Gap in IBIS for sampling with statistical mode AMI models

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Acknowledgements

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- Richard Mellitz for discussions on the COM tool settings.
- Adam Gregory for discussions on the IBIS-AMI flow.
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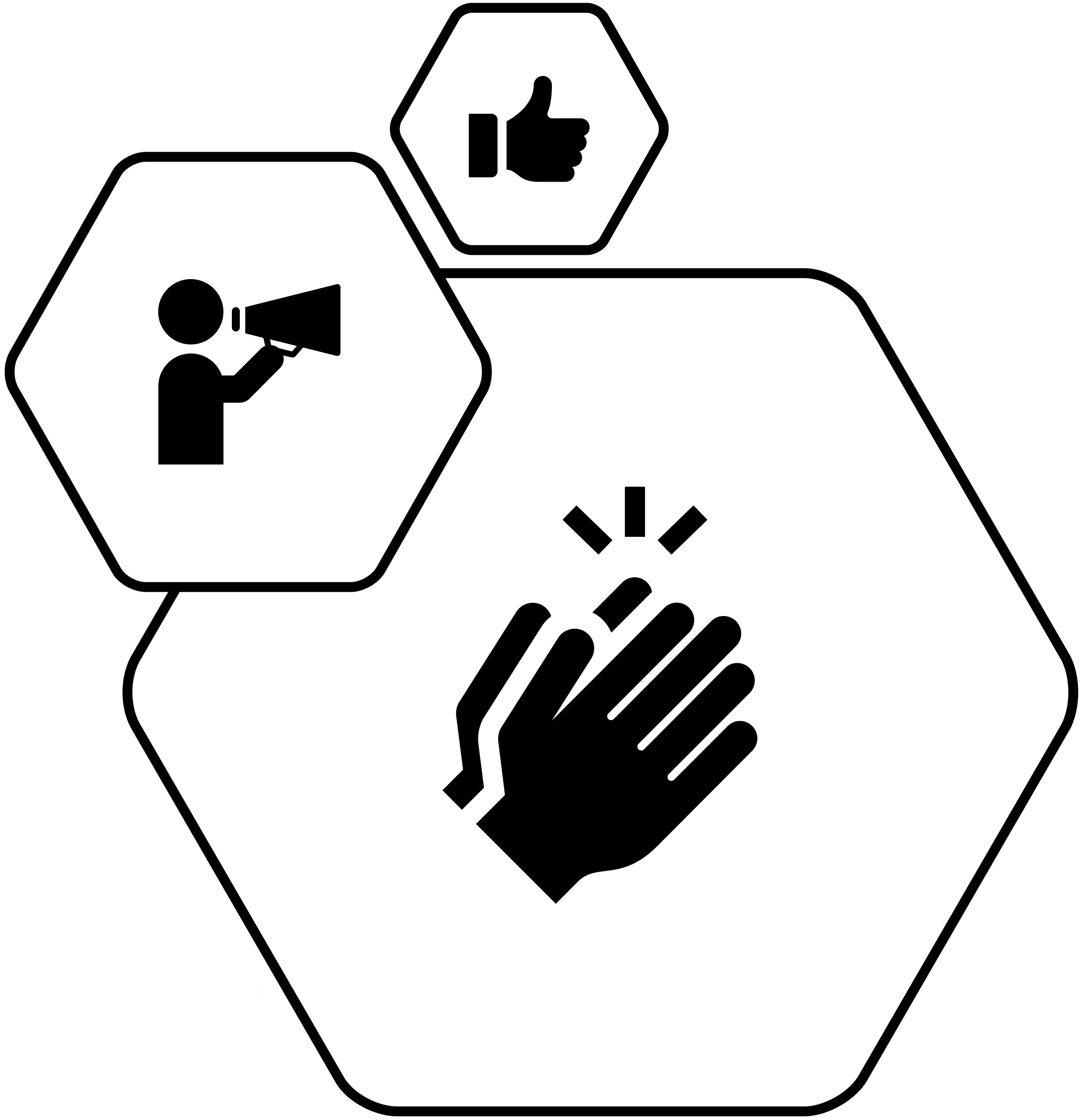
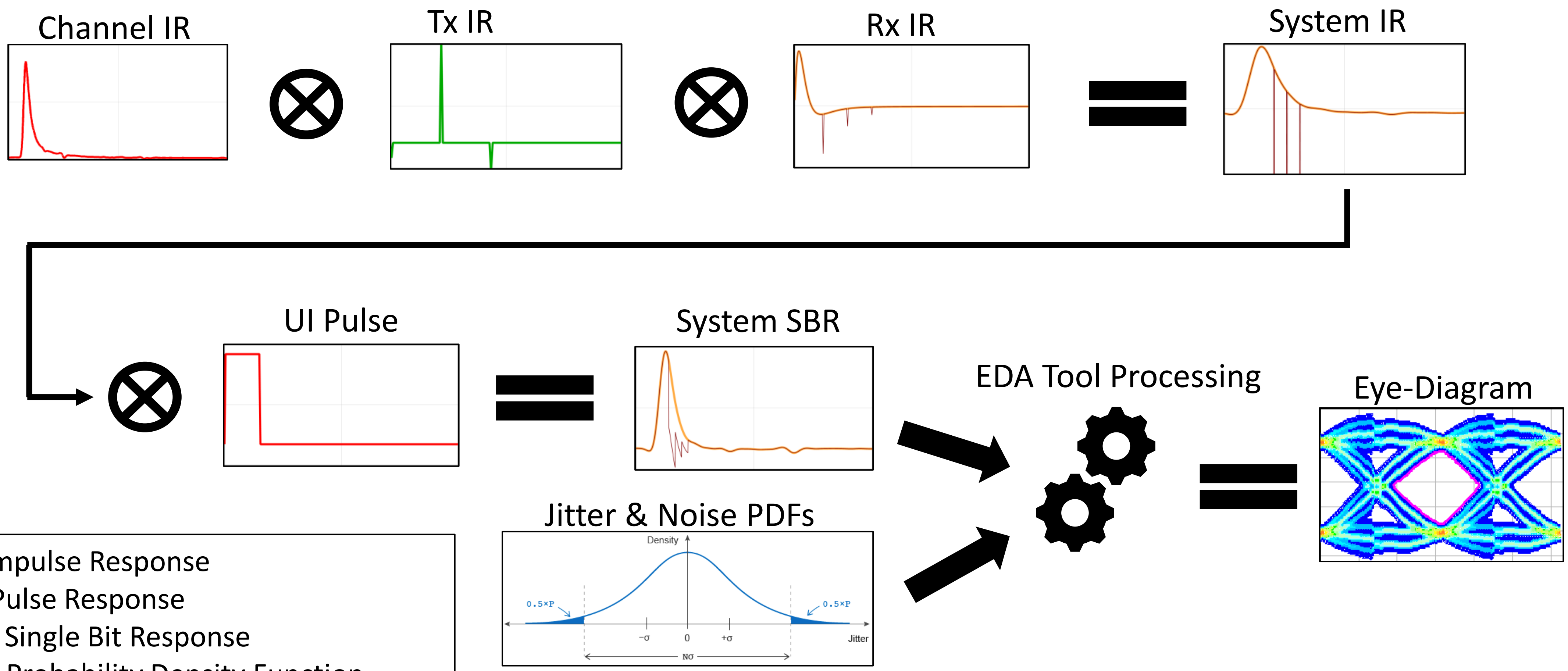
- Ambrish Varma and Ken Willis for analysis contributions and prompt responses.
- Barry Katz, Eric Brock and Steve Silva for analysis contributions and deep dive discussions during debugging.



Presentation Overview

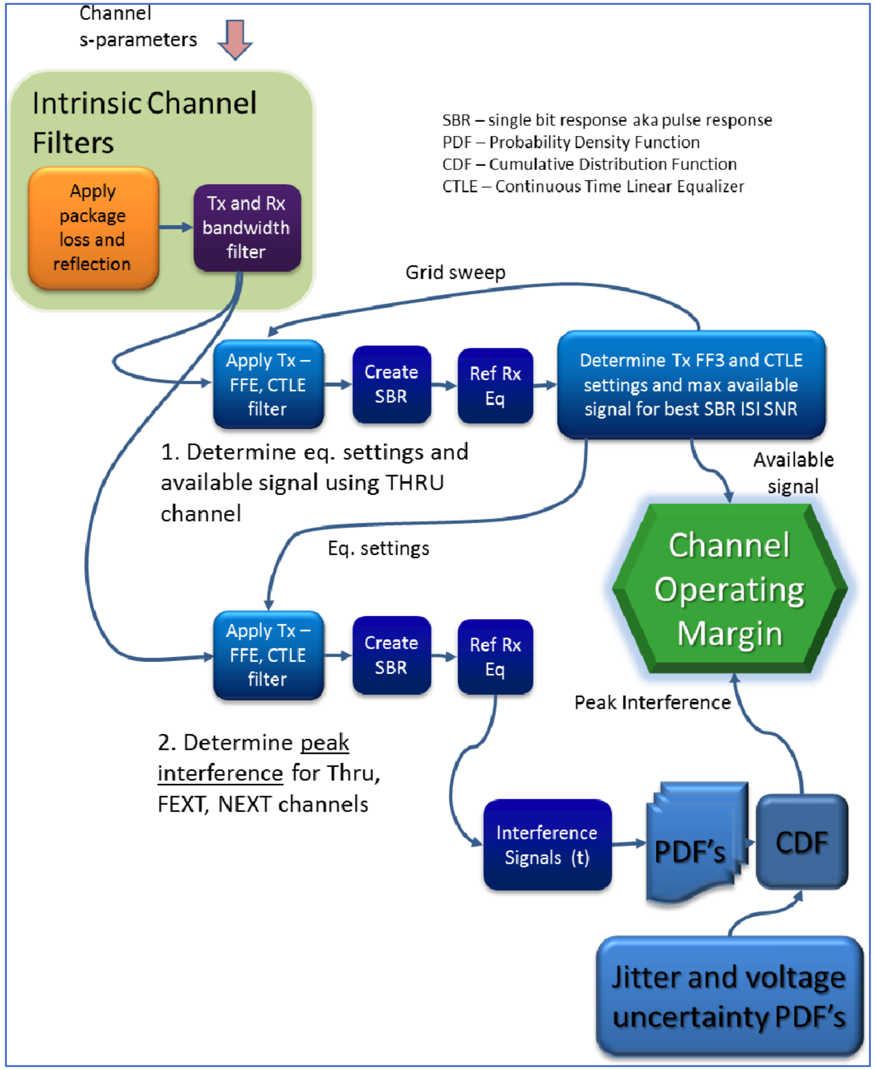
- Background on Problem Statement
- Results
- Call to Action
- Resolution
- Backup

