Exploration on the worst case DFE weight of DFE error propagation effect

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Background

Decision Feedback Equalizer (DFE) error propagation impacts the FEC performance significantly. Two baseline reference receivers are under consideration (lu_3ck_adhoc_01a_121218).

- ‘m-pre & 0-post’ FFE + **n-tap DFE** (FFE-lite)
- ‘m-pre & n-post’ FFE + **1-tap DFE** (FFE-heavy)

Contributions on DFE error propagation, precoding, PMA/FEC interleaving are discussed in IEEE802.3ck Task Force. (More works can be found in IEEE and also published papers)

- healey_100GEL_01_0318, gustlin_3ck_01_0718, zhang_3ck_01a_0918, anslow_3ck_01_0918, gustlin_3ck_01_1118, anslow_3ck_01_1118

Techniques to reduce the impact of DFE error propagation includes:

- **Precoding**: Mandatory, Optional or Negotiable?
- **PMA interleaving**: Bit-Mux or Symbol-Mux?
- **FEC interleaving**: single FEC or two interleaved FECs for 100GE case?
  - Use interleaved FEC to guarantee performance while requiring extra latency and complexity?
  - Interleaved FEC to be mandatory or optional; configurable or negotiable? Cover all cases or just specific scenarios?

The worst case DFE weight for real channels is needed in the analysis. A simple way to derive the worst case DFE weight will be provided in this presentation.

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DFE error propagation mechanisms

- DFE burst errors exhibit “+1, -1” zig-zag patterns.
- DFE burst errors terminate when equalized signal is out of range.

Equivalent 1-tap model for n-tap DFE (Semi-analytical, boundary analysis)

- n-tap DFE is equivalent to 1-tap DFE with time-variant DFE weight.
- Simulation of DFE error propagation probability p for n-tap DFE is provided.

Analysis of n-tap DFE error propagation

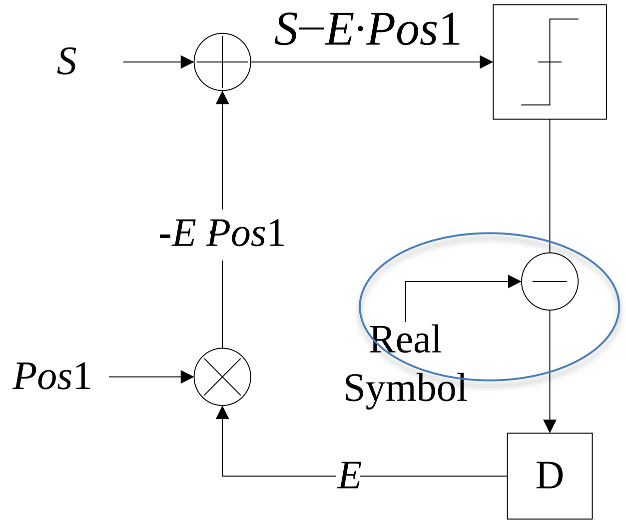
- The two DFE weight configurations considered previously:

  DFE weight = [0.7, 0, 0.2, 0, 0.2] & DFE weight = [0.7, -0.1, 0.1, -0.1, 0.1]
- Recommended worst case n-tap DFE weights from COM reference receivers

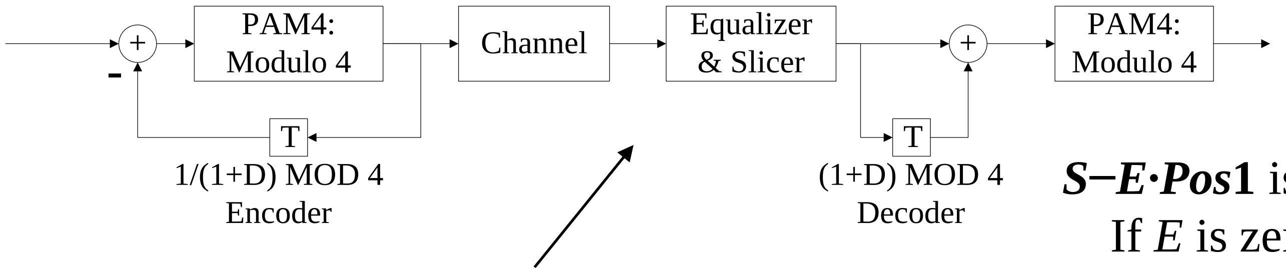
Summary

DFE burst errors exhibit “+1, -1” zig-zag patterns

Pos1/Main	0.7																			
1/(1+D) Encoder Input	1	0	1	3	3	0	3	2	0	1	3	3	0	0	0	0	2	3	0	3
1/(1+D) Encoder Output	1	3	2	1	2	2	1	1	3	2	1	2	2	2	2	2	0	3	1	2
After [1, Pos1] Channel	1	4	4	2	3	3	2	2	4	4	2	3	3	3	3	3	1	3	3	3
After DFE Equalizer	1	3	2	2	1	3	0	2	2	3	0	3	1	3	1	3	-1	3	1	2
DFE Slicer Output	1	3	1	2	1	3	0	2	2	3	0	3	1	3	1	3	0	3	1	2
DFE Error Pattern	0	0	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	0	0	0	0
(1+D) Decoder Output	1	0	0	3	3	0	3	2	0	1	3	3	0	0	0	0	3	3	0	3
Pre-Coding Error Pattern	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Symbol ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20



Equivalent DFE architecture



Precoding correlated the adjacent symbols. “+1, -1” error patterns will be cancelled after decoding. Long burst errors will be converted in to individual errors at the head and tail.

S−E·Pos1 is slicer input for the next symbol,

- If E is zero $S-E\cdot Pos1=S$, next E will be probably be zero.
- If E is positive $S-E\cdot Pos1<S$, next E will be probably negative.
- If E is negative $S-E\cdot Pos1>S$, next E will be probably positive .

Y.C. Lu, et al “DFE Error Propagation Characteristics in Real 56Gbps PAM4 High-Speed Links with Pre-Coding and Impact on the FEC Performance”, DesignCon 2017.

