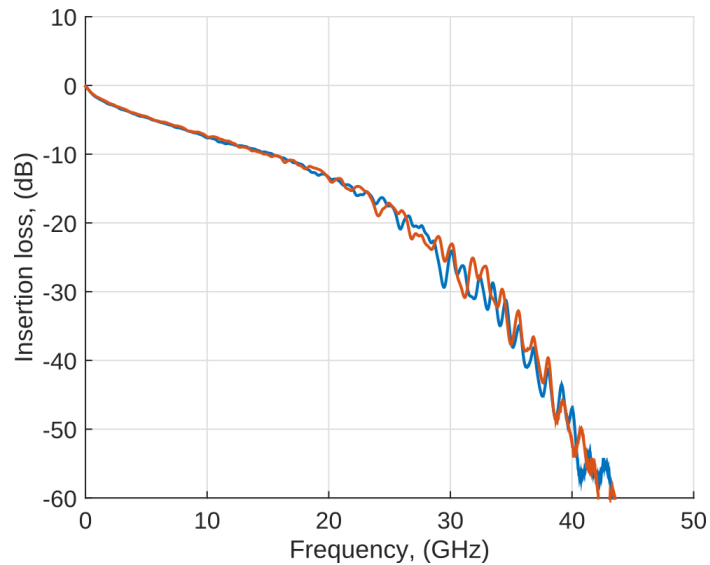

Figure 17: Insertion loss of two links through an ExaMAX® DMO connector.

The average channel loss of the ExaMAX® DMO connector is approximately 0.79 dB/GHz (averaged up to 30 GHz). From Figure 7 it follows that this amount of channel loss will lead to DB having the largest eye height at the Rx for a 100 Gb/s transmission.

To verify the theory a new DB Tx is currently under development. Results of the measurements using this Tx and transmission across the ExaMAX® DMO connector will be presented at the conference.

4.3 Measurements on 26AWG twin-ax cable

Another important transmission medium for future 100 Gb/s transmissions is the 26AWG twin-ax cable. Again the insertion loss of this cable for different lengths was measured and is shown in Figure 18.
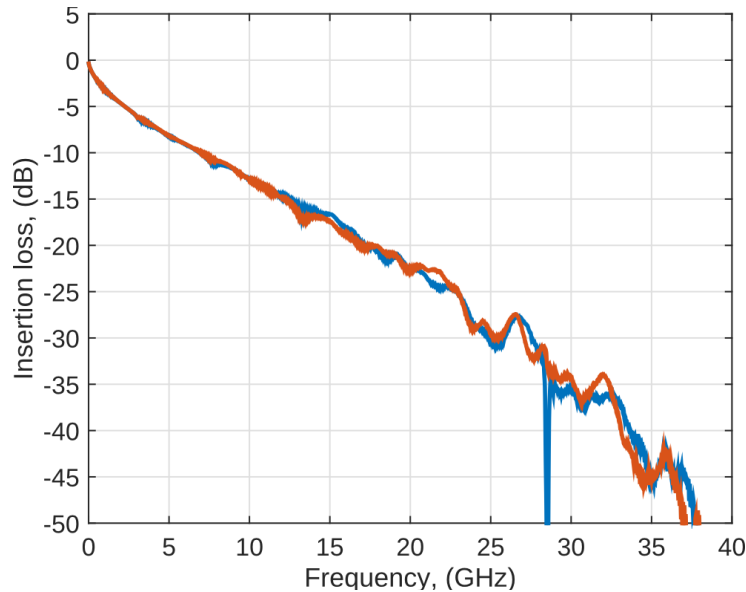
Figure 18: Insertion loss of two 26AWG QSFP links with a length of 3m of which one has a suck-out around 28.5 GHz.

The average channel loss of the two three meter 26AWG QSFP links is roughly 1.1 dB/GHz (averaged up to 25 GHz to avoid effect of suck-out on overall channel loss) which means that in theory PAM4 should provide a larger vertical eye opening for a 100 Gb/s transmission.

