400G Forward Error Correction and Optical Receiver Stress Test

400G FEC前向糾錯及ORST光接收器壓力測試

Joe Lin

2020.12.16

Project Manager / Keysight Technologies

KEYSIGHT TECHNOLOGIES

Part 1

400G Optical Receiver Stress Test

400G ORST光接收器壓力測試

Joe Lin	2020.12.16
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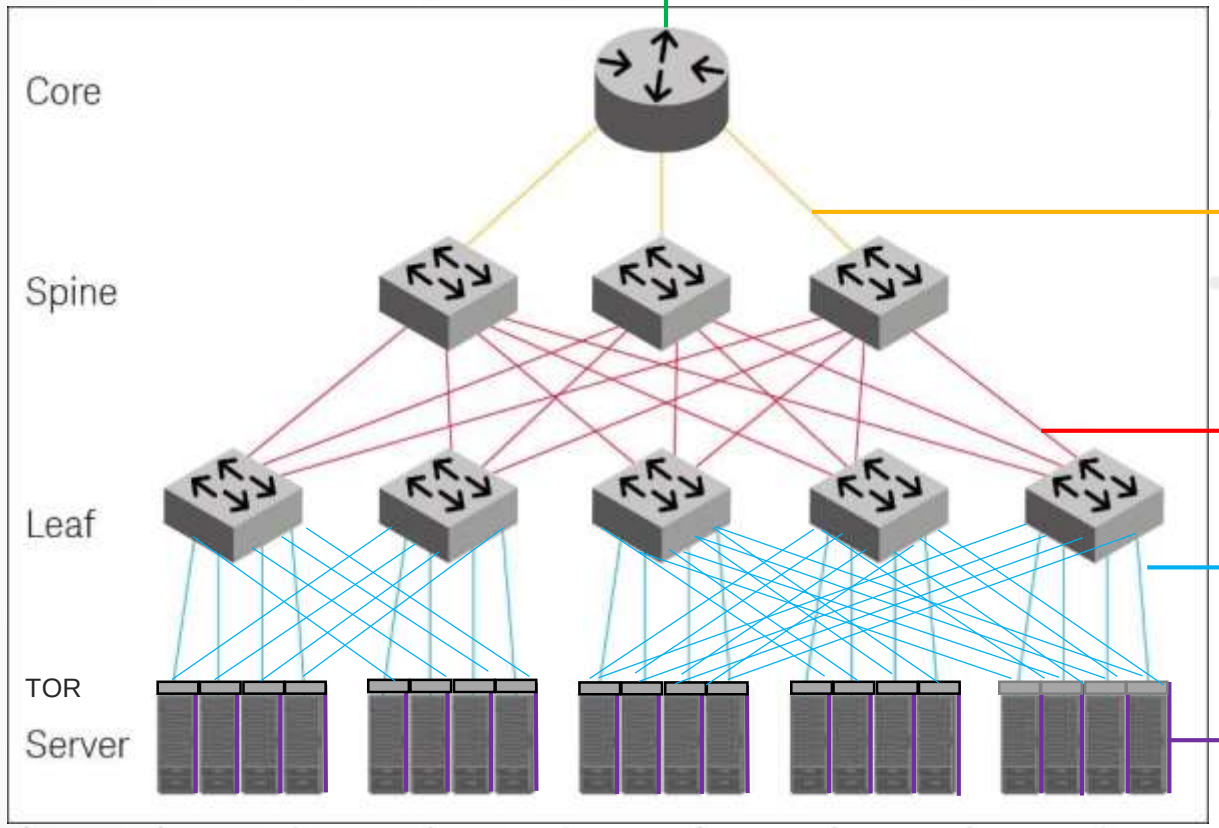
KEYSIGHT TECHNOLOGIES

Agenda

- **100G & 400G TRX ecosystem**
- Keysight TRX test solutions
- Optical Receiver Stress Test
- DUT Test

