Methodology Used to Determine SuperSpeed USB 10 Gbps (USB 3.1) – Gen2 Channel and Cable Assembly High Speed Compliance

Yun Ling and Kuan-Yu Chen
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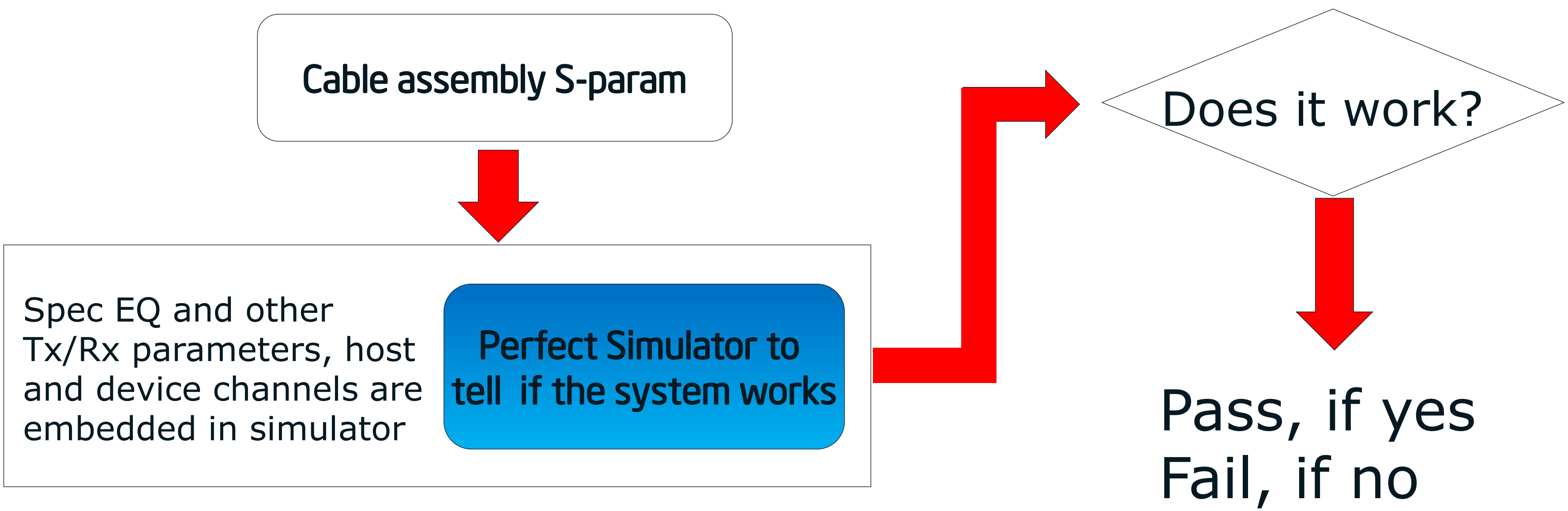
Agenda

- ❑ Objective
- ❑ Channel Electrical Metrics Review
- ❑ Correlation with End-to-End Margin
- ❑ Cable Assembly Spec and Compliance
- ❑ Discussion
- ❑ Summary

Objective

- *Develop a SuperSpeed USB 10 Gbps (USB 3.1) Gen2 cable assembly compliance specification that directly correlates to the end-to-end link performance/margin.*

In an ideal world …

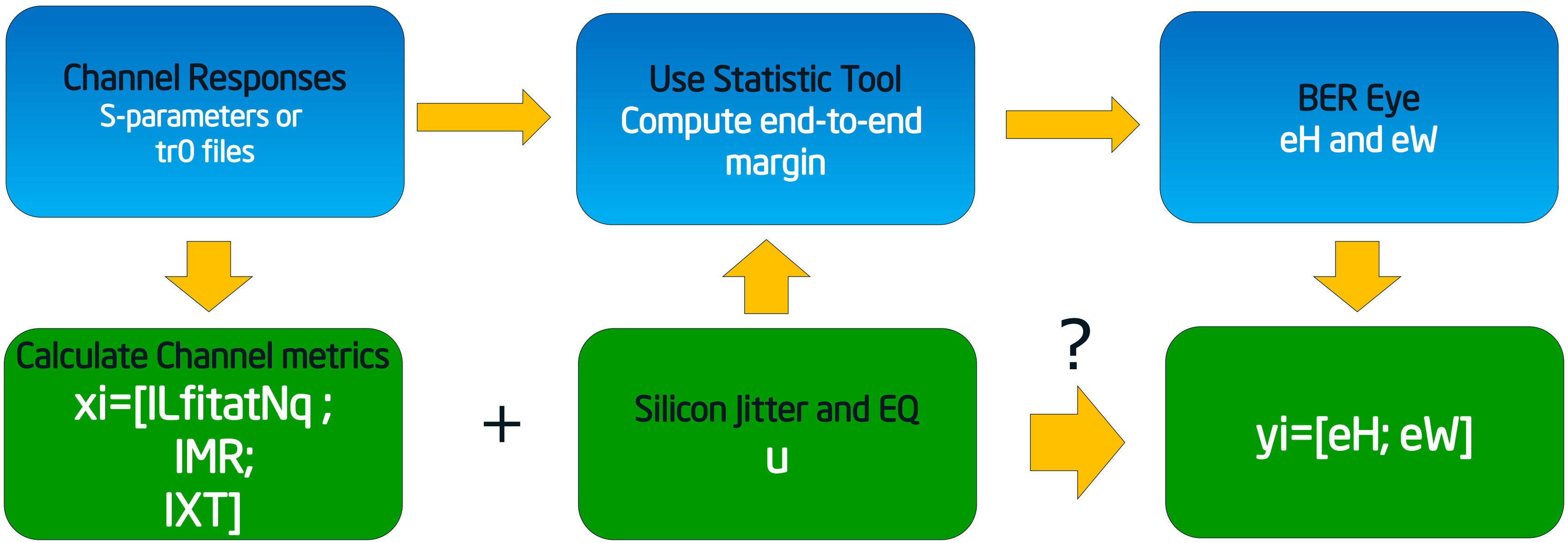


Review of channel metrics

- The following parameters are used to specify passive channel electrical performance:
  - Insertion fit at Nyquist frequency (*ILfitatNq*)
  - Integrated multi-reflection (*IMR*)
  - Integrated crosstalk (*IXT*)
- The justification of using those three parameters is based on physical interpretation and *end-to-end correlation*.

See backup

Establishing end-to-end correlation



Establish relationship

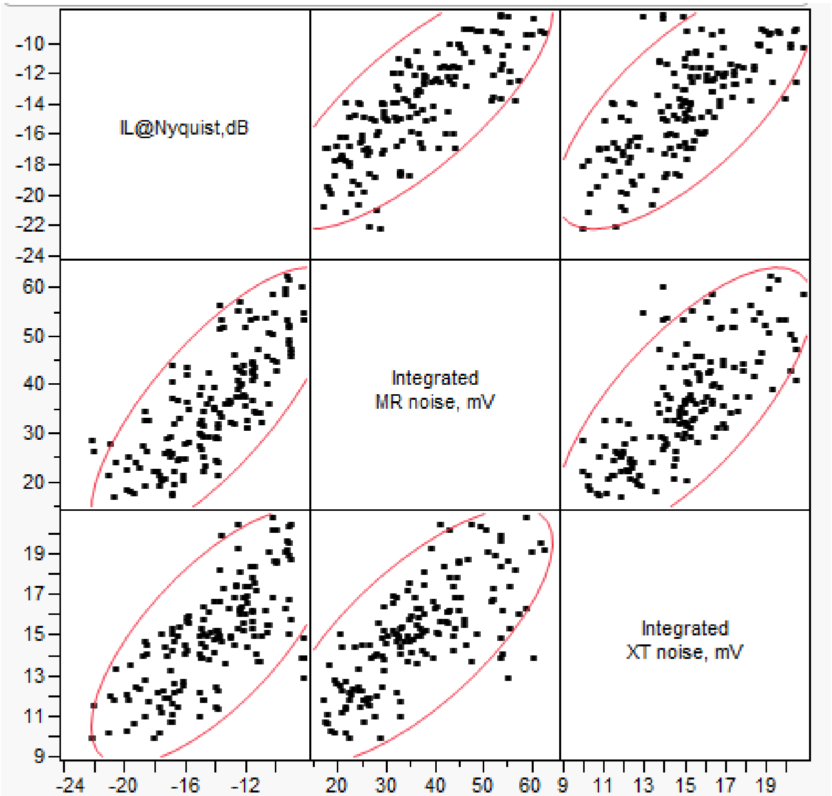
$$y=f(x; u)$$

y=End-to-end margin
f =Prediction function
X=Channel metrics
u=Silicon parameters

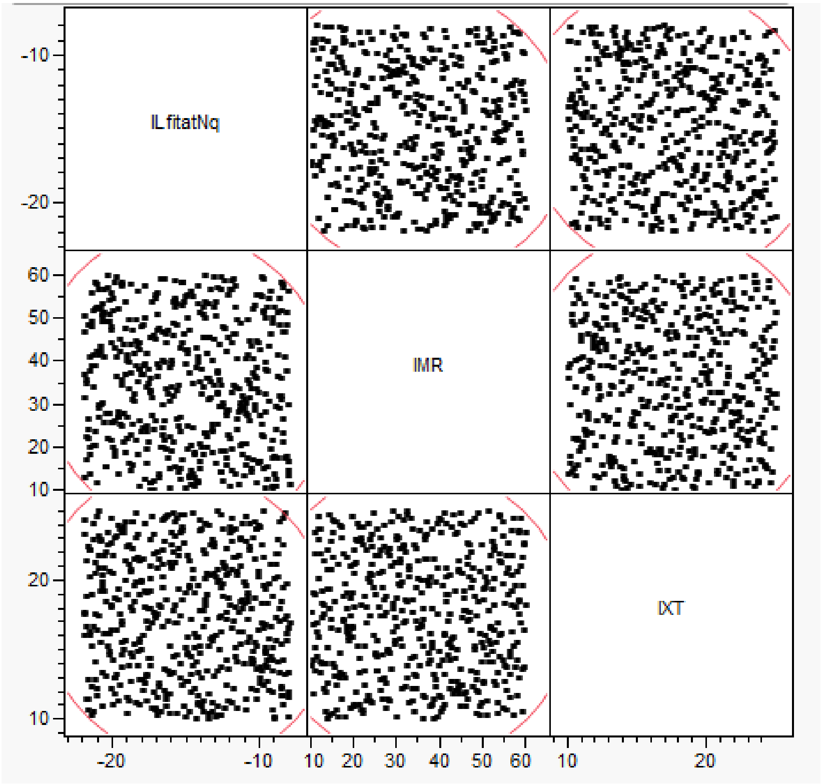
based on input {xi;u} and "observation" {yi}, i=1:n

Neural network fitting and space filling

- ❑ Powerful tool capable of fitting any smooth function.
- ❑ Important to have sufficient and well-distributed samples.



Not good



Better

Settings for end-to-end simulations

- EQ
  - Spec reference CTLE's
  - 1-tap DFE with a 50 mV max tap value
  - De-emphasis with and without pre-cursor tap (separate runs)
    - [-0.1 -0.125] or [0 -0.125].
- Buffer
  - 800 mV voltage swing (minimum voltage swing)
  - Risetime: 0.2UI (0-100%)
  - Cpad: 1.1pF (Tx) and 1.0pF (Rx)
- Jitter and noise
  - Per USB 3.1 spec
- Channels
  - ~2500 channels with well-distributed and a wide range of ILfitatNq, IMR and IXT

Fitting results

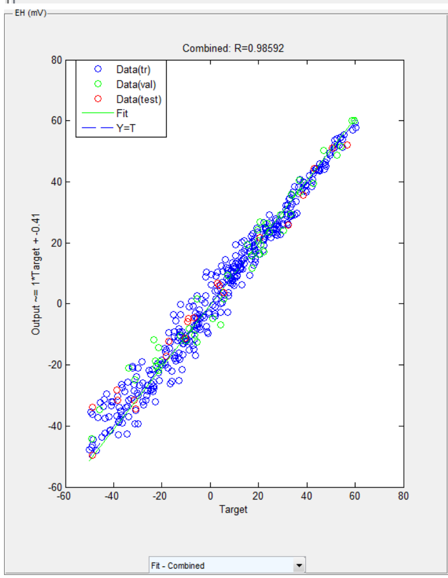
- ❑ Fitting is reasonably good.
  - Typical 95% confidence level: ~±10 mV for eye height and ~±5 ps for eye width
  - Further improvement is difficult, but we are still trying

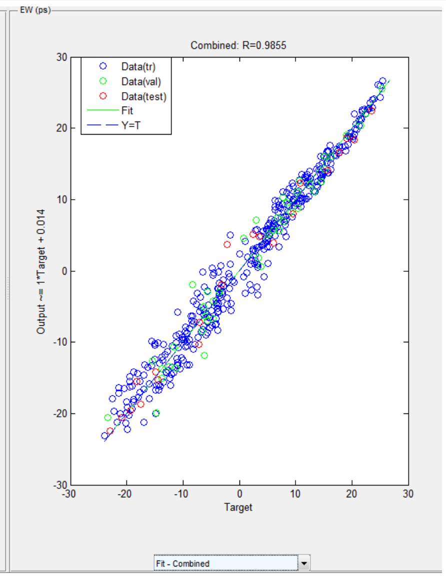
Summary: EH (mV)

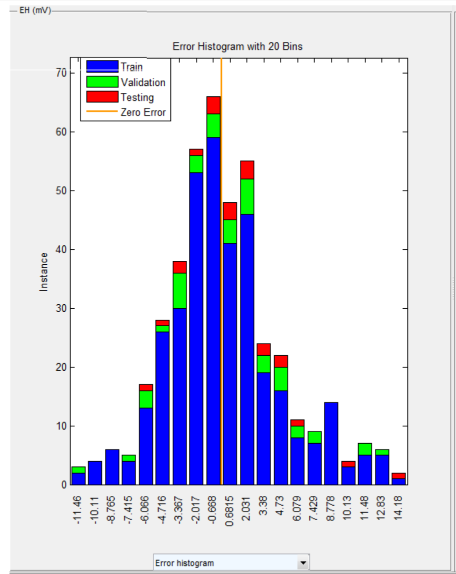
Models	R_train	R_val	R_test	RMSE_train	RMSE_val	RMSE_test
7	0.9858	0.9846	0.9908	4.5390	5.1488	5.0878

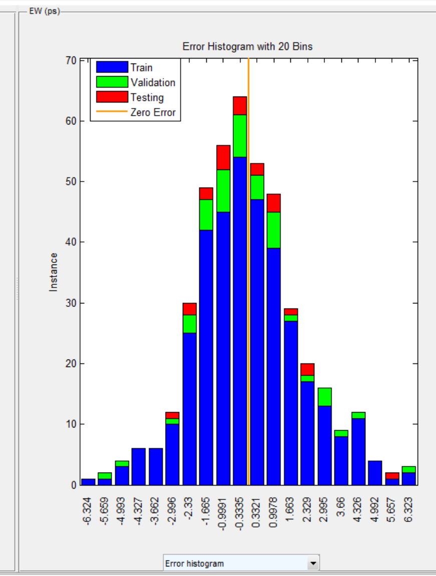
Summary: EW (ps)

Models	R_train	R_val	R_test	RMSE_train	RMSE_val	RMSE_test
7	0.9854	0.9816	0.9913	2.0997	2.2670	1.9791









Channel spec

- ❑ The fitting function or prediction formula may be served as the (passive) channel spec:

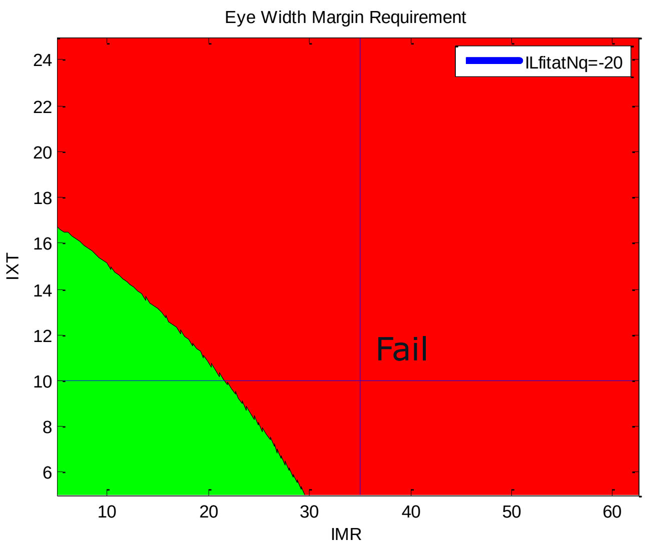
ILfitatNq, IMR, IXT

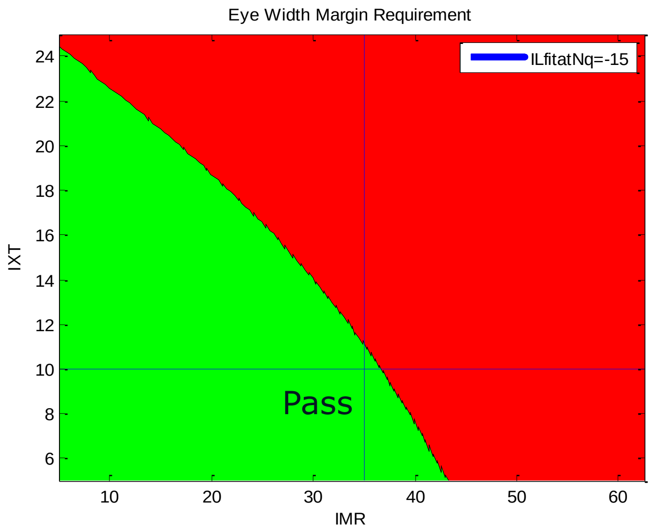
eH
eW

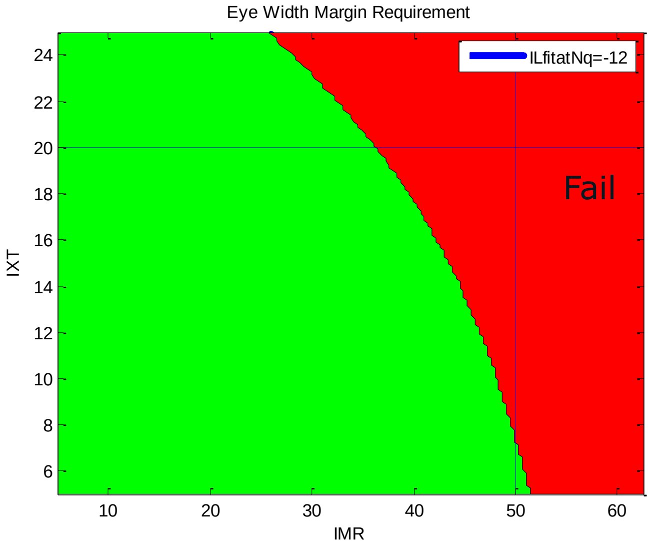
$$y=f(x)>\text{threshold}$$

- ❑ The threshold usually is zero. But we may need some guard-band (for fitting error and other factors), for example, a 5 ps threshold for eye width.
- ❑ We choose either eye height or eye width as the pass/fail criterion
  - eH and eW are correlated
  - The choice may depend on fitting quality

