APPLICATION NOTE

Exploring the Requirements for 224 Gbps Channel Characterization Using Simulations and Measurements

KEYSIGHT

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Abstract

The pandemic has shifted many digital modernization projects within the internet infrastructure to occur more swiftly. Similar to the way cloud architectures have changed networking in the past decade, we now see rapid transitions to new technologies. In the next 2-3 years the future ethernet speed will evolve toward the 224 Gbps per lane. Consider, at this serial data rate, transition times are about 4 picoseconds and unit intervals are below 10 picoseconds for PAM-4 modulation. The development of a reliable end-to-end copper communications channel require careful examination of semiconductor devices, packages, PCBs, connectors, and cable assemblies within this context.

Ensuring proper equalization schemes at both transmitter and receiver ends is a critical step of this strategic goal for high-speed channel design. This work highlights significant aspects of good signal integrity design and provides reasonable solutions for achieving feasible physical layer channel performances. This includes post-DFE eye opening at a given BER for a real-world physical channel example and compares to the important channel operating margin (COM) figure-of-merit. The objective is to present precise measurement techniques for accurately characterizing the channel, and for adequately developing equalization schemes at both TX and RX sides. This also includes the parametric adjustments to COM methodologies. These techniques are necessary for effectively exploring feasible design solutions.

Exploring the Requirements for 224 Gbps Channel Characterization Using Simulations and Measurement

This work highlights significant aspects of good signal integrity design and provides reasonable solutions for achieving feasible physical layer channel performances. This includes a real-world physical channel example.

Introduction

Today's telecommunication systems are approaching Terabits per second [1]-[2]. Although the current standards being developed by the IEEE 802.3® and OIF Working Groups are setting the requirements for the next generation types of interconnects operating at 100 Gbps [3], the demand for higher data rates forces the development of new technologies. Such a challenging task is already being approached by companies dealing with the design of semiconductor chips, PCBs, connectors, and cables. However, once a prototype of a complete channel is designed to operate at such extreme data rates, the validation of each component as well as of the complete channel evaluation is an essential step to ensure system reliability. Performing such validation based only on experimental testing may be a long and expensive task. Furthermore, hardware analysis alone cannot be performed since such data rates provides an output eye diagram prior to equalization that is completely closed. Therefore, adequate equalization schemes need to be applied within the receiver testing instrument to mimic the real waveform processing at the receiver [4]. Alternatively, relying only on channel simulation may lead to uncorrelated outcomes. To achieve an effective channel evaluation, a reasonable solution must be based on appropriately combining measured data with simulation processes [5]-[6]. The Channel Operating Margin (COM) is a powerful tool for achieving this target metric, since it is based on the measured S-parameters of the passive portion of the channel and on a precise experimental characterization of the source features (i.e. jitter, noise and signal amplitudes, and rise time among others) and receiver response (i.e. bandwidth, noise, and jitter). This paper describes a testing workflow applied to an ethernet interface operating at 224 Gbps. The experimental setup employs an instrumentation source to fully characterize its output waveform and directly extracts the relevant source parameters to be passed to the COM algorithm through the analysis of the pulse response derived from the measured waveform. An observable source is used for a rigorous and accurate analysis without involving embedding and modeling processes for moving the measurable transmitter (TX) reference point toward the source, as in a real chip TX. The receiver (RX) instrument is equipped with the adequate processing for applying the filtering and equalization schemes to identify augmentation of the COM methods and data from the Standard IEEE 802.3 defined at lower data-rates for the determination of the Vertical Eye Closure (VEC). Similar to the work carried out in [7] at 106 Gbps, the outcome of this work highlights the most relevant technical aspects for reliable extraction of the COM input parameters and for accurate application of the COM statistical process. The extracted COM/VEC parameters are used as the reference for a direct comparison between the corresponding values from a full channel simulation versus direct experimental measurements of VEC.

1. Channel Description

The channel consists of a PCB-PCB assembly interconnected by a 224 Gbps NovaRay® Characterization Kit Male+Female mezzanine connector for high speed and high-density applications as sketched in Fig.1a, which will be shown is able to meet the requirements for 200 Gbps data rates per single differential channel pair [8]. It is developed for such applications by fully shielding each differential pair aimed at minimizing the crosstalk Information Classification: General and the impedance variation. It is demonstrated very reliable since each connection between the pins of the male and the female portions is ensured by two points of contact [9]. Also, the connection to the PCB is ensured by a BGA for surface connection without the strict need of vias and thus minimizing the impedance discontinuities for a controlled impedance environment at the launch point. The PCBs are equipped with 1mm coaxial connectors for accessing the 32 differential pairs routed between the two PCBs. An overview of the overall DUT is shown in Fig. 1b, whereas the differential insertion loss S_{dd21} and the differential return loss Sdd11 of one of the pairs is shown in Fig. 1b. The S_{dd21} is about 14.1 dB at the Nyquist frequency of $f_{Nyquist}$ = 53.125 GHz since the baud-rate is 106.25 Gbaud/s corresponding to a bit rate 212.5 Gbps based on a PAM4 type of modulation. The 212.5 Gbps value corresponds to the bit rate of the signal physically propagating on each channel; such value lowers to the nominal 200 Gbps after applying the Forward Error Correction (FEC), also referred to as the post-FEC bit rate. The value of the S_{dd21} = 14.1 dB is a typical loss for a Chip-to-Module (C2M) type of interface as it is defined by the IEEE Project P802.3ck for Ethernet Communications [3]. Therefore, although an ad-hoc DUT for C2M verification at 200 Gbps is not yet available, the present analysis can be considered appropriate for well representing the performances of a C2M interface. The physical DUT is measured up to 110 GHz with calibration performed with a mechanical calibration kit at all four ports. However, the dynamic range of the DUT at the upper frequency levels was not adequate to provide meaningful information throughout the complete bandwidth of the measurement. Therefore, the S-parameters were truncated at 90GHz to input into the COM process characterization.

