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COM & IBIS-AMI How They Relate & Where They Diverge

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Abstract

Channel Operating Margin (COM) has become the standard channel compliance test method since 2014 (IEEE 802.3bj 25Gbps Ethernet). It has since evolved with increasing data rates, complexities, and utilizations in the areas of device stress and compliance tests. IBIS-AMI is the de facto device modeling format for transceivers and it is used to emulate realistic link behaviors and estimate link margins. In this paper, we will conduct experiments and see how COM and IBIS-AMI relate to each other (e.g. COM 3dB vs. eye diagram) and, most importantly, identify the differences between them and the impacts in link performance analysis.

Author(s) Biography

Dr. Hsinho Wu is a design engineer at Intel Corporation's Programmable Solutions Group (formerly Altera). He presently works on high-speed communication systems of FPGA products. His development and research interests include signal integrity, clock and data recovery, equalizations, device and system modeling, simulation techniques, and software architecture.

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1 Introduction

Channel Operating Margin (COM) is an efficient method to assess the link margin with provided channel models where it calculates the ratio between effective signal amplitude and residual/accumulated noise of a serial link. COM methodology has been adapted by various IEEE 802.3 and OIF CEI standards that operate above 25 Gbps. JEDEC JC-16 Interface Technology JESD204C task group also adapted COM methodology and produced JCOM for its compliance tests.

IBIS-AMI is an extension from venerable IBIS standards which supports high-speed serial link with serializer/deserializer (SerDes) design. IBIS-AMI provides a flexible and capable platform where mechanism such as channel equalizations and link adaptations, can be implemented and executed effectively and efficiently.

In this paper, we begin with providing an overview of these two modeling and analysis approaches. Then, a series of case studies were conducted where we looked into how the COM value is calculated along with an IBIS-AMI simulation with same configuration. Through the comparison and data analysis, we will provide the linkage and identify the differences between these two approaches.

2 COM Methodology

Channel Operating Margin (COM) is an efficient method to assess the link margin with provided channel models, mostly in Touchstone S-parameter format, and pre-defined device characteristics, specified by associated standards. The COM methodology provides a platform where it allows the use of reference devices and channel components so that device and channel compliance tests can be conducted. COM has been adapted by numerous IEEE 802.3 and OIF CEI standards above 25 Gbps.

From the top level, COM is a figure of merit (FOM) which is a ratio, as shown in Equation 1 (Equation 93A-1 from *[1]*), between available signal amplitude and broad-sense noises, from uncompensated channel effects, crosstalk, device jitter and noise, and amplitude distortions. The overall flow chart of COM is shown in Figure 1. There are numerous references and studies on COM methodology accumulated throughout the years *[1][2]*.

$$\boldsymbol{COM = 20 \times log_{10}(\frac{A_s}{A_{ni}})} \qquad \textbf{(1)}$$

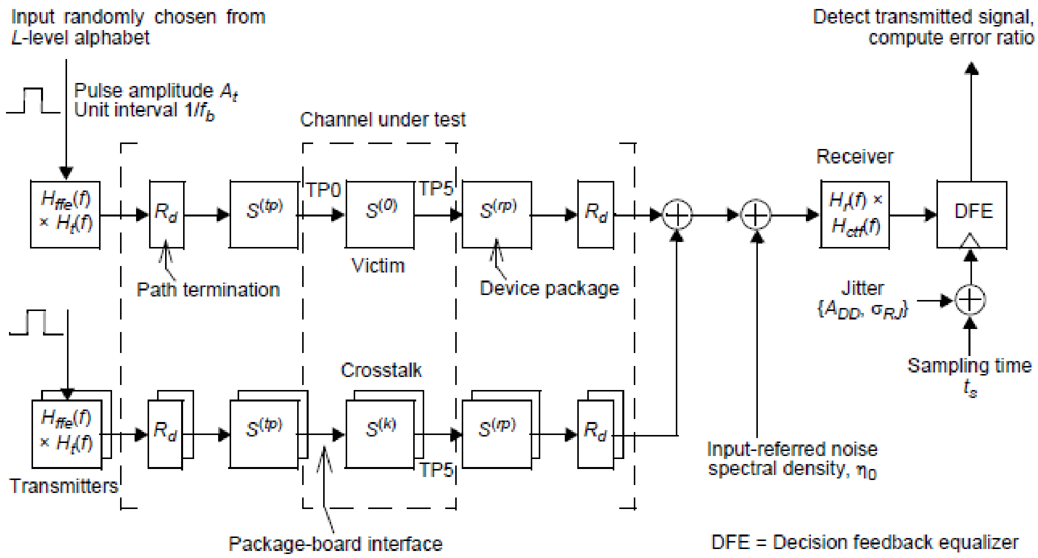


Figure 1 COM reference model (from *Figure 93A-1* in *[1]*)

3 IBIS-AMI Overview

Input/Output Buffer Information Specification (IBIS, [3]) has been an essential electrical simulation model for many years. It provides an accurate and easy-to-use alternative to SPICE based transistor models. In 2005, the IBIS committee introduced the Algorithmic Interface Model (IBIS-AMI) standard which further improves its support in high-speed serial link simulations. Due to the flexibility of executables, complex signal processing blocks can be modeled algorithmically. AMI models also enable standardized, interoperable simulation of SerDes with high simulation speed, performance and accuracy. Crosstalk and jitter analysis may be added while maintaining fast simulation speeds. In addition to strong modeling and simulation capabilities, IBIS-AMI has the following benefits, which allowed it to become an industry standard where majority of silicon/IP vendors provide and support IBIS-AMI model for their devices.

- Interoperability – Models from different semiconductor vendors can run together in the same simulation
- Transportability – The same model runs in different simulation platforms
- Accuracy – IBIS-AMI based simulations provide results comparable to those obtained with proprietary semiconductor vendor tools
- IP Protection – Semiconductor vendors are able to provide accurate models of their devices without disclosing internal architectural details

IBIS-AMI provides two major simulation flows: statistical simulation flow and waveform simulation flow. Statistical analysis produces an eye diagram showing the probabilities of signal distribution at the receiver without using a specific data pattern. Statistical analysis has the advantage of fast simulation speeds but can only implement linear time invariant (LTI) algorithms, such as continuous time linear equalizer (CTLE), but not non-

LTI blocks, such as decision feedback equalizer (DFE) and clock data recovery circuitry (CDR). Statistical analysis flow is shown in Figure 2.