A few pass/fail examples

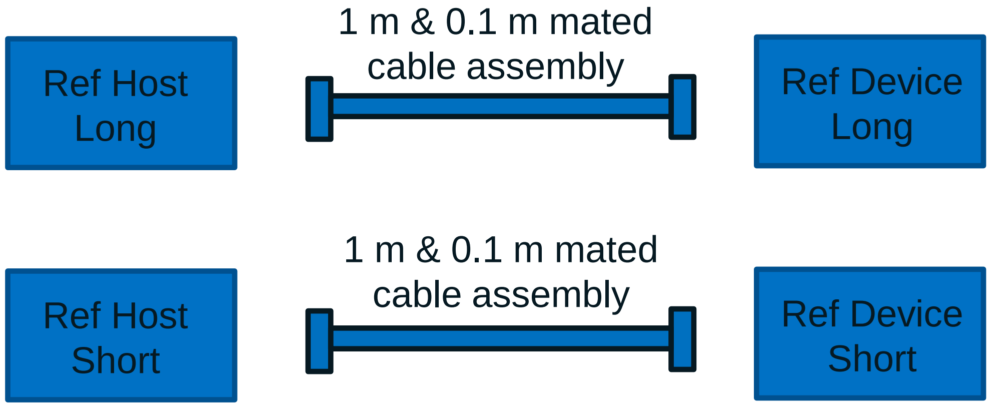






Reference hosts and devices

- Cable assembly S-param shall be combined with ref host and device to form a full channel.
  - Reference host and device may be viewed as the test fixture for cable assembly.
- Ref hosts/devices shall somewhat represent the "worst-case" hosts/devices.
- A cable assembly shall pass with both "long" host/device and "short" host/device



Long ref channel to expose loss

Short ref channel to expose multi-reflection (and crosstalk)

Long reference channel results

- BCss stands for USB 3.1 Gen1 (5 Gbps) Std-A to Std-B mated cable assembly.
- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 100 ohms.
- The pass/fail criterion set by prediction is eW < 2 ps.
- *Gen1 connectors need improvement and the cable assembly compliance test must weed them out.*

Cable Assembly	ILfitatNq	IMR, mV	IXT, mV	eH, mV	eW, ps	Prediction
Long_BCss_10cm.mat	-15.9	30.3	18.4	-6	-3	Fail
Long_BCss_14cm.mat	-16.1	29.6	18.1	-7	-4	Fail
Long_BCss_18cm.mat	-16.3	29.2	18.0	-8	-4	Fail
Long_BCss_22cm.mat	-16.5	28.7	17.3	-5	-4	Fail
Long_BCss_28cm.mat	-16.7	27.7	17.2	-6	-4	Fail
Long_BCss_32cm.mat	-16.9	27.2	16.6	-2	-1	Fail
Long_BCss_36cm.mat	-17.1	26.6	16.5	-4	-2	Fail
Long_BCss_40cm.mat	-17.3	26.0	15.9	-9	-5	Fail
Long_BCss_44cm.mat	-17.4	25.6	15.6	-9	-6	Fail
Long_BCss_48cm.mat	-17.6	25.1	15.5	-9	-5	Fail
Long_BCss_52cm.mat	-17.8	24.6	15.1	-7	-5	Fail
Long_BCss_56cm.mat	-18.0	24.2	14.8	-7	-4	Fail
Long_BCss_60cm.mat	-18.1	23.9	14.7	-5	-3	Fail
Long_BCss_64cm.mat	-18.4	23.4	14.3	-5	-3	Fail
Long_BCss_68cm.mat	-18.6	22.9	14.0	-5	-3	Fail
Long_BCss_72cm.mat	-18.9	22.4	13.7	-11	-6	Fail
Long_BCss_76cm.mat	-19.2	21.8	13.3	-11	-6	Fail
Long_BCss_80cm.mat	-19.4	21.3	13.0	-8	-5	Fail
Long_BCss_84cm.mat	-19.7	20.9	12.8	-7	-5	Fail
Long_BCss_88cm.mat	-20.0	20.5	12.5	-6	-4	Fail
Long_BCss_92cm.mat	-20.2	20.1	12.2	-5	-3	Fail
Long_BCss_96cm.mat	-20.5	19.7	12.0	-12	-6	Fail
Long_BCss_100cm.mat	-20.8	19.3	11.8	-9	-4	Fail

Long reference channel results, cont.

- BCsm stands for USB 3.1 Gen1 (5 Gbps) Std-A to Micro-B mated cable assembly.
- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 100 ohms.
- The pass/fail criterion set by prediction is eW < 2 ps.
- Gen1 connectors need improvement.

Cable Assembly	ILfitatNq	IMR, mV	IXT, mV	eH, mV	eW, ps	Prediction
Long_BCsm_10cm_100ohı	-15.7	31.9	16.7	-5	-4	Fail
Long_BCsm_14cm_100ohı	-15.8	30.9	16.6	-1	-1	Fail
Long_BCsm_18cm_100ohı	-16.0	30.1	16.3	0	0	Fail
Long_BCsm_22cm_100ohı	-16.2	29.3	16.0	2	2	Fail
Long_BCsm_28cm_100ohı	-16.5	28.6	15.7	-1	-1	Fail
Long_BCsm_32cm_100ohı	-16.6	27.9	15.5	3	3	Fail
Long_BCsm_36cm_100ohı	-16.8	27.4	15.3	1	1	Fail
Long_BCsm_40cm_100ohı	-17.0	26.9	15.1	2	1	Fail
Long_BCsm_44cm_100ohı	-17.2	26.4	14.9	3	2	Fail
Long_BCsm_48cm_100ohı	-17.4	25.9	14.7	3	3	Pass
Long_BCsm_52cm_100ohı	-17.5	25.5	14.5	2	2	Pass
Long_BCsm_56cm_100ohı	-17.7	25.1	14.4	-2	-2	Fail
Long_BCsm_60cm_100ohı	-17.9	24.6	14.2	4	2	Fail
Long_BCsm_64cm_100ohı	-18.1	24.1	14.1	-2	-2	Fail
Long_BCsm_68cm_100ohı	-18.2	23.7	13.9	2	2	Pass
Long_BCsm_72cm_100ohı	-18.5	23.3	13.7	-1	-1	Fail
Long_BCsm_76cm_100ohı	-18.7	22.8	13.5	1	1	Fail
Long_BCsm_80cm_100ohı	-19.0	22.2	13.3	-1	-2	Fail
Long_BCsm_84cm_100ohı	-19.3	21.7	13.1	2	1	Fail
Long_BCsm_88cm_100ohı	-19.5	21.2	13.0	-3	-3	Fail
Long_BCsm_92cm_100ohı	-19.8	20.8	12.8	-2	-1	Fail
Long_BCsm_96cm_100ohı	-20.1	20.4	12.6	-3	-2	Fail
Long_BCsm_100cm_100oł	-20.3	19.9	12.5	-1	-1	Fail

Long reference channel results, cont.

- BCsm stands for USB 3.1 Gen1 (5 Gbps) Std-A to Micro-B mated cable assembly.
- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 80 ohms.
- Lower cable impedance has less reflection, so more opened eye.
- The pass/fail criterion set by prediction is eW < 2 ps.

Cable Assembly	ILfitatNq	IMR, mV	IXT, mV	eH, mV	eW, ps	Prediction
Long_BCsm_10cm.mat	-15.6	27.1	17.3	7	4	Pass
Long_BCsm_14cm.mat	-15.8	28.0	17.2	5	3	Pass
Long_BCsm_18cm.mat	-16.0	27.1	16.9	4	3	Pass
Long_BCsm_22cm.mat	-16.2	26.4	16.6	4	3	Pass
Long_BCsm_28cm.mat	-16.4	25.6	16.3	4	3	Pass
Long_BCsm_32cm.mat	-16.6	24.9	16.1	5	3	Pass
Long_BCsm_36cm.mat	-16.8	24.4	15.8	5	3	Pass
Long_BCsm_40cm.mat	-17.0	24.0	15.6	7	4	Pass
Long_BCsm_44cm.mat	-17.2	23.5	15.4	6	5	Pass
Long_BCsm_48cm.mat	-17.3	23.0	15.2	5	4	Pass
Long_BCsm_52cm.mat	-17.5	22.5	15.0	6	4	Pass
Long_BCsm_56cm.mat	-17.7	22.1	14.8	3	2	Pass
Long_BCsm_60cm.mat	-18.1	21.6	14.7	3	2	Pass
Long_BCsm_64cm.mat	-18.3	21.1	14.5	3	2	Pass
Long_BCsm_68cm.mat	-18.5	20.7	14.4	4	3	Pass
Long_BCsm_72cm.mat	-18.7	20.3	14.2	5	3	Pass
Long_BCsm_76cm.mat	-19.0	19.7	13.9	6	3	Pass
Long_BCsm_80cm.mat	-19.3	19.1	13.7	4	3	Pass
Long_BCsm_84cm.mat	-19.5	18.7	13.5	1	2	Pass
Long_BCsm_88cm.mat	-19.8	18.2	13.3	3	2	Pass
Long_BCsm_92cm.mat	-20.1	17.7	13.2	2	2	Pass
Long_BCsm_96cm.mat	-20.3	17.4	13.0	2	2	Pass
Long_BCsm_100cm.mat	-20.6	16.9	12.8	3	2	Pass

80 ohm cable is better than 100 ohm cable

Long reference channel results, cont.

- Chs stands for USB 3.1 Gen2 (10 Gbps) Std-A to Std-B mated cable assembly.
- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 100 ohms.
- The pass/fail criterion set by prediction is eW < 2 ps.
- Gen2 connectors have some improvement but the margin is still at the borderline.

Cable Assembly	ILfitatNq	IMR, mV	IXT, mV	eH, mV	eW, ps	Prediction
Long_Chs_10cm.mat	-15.7	34.7	15.9	4	2	Fail
Long_Chs_14cm.mat	-15.9	33.3	16.2	4	3	Fail
Long_Chs_18cm.mat	-16.1	32.6	16.4	0	0	Fail
Long_Chs_22cm.mat	-16.2	32.2	16.1	-1	-1	Fail
Long_Chs_28cm.mat	-16.5	31.1	15.3	-1	-1	Fail
Long_Chs_32cm.mat	-16.7	30.5	14.9	1	1	Fail
Long_Chs_36cm.mat	-16.9	29.9	14.8	1	1	Fail
Long_Chs_40cm.mat	-17.0	29.3	14.4	2	1	Fail
Long_Chs_44cm.mat	-17.2	28.8	13.9	2	1	Fail
Long_Chs_48cm.mat	-17.4	28.3	13.8	2	2	Fail
Long_Chs_52cm.mat	-17.6	27.8	13.5	1	1	Fail
Long_Chs_56cm.mat	-17.8	27.3	13.2	0	0	Fail
Long_Chs_60cm.mat	-17.9	26.9	13.0	3	2	Fail
Long_Chs_64cm.mat	-18.2	26.3	12.7	2	2	Pass
Long_Chs_68cm.mat	-18.4	25.7	12.3	1	2	Pass
Long_Chs_72cm.mat	-18.7	25.1	12.0	2	2	Pass
Long_Chs_76cm.mat	-19.0	24.5	11.7	2	2	Pass
Long_Chs_80cm.mat	-19.2	23.9	11.4	-3	-2	Pass
Long_Chs_84cm.mat	-19.5	23.4	11.1	-2	-2	Pass
Long_Chs_88cm.mat	-19.8	22.9	10.8	-1	-1	Pass
Long_Chs_92cm.mat	-20.0	22.5	10.6	1	1	Pass
Long_Chs_96cm.mat	-20.3	22.0	10.3	1	1	Pass
Long_Chs_100cm.mat	-20.6	21.5	10.1	3	2	Pass

Long reference channel results, cont.

- Csm stands for USB 3.1 Gen2 (10 Gbps) Std-A to Micro-B mated cable assembly.
- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 100 ohms.
- The pass/fail criterion set by prediction is eW < 2 ps.
- Gen2 connectors have some improvement and the timing margin is decent.

Cable Assembly	ILfitatNq	IMR, mV	IXT, mV	eH, mV	eW, ps	Prediction
Long_Csm_v2_10cm_100ohn	-15.8	33.3	14.6	7	4	Pass
Long_Csm_v2_14cm_100ohn	-16.0	31.7	14.6	12	6	Pass
Long_Csm_v2_18cm_100ohn	-16.1	30.8	14.0	9	5	Pass
Long_Csm_v2_22cm_100ohn	-16.3	30.1	13.8	12	6	Pass
Long_Csm_v2_28cm_100ohn	-16.6	29.2	13.2	12	6	Pass
Long_Csm_v2_32cm_100ohn	-16.8	28.6	13.0	10	5	Pass
Long_Csm_v2_36cm_100ohn	-16.9	28.0	12.7	10	5	Pass
Long_Csm_v2_40cm_100ohn	-17.1	27.5	12.3	11	6	Pass
Long_Csm_v2_44cm_100ohn	-17.3	27.0	12.0	11	6	Pass
Long_Csm_v2_48cm_100ohn	-17.5	26.6	11.8	12	6	Pass
Long_Csm_v2_52cm_100ohn	-17.7	26.1	11.5	14	6	Pass
Long_Csm_v2_56cm_100ohn	-17.8	25.6	11.3	13	6	Pass
Long_Csm_v2_60cm_100ohn	-18.0	25.2	11.0	13	6	Pass
Long_Csm_v2_64cm_100ohn	-18.2	24.8	10.8	12	6	Pass
Long_Csm_v2_68cm_100ohn	-18.4	24.4	10.6	11	6	Pass
Long_Csm_v2_72cm_100ohn	-18.6	23.9	10.3	12	7	Pass
Long_Csm_v2_76cm_100ohn	-18.9	23.3	10.0	12	7	Pass
Long_Csm_v2_80cm_100ohn	-19.1	22.8	9.7	14	7	Pass
Long_Csm_v2_84cm_100ohn	-19.4	22.3	9.5	10	5	Pass
Long_Csm_v2_88cm_100ohn	-19.7	21.8	9.2	14	7	Pass
Long_Csm_v2_92cm_100ohn	-19.9	21.3	9.0	12	6	Pass
Long_Csm_v2_96cm_100ohn	-20.2	20.9	8.8	10	5	Pass
Long_Csm_v2_100cm_100oh	-20.5	20.5	8.5	11	6	Pass

Long reference channel results, cont.

- Csm stands for USB 3.1 Gen2 (10 Gbps) Std-A to Micro-B mated cable assembly.
- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 80 ohms.
- The pass/fail criterion set by prediction is eW < 2 ps.
- Gen2 connectors have some improvement and the timing margin is decent.

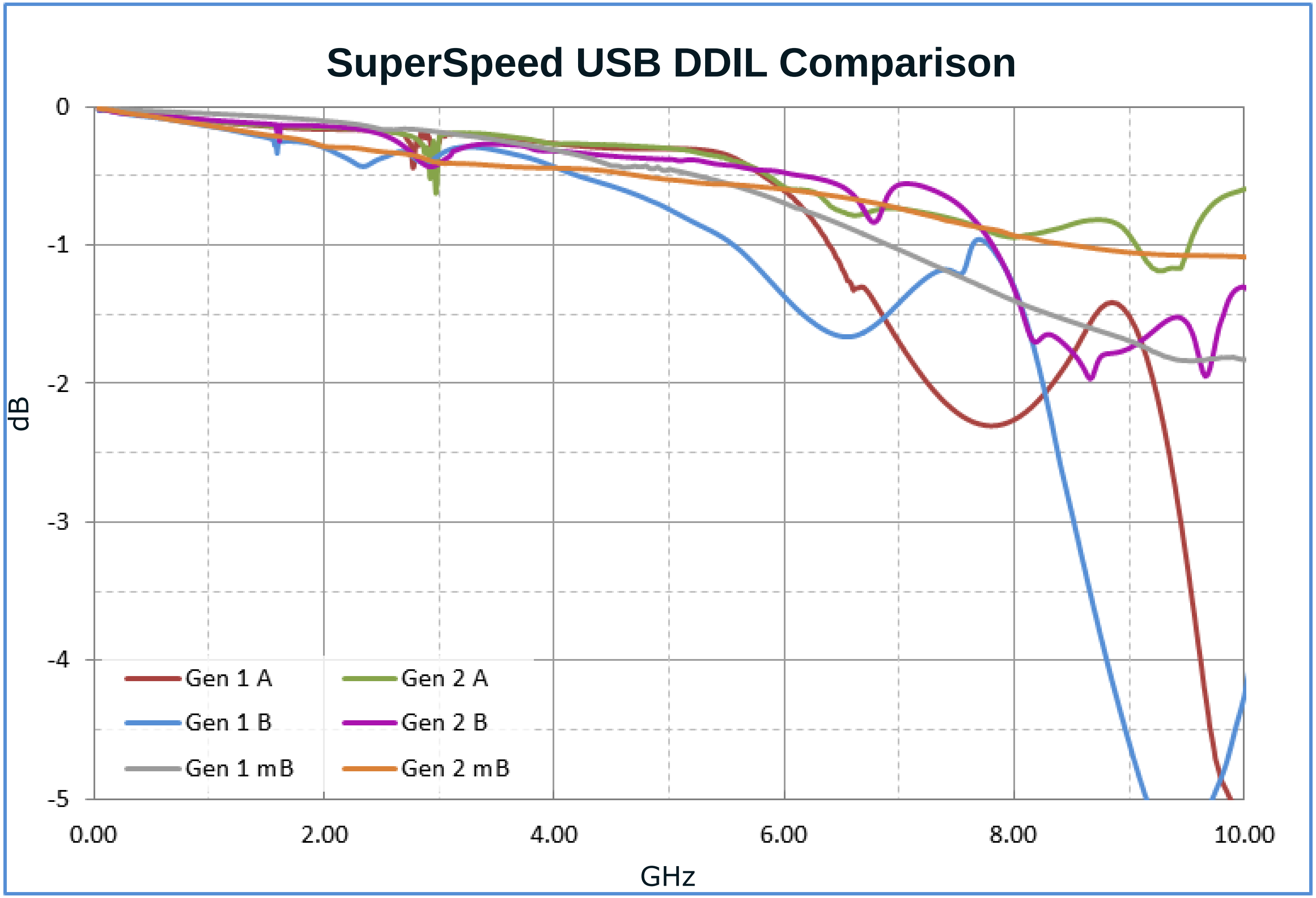
Cable Assembly	ILfitatNq	IMR, mV	IXT, mV	eH, mV	eW, ps	Prediction
Long_Csm_v2_10cm.mat	-15.7	27.8	15.3	16	8	Pass
Long_Csm_v2_14cm.mat	-15.9	27.6	15.2	13	8	Pass
Long_Csm_v2_18cm.mat	-16.1	26.8	14.9	14	8	Pass
Long_Csm_v2_22cm.mat	-16.3	26.1	14.6	14	8	Pass
Long_Csm_v2_28cm.mat	-16.5	25.3	14.1	14	7	Pass
Long_Csm_v2_32cm.mat	-16.7	24.7	13.8	13	7	Pass
Long_Csm_v2_36cm.mat	-16.9	24.1	13.4	16	8	Pass
Long_Csm_v2_40cm.mat	-17.1	23.6	13.1	17	8	Pass
Long_Csm_v2_44cm.mat	-17.3	23.1	12.8	16	8	Pass
Long_Csm_v2_48cm.mat	-17.4	22.7	12.6	12	7	Pass
Long_Csm_v2_52cm.mat	-17.6	22.2	12.3	16	8	Pass
Long_Csm_v2_56cm.mat	-17.8	21.8	12.1	17	9	Pass
Long_Csm_v2_60cm.mat	-18.0	21.4	11.8	15	7	Pass
Long_Csm_v2_64cm.mat	-18.2	20.9	11.6	16	9	Pass
Long_Csm_v2_68cm.mat	-18.3	20.6	11.4	16	9	Pass
Long_Csm_v2_72cm.mat	-18.9	20.1	11.1	17	8	Pass
Long_Csm_v2_76cm.mat	-19.2	19.5	10.8	18	9	Pass
Long_Csm_v2_80cm.mat	-19.5	19.0	10.5	18	9	Pass
Long_Csm_v2_84cm.mat	-19.7	18.5	10.2	19	10	Pass
Long_Csm_v2_88cm.mat	-20.0	18.0	10.0	20	10	Pass
Long_Csm_v2_92cm.mat	-20.3	17.5	9.8	21	10	Pass
Long_Csm_v2_96cm.mat	-20.5	17.1	9.5	21	10	Pass
Long_Csm_v2_100cm.mat	-20.8	16.7	9.3	21	10	Pass

Short reference channel results

- Csm stands for USB 3.1 Gen2 (10 Gbps) Std-A to Micro-B mated cable assembly.
- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 80 ohms.
- The pass/fail criterion set by prediction is eW < 2 ps.
- Gen2 connectors have some improvement and the timing margin is decent.