DFE burst errors terminate when equalized signal is out of range

Underflow

(a)

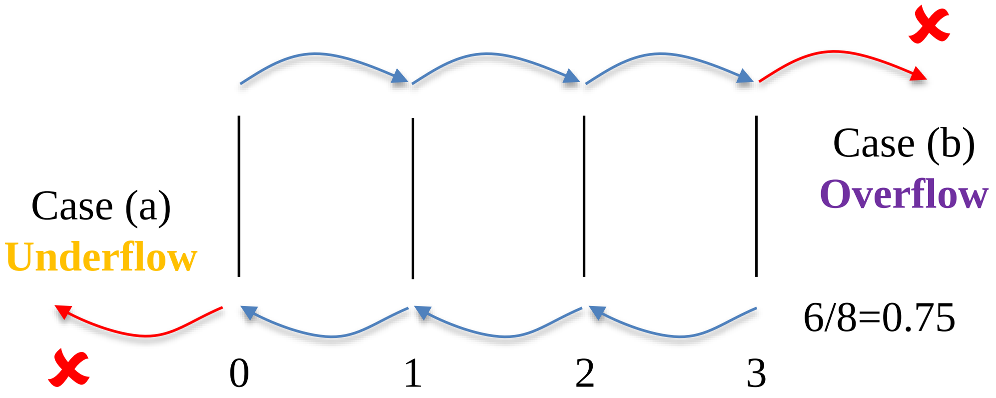
Pos1/Main	0.7																			
1/(1+D) Encoder Input	1	0	1	3	3	0	3	2	0	1	3	3	0	0	0	0	2	3	0	3
1/(1+D) Encoder Output	1	3	2	1	2	2	1	1	3	2	1	2	2	2	2	2	0	3	1	2
After [1, Pos1] Channel	1	3.7	4.1	2.4	2.7	3.4	2.4	1.7	3.7	4.1	2.4	2.7	3.4	3.4	3.4	3.4	1.4	3	3.1	2.7
After DFE Equalizer	1	3	2	1.7	1.3	2.7	0.3	1.7	2.3	2.7	0.3	2.7	1.3	2.7	1.3	2.7	-0.7	3	1	2
DFE Slicer Output	1	3	1	2	1	3	0	2	2	3	0	3	1	3	1	3	0	3	1	2
DFE Error Pattern	0	0	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	0	0	0	0
(1+D) Decoder Output	1	0	0	3	3	0	3	2	0	1	3	3	0	0	0	0	3	3	0	3
Pre-Coding Error Pattern	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Symbol ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

Random error that triggers the burst error

(b)

Pos1/Main	0.7																			
1/(1+D) Encoder Input	1	0	1	3	3	0	3	2	0	1	3	3	0	2	1	3	0	1	0	3
1/(1+D) Encoder Output	1	3	2	1	2	2	1	1	3	2	1	2	2	0	1	2	2	3	1	2
After [1, Pos1] Channel	1	3.7	4.1	2.4	2.7	3.4	2.4	1.7	3.7	4.1	2.4	2.7	3.4	1.4	1	2.7	3.4	4.4	3.1	2.7
After DFE Equalizer	1	3	2	1.7	1.3	2.7	0.3	1.7	2.3	2.7	0.3	2.7	1.3	0.7	0.3	2.7	1.3	3.7	1	2
DFE Slicer Output	1	3	1	2	1	3	0	2	2	3	0	3	1	1	0	3	1	3	1	2
DFE Error Pattern	0	0	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	0	0	0
(1+D) Decoder Output	1	0	0	3	3	0	3	2	0	1	3	3	0	2	1	3	0	0	0	3
Pre-Coding Error Pattern	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0
Symbol ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

Overflow



1. The termination of DFE burst error is related to the **data pattern**. It is also true for n-tap DFEs.
2. Error propagation probability p is related to the "**feedback error**" by n-tap DFE and the **signal to noise ratio** (SNR).
3. The DFE termination mechanism and the uniform distribution of the PAM-4 symbols give a maximum 0.75 error propagation probability for 1-tap DFE.

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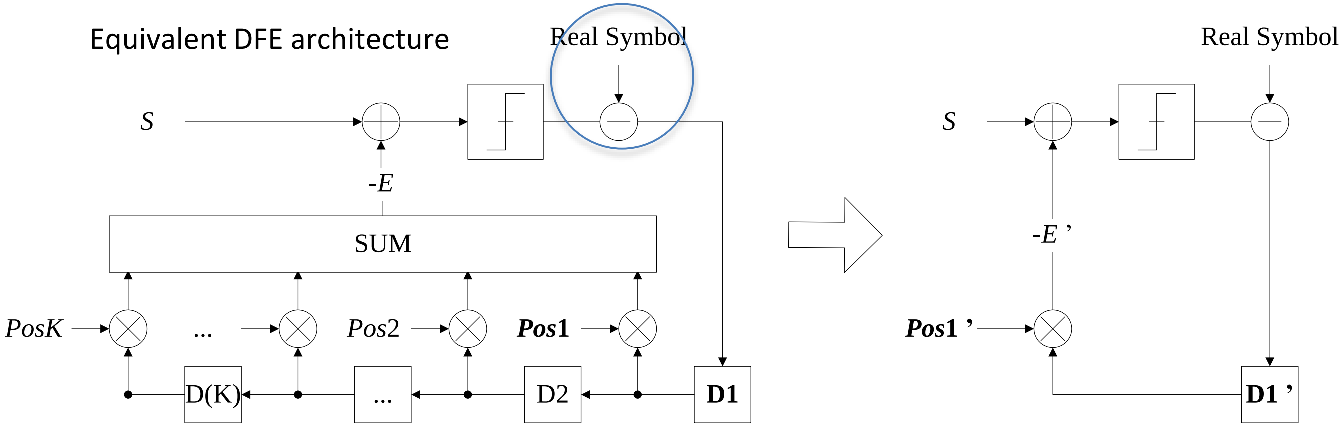
n-tap DFE is equivalent to 1-tap DFE with time-variant DFE weight