100G/400G TRX

IN DATACENTERS



- 100G DCO
- 100G-ER4*
- 100G-LR4*
- 4WDM

- 400G-ZR**
- 400G DCO
- 400G-ER8*
- 400G-LR8*

- CWDM4
- CLR4
- 4WDM
- 100G-LR4*

- 400G-FR4*
- 400G-FR8*
- 400G CWDM8

- PSM4
- CWDM4

- 400G-DR4*
- 400G-FR4

- 100G-SR4*
- 100G AOC

- 400G SR8*
- 400G-SR16*
- 400G AOC

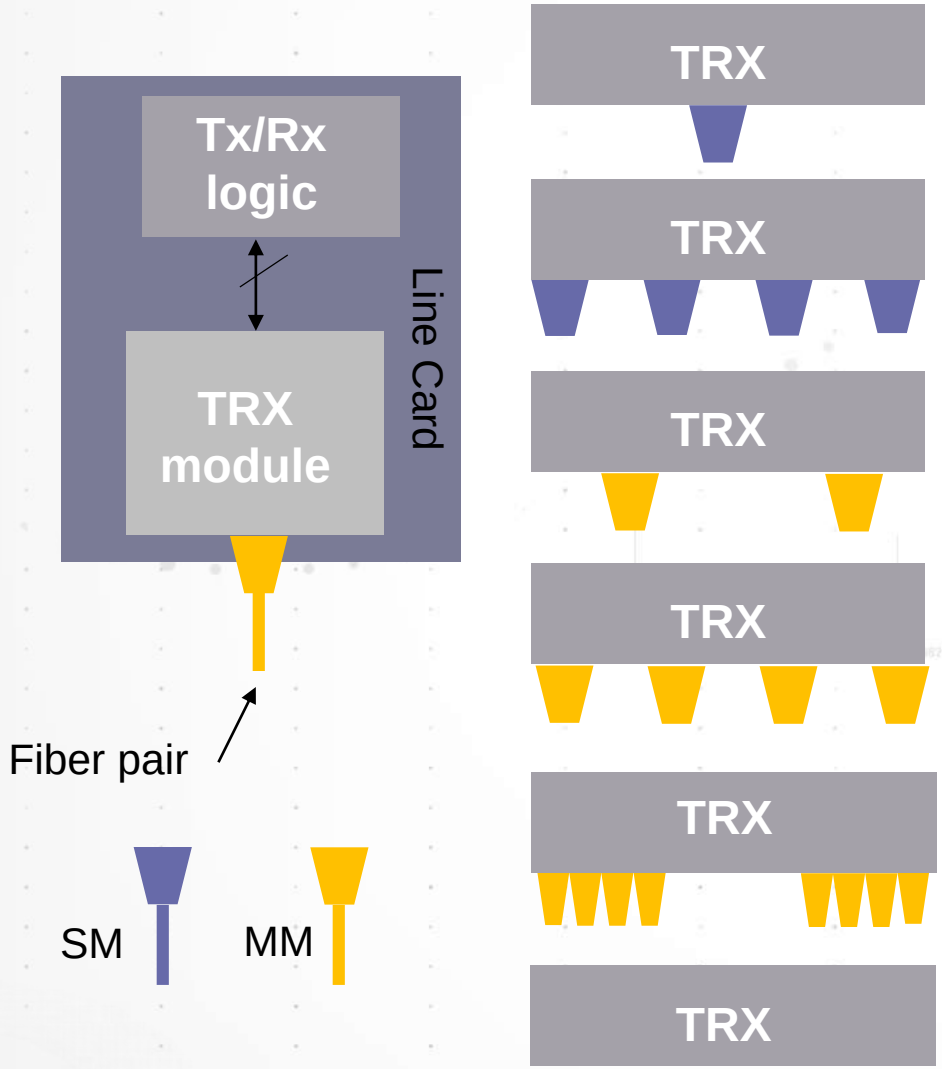
- 25G AOC
- 25G-CR*
- 100G CR4*

- 100G SR4*
- 50-CR*
- 400G CR8*

* IEEE
** OIF

100G/400G TRX

OPTICAL INTERFACE

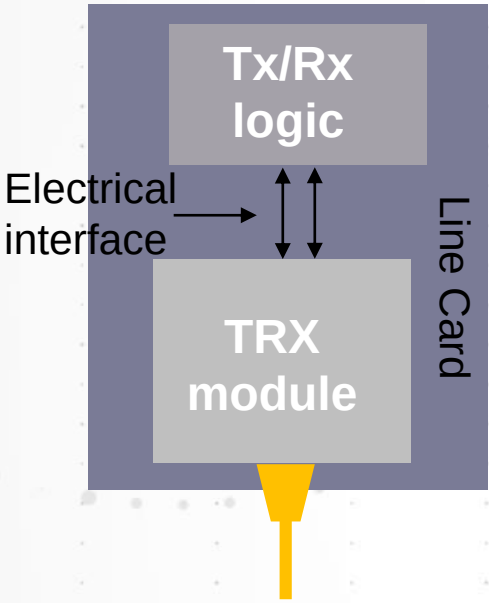


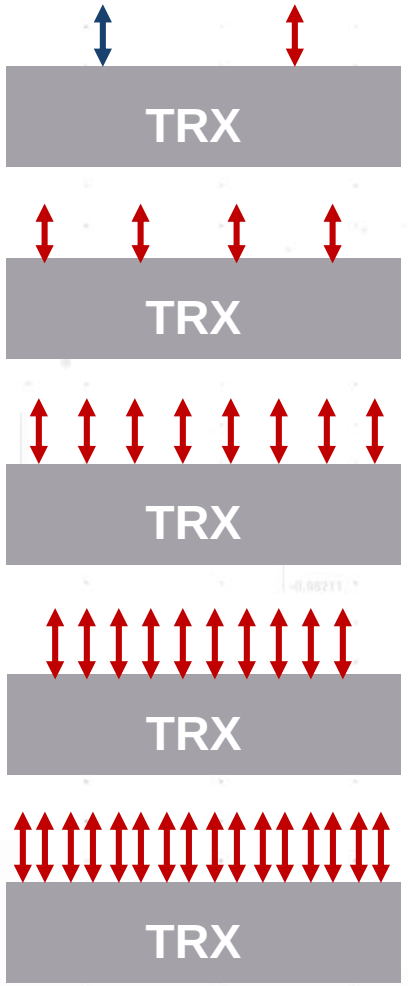
	Modulation	Modulation speed (Gbaud)	Lanes
100GBASE DR	PAM4	53.12	1
200GBASE FR4/LR4	PAM4	26.56	4
400G FR4/-LR4*	PAM4	26.56	4
400GBASE-FR8/LR8/ER8	PAM4	26.56	8
100GBASE LR4/ER4	NRZ	25.78	4
100G CLR4*	NRZ	25.78	4
100GFC CWDM4*	NRZ	25.78	4
100G 4WDM*	NRZ	25.78	4
400GBASE DR4	PAM4	53.12	4
200GBASE DR4	PAM4	26.56	4
64/256GFC	PAM4	28.9	4
100G PSM4*	NRZ	25.78	4
100GBASE SR2	PAM4	26.56	2
400GBASE SR4.2	PAM4	26.56	4
200GBASE SR4	PAM4	26.56	4
100GBASE SR4	NRZ	25.78	4
128GFC SWM4*	NRZ	28.05	4
400GBASE SR8	PAM4	26.56	8
100GBASE SR10	NRZ	10.3125	10
400GBASE-SR16	NRZ	26.56	16

* Multi Source Agreement (MSA)

100G/400G TRX

ELECTRICAL INTERFACE





	Modulation	Modulation speed (Gbaud)	Lanes
CAUI-2	PAM4	26.562	
CPPI-4/CAUI-4	NRZ	25.78	4
CEI-28G-VSR	NRZ	25.78	4
200GAUI-4	PAM4	26.56	4
64/256GFC	PAM4	29.02	4
CEI-112G	PAM	53.1	2-4
200GAUI-8	NRZ	26.56	8
400GAUI-8	**PAM4**	**26.56**	**8**
CEI-56G-VSR-NRZ	NRZ	53.1	1-8
CEI-56G-VSR-PAM4	PAM	26.56	1-8
CAUI-10	NRZ	10.31	10
400GAUI-16	NRZ	26.56	16

100G/200G/400G optical PMD

	IEEE Clause	PHY	Flavor	Fiber pairs	Carriers / Fiber	Fiber type	Wavel. -Grid	Wavelength-Range	Symbol Rate Gbaud	Mod.- format	Reach
802.3	88	100GBASE	-LR4	1	4	SM	5nm	1294.5nm to 1310.2nm	25.78125	NRZ	10km
802.3	88	100GBASE	-ER4	1	4	SM	5nm	1294.5nm to 1310.2nm	25.78125	NRZ	40km
802.3	95	100GBASE	-SR4	4	1	MM	-	850nm	25.78125	NRZ	100m
CWDM4	88*	100G		1	4	SM	20nm	1264.5nm to 1337.5nm	25.78125	NRZ	2km
CLR4	88*	100G	w/(o) FEC	1	4	SM	20nm	1264.5nm to 1337.5nm	25.78125	NRZ	2km
4WDM	88*	100G	20/40	1	4	SM	5nm	1294.5nm to 1310.2nm	25.78125	NRZ	20/40km
4WDM	88*	100G	10	1	4	SM	20nm	1264.5nm to 1337.5nm	25.78125	NRZ	10km
PSM4	52*	100G		4	1	SM	-	1310nm	25.78125	NRZ	500m
SWDM4	95*	100G		1	4	MM	30nm	844-948nm	25.78125	NRZ	150m (OM5)
SWDM4	95*	100G	e	1	4	MM	30nm	844-948nm	25.78125	NRZ	400m (OM5)
100G/λ	140*	100G	-FR	1	1	SM	-	1304.5nm to 1317.5nm	53.125	PAM4	2km
100G/λ	140*	100G	-LR	1	1	SM	-	1304.5nm to 1317.5nm	53.125	PAM4	10km
802.3cd	140	100GBASE	-DR	1	1	SM	-	1304.5nm to 1317.5nm	53.125	PAM4	500m
802.3cd	138	100GBASE	-SR2	2	1	MM	-	850nm	53.125	PAM4	100m
FC		64GFC	-LW	1	1	SM	-	1304.5nm to 1317.5nm	28.9	PAM4	10km
FC		64GFC	-SW	1	1	MM	-	850nm	28.9	PAM4	100m