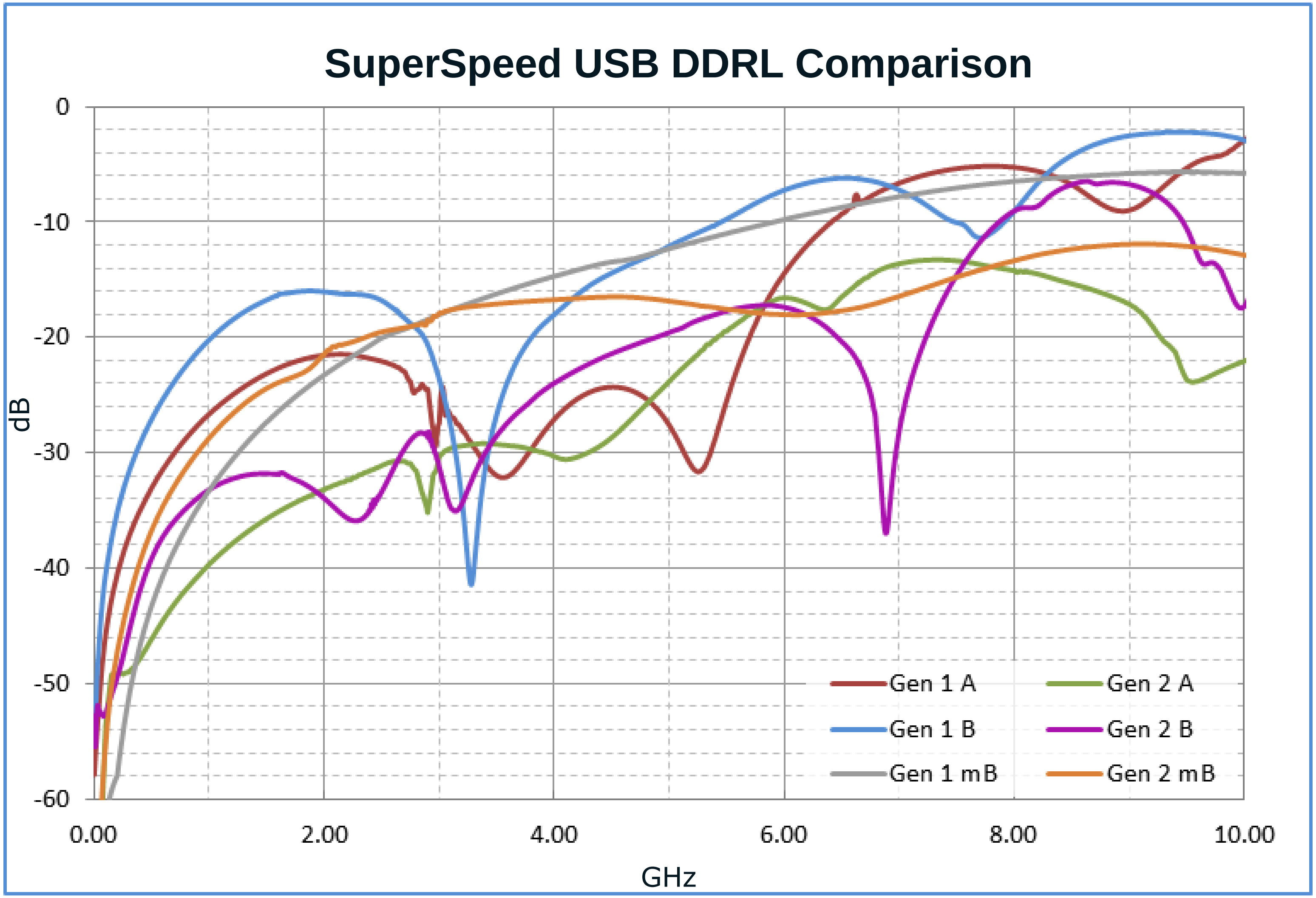
Cable Assembly	ILfitatNq	IMR, mV	IXT, mV	eH, mV	eW, ps	Prediction
Short_Csm_v2_10cm.mat	-10.3	48.7	17.7	21	11	Pass
Short_Csm_v2_14cm.mat	-10.5	47.5	17.4	22	12	Pass
Short_Csm_v2_18cm.mat	-10.7	46.4	17.0	21	12	Pass
Short_Csm_v2_22cm.mat	-10.8	45.3	16.8	19	11	Pass
Short_Csm_v2_28cm.mat	-11.1	43.7	16.1	18	11	Pass
Short_Csm_v2_32cm.mat	-11.3	42.8	15.7	16	10	Pass
Short_Csm_v2_36cm.mat	-11.5	41.9	15.4	22	12	Pass
Short_Csm_v2_40cm.mat	-11.6	41.0	15.0	23	12	Pass
Short_Csm_v2_44cm.mat	-11.8	40.2	14.7	21	12	Pass
Short_Csm_v2_48cm.mat	-12.0	39.4	14.4	22	12	Pass
Short_Csm_v2_52cm.mat	-12.2	38.7	14.1	20	12	Pass
Short_Csm_v2_56cm.mat	-12.4	38.0	13.8	23	12	Pass
Short_Csm_v2_60cm.mat	-12.5	37.2	13.6	24	13	Pass
Short_Csm_v2_64cm.mat	-12.7	36.6	13.3	25	13	Pass
Short_Csm_v2_68cm.mat	-12.9	35.9	13.1	27	12	Pass
Short_Csm_v2_72cm.mat	-13.1	35.2	12.8	25	12	Pass
Short_Csm_v2_76cm.mat	-13.4	34.3	12.5	24	12	Pass
Short_Csm_v2_80cm.mat	-13.6	33.4	12.2	26	13	Pass
Short_Csm_v2_84cm.mat	-13.9	32.6	12.0	24	13	Pass
Short_Csm_v2_88cm.mat	-14.1	31.9	11.7	24	12	Pass
Short_Csm_v2_92cm.mat	-14.4	31.0	11.5	20	12	Pass
Short_Csm_v2_96cm.mat	-14.7	30.3	11.2	25	13	Pass
Short_Csm_v2_100cm.ma	-14.9	29.7	11.0	24	12	Pass

Connector Frequency Response



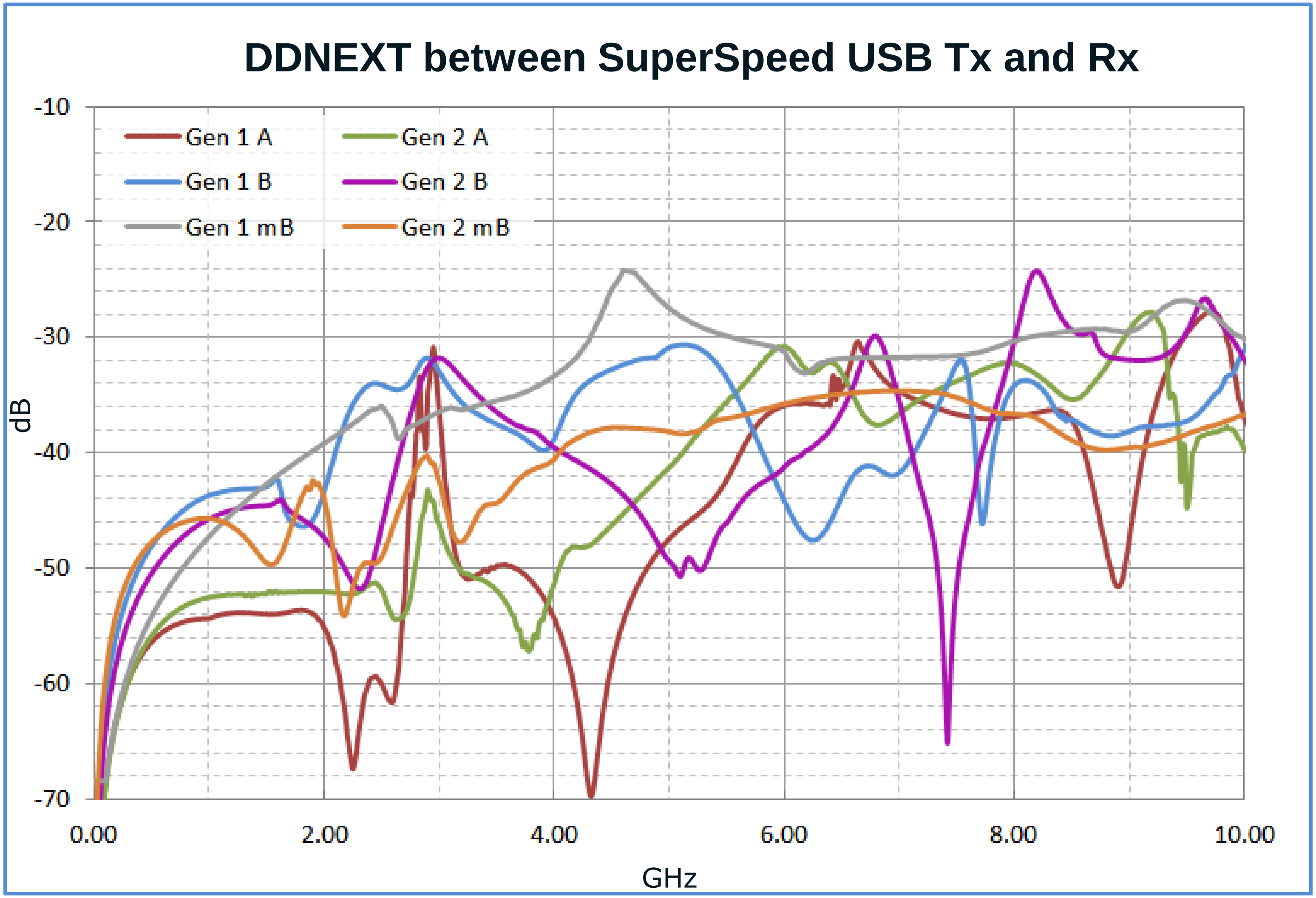
USB 3.1 Gen1 (5 Gbps); Gen2 (10 Gbps)

Connector Frequency Response, cont.



USB 3.1 Gen1 (5 Gbps); Gen2 (10 Gbps)

Connector Frequency Response, cont.



USB 3.1 Gen1 (5 Gbps); Gen2 (10 Gbps)

Observation and discussion

- ❑ Not much margin overall.
  - Options to improve margin:
    - Reference host/device with better performance
    - Better EQ capabilities
    - Tighter Si parameters
- ❑ The margin prediction function does its job.
  - Majority of failure cases are caught and some borderline passing cases are predicted “failing” – looking for further fitting accuracy improvement.
- ❑ The Gen 1 connectors need improvement, as expected.
  - Gen 2 Std-A to Gen 2 Micro-B cable has the best margin.
- ❑ The 80-ohm cable gives better margin than 100-ohm cable
  - Assume they have the same loss.

Cable assembly spec

- Informative – design targets or guidelines; traditional approach.
  - Mated impedance / return loss
  - Insertion loss
  - Crosstalk

- Normative – pass/fail, compliance criteria
  - Using the prediction function derived from neural network fitting, say, *eW = f(ILfitatNq, IMR, IXT) > eWmin*.
    - Spec should include definitions of
      - ILfitatNq, IMR an IXT
      - Reference hosts and devices
      - Standard test fixtures (requirements)
  - Other parameters
    - Mode conversion (SCD21)
    - Other EMC requirements

Summary

- Traditionally, (passive) channel electrical spec defines separate hard limits for insertion loss, return loss and crosstalk over certain frequency range.
- The shortcomings of such a methodology are:
  - Specifying limits over a frequency range is challenging and violating the limits at any frequency will fail the spec. But in reality, such channels may work just fine.
  - It does not allow tradeoffs among insertion loss, return loss and crosstalk.
    - Channels with less crosstalk or reflection may allow more insertion loss.
    - Channel with less loss can tolerate more crosstalk or reflection.

Summary

- A new approach is proposed for cable assembly compliance, using three simple parameters ILfitatNq, IMR and IXT.
- The compliance criterion is directly related to the end-to-end link performance (BER eye margin).
  - Reasonably good fit was achieved.
- The new spec allows tradeoffs among loss, reflection and crosstalk.
- Continued improvement needed
  - Fitting accuracy
  - Reference hosts/devices
  - Connector designs
  - Si parameters

Backups

Introducing Channel Electrical Metrics

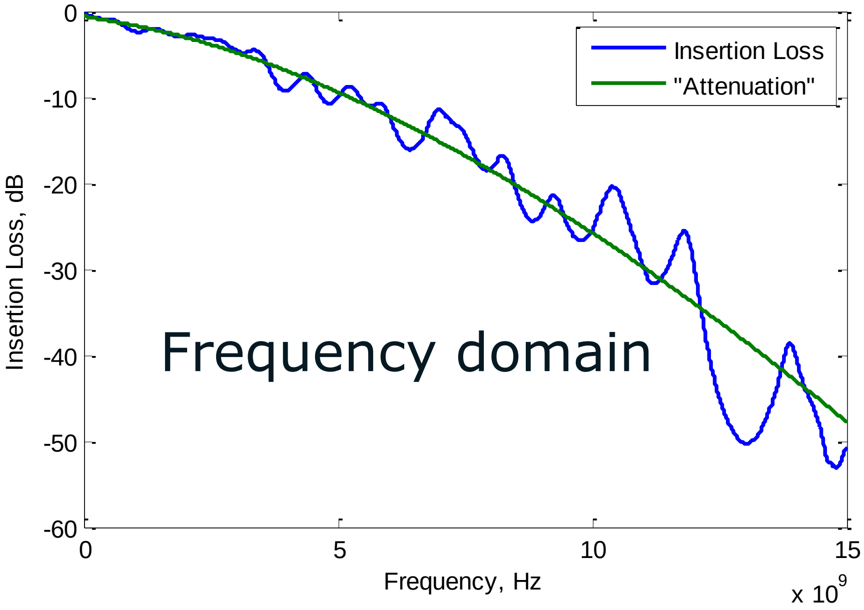
Start with Defining Channel Electrical Metrics

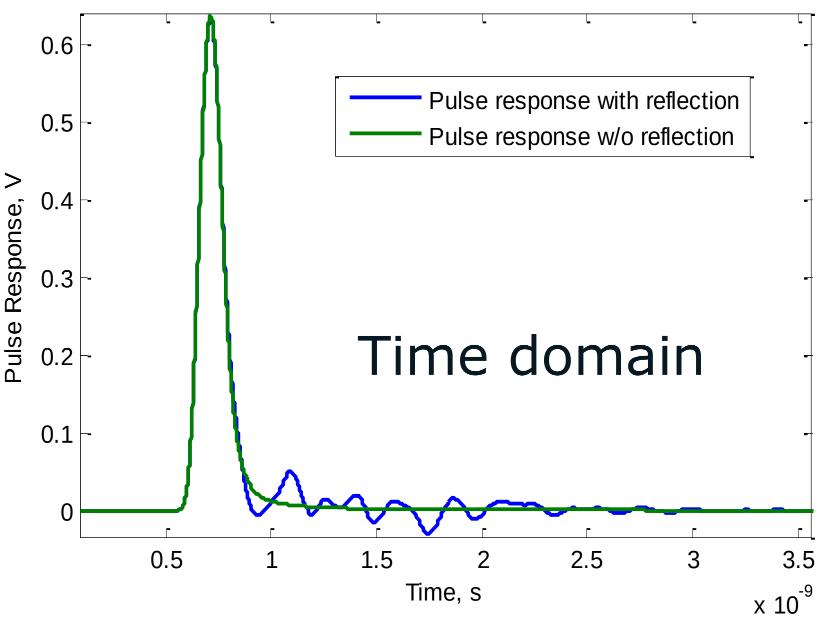
Signal Integrity Impairments

- There are three impairments that impact channel signal integrity:
  - Attenuation
  - Reflection
  - Crosstalk
- Passive channel electrical spec is all about managing those three signal integrity impairments.
- What are the appropriate metrics to describe those three impairments?

Channel Insertion Loss

- ❑ The effect of attenuation and (multi) reflection is included in channel insertion loss.