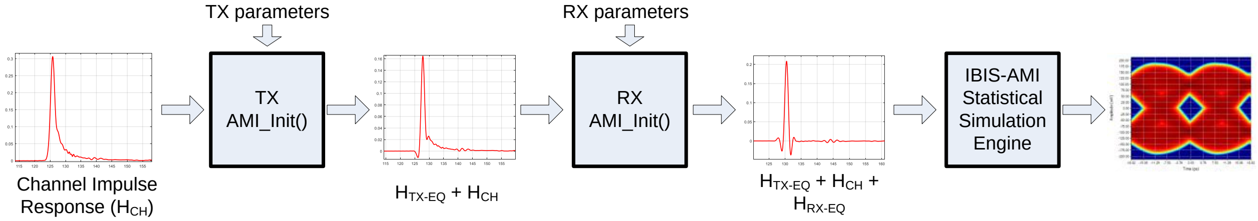


Figure 2 IBIS-AMI statistical simulation flow

On the other hand, the waveform simulation flow behaves much like traditional SPICE-based analysis, which generates bit by bit time domain waveform. In waveform simulation and analysis flow, the input stimulus is convolved with the channel impulse response and a waveform representing the circuit's behavior is generated. Waveform-domain analysis speed is relatively slower than that of statistical simulation method. This form of analysis is good for modeling non-LTI blocks, such as the adaptive behavior of DFE control loops, and can model clock data recovery circuitry. Figure 3 illustrates the waveform-domain analysis flow.

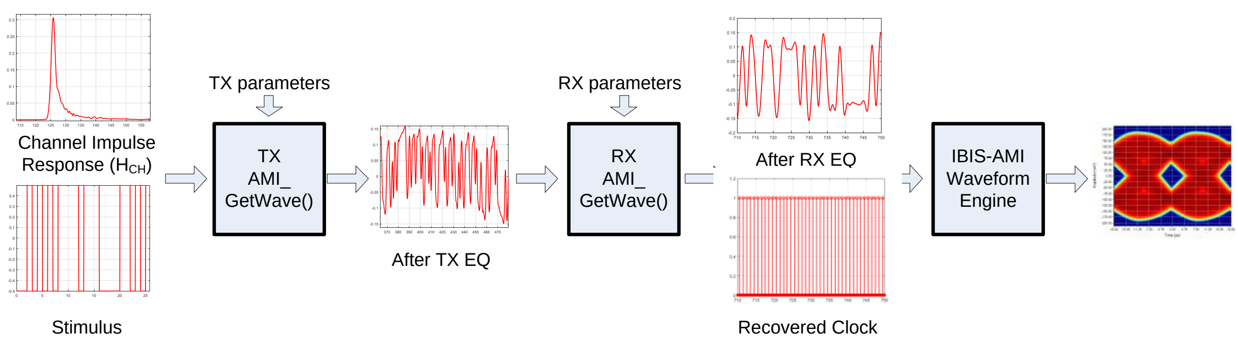


Figure 3 IBIS-AMI waveform simulation flow

4 COM vs IBIS-AMI

As illustrated in Figure 1, it is obvious that COM computation flow resembles a link simulation, e.g. a stimulus (ideal pulse) is fed into a transmitter and then the signal travels through channel and the receiver where a signal-to-distortion/nose-ratio (SNDR) is calculated. Other than the final SNDR calculation step, COM and IBIS-AMI are similar in terms of the simulation flow. However, we also noticed the differences in these areas:

- Jitter and noise definition and injection locations
- Equalization tuning methodology
- Link margin determination methodology
- Handling of nonlinear behaviors in the link
- Use of reference transmitter and receiver and packages

The last factor, i.e. the use of reference devices and package models, usually renders the COM vs IBIS-AMI an orange-and-apple comparison. However, it will be beneficial to system developers and the industrial to know how COM results are affected by the above-mentioned factors and the possible implications in a real system, which can usually be more realistically modelled and accurately simulated in an IBIS-AMI environment.

To remedy, to certain degree, the orange-and-apple comparison issue, we built a pair of transmitter and receiver IBIS-AMI models, include packages, that closely resemble the reference device/package models as specified in *IEEE 802.3 50GBASE-KR/200GBASE-KR4*, also known as *802.3cd*. We also applied COM's jitter/noise settings, in amplitude and locations, in the IBIS-AMI domain. The IBIS-AMI models and the jitter/noise modeling will then be augmented and/or modified with certain characteristics that are common in real circuit designs. In this process, we can observe and analyze how COM and IBIS-AMI relate-to and differ-from each other.

4.1 COM Computation

We first configured a *53.125Gbps* COM simulation, which is similar to *50GBASE-KR/100GBASE-KR2/200GBASE-KR4* settings shown in Table 1, using a victim channel without crosstalk and *30mm* transmitter (TX) and receiver (RX) packages. The characteristics of the channel and packages are shown in Figure 4.