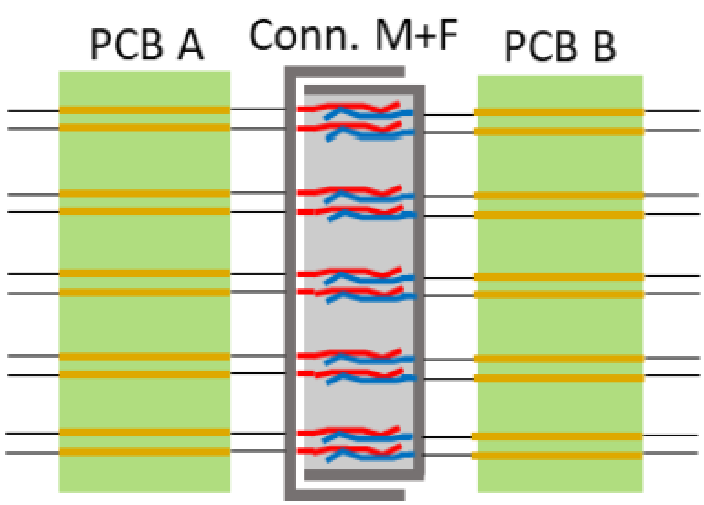

Figure 1a. Sketch of the DUT

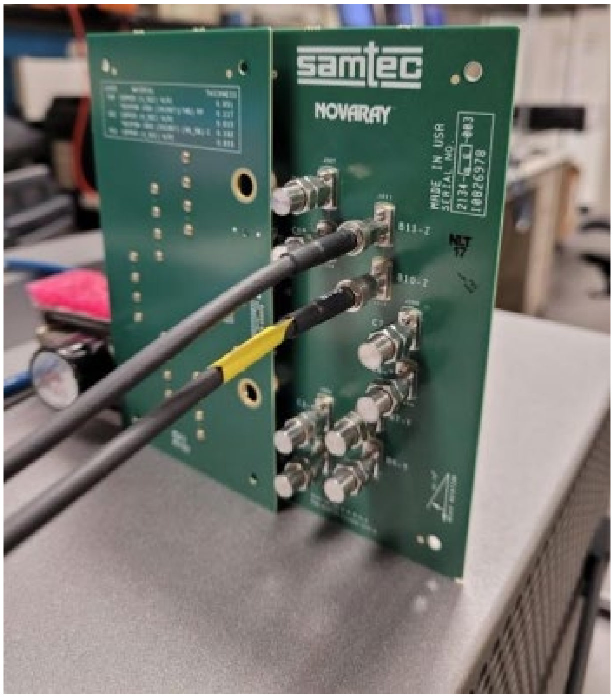

Figure 1b. Overview of the DUT (PCB- NovaRay®/Male- NovaRay®/Female-PCB

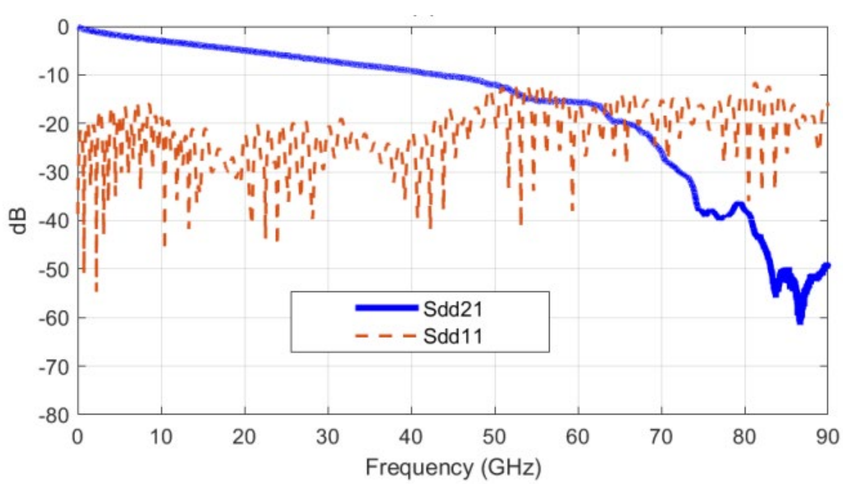

Figure 1c. S_{dd21} and S_{dd11} of one of the pairs of the DUT

2. Measurement Setup

Two different time domain measurement setups are required for the evaluation of the DUT performances by the COM algorithm. The TP0 setup consists of a signal source achieved by an Arbitrary Waveform Generator (M8199A) and the receiving scope (N1046A 110GHz Remote Head and N1000A DCA); the TP1a setup, as defined in [3] embeds the DUT into the previous setup. Specifically, the TP0 setup is used to extract the AWG output waveform, and to compute several parameters required for running the COM Information Classification: General algorithm as detailed in Section 2.1. The TP1a setup, instead, allows the direct evaluation of the channel performances, having the required equalization processing (CTLE and DFE) available within the scope software.

2.1 TPO Setup: Source – Cable – Scope

As mentioned above, the TP0 setup consists of an AWG and a Scope connected by 4 inches low-loss instrumentation cable; the scope receiver is equipped with the appropriate waveform processing run by the FlexDCA software. The TP0 setup is sketched in Fig. 2. The AWG generates a 106.25 Gbaud/s PAM4 PRBS13Q waveform directly measured by the scope. The scope, as required by [3], applies first a 4th order Butterworth filter with a -3dB bandwidth set at 84 GHz. This bandwidth limit is usually selected as ¾ of the baud-rate; in this case the higher limit based on the OIF 112 Gbaud is used instead of calculating from the 106.25 Gbaud of the IEEE Standard whose value would be 80 GHz. Nevertheless, both values are smaller than the 90 GHz limit of the measured DUT S-parameters.