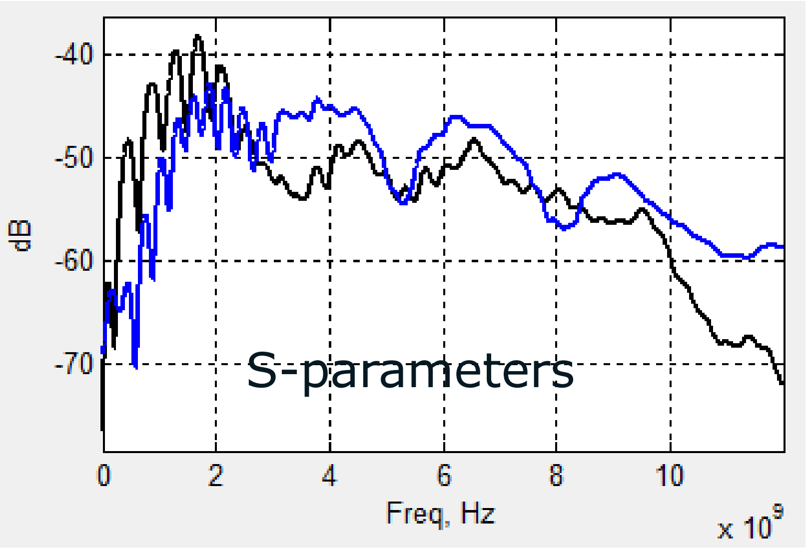


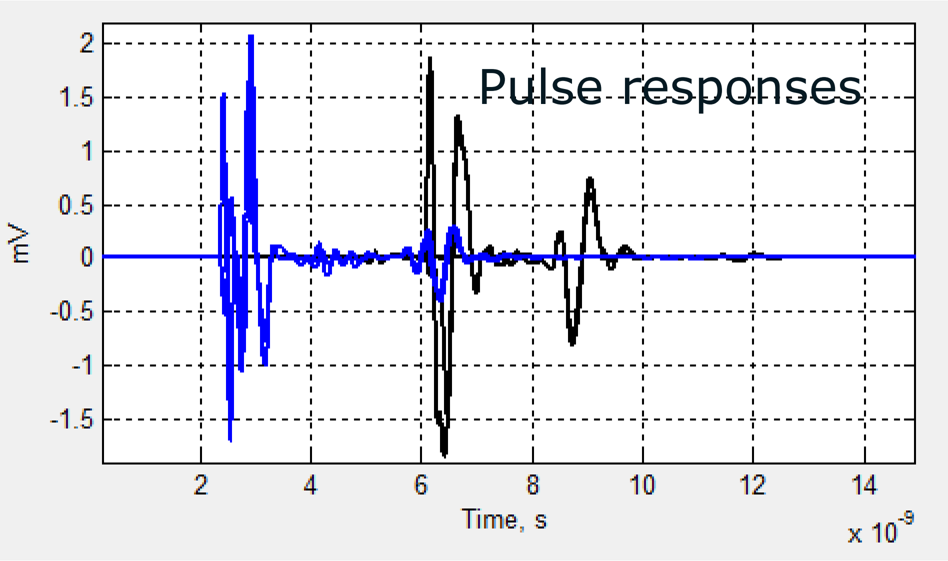


- •The smooth curve represents “attenuation” without multi-reflection.
- •The ripples represent multi-reflection.

Channel Crosstalk

- Channel crosstalk can be described in frequency (S-parameter) or time domain (pulse response) also.
  - Power sum is commonly used to combine multiple crosstalks into one.





Appropriate Channel Metrics

- The appropriate (passive) channel metrics should have the following characteristics:
  - Correlate to the channel end-to-end electrical performance.
  - Represent the three channel signal integrity impairments.
  - Are simple scalar parameters, not the whole frequency or time responses or profiles.
  - Can be easily and consistently derived from the channel frequency or time domain responses.

Learn from Backplane Community

- The backplane community has have been using the following parameters to specify passive channel electrical performance:
  - Insertion fit at Nyquist frequency
  - Integrated multi-reflection
  - Integrated crosstalk
- The justification of using those three parameters will be based on physical interpretation and end-to-end correlation.

Details of Channel Electrical Metrics

Obtaining Channel IL from tr0

- Channel IL, or more appropriately, transfer function may come from time or frequency domain.

- Deriving channel IL from time domain response is common at Intel, using a Hspice. The result is a tr0 file or a channel step response.
  - *The Tx buffer strength and risetime, and Tx and Rx terminations are included in the step response.*

- Let sr(t) be the channel step response. The channel impulse response is then simply: **ir(t)=diff(sr(t))**.

- The channel IL is then: **IL(f)=fft(ir(t))/Vsw**, where Vsw is the magnitude of the stimulus, inputting to the channel.
  - Dividing with Vsw is necessary to be consistent with the IL or transfer function definition – the magnitude of the stimulus impulse to the transfer function should be unit or 1

Obtaining Channel IL from S-parameter

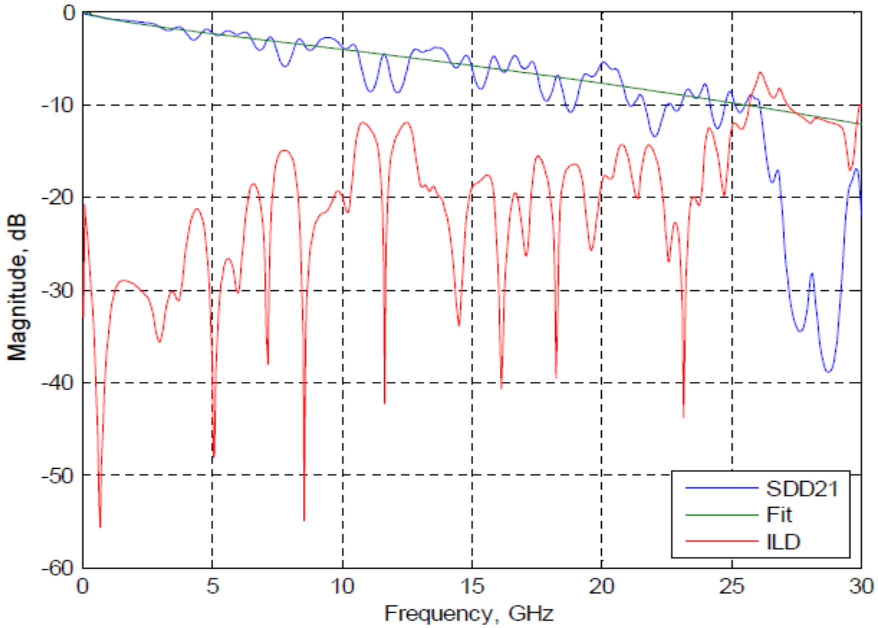
- Channel S-parameters usually does not include Tx and Rx terminations.
- So the first step is to add Tx and Rx termination to the channel S-parameters.
  - This can be done by cascading abcd-matrices (there are other ways to do so also)
  - The resulting abcd parameters can be converted to z-parameter Z(f). The transfer function IL (f) is then

$$V_{rx}(f) = IL(f)V_{in}(f)$$

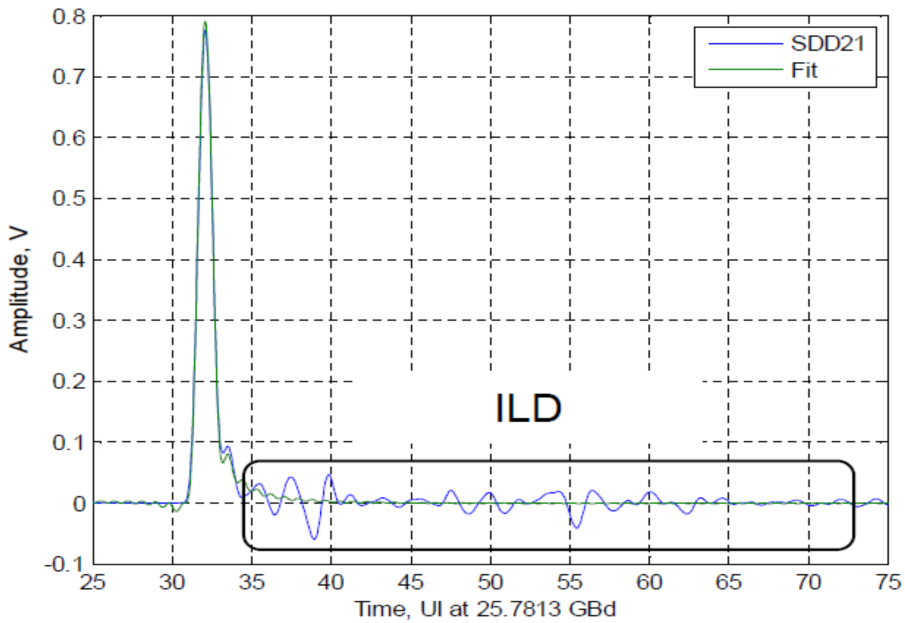
where $$IL(f) = \frac{Z(f)}{R_{tx}}$$ Z(f) is the Z-parameter

Decomposing IL

S-parameter



Pulse response

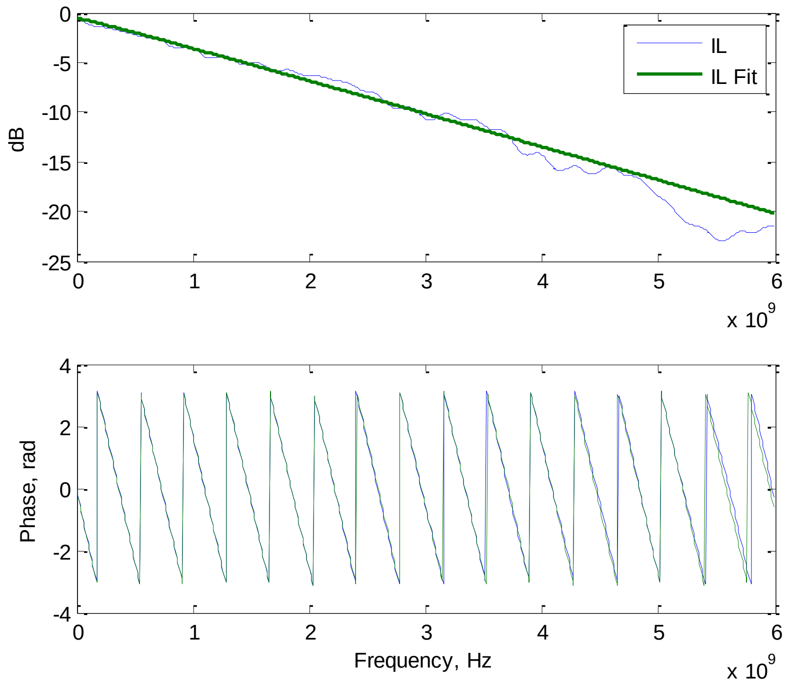


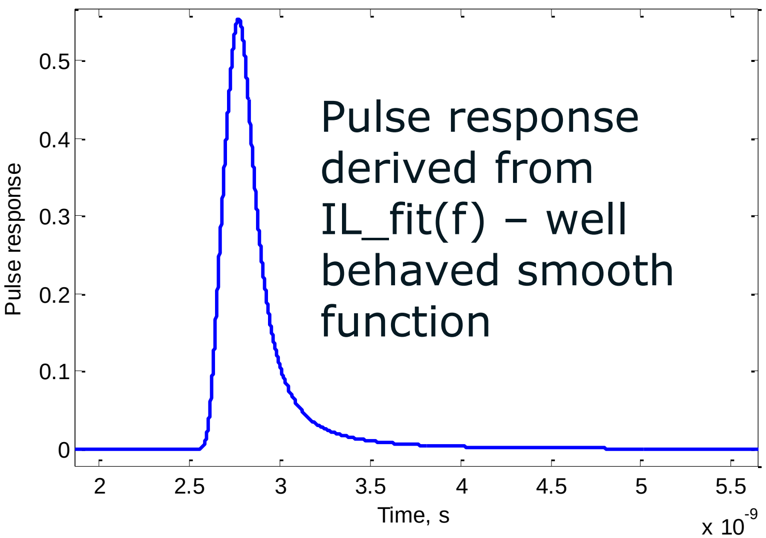
- Insertion loss fit is a smooth function fit of the insertion loss IL(f), representing the *loss without multi-reflection*.
- Insertion loss deviation represents the loss caused by *multi-reflection*.

IL(f)=IL_fit(f)+ILD(f)　　ILD(f)=IL(f)-IL_fit(f)

Insertion Loss Fit

- Use **IL_fit(f)=exp(a+b*sqrt(f)+c*f+d*f^1.5)** to fit the insertion loss
  - a – DC loss
  - b*sqrt(f) – skin effect
  - rest – dielectric loss

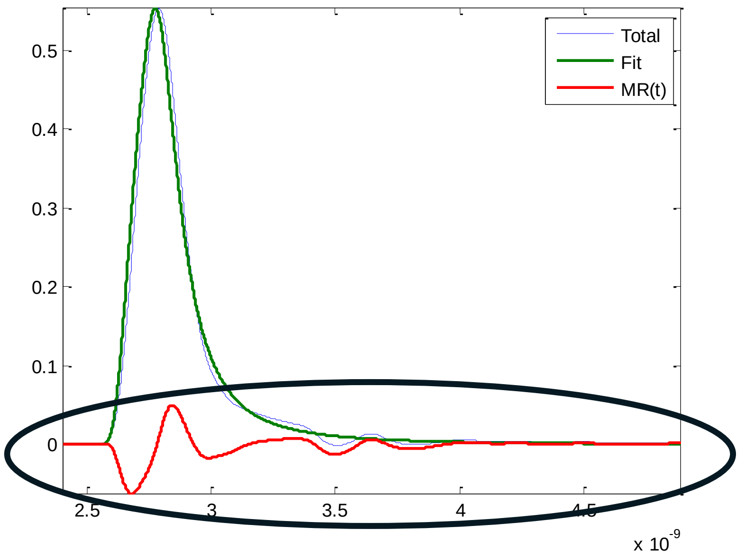


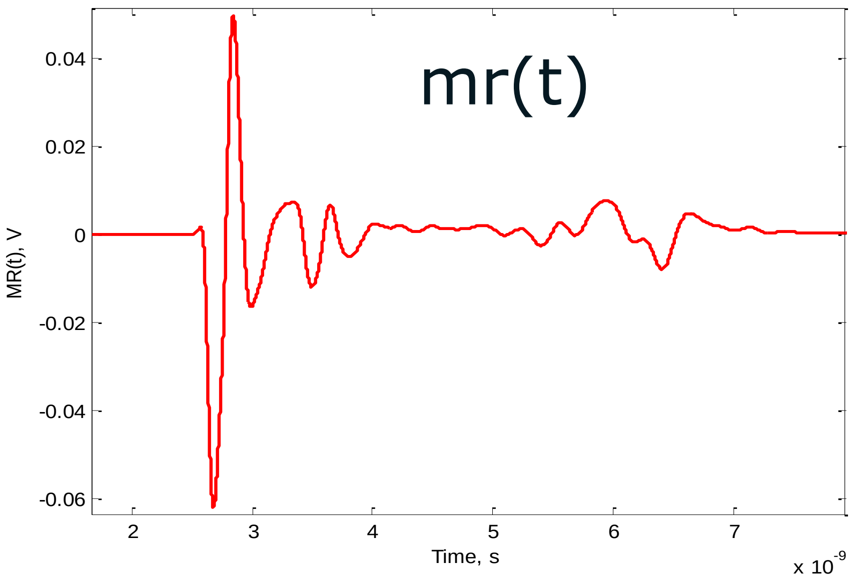


IL fit at the Nyquist frequency, IL_fit(f0), is a good measure of the amplitude and shape of the IL fit pulse response

Multi-reflection

- Multi-reflection noise in frequency domain
  - **$MR(f)=V_{in}(f)*ILD(f)$**, where $V_{in}(f)$ is the input pulse spectrum
- Multi-reflection noise in time domain
  - **$mr(t)=v_{in}(t)\otimes(ir_{IL}(t)-ir_{fit}(t))= pr_{IL}(t)-pr_{fit}(t)$**, where ir= impulse response, pr=pulse response





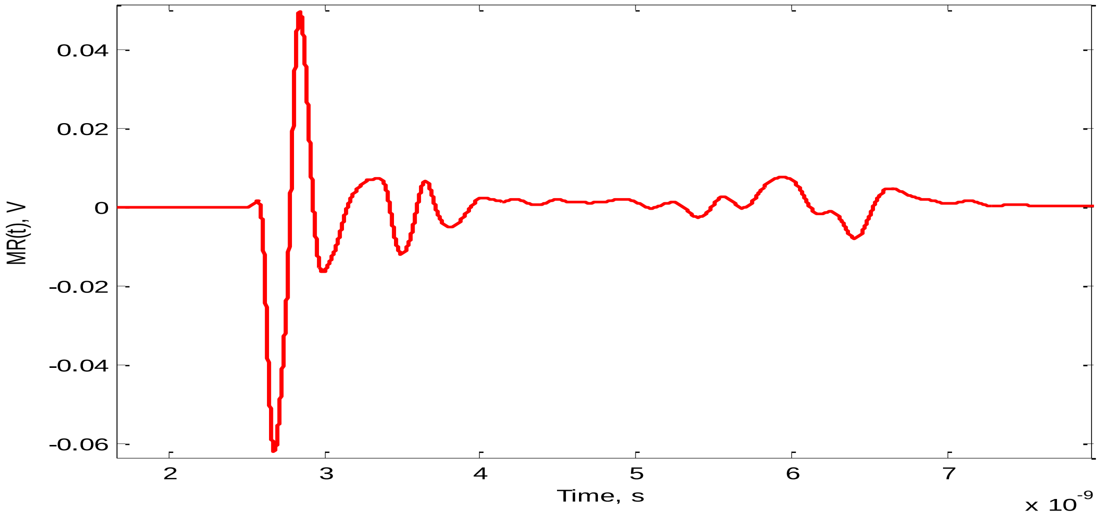
Integrated Multi-reflection

- Power due to multi-reflection is:

$$E_{mr} = \int_{-\infty}^{+\infty} \left| mr(t) \right|^2 dt = \int_{-\infty}^{+\infty} \left| MR(f) \right|^2 df$$ (Parceval's theorem)

- Define the integrated multi-reflection as

$$IMR = V_{sw} \sqrt{\frac{E_{mr}}{E}}$$ in V or mV, normalized with a factor of E



Trick about IL Decomposition

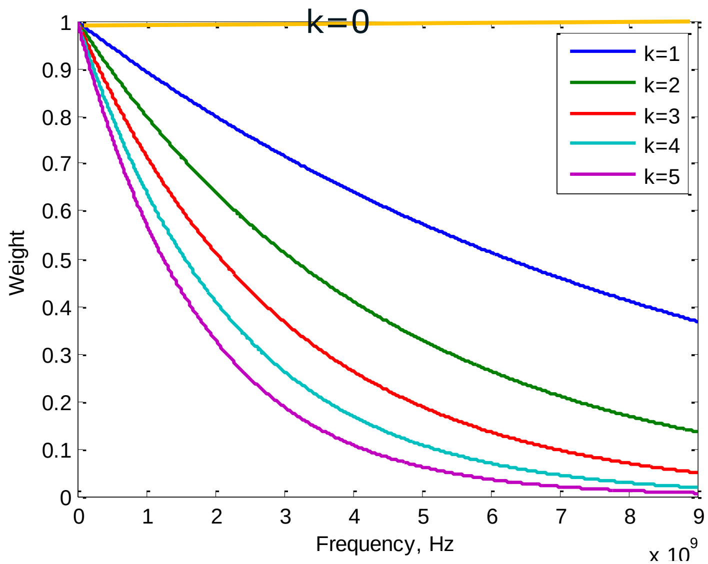
- Quality of insertion loss fit is VERY important – poor IL fit will result in a large (unreal) IMR
- Fitting is usually done from f=0 to the 2nd or 3rd harmonic
- Appropriate weighting function *must* be used in IL fit – more emphasis should be given from DC to Nyquist frequency
- Use **IL_fit(f)=exp(a+b*sqrt(f)+c*f+d*f^1.5)** as the standard fitting equation- the last term is to improve fitting accuracy
- Use **w=exp(-k*f/Δf)** as the standard weighting function for the least square fit, *where k is an adaptive factor*

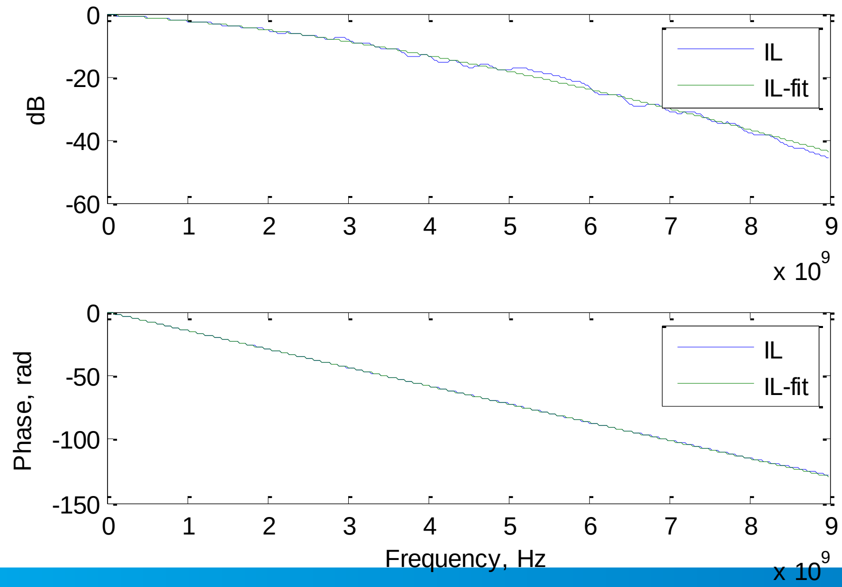
Trick about IL Decomposition, cont.

