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

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Contents

Channel Operating Margin (COM)

- COM is a FOM defined as

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

where A_s is available signal strength after channel, device characteristics, and equalizations, A_{ni} is the combination of uncompensated channel effects (e.g. ISI), intrinsic jitter/noise, and external jitter/noise (e.g. crosstalk)

- COM has been adopted various standards since ~2014 for >25Gb/s NRZ/PAM4 links
  - IEEE 802.3
  - OIF CEI
  - JEDEC 204C
- COM has been widely used for channel and Tx/Rx compliance tests

COM Methodology

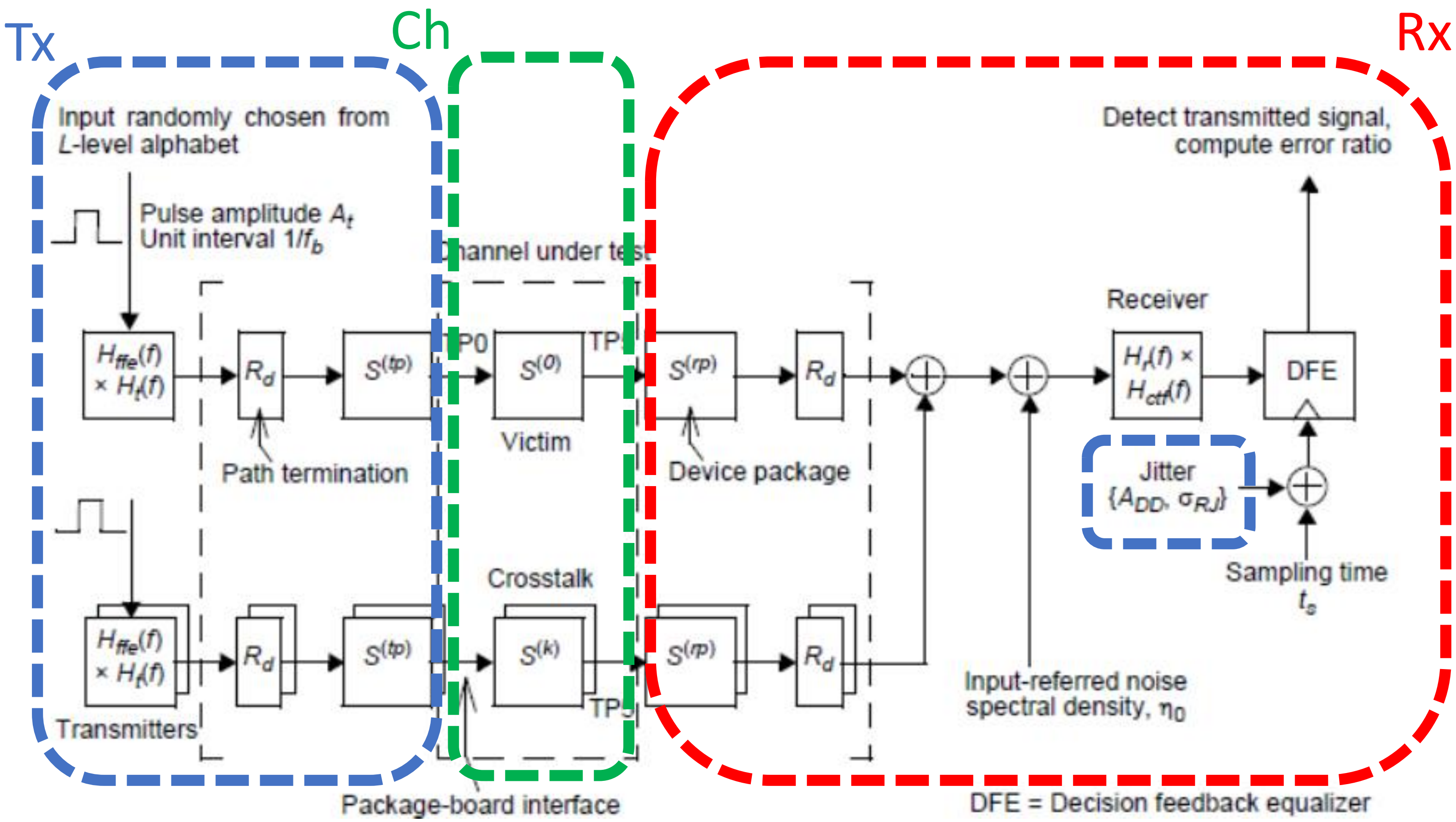
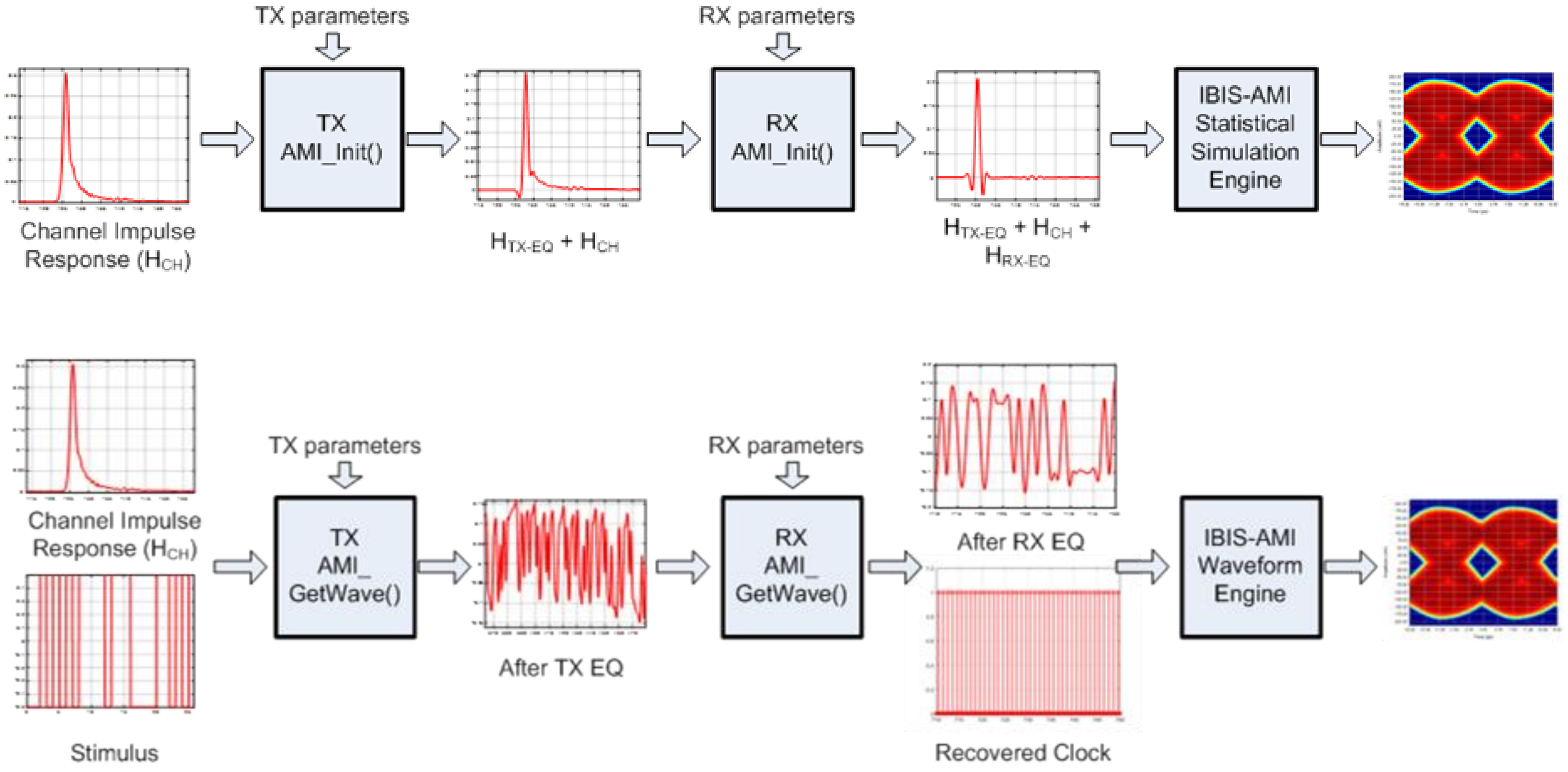