* with exceptions

100G/200G/400G optical PMD

	IEEE Clause	PHY	Flavor	Fiber pairs	Carriers / Fiber	Fiber type	Wavel. -Grid	Wavelength-Range	Symbol Rate Gbaud	Mod.- format	Reach
CWDM8	88*, 95*	400G	CWDM8	1	1	SM	20nm	1264.5nm to 1417.5nm	53.125	NRZ	2/10km
100G/λ	140*	400G	-FR4/LR4	1	4	SM	20nm	1264.5nm to 1337.5nm	53.125	PAM4	2/ 10km
802.3bs	123	400GBASE	-SR16	16	1	MM 50/125 -OM3, -OM4	-	840.0nm to 860.0nm	26.5625	NRZ	OM3: 70m OM4: 100m
802.3bs	121	200GBASE	-DR4	4	1	SM	-	1304.5nm to 1317.5nm	26.5625	PAM4	500m
802.3bs	124	400GBASE	-DR4	4	1	SM	-	1304.5nm to 1317.5nm	53.1250	PAM4	500m
802.3bs	122	200GBASE	-FR4 -LR4	1	4	SM	20nm 5nm	1264.5nm to 1337.5nm 1294.5nm to 1310.2nm	26.5625	PAM4	FRx: 2km LRx: 10km
		400GBASE	-FR8 / -LR8	1	8	SM	800GHz	1272.5nm to 1310.2nm			
802.3cd	138	50GBASE	-SR	1	1	MM 50/125 -OM3, -OM4	-	840.0nm to 860.0nm	26.5625	PAM4	OM3: 70m OM4: 100m
		100GBASE	-SR2	2							
		200GBASE	-SR4	4							
802.3cm	*138* *150*	*400GBASE*	*-SR8* *-SR4.2*	*8* *4*	*1* *2*	*MM*			26.5625	*PAM4*	OM4: 100m
802.3cn	122	400GBASE	-ER8	1	8	SM	-	1264.5nm to 1337.5nm	26.5625	PAM4	40km

* with exceptions

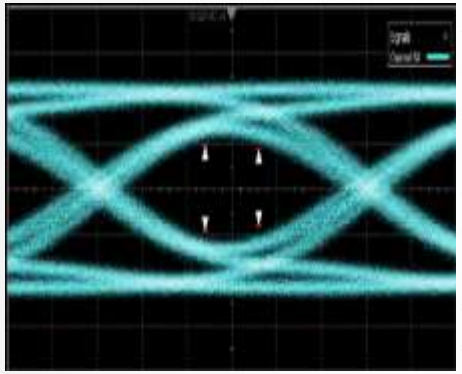
Agenda

- 100G & 400G TRX ecosystem
- **Keysight TRX test solutions**
- Optical Receiver Stress Test
- DUT Test

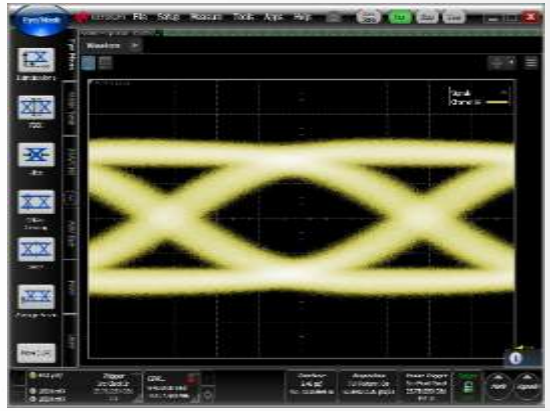
Optical Transceiver Modules Compliance Tests

100GBASE-LR4/-ER4/-SR4

25.78 Gb NRZ



25.78 Gb NRZ



IEEE802.3 Annex 83E

IEEE802.3 clause 88 & 95

Electrical Tx test
Eye width/height, VEC, rise/fall-time
(waveform analysis)

Electrical Rx test
SRS, Jtol (BER)

Optical Rx test
SRS, Jtol (BER)

Optical Tx test
VECP, SEC, OMA, ER, Jitter
(waveform analysis)

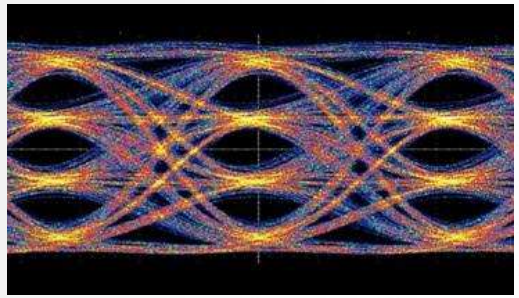
CAUI-4

100GBASE-ER4/-LR4/-SR4

Optical Transceiver Modules Compliance Tests

400GBASE-LR8/-FR8

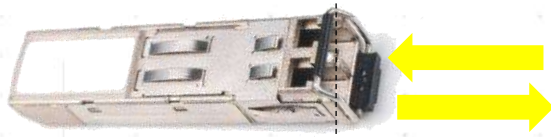
26.6Gbaud PAM4



IEEE802.3bs Annex 120E
Chip-to-module 200 Gb/s four-lane Attachment Unit Interface (200GAUI-4 C2M) and 400 Gb/s eight-lane Attachment Unit Interface (400GAUI-8 C2M)

Electrical Tx test
Linearity, ISI, Mask
(Waveform analysis)

Electrical Rx test
SRS, Jtol (BER)



400GAUI-8 C2M

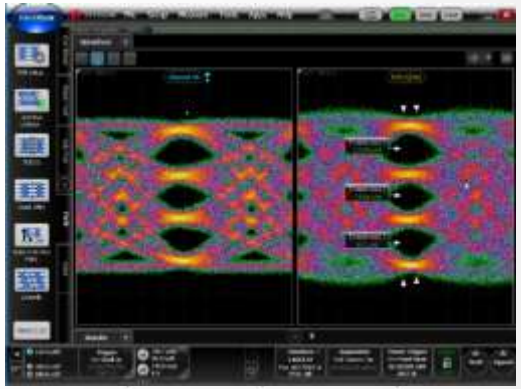
IEEE802.3bs clause 122
Physical Medium Dependent (PMD) sublayer and medium, type 200GBASE-FR4, 200GBASE-LR4, 400GBASE-FR8, and 400GBASE-LR8

Optical Rx test
SRS, Jtol (BER)

Optical Tx test
TDECQ,OMA, OER
(Waveform analysis)

400GBASE-FR8/LR8

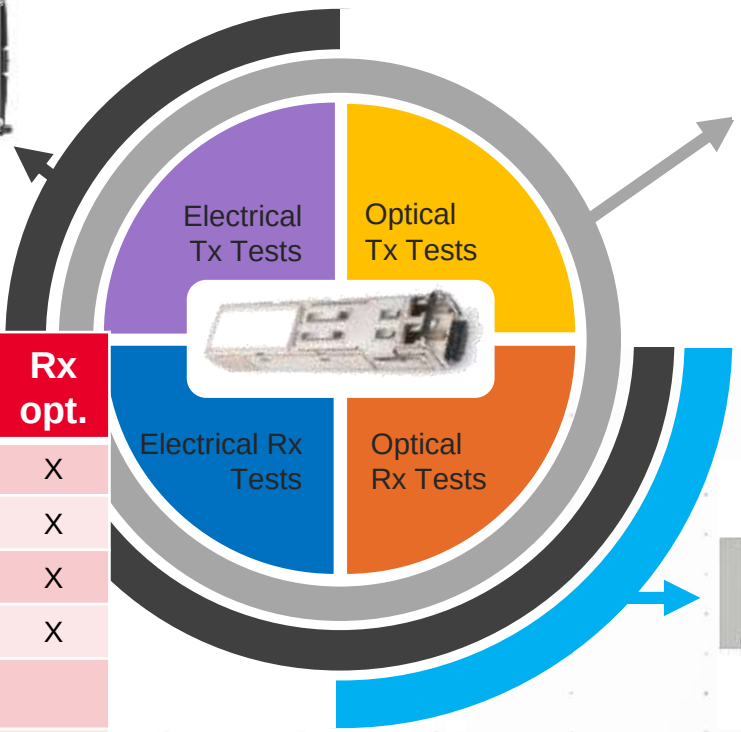
26.6Gbaud PAM4



25.78125→ 26.5625Gbd
enhanced RS **FEC** (528,514)→ (544,514)

