11/18/2022

A Path toward Incorporating Advanced Signal Processing in Electrical Channel Performance Assessment

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November 15, 2022

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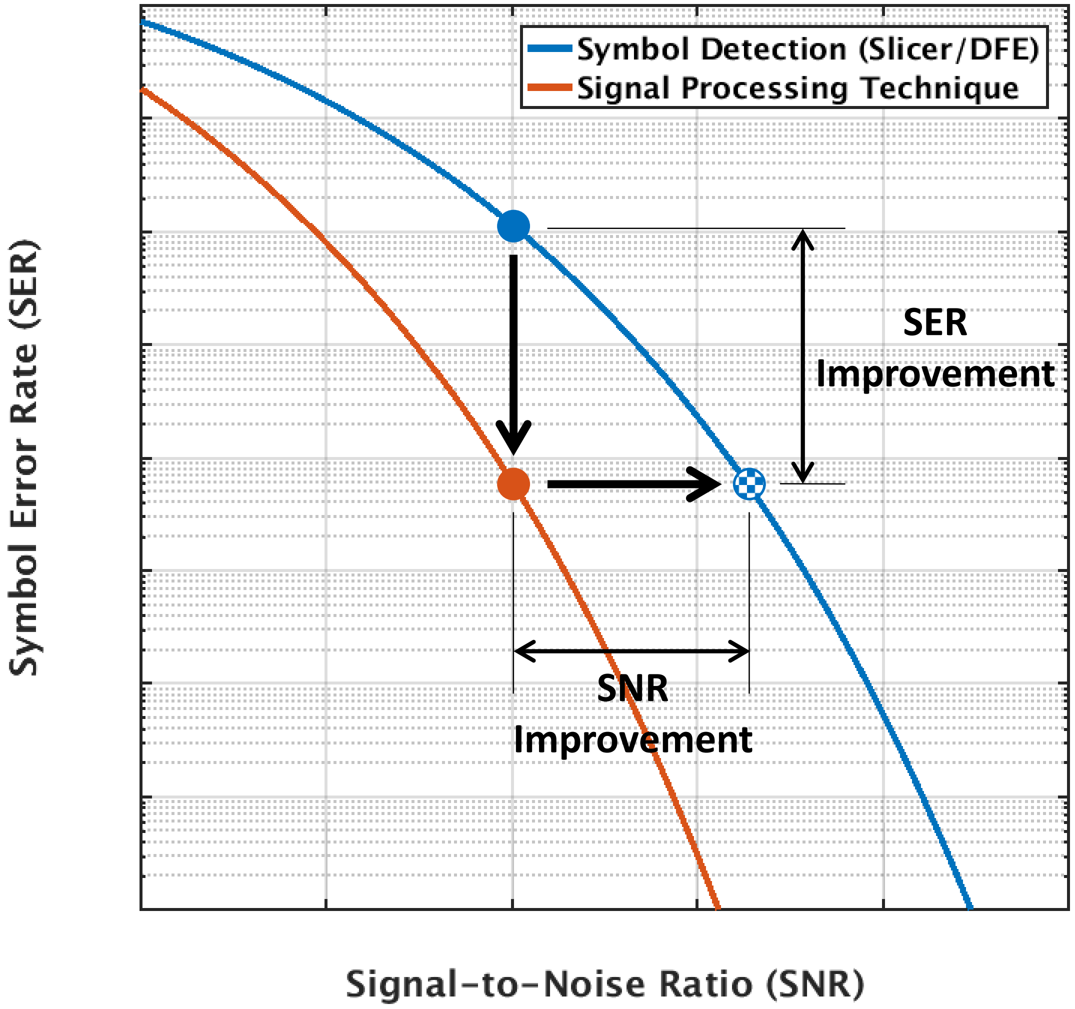
Motivation

- Justification for equipping COM with enhanced capabilities was introduced in brown_3df_02_2211
- COM limits processing capabilities in the receiver to CTLE and DFE
- As rates continue to increase and margins shrink, more processing power is needed
- Maximum-Likelihood Sequence Estimation/Detection (MLSE/MLSD) is an immediate example
- COM analysis is statistical-based and faces challenges with incorporating time-based processing techniques (e.g. sequence processing in time)
- This contribution proposes a method for incorporating MLSE in COM analysis and provides a path for extension to other processing techniques
- To enable the capability, simple updates are suggested to be made to COM
- In order to handle increased challenges for performance assessment, the proposed changes are deemed organic and inevitable