Figure 93A-1, IEEE 802.3 Annex 93A

IBIS-AMI

- Input/Output Buffer Information Specification (IBIS) Algorithmic Modeling Interface (AMI)
- Standards for I/O buffers and transceivers/PHYs behavior model, which
  - is more simulation time efficient (than SPICE simulations)
    - Allow simulation of millions of bits for low BER (bit error rate) performance estimation
  - protects IP's and allow simulations between devices from different vendors
  - is governed by IBIS Open Forum
- What's inside an IBIS-AMI model
  - Analog model: drive strength/amplitude, rise/fall time, impedance
  - Algorithmic model: Equalizer (CTLE, FFE, DFE) , clock data recovery (CDR in receiver), jitter/noise

IBIS-AMI Simulation and Analysis Flow

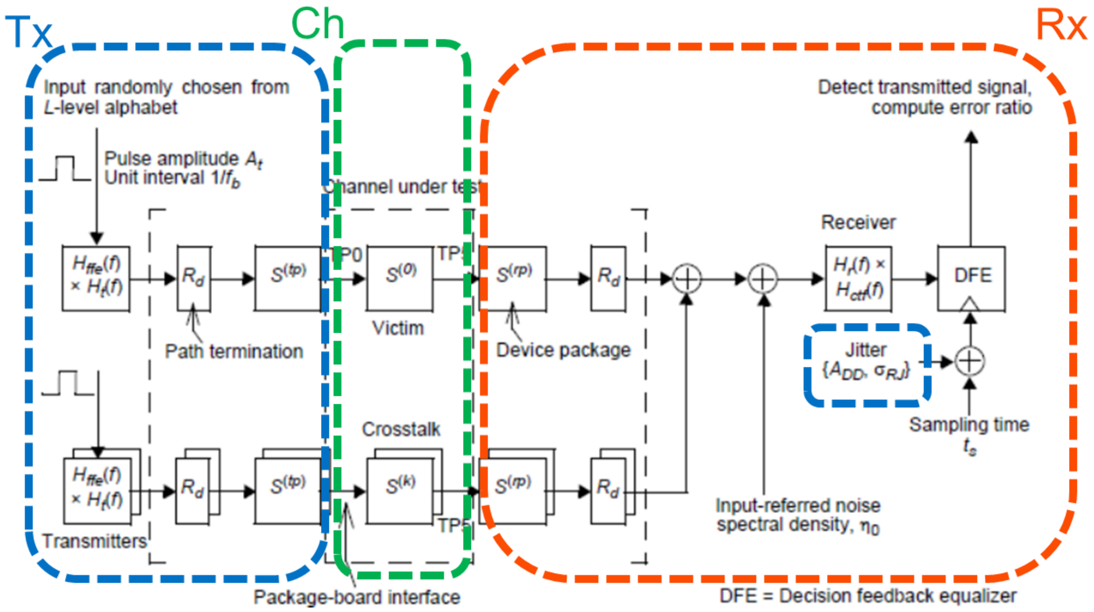


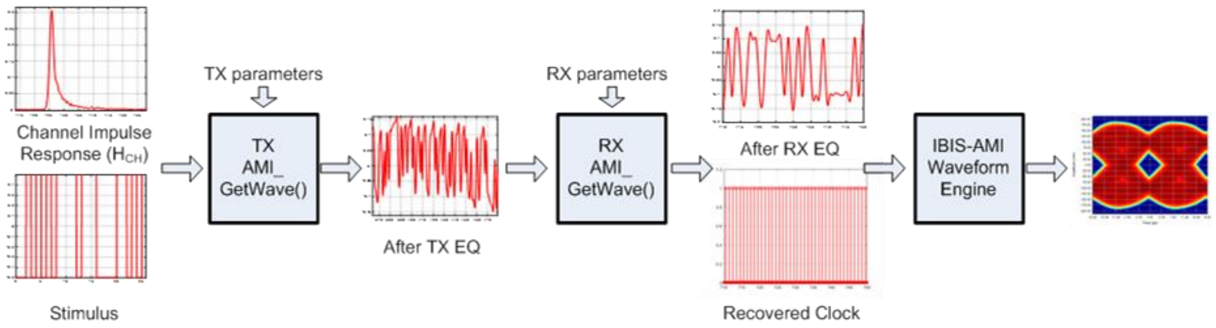
COM vs. IBIS-AMI: Why we want to compare them?

- Similarity
  - Both are link simulations: Stimulus => Tx => Channel => Rx w/ jitter/noise
- Why the comparison?
  - Can I use COM to simulate ***My*** link?
    - COM is free and from standards
    - But I also knew IBIS-AMI should be more accurate
  - What do the COM values mean to my link?