Optical Transceiver Modules Compliance Tests

E.G. 400G SOLUTIONS

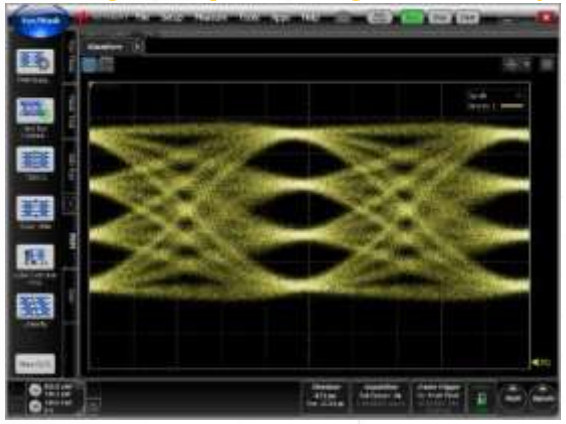


SW	Description	Tx elec.	Rx elec.	Tx opt.	Rx opt.
N1010A	FlexDCA	X	X	X	X
N1010100A	R&D SW Package for the DCA	X	X	X	X
M8070B	System SW for M8000 series	X	X		X
N4917BSCB	Optical RX Test for IEEE 802.3bs/cd + MSAs				X
M8091BSPA	Electrical RX Test for IEEE P802.3bs		X		
M809256PA	Electrical RX Test for OIF-CEI-4.0 (VSR)		X		
N1095BSCA	Optical TX Test for IEEE 802.3bs/cd			X	
N1091BSCB	Electrical TX Test for IEEE 802.3bs/cd	X			
N109256CB	Electrical TX Test for OIF-CEI-4.0 (VSR/MR/LR)	X			

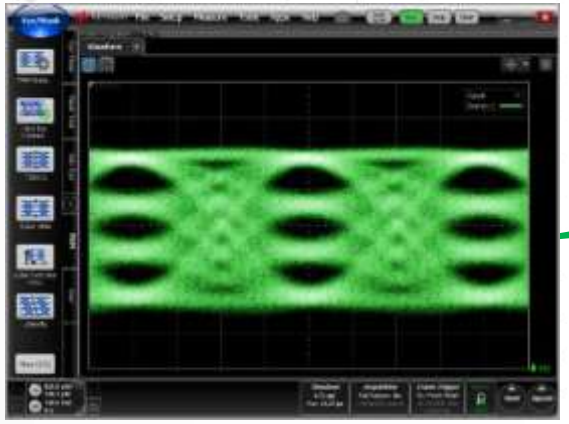
Optical Transceiver Modules Compliance Tests

E.G. 400G SOLUTIONS

DCA-based optical waveform analysis (TDECQ, OER,…)



Optical stressed signal



Tx out

Rx in

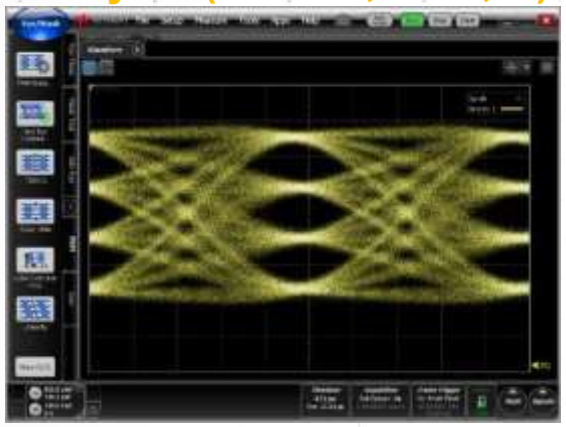
?

BERT- based performance analysis

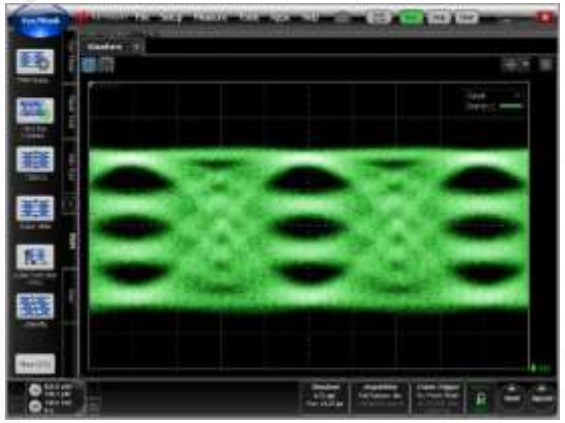
Optical Transceiver Modules Compliance Tests

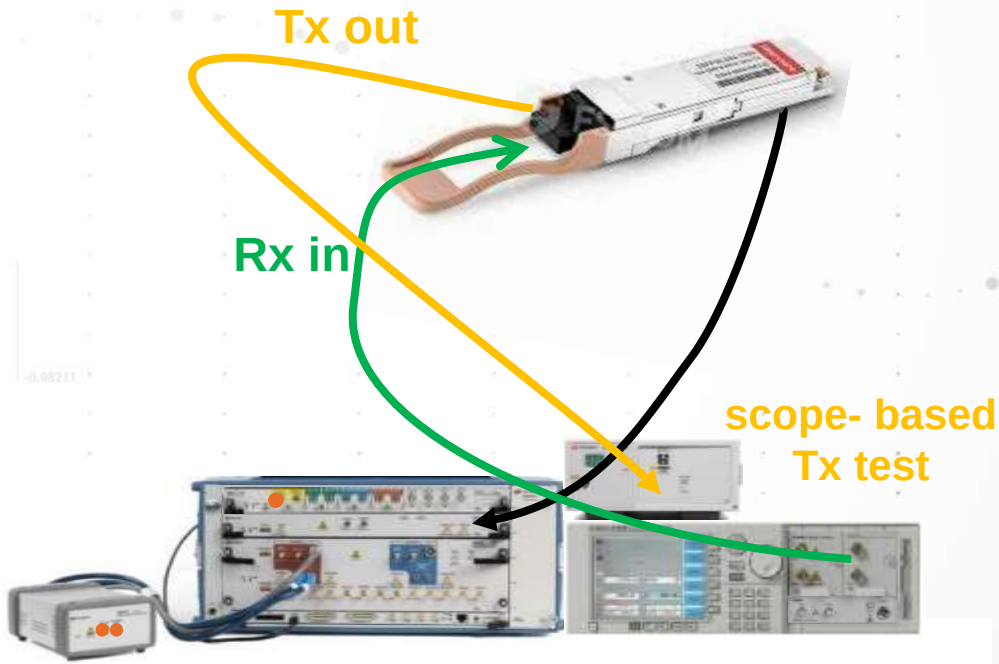
E.G. 400G SOLUTIONS

DCA-based optical waveform analysis (TDECQ, OER,…)