n-tap DFE

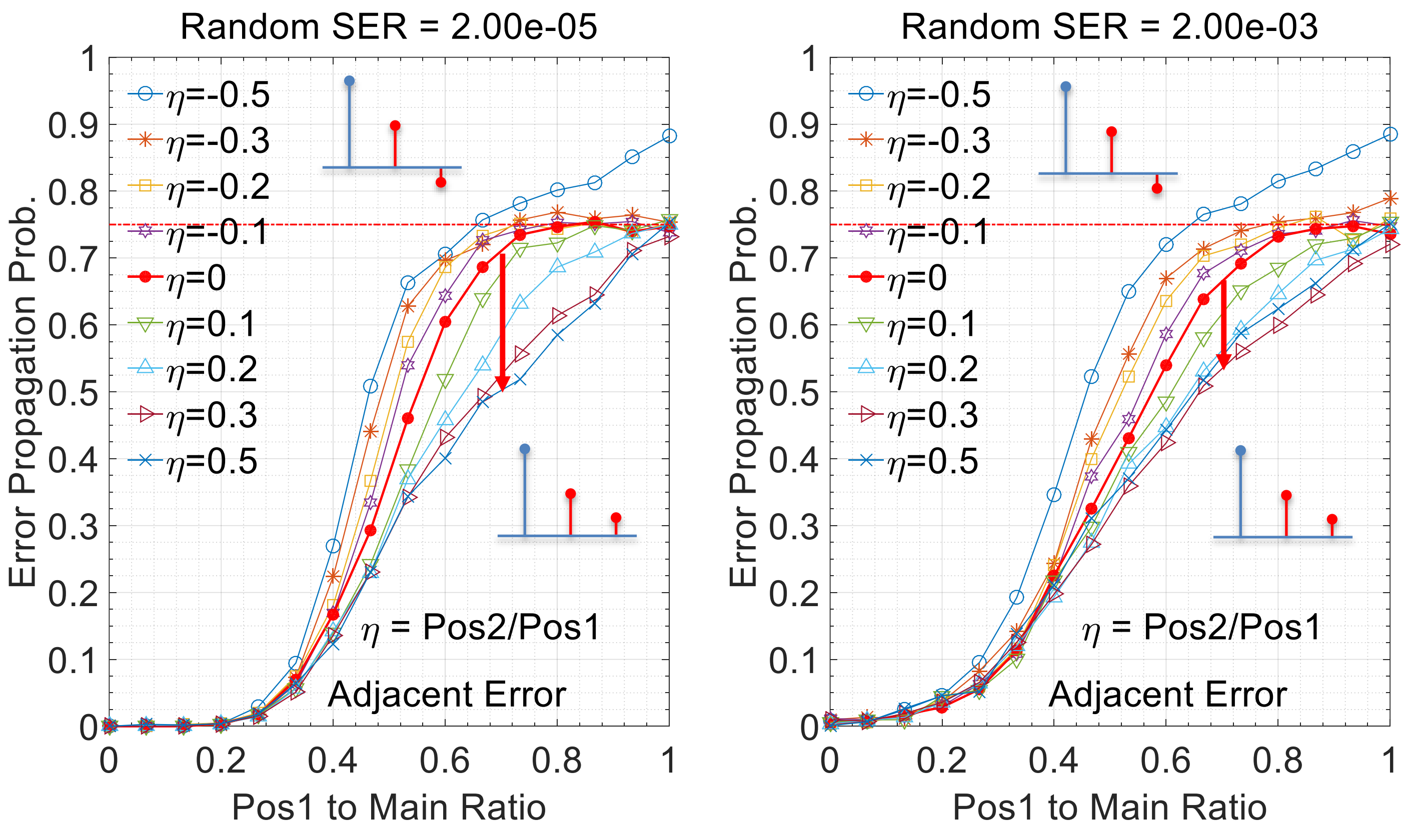
1-tap DFE

Time	D_1	D_2	D_3	D_4	…	Pos1’
0	0	0	0	0	…	0
1	E_1	0	0	0	…	Pos1
2	E_2	E_1	0	0	…	Pos1-Pos2
3	E_3	E_2	E_1	0	…	Pos1-Pos2+Pos3
…	…	…	…	…	…	…
L+1	E_L	E_{L-1}	E_{L-2}	E_{L-3}	…	Pos1-Pos2+Pos3-Pos4+…

- n-tap DFE can be viewed as 1 tap DFE with time-variant DFE coefficient.
- Tap k DFE will assist the error propagation
  - “k is even and $\frac{\text{Pos(k)}}{\text{Pos(1)}} < 0$” ;
  - “k is odd and $\frac{\text{Pos(k)}}{\text{Pos(1)}} > 0$”.
- Tap k DFE will hinder the error propagation
  - “k is even and $\frac{\text{Pos(k)}}{\text{Pos(1)}} > 0$” ;
  - “k is odd and $\frac{\text{Pos(k)}}{\text{Pos(1)}} < 0$”.

Y.C. Lu, et al “DFE Error Propagation Characteristics in Real 56Gbps PAM4 High-Speed Links with Pre-Coding and Impact on the FEC Performance”, DesignCon 2017.