First-Order Differences between COM and IBIS-AMI

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

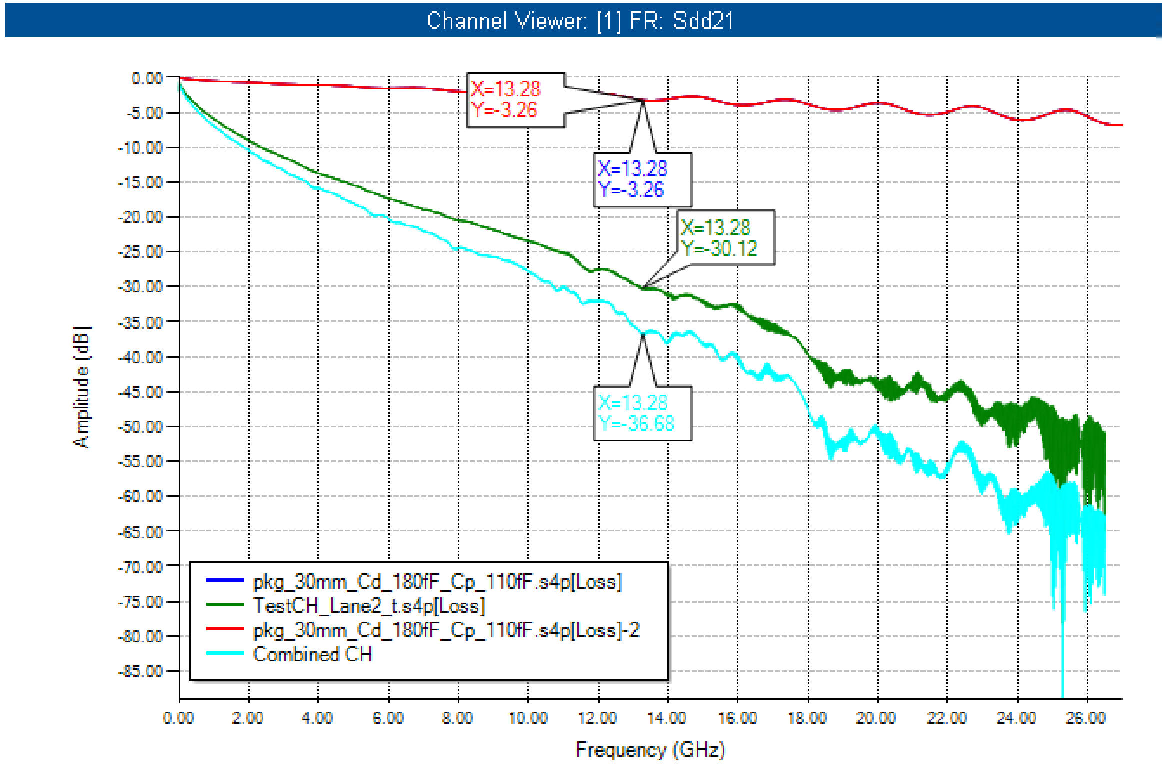


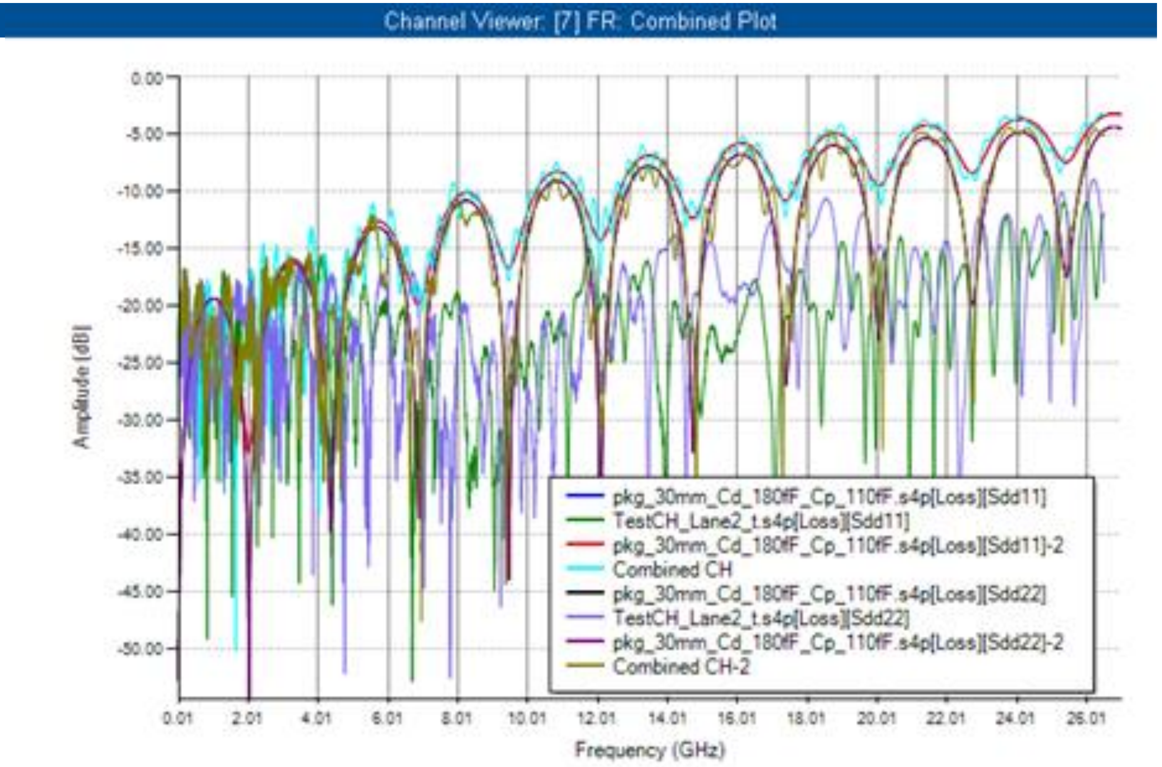


Link Configuration and Comparison Methodology

- Configure a COM simulation that approximates a 50GBASE-KR/200GBASE-KR4 (802.3cd) link
- Build and re-configure a general purpose IBIS-AMI model with Tx/Rx characteristics that approximates 50GBASE-KR/200GBASE-KR4 (802.3cd) specifications
  - Tx: rise/fall time, impedance (Z_d, C_d), Tx EQ
  - Rx: Impedance (Z_d, C_d), AFE, EQ (CTLE, DFE) with LMS-based adaptation engine
  - Package: using COM method (C_d+*T-line*+C_p) and use it as part of the channel
- Inject COM jitter/noise in IBIS-AMI framework
  - DJ (A_{DD}), RJ (Sigma_{RJ}), SNR_{TX}, Rx Input noise (η_0)
- Tuning and improve the simulation settings and simulation platform to emulate COM methodology
- Does not include crosstalk in this paper
  - To simplify the comparison tasks