- k may vary from 0 to 20 – increasing k shifts more emphasis to lower frequencies. In the extreme case of k=0, w=1 for all frequencies, which means no weight or equal weight for all frequencies!

- *Adaptively choose k such that IMR is a minimal. This allows us to get consistent/unique IL fit for each IL*

IL fit with $\min_{k} IMR$





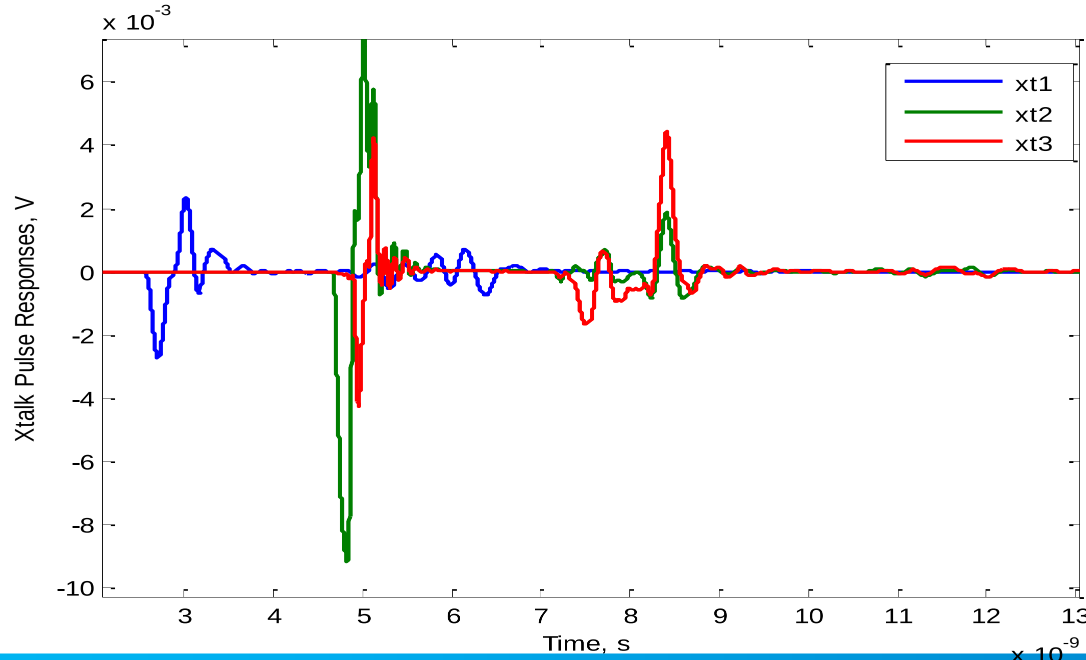
Integrated Crosstalk

- Integrated crosstalk noise is defined as the power sum of all crosstalk sources:

$$E_{xt} = \sum \int_{-\infty}^{+\infty} |xt_i(t)|^2 dt = \sum \int_{-\infty}^{+\infty} |XT_i(f)|^2 df$$

$$IXT = V_{sw} \sqrt{E_{xt} / E}$$

in V or mV, normalized with a factor E



Channel Electrical Metrics Summary

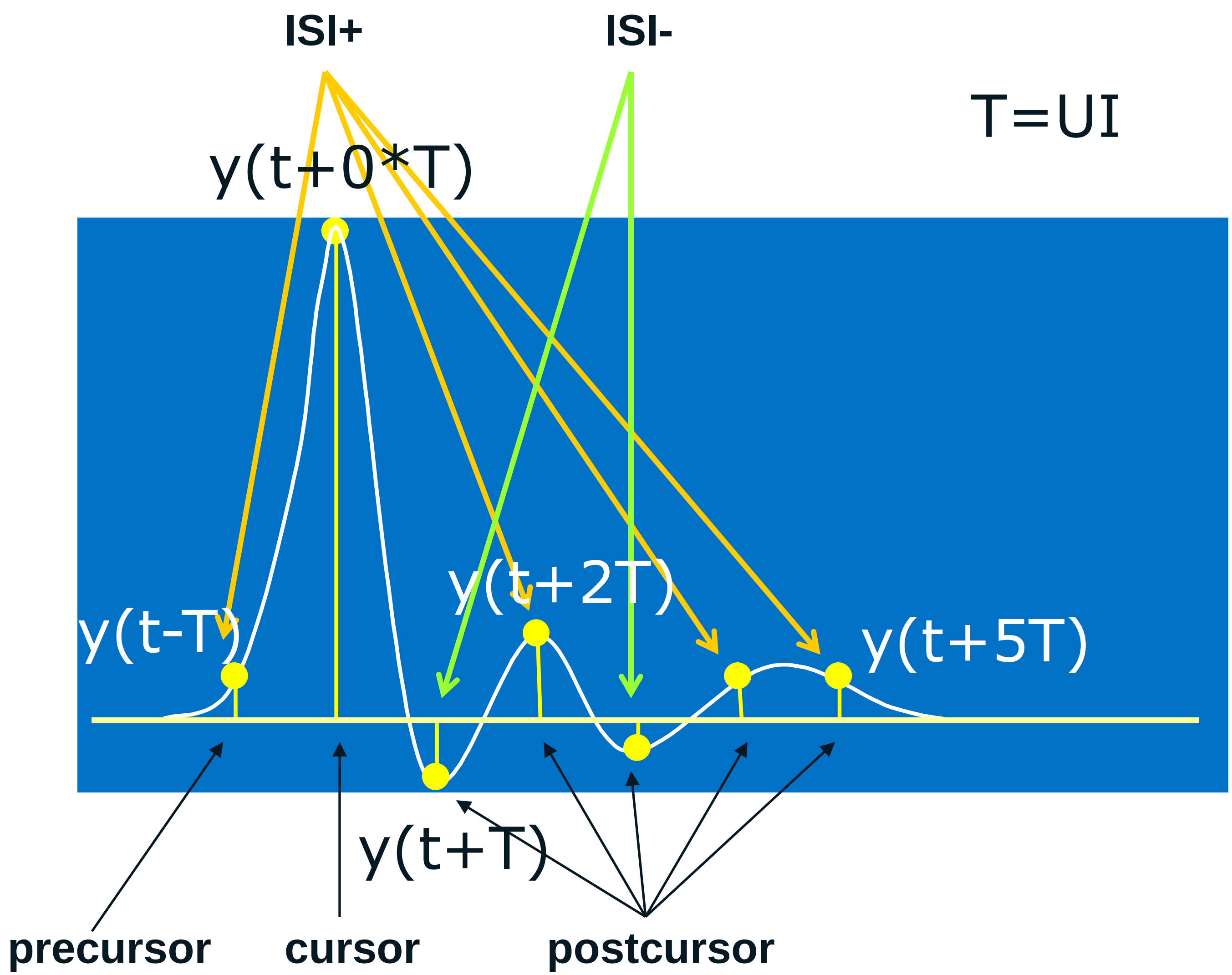
- Three simple (scalar) parameters are used as the channel electrical metrics to account for three different impairments
  - IL fit at Nyquist frequency: ILfitatNq
  - Integrated multi-reflection: IMR
  - Integrated crosstalk: IXT

- Parceval’s theorem establishes the frequency and time domain equivalency!

- An adaptive method is used for IL fit, which uniquely defines the IMR
  - The IL fit is done such that the IMR is minimized!

Channel Electrical Metrics and PDA

Start with pulse response



PDA Eye Equations

$$s_1(t) = y(t) + \sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} y(t-kT)\Big|_{y(t-kT)<0} + \sum_{i=1}^{n} \sum_{k=-\infty}^{\infty} y^i(t-kT-t_i)\Big|_{y^i(t-kT-t_i)<0}$$

cursor ISI- Sum all crosstalk ith Crosstalk

Worst-case 1 eye edge

where t_i is the relative sampling point of each crosstalk pulse response.

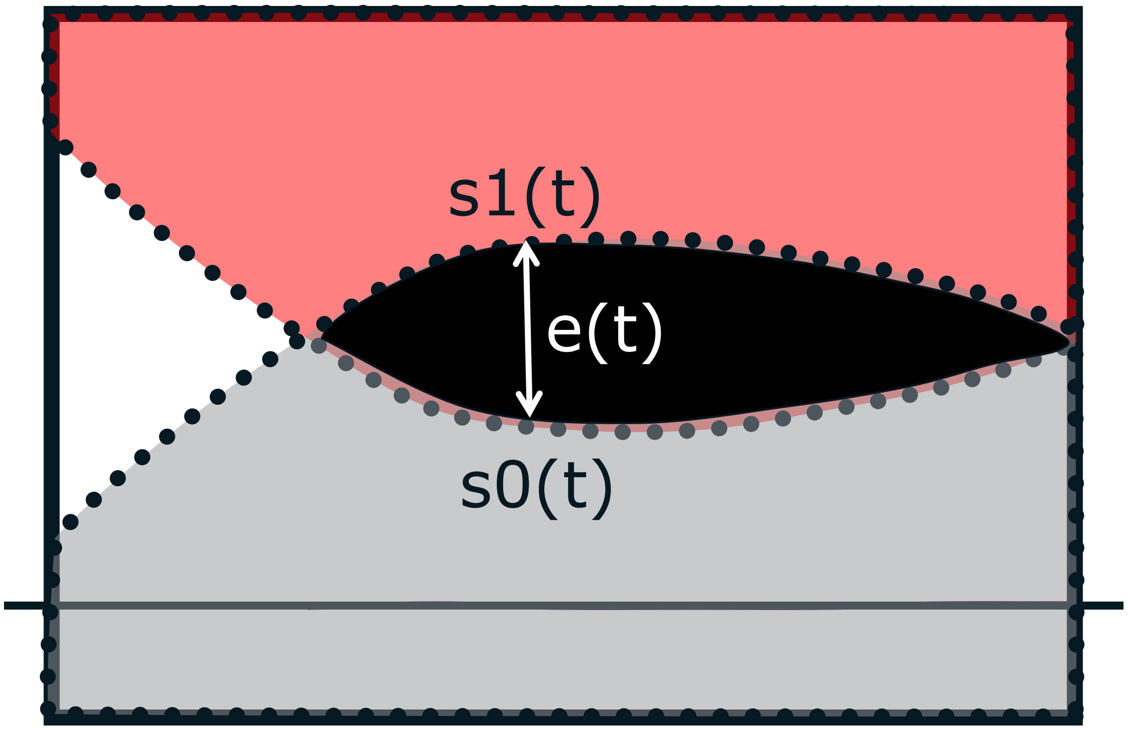
$$s_0(t) = \sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} y(t-kT)\Big|_{y(t-kT)>0} + \sum_{i=1}^{n} \sum_{k=-\infty}^{\infty} y^i(t-kT-t_i)\Big|_{y^i(t-kT-t_i)>0.}$$

ISI+

Worst-case 0 eye edge

PDA Eye

$$e(t) = s_1(t) - s_0(t) = y(t) - \sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} \left| y(t-kT) \right| - \sum_{i=1}^{n} \sum_{k=-\infty}^{\infty} \left| y^i(t-kT-t_i) \right|$$



Re-arranging the PDA Equation

Decomposing ISI pulse into attenuation and multi-reflection

$$y(t) = y_{att}(t) + mr(t)$$

PDA eye becomes:

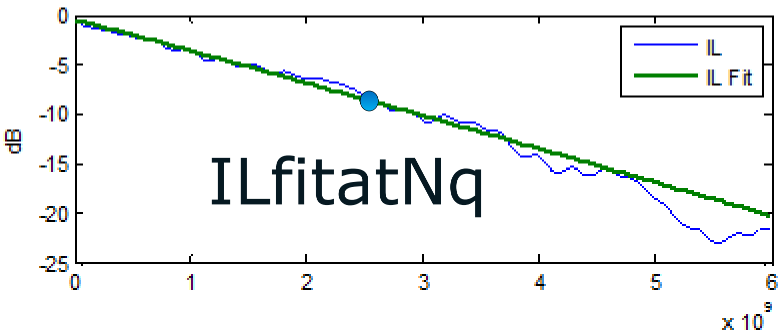
$$xt_i(t) = y^i(t)$$

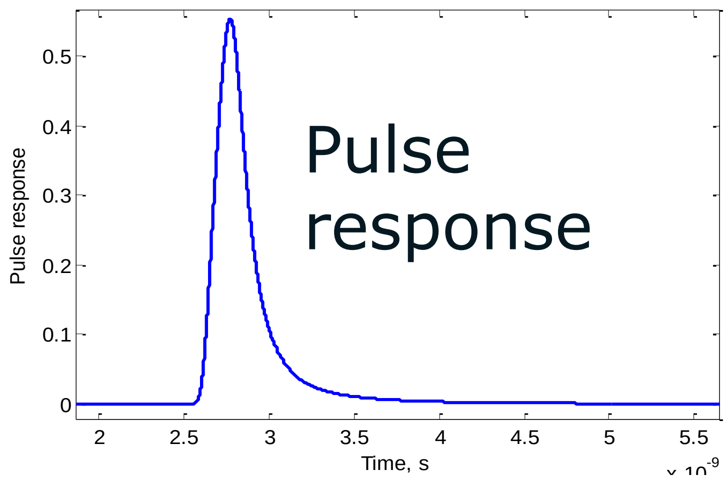
$$e(t) = \left[y_{att}(t) - \sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} \left| y_{att}(t-kT) \right| \right] - \left[\sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} \left| mr(t-kT) \right| - mr(t) \right] - \left[\sum_{i=1}^{n} \sum_{k=-\infty}^{\infty} \left| xt_i(t-kT-t_i) \right| \right]$$

Attenuation — Multi-reflection — Crosstalk

IL fit at Nyquist Frequency (ILfitatNq)

- ILfitatNq is measured at the IL fit, which is a smooth, monotonic curve (almost like straight line in dB at relatively high frequency)
- It is a reasonable representation of the “reflection-free” pulse response
- So ILfitatNq roughly catches the first term (attenuation)



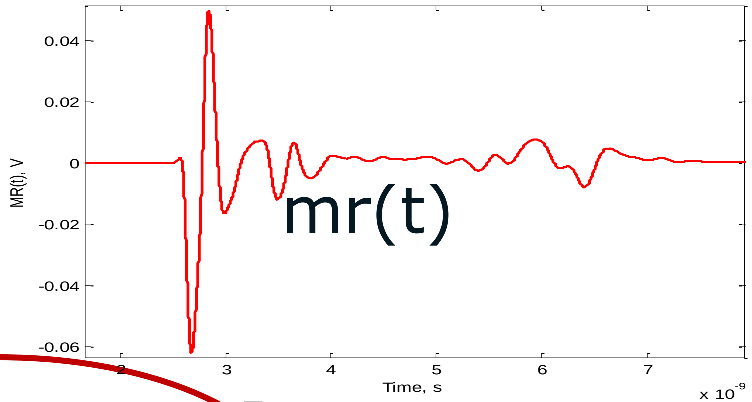


$$e(t) = \left[y_{att}(t) - \sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} \left| y_{att}(t-kT) \right| \right] - \left[\sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} \left| mr(t-kT) \right| - mr(t) \right] - \left[\sum_{i=1}^{n} \sum_{k=-\infty}^{\infty} \left| xt_i(t-kT-t_i) \right| \right]$$

Integrated Multi-reflection (IMR)

- IMR by definition is the integration of mr(t)^2. Alternatively, the integration of |mr(t)| is probably equally valid
  - Integration of power mr(t)^2 is probably better because of the Parceval's theorem of time and frequency domain equivalency
- IMR is a figure of merit for multi-reflection impact
  - Summation and integration are directly correlated

$$IMR \propto \int_{-\infty}^{+\infty} \left| mr(t) \right|^2 dt = \int_{-\infty}^{+\infty} \left| MR(f) \right|^2 df$$



$$e(t) = \left[y_{att}(t) - \sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} \left| y_{att}(t-kT) \right| \right] - \left[\sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} \left| mr(t-kT) \right| - mr(t) \right] - \left[\sum_{i=1}^{n} \sum_{k=-\infty}^{\infty} \left| xt_i(t-kT-t_i) \right| \right]$$

Integrated Crosstalk (IXT)

- IXT by definition is integration and power sum of all crosstalk sources
- In PDA, the crosstalk term is the summation of all crosstalk sources at a certain fixed phase ti
- In statistic analysis, crosstalks are often uncorrelated with random phase and power sum is probably more appropriate

$$IXT \propto \sum \int_{-\infty}^{+\infty} \left| xt_i(t) \right|^2 dt = \sum \int_{-\infty}^{+\infty} \left| XT_i(f) \right|^2 df$$