Explaining the General Idea

- COM handles performance analysis of symbol detection (i.e. slicer or DFE) based on statistical eye analysis at sampling point
- If performance effect of a signal processing technique can be translated to an equivalent symbol detection, the same statistical eye analysis can be applied to mimic the effect
- This provides a path forward by incrementally adding capabilities on the existing COM platform
- In most cases, performance of the signal processing technique can be obtained by analysis (COM is also based on analysis)



Case Studies

- Consider MLSE processing and application of the idea to few wireline examples

Channel	Variant	IL [dB] @ 56GHz	ILD [dB]
Huawei C2M Bump-to-Bump	Channel 1	29.5	1.33
	Channel 2	28.4	1.01
	Channel 3	28.7	1.47
	Channel 4	28.2	1.43
Samtec LR DAC oif2022.194.00	Case 1	27.0	0.93
	Case 2	24.4	0.96
	Case 3	29.5	0.96
	Case 4	32.0	1.12
TE CR DAC oif2022.313.01	Conventional	33.0	1.49
	CPP	21.8	1.55
	NCC	28.3	1.71

Link Parameters

Channel	Bit Rate [Gb/s]	Thru Swing [mV]	Fext Swing [mV]	Next Swing [mV]	TX FIR [Pre / Post]	Die Model C_d [fF] L_s [pH]	C_b [fF]	Package [mm] [Ω]	RX Filter BW	CTLE Pole/Zero Ratio	DFE [# of Taps]	RX FFE [Pre / Post]	TX SNR [dB]	RX Noise [V^2/GHz]	Jitter Rand / DD [UI]	k_N *
Huawei	224	413	413	608	3 / 1	40/90/110 130/150/140	Included in the model	Included in the model	0.75 x f_b	80 / 2.5 / 1	1	6 / 8	32.5	4.1E-8 x k_N	0.01 / 0.02	6
Samtec	224	442	442 x k_N	608 x k_N	3 / 1	40/90/110 130/150/140	30	30 92.5	0.75 x f_b	100 / 2.5 / 1	1	0 / 24	33 - $20\log_{10}(k_N)$	4.1E-8 x k_N^2	0.01 / 0.02 x k_N	2
TE	224	413	413 x k_N	608 x k_N	3 / 1	40/90/110 130/150/140	30	30 92.5	0.75 x f_b	80 / 2.5 / 1	1	0 / 24	33 - $20\log_{10}(k_N)$	4.1E-8 x k_N^2	0.01 / 0.02 x k_N	1 / 2 / 1