Error propagation probability p may reduce for n-tap DFEs



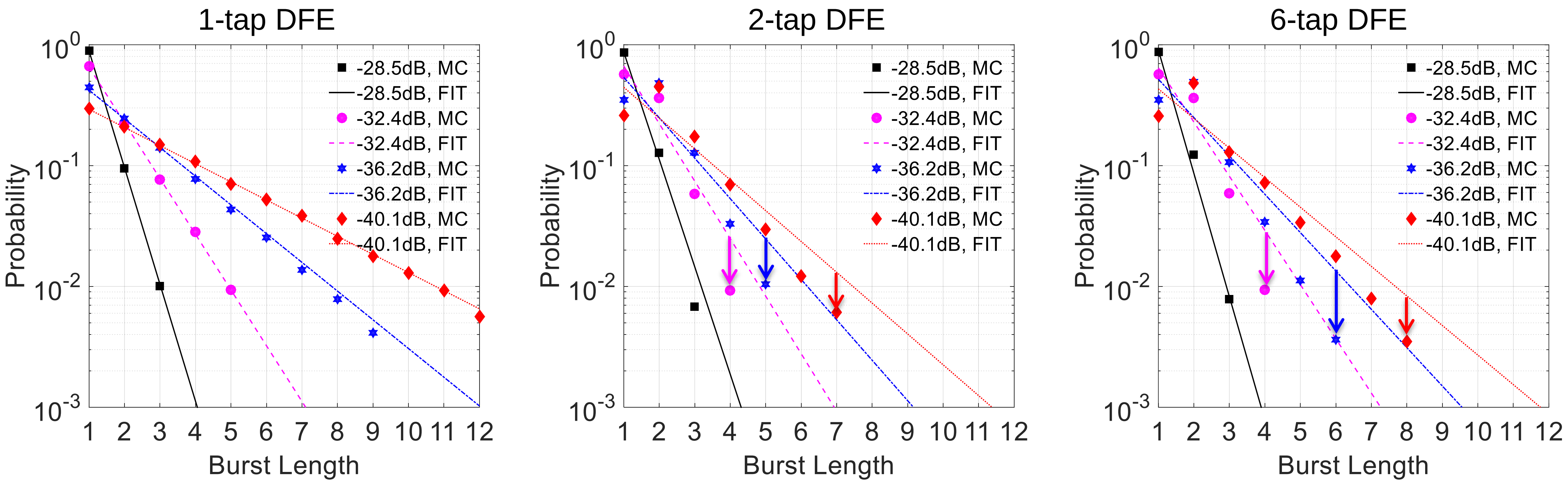
1. The 2nd DFE tap may assist or hinder the error propagation which depends on 'Pos2/Pos1'. This rule applies to scenarios with beyond 2-tap DFEs.
2. If Pos2/Pos1=0.3, the error propagation probability will reduce from 0.7 to 0.5 for random SER = 2e-5; and reduce from 0.65 to 0.52 for random SER=2e-3.
3. This model can be generalized to n-tap DFE easily.
4. **Error propagation probability p is dominant even for 'Pecoded' cases.**
5. Smaller p → low probability of long burst → low probability of segmented error pattern (-1 1 0 0 -1 1 -1 0 0 0 -1 1 -1 1 -1) → smaller # of error symbols (μ) that a burst will be converted to by 'Precoding'→ low probability of 'Precoding' failure.

The error propagation probablity is obtained from Monte-Carlo simulation (no assumption was made):

$$p = \text{Prob.}(E_{k+1}|E_k = 1 \text{ or } S_k = 1) = \frac{\text{Total \# of error prop. events}}{\text{Total \# of error prop. trials}} = \frac{\sum_k (BL[k]-1)}{\sum_k BL[k]}$$

Y.C. Lu, et al "DFE Error Propagation Characteristics in Real 56Gbps PAM4 High-Speed Links with Pre-Coding and Impact on the FEC Performance", DesignCon 2017.

n-tap DFE has lower error propagation probability than 1-tap DFE



- n-tap DFE has lower error propagation probability than 1-tap DFE in real channels. The k-th tap DFE, k>2, will cancel the feedback error of the 1st-tap DFE, which will give a lower equivalent 1-tap DFE weight.
- Investigated with Monte-Carlo simulation of real 56Gbps PAM4 channels, the conclusion is applicable for 112Gbps PAM4 links.
- Error propagation probability: $p = \text{Prob.}\,(E_{k+1}|E_k = 1 \text{ or } S_k = 1) = \frac{\text{Total \# of error prop. events}}{\text{Total \# of error prop.trials}} = \frac{\sum_k (BL[k]-1)}{\sum_k BL[k]}$.
- Probability fitting function for 1-tap DFE: $\text{Prob.}\,(BL) = p^{BL-1}(1-p), BL \geq 1$

Y.C. Lu, et al “DFE Error Propagation Characteristics in Real 56Gbps PAM4 High-Speed Links with Pre-Coding and Impact on the FEC Performance”, DesignCon 2017.

Examples for n-tap DFE error propagation: Always propagate

- The error propagation probability p of two DFE weight investigated in anslow_3ck_01_0918 is beyond **0.75**; and the equivalent 1-tap DFE weight is **1.1**. It may be too pessimistic for the investigation of DFE error propagation and its impact on FEC performance.
  - Configuration 1: [0.7, 0 , 0.2, 0 , 0.2] equivalent 1-tap DFE weight is **1.1**.
  - Configuration 2: [0.7, -0.1, 0.1, -0.1, 0.1] equivalent 1-tap DFE weight is **1.1**.

Time	D_1	D_2	D_3	D_4	D_5	Pos1'
	0.7	**0**	**0.2**	**0**	**0.2**	0
0	0	0	0	0	0	0
1	+*E*	0	0	0	0	0.7
2	-*E*	+*E*	0	0	0	0.7-0=0.7
3	+*E*	-*E*	+*E*	0	0	0.7-0+0.2=0.9
4	-*E*	+*E*	-*E*	+*E*	0	0.7-0+0.2-0=0.9
5	+*E*	-*E*	+*E*	-*E*	+*E*	0.7-0+0.2-0+0.2=1.1
6	-*E*	*E*	-*E*	+*E*	-*E*	**1.1**
…	…	…	…	…	…	…

DFE weight = [0.7, **0**, 0.2, **0**, 0.2]

Time	D_1	D_2	D_3	D_4	D_5	Pos1'
	0.7	**-0.1**	**0.1**	**-0.1**	**0.1**	0
0	0	0	0	0	0	0
1	+*E*	0	0	0	0	0.7
2	-*E*	+*E*	0	0	0	0.7-(-0.1)=0.8
3	+*E*	-*E*	+*E*	0	0	0.7-(-0.1)+0.1=0.9
4	-E	+*E*	-*E*	+*E*	0	0.7-(-0.1)+0.1-(-0.1)=1.0
5	+*E*	-*E*	+*E*	-*E*	+*E*	0.7-(-0.1)+0.1-(-0.1)+1.0=1.1
6	-*E*	+*E*	-*E*	+*E*	-*E*	**1.1**
…	…	…	…	…	…	…

DFE weight = [0.7, **-0.1**, 0.1, **-0.1**, 0.1]