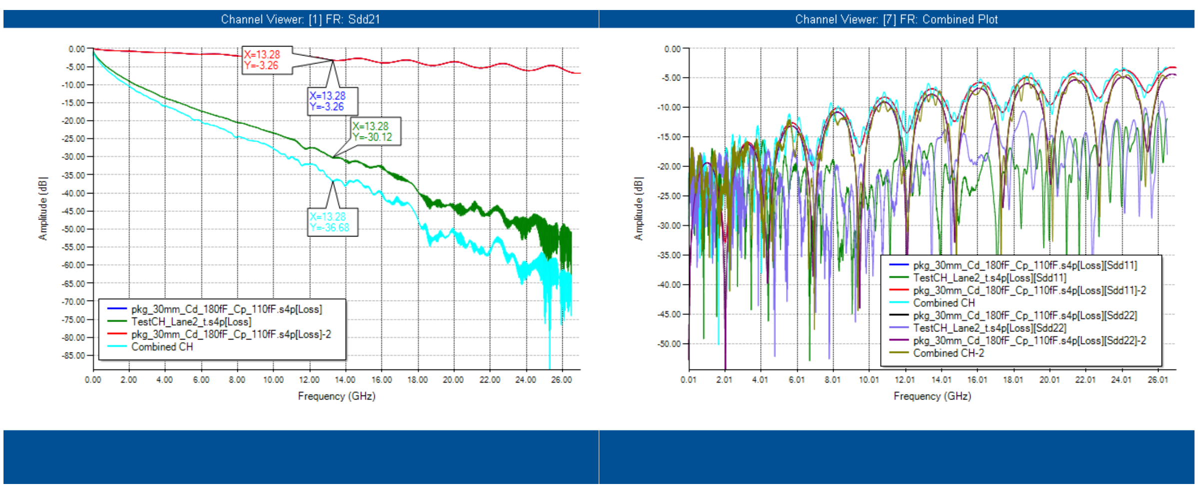


Figure 4 Test Channel Characteristics

Table 1 53.125Gbps PAM4 COM Configuration

Table 93A-1 parameters					Receiver testing				Table 93A–3 parameters		
Parameter	Setting	Units	Information		RX_CALIBRATION	0	logical		Parameter	Setting	Units
f_b	26.5625	GBd			Sigma BBN step	5.00E-03	V		package_tl_gamma0_a1_a2	[0 1.734e-3 1.455e-4]	
f_min	0.05	GHz			IDEAL_TX_TERM	0	logical		package_tl_tau	6.141E-03	ns/mm
Delta_f	0.01	GHz			T_r	0.012	ns		package_Z_c	90	Ohm (tdr sel)
C_d	[1.8e-4 1.8e-4]	nF	[TX RX]		FORCE_TR	1	logical				
z_p select	[2]		[test cases to run]						Table 92–12 parameters		
z_p (TX)	[12 30]	mm	[test cases]		Operational control				Parameter	Setting	
z_p (NEXT)	[12 12]	mm	[test cases]		COM Pass threshold	3	dB		board_tl_gamma0_a1_a2	[0 4.114e-4 2.547e-4]	
z_p (FEXT)	[12 30]	mm	[test cases]		Include PCB	0	Value		board_tl_tau	6.191E-03	ns/mm
z_p (RX)	[12 30]	mm	[test cases]						board_Z_c	110	Ohm
C_p	[1.1e-4 1.1e-4]	nF	[TX RX]		g_DC2	[-6:1:0]			z_bp (TX)	151	Mm
R_0	50	Ohm			f_LF	0.6640625	GHz		z_bp (NEXT)	72	Mm
R_d	[55 55]	Ohm	[TX RX] or selected						z_bp (FEXT)	72	Mm
f_r	0.75	*fb							z_bp (RX)	151	Mm
c(0)	0.6		min								
c(-1)	[-0.25:0.05:0]		[min:step:max]								
c(-2)	[0:0.025:0.1]		[min:step:max]								
c(1)	[-0.25:0.05:0]		[min:step:max]								
g_DC	[-20:1:0]	dB	[min:step:max]								
f_z	10.625	GHz									
f_p1	10.625	GHz									
f_p2	53.125	GHz									
A_v	0.45	V	tdr selected								
A_fe	0.45	V	tdr selected								
A_ne	0.63	V	tdr selected								
L	4										
M	32										
N_b	12	UI									
b_max(1)	0.7										
b_max(2..N_b)	0.2										
sigma_RJ	0.01	UI									
A_DD	0.02	UI									
eta_0	1.64E-08	V^2/GHz									
SNR_TX	32.5	dB	tdr selected								
R_LM	0.95										
DER_0	1.00E-04										

From the COM configuration, this link has the following characteristics:

Transmitter

- Baud rate: *26.5625GBd* (f_b in *[1]*)
- Differential output amplitude: $900mV_{peak\text{-}peak}$ (A_v in *[1]*)
- 20%-80% rise fall time: 12ps shaped by a Gaussian low-pass filter ($H_t(f)$ in *[1]*)
- Termination: *55ohms* (single-ended) (Z_d in *[1]*)
- Equalization: 4-tap FIR (2 pre-taps and 1 post-tap)
- Transmitter output SNR: 32.5dB (SNR_{TX} in *[1]*)
- PAM4 Level Mismatch (R_{LM}): 0.95 (R_{LM} in *[1]*)
- Deterministic Jitter: $0.04UI_{peak\text{-}peak}$ in dual-Dirac distribution (double the amount of A_{DD} in *[1]*)
- Random Jitter: $0.01UI_{RMS}$ (σ_{RJ} in *[1]*)

Receiver

- Equalization
  - Continuous Time Linear Equalizer (CTLE): CTLE is defined by *Equation 93A-22* in *[1]*, where $f_z = 10.625GHz$, $f_{p1} = 10.625GHz$, $f_{p2} = 53.125GHz$, f_{LF}

= *0.664GHz*, g_{DC}, which is high frequency gain, is between *0* and *20dB*, and g_{DC2}, which is low frequency gain, is between *0* and *6dB*

  - Decision Feedback Equalizer (DFE): DFE's tap length is *12* (N_b *in [1])*. DFE coefficients are found using zero-force method where post-cursor inter-symbol interference (ISI) is ideally cancelled out if the first post-cursor ISI is less than *70%* (*bmax(1)* in *[1]*) of the main cursor amplitude and less than *20%* ($b_{max}(2)$ *to* $b_{max}(12)$) for the remaining post-cursor locations.
- Noise Filter: COM uses a noise filter to shape both the input waveform and noises. It is defined by *Equation 93A-20* in *[1]*. The parameter f_r is *75%* of the baud rate.
- Receiver Input Noise: The receiver input noise is modelled using one-sided noise spectral density (η_0 in *[1]*) which is $1.64x10^{-8}$ V^2/GHz and represents uncounted system noises such as power supply noise, die-level, and package-level crosstalk. The noise at receiver slicer will be calculated by integrating the noise spectral density figure through CTLE and receiver noise filter characteristics.

Package

- Constructed using π-structure with a *30mm* transmission line (per *[1]*) sandwiched between a *0.18pF* die-capacitance (C_d in *[1]*) and a *0.11pF* package-PCB capacitance (C_p in *[1]*)

As highlighted in Section 2, COM first constructed a single-bit response (SBR) of the link, which include TX package, victim channel, RX package, and TX/RX termination, and then swept through all TX FIR and RX CTLE settings while applying zero-force DEF and calculating associated penalties caused by jitter and noise. A COM value of *4.36dB* was found and the final link SBR and Bathtub curves are shown in Figure 5. The COM simulation log showed the following EQ configurations:

- TX FIR: *[0 0 0.0250 -0.2000 0.7750 0]*
- RX CTLE: g_{DC} = *-13* and g_{DC2} = *-5*
- RX DFE: *[0.6741 0.1704 0.0936 0.0511 0.0351 0.0228 0.0105 0.0059 0.0100 -0.0251 0.0121 0.0026]* (in ratio with respect to CTLE output's main cursor amplitude)
- VEC (Vertical Eye Opening): *8.07dB*
- COM: *4.36dB*
- BER: 10^{-4}

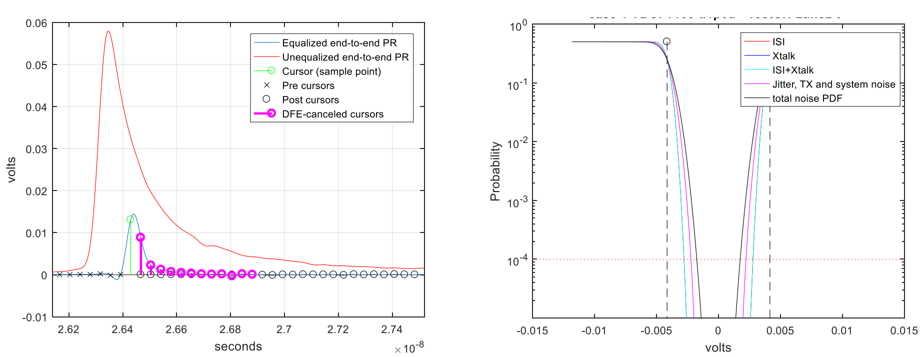


Figure 5 COM Simulation Result

4.2 IBIS-AMI Simulations

The experimental transmitter and receiver IBIS-AMI models were constructed to match the COM reference device models with the COM configurations mentioned in Section 4.1. Specifically, the transmitter has *20%-80%* rise/fall time of *12ps* and is with termination of *55ohms*. The receiver is equipped with analog front end (*AFE*) which is the same as COM's noise filter (H_r in *[1]*), 2-stage CTLE (H_{ctf} in *[1]*), and 12-tap DFE. We also mapped the COM jitter/noise values into corresponding IBIS-AMI jitter/noise values as shown in Table 2. The IBIS-AMI models support both statistical simulation and waveform simulation modes.