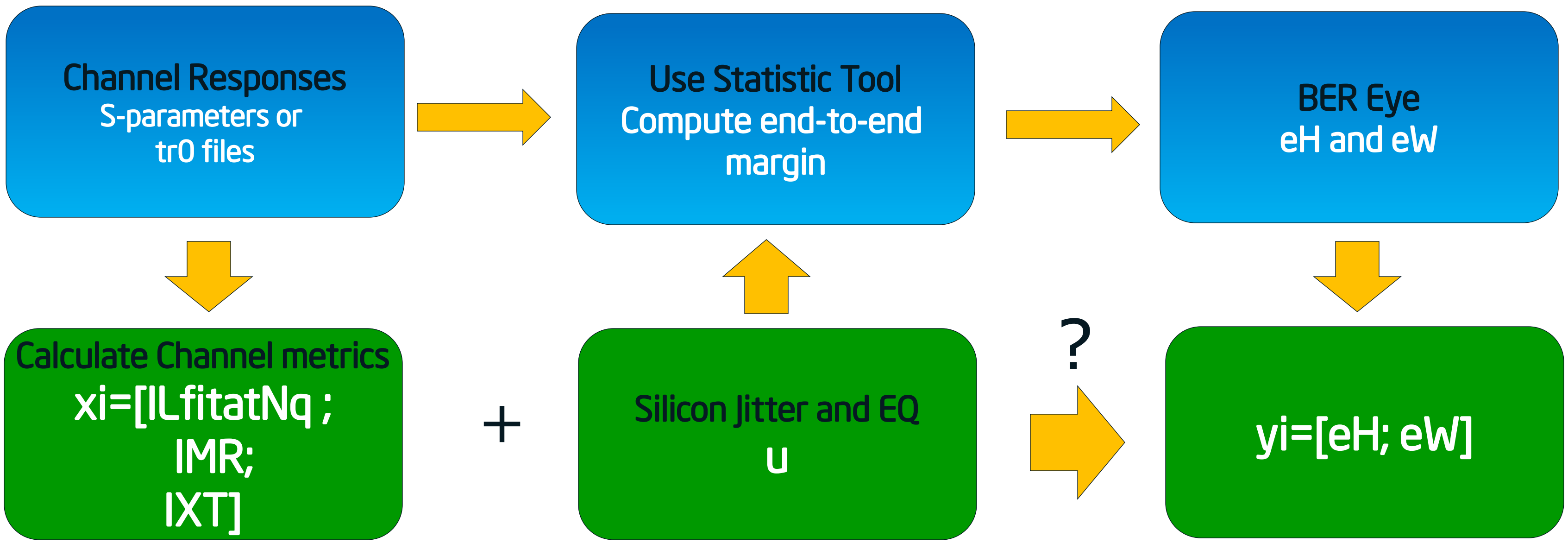
$$e(t) = \left[y_{att}(t) - \sum_{\substack{k=-\infty \\ k \neq 0}}^{\infty} \left| y_{att}(t-kT) \right| \right] - \left[\sum_{\substack{k=-\infty \\ k \neq 0}}^{\infty} \left| mr(t-kT) \right| - mr(t) \right] - \left[\sum_{i=1}^{n} \sum_{k=-\infty}^{\infty} \left| xt_i(t-kT-t_i) \right| \right]$$

Channel Metrics and PDA

- The development of the channel electrical metrics directly parallels the contribution to PDA eye by attenuation, multi-reflection and crosstalk.
- It is known that PDA eye is closely correlated with the channel end-to-end performance
- So it is reasonable to expect the proposed channel metrics to correlate with channel end-to-end performance also
- *The ultimate justification is to directly demonstrate the correlation between ILfitatNq, IMR and IXT and the end-to-end BER eye margin*

Establishing End-to-End Correlation

Flow to Establish Correlation



Establish relationship

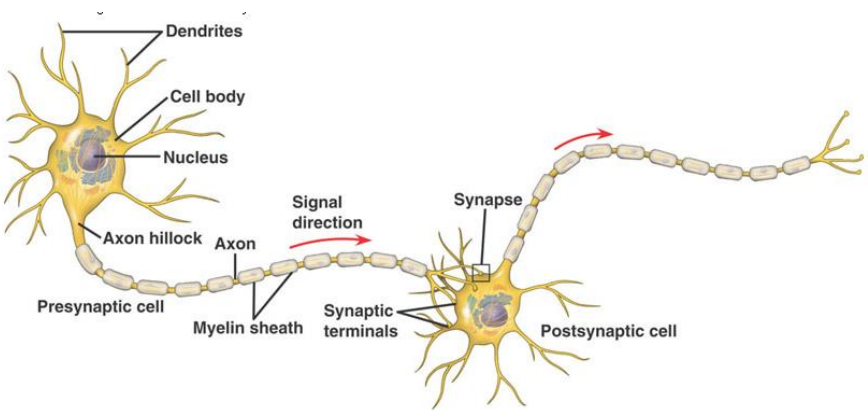
$$y=f(x;\,u)$$

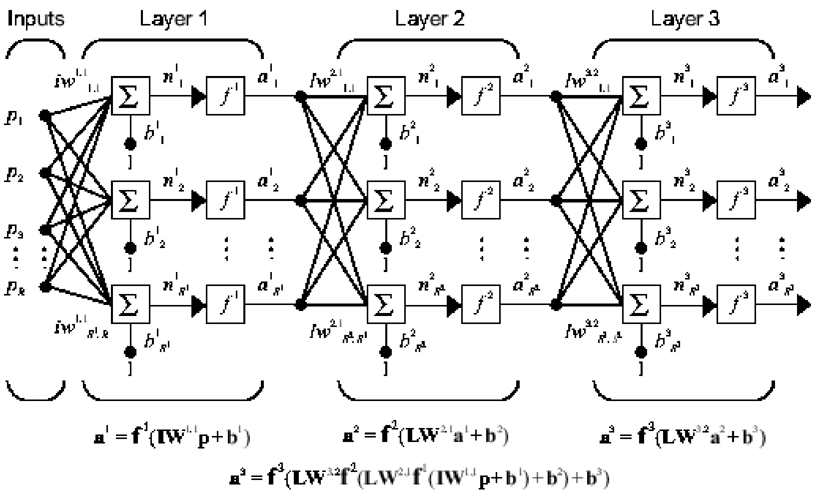
y=End-to-end margin
f =Prediction function
X=Channel metrics
u=Silicon parameters

based on input {xi;u} and “observation” {yi}, i=1:n

Neural Network Fit

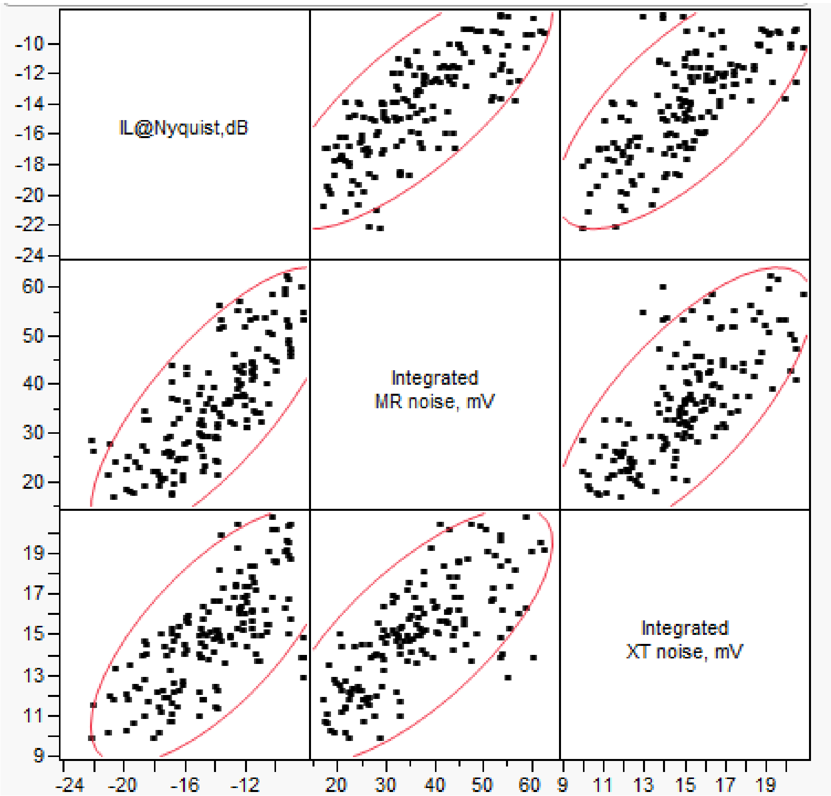
- Neural network fitting is a powerful tool, capable of fitting almost any smooth function
- Neural network fitting can be used to establish the relationship between {x; u} and {y}. (Note that u may be mostly fixed, hidden from customers)
- *The key to get good fit with neural network is appropriate space filling*



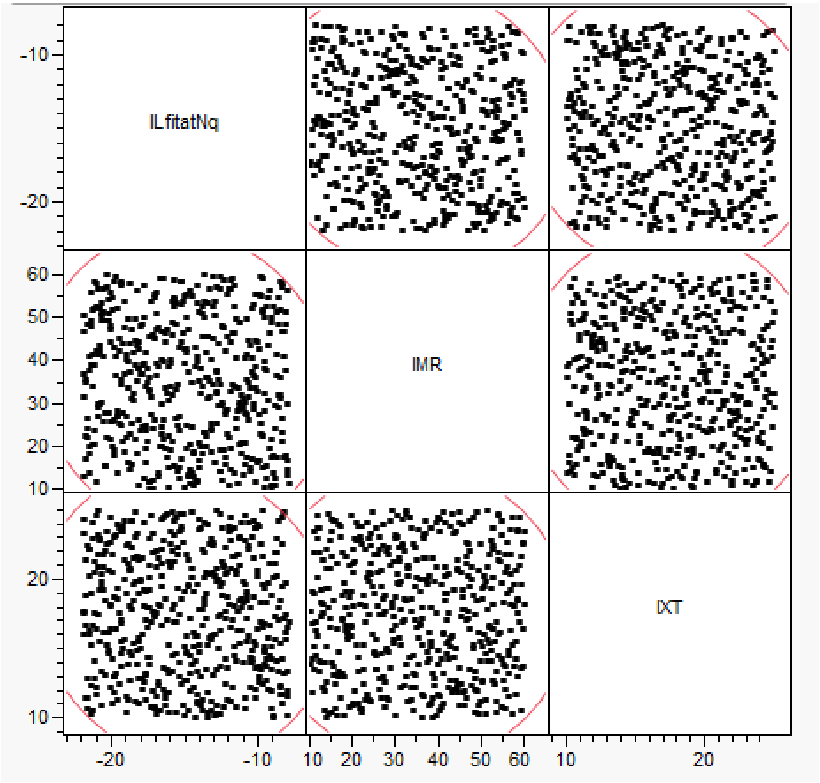


Space Filling

- The independent variables shall fill up the whole intended "design" space as uniformly as possible
- Not doing so will cause inaccurate fitting such as overfit

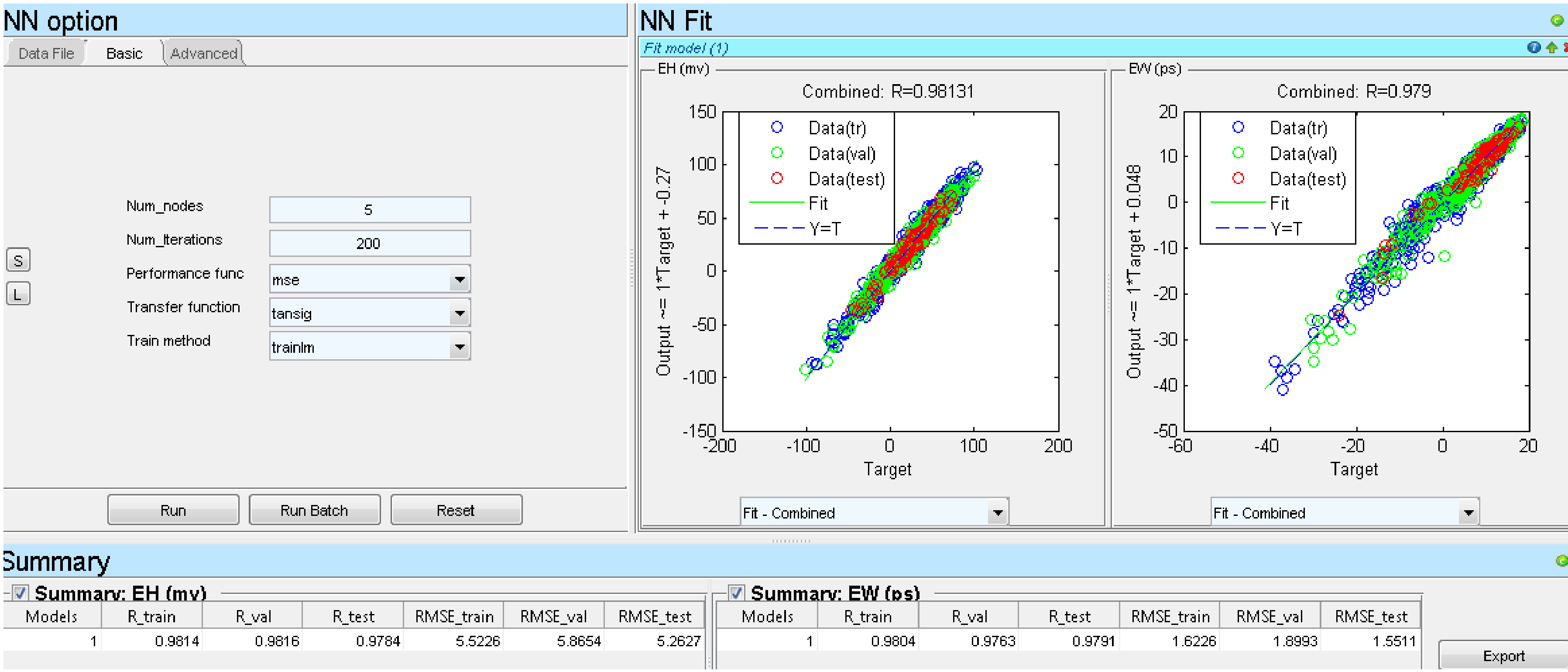


Not good



Desirable

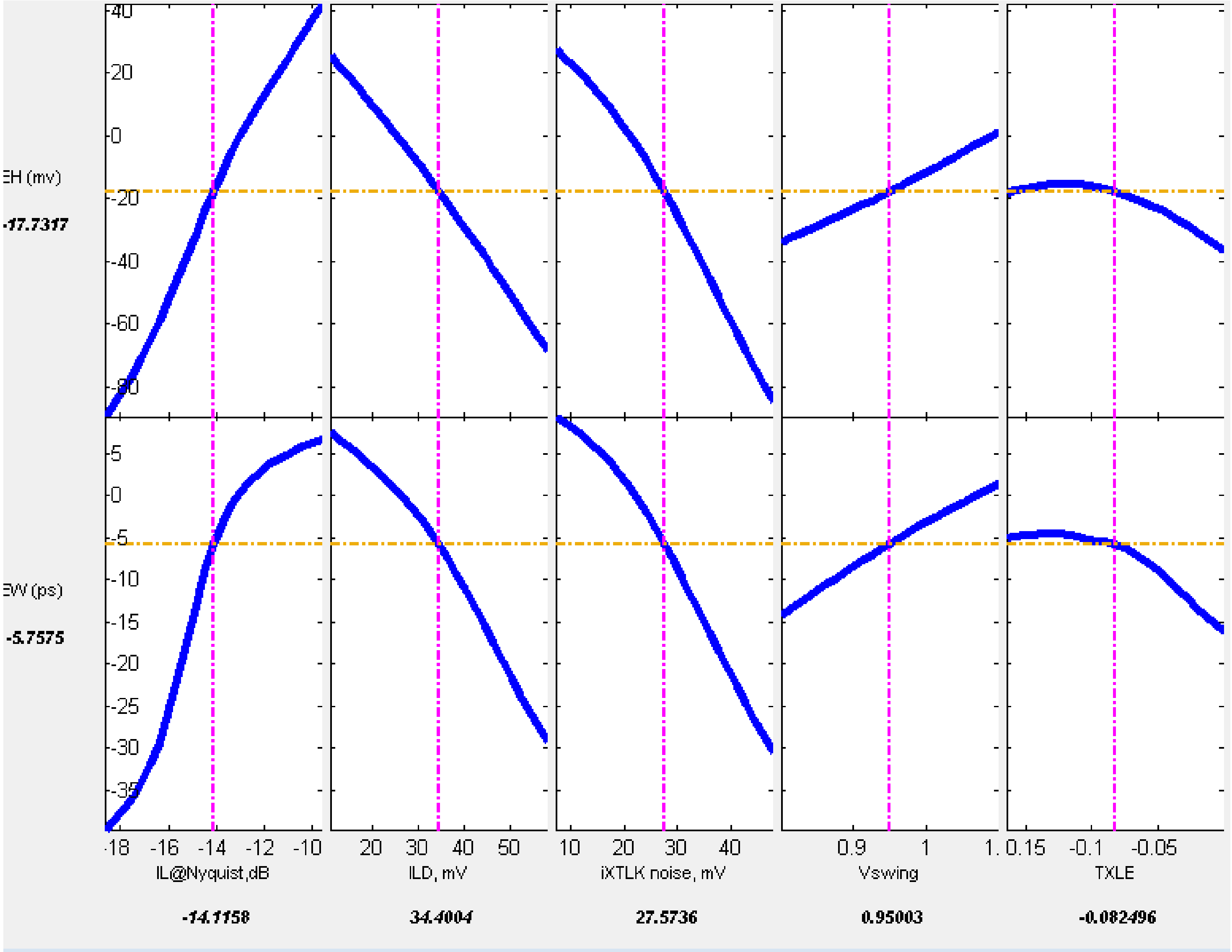
SATA Direct-Connect Rx Fit



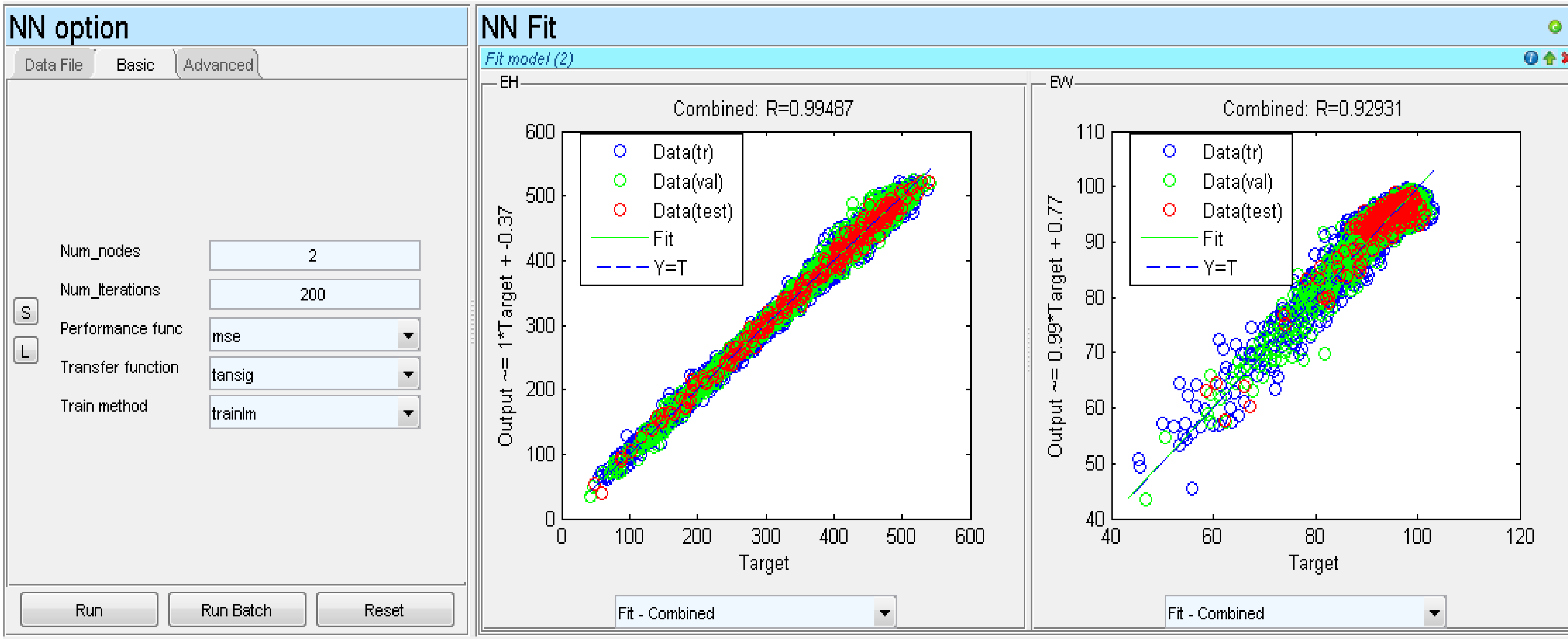
EH
R=0.981
RMSE=6 mv

EW
R=0.979
RMSE=2 ps

SATA Rx Fit Profiler



SATA Direct-Connect Tx Fit



Summary

Summary: EH

Models	R_train	R_val	R_test	RMSE_train	RMSE_val	RMSE_test
2	0.9950	0.9944	0.9960	10.3157	10.8315	9.5388