Optical stressed signal



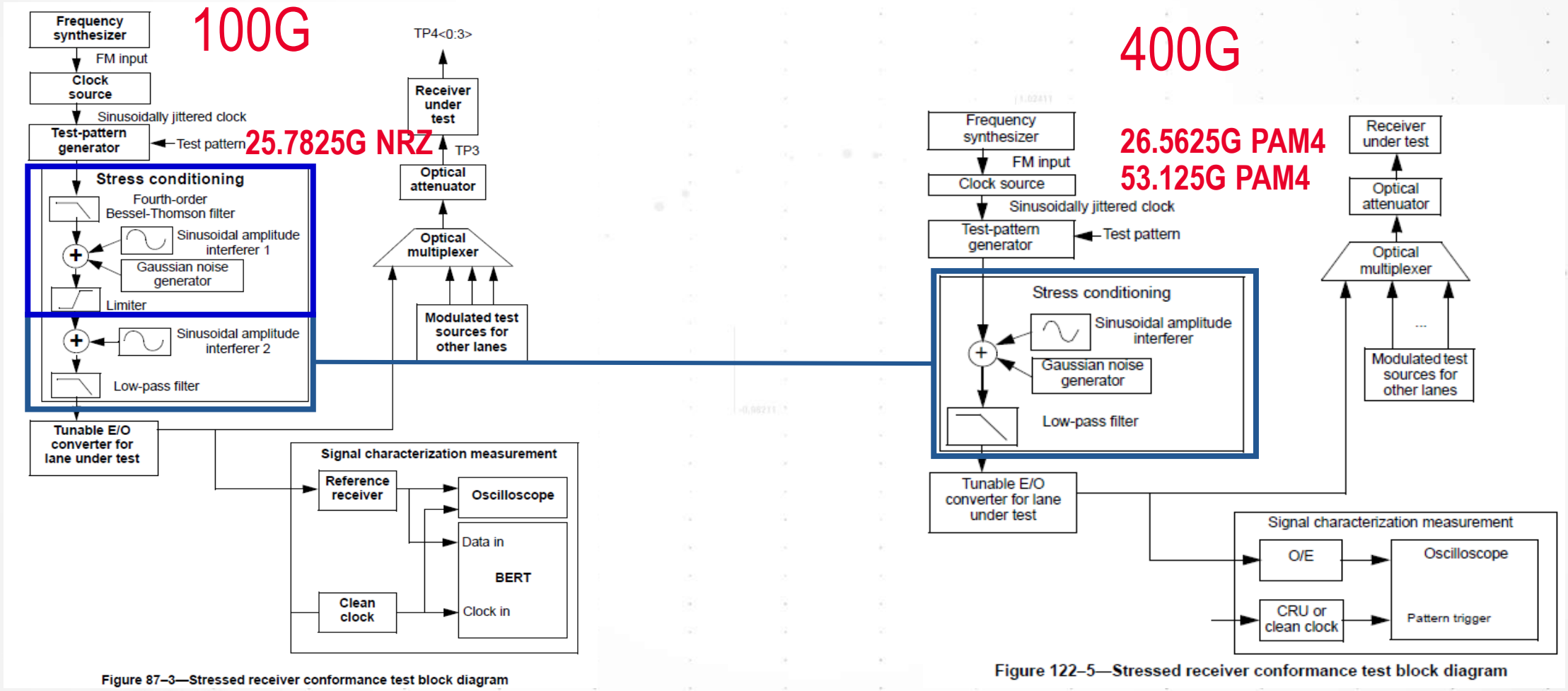


Agenda

- 100G & 400G TRX ecosystem
- Keysight TRX test solutions
- **Optical Receiver Stress Test**
- DUT Test

100G / 400G Optical Receiver Stress Test

STRESSED RECEIVER CONFORMANCE TEST BLOCK DIAGRAMS



M8020A-based ORST solution

ONE SW, ONE HW ALL 10G/40G/100G FLAVORS

- **100G ORST**

100GBASE-LR4
100GBASE-ER4
100GBASE-SR4
100G CLR4
100G CWDM4
100G 4WDM

- **10/40G ORST**

10GBASE-LR
10GBASE-ER
40GBASE-LR4
40GBASE-ER4

N4917B 100G ORST SW
N4917CPCA 10G/40G/CPRI

M8020A PPG / ED

81160A pulse gen

DCA-X/M

8164B & 8149x Ref optical Tx

Complete optical receiver stress test solution for
100GbE (IEEE, MSAs) & 400GbE optical transceivers
with automated stress eye calibration and performance compliance testing

M8040A-based ORST solution

ONE SW, ONE HW ALL 100G/400G FLAVORS

- **100G ORST (NRZ)**
100GBASE-LR4
100GBASE-ER4
100GBASE-SR4
100G MSAs

- **400G ORST (SM)**
200GBASE-DR4
400GBASE-FR8
200GBASE-FR4
400GBASE-LR8
200GBASE-LR4
400GBASE-DR4
100GBASE-DR
50GBASE-FR/-LR
400G-FR4
100G-FR/-LR

- **400G ORST (MM)**
50GBASE-SR
100GBASE-SR2200GBASE-SR4
400GBASE-SR8

N4917BACA 100G ORST SW
N4917BSC**B** 400G ORST SW

M8040A PPG / ED

M819x AWG

DCA-X/M

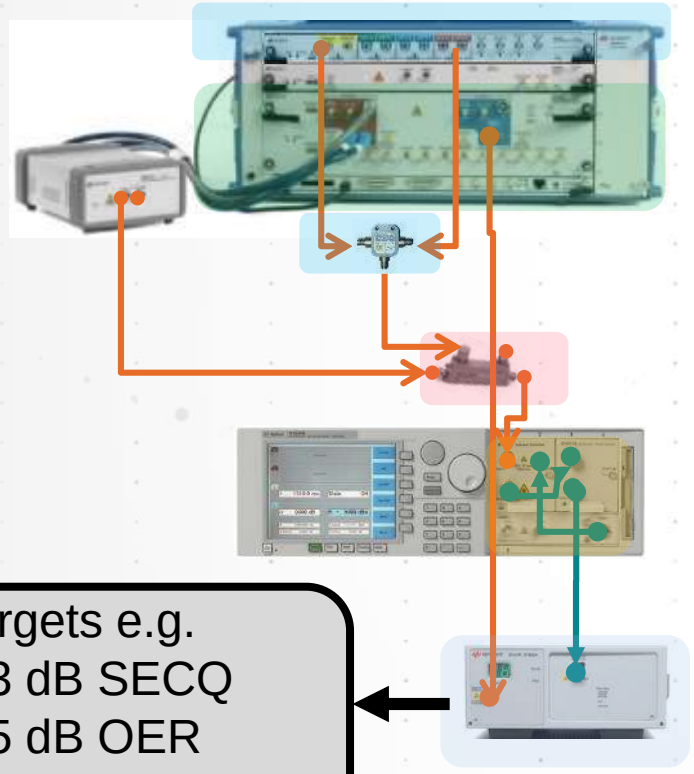
8164B & 8149x Ref optical Tx

Complete optical receiver stress test solution for
100GbE (IEEE, MSAs) & 400GbE optical transceivers
with automated stress eye calibration and performance compliance testing