Table 2 Jitter/Noise Configurations in IBIS-AMI Simulations

COM		IBIS-AMI		Note
Jitter/Noise Name	**Value**	**Jitter/Noise Name**	**Value**	
A_{DD}	*0.02* UI_{peak}	**Tx_DCD**	*0.02* UI_{peak}	*Distribution: Dual-Dirac*
σ_{RJ}	*0.01* UI_{RMS}	**Tx_RJ**	*0.01* UI_{RMS}	*Distribution: Gaussian*
SNR_{TX}	*32.5 dB*	**Tx_RN (Proprietary)**	*32. dB or 10.67* mV_{RMS} *@TX die(in IBIS-AMI simulation)*	*Distribution: AWGN* *COM: Constant SNR throughout the link* *IBIS-AMI: TX differential output amplitude=900mV, supported in the Advanced Link Analyzer*
η_0	$1.64*10^{-8}$ V^2/GHz	**Rx_InpN (Proprietary)**	$1.64*10^{-8}$ V^2/GHz	*Not supported in IBIS standards* *Supported in the Advanced Link Analyzer*

The first notable differences in setting the IBIS-AMI simulation with respect to the COM link topology is the interpretation and implementation of device impedance/termination models. In IBIS-AMI simulations, device impedance and capacitance load are modeled in IBIS, e.g. using voltage-current (*V-I*, e.g. *pulldown/pullup)* table and *C_comp* parameter, or in AMI, e.g. using on-die S-parameter using AMI keyword *Ts4File*. In COM, device's impedance characteristics are captured using Z_d, e.g. resistive impedance, and C_d, e.g. device capacitive load and die-package capacitance, parameter. There are also subtle differences on how COM and IBIS-AMI utilize resistive impedance and capacitive load in the transmitter side. In IBIS-AMI, transmitter's *V-I* and *C_comp* are used to shape return loss profile but not the transient characteristics. In COM, Z_d and C_d shape transmitter's return loss and transient characteristics simultaneously. In this experiment, we constructed package models in COM's approach with C_d, *30mm* transmission line, and C_p in S-parameter files and then include them in the link schematic so that COM and IBIS-AMI will match each other. This been said, these package models do not represent actual device packages in real world as C_d should largely belongs to the device/circuit's characteristics rather than the package's.

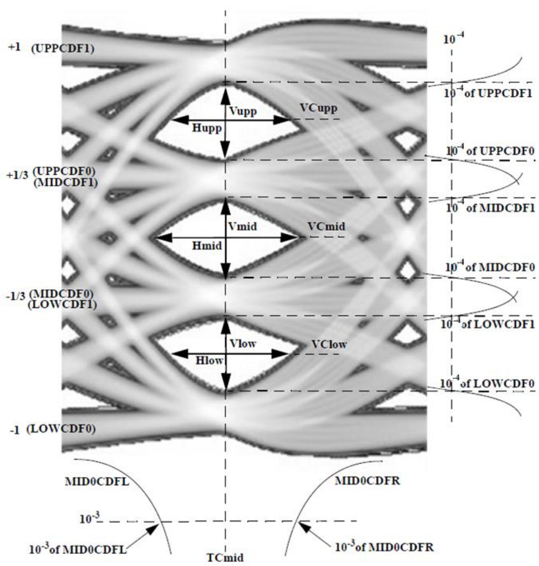
The second step to emulate the COM configuration in the IBIS-AMI simulation is to inject random noise at transmitter output, which is supported in our IBIS-AMI simulator (*Advanced Link Analyzer [4][5]*), and to maintain the constant SNR condition. In COM, it is assumed that the link's signal-to-noise-ratio up to the receiver's slicer input point, which is specified by COM's SNR_{TX} parameter, is kept constant (*Equation 93A-30* in *[1]*). In the IBIS-

AMI simulation flow, the random noise injected at transmitter output will be altered and shaped by each link component in its frequency spectrum and amplitude. In this experiment, we modified the simulation engine so that it will monitor and adjust the noise amplitude to achieve the constant SNR condition.

The third component is to enable receiver input referred noise modeling in the IBIS-AMI simulation. We added this capability in the receiver IBIS-AMI model and associated simulation engine support so that the two sides can match.

To compare COM and IBIS-AMI results, we need to find a metric from the IBIS-AMI simulation results that best resemble the COM. As COM is a ratio-based and IBIS-AMI is based on eye diagram measurements, we will need a figure of merit (FOM) from the receiver output eye diagrams that is comparable to COM for this study. The closest FOM we found is the *Vertical Eye Closure* (*VEC*) as defined in *IEEE 802.3 Annex 120E* for *53.125Gbps* PAM4 links. We adapted the *Annex 120E* methodology and measured *VEC* at BER of 10^{-4} at receiver slicer input in the IBIS-AMI simulations. The definition of *VEC* in this experiment is shown in Equation 2 and Figure 6:

$$VEC = 20log_{10}\left(\max\left(\frac{AV_{upp}}{V_{upp}}, \frac{AV_{mid}}{V_{mid}}, \frac{AV_{low}}{V_{low}}\right)\right)(dB) \qquad (2)$$



V_{upp} is the 10^{-4} upper eye height
V_{mid} is the 10^{-4} middle eye height
V_{low} is the 10^{-4} lower eye height
AV_{upp} is the amplitude of the upper eye (AV_{upp}), equal to VM_3–VM_2
AV_{mid} is the amplitude of the middle eye (AV_{mid}), equal to VM_2–VM_1
AV_{low} is the amplitude of the lower eye (AV_{low}), equal to VM_1–VM_0
VM_3 is the mean of the differential equalized signal above VC_{upp} at CDR sampling clock
VM_2 is the mean of the differential equalized signal between VC_{upp} and VC_{mid} at CDR sampling clock
VM_1 is the mean of the differential equalized signal between VC_{mid} and VC_{low} at CDR sampling clock
VM_0 is the mean of the differential equalized signal below VC_{low} at CDR sampling clock
VC_{upp} is the voltage center of the upper eye
VC_{mid} is the voltage center of the middle eye
VC_{low} is the voltage center of the lower eye

Figure 6 Definition of VEC used in this experiment (adapted from *IEEE 802.3 Annex 120E*)

With simple mathematical manipulations, we can compute the *Vertical Eye Opening Ratio* (*VEOR*) as defined in *Equation 3* which is similar to COM's definition.

$$VEOR = -20log_{10}\left(\frac{v-1}{v}\right)$$
$$where\ \ v = 10^{\frac{VEC}{20}} \qquad (3)$$

A set of IBIS-AMI simulations with the link topology shown in Figure 7 were conducted. The first simulation is in IBIS-AMI statistical mode. The results were shown in Figure 8.