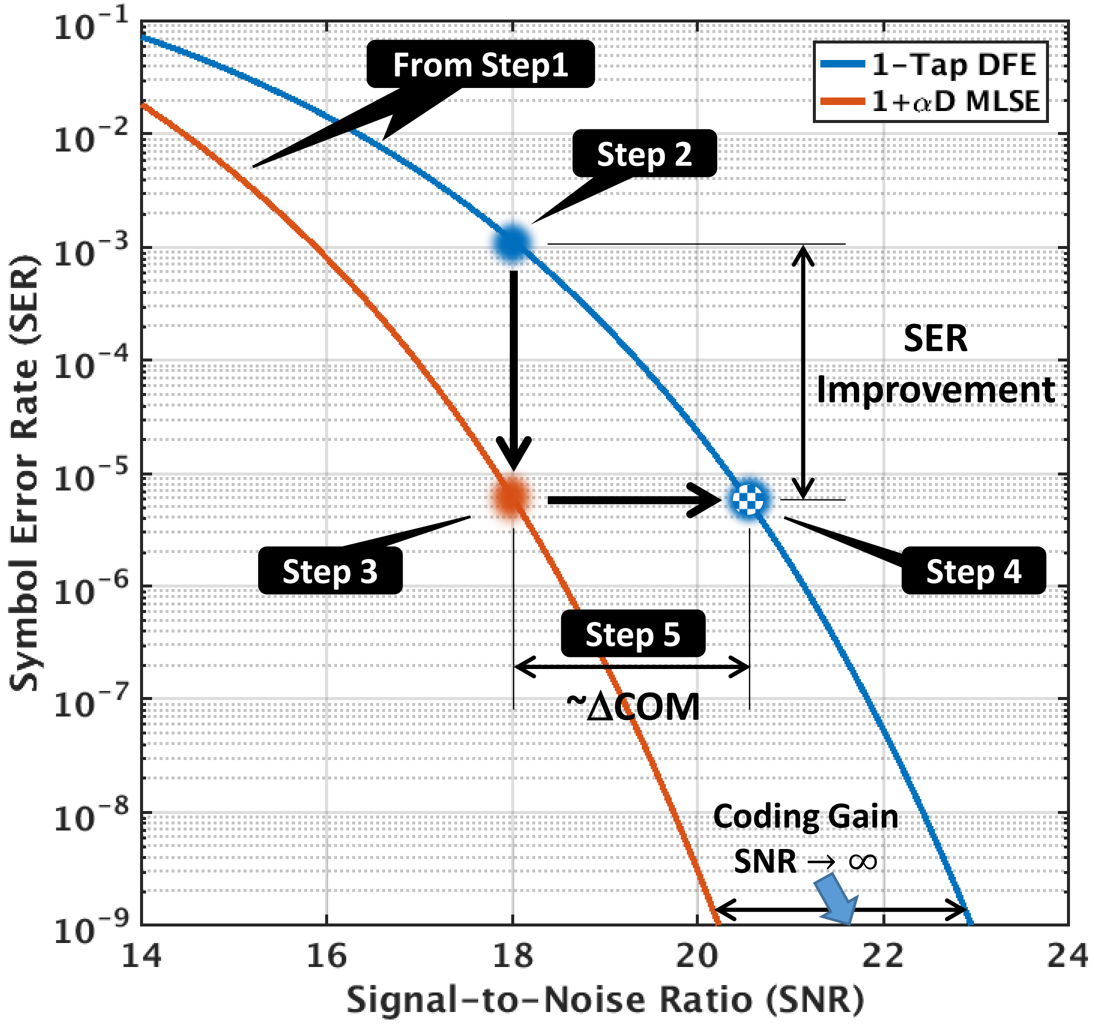
* Applied to force more errors to facilitate time-domain simulation verifications

- TX FIR taps, CTLE gDC and gDC2, Sampling Phase, RX FFE taps, and DFE tap were optimized based on maximizing FOM as defined by COM
- Proprietary COM/Statistical eye analysis tool was used to support RX FFE, DFE error propagation (with or without precoding), and additions needed to support MLSE
- Note that for the purpose of quantifying and verifying the MLSE improvement, the exact channel parameters are not as important as the diversity in channels and conditions

Proposal to Incorporate 1+αD MLSE in COM

1) Use COM analysis to find the DFE tap value
2) Use statistical eye analysis to find SNR_{DFE} and SER_{DFE} (including error propagation effect) for the 1-tap DFE
3) Assign α = DFE Tap Value and use analysis to calculate SER_{MLSE} at SNR_{DFE} for a 1+αD MLSE
4) Calculate $SNR_{DFE,equivalent}$ for the DFE that yields the same SER_{MLSE}
5) $\Delta SNR = SNR_{DFE,equivalent} - SNR_{DFE}$ is a good estimate of COM improvement (ΔCOM) offered by the MLSE (Much better than the asymptotic coding gain $10\log(1+\alpha^2)$)

➢ COM is SNR that includes SER or the so-called Q factor



The Coding View

- The entire end-to-end signal path response (e.g. TX FFE + TX Filters + Channel + RX Filters + CTLE + RX FFE) is optimally equalized to $1+\alpha D$ (historically, α would be the DFE tap)
- $1+\alpha D$ increases the number of signal levels
  - e.g. increase 4 levels of PAM4 (± 1, $\pm 1/3$) to generally 16 levels ($\pm 1 \pm \alpha$, $\pm 1 \pm \alpha/3$, $\pm 1/3 \pm \alpha$, $\pm 1/3 \pm \alpha/3$)
- Depending on α, some of the levels may merge and become not equally-likely
  - e.g. for $\alpha=1$, increase 4 levels of PAM4 (± 1, $\pm 1/3$) to 7 levels (± 2, $\pm 4/3$, $\pm 2/3$, 0)
- $1+\alpha D$ is indeed a level-coding operation since the generated levels are correlated and not all level transitions in a sequence of transitions are allowed (redundancy)
  - e.g. level $1+\alpha$ can only transition to one of 4 levels $\pm 1+\alpha$ and $\pm 1/3+\alpha$
- $1+\alpha D$ is the simplest form of Partial Response Signaling (PRS), also known as correlative level coding, and has coding properties due to its built-in redundancy
- Essentially it can act as a FEC!
  - In amplitude domain, not time