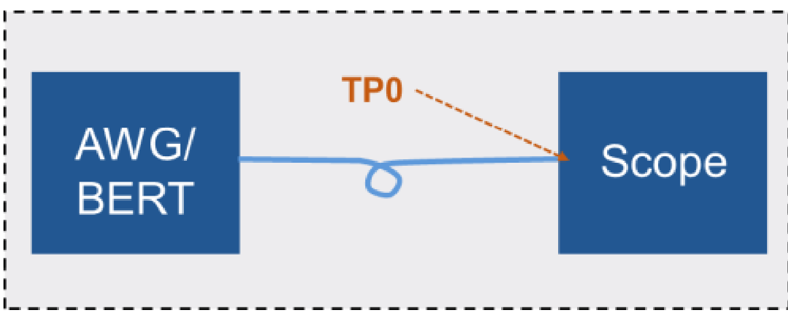

Figure 2a. TP0 setup - Sketch of the block diagram

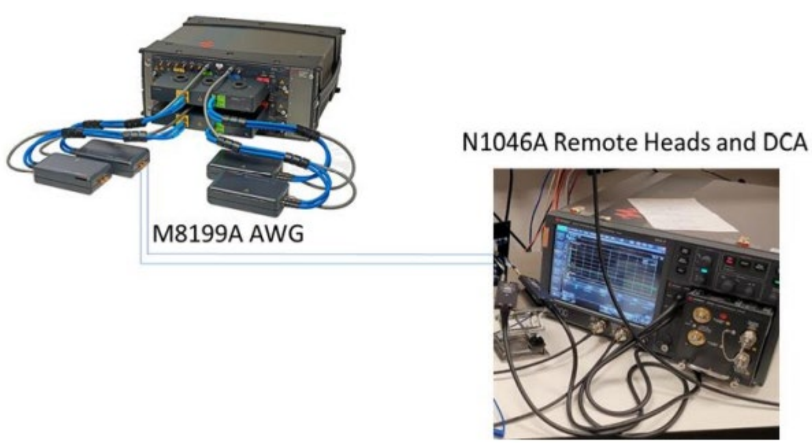

Figure 2b. TP0 setup- Lab setup

The FlexDCA and Infiniium processing allows to implement the math on the waveform at 106.25 Gbaud detailed into [3] to extract several noise and jitter parameters, as listed below:

- Signal to noise distortion ratio SNDR = 31.74 dB
- Level mismatch ratio RLM = 0.99 Direct extraction of the jitter amplitude based on the Dual-Dirac model ADD = 0.0153 UI
- Amplitude of the Even-Odd jitter EOJ = 0.009 UI
- Measured single-side spectral density of the random noise associated to the AWG waveform σ_{RJ} = .006 UI

The A_{DD} and EOJ jitter components have different causes; however, they have the same type of impact on the jitter distribution, therefore the ADD value to be used in COM is calculated by summing up the two contributions to obtain the Dual-Dirac model amplitude equal to .0162 UI.

About the extraction of the rise time Tr, the idea is to align the pulse measured at TP0 (being considered a pulse response without Feed Forward Equalization - FFE) to the pulse response at TP0 determined in COM again without FFE. The alignment is accomplished iteratively by adjusting a FFE pre cursor and post-cursor taps applied to the measured pulse response at TP0, whereas the transition time, Tr, is tuned by COM for the corresponding pulse response. This iterative process ends when the COM algorithm outputs a pulse response that matches the measured one. These FFE coefficients will subsequently be used in COM to offset the normal COM FFE transmitter ranges. Once the pulse response match is obtained, the transition time Tr to be used in COM is determined. The tuning process assumed the following ranges for the pre-cursor and postcursor taps:

Initial TX EQ. range:

a) c(1) = [-0.2:0.02:0]

b) c(-1) = [-0.34:0.02:0]

The proposed iterative yielded on pre cursor and one post cursor offset values to be added to the c(-1) and c(1) ranges in the COM configuration spreadsheet; such values are c(1)= 0.14 and c(2) = 0.125. Therefore, the new TX range for COM optimization will be offset as follows:

a) C(1) = [-0.2:0.02:0] + 0.125

b) C(-1) = [-0.34:0.02:0] + 0.14

The result of the pulse response comparison is illustrated in Fig. 3a. The pre-cursor and post-cursor taps applied to the measured pulse response help to minimize the voltage drop right before and right after the main pulse for a better alignment to the pulse response computed by the COM algorithm. The TP0 setup is also necessary to extract the information regarding the signal amplitude Av and the rise time Tr. This is accomplished by the following procedure. The amplitude Av is voltage source extracted from the measured pulse response after converting it into a step response. The Av is the voltage value corresponding to the point after the step response settles out for the measured step response with FFE Gain. This process yields an Av = 0.829 V. Basically, the pattern generation produces a signal which corresponds to an Av of about 0.25 volts. However, the DCA software's FFE introduces a gain so the Av used in COM which a passive analysis is adjusted to pattern generator Av times the FFE gain results in an Av value of 0.829, as shown in Fig. 3b.

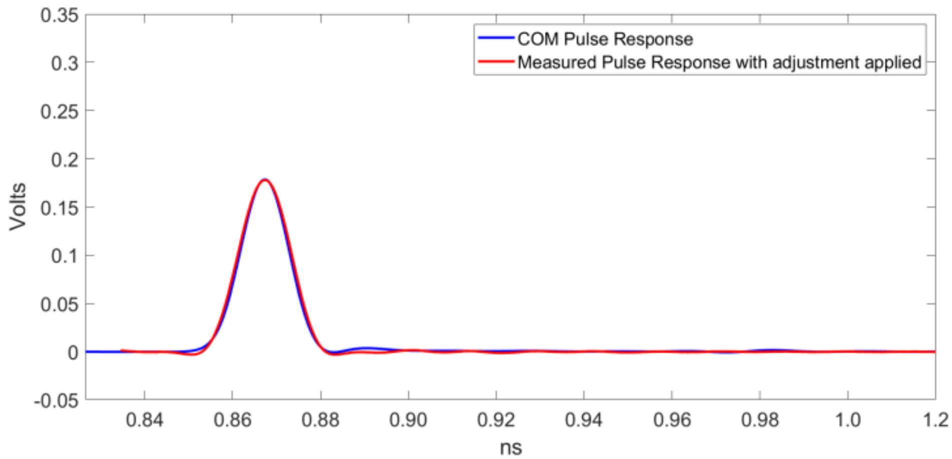

Figure 3a. Tuned pulse response in COM for matching the measured pulse response at TP0 with pre cursor and post-cursor applied.