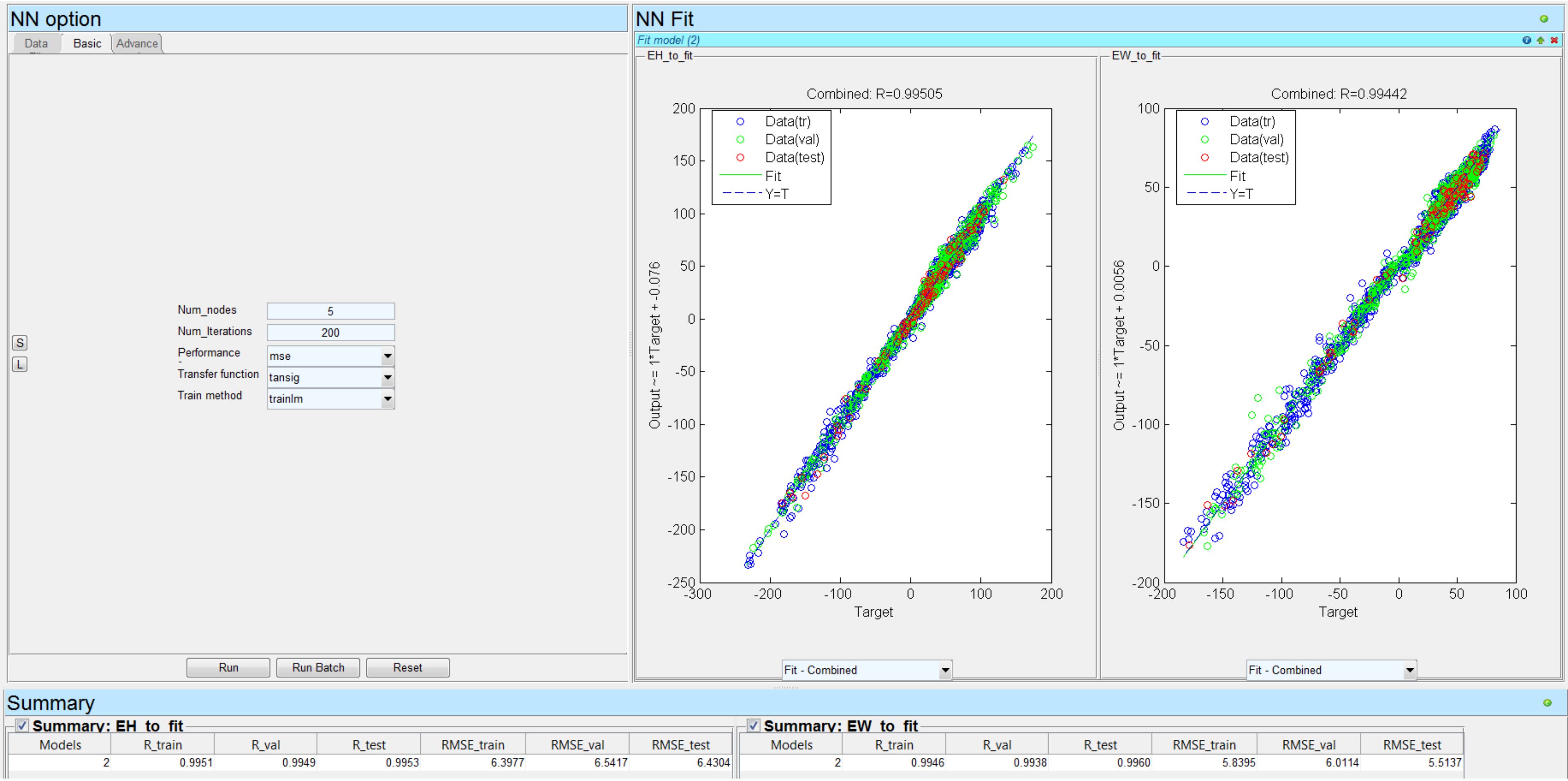
Summary: EW

Models	R_train	R_val	R_test	RMSE_train	RMSE_val	RMSE_test
2	0.9277	0.9338	0.9231	2.3661	2.2775	2.3558

Export

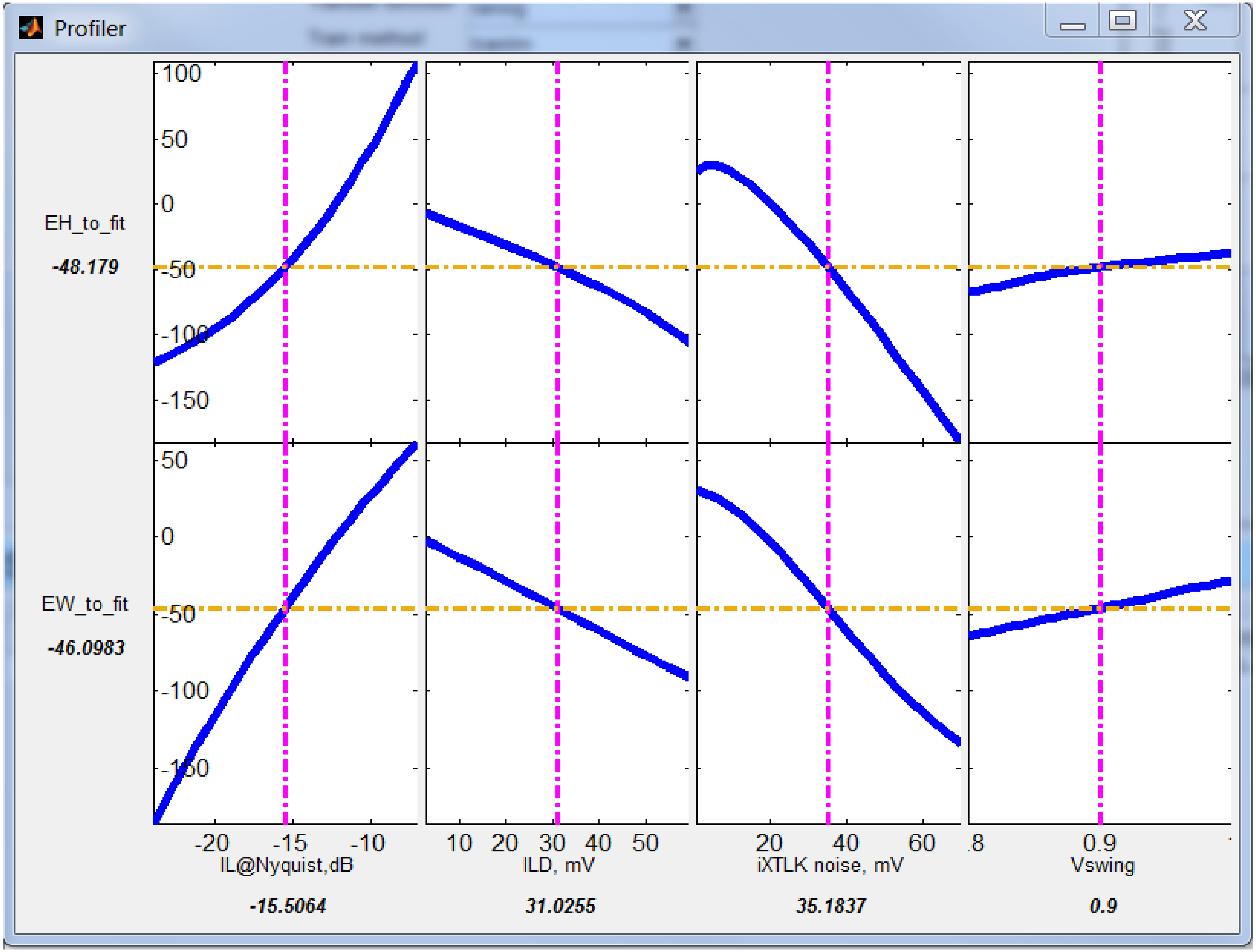
Very good fit for EH and reasonable fit for EW

USB 3 Rx Fit Quality

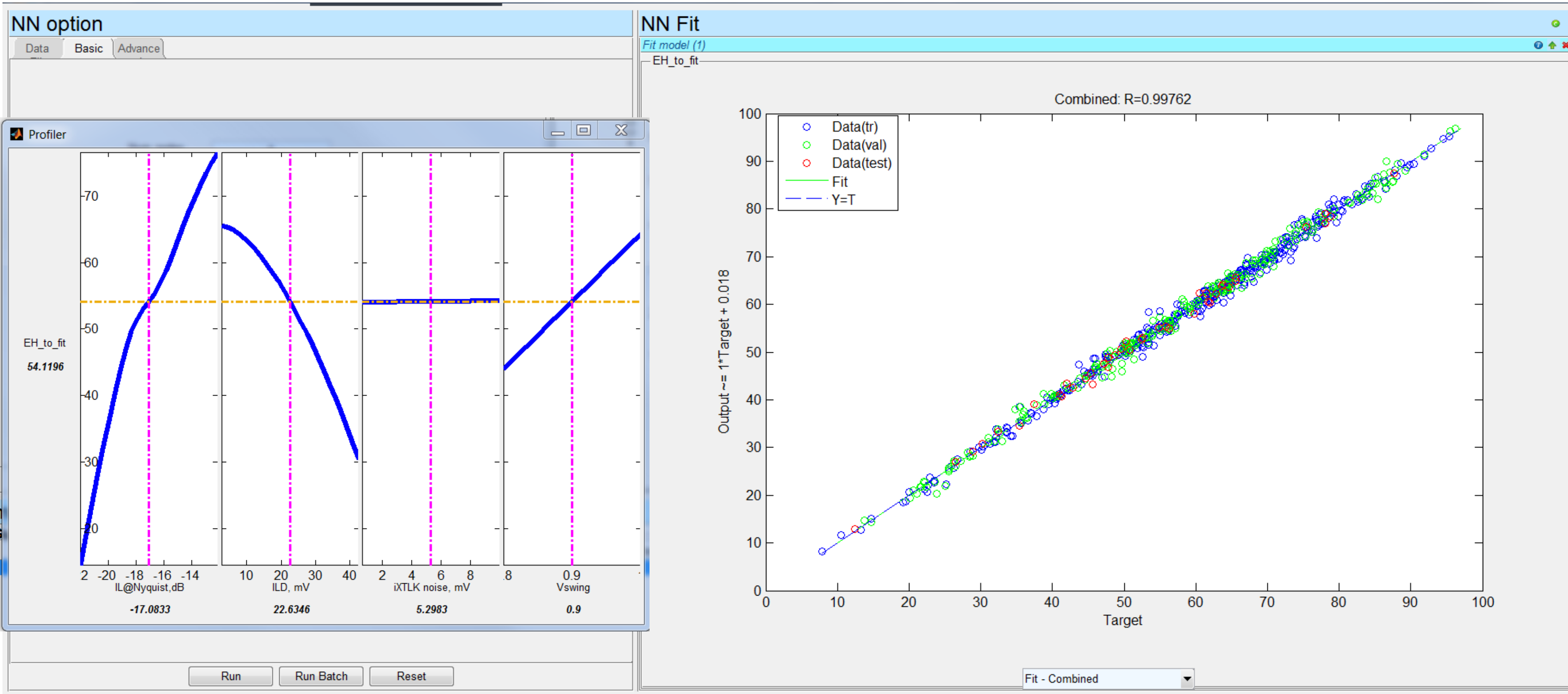


EH	EW
R=0.995	R=0.994
RMSE=6 mv	RMSE=6 ps

USB 3 Rx Fit Profiler



USB 3 Tx EH Fit



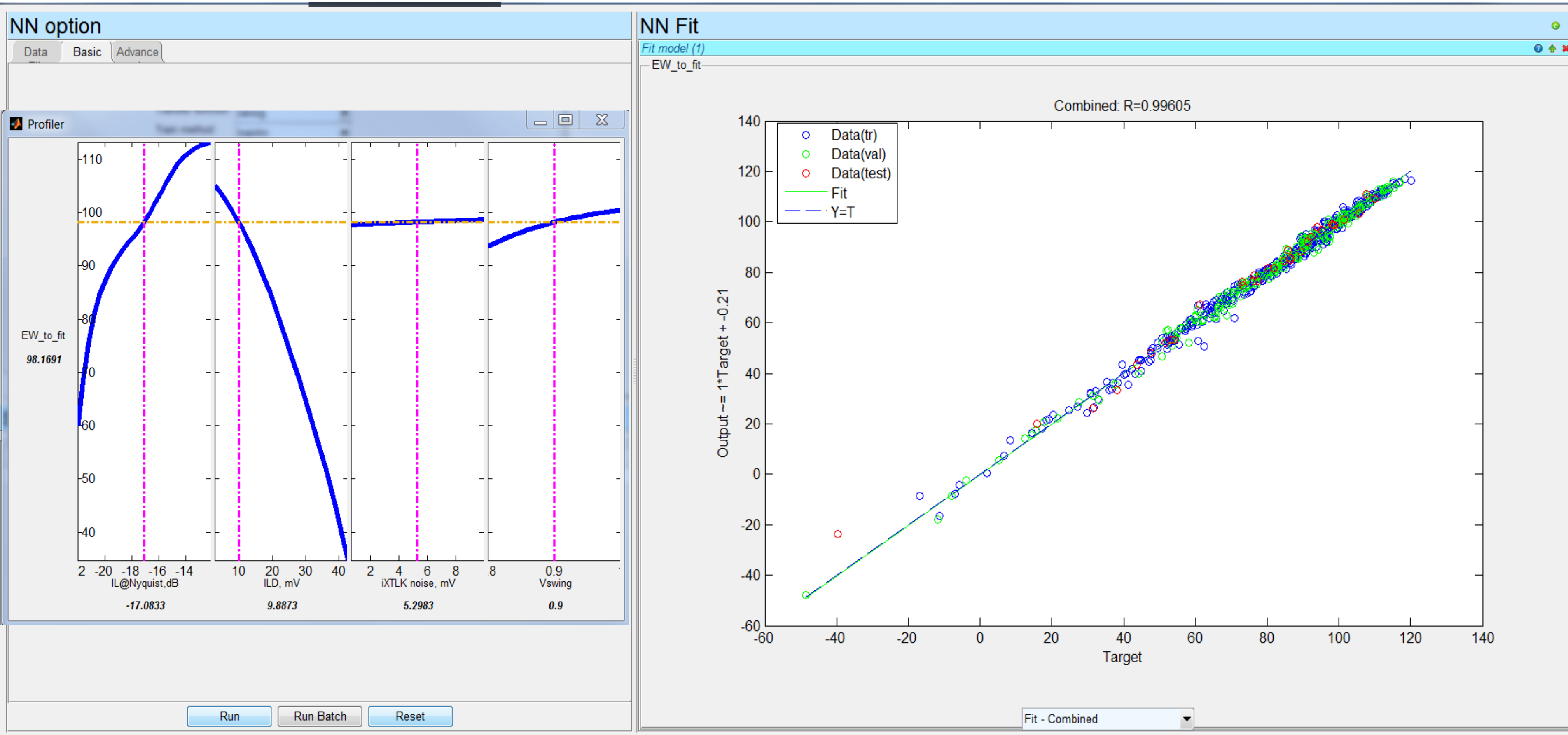
Summary

Summary: EH_to_fit

Models	R_train	R_val	R_test	RMSE_train	RMSE_val	RMSE_test
1	0.9976	0.9975	0.9982	1.1815	1.2428	0.9450