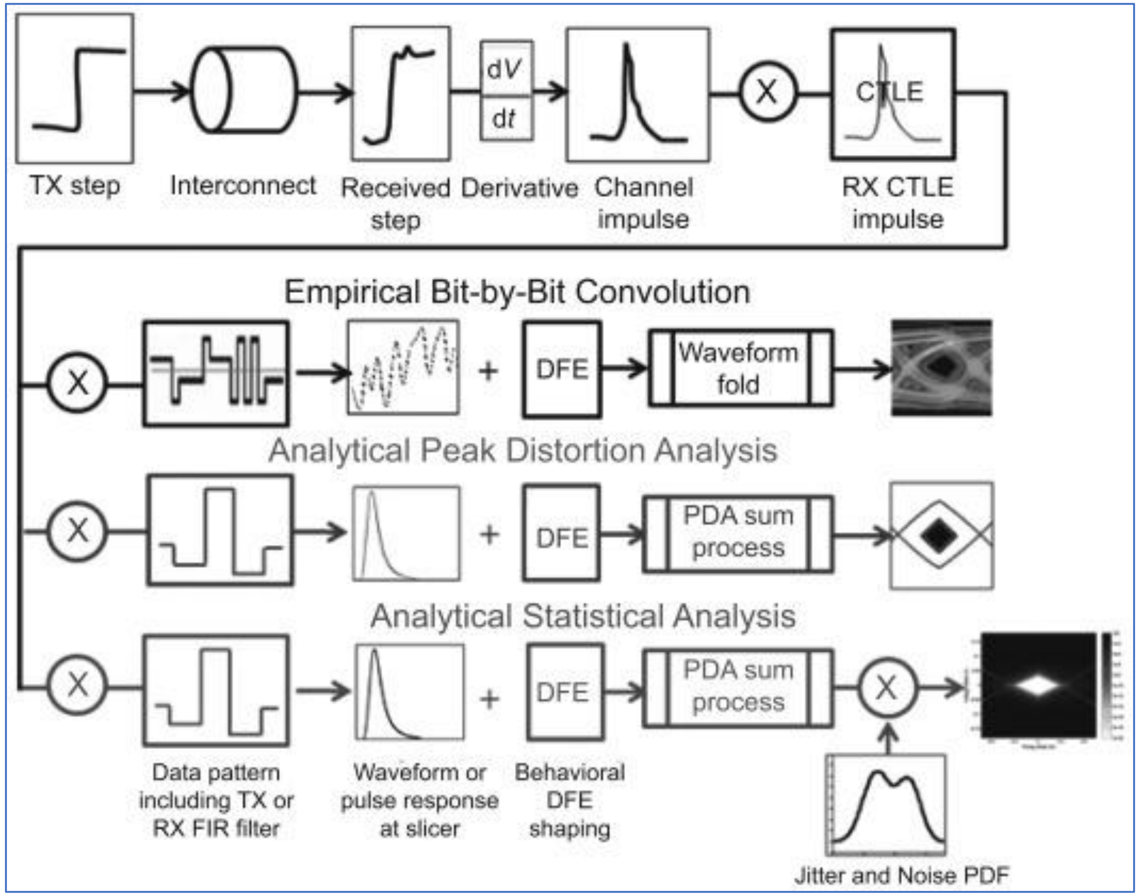
How IBIS-AMI Statistical Generates Eye Diagrams



IR = Impulse Response
PR = Pulse Response
SBR = Single Bit Response
PDF = Probability Density Function
UI = Unit Interval

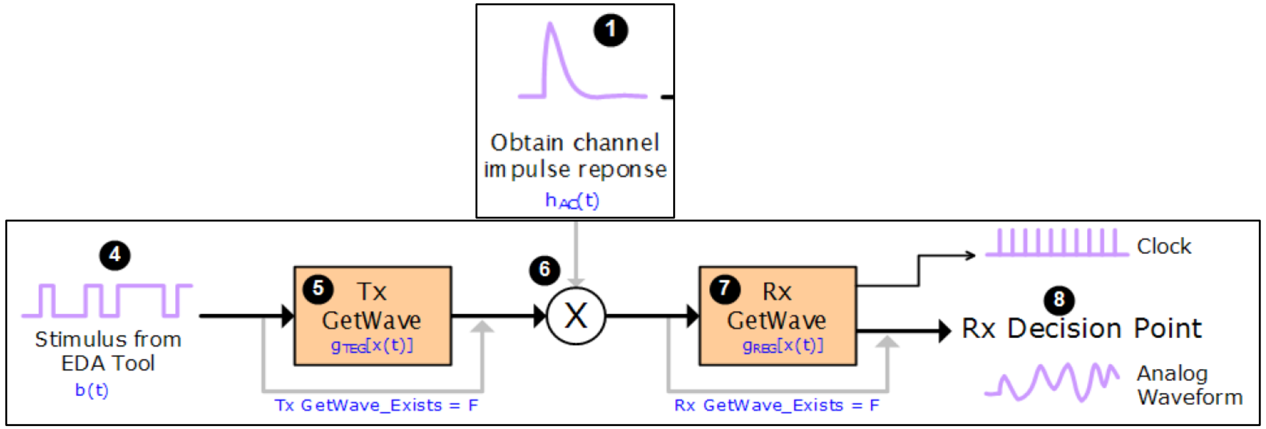
How Industry Methods Create Eye Diagrams



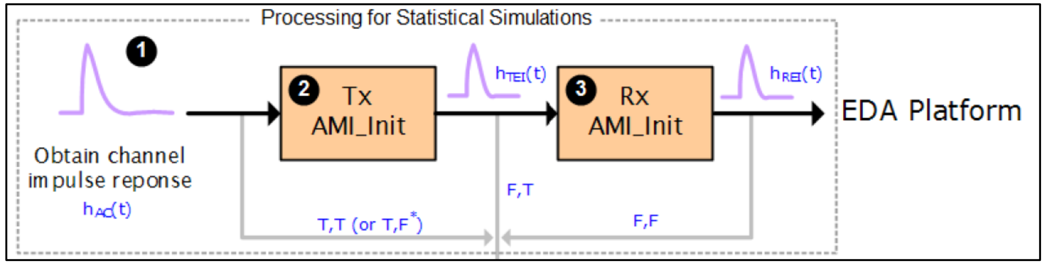


- https://www.sciencedirect.com/topics/computer-science/channel-impulse-response
- https://www.semanticscholar.org/paper/Channel-Operating-Margin-(COM)%3A-Evolution-of-for-25-Mellitz-Corp/7e9cb8b162fe93a131d37fa1408fb56d9e5b05f8

AMI Modeler's Control Over Sampling



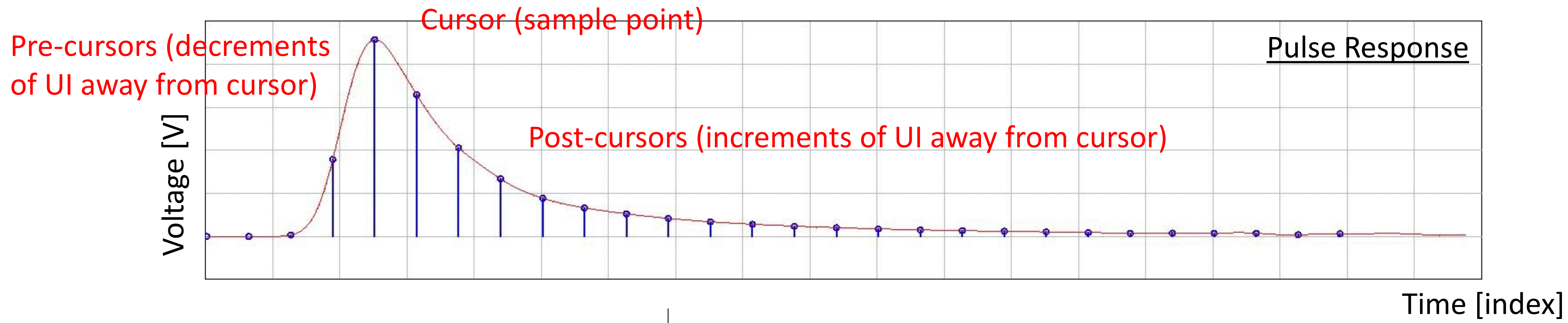

```
long AMI_GetWave (double *wave,
long wave_size,
double *clock_times,
char **AMI_parameters_out,
void *AMI_memory)
```




```
long AMI_Init (double *impulse_matrix,
long number_of_rows,
long aggressors,
double sample_interval,
double bit_time,
char *AMI_parameters_in,
char **AMI_parameters_out,
void **AMI_memory_handle,
char **msg)
```

- For AMI_GetWave simulation, the model developer can use clock_times to control where Rx output data is sampled.
- For AMI_Init simulation, there is no similar sampling point control.
- https://www.keysight.com/us/en/assets/7018-03143/application-notes/5990-9111.pdf

What Do We Mean by Sampling?



- Waveform may be somewhat continuous in time, but some things are applied at discrete sample points
  - DFE (decision-feedback equalization) slicer point.
  - Voltage margin.
  - Timing margin.

Examples of Types of Statistical Sampling:

1. Peak of pulse response – align the sampling clock as the **peak** of the pulse.
2. Mueller-Muller – align the sampling clock so that precursor ISI equals to post-cursor ISI.
3. Modified Mueller-Muller – modified version of the Mueller-Muller PD where the impact of first pre-cursor (pre-1) is removed.
4. Hula hoop algorithm – align the sampling clock based on half way between the transition times for a 010 data pattern in isolation.

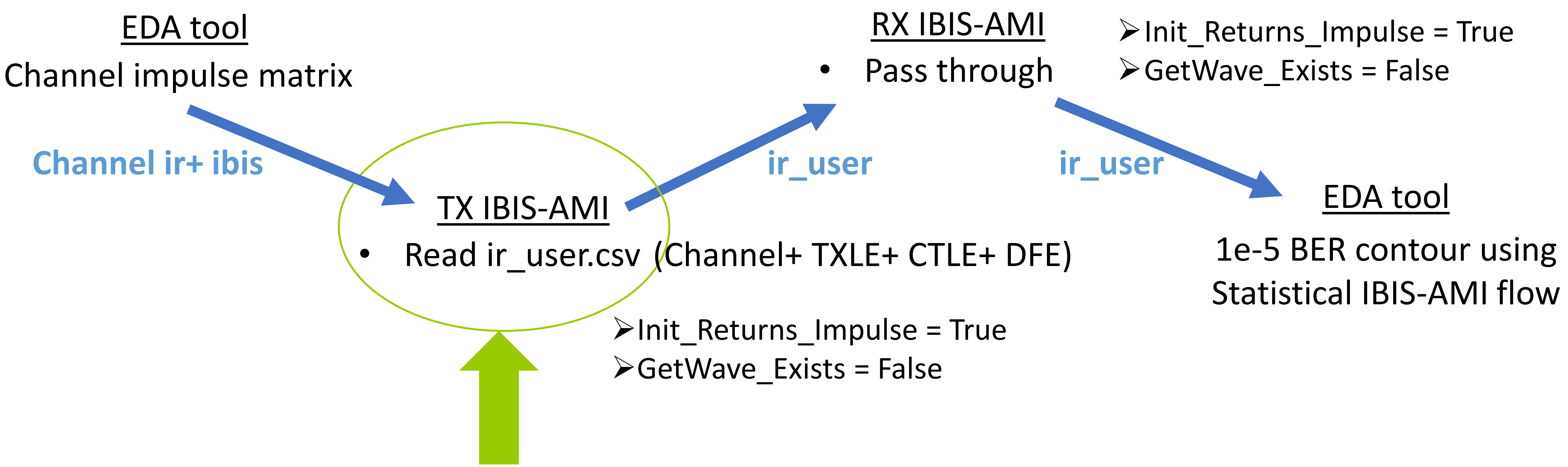
Do We Really Need Sampling Info from AMI_Init?

- Experiment 1: Statistical BER contour in different EDA tools.