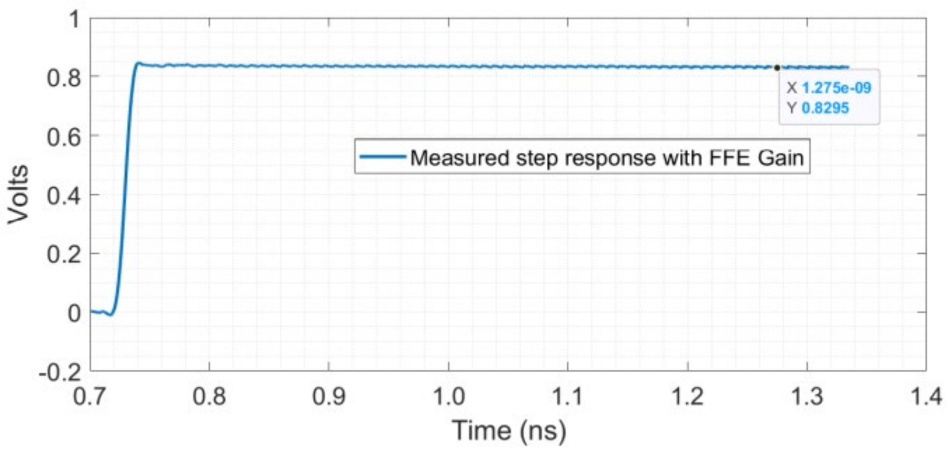

Figure 3b. Measured step response after applying the FFE equalization with the corresponding gain

A further step to accurately define the input parameters in COM is to extract the information regarding the package parameters and device load. Since the application of COM for 200 Gbps data rate is being attempted based on a receiver instrument rather than on a real device, the values of the package and device circuit elements described in Information Classification: General Fig. 4a may not correspond to the typical values defined in [3]. The parameters that have been adjusted with respect to those being proposed in [3] are those highlighted in yellow in Fig. 4. Such values are derived by looking at the TDR response derived from the return loss at TP0. Again, such step involves an iterative process by tuning the parameters highlighted in yellow in Fig. 4b. A comparison of the package model insertion loss obtained with the updated parameters with respect to those proposed in [3] is reported in Fig. 5a. The impact of the package on the DUT insertion loss is shown in Fig. 5b. This equivalent package of the AWG pattern generator return loss is modeled with 4 cascaded transmission lines with length z_p of 8 mm, 5 mm, 8 mm, and 2 mm, respectively, with the corresponding characteristic impedance Z_c of 100 Ω, 106 Ω, 93 Ω, and 104 Ω.

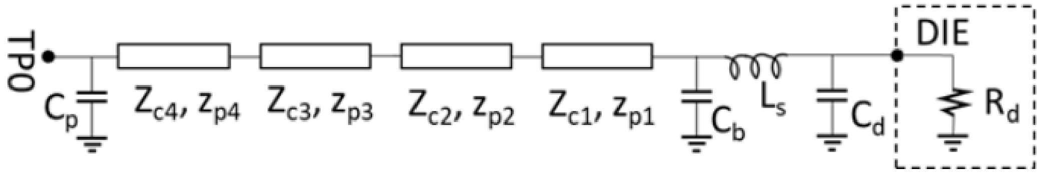

Figure 4a. Package equivalent circuit model.

Parameter (ms)	Setting	Units	
package_tl_gamma0_a1_a2	[0 0.000009909 0.000002772]		
package_tl_tau	0.006141	ns/mm	
package_Z_c	[100 100 ; 106 100; 93 100; 104 100]	Ohm	
C_d	[1.0e-4 ,0]	nF	
L_s	[0.2 0]	nH	[TX RX]
C_b	[0.4e-4 0]	nF	[TX RX]
Z_p select	[1]		[TX RX]
z_p (TX)	[8 ; 5 ; 8 ; 2]	Mm	[test cases to run]
Z_p (NEXT)	[0 ; 0 ; 0 ; 0]	Mm	[test cases]
Z_p (FEXT)	[0 ; 0 ; 0 ; 0]	mm	[test cases]
Z_p (RX)	[8 ; 5 ; 8 ; 2]	mm	[test cases]
C_p	[0 0]	nF	[TX RX]
R_0	50	Ohm	
R_d	54.35 50]	Ohm	[TX RX]

Figure 4b. Package parameters for the specific case considered herein (values modified with respect to those being proposed in [3] are highlighted

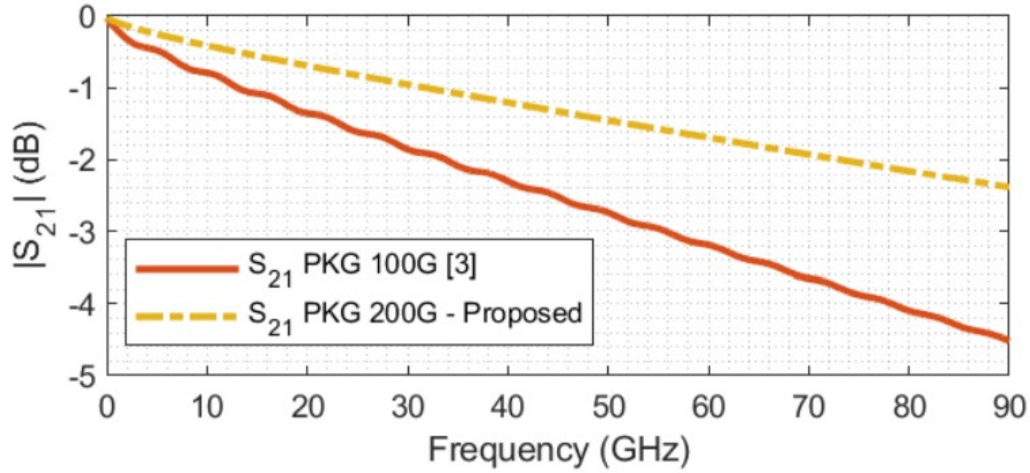

Figure 5a.

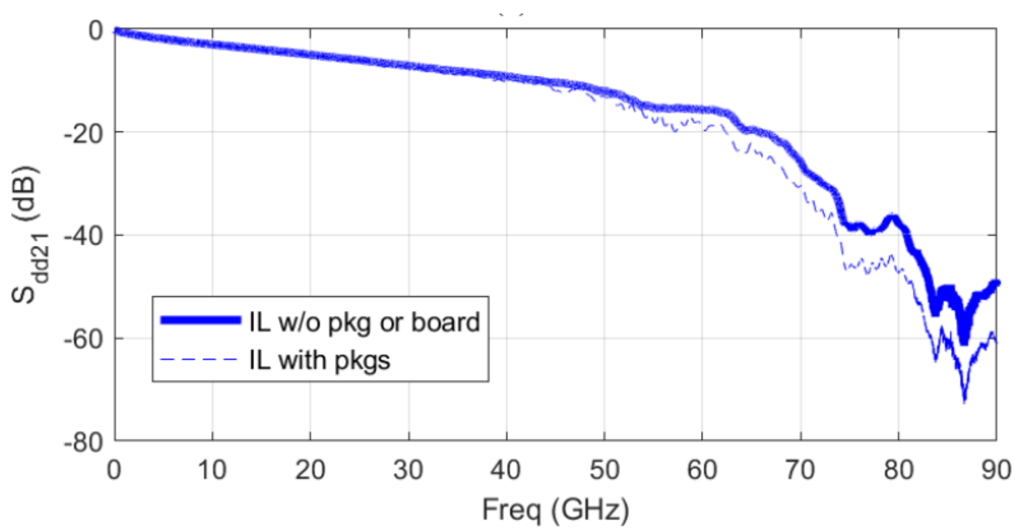

Figure 5b. Differential insertion loss of the DUT alone, as the one shown in figure 1, and after adding the derived package model

The final COM configuration spreadsheet is reported in figure 6.