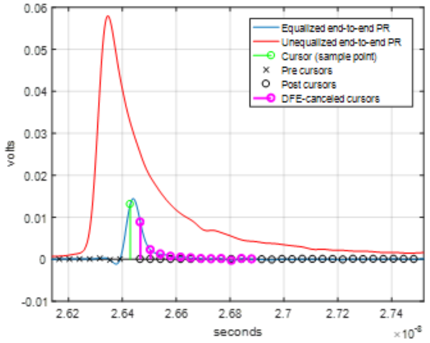
Test Channel Characteristics

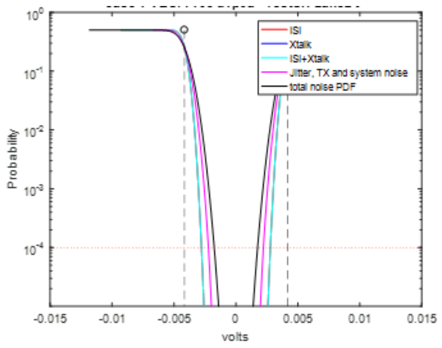




COM Configuration and Results

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								

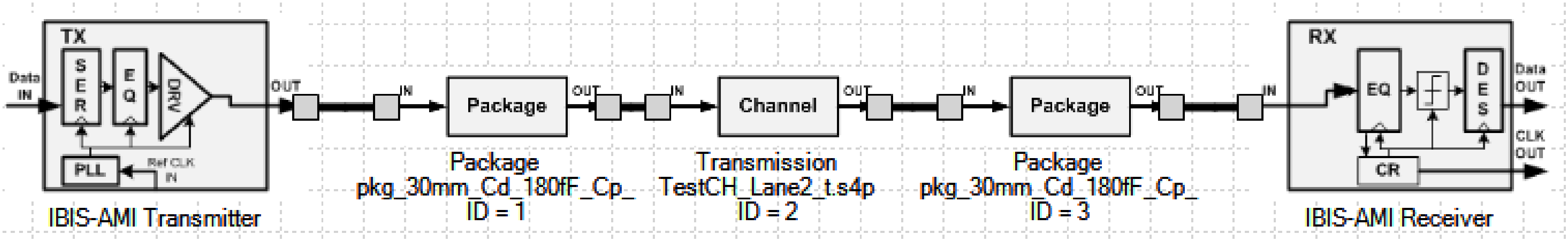




- TX FIR: *[0 0 0.0250 -0.2000 0.7750 0]*
- RX CTLE: g_{DC} = *-13* and g_{DC2} = *-5*
- RX DFE: *[0.6741 0.1704 0.0936 0.0511 0.0351 0.0228 0.0105 0.0059 0.0100 -0.0251 0.0121 0.0026]* (in ratio with respect to CTLE output's main cursor amplitude)
- VEC (Vertical Eye Closure): *8.07dB*
- BER: 10^{-4}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

IBIS-AMI Simulation Configurations

- Topology



- Tx/Rx Impedance and Packages
  - Tx 20-80% rise/fall time:12ps
  - Tx/Rx Impedance and Return Loss
    - R = *50ohms*
    - Capacitive loads (*C_comp*): To be included in the package model
  - Package (contains both die impedance and package models)
    - Die Capacitance (*Cd*): *180fF*
    - 30mm T-line
    - PCB Capacitance (*Cp*): *110fF*

IBIS-AMI Simulation Configurations (cont.)

- Jitter/Noise

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*2)***	32. dB or 10.67 mV_{RMS} @TX die*3	Distribution: AWGN *: COM: Constant SNR throughout the link *2: Supported in the Advanced Link Analyzer *3: Tx_RN value is calculated with Tx differential output amplitude=900mV
η_0	1.64*10-8 V2/GHz	***Rx_InpN (Proprietary*4)***	1.64*10-8 V2/GHz	*4: Supported in the Advanced Link Analyzer

- TX Noise (SNR_{TX})
  - COM does not specify characteristics of Tx Noise, e.g. BW, distribution, …etc.
  - COM assume SNR_{TX} is constant throughout the link and inside device
  - IBIS-AMI does not support Tx noise
    - Modelled as *Tx_RN* in our simulation platform
      - Options: Amplitude, BW, distribution, and constant SNR enforcement option
- Receiver Input Noise (η_0)
  - IBIS-AMI does not support Rx Input Noise η_0
    - Supported in our simulation platform as *Rx_InpN*

IBIS-AMI Simulation: FOM for COM comparison

- VEC (Vertical Eye Closure)

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

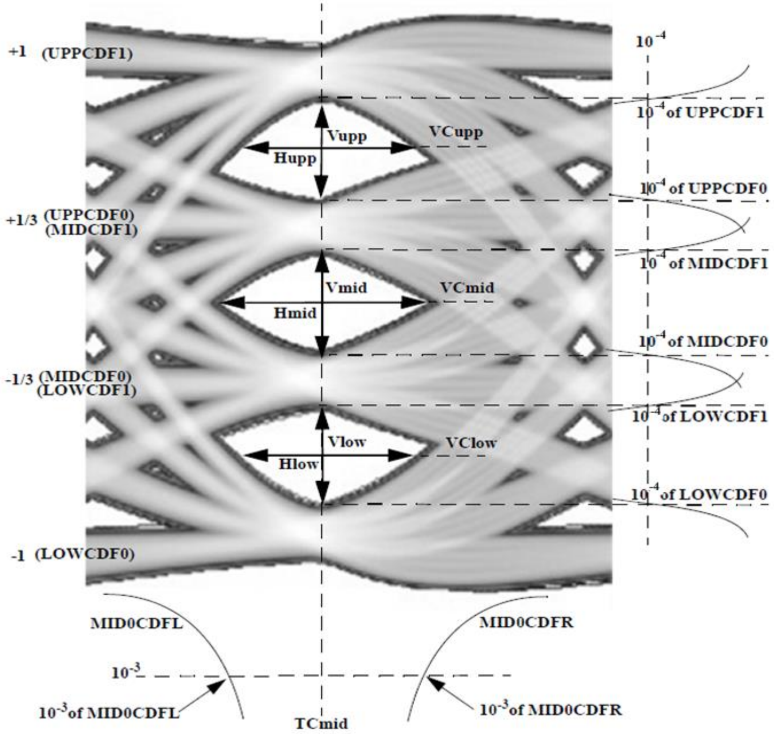
  - Defined in IEEE 802.3 Annex 120E
  - In this paper, we measure VEC at BER 10^{-4}