M8040A-based ORST solution

HW CONFIGURATION

Keysight HW configuration



Targets e.g.
3.3 dB SECQ
3.5 dB OER
-3.6 dBm OMA

Reference Rx
- *BW~ Signal Nyquist freq.*
- *5 Taps T-spaced FIR.*

IEEE stress signal generation procedure

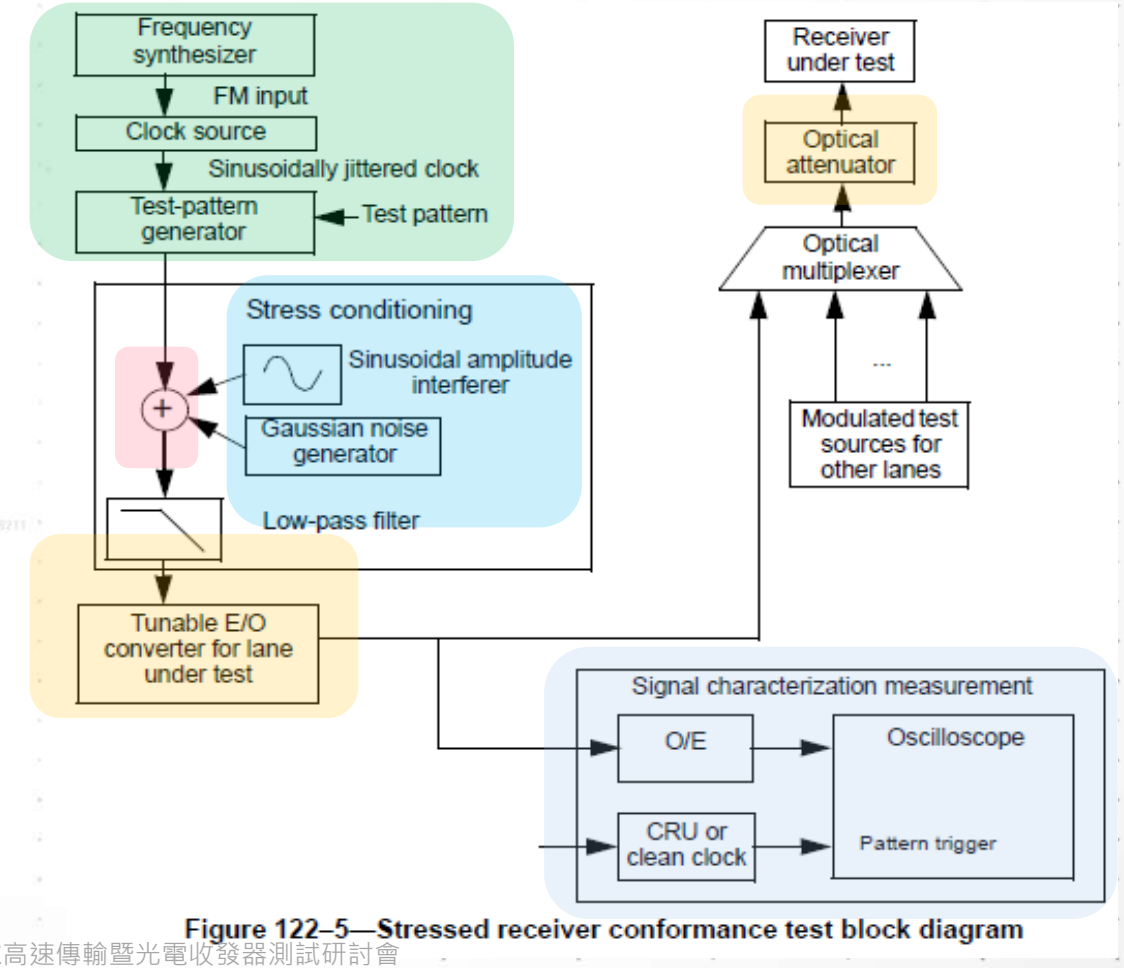
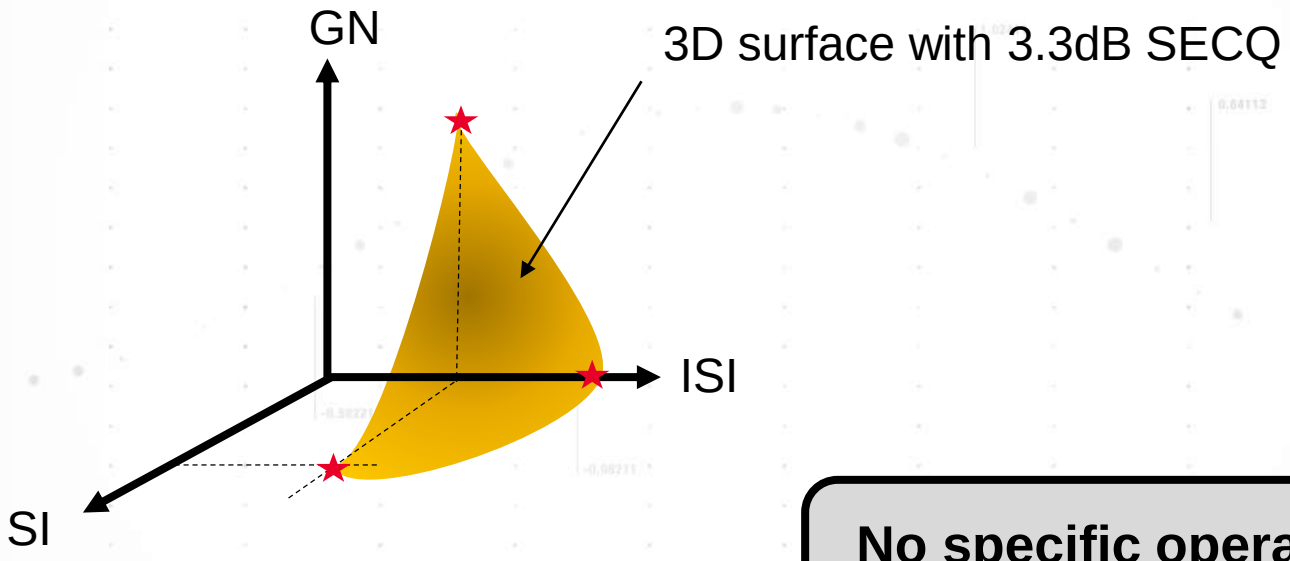


Figure 122–5—Stressed receiver conformance test block diagram

200/400GBASE Stressed Rx Test Setups

802.3BS STANDARD RECOMMENDATIONS

Contribution to SECQ: {ISI*, GN**, SI***}:



* At least ½ SECQ due to ISI
** Broadband GN (>signal Nyquist freq.)
*** Large frequency range

No specific operating point recommended by the standard. Use anyone?

200/400GBASE Stressed Rx Test Setups

THE ACTUAL STRESS MIX DOES MATTER!