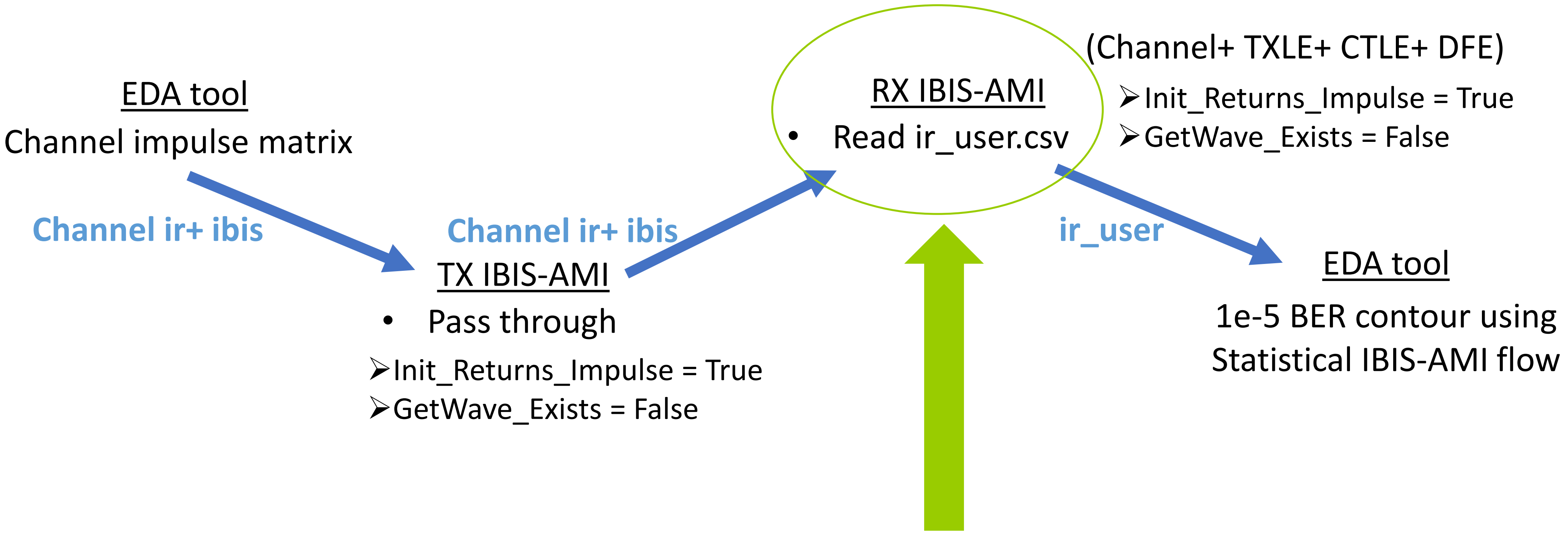
- Experiment 2: Importance of sampling position.
  Peak-of-pulse Phase vs. Mueller-Muller Phase Detectors (PDs)

- Experiment 3: Problem with timing margin.
  EDA tools must "guess" the sampling in statistical mode given the DFE is applied in the IBIS-AMI model

1. IBIS-AMI Simulation Setup



- The idea is to use a developed IBIS-AMI model which bypasses the impulse matrix from the EDA tool with that from a .csv.
- In this way, we set the same input in studying the statistical eye in different EDA tools.



- The idea is to use a developed IBIS-AMI model which bypasses the impulse_matrix from the EDA tool with that from a .csv.
- In this way, we set the same input in studying the statistical eye in different EDA tools.

2. IBIS-AMI Models Used

A. <u>TX IBIS-AMI</u>

- tx_read_ir.ibs
- tx_read_ir.ami
  - Init_Returns_Impulse= True; GetWave_Exists= False
  - read_ir= 1 (yes) and 0 (no); read_ir_filename= 'C:\ir.csv'
- tx_read_ir_x64.dll

B. <u>RX IBIS-AMI</u>

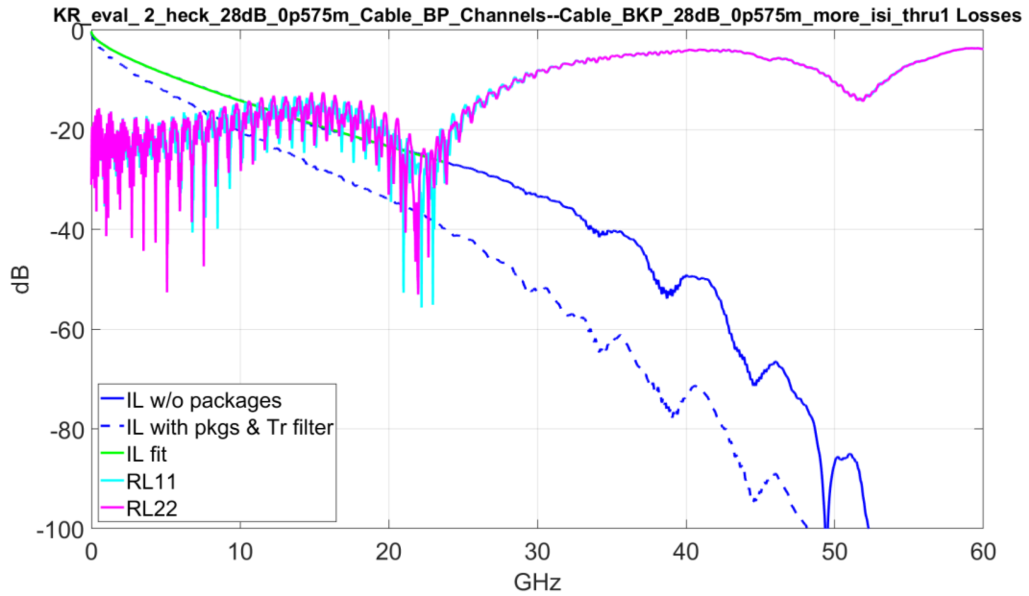
- rx_pass_through.ibs
- rx_pass_through.ami
  - Init_Returns_Impulse= True; GetWave_Exists= False
  - Gain= 1
- rx_pass_through_x64.dll

3. Simulation Setup

1. No jitter and noise!
2. No crosstalk!
3. No encoding (8b10b)!
4. Same impulse response input and plot the eye in different EDA tools!

1. Data Rate = 32 Gbps NRZ
2. Random pattern or PRBS Register Length = 31
3. 1e-5 BER eye contour using statistical IBIS-AMI flow
4. Samples per UI = 32
5. Channel is an .s4p - a dummy S-parameter, given an equalized impulse matrix will be brought in through a .csv at the TX
6. Equalized impulse_matrix.csv generated using the COM tool v2.76

4. Channel Response and Equalization



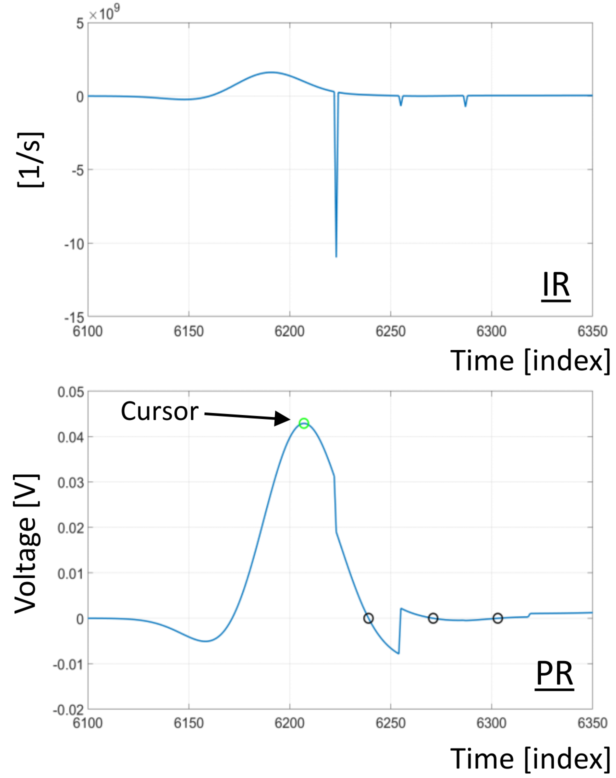
- Channel taken from IEEE 802.3 public area.
- -28.53 dB @ 16 GHz.

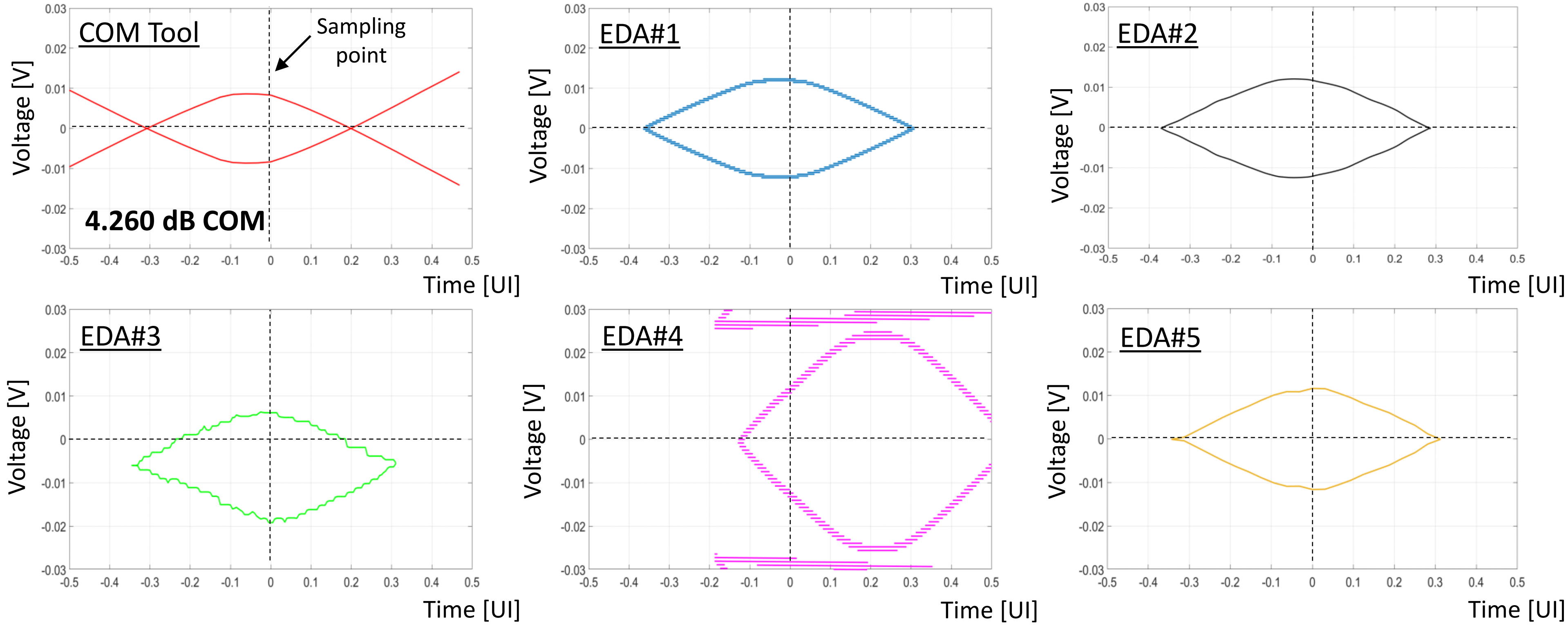
	A	B	C	D	E	F	G	H	I	J	K	L
1	Table 93A-1 parameters					I/O control				Table 93A–3 parameters		
2	Parameter	Setting	Units	Information		DIAGNOSTICS	1	logical		Parameter	Setting	Units
3	f_b	32	GBd			DISPLAY_WINDOW	1	logical		package_tl_gamma0_a1_a2	[0 0.002 0.0003]	
4	f_min	0.05	GHz			CSV_REPORT	1	logical		package_tl_tau	6.141E-03	ns/mm
5	Delta_f	0.01	GHz			RESULT_DIR	.\results\100GEL_1_PK_KR_{date}			package_Z_c	[87.5 87.5 ; 92.5 92.5]	Ohm
6	C_d	[1.2e-4 1.2e-4]	nF	[TX RX]		SAVE_FIGURES	0	logical		benartsi_3ck_01_0119 & mellitz_3ck_01_0119		
7	L_s	[0 0]	nH	[TX RX]		Port Order	[1 3 2 4]			Table 92–12 parameters		
8	C_b	[0 0]	nF	[TX RX]		RUNTAG	KR_eval_			Parameter	Setting	
9	z_p select	[2]		[test cases to run]		COM_CONTRIBUTION	0	logical		board_tl_gamma0_a1_a2	[0 3.8206e-04 9.5909e-05]	
10	z_p (TX)	[12 31; 1.8 1.8]	mm	[test cases]		Operational				board_tl_tau	5.790E-03	ns/mm
11	z_p (NEXT)	[12 29; 1.8 1.8]	mm	[test cases]		COM Pass threshold	3	dB		board_Z_c	100	Ohm
12	z_p (FEXT)	[12 31; 1.8 1.8]	mm	[test cases]		ERL Pass threshold	10.5	dB		z_bp (TX)	110.3	mm
13	z_p (RX)	[12 29; 1.8 1.8]	mm	[test cases]		DER_0	1.00E-05			z_bp (NEXT)	110.3	mm
14	C_p	[0.87e-4 0.87e-4]	nF	[TX RX]		T_r	6.16E-03	ns		z_bp (FEXT)	110.3	mm
15	R_0	50	Ohm			FORCE_TR	1	logical		z_bp (RX)	110.3	mm
16	R_d	[50 50]	Ohm	[TX RX]						C_0	[0.29e-4]	nF
17	A_v	0.415	V			TDR and ERL options				C_1	[0.19e-4]	nF
18	A_fe	0.415	V			TDR	1	logical		Include PCB	0	logical
19	A_ne	0.608	V			ERL	1	logical				
20	L	2				ERL_ONLY	0	logical		Floating Tap Control		
21	M	32				TR_TDR	0.01	ns		N_bg	0	0 1 2 or 3 groups
22	filter and Eq					N	3000			N_bf	0	taps per group
23	f_r	0.75	*fb			beta_x	2.3407E+09			N_f	0	UI span for floating taps
24	c(0)	0.54		min		rho_x	0.19			bmaxg	0.2	max DFE value for floating taps
25	c(-1)	[-0.1667]		[min:step:max]		fixture delay time	[0 0]	[port1 port2]		cable assemblies require this for each HCB		
26	c(-2)	[0]		[min:step:max]		TDR_W_TXPKG	0			ICN parameters (v2.73)		
27	c(-3)	[0]		[min:step:max]		N_bx	3	UI		f_f	21.448	
28	c(1)	[-0.0417]		[min:step:max]		Receiver testing				f_n	21.448	
29	N_b	3	UI			RX_CALIBRATION	0	logical		f_2	24.000	
30	b_max(1)	0.8				Sigma BBN step	5.00E-03	V		A_ft	0.600	
31	b_max(2..N_b)	0.3				Noise, jitter				A_nt	0.600	
32	g_DC	[-15]	dB	[min:step:max]		sigma_RJ	0	UI		heck_3ck_03b_0319	Adopted Mar 2019	
33	f_z	12.8	GHz			A_DD	0	UI		walker_3ck_01d_0719	Adopted July 2019	
34	f_p1	12.8	GHz			eta_0	8.2E-09	V^2/GHz		result of R_d=50		
35	f_p2	32	GHz			SNR_TX	100	dB		benartsi_3ck_01a_0719	no used for KR	
36	g_DC_HP	[0]		[min:step:max]		R_LM	1			mellitz_3ck_03_0919		
37	f_HP_PZ	0.4	GHz			CDR	Mod-MM	M or Mod-MM		under consideration		