Examples for n-tap DFE error propagation: Propagation terminate

Time	D_1	D_2	D_3	D_4	D_5	Pos1'
	0.7	0	0.2	0	0.2	0
0	0	0	0	0	0	0
1	+E	0	0	0	0	0.7
2	0	+E	0	0	0	0
3	0	0	+E	0	0	0-0+0.2=0.2
4	0	0	0	+E	0	0-0+0-0=0.0
5	0	0	0	0	+E	0-0+0-0+0.2=0.2
6	0	0	0	0	0	0-0+0-0+0=0
…	…	…	…	…	…	…

DFE weight = [0.7, **0**, 0.2, **0**, 0.2]

Time	D_1	D_2	D_3	D_4	D_5	Pos1'
	0.7	-0.1	0.1	-0.1	0.1	0
0	0	0	0	0	0	0
1	+E	0	0	0	0	0.7
2	0	+E	0	0	0	0-(-0.1)=0.1
3	0	0	+E	0	0	0-0+0.1=0.1
4	0	0	0	+E	0	0-0+0-0.1=-0.1
5	0	0	0	0	+E	0-0+0-0+0.1=-0.1
6	0	0	0	0	0	0-0+0-0+0=0
…	…	…	…	…	…	…

DFE weight = [0.7, **-0.1**, 0.1, **-0.1**, 0.1]

- The error propagation probability p of (pos1/main)=0.2 is <**0.02**.
- The error propagation probability p of (pos1/main)=0.7 is ~**0.7**.

>35 times difference.

- As long as the DFE burst error terminate, the impact of the 1st tap DFE is eliminated, the impact of remaining DFE taps (2, 3, 4, … taps) is minor.
- The impact of n-tap DFE error propagation effects should be similar to the 1-tap DFE case.

Examples for n-tap DFE error propagation: Segmented error

Another burst error

Time	D_1	D_2	D_3	D_4	D_5	Pos1'
	0.7	0	0.2	0	0.2	0
0	0	0	0	0	0	0
1	+E	0	0	0	0	0.7
2	0	+E	0	0	0	0-0=0
3	+E	0	+E	0	0	0.7-0+0.2=0.9
4	-E	E	0	+E	0	0.7-0+0-0=0.7
5	+E	-E	+E	0	+E	0.7-0+0.2-0+0.2=1.1
6	-E	+E	-E	+E	0	0.7-0+0.2-0+0=0.9
7	+E	-E	+E	-E	+E	**1.1**
8	-E	+E	-E	+E	-E	**1.1**
…	…	…	…	…	…	…

DFE weight = [0.7, **0**, 0.2, **0**, 0.2]

Time	D_1	D_2	D_3	D_4	D_5	Pos1'
	0.7	-0.1	0.1	-0.1	0.1	0
0	0	0	0	0	0	0
1	+E	0	0	0	0	0.7
2	0	+E	0	0	0	0-(-0.1)=0.1
3	+E	0	+E	0	0	0.7-(0)+0.1=0.8
4	-E	+E	0	+E	0	0.7-(-0.1)+0-(-0.1)=0.9
5	+E	-E	+E	0	+E	0.7-(-0.1)+0.1-0+0.1=1.0
6	-E	+E	-E	+E	0	0.7-(-0.1)+0.1-0+0=0.9
7	+E	-E	+E	-E	+E	**1.1**
8	-E	+E	-E	+E	-E	**1.1**
…	…	…	…	…	…	…

Another burst error

DFE weight = [0.7, **-0.1**, 0.1, **-0.1**, 0.1]

- The error propagation probability p of (pos1/main)=0.2 is <**0.02**.
- The error propagation probability p of (pos1/main)=0.7 is ~**0.7**.

>35 times difference.

- As long as the DFE burst error terminate, the impact of the 1st tap DFE is eliminated. The error propagation effect due to the 2,3, 4, … taps is minor.
- The probability of "segmented error" is close to "One burst error run into another one.". **<BER^2=(1e-4)^2=1e-8**.

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DFE weights from COM reference receivers

IL Range (dB)	IL (dB)	ICN (mV)	ILD (dB)	COM (dB)	DFE Weight					Equivalent 1-tap DFE Weight				
					b1	b2	b3	b4	b5	Post1'(1)	Post1'(2)	Post1'(3)	Post1'(4)	Post1'(5)
26~27	-26.0	0.89	0.46	3.52	**0.78**	**0.07**	**-0.01**	**0.03**	**0.02**	**0.78**	0.7	0.67	0.69	**0.71**
	-26.2	0.40	0.45	2.22	0.69	0.15	0.13	0.10	0.06	0.69	0.67	0.57	0.63	0.54
	-26.2	0.40	0.32	3.20	0.71	0.10	0.01	0.02	0.01	0.71	0.62	0.6	0.61	0.61
	-26.5	0.84	0.85	2.17	0.71	0.19	0.08	0.03	0.04	0.71	0.6	0.57	0.61	0.52
	-26.7	0.49	0.51	4.01	0.73	0.12	0.01	-0.01	0.00	0.73	0.62	0.63	0.63	0.61
	-26.9	0.40	0.47	2.01	0.72	0.13	0.12	0.09	0.06	0.72	0.71	0.62	0.68	0.59
	-27.0	1.32	0.58	1.74	0.73	0.13	0.03	0.01	0.02	0.73	0.63	0.62	0.64	0.6
27~28	-27.4	0.29	0.27	4.22	**0.77**	**0.10**	**0.01**	**0.02**	**0.01**	**0.77**	0.68	0.66	0.67	**0.67**
	-27.5	1.32	0.60	1.64	0.74	0.12	0.02	0.00	0.01	0.74	0.64	0.64	0.65	0.62
	-27.6	0.42	0.26	3.86	0.71	0.13	-0.03	-0.04	-0.03	0.71	0.55	0.59	0.56	0.58
	-27.8	0.40	0.50	1.70	0.76	0.11	0.09	0.07	0.04	0.76	0.74	0.67	0.71	0.65
	-27.8	0.35	0.27	2.83	0.72	0.15	0.05	0.04	0.03	0.72	0.62	0.58	0.61	0.57
	-27.8	0.40	0.36	2.44	0.74	0.13	0.02	0.01	0.01	0.74	0.63	0.62	0.63	0.61
	-28.0	0.00	0.00	4.07	0.72	0.14	-0.04	-0.05	-0.04	0.72	0.54	0.59	0.55	0.58
28~29	-28.0	0.00	0.03	4.43	0.74	0.09	-0.08	-0.08	-0.05	0.74	0.57	0.65	0.6	0.65
	-28.4	0.40	0.39	2.43	0.73	0.08	-0.03	-0.03	-0.02	0.73	0.62	0.65	0.63	0.65
	-28.7	0.52	0.90	1.65	0.72	0.18	0.05	0.01	0.01	0.72	0.59	0.58	0.59	0.54
29~30	-29.4	1.16	1.07	1.53	0.75	0.11	-0.03	-0.08	-0.05	0.75	0.61	0.69	0.64	0.64
	-29.7	1.15	1.02	1.78	0.76	0.13	-0.02	-0.09	-0.06	0.76	0.61	0.7	0.64	0.63