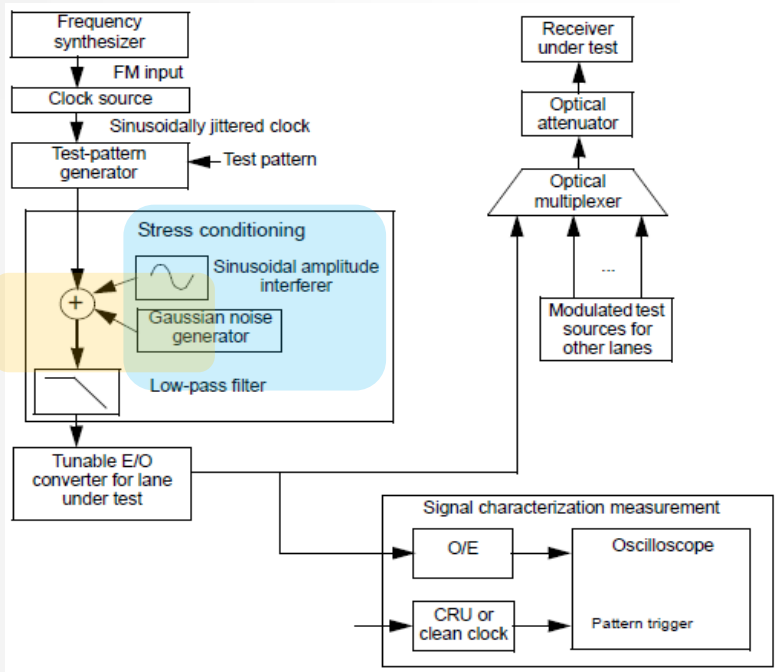
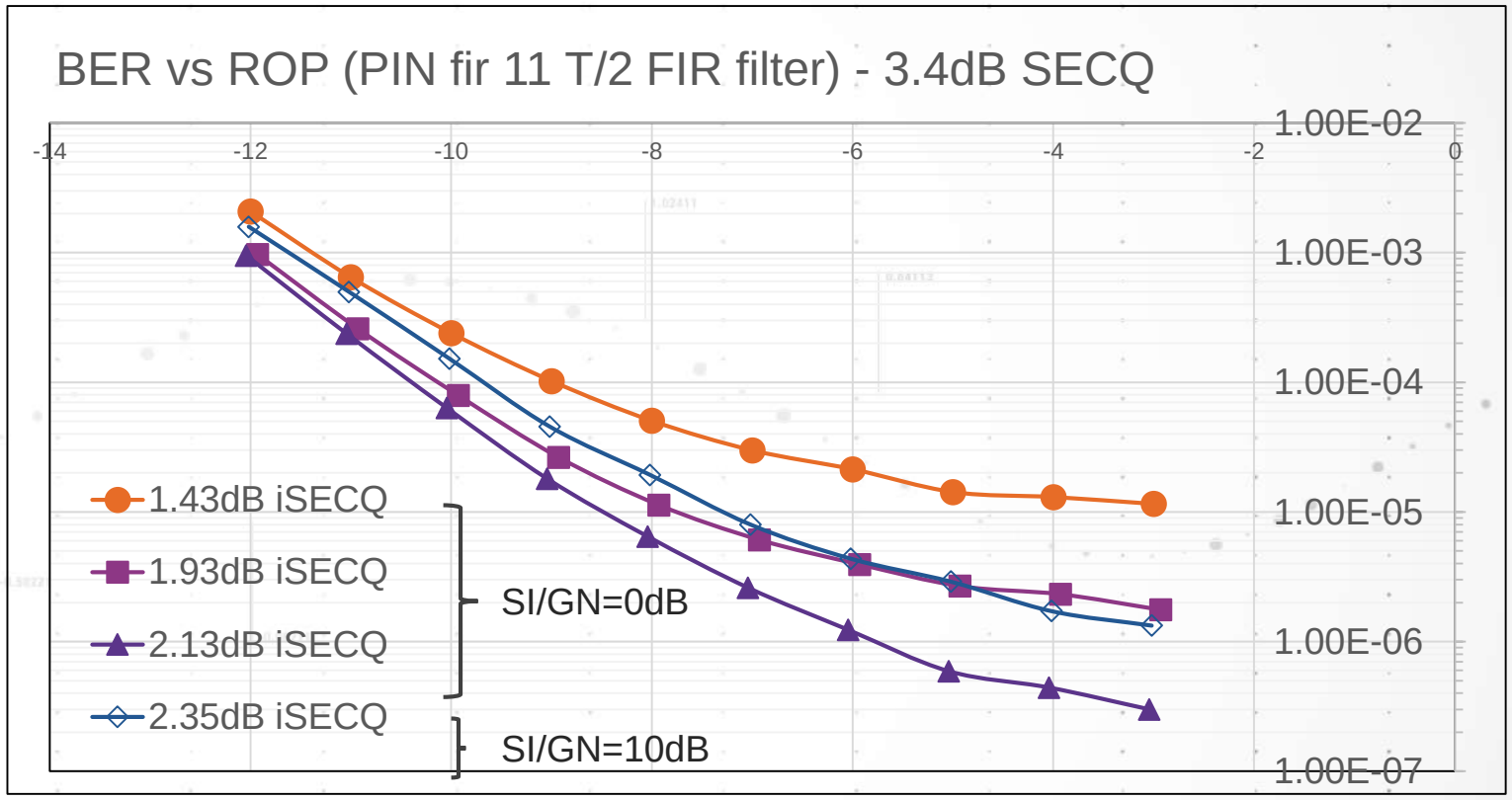


Figure 122–5—Stressed receiver conformance test block diagram



Same SECQ but different performance ⇒ Stress mix must be controlled accurately!