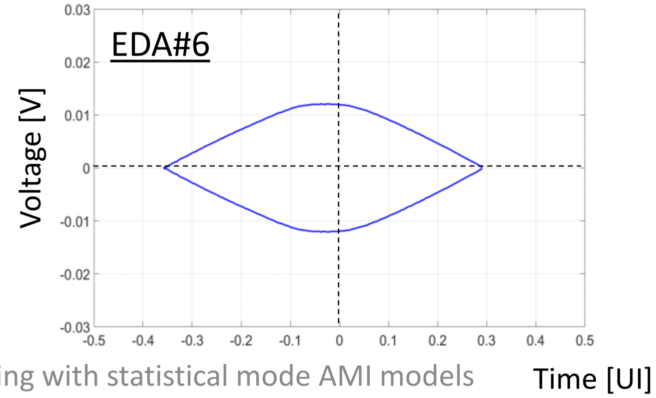
- COM ver2.75.
- Fixed TXLE, Fixed CTLE and 3-tap DFE.

Experiment 1 – Statistical BER contour in different EDA tool

1. TXLE+ CTLE+ DFE based on Peak of Pulse





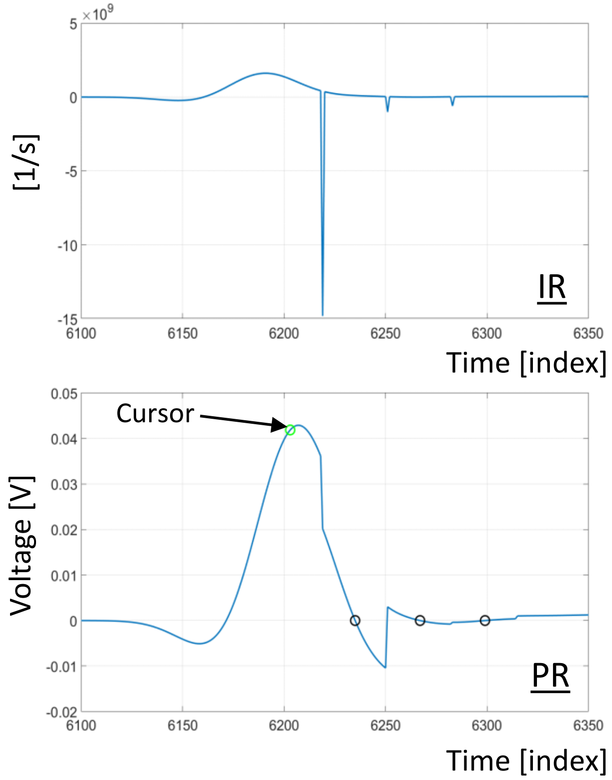


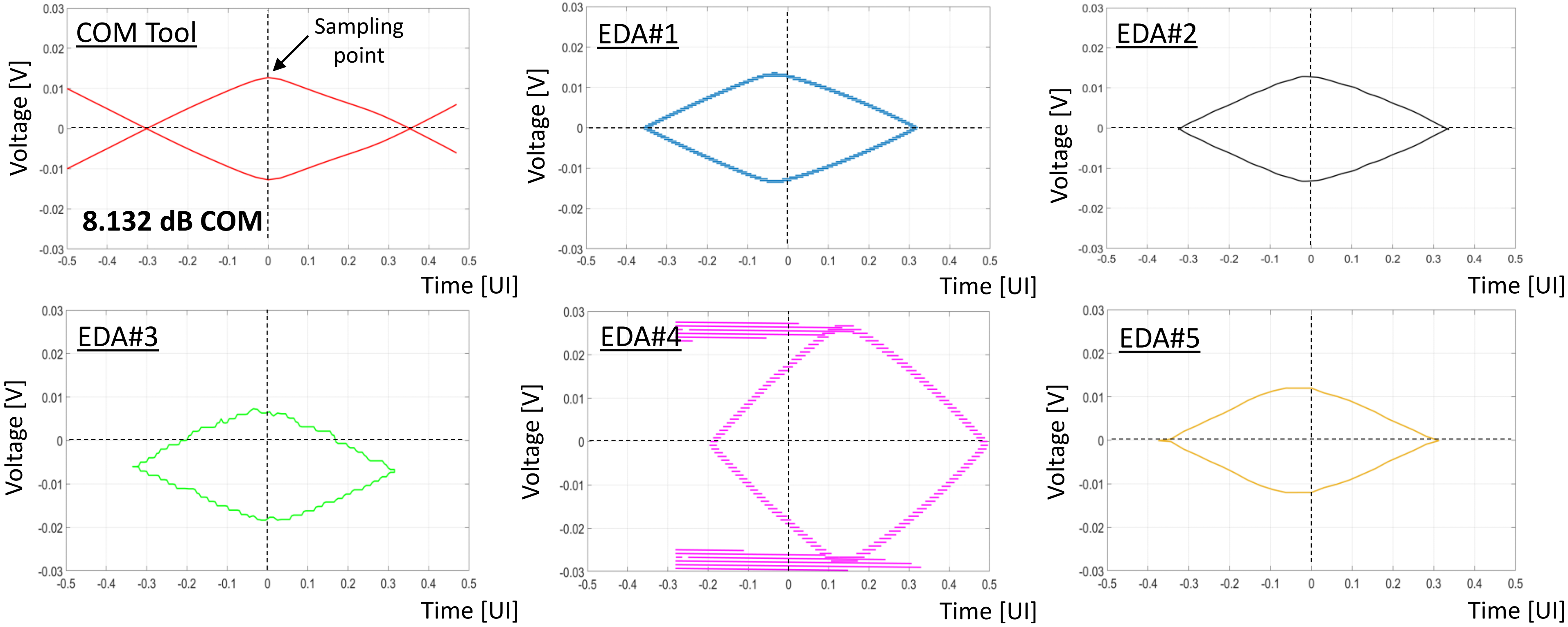
EDA tools showing significant differences in margin.

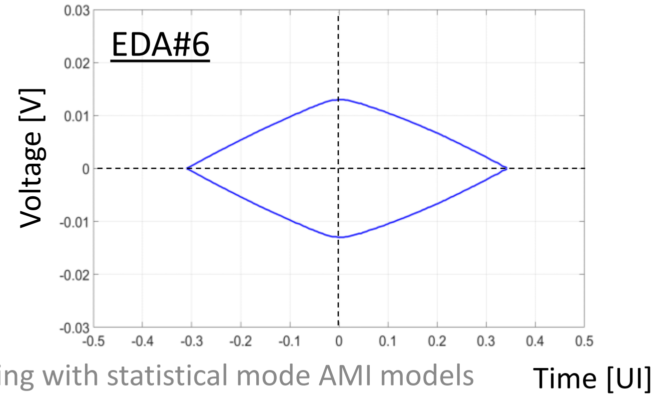
@BER 1e-5

Experiment 1 – Statistical BER contour in different EDA tool

2. TXLE+ CTLE+ DFE based on Mueller-Muller (MM) PD



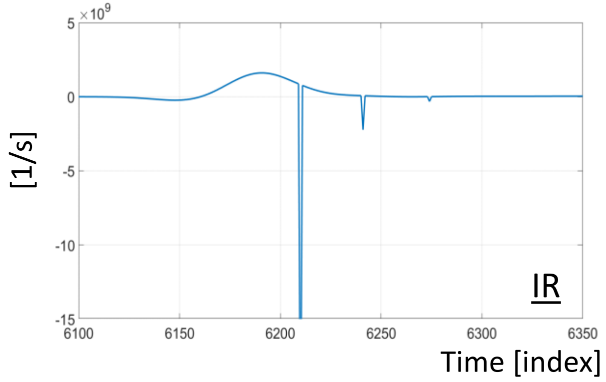


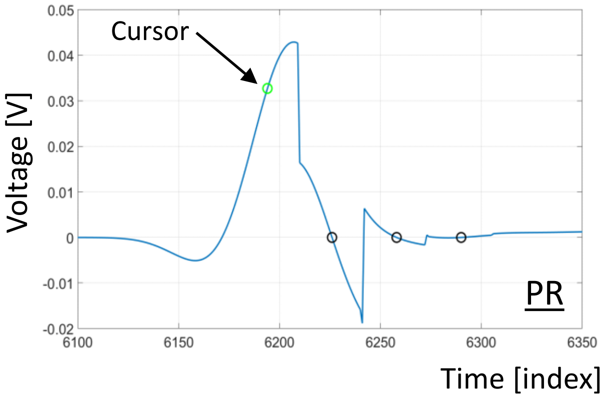


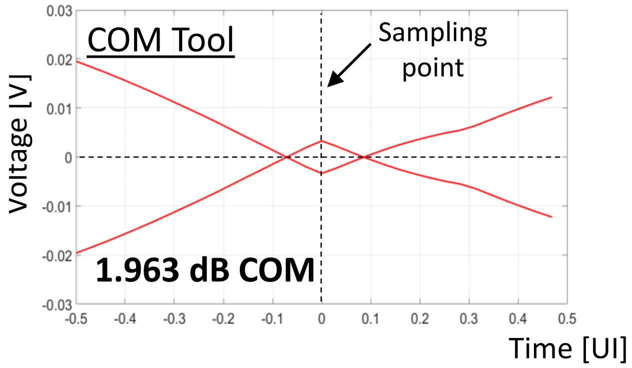
EDA tools showing significant differences in margin.