Table 93A-1 parameters			
Parameter	Setting	Units	Information
f_b	106.25	GBd	
f_min	0.05	GHz	
Delta_f	0.01	GHz	
C_d	[1.0e-4 ,0]	nF	[TX RX]
L_s	[0.2 0]	nH	[TX RX]
C_b	[0.4e-4 0]	nF	[TX RX]
z_p select	[1]		[test cases to run]
z_p (TX)	[8 ; 5 ; 8 ; 2]	mm	[test cases]
z_p (NEXT)	[0 ; 0 ; 0 ; 0]	mm	[test cases]
z_p (FEXT)	[0 ; 0 ; 0 ; 0]	mm	[test cases]
z_p (RX)	[8 ; 5 ; 8 ; 2]	mm	[test cases]
C_p	[0 0]	nF	[TX RX]
R_0	50	Ohm	
R_d	[54.35 50]	Ohm	[TX RX]
A_v	0.8294	V	
A_fe	0.8294	V	
A_ne	0.8294	V	
L	4		
M	32	Samp/UI	
samples_for_C2M	100	Samp/UI	
T_O	50	mUI	
AC_CM_RMS	0	V	[test cases]
filter and Eq			
f_r	0.75	*fb	
c(0)	0.54		min
c(-1)	[-0.34:0.02:0] + 0.14		[min:step:max]
c(-2)	[0:0.02:0.12]		[min:step:max]
c(-3)	[0]		[min:step:max]
c(1)	[-0.2:0.02:0]+ 0.125		[min:step:max]
N_b	24	UI	
b_max(1)	0.85		
b_max(2..N_b)	[0.3 0.2*ones(1,11) 0.1*ones(1,11)]		
b_min(1)	0.3		
b_min(2..N_b)	[0.05 -0.05*ones(1,22)]		
g_DC	[-12:1:-0]	dB	[min:step:max]
f_z	42.5	GHz	
f_p1	42.5	GHz	
f_p2	106.25	GHz	
g_DC_HP	[-4:0.5:0]		[min:step:max]
f_HP_PZ	2.65625	GHz	

I/O control		
DIAGNOSTICS	1	logical
DISPLAY_WINDOW	1	logical
CSV_REPORT	1	logical
RESULT_DIR	C:\Users\richardm\Documents\Scratch\results\200GEL_VSR_host_TP1a_{date}\	
SAVE_FIGURES	1	logical
Port Order	[1 3 2 4]	
RUNTAG	VSR_TP1a_eval_	
COM_CONTRIBUTION	0	logical

Floating Tap Control		
N_bg	3	0 1 2 or 3 groups
N_bf	6	taps per group
N_f	64	UI span for floating taps
bmaxg	0.2	max DFE value for floating taps

TDR and ERL options		
TDR	1	logical
ERL	1	logical
ERL_ONLY	0	logical
TR_TDR	0.01	ns
N	800	
beta_x	0	
rho_x	0.618	
fixture delay time	[0 0]	[port1 port2]
TDR_W_TXPKG	1	
N_bx	0	UI
Tukey_Window	1	
Receiver testing		
RX_CALIBRATION	0	logical
Sigma BBN step	5.00E-03	V
Noise, jitter		
sigma_RJ	0.006	UI
A_DD	0.0162	UI
eta_0	2E-20	V^2/GHz
SNR_TX	31.744	dB
R_LM	0.9895	

Table 93A–3 parameters		
Parameter (ms)	Setting	Units
package_tl_gamma0_a1_a2	[0 0.000009909 0.000002772]	
package_tl_tau	0.006141	ns/mm
package_Z_c	[100 100 ; 106 100; 93 100; 104 100]	Ohm

Operational		
VEC Pass threshold	9	db
EH_min	10	mV
ERL Pass threshold	0	dB
Min_VEO_Test	8	mV
DER_0	1.00E-05	
T_r	0.0045	ns
FORCE_TR	1	logical
PMD_type	C2M	
BREAD_CRUMBS	0	logical
SAVE_CONFIG2MAT	1	logical
PLOT_CM	0	logical
Dynamic TXFFE	1	
FloatingDFE_Development	1	
Local Search	2	
Optimize_loop_speed_up	1	

Histogram_Window_Weight	gaussian	Seletions (rectangle, gaussian,dual_rayleigh,triangle
sigma_r	0.02	

Figure 6. The ad-hoc derived configuration settings for running COM

2.2 TPIa Setup: Souce – DUT - Scope

The 224 Gbps NovaRay® Characterization Kit DUT (PCB + NovaRay® M-F + PCB) is included into the setup to evaluate the channel output metrics obtained from COM and from FlexDCA receiver processing. This step is accomplished by adding the DUT into the FlexDCA simulation path as an S-parameter block. The setup simulation setup is shown in Fig. 7. The FFE taps computed by COM should be directly applied to the AWG source; this cannot be done in the 224 Gbps NovaRay® Characterization Kit that is being used. However, due to the linearity of the system, at least before the DFE, the FFE can be effectively and reliably applied at the receiver. The DFE within the FlexDCA is characterized by 9 taps, whereas a parametric analysis is run by COM. Such analysis helps to highlight a key contribution taken into account by COM that is expected to be effective for 200Gbps per-lane transmission, the DFE floating taps. They can fix ISI at specific location, without the need of a very complex DFE with tens of taps. Specifically, the floating taps are defined as groups, in this case N_bg = 3 groups are considered. Each group can include N_bf = 6 taps, and the N_bg groups can span up to N_f = 64 UIs after the N_b UI of the fixed-tap DFE length. The results while running COM are summarized in Table I, where the outputs of the experimental setups are also included based on different value of the injected η0 noise. By looking at the first 4 rows of Table I, it is evident how a larger number of taps, and more importantly, the use of the floating taps, are effective in the improvement of the eye height, and for the VEC reduction. Their impact is expected to be more relevant when real TX and RX devices are embedded in the channel design since they will be characterized by larger noise and package/die impedance mismatch, compared to the “more ideal” instrumental source and scope receiver.