- VEOR (Vertical Eye Opening Ratio)

$$VEOR = -20log_{10}\left(\frac{v-1}{v}\right)$$

$$where\ \ v = 10^{\frac{VEC}{20}}$$

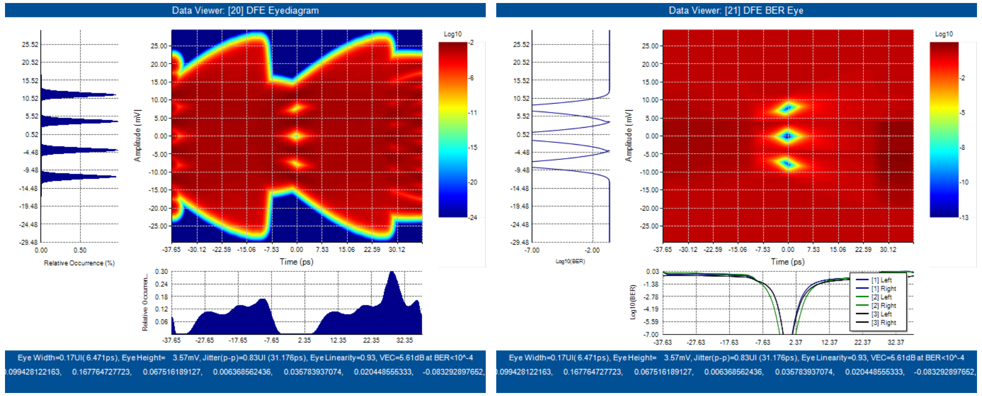
  - Similar to COM and will be used as the FOM in IBIS-AMI simulation result assessments



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

IBIS-AMI Simulation #1

Statistical Mode



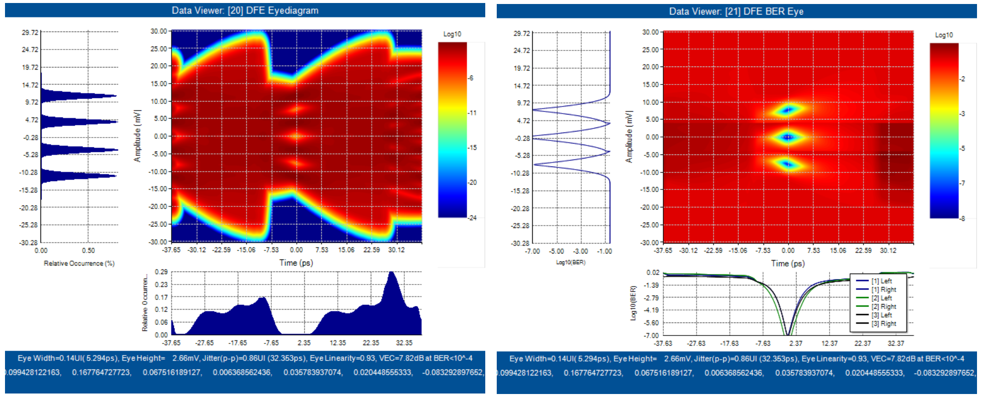
VEC = 5.61dB

VEOR = 6.45dB (vs 4.36dB COM)

- Similarity between IBIS-AMI statistical mode and COM
  - LTI-based simulation
  - No jitter interactions
- Observations
  - IBIS-AMI result is ~2dB better than COM
  - Cause: Residual TX noise at RX slicer is seen to be much smaller than COM's
- Discussions
  - Should TX noise to be shaped and filtered by device and channel?
  - What is TX noise's characteristics?
  - Is constant SNR_{TX} realistic?

IBIS-AMI Simulation #2

Statistical Simulation Mode w/ Constant SNR_{TX}



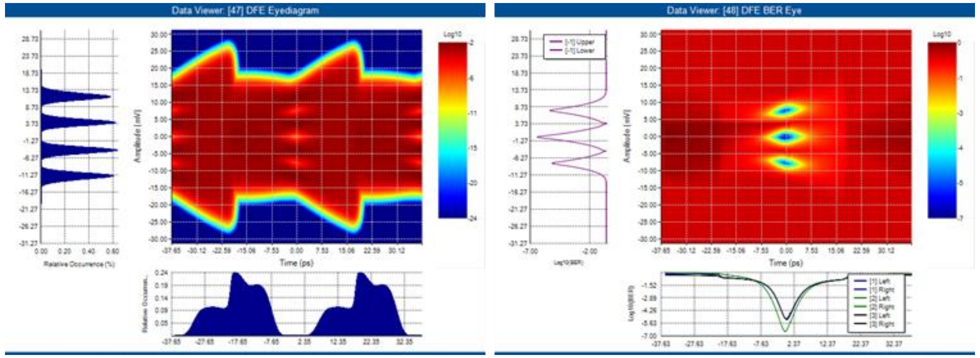
VEC = 7.82dB

VEOR = 4.53dB (vs 4.36dB COM)

- Observation
  - Good match between IBIS-AMI and COM
- Discussions
  - Is constant SNR_{TX} realistic?
    - True when Tx noise is highly nonlinear and/or with low BW
    - If your Tx's output noise is AWGN and/or w/ better SNR, COM value will be too pessimistic
  - Jitter/Noise Handling
    - COM's Jitter-to-Noise conversion (IEEE 802.3 Eq. 93A-27)
    - IBIS-AMI jitter-to-noise conversion: 2-D convolution
  - CDR Effect in COM
    - No explicit CDR jitter/noise
  - Nonlinearity
    - COM includes TX level mismatch (RLM) adjustment
    - IBIS-AMI stat. mode: Platform dependent
  - EQ adaptation
    - COM vs IBIS-AMI: LMS-based algorithm