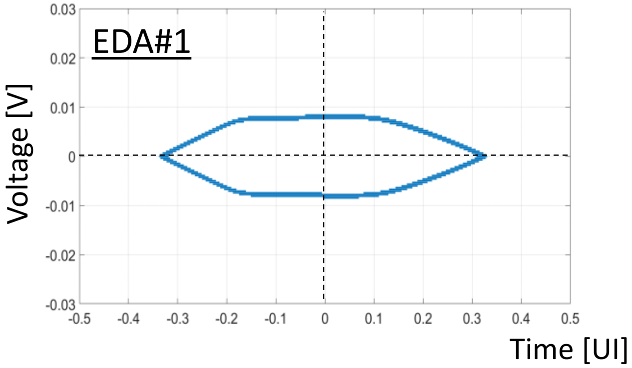
Experiment 1 – Statistical BER contour in different EDA tool

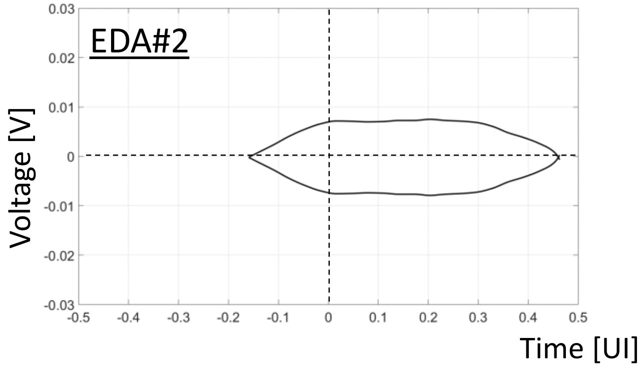
3. TXLE+ CTLE+ DFE based on modified Mueller-Muller (Mod-MM) PD

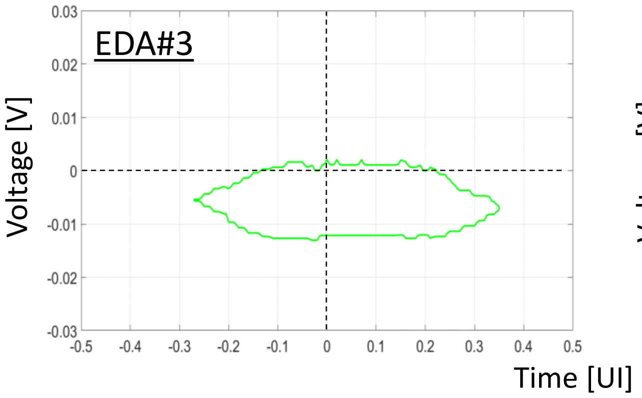


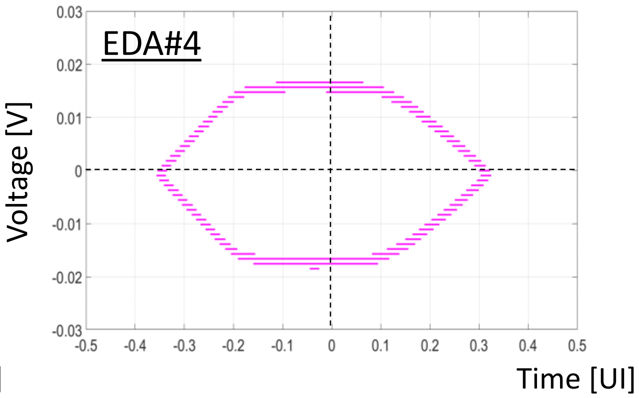


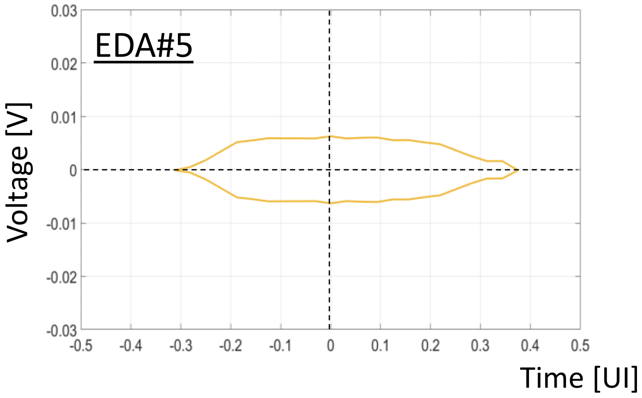


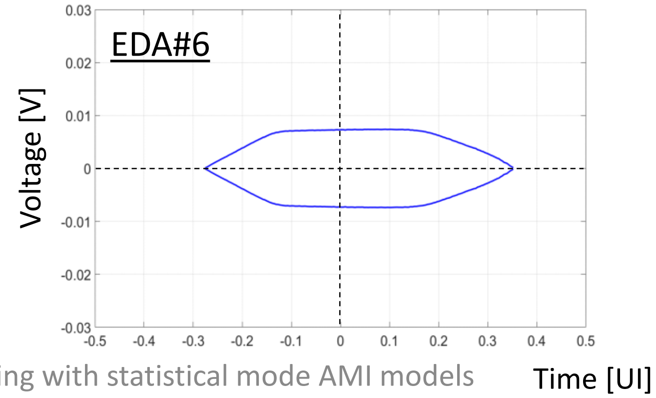










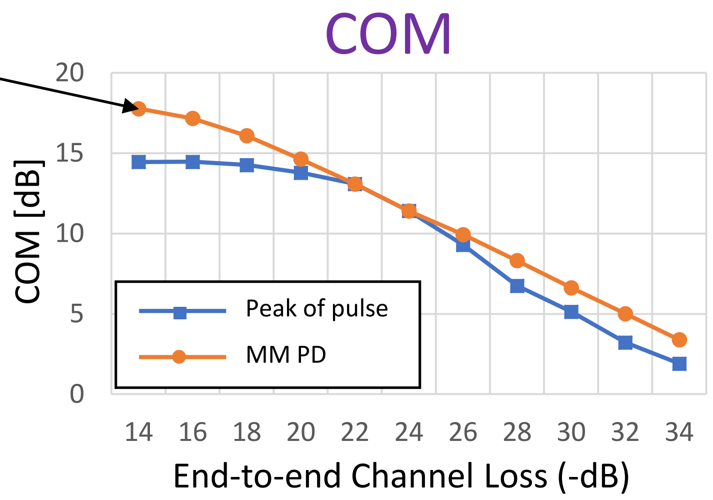


EDA tools showing significant differences in margin.

Experiment 2 – Importance of Sampling Position

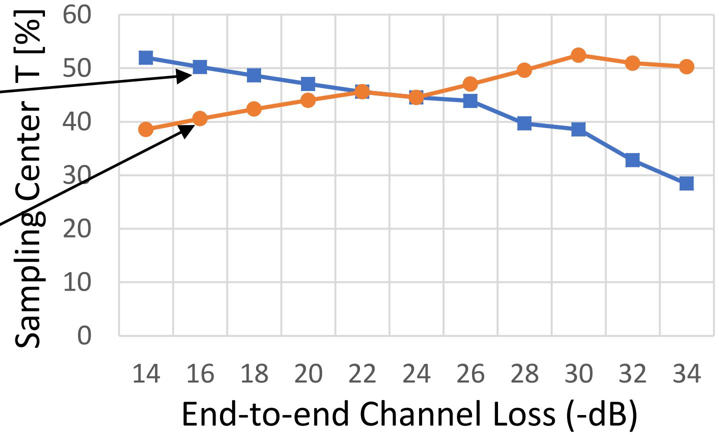
Peak-of-pulse Phase vs. Mueller-Muller Phase Detectors (PDs)

1. **MM PD outperforms peak-of-pulse PD**



2. **Peak-of-pulse PD fails to maintain a balanced eye for high loss cases**

3. **MM PD is able to retain a relatively balanced eye for a range of loss**



Sampling center T [%]

= 100*TM_L/(TM_L+ TM_R)

Experiment 2 – Importance of Sampling Position

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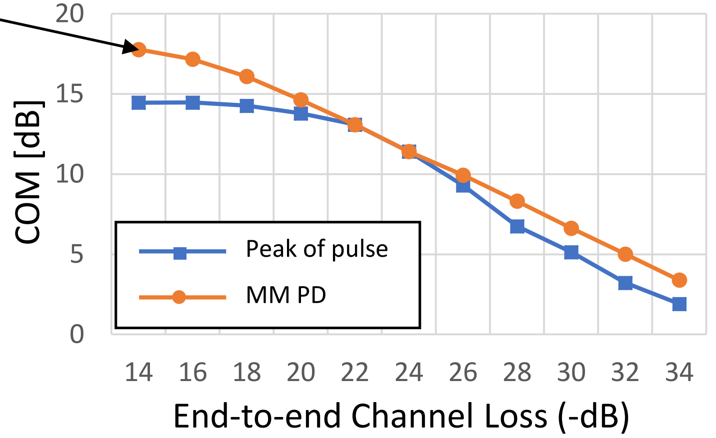
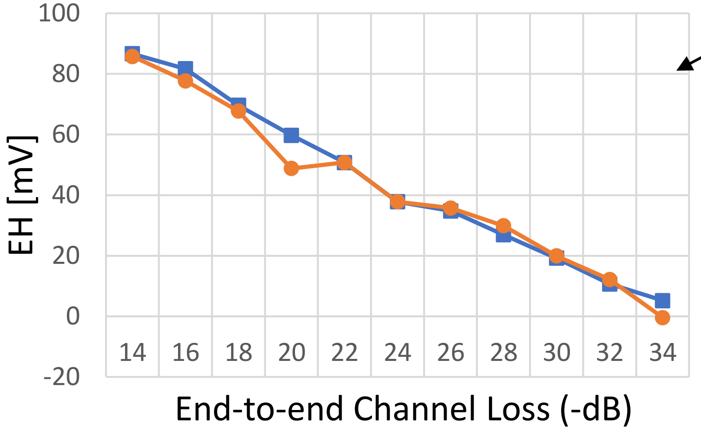
1. MM PD outperforms peak-of-pulse PD