Results of the measurements using the new Tx currently being developed and transmission across a 26AWG QFSP cable will also be presented at the conference.

5   Conclusions and Future Work

In this paper the feasibility of 100 Gb/s DB transmission is investigated across cable channels likely to be used in future 100 Gb/s systems. A theoretical comparison of the eye height and SNR at the Rx when using either NRZ, DB or PAM4 as a function of the channel loss has been given. Furthermore a simulation based analysis shows the influence of suck-outs in a channel on the received eye in case of a 100 Gb/s DB and PAM4 transmission.

The discussed application of DB for data rates above 50 Gb/s is currently being verified using a newly developed DB Tx chip transmitting across different backplane and cable channels (with different AWG sizes and different lengths). Results of these measurements will be presented at the conference.

Acknowledgements

References

[1] OIF CEI-56G-VSR/MR standard, http://www.oiforum.com

[2] IEEE P802.3bs 400 GbE standard, http://www.ieee802.org/3/bs/

[3] T. De Keulenaer, J. De Geest, G. Torfs, J. Bauwelinck, Y. Ban, J. Sinsky, and B. Kozicki, "56+ Gb/s serial transmission using duo-binary signaling", DesignCon 2015, vol. 10TH-3, Jan. 2015

[4] A. Lender, "The duo-binary technique for high-speed data transmission", IEEE Trans. Communications Electronics, vol. 82, no. 2, pp. 214-218, May 1963.

[5] S. Pasupathy, "Correlative Coding: a bandwidth efficient signaling scheme", Invited paper, IEEE Communications Society Magazine, vol. 15, no. 4, pp. 4-11, July 1977.

[6] P. Kabal, S. Pasupathy, "Partial-response signaling", IEEE Transactions on Communications, vol. COM-23, no. 9, pp. 921-934, Sept. 1975.

[7] V. Houtsma, D. van Veen, "Demonstration of symmetrical 25 Gbps TDM-PON with 31.5 dB optical power budget using only 10 Gbps optical components", ECOC 2015 post-deadline papers, pp. 1 - 3, Sept. 2015

[8] R. Vaernewyck, X. Yin, J. Verbrugghe, G. Torfs, X. Z. Qiu, E. Kehayas, and J. Bauwelinck, "A low power 2x28 Gb/s electroabsorption modulator driver array with on-chip duo-binary encoding", IEICE Transactions on Communications, vol. E97-B, no. 8, pp. 1623 - 1629, August 2014

[9] X. Yin, J. Verbist, T. De Keulenaer, B. Moeneclaey, J. Verbrugghe, X. Z. Qiu, and J. Bauwelinck, "25Gb/s 3-level burst-mode receiver for high serial rate TDM-PONs", OFC 2015, vol. Th4H.2, pp. 1 – 3, March 2015

[10] K. Yamaguchi, K. Sunaga, S. Kaeriyama, T. Nedachi, M. Takamiya, K. Nose, Y. Nakagawa, M. Sugawara, M. Fukaishi, "12Gb/s duobinary signaling with ×2 oversampled edge equalization", ISSCC. 2005, vol. 1, pp.70– 71, Feb. 2005

[11] J.H. Sinsky, M. Duelk, A. Adamiecki, "High-speed electrical backplane transmission using duobinary signaling", IEEE Transactions On Microwave Theory and Techniques, vol. 53, no. 1, pp. 152-160, Jan. 2005

[12] J. Lee, M.-S. Chen, H.-D. Wang, "Design and comparison of three 20-Gb/s backplane transceivers for duobinary, PAM4 and NRZ data", IEEE Journal Of Solid-State Circuits, vol.43, no.9, pp. 2120 – 2133, Sept. 2008

[13] D. Banas, "The mysterious disappearance of duo-binary signaling", EDN, March 2015

[14] J.H. Sinsky, A. Adamiecki, M. Duelk, "10 Gb/s electrical backplane transmission using duobinary signaling", IMS-2005, June 2004