The Coding View

- Compare the two following options:

1) Use a 1-tap DFE
   - DFE removes the first cursor ISI (the αD term in the $1+\alpha D$ expression), ignoring and wasting the redundancy
2) Use a $1+\alpha D$ MLSE
   - Sequence processing can leverage the correlation between levels and the redundancy to detect illegal level transitions in the receiver (error detection) and provide best estimate to the sequence it believes was most likely transmitted (error correction)
   - Encoding is already done for free, just need to decode (likely more efficient than moving to a stronger FEC)

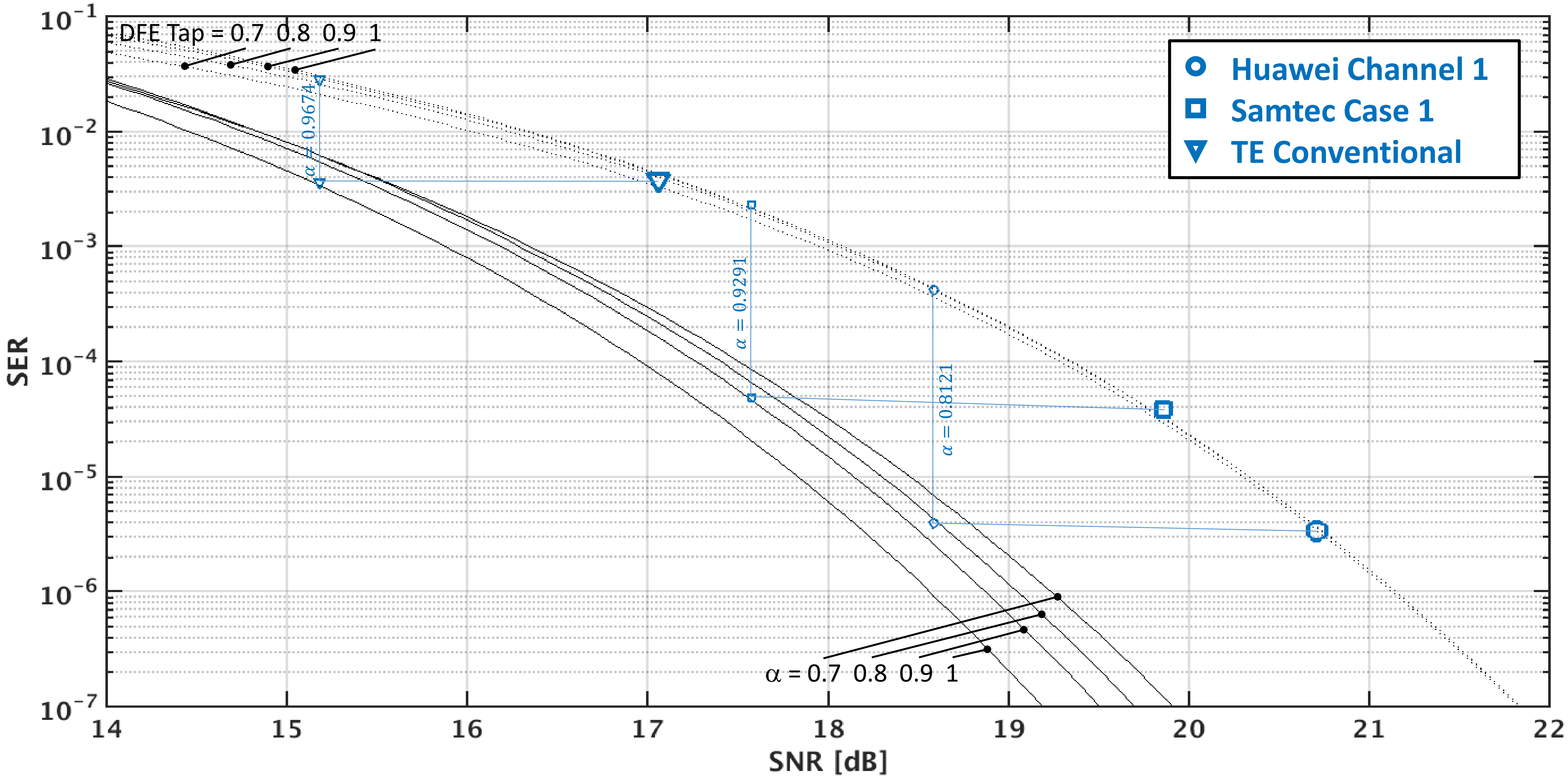
- Similar to any other coding scheme (such as RS FEC), the advantage can be expressed by a coding gain (usually in dB)
- Coding gain of the $1+\alpha D$ MLSE scheme is $10\log_{10}(1+\alpha^2)$
- Coding gain can only be achieved asymptotically and our proposal provides a simple and COM-compatible way of calculating the actual advantage based on the channel and link parameters
- The idea and proposal can be extended to higher-order PRS polynomials