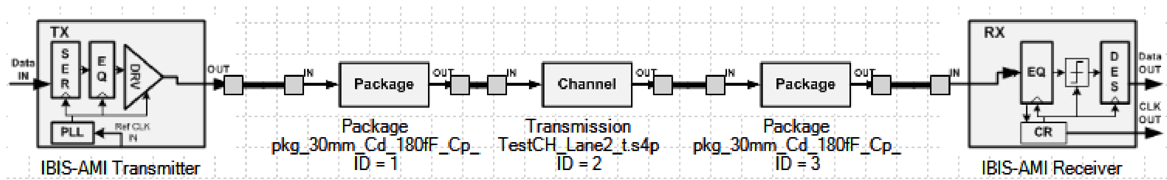


Figure 7 IBIS-AMI Simulation Topology

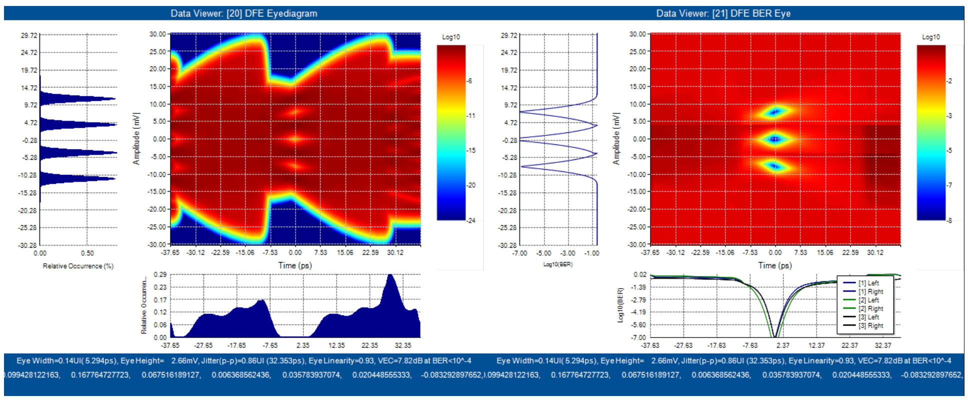


Figure 8 IBIS-AMI statistical mode simulation results with constant SNR condition

The IBIS-AMI statistical simulation yields a *VEC* of *7.82dB* and *VEOR* of 4*.53dB* as defined in Equation 2 and 3. The EQ settings are:

- TX FIR: *[0.025 -0.20 0.75 -0.025]*
- RX CTLE: $g_{DC} = -17$ *and* $g_{DC2} = -4$
- RX DFE: *[-0.5395 -0.0039 0.0087 0.0147 0.0059 0.0006 0.0031 0.0018 -0.0073 0.0283 -0.0156 -0.0046]* in ratio to estimated main cursor amplitude

The resulting *VEOR* value is close to COM value found in Section 4.1 which indicates that COM computation can be closely emulated using IBIS-AMI's statistical simulation method where both utilize SBR and LTI assumptions and with the three above mentioned adjustments/conditions applied. We also observed that the EQ settings found by the IBIS-AMI flow differ from that of COM's. By further checking the COM definitions and the COM code implementation, we found that the differences were caused by the following four factors:

- Jitter to noise amplitude conversion: COM is an amplitude-based FOM. So, jitter, e.g. A_{DD} and σ_{RJ}, are converted to equivalent noise amplitude through a jitter-to-noise transfer function $h_J(n)$ (*Equation 3*, from *Equation 93A-28* in *[1]*)

$$h_J(n) = \frac{h^{(0)}\left(t_s+\left(n+\frac{1}{M}\right)T_b\right)-h^{(0)}\left(t_s+\left(n-\frac{1}{M}\right)T_b\right)}{2/M} \qquad (3)$$

which computes the slope of system SBR, which includes device, channel, and EQ characteristics, before and after the sampling time t_s. Then, jitter is converted to noise by multiplying jitter (in time) to the square sum of $h_J(n)$ across sampling points (*Equation 93A-32* in *[1]*). In IBIS-AMI statistical simulation mode, jitter-to-noise interactions are done through convolutions across link SBR *[7]*.

- CDR modeling: COM specifies a static main cursor phase picker methodology (*Equation 93A-25* in *[1]*) that resembles the CDR in a receiver. In IBIS-AMI's statistical simulation mode, main cursor location is determined by the peak location of the link SBR. While this method is more ideal than COM's, IBIS-AMI provides additional jitter parameters, e.g. *Rx_Clock_Recovery_Dj*, *Rx_Clock_Recovery_Rj*, … etc., to account for CDR's characteristics. However, we did not utilize these CDR jitter parameters in this experiment.
- Equalization adaptation and optimization: As stated in Section 4.1, COM sweeps TX FIR and RX CTLE and uses zero-force DFE. This approach is resource expensive, due to physical and time limitations, and also too ideal in IBIS-AMI platforms as well as in real physical links. On the other hand, our IBIS-AMI models use more realistic approach to find equalization settings with LMS-based method. Compared to zero-force, the LMS-based method is over-determined which can be influenced by noise/jitter as well as channel ISI outside the equalizer range, e.g. ISI from locations that are beyond the number of DFE taps.
- Channel handling: S-parameter handling is platform dependent. The commonly used COM reference implementation has algorithms that handle causality enforcement and interpolation/extrapolation in frequency/time domains which are not part of COM definition *[1]*. In IBIS-AMI, likewise, channel handling is also a responsibility belongs to simulation platforms where they perform channel integrity enforcement, impulse response extraction/convolution (in statistical simulation mode), and waveform construction (in waveform simulation mode). Therefore, the channel characteristics seen by the equalizers can differ in certain degree.

Because COM is used to estimate link margins given the EQ is optimal or best tuned, the specific EQ settings are less concerning as long as they are not on or close to their limits.

Given the established COM vs IBIS-AMI simulation baseline, we will use the second IBIS-AMI simulation to see how the constant SNR impacts the link performance. In this experiment, we will remove the constant SNR condition where the injected transmitter AWGN noise will be filtered and shaped by the channel and receiver. The simulation results were shown in Figure 9.