EH:R=0.998, RMSE=2 mV

USB 3 Tx EW Fit



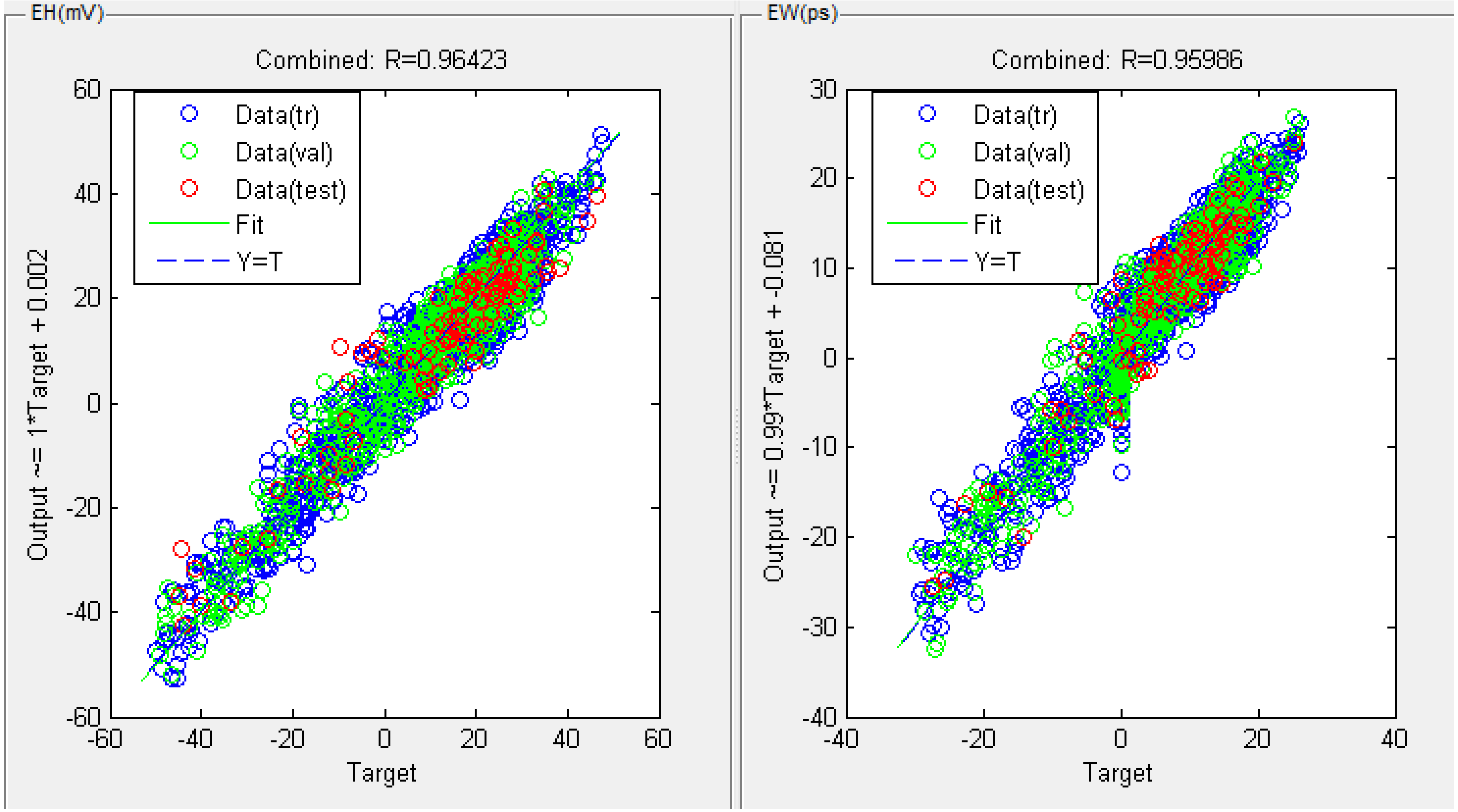
Summary

☑ **Summary: EW_to_fit**

Models	R_train	R_val	R_test	RMSE_train	RMSE_val	RMSE_test
1	0.9959	0.9970	0.9940	2.1685	2.0625	3.6717

EW: R=0.996, RMSE=3 ps

PCIe3 Example – LGA Rx: fitting quality



Summary: EH(mV)

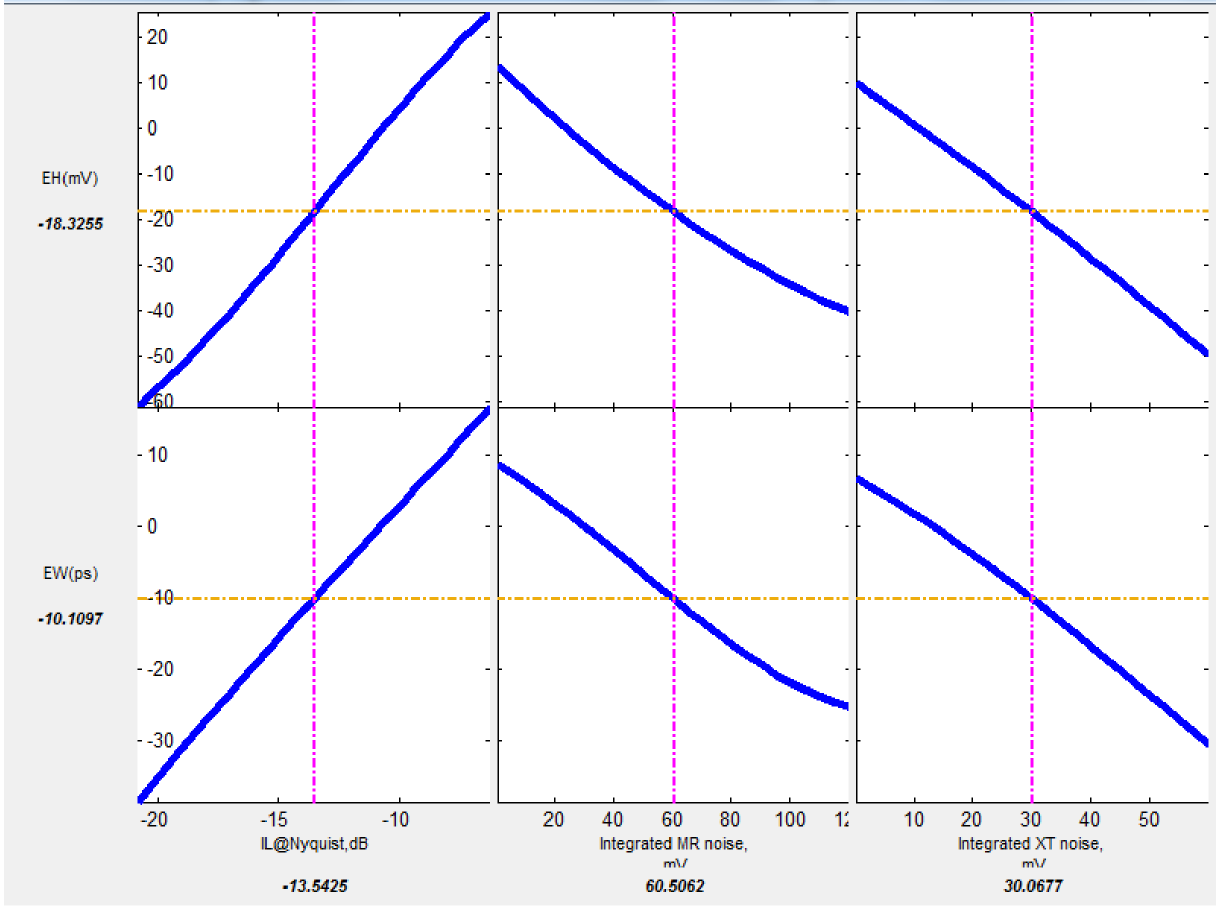
Models	R_train	R_val	R_test	RMSE_train	RMSE_val	RMSE_test
1	0.9647	0.9653	0.9544	5.0887	5.2277	6.2706

Summary: EW(ps)

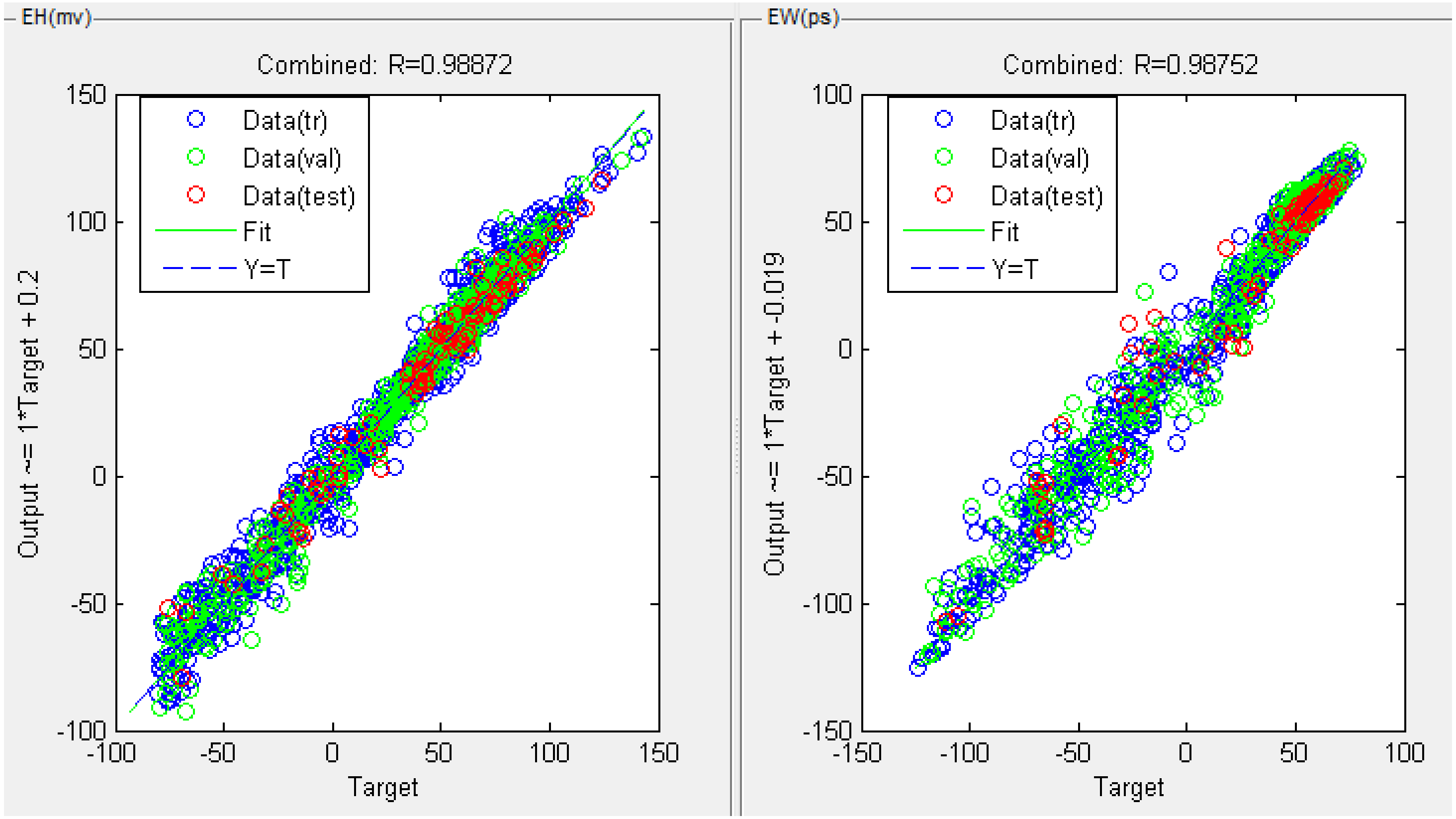
Models	R_train	R_val	R_test	RMSE_train	RMSE_val	RMSE_test
1	0.9598	0.9625	0.9422	3.0498	3.1199	3.3875

PCIe3 Example – LGA Rx: Profiler

Fitting with ILfit@Nquist, IMR, IXtlk



PCIe3 Example – LGA Tx: fitting quality



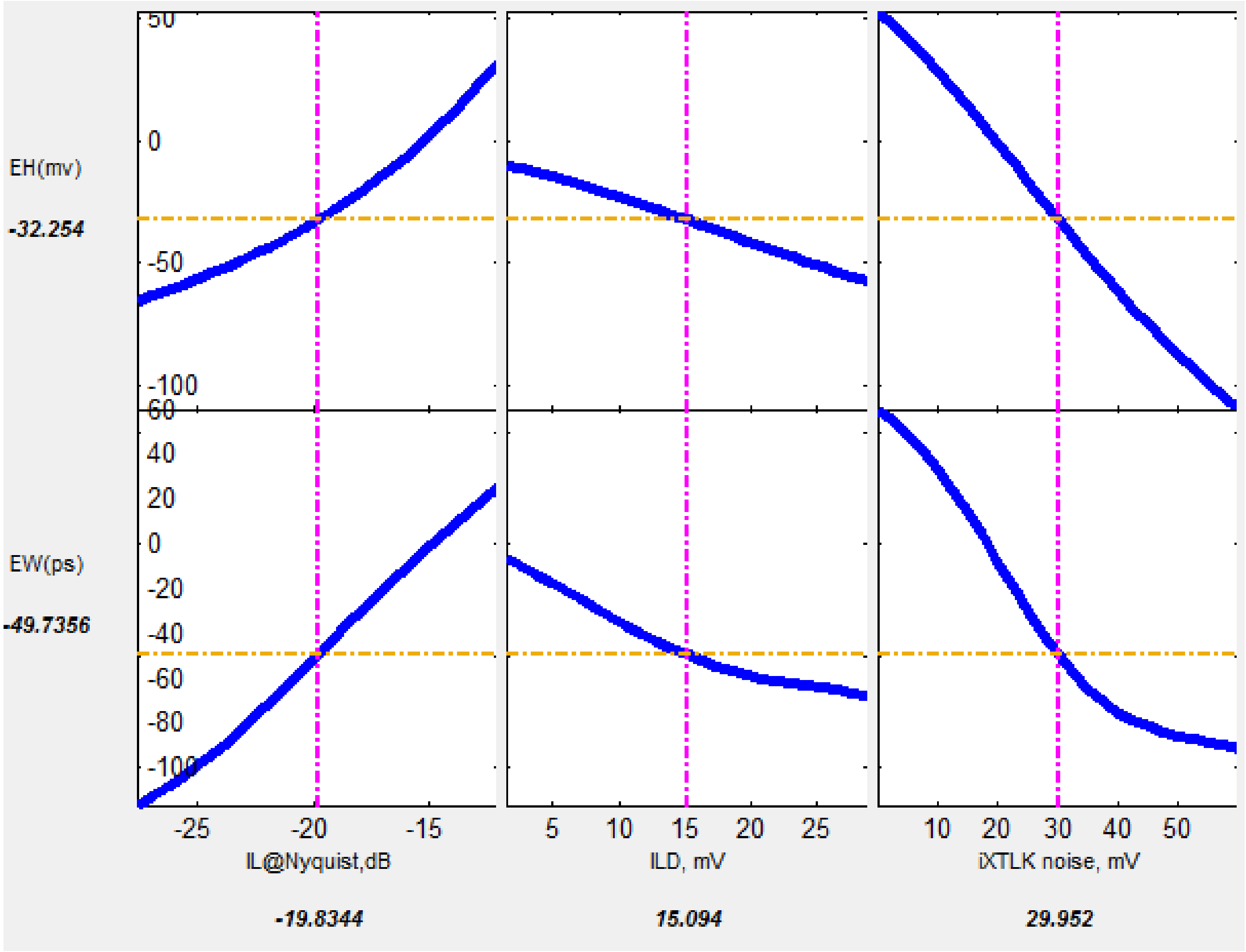
Summary: EH(mv)

Models	R_train	R_val	R_test	RMSE_train	RMSE_val	RMSE_test
1	0.9888	0.9889	0.9869	6.8067	6.7239	7.2564

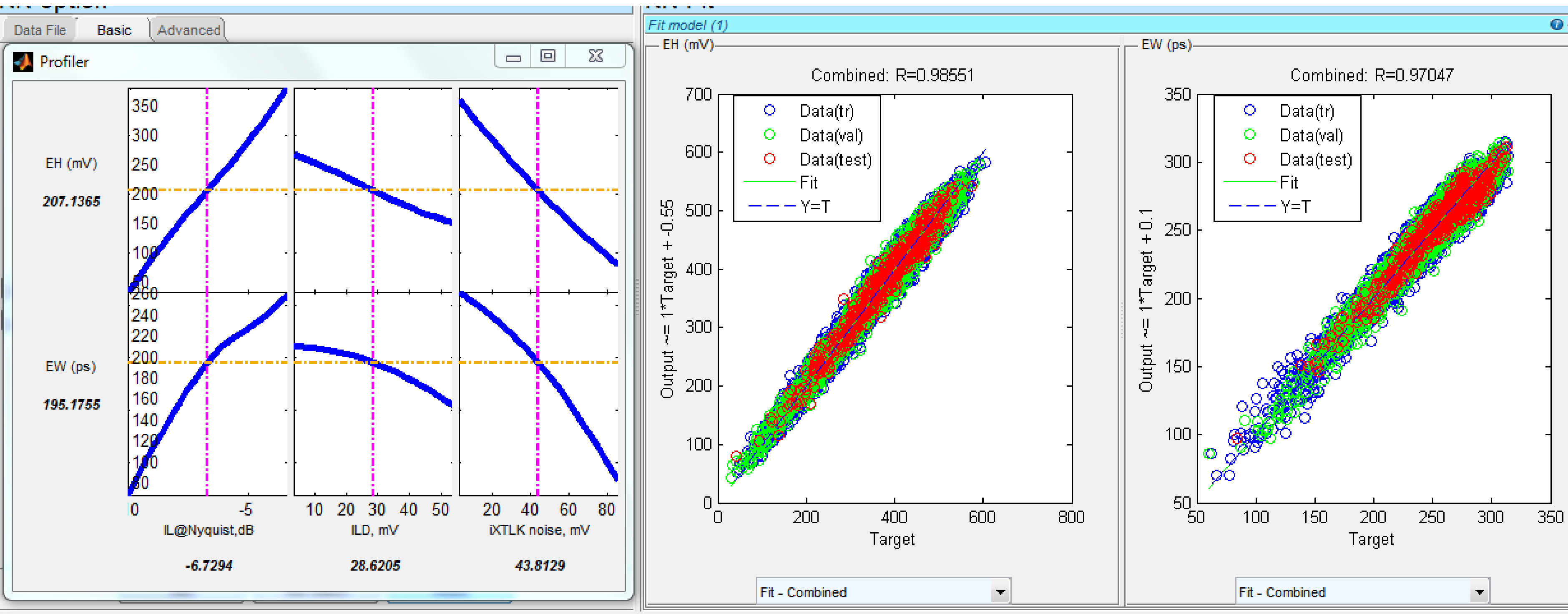
Summary: EW(ps)

Models	R_train	R_val	R_test	RMSE_train	RMSE_val	RMSE_test
1	0.9887	0.9864	0.9795	6.9995	8.2069	9.1955

PCIe3 Example – LGA Tx: profiler



DisplayPort HBR1 Fit



Summary

Summary: EH (mV)

Models	R_train	R_val	R_test	RMSE_train	RMSE_val	RMSE_test
1	0.9851	0.9867	0.9830	15.9337	15.6010	16.2196

Summary: EW (ps)

Models	R_train	R_val	R_test	RMSE_train	RMSE_val	RMSE_test
1	0.9710	0.9693	0.9702	8.2380	8.2616	8.0083

Summary

Summary

- Three simple (scalar) parameters are used as the channel electrical metrics to account for three different impairments
  - IL fit at Nyquist frequency: ILfitatNq
  - Integrated multi-reflection: IMR
  - Integrated crosstalk: IXT
- Parceval's theorem establishes the frequency and time domain equivalency!
  - It doesn't matter in time domain or freq domain!
- An adaptive method is used for IL fit, which uniquely defines the IMR
  - The IL fit is done such that the IMR is minimized!

Summary, cont.

- Neural network fitting together with space filling is used to fit the channel electrical metrics against the end-to-end eye margin to establish the (passive) channel electrical spec

- The proposed (passive) channel electrical metrics, ILfitatNq, IMR and IXT, are closely correlated with the channel end2end BER eye margins
  - *We have tested this for virtually all differential interfaces and haven't found any exception so far*

- The fitting quality is in general good, usually better than the typical fitting in DOE.

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