Summary of the Case Study Results (Table)

Channel	Variant	DFE Tap $= \alpha$	Theoretical Coding Gain [dB]	SER_{DFE}	SER_{MLSE}	$\Delta SNR \approx \Delta COM$ [dB]	$SER_{DFE,equivalent}$	ΔCOM @ 1 E-4 [dB]	SER Ratio [Order of Magnitude]	Preliminary SER Simulation Results *		
										DFE	MLSE	DFE,equivalent
Huawei VSR Bump-to-Bump	Channel 1	**0.8121**	2.1999	4.1875 E-4	3.9657 E-6	**2.0485**	3.3441 E-6	2.1233	**2.10**	5.4 E-4	0 …	…
	Channel 2	**0.7683**	2.0148	2.7003 E-4	2.5990 E-6	**2.0010**	2.6016 E-6	2.0048	**2.02**	…	…	…
	Channel 3	**0.7768**	2.0505	8.9849 E-4	1.8406 E-5	**1.9506**	1.8080 E-5	1.9842	**1.70**	…	…	…
	Channel 4	**0.7842**	2.0816	4.3902 E-4	5.0902 E-6	**2.0183**	4.7832 E-6	2.0308	**1.96**	…	…	…
Samtec LR DAC oif2022.194.00	Case 1	**0.9291**	2.7027	2.3056 E-3	4.8686 E-5	**2.1897**	3.8811 E-5	2.2757	**1.77**	…	…	…
	Case 2	**0.8219**	2.2417	9.4528 E-4	1.7723 E-5	**2.0389**	1.5112 E-5	2.1112	**1.80**	…	…	…
	Case 3	**0.9294**	2.7041	6.6244 E-3	3.1834 E-4	**2.0686**	2.6826 E-4	2.1373	**1.39**	6.52 E-3	3.33 E-4	1.8 E-4
	Case 4	**0.9132**	2.6339	2.0091 E-2	2.6352 E-3	**1.7866**	2.4823 E-3	1.8852	**0.91**	2.65 E-2	2.54 E-3	2.57 E-3
TE CR DAC oif2022.313.01	Conventional	**0.9674**	2.8686	2.8589 E-2	3.6476 E-3	**1.8995**	3.8064 E-3	1.9087	**0.88**	3.02 E-2	4.51 E-3	4.87 E-3
	CPP	**0.9839**	2.9402	1.5229 E-2	1.0555 E-3	**2.1291**	9.9438 E-4	2.1689	**1.19**	1.66 E-2	6.5 E-4	8.1 E-4
	NCC	**0.9886**	2.9606	1.2067 E-2	6.0958 E-4	**2.2342**	5.7496 E-4	2.2855	**1.32**	1.48 E-2	7.7 E-4	4.0 E-4

* Simulations do not include CDR; Xtalk is scaled to the calculated COM level; jitter is applied using COM method; Run for maximum 1M symbols

Summary of the Case Study Results (Graphic)