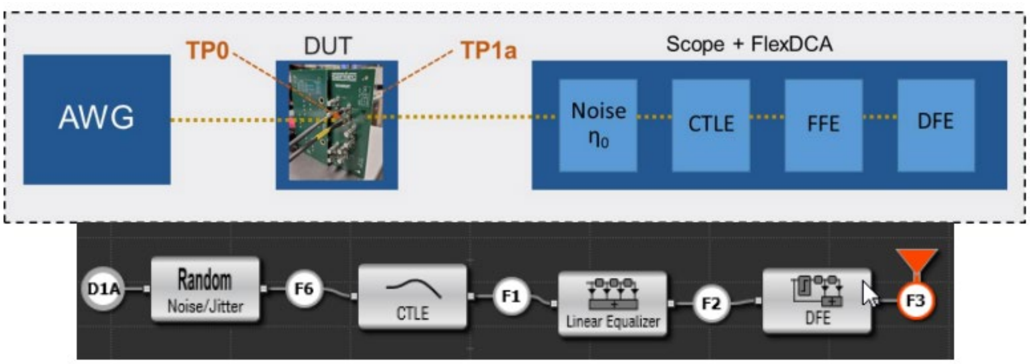

Figure 7. The TPIa setup for the DUT evaluation

Table I. Summary of results and comparisons between the COM and experimental outputs

	Method	DFE fixed taps	DFE floating taps	Noise η0 (V^2 /GHz)	Eye height (mV)	VEC (DB)
1	COM	24	18	$1\text{-}10^{-20}$	33.120	8.382
2	COM	24	-	$1\text{-}10^{-20}$	31.210	8.841
3	COM	9	-	$1\text{-}10^{-20}$	31.86	9.439
4	COM	9	-	2.10^{-8}	31.31	9.59
5	Exp Setup	9	-	1.10^{-20}	32.3	6.78
6	Exp Setup	9	-	$2\text{-}10^{-8}$	30.1	7.51

Basically, a one-to-one comparison can be done between the Cases 3 and 5 in Table I, and Cases 4 and 6 based on the same settings. The eye height predicted by COM is very close to the one obtained by the experimental setup, whereas slight discrepancies are obtained for the value of VEC, about 2.08 and 2.66 dB better for the experimental setup for the two pairs of comparisons. Both cases are also reported below in terms of measured eye diagram and the eye contour predicted by COM.

Figure 9a shows the eye diagram predicted by COM for case 4 ($\eta_0 = 2 \cdot 10^{-8}\ V^2$ /GHz), whereas Fig. 9b reports the measured eye diagram with the eye by COM overlapped in red. Good agreement is obtained, as anticipated by the EH in Table I.

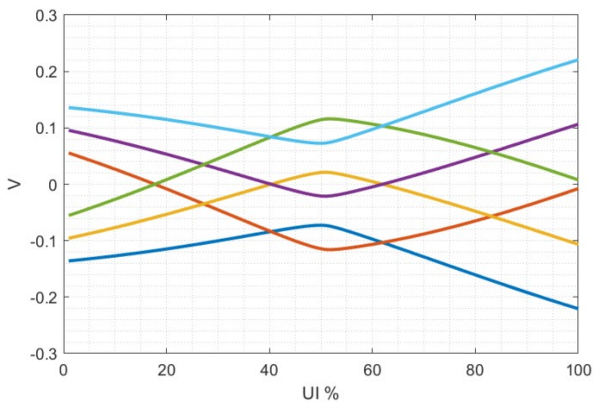

Figure 8a.

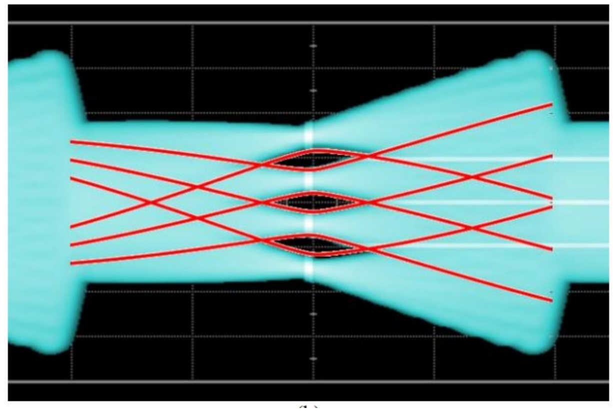

Figure 8b. Comparison between the eye contours obtained by COM for the Case 3 in Table 1 (a), and the measured eye (Case 5 in Table 5).

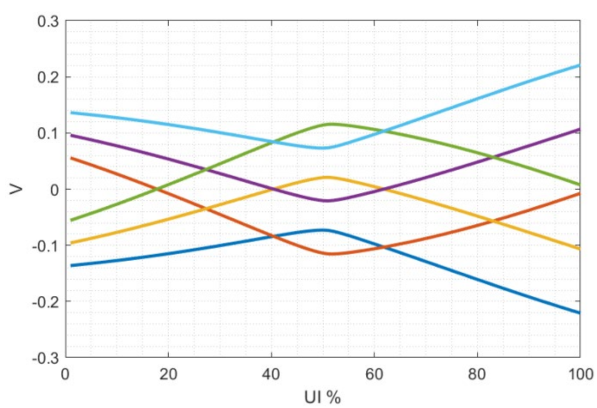

Figure 9a.