Post1'(n) = b(1) – b(2) +…$(-1)^{n-1}$b(n)

Configuration: FFE-lite, Modified-PD lu_3ck_adhoc_01a_121218, **$b(1)_{max}=0.6$**, COM >1.5.

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DFE weights from COM reference receivers

IL Range (dB)	IL (dB)	ICN (mV)	ILD (dB)	COM (dB)	DFE Weight					Equivalent 1-tap DFE Weight				
					b1	b2	b3	b4	b5	Post1'(1)	Post1'(2)	Post1'(3)	Post1'(4)	Post1'(5)
26~27	-26.0	0.89	0.46	3.67	**0.87**	**0.22**	**0.09**	**0.09**	**0.06**	**0.87**	0.65	0.74	0.65	**0.71**
	-26.1	1.32	0.66	1.59	0.79	0.29	0.22	0.15	0.11	0.79	0.51	0.72	0.58	0.68
	-26.2	0.40	0.45	2.42	0.80	0.26	0.21	0.16	0.10	0.80	0.54	0.75	0.59	0.69
	-26.2	0.40	0.32	3.43	0.82	0.23	0.11	0.08	0.05	0.82	0.59	0.69	0.61	0.67
	-26.5	0.84	0.85	2.31	0.80	0.33	0.19	0.11	0.10	0.80	0.47	0.67	0.55	0.65
	-26.7	0.49	0.51	4.15	0.80	0.28	0.15	0.10	0.07	0.80	0.52	0.67	0.58	0.65
	-26.9	0.40	0.47	2.18	0.78	0.27	0.21	0.16	0.11	0.78	0.51	0.73	0.57	0.68
	-27.0	1.32	0.58	1.96	0.83	0.28	0.15	0.10	0.08	0.83	0.55	0.70	0.60	0.68
27~28	-27.4	0.29	0.27	4.36	**0.89**	**0.21**	**0.08**	**0.07**	**0.05**	**0.89**	0.68	0.76	0.70	**0.74**
	-27.5	1.32	0.60	1.89	0.84	0.26	0.12	0.07	0.06	0.84	0.59	0.71	0.64	0.70
	-27.6	0.42	0.26	3.99	0.83	0.26	0.07	0.04	0.03	0.83	0.57	0.64	0.60	0.63
	-27.8	0.40	0.50	1.86	0.85	0.22	0.17	0.13	0.09	0.85	0.63	0.80	0.67	0.76
	-27.8	0.35	0.27	3.04	0.82	0.26	0.13	0.09	0.07	0.82	0.57	0.70	0.60	0.67
	-27.8	0.40	0.36	2.63	0.84	0.23	0.10	0.06	0.05	0.84	0.61	0.70	0.64	0.69
	-28.0	0.00	0.00	4.34	0.81	0.20	0.00	-0.03	-0.02	0.81	0.61	0.61	0.64	0.61
28~29	-28.0	0.00	0.03	4.84	0.86	0.18	-0.07	-0.10	-0.07	0.86	0.68	0.61	0.71	0.63
	-28.4	0.40	0.39	2.68	0.82	0.24	0.11	0.07	0.05	0.82	0.59	0.69	0.62	0.67
	-28.7	0.52	0.90	1.78	0.82	0.28	0.12	0.06	0.05	0.82	0.55	0.67	0.61	0.66
	-28.9	0.40	0.54	1.56	0.86	0.20	0.15	0.12	0.08	0.86	0.66	0.80	0.69	0.77
29~30	-29.4	1.16	1.07	1.82	0.84	0.20	0.04	-0.03	-0.02	0.84	0.64	0.68	0.71	0.69
	-29.7	1.15	1.02	2.11	0.87	0.23	0.06	-0.03	-0.01	0.87	0.64	0.70	0.73	0.71

$Post1'(n) = b(1) – b(2) +…(-1)^{n-1}b(n)$

Configuration: FFE-lite, Modified-PD lu_3ck_adhoc_01a_121218, **$b(1)_{max}$=0.7**, COM >1.5.

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Summary

- DFE error propagation mechanisms are reviewed.
  - ‘Zig-Zag’ error pattern: Precoding can convert long burst to individual errors at head and tail.
  - Terminate with signal out of range: There is a chance to correct the error at the tail.
- Equivalent 1-tap model for n-tap DFE is discussed. (Based on Monte-Carlo experiments)
  - n-tap DFE is equivalent to 1-tap DFE with time-variant DFE weight.
  - n-tap DFE may have lower error propagation probability than 1-tap DFE in real channels.
- The n-tap DFE error propagation is re-examined with equivalent 1-tap model.
  - First DFE tap is dominant in the error propagation. The probability of “Segmented burst errors” is similar to “burst errors run into each other”. The Precoding failure probability is small.