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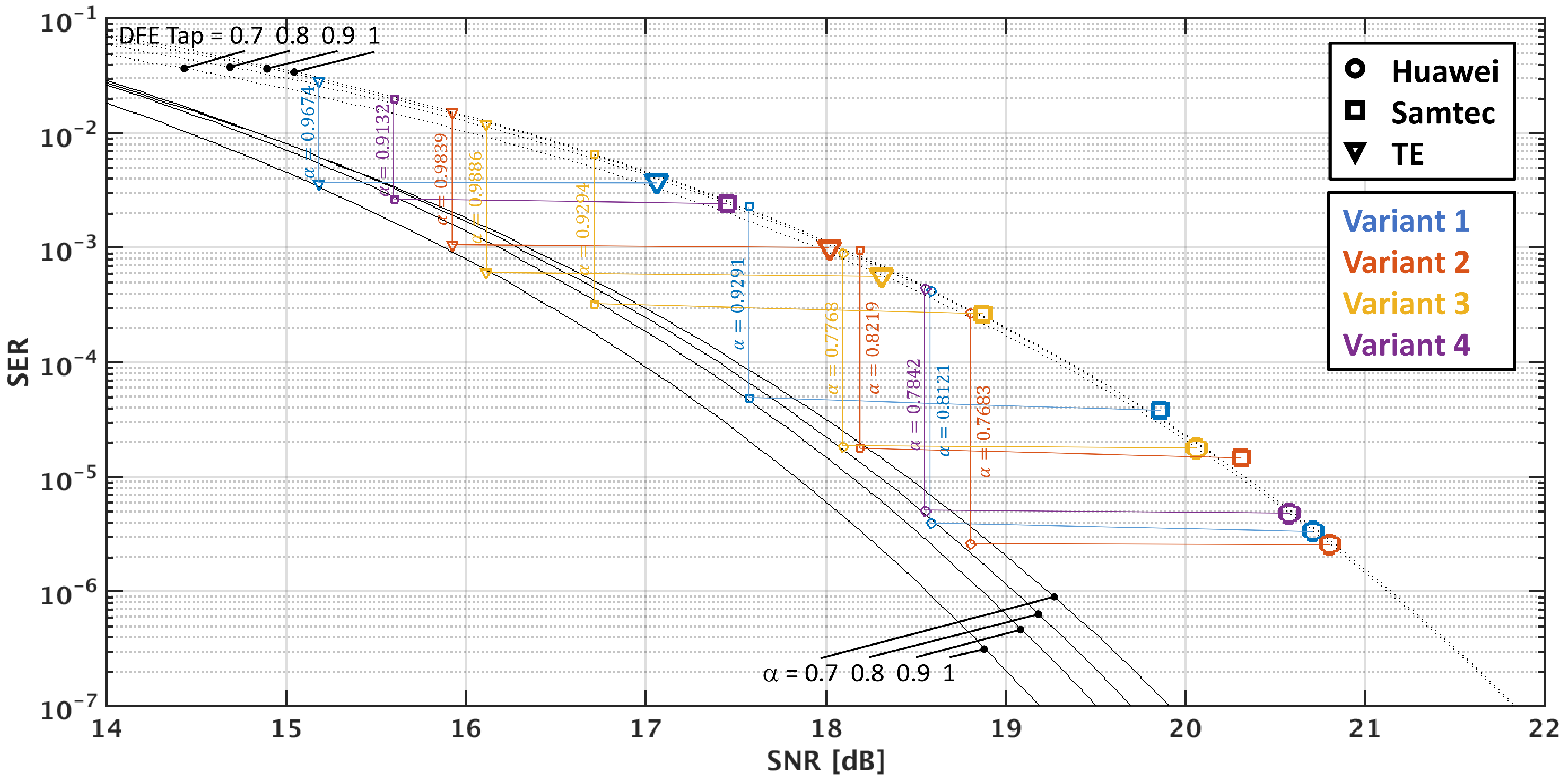

Implications and Future Actions

- For step 1, the current no-FFE + multi-tap DFE must change to multi-tap FFE + 1-tap DFE
  - COM (IEEE 802.3 Annex 93A) does not include FFE
- Steps 2 to 5, require equations from DFE and MLSE analysis using parameters obtained from statistical analysis
  - Equations are already developed
  - They are in the process of verification with good existing evidence
- Equations for steps 2 to 5 can be easily incorporated into COM
  - All equations will be provided in follow-on contributions
- Margining for practical reasons needs to be further studied
- Time-domain simulations and lab investigations are essential parts of verification and can help close possible gaps
- We are exploring more options and improvements and plan to provide future updates