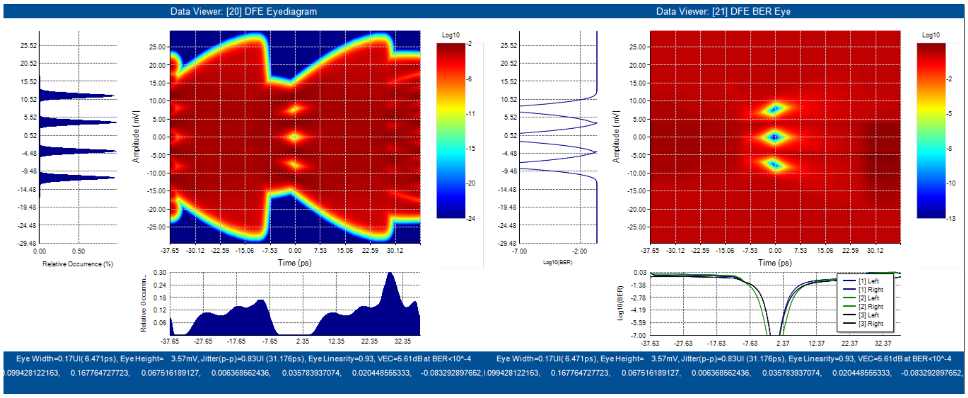


Figure 9 IBIS-AMI statistical mode simulation results with normal IBIS-AMI noise handling

The second statistical simulation showed that the VEC of *5.61dB* and VEOR of *6.45dB*. This represents an increase of *~1.92dB* in VEOR. With the transmitter's $900mV_{peak\text{-}peak}$ output signal and $32.5dB\ SNR_{TX}$, the noise is $\sim 10.67mV_{RMS}$. Because standards and COM do not specify the exact characteristics of transmission noise, it is usually assume that the noise is AWGN with flat spectrum. When the AWGN noise goes through the packages, channel, and receiver's noise filter and CTLE, it will be shaped and filtered when it reaches the receiver slicer. The IBIS-AMI simulation indicated much weaker noise ($\sim 0.37mV_{RMS}$ vs $\sim 0.49mV_{RMS}$ as in COM or IBIS-AMI with constant SNR condition) is observed at receiver slicer. So, this raises the question for the transmitter noise and its usage in COM.

The third simulation we conducted is waveform-domain simulation with constant SNR noise. In the IBIS-AMI waveform simulation mode, jitter and noise will be injected in the waveform at various locations, e.g. jitter is injected in the stimulus, TX noise is injected at TX output waveform, and RX noise is injected at the receiver input port. Receiver's EQ and DFE coefficients will be continuously adapted throughout the simulation. The simulation results are shown in Figure 10.

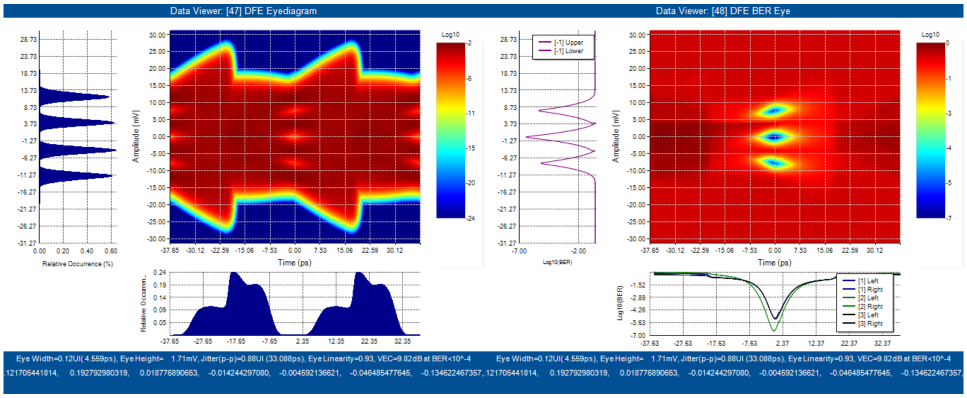


Figure 10 Waveform mode simulation results with constant SNR

The IBIS-AMI waveform mode simulation yields a VEC of *9.82dB* and *VEOR 3.39dB* which resulted in a difference *of -0.97dB* from COM and *-1.14dB* from *VEOR* obtained from the same simulation in statistical mode. As we learned from classical comparisons between the statistical simulation mode and waveform simulation mode, the decrease in link margin came from the following factors:

- TX level mismatch (R_{LM}): R_{LM} is nonlinear behavior and its impact usually is not completed covered in statistical simulations. For instance, R_{LM} usually results squeezed outer symbols, i.e. symbols represented by highest and lowest levels, in PAM4 links and, unfortunately, the outer symbols are also impacted the most by transmitter bandwidth, i.e. rise/fall time. While waveform simulations capture these effects simultaneously, COM and most statistical simulations, depending on implementations, only reflect the amplitude factor.
- TX FIR nonlinearity: Depending on circuit implementations, TX FIR can be implemented in logic level or using analog summation. If there is no jitter, TX FIR is a linear process where statistical and waveform simulations are the same. With the presence of jitter, specifically the jitter in the TX clock domain, TX FIR many exhibit nonlinear behavior. COM and statistical both miss this nonlinear effect. Note that most of IBIS-AMI TX models implemented linear filters in frequency domain to emulate the TX FIR operations. This approach might not accurately reflect TX FIR's physical design and its jittery effects.
- Jitter amplification: Jitter interacts with channel characteristics, device behaviors, and with other jitter/noise components. Numerous studies *[8][9]* have shown that the amount of jitter amplification depend on jitter's characteristics. In this experiment, we inject dual-Dirac jitter (i.e. A_{DD} and *Tx_DCD*) which is shown to have the most severe jitter amplification among the types of jitter types of distributions.
- EQ adaptation: In waveform simulation mode, the receiver equalizer is adapting throughout the length and under noisy/jittery condition. As CTLE's adaptation loop is considerable slower than that of DFE's, only DFE tap coefficients is changing in our simulations. This will results in differences between statistical and waveform simulation modes. Again, the DFE coefficients in our IBIS-AMI RX model were found by using LMS-based algorithm which differs from COM's zero-force approach.

In order to investigate the effect of jitter amplification and its interactions with equalization adaptation process, we re-configured our simulation platform so that jitter and noise will be post processed and added after the IBIS-AMI waveform simulation. With this configuration, the waveform which went through TX and RX IBIS-AMI models was jitter/noise-free and hence no jitter/noise amplification and equalization interaction. The simulation results (shown in Figure 11) indicated that VEC is *8.67dB* and VEOR is *3.99dB* which represent an improvement of *0.6dB* in *VEOR* compared to the previous case. The jitter amplification and interaction with channel and equalization accounted for about half of the difference (in dB) between statistical mode's and waveform mode's *VEOR* difference.