IBIS-AMI Simulation #3

Waveform Simulation Mode w/ Constant SNR_{TX}



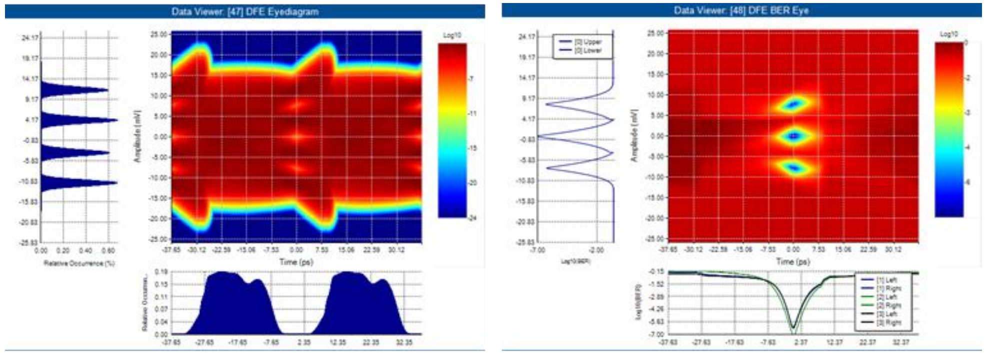
VEC = 9.82dB
VEOR = 3.39dB (vs 4.36dB COM)

- Observations
  - IBIS-AMI's waveform simulation mode includes
    - Nonlinear effects
      - CDR
      - Jitter/noise amplification
      - PAM4 Level mismatch (R_{LM})
    - Link adaptation
    - Resulting worse *VEOR* by *~1.14dB*
- Discussions
  - Nonlinearity has shown to become more dominate in higher data rates and PAM4 links
  - If your Tx/Rx have more nonlinear characteristics, COM value can be too optimistic
  - Depending on jitter/noise characteristics, COM value can be either optimistic or pessimistic

IBIS-AMI Simulation #4 and #5

Waveform Simulation w/o jitter/noise amplification and w/o Const. SNR_{TX}

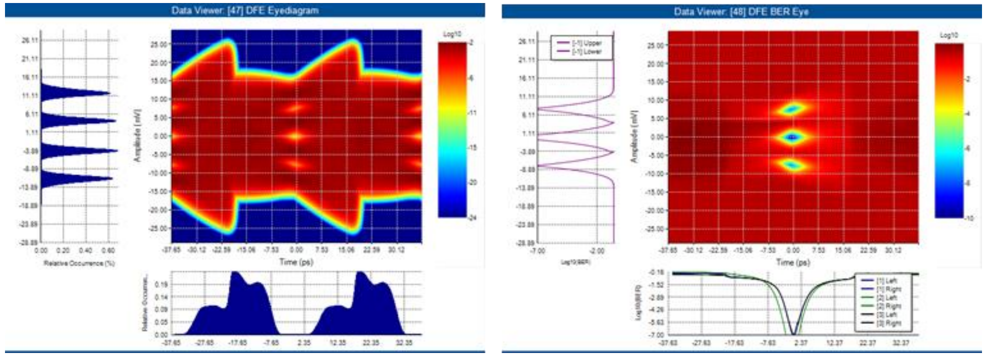
w/o jitter/noise amplification



VEC = 8.67dB
VEOR = 3.99dB (vs 4.36dB COM)

- w/o Jitter/Noise Amplification
  - Jitter/Noises are post-processed at the Rx Slicer output
  - Jitter/noise also affect EQ adaptation
  - Improved *VEOR* by *~0.6dB*

w/o Constant SNR_{TX}



VEC = 7.14dB
VEOR = 5.02dB (vs 4.36dB COM)

- w/o Constant SNR_{TX}
  - Similar to statistical simulation result, Tx noise was shaped by channel and device characteristics
  - Improve *VEOR* by *~1.0dB*

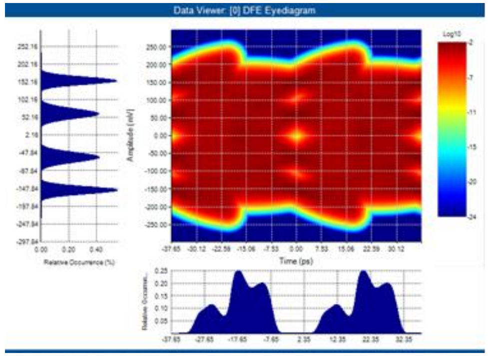
IBIS-AMI Simulation #6

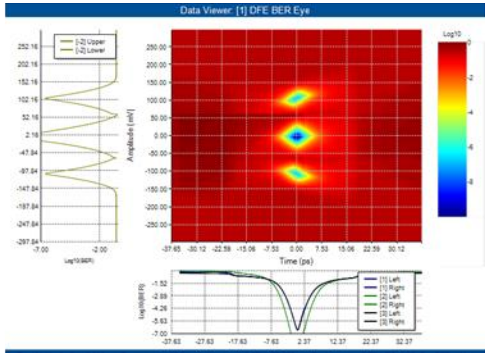
Waveform Simulation Mode w/ realistic Tx/Rx characteristics

- Link and Device Configurations
  - **Transmitter**
    - Output amplitude: $1V_{peak\text{-}peak\text{-}differential}$
    - Termination
      - $R_d = 50ohms$
      - $C_d = 0.13pF$
    - PAM4 Level Mismatch
      - $R_{LM} = 0.95$
    - 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/DFE
      - CTLE AC gain: 0 to 16dB
      - VGA Gain: *0 to 20dB*
      - 12-tap DFE
    - Jitter and Noise
      - RJ = $0.015UI_{RMS}$
      - RN = $4.6mV_{RMS}$
      - Input referred noise = $1.3x10^{-8}\ V^2/GHz$
    - Slicer Sensitivity
      - $30mV_{peak\text{-}peak}$