    2 segments: $BER^2 = (10^{-4})^2 = 10^{-8}$; 3 segments: $BER^3 = (10^{-4})^3 = 10^{-12}$; …
  - DFE weights [0.7, 0 , 0.2, 0, 0.2] and [0.7, -0.1, 0.1, -0.1, 0.1] might be too pessimistic for real channels.
  - DFE weights with FFE-lite model is provided for error propagation investigation.

    b1max=0.6, b(1)~=0.7: [0.78, 0.07, -0.01, 0.03, 0.02] (post’=0.71); [0.77, 0.10, 0.01, 0.02, 0.01] (post’=0.67)

    b1max=0.7, b(1)~=0.8: [0.87, 0.22, 0.09, 0.09, 0.06] (post’=0.71); [0.89, 0.21, 0.08, 0.07, 0.05] (post’=0.74)
- The worst case DFE weights derived from reference receivers and real channels (with the largest equivalent 1-tap DFE weight) are recommended to be used in the DFE error propagation analysis.

Thank you！

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Average # of error symbols per burst error after precoding (μ)

	Insertion Loss	1 tap DFE	2 tap DFE	3 tap DFE	4 tap DFE	5 tap DFE	6 tap DFE	7 tap DFE	8 tap DFE	9 tap DFE
α=0.6 Under-equalized	40.1dB	2.000	**2.891**	2.442	2.387	2.352	2.356	2.352	2.351	2.357
	38.2dB	2.000	2.480	2.275	2.244	2.233	2.228	2.239	2.244	2.242
	36.2dB	2.000	2.258	2.154	2.158	2.147	2.141	2.146	2.146	2.140
	34.2dB	2.000	2.123	2.083	2.076	2.077	2.080	2.080	2.082	2.078
	32.4dB	2.000	2.067	2.045	2.053	2.051	2.048	2.050	2.048	2.047
α=0.8 Under-equalized	40.1dB	2.000	**2.181**	2.115	2.107	2.100	2.113	2.104	2.111	2.113
	38.2dB	2.000	2.088	2.052	2.054	2.054	2.056	2.052	2.050	2.054
	36.2dB	2.000	2.037	2.028	2.026	2.024	2.026	2.024	2.030	2.028
	34.2dB	2.000	2.017	2.014	2.013	2.013	2.012	2.015	2.016	2.014
	32.4dB	2.000	2.009	2.007	2.006	2.007	2.008	2.008	2.007	2.008
α=1.0 Optimal-equalized	40.1dB	2.000	**2.033**	2.021	2.018	2.020	2.022	2.021	2.020	2.022
	38.2dB	2.000	2.012	2.009	2.010	2.008	2.010	2.010	2.009	2.010
	36.2dB	2.000	2.006	2.004	2.003	2.004	2.006	2.005	2.003	2.003
	34.2dB	2.000	2.002	2.002	2.001	2.002	2.002	2.002	2.002	2.002
	32.4dB	2.000	2.001	2.001	2.001	2.002	2.001	2.001	2.001	2.001
α=1.2 Over-equalized	40.1dB	2.000	**2.004**	2.006	2.007	2.006	2.008	2.007	2.007	2.006
	38.2dB	2.000	2.001	2.002	2.003	2.003	2.002	2.002	2.002	2.003
	36.2dB	2.000	2.000	2.002	2.001	2.001	2.002	2.002	2.002	2.002
	34.2dB	2.000	2.000	2.000	2.001	2.001	2.001	2.000	2.001	2.000
	32.4dB	2.000	2.000	2.001	2.001	2.001	2.001	2.000	2.001	2.001

Average # of PAM-4 symbol error that pre-coding will convert a burst error train into.

1. For 1 tap DFE case, the pre-coding probably convert the burst error into 2 PAM4 symbol errors.
2. If the CTLE is chosen properly, α=0.8, 1.0, 1.2, the burst errors will be probably converted to two PAM4 symbol errors.
3. The upper bounds for the # of PAM-4 symbol errors that converted from burst error trains by pre-coding is 3.
4. The tap 2 DFE has the largest impact on the # of PAM-4 symbol errors that converted from burst error trains by pre-coding. There is no obvious dependency of this number on DFE tap #, when it goes beyond 2.
5. We use 2.0≤η ≤ 4.0 as a multiplication factor of bit errors in our pre-coded formula of FEC.

Y.C. Lu, et al "DFE Error Propagation Characteristics in Real 56Gbps PAM4 High-Speed Links with Pre-Coding and Impact on the FEC Performance", DesignCon 2017.

DFE weights from COM reference receivers

IL Range (dB)	Channel	IL (dB)	ICN (mV)	ILD (dB)	COM (dB)	DFE Weight					Equivalent 1-tap DFE Weight
						b1	b2	b3	b4	b5	
26~27	zambell_3ck_01_1118_Link_7	-26.0	0.89	0.46	3.52	0.78	0.07	-0.01	0.03	0.02	0.71
	kareti_3ck_01_1118_cabledBP_CAch2_a2p5	-26.2	0.40	0.45	2.22	0.69	0.15	0.13	0.10	0.06	0.54
	kareti_3ck_01_1118_cabledBP_CAch2_b6	-26.2	0.40	0.32	3.20	0.71	0.10	0.01	0.02	0.01	0.61
	kareti_3ck_01_1118_ortho_OAch3	-26.5	0.84	0.85	2.17	0.71	0.19	0.08	0.03	0.04	0.52
	mellitz_3ck_adhoc_02_081518_cabledbackplane_Opt2	-26.7	0.49	0.51	4.01	0.73	0.12	0.01	-0.01	0.00	0.61
	kareti_3ck_01_1118_cabledBP_CAch2_a5	-26.9	0.40	0.47	2.01	0.72	0.13	0.12	0.09	0.06	0.59
	kareti_3ck_01_1118_backplane_Bch2_b7p5_7	-27.0	1.32	0.58	1.74	0.73	0.13	0.03	0.01	0.02	0.6
27~28	zambell_100GEL_02_0318	-27.4	0.29	0.27	4.22	0.77	0.10	0.01	0.02	0.01	0.67
	kareti_3ck_01_1118_backplane_Bch2_b8_7	-27.5	1.32	0.60	1.64	0.74	0.12	0.02	0.00	0.01	0.62
	mellitz_3ck_adhoc_02_081518_cabledbackplane_Opt1	-27.6	0.42	0.26	3.86	0.71	0.13	-0.03	-0.04	-0.03	0.58
	kareti_3ck_01_1118_cabledBP_CAch2_a7p5	-27.8	0.40	0.50	1.70	0.76	0.11	0.09	0.07	0.04	0.65
	kareti_3ck_01_1118_cabledBP_CAch3_b2	-27.8	0.35	0.27	2.83	0.72	0.15	0.05	0.04	0.03	0.57
	kareti_3ck_01_1118_cabledBP_CAch2_b7p5	-27.8	0.40	0.36	2.44	0.74	0.13	0.02	0.01	0.01	0.61
	mellitz_3ck_adhoc_02_072518_channels	-28.0	0.00	0.00	4.07	0.72	0.14	-0.04	-0.05	-0.04	0.58
28~29	mellitz_3ck_adhoc_02_072518_channels	-28.0	0.00	0.03	4.43	0.74	0.09	-0.08	-0.08	-0.05	0.65
	kareti_3ck_01_1118_cabledBP_CAch2_b8	-28.4	0.40	0.39	2.43	0.73	0.08	-0.03	-0.03	-0.02	0.65
	kareti_3ck_01_1118_ortho_OAch4	-28.7	0.52	0.90	1.65	0.72	0.18	0.05	0.01	0.01	0.54
29~30	heck_3ck_01_1118_cable_BKP_28dB_0p575m_more_isi	-29.4	1.16	1.07	1.53	0.75	0.11	-0.03	-0.08	-0.05	0.64
	heck_3ck_01_1118_cable_BKP_28dB_0p575m	-29.7	1.15	1.02	1.78	0.76	0.13	-0.02	-0.09	-0.06	0.63