COM



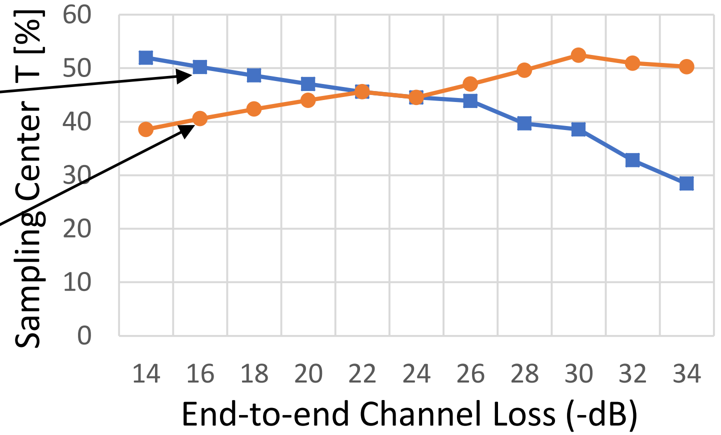
AMI_Init

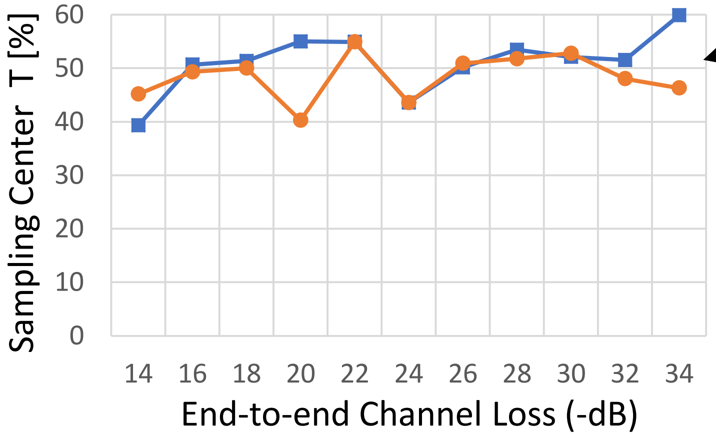


4. Statistical IBIS-AMI flow is not showing much difference in EH between the phase detectors

2. Peak-of-pulse PD fails to maintain a balanced eye for high loss cases

3. MM PD is able to retain a relatively balanced eye for a range of loss





5. Statistical IBIS-AMI flow is not able to model the sampling position

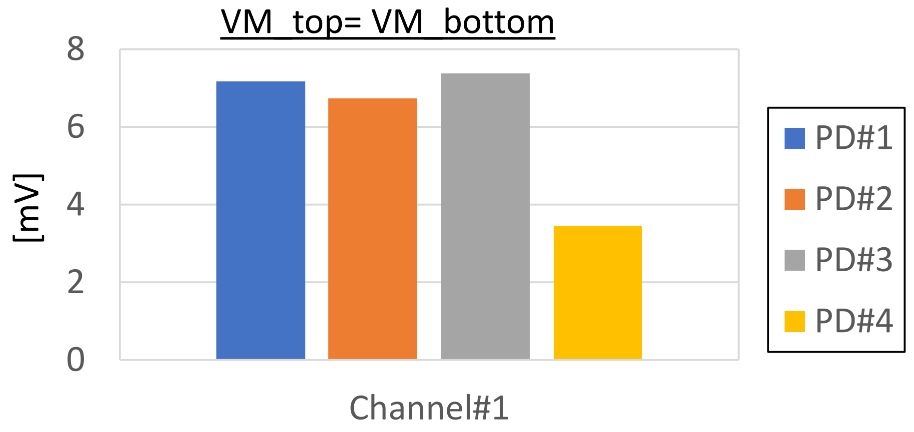
Sampling center T [%]

= 100*TM_L/(TM_L+ TM_R)

Experiment 3 – Problem with Timing Margin

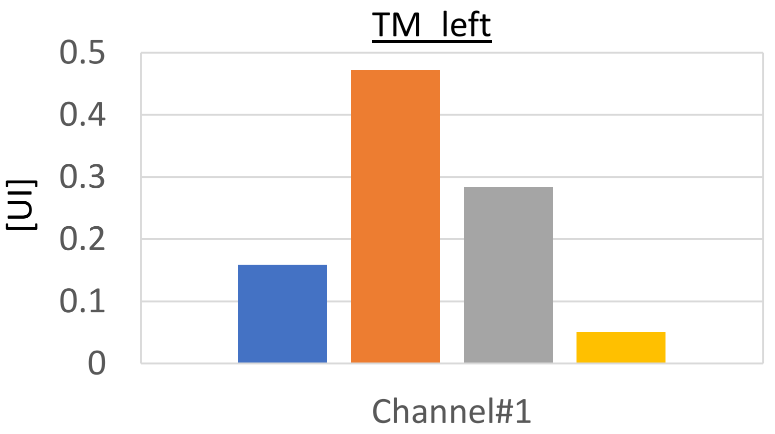
EDA tools must “guess” the sampling in statistical mode given the DFE is applied in the IBIS-AMI model.

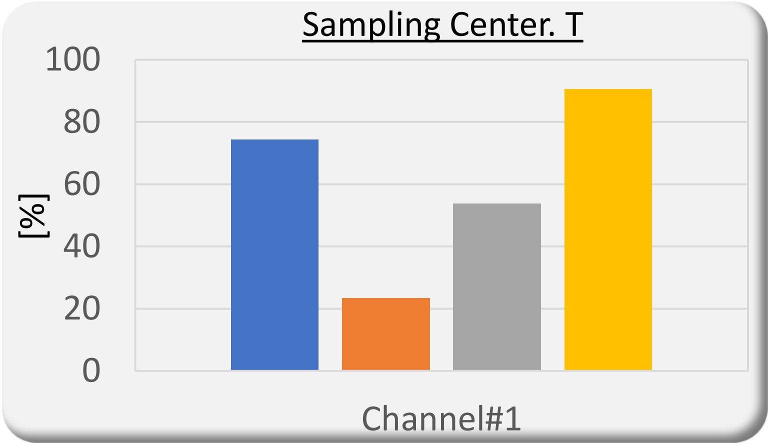
- Same equalized (TXLE+ CTLE+ DFE) impulse response.
- Four different phase detectors (PD).

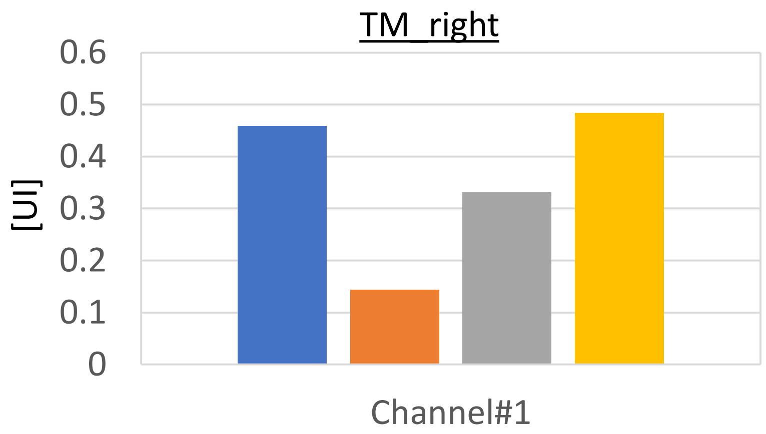


Sampling center T [%]

= 100*TM_L/(TM_L+ TM_R)







The use of different phase detectors shows varying timing margins even in the same EDA tool.

Call to Action

1. Statistical-mode-based simulations are widely used.
2. IBIS specification has a gap if we want IBIS-AMI to behave accurately to silicon design consistently across EDA tools. We should consider adding sampling point information to AMI_Init.

The Larger Question: Who controls the presentation & calculation of the eye?

Should not model-makers be able to represent silicon behavior completely, including sampling, in both statistical and time-domain modes?

Resolution

Why not follow the BIRD process? Some possible options we've come up with:

1. Sampling index from Rx AMI_Init
   - If simulator had sampling index returned from Rx AMI_Init, it would have information to align its sampling assumptions.
   - Sampling index would be similar in function as AMI_GetWave clock_times
2. Options from EDA tools on phase detectors
   - Simulator could give users different phase detector sampling controls in statistical mode.
3. Sampling extraction method from IR
   - Come up with an extraction methodology for simulators to use when determining sampling point in statistical mode.
4. AMI model to provide results directly
   - To ensure similar results due to the use of the AMI standard, allow models to report eyes, bathtub curves, etc.

Thank You

Backup Material

- Experiment2 channel building
- Peak Sampling
- Edge Detect Sampling
- Mueller-Muller Sampling
- Modified Mueller-Muller Sampling
- Hula Hoop Algorithm
- Unit Impulse Response Definition

Experiment 2 channel building

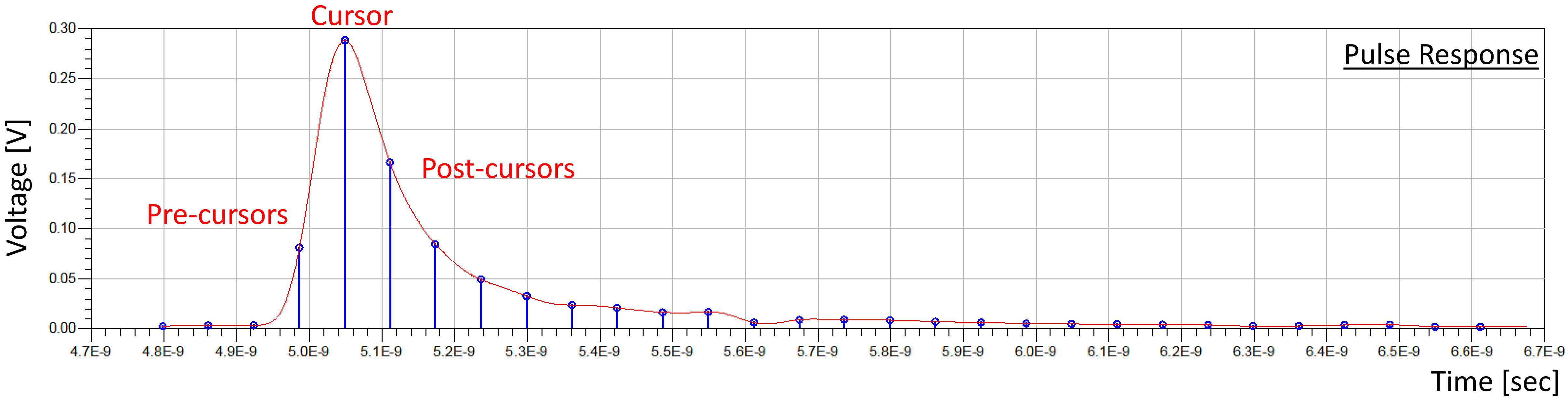
	A	B	C	D
1	Table 93A-1 parameters			
2	Parameter	Setting	Units	Information
3	f_b	32	GBd	
4	f_min	0.05	GHz	
5	Delta_f	0.01	GHz	
6	C_d	[1.2e-4 1.2e-4]	nF	[TX RX]
7	L_s	[0 0]	nH	[TX RX]
8	C_b	[0 0]	nF	[TX RX]
9	z_p select	[2]		[test cases to run]
10	z_p (TX)	[12 31; 1.8 1.8]	mm	[test cases]
11	z_p (NEXT)	[12 29; 1.8 1.8]	mm	[test cases]
12	z_p (FEXT)	[12 31; 1.8 1.8]	mm	[test cases]
13	z_p (RX)	[12 29; 1.8 1.8]	mm	[test cases]
14	C_p	[0.87e-4 0.87e-4]	nF	[TX RX]
15	R_0	50	Ohm	
16	R_d	[50 50]	Ohm	[TX RX]
17	A_v	0.415	V	
18	A_fe	0.415	V	
19	A_ne	0.608	V	
20	L	2		
21	M	32		
22	filter and Eq			
23	f_r	0.75	*fb	
24	c(0)	0.54		min
25	c(-1)	[-0.1667]		[min:step:max]
26	c(-2)	[0]		[min:step:max]
27	c(-3)	[0]		[min:step:max]
28	c(1)	[-0.0417]		[min:step:max]
29	N_b	3	UI	
30	b_max(1)	0.8		
31	b_max(2..N_b)	0.3		
32	g_DC	[-15]	dB	[min:step:max]
33	f_z	12.8	GHz	
34	f_p1	12.8	GHz	
35	f_p2	32	GHz	
36	g_DC_HP	[0]		[min:step:max]
37	f_HP_PZ	0.4	GHz	