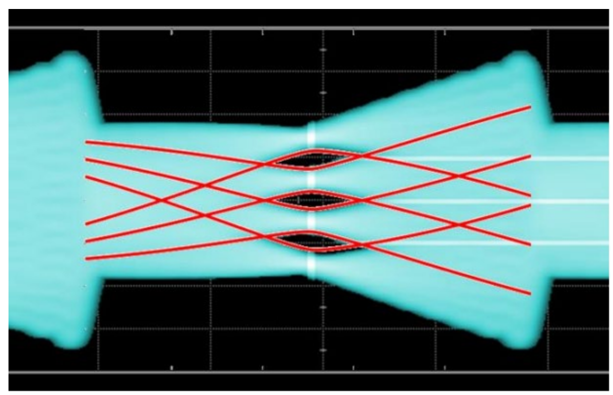

Figure 9b. Comparison between the eye contours obtained by COM for the Case 4 in Table I (a), and the measured eye (Case 6 in Table 1).

3. Parametric Analysis on S-parameter Bandwidth for COM

An important aspect that needs to be addressed while working at such very high data rate is the required bandwidth of the S-parameters data to be used in COM. The upper frequency limit of the S-parameter required for a reliable prediction of the channel performances by the COM methods directly impact several aspects, such as VNA band, connector type of the DUT, instrumentation cables just to mention the main ones. All of them directly impact the costs. As an example, if the required bandwidth exceeds 67 GHz, then 1.85mm cables and connectors reliably operating up to 67 GHz should be replaced by their smaller 1.0mm counterpart for reaching 110 GHz. This change impacts also the VNA. The step for acquiring a setup up to 110 GHz compared to a 67 GHz setup is achieved at least at 3 times the cost due to the more expensive materials, manufacturing processes, and RF design of cables, connectors and instrumentation. In this Section a parametric analysis is carried out based on the 90 GHz S-parameter of the measured DUT, and by cutting down the upper limit of this dataset. The frequency is lowered to 80 GHz, 70 GHz, 60 GHz, and 53.13 GHz, with the latter being the Nyquist frequency of a PAM4 modulated 212.5 Gbps signal. The cases are reported in Table II.

Table II. Summary of results of COM while changing the bandwidth of the DUT S-parameters

	Method	DFE fixed taps	Noise η0 (V^2 /GHz)	fmax	Eye height (mV)	VEC (DB)
4	COM	9	2.10^{-8}	90 GHz	33.31	9.59
4a	COM	9	2.10^{-8}	80 GHz	31.33	9.584
4b	COM	9	2.10^{-8}	70 GHz	30.42	9.818
4c	COM	9	2.10^{-8}	60 GHz	32.50	9.250
4d	COM	9	2.10^{-8}	53.13 GHz	23.53	12.253

The results corresponding to the bandwidth variation in terms of EH and VEC are reported in Table II, whereas the pulse responses and of the predicted PAM4 eye diagram contours are shown in Fig. 10 and Fig. 11, respectively. By looking at the pulse responses in Fig. 10 it is evident that the limitation at 60 GHz and 53.13 GHz generates non-real artifacts and ringing in the un-equalized pulse response, thus affecting the calculation of the DFE taps and of the equalized pulse response, although the DFE attempts to attenuate the main spikes. The impact of the residual ringing after the DFE is evident in the results in Fig. 11, where the equal eye contours for the 80 GHz and 70 GHz cases starts to be distorted when the S-parameter bandwidth is cut at 60 GHz; a more detrimental impact is clearly visible for the 53.13 GHz case in Fig. 11d.

Pulse responses computed by COM for the DUT S-parameters limited at:

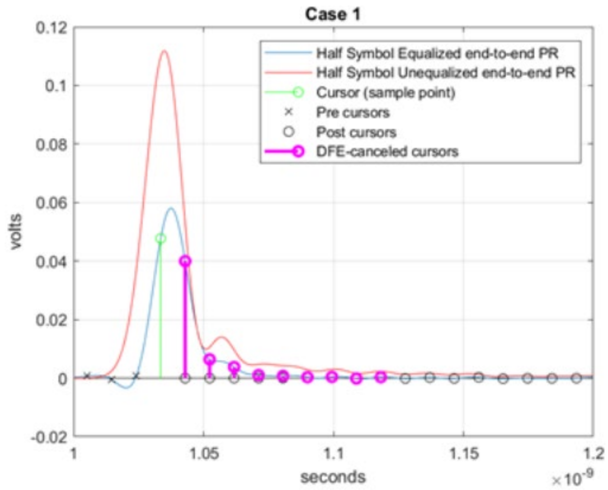

Figure 10a. 80GHz

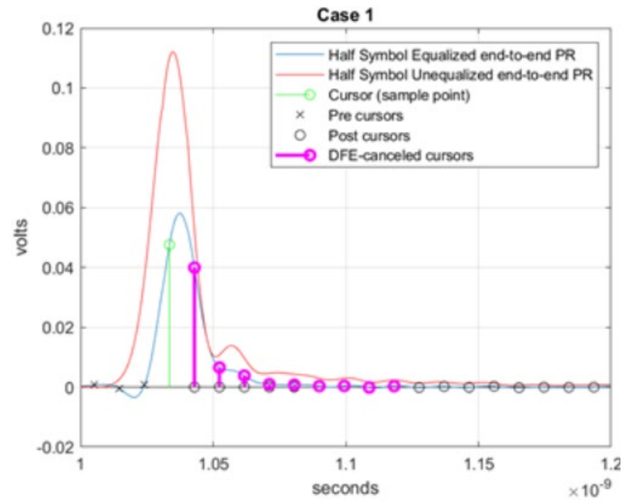

Figure 10b. 70 GHz

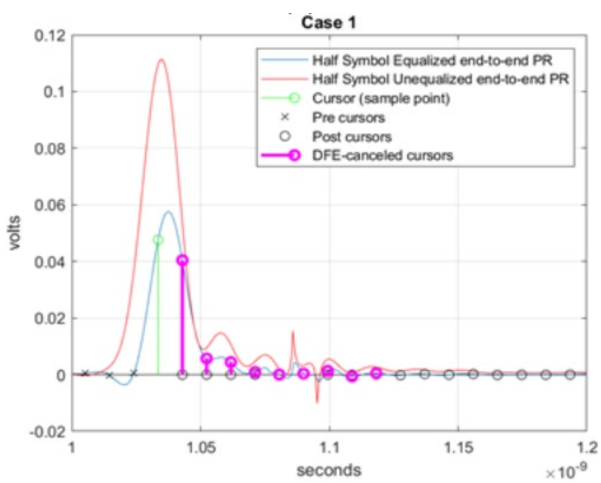

Figure 10c. 60 GHz

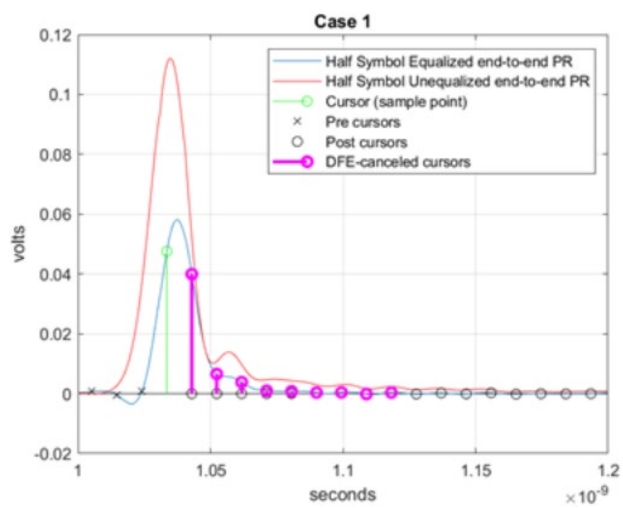

Figure 10d. 53.13 GHz

Eye contours computed by COM for the DUT S-parameters limited at:

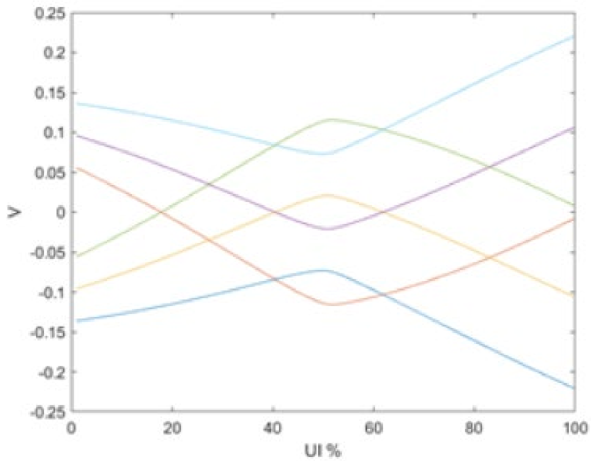

Figure 11a. 80 GHz

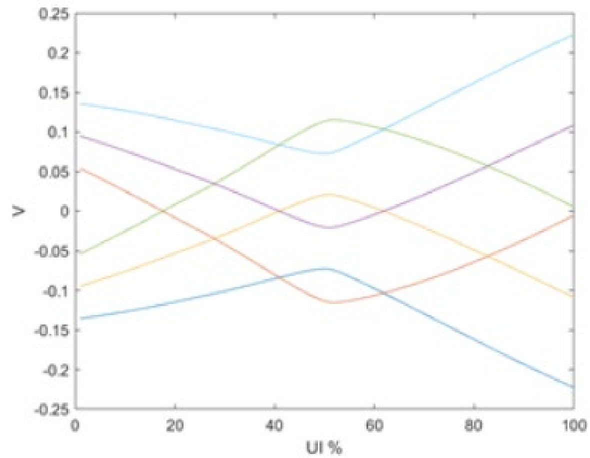

Figure 11b. 70 GHz

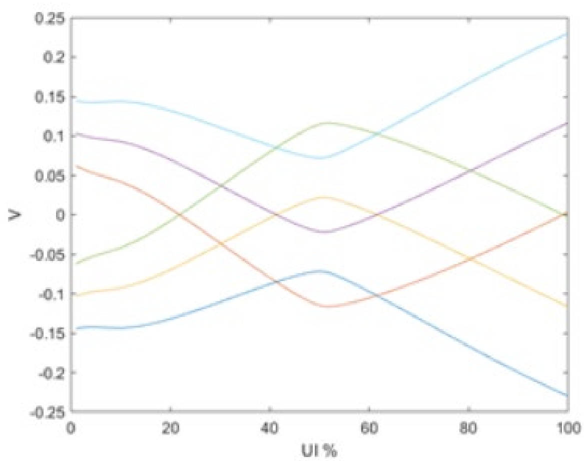

Figure 11c. 60 GHz

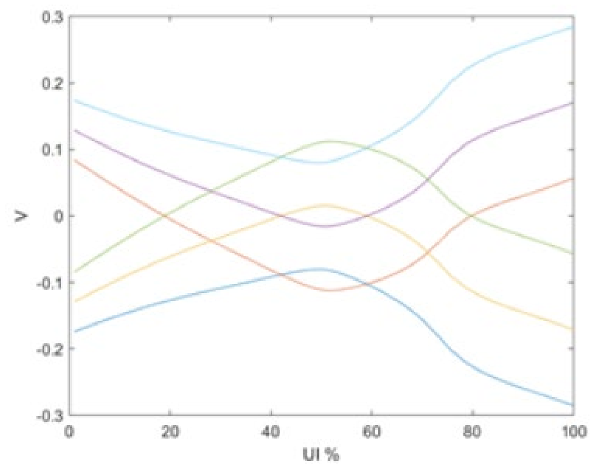

Figure 11d. 53.13 GHz

4. Discussion and Conclusions

A preliminary work is carried out in this paper to verify if and how the COM methods can be effectively applied at data-rates at and exceeding 200 Gbps. The AWG source is accurately characterized by its pulse response for extracting the main parameters used in COM in terms of signal amplitude, rise time, noise and jitter parameters. The DUT considered in this case, being characterized by an S_{dd21} bringing losses similar to a typical C2M interface, is measured up to 90 GHz and used for the application of the measured AWG waveform and of the equalization settings at the receiving scope. The COM metrics of eye height and VEC are used to validate the agreement between the COM outputs and the corresponding values obtained by the sampling scope processing by the FlexDCA software. Good agreement is obtained in terms of eye opening, also confirmed by the eye contours predicted by COM when compared to the eye diagram from the oscilloscope. The comparison of the VEC still provides some discrepancies of about 2 dB, with the VEC predicted by COM being worse. This suggests that the noise parameters extracted from the AWG waveform may require a more precise evaluation, thus a deeper investigation is necessary and it will be matter of future work. Moreover, having reference COM metrics validated as summarized above, the COM method is applied iteratively to the S-parameter dataset while cutting its bandwidth to identify the frequency limit, with respect to the Nyquist frequency, that must be used to ensure obtaining reliable results. The limit for the case analyzed here is at 70 GHz, thus at about 1.3 times the Nyquist frequency.

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