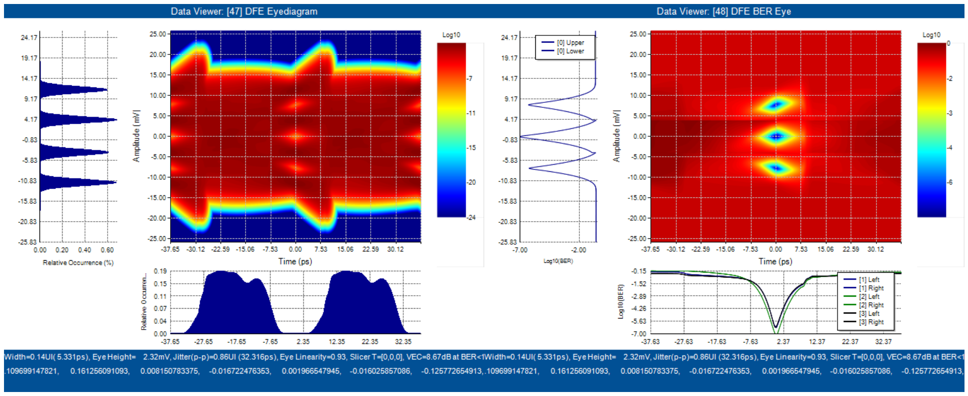


Figure 11 IBIS-AMI waveform mode simulation results where AMI models saw jitter/noise-free waveform and jitter/noise were post processed in the final stage

The fifth simulation is again a waveform-domain IBIS-AMI simulation but with normal IBIS-AMI noise modeling. The simulation results are shown in Figure 12 and they follow the trend we observed in the statistical mode simulations: VEC = *7.14dB* and VOER = *5.02dB.*

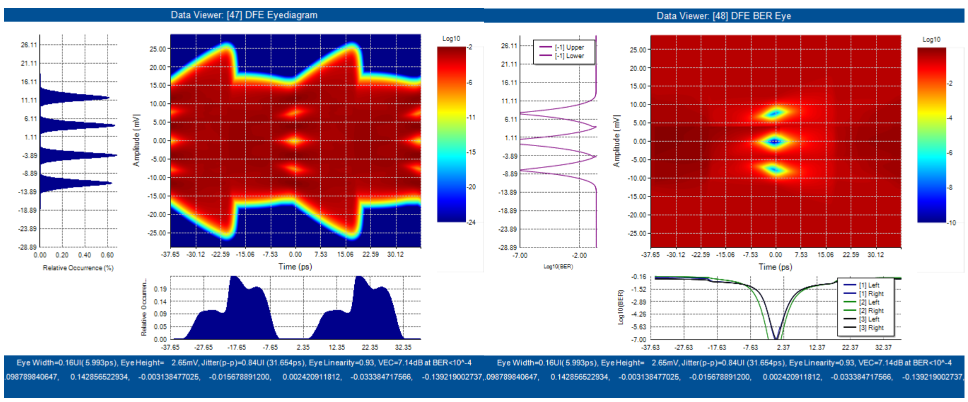


Figure 12 IBIS-AMI waveform mode simulation results with normal IBIS-AMI noise handling

In the next experiment, we made the following changes to the experimental IBIS-AMI models so that it can be more aligned with realistic *53Gbp* PAM4 transceivers exist today:

Transmitter

- Output amplitude: $1V_{peak\text{-}peak\text{-}differential}$
- Termination
  - $R_d = 50ohms$
  - $C_d = 0.13pF$
- Jitter and Noise
  - BUJ = $0.04UI_{peak\text{-}peak}$ with uniform distribution
  - DCD = $0.019UI_{peak\text{-}peak}$ with dual-Dirac distribution
  - RJ = $0.01UI_{RMS}$ with Gaussian distribution
  - RN = $2mV_{RMS}$

Receiver

- Termination
  - $R_d = 50ohms$

  - $C_d = 0.13pF$
- CTLE/VGA
  - CTLE AC gain: Similar to previous cases
  - DC Gain: *0 to 20dB*
- Jitter and Noise
  - RJ = $0.015UI_{RMS}$
  - RN = $4.6mV_{RMS}$
  - Input referred noise = $1.3x10^{-8}\ V^2/GHz$

With this configuration, we ran the IBIS-AMI waveform mode simulation with normal noise handling and the results were shown in Figure 13. With this more realistic configuration, actual eye height and eye width (at BER=10^{-4}) are found to be *~32.5mV* and *0.15UI* which should be sufficient to meet the receiver slicer sensitivity requirement with today's technology. We can also calculate VEC (*6.05dB*) and VEOR (*5.79dB*) for this link but these two figures are not as critical in judging the link performance as in the previous test cases.

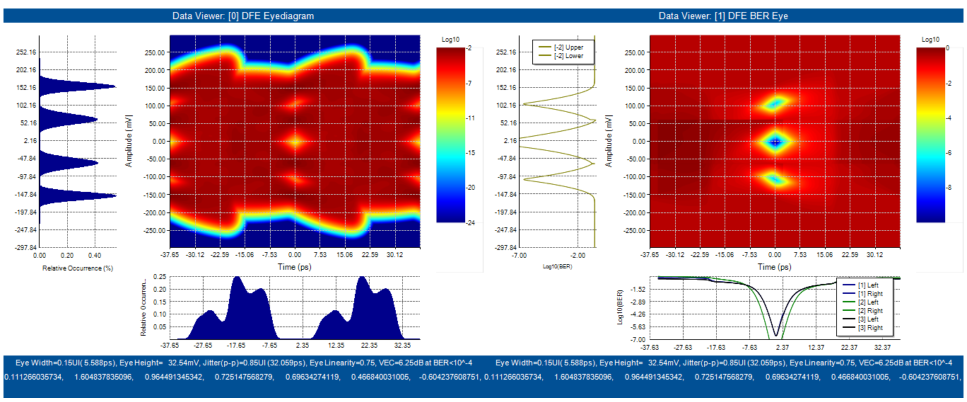


Figure 13 IBIS-AMI waveform mode simulation results with realistic device configuration