	F	G	H
1	I/O control		
2	DIAGNOSTICS	1	logical
3	DISPLAY_WINDOW	1	logical
4	CSV_REPORT	1	logical
5	RESULT_DIR	.\results\100GEL_1_PK_KR_{date}	
6	SAVE_FIGURES	0	logical
7	Port Order	[1 3 2 4]	
8	RUNTAG	KR_eval_	
9	COM_CONTRIBUTION	0	logical
10	Operational		
11	COM Pass threshold	3	dB
12	ERL Pass threshold	10.5	dB
13	DER_0	1.00E-12	
14	T_r	6.16E-03	ns
15	FORCE_TR	1	logical
16			
17	TDR and ERL options		
18	TDR	1	logical
19	ERL	1	logical
20	ERL_ONLY	0	logical
21	TR_TDR	0.01	ns
22	N	3000	
23	beta_x	2.3407E+09	
24	rho_x	0.19	
25	fixture delay time	[0 0]	port1 port2]
26	TDR_W_TXPKG	0	
27	N_bx	3	UI
28	Receiver testing		
29	RX_CALIBRATION	0	logical
30	Sigma BBN step	5.00E-03	V
31	Noise, jitter		
32	sigma_RJ	0	UI
33	A_DD	0	UI
34	eta_0	8.2E-09	V^2/GHz
35	SNR_TX	100	dB
36	R_LM	1	
37	CDR	PK	M or Mod-MM

	J	K	L
1	Table 93A–3 parameters		
2	Parameter	Setting	Units
3	package_tl_gamma0_a1_a2	[0 0.002 0.0003]	
4	package_tl_tau	6.141E-03	ns/mm
5	package_Z_c	[87.5 87.5 ; 92.5 92.5]	Ohm
6	benartsi_3ck_01_0119 & mellitz_3ck_01_0119		
7	Table 92–12 parameters		
8	Parameter	Setting	
9	board_tl_gamma0_a1_a2	[0 3.8206e-04 9.5909e-05]	
10	board_tl_tau	5.790E-03	ns/mm
11	board_Z_c	100	Ohm
12	z_bp (TX)	110.3	mm
13	z_bp (NEXT)	110.3	mm
14	z_bp (FEXT)	110.3	mm
15	z_bp (RX)	110.3	mm
16	C_0	[0]	nF
17	C_1	[0]	nF
18	Include PCB	1	logical
19			
20	Floating Tap Control		
21	N_bg	0	0 1 2 or 3 groups
22	N_bf	0	taps per group
23	N_f	0	UI span for floating taps
24	bmaxg	0.2	max DFE value for floating taps
25	cable assemblies require this for each HCB		
26	ICN parameters (v2.73)		
27	f_f	21.448	
28	f_n	21.448	
29	f_2	24.000	
30	A_ft	0.600	
31	A_nt	0.600	
32	heck_3ck_03b_0319	Adopted Mar 2019	
33	walker_3ck_01d_0719	Adopted July 2019	
34	result of R_d=50		
35	benartsi_3ck_01a_0719	no used for KR	
36	mellitz_3ck_03_0919		
37	under consideration		

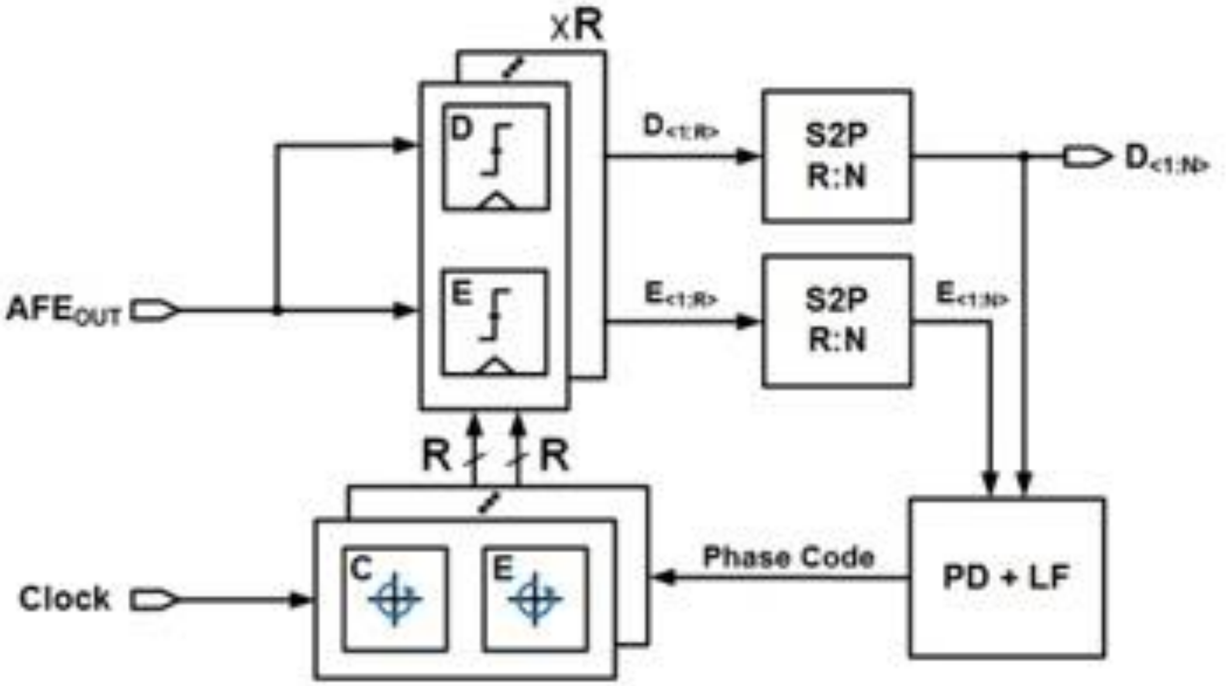
- Scaled z_bp in targeting a certain loss.

Peak sampling



- Cursor value is selected at peak of pulse response
- Pre-cursor = cursor – UI
- Post-cursor = cursor + UI

Edge Detect Phase Detector



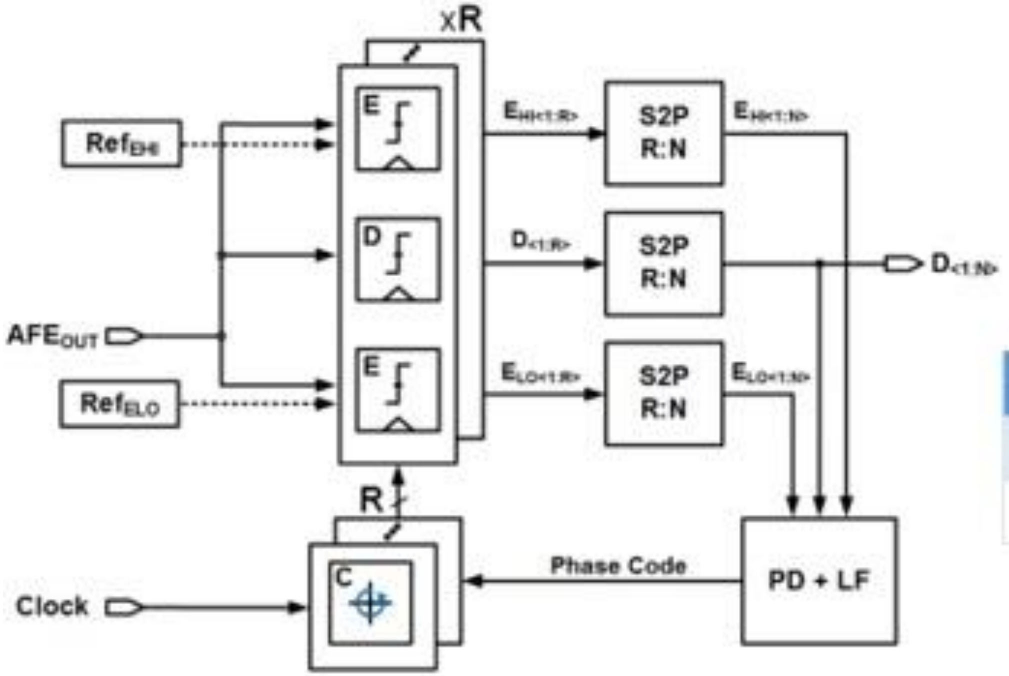
PD Logic

D_N	E_N	D_{N+1}	PD_{OUT}
0	0/1	1	Early/Late
1	0/1	0	Late/Early

Figure 19: R-rate receiver architecture for center sampling using BB-PD

https://www.signalintegrityjournal.com/articles/1293-methodology-for-performance-comparison-of-center-and-edge-sampling-in-serial-links?page=2

MM Phase Detector



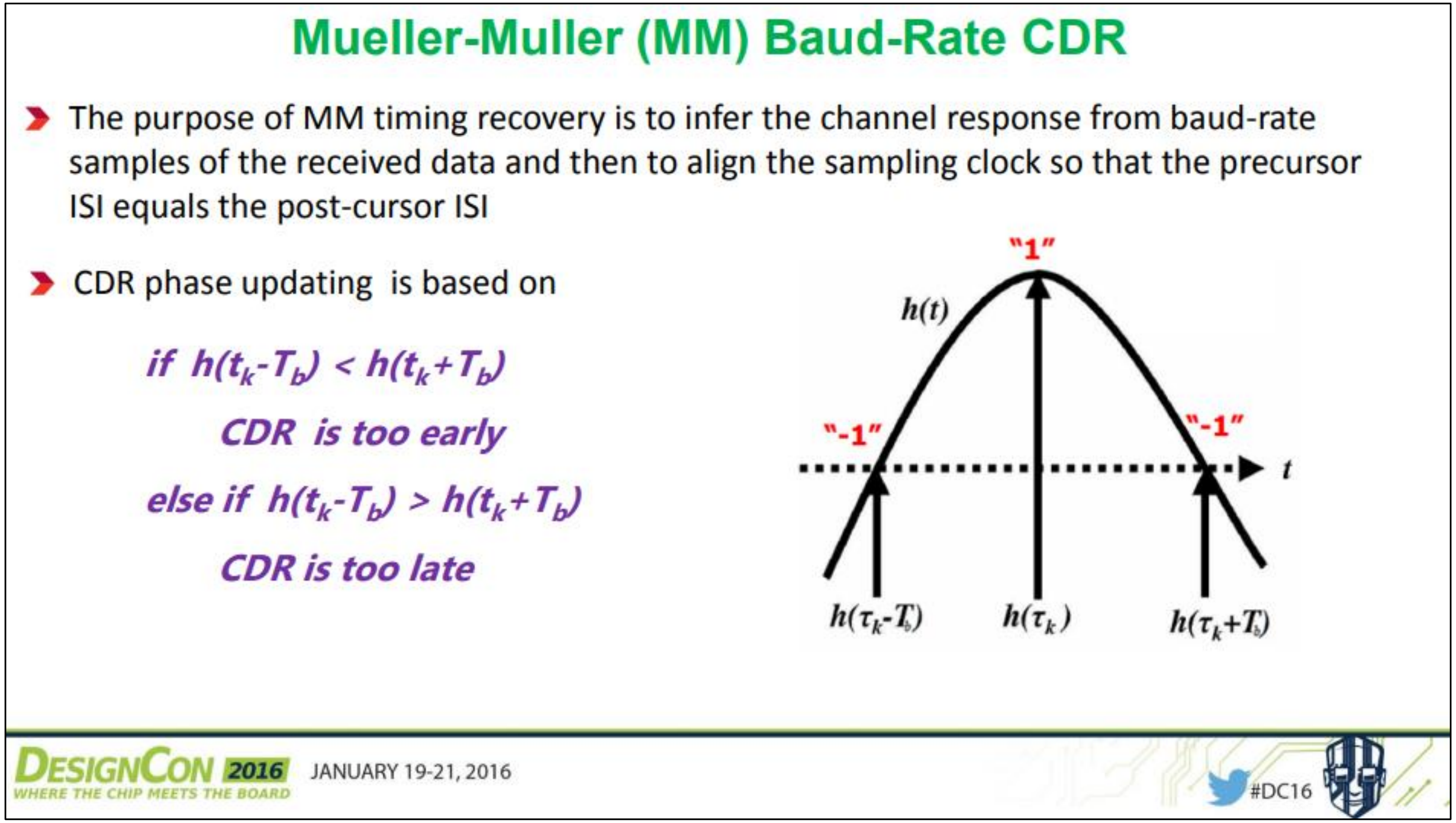
PD Logic

D_N	D_{N+1}	E_N	E_{N+1}	PD_{OUT}
0	1	-1/0	0/+1	Early/Late
1	0	+1/0	0/-1	Late/Early