IBIS-AMI Simulation #6

Waveform Simulation Mode w/ realistic Tx/Rx characteristics *(cont.)*





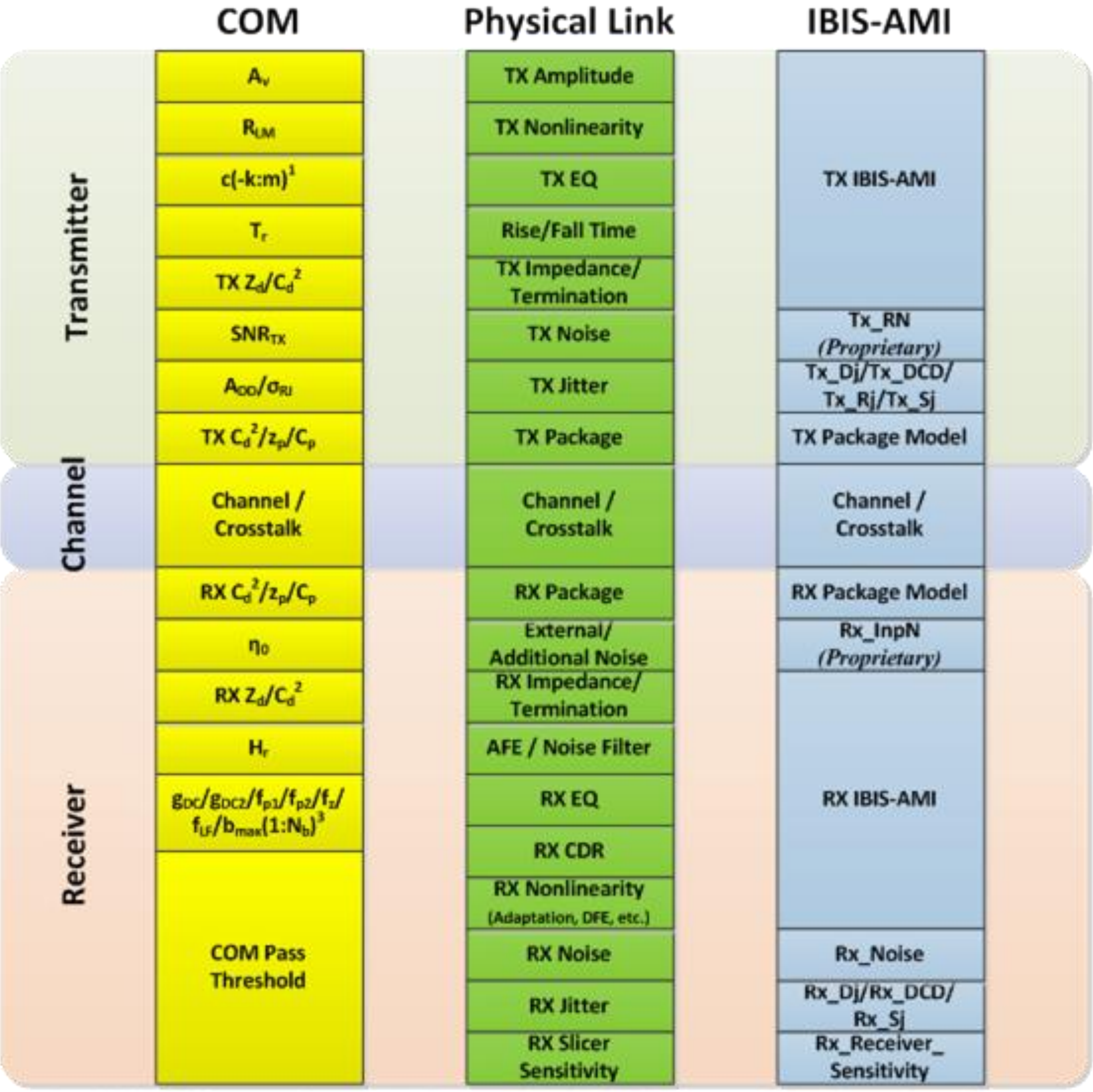
Eye Opening Width (EW) = 0.15UI
Eye Opening Height (EH) = 32.5 mV
VEC = 6.05dB
VEOR = 5.79dB

- Observations
  - Both Tx and Rx are better than reference devices in COM. However
    - Both Tx and Rx have more and detailed jitter/noise components: Tx BUJ/DCD/RJ/RN and Rx RJ/RN
    - Eye opening height and width need to meet Rx slicer sensitivity for correct symbol recovery
      - VEC and VEOR are not critical in determining link pass/fail
  - The link was shown to have sufficient link margins at 53.625 Gb/s

COM vs. 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

COM vs IBIS-AMI Summary



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.

Conclusions

- By carefully configuring IBIS-AMI models and simulations, we are able to replicate COM results in IBIS-AMI simulation environment
- COM result can be approximated by running IBIS-AMI in statistical mode and measuring VEOR value
- Using COM to estimate actual link performance is difficult and unrealistic, because:
  - COM uses reference device models which differ from actual device
  - COM pass threshold is highly abstract and hard to match to exact link and device characteristics
- COM's abstract nature, however, is shown to be a good vehicle for channel compliance and specification setting
  - i.e. Passing COM usually leads to working links
- Should use IBIS-AMI waveform simulation mode to assess accurate link margins

Next Step

- Investigate ways to improve COM in the following areas
  - Tx noise characteristics and SNR_{TX} definition
  - Jitter/noise amplification
  - COM pass threshold
- To include in future COM vs. IBIS-AMI studies
  - Crosstalk
  - Voltage and timing BER bathtub curves