4.3 Observations

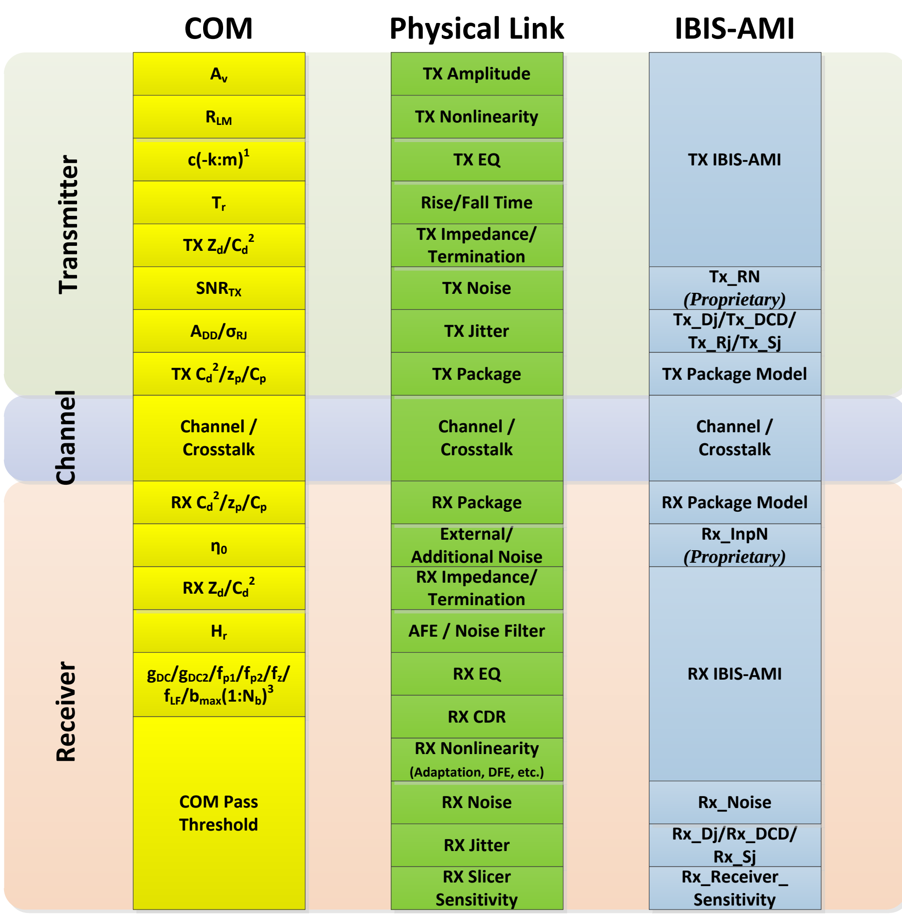
By putting COM and IBIS-AMI simulation results together (shown in Table 3) and mapping COM parameters with IBIS-AMI functional blocks (shown in Figure 14), we have the following observations:

- By carefully configuring the IBIS-AMI device models and jitter/noise modeling methodology in accordance with COM's definition, we can approximate COM value with *VEOR* value using IBIS-AMI's statistical simulation mode
- COM's SNR_{TX} definition and the way transmitter noise is handled affect the *VEOR* values by *~1.5~2dB* which is quite significant
- IBIS-AMI waveform simulation mode resulted in a reduction of *VEOR* by *1~1.5dB* from that of statistical simulation mode caused by nonlinearity characteristics, such as R_{LM}, jitter amplification, and equalizer adaptation, in the link and devices
- Waveform simulation results indicated that jitter amplification accounts for about half of the nonlinear effects

- Interestingly, IBIS-AMI waveform simulations with normal noise handling brought the *VOER* values closer to the COM value
- The IBIS-AMI simulation with more realistic device characteristics showed that the link can operate and have sufficient link margins at target BER

Table 3 COM and IBIS-AMI Simulation Results Summary

	COM (dB)	VEOR (dB)	VEC (dB)	Eye Height (mV)	Eye Width (UI)
COM	4.36	n/a	8.07	n/a	n/a
Statistical w/ Constant SNR	n/a	4.53	7.82	2.66	0.14
Statistical w/o Constant SNR	n/a	6.45	5.61	3.57	0.17
Waveform w/ Constant SNR	n/a	3.39	9.82	1.71	0.12
Waveform w/ Constant SNR & Jitter/Noise post-processing	n/a	3.99	8.67	2.32	0.14
Waveform w/o Constant SNR	n/a	5.02	7.14	2.65	0.16
Waveform w/o Constant SNR w/ realistic device characteristics	n/a	5.13	7.01	32.67	0.15



Note: 1: k is TX EQ's pre-tap length and m is post-tap length. 2: Cd represents device die and die-package capacitance in COM. 3: COM includes a static main cursor phase picker which resembles a CDR.

Figure 14 COM parameters vs IBIS-AMI functional blocks

5 Conclusions and Next Steps

In this paper, we briefly explained the methodology behind COM and IBIS-AMI methodologies. We also highlighted the assumptions and differences between these two schemes. Then, six study cases were conducted to show the linkage between the COM value and IBIS-AMI simulation results. The study showed that the receiver output voltage eye opening ratio (*VOER*) located at recovered clock ticks can be calculated and shown to resemble the COM value.

From the IBIS-AMI simulation results, we can draw the following conclusions:

- *VOER* value is a good indicator which can be used to associate with COM value
- COM's SNR_{TX} definition is not clear and the way TX noise is handled does not align with our waveform simulation results. The constant SNR approach used in COM calculation does not match well with how noise is treated in real channel and devices. The constant SNR assumption can only be true under very restricted scenario, for example, a transmitter with strong nonlinear characteristics or with narrow noise spectrum.
- Link performance estimations from IBIS-AMI's waveform simulation mode are more accurate than COM simulation methodology and IBIS-AMI's statistical simulation mode. The reason is waveform simulation mode can accurately model and account for the impacts from link's nonlinear behaviors and characteristics.
- Though COM simulation method is less accurate than IBIS-AMI waveform simulation mode, its device configurations, such as SNR_{TX}, A_{DD}, and pass/fall COM value threshold (e.g. *3dB*), are shown to be over-generalized and provide "hidden" margins that can be used to account for nonlinear characteristics exists in the link. The IBIS-AMI waveform mode simulations that utilize more realistic noise modeling and include nonlinear effects showed that the link margins, in terms of *VEOR*, were again approaching closer to the COM value. So, COM methodology, as a whole, is useful as a standard compliance vehicle.

In all, COM is a good methodology for standard definition and compliance tests because it provides sufficient capabilities in modeling baseline transmitters and receivers and ample flexibilities in abstracting and budging link's non-idealities. At the same time, we also showed that it lacks the accuracy as a high-speed serial link simulation platform. To determine the link margin accurately, IBIS-AMI's waveform simulation mode is clearly the better choice.

Looking forward, as we did not include crosstalk in this paper so that we can more clearly observe the differences between COM and IBIS-AMI, studying how crosstalk is modeled and how it impacts link margins in COM and IBIS-AMI is in our list. Another area is to improve COM methodology so that it can be more precise, in terms of parameter definitions, and simulation methodology that improve accuracy, such as jitter to noise amplitude conversion. The motivation is simply that the nonlinearity and higher-order jitter/noise characteristics will be more dominate in the next-generation serial links.

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