Configuration: FFE-lite, Modified-PD lu_3ck_adhoc_01a_121218, **$b(1)_{max}$=0.6**, COM >1.5.
Package model: COM2.50 with Cd=130fF, Cp=110fF, COM2.58 with modified PD support is recommended to use.

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DFE weights from COM reference receivers

IL Range (dB)	Channel	IL (dB)	ICN (mV)	ILD (dB)	COM (dB)	DFE Weight					Equivalent 1-tap DFE Weight
						b1	b2	b3	b4	b5	
26~27	zambell_3ck_01_1118_Link_7	-26.0	0.89	0.46	3.67	0.87	0.22	0.09	0.09	0.06	0.71
	kareti_3ck_01_1118_backplane_Bch2_a5_7	-26.1	1.32	0.66	1.59	0.79	0.29	0.22	0.15	0.11	0.68
	kareti_3ck_01_1118_cabledBP_CAch2_a2p5	-26.2	0.40	0.45	2.42	0.80	0.26	0.21	0.16	0.10	0.69
	kareti_3ck_01_1118_cabledBP_CAch2_b6	-26.2	0.40	0.32	3.43	0.82	0.23	0.11	0.08	0.05	0.67
	kareti_3ck_01_1118_ortho_OAch3	-26.5	0.84	0.85	2.31	0.80	0.33	0.19	0.11	0.10	0.65
	mellitz_3ck_adhoc_02_081518_cabledbackplane_Opt2	-26.7	0.49	0.51	4.15	0.80	0.28	0.15	0.10	0.07	0.65
	kareti_3ck_01_1118_cabledBP_CAch2_a5	-26.9	0.40	0.47	2.18	0.78	0.27	0.21	0.16	0.11	0.68
	kareti_3ck_01_1118_backplane_Bch2_b7p5_7	-27.0	1.32	0.58	1.96	0.83	0.28	0.15	0.10	0.08	0.68
27~28	zambell_100GEL_02_0318	-27.4	0.29	0.27	4.36	0.89	0.21	0.08	0.07	0.05	0.74
	kareti_3ck_01_1118_backplane_Bch2_b8_7	-27.5	1.32	0.60	1.89	0.84	0.26	0.12	0.07	0.06	0.70
	mellitz_3ck_adhoc_02_081518_cabledbackplane_Opt1	-27.6	0.42	0.26	3.99	0.83	0.26	0.07	0.04	0.03	0.63
	kareti_3ck_01_1118_cabledBP_CAch2_a7p5	-27.8	0.40	0.50	1.86	0.85	0.22	0.17	0.13	0.09	0.76
	kareti_3ck_01_1118_cabledBP_CAch3_b2	-27.8	0.35	0.27	3.04	0.82	0.26	0.13	0.09	0.07	0.67
	kareti_3ck_01_1118_cabledBP_CAch2_b7p5	-27.8	0.40	0.36	2.63	0.84	0.23	0.10	0.06	0.05	0.69
	mellitz_3ck_adhoc_02_072518_channels	-28.0	0.00	0.00	4.34	0.81	0.20	0.00	-0.03	-0.02	0.61
28~29	mellitz_3ck_adhoc_02_072518_channels	-28.0	0.00	0.03	4.84	0.86	0.18	-0.07	-0.10	-0.07	0.63
	kareti_3ck_01_1118_cabledBP_CAch2_b8	-28.4	0.40	0.39	2.68	0.82	0.24	0.11	0.07	0.05	0.67
	kareti_3ck_01_1118_ortho_OAch4	-28.7	0.52	0.90	1.78	0.82	0.28	0.12	0.06	0.05	0.66
	kareti_3ck_01_1118_cabledBP_CAch2_a10	-28.9	0.40	0.54	1.56	0.86	0.20	0.15	0.12	0.08	0.77
29~30	heck_3ck_01_1118_cable_BKP_28dB_0p575m_more_isi	-29.4	1.16	1.07	1.82	0.84	0.20	0.04	-0.03	-0.02	0.69
	heck_3ck_01_1118_cable_BKP_28dB_0p575m	-29.7	1.15	1.02	2.11	0.87	0.23	0.06	-0.03	-0.01	0.71

Configuration: FFE-lite, Modified-PD lu_3ck_adhoc_01a_121218, **$b(1)_{max}$=0.7**, COM >1.5.
Package model: COM2.50 with Cd=130fF, Cp=110fF, COM2.58 with modified PD support is recommended to use.

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