Figure 20: R-rate receiver architecture for center sampling using MM-PD

https://www.signalintegrityjournal.com/articles/1293-methodology-for-performance-comparison-of-center-and-edge-sampling-in-serial-links?page=2

http://www.ieee802.org/3/ck/public/adhoc/dec12_18/lu_3ck_adhoc_01_121218.pdf



H. Zhang et al., “PAM4 Signaling for 56G Serial Link Applications – A Tutorial“, DesignCon 2016.

F. Spagna *et al*., "A 78mW 11.8Gb/s serial link transceiver with adaptive RX equalization and baud-rate CDR in 32nm CMOS," *2010 IEEE International Solid-State Circuits Conference - (ISSCC)*, San Francisco, CA, 2010, pp. 366-367.

Modified Mueller-Muller (Mod-MM) Phase Detector

MM-PD : $h(t_s - Tb) = h(t_s + Tb) - h(t_s)b(1)$, Annex(93A)

Modified PD : $0 = h(t_s + Tb) - h(t_s)b(1)$, Remove the impact of pre-1 cursor (New).

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Where,
b(1) is the DFE magnitude, first coefficient

Comparison of COM reference receivers with different configurations

#	A: DFE n-tap DFE		B: FFE-lite 'm-pre & 0-post' FFE + n-tap DFE			C: FFE-heavy 'm-pre & n-post' FFE + 1-tap DFE
Sampling Phase	MM-PD	MM-PD/ Modified PD	MM-PD	Modified PD	Modified PD	Do not care.
b_max	0.7	1.0	0.7	0.7	0.6	0.7
Performance	Lowest ✗	Low ✗	High ✓	High ✓	High ✓	High ✓
Control of b(1)	Good 0.7~0.8	Better ~0.7	Worst 0.8~1.1 ✗	Good 0.73~0.86	Better 0.65~0.74 ✓	Best =0.7 ✓
Correlation with others	Less COM correlation with FFE-based receivers ✗		Highly correlated with each other ✓			
Support C2M FFE receiver	No ✗	No ✗	Yes (set b_max=0, and adjust FFE configuration.) ✓			Yes (set b_max=0) ✓
DFE error propagation modeling complexity	High	High	High	High	High	Low
Post-FEC performance	Low?	Low?	Low?	Low?	Low?	High
Implementation Compliance	Good	Good	Low	Low	Low	High
Implementation Complexity	Low	Low	High	High	High	Low

- DFE based receiver has performance concern, even removes the 'b_max=0.7' constrain.
- Modified PD is recommended to achieve better b(1) control for FFE-lite and DFE receivers.
- Both FFE-lite and FFE-heavy are usable as COM reference receiver, the correlations of these two receivers are high.

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http://www.ieee802.org/3/ck/public/adhoc/dec12_18/lu_3ck_adhoc_01a_121218.pdf

Hula Hoop algorithm

Figure 6 illustrates the procedure as applied in a waveform viewer. This procedure only takes a minute or two, and is quite precise.

1. The user starts by placing two vertical markers exactly one UI apart in a position that straddles the main pulse.
2. The user places a horizontal marker that is centered between the points where the vertical markers intersect the pulse response.
3. The user shifts both vertical markers to approximately the intersection of the horizontal marker with the pulse response, while keeping them exactly one UI apart.
4. Steps 2 and 3 are repeated until both the vertical markers and horizontal marker intersect the pulse response while the vertical markers have remained one UI apart.
5. The recovered clock time is half way between the two vertical markers. This recovered clock time and times before and after that are an integer number of UI away are the times at which the intersymbol interference is to be evaluated.

http://siguys.com/wp-content/uploads/2016/01/2016_DesignCon_NewTechniquesPerformanceTuning.pdf

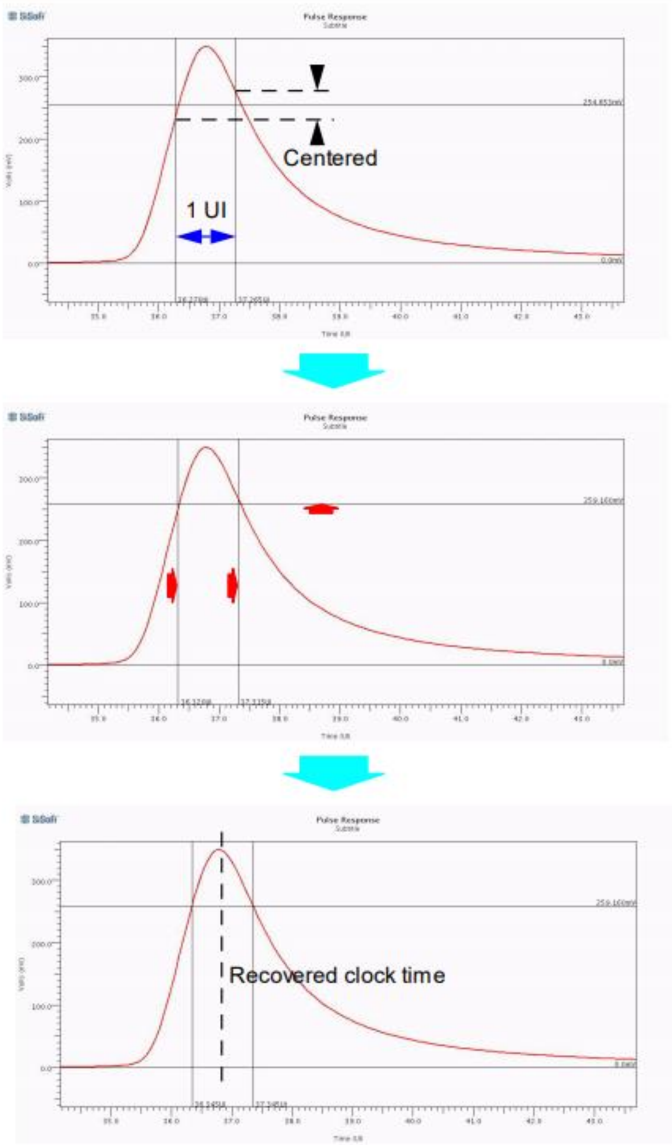
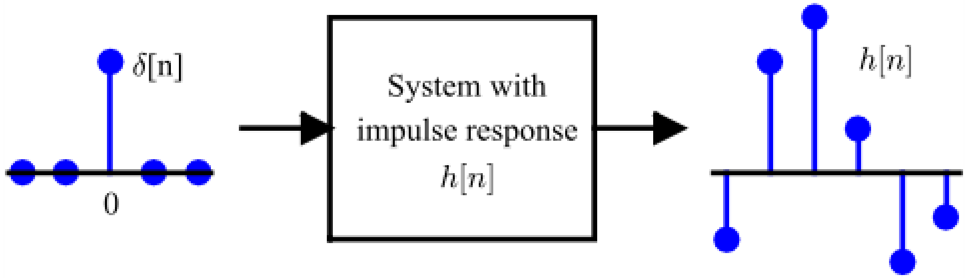
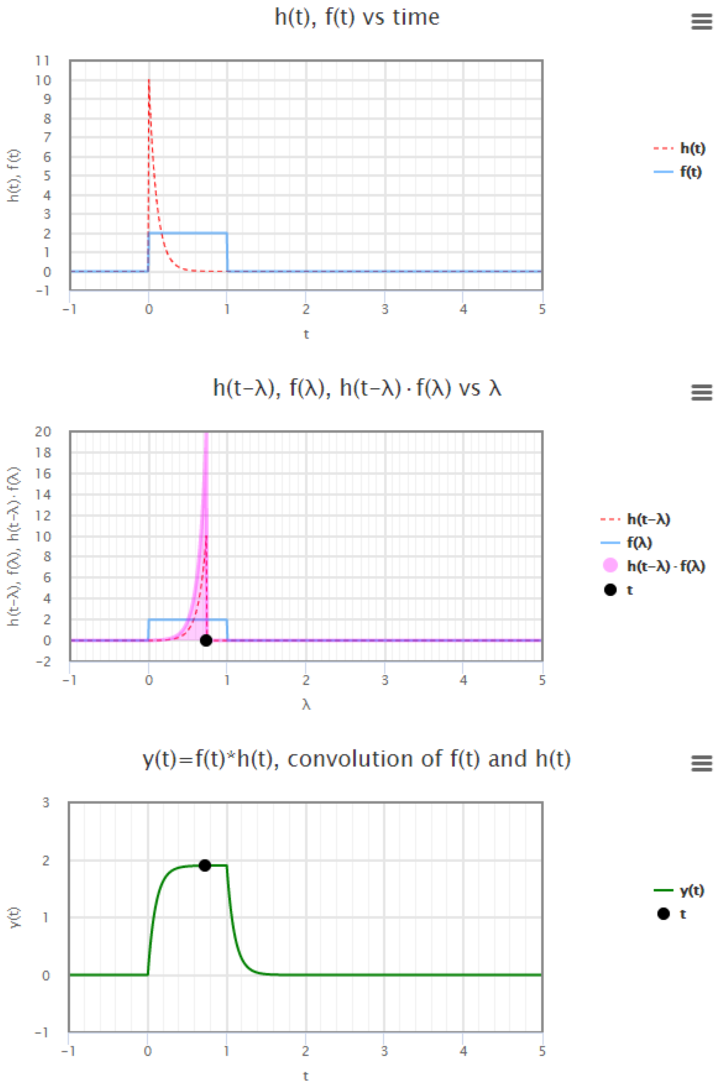


Figure 6: Hula Hoop Algorithm as Implemented in a Waveform Veiwer

10

Unit Impulse Response definition





- The derivate of the unit step function is the unit impulse function.
- The impulse response of a system is important because the response of a system to any arbitrary input can calculated from the system impulse response using a convolution integral.
- Units of the unit impulse are 1/s (i.e., inverse seconds). If system input has units of volts then we must implicitly multiply the unit impulse by its area, or 1V-s.
- It is important to keep in mind that the impulse response of a system is a zero state response (i.e., all initial conditions equal to zero at t=0-).
- https://lpsa.swarthmore.edu/Transient/TransInputs/TransImpulseTime.html
- https://lpsa.swarthmore.edu/Convolution/CI.html