200/400GBASE Stressed Rx Test Setups

USING AN AWG AS STRESS SOURCE

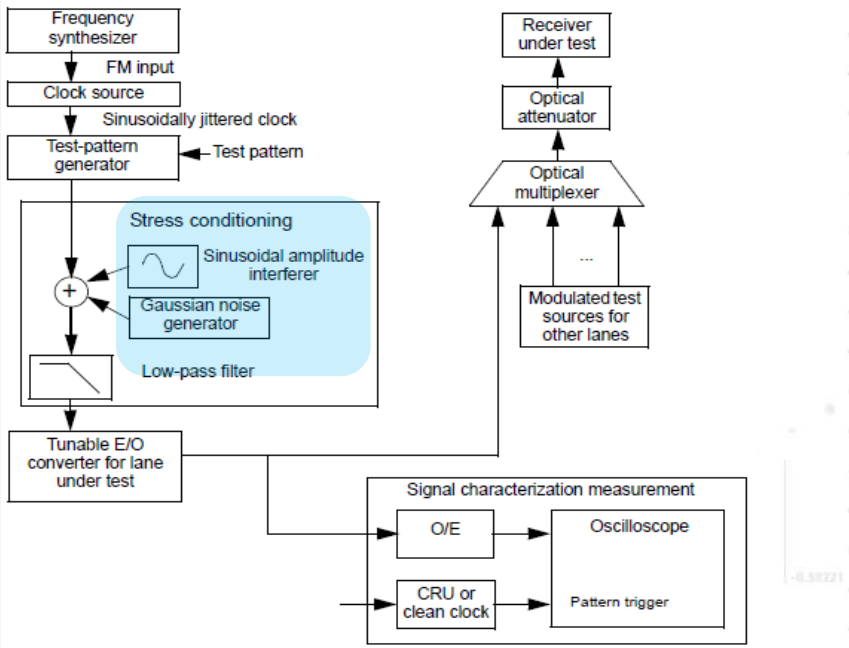
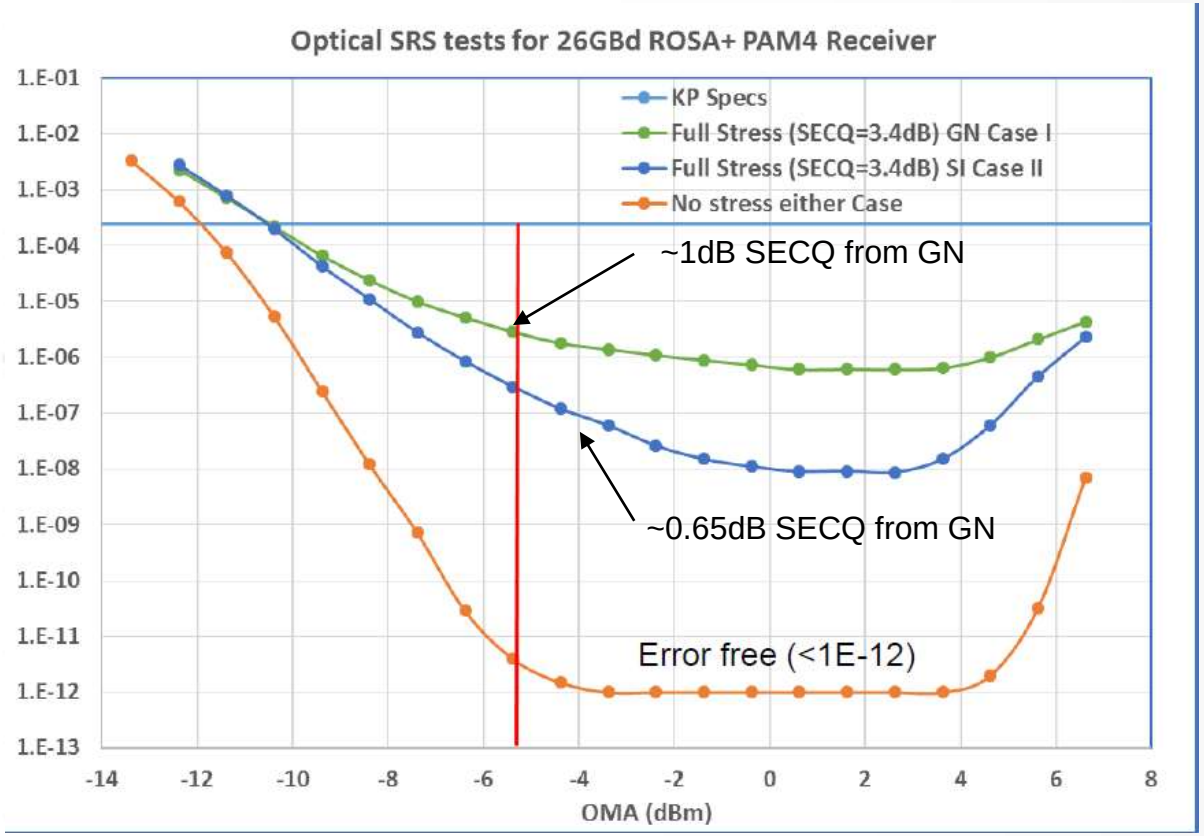


Figure 122–5—Stressed receiver conformance test block diagram



Same SECQ but different performance ⇒ Stress mix must be controlled accurately!

From *Frank Chang et al*, ***Optical PAM4 RX SRS Results Update***

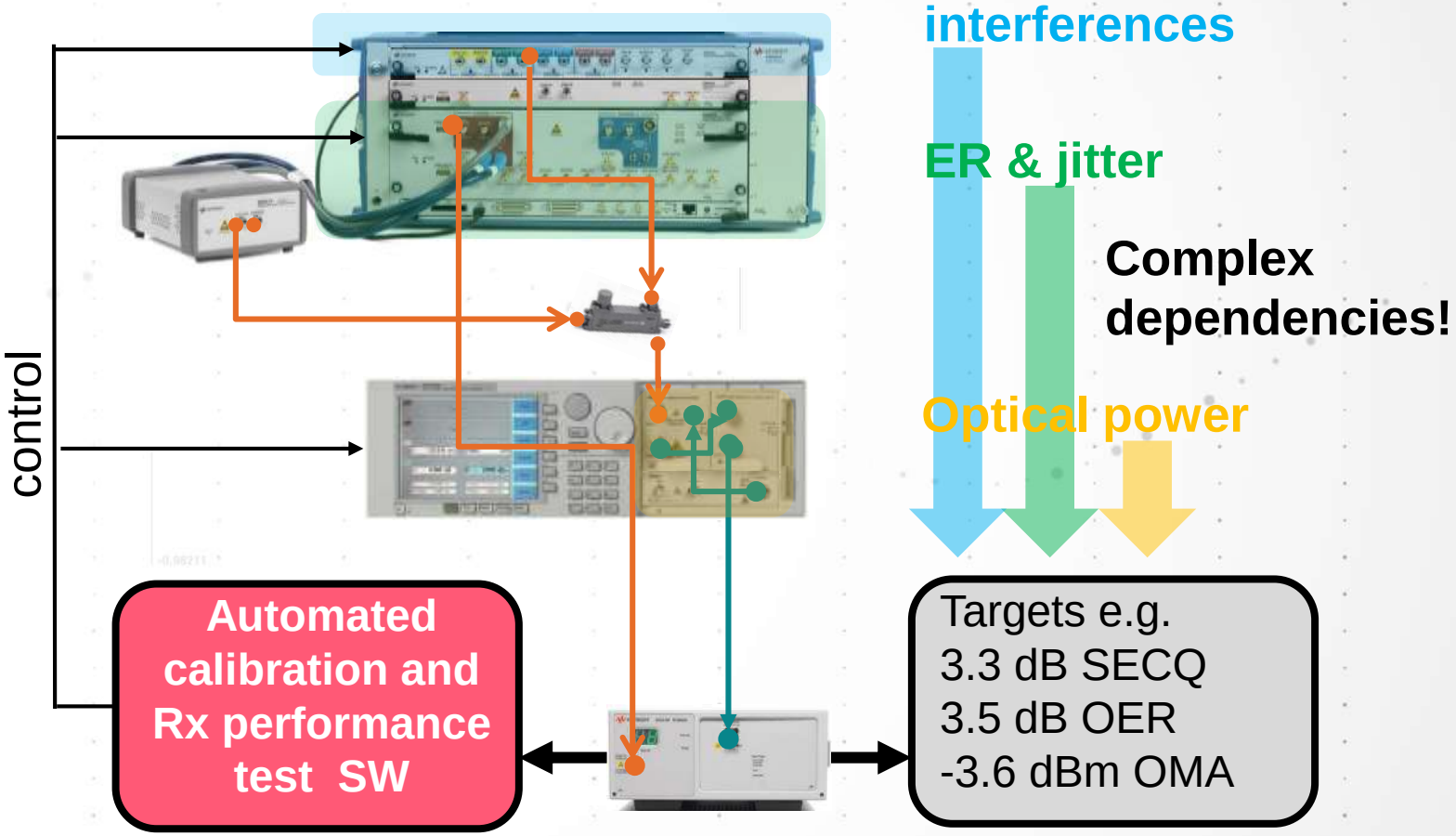
Download full study here:
http://grouper.ieee.org/groups/802/3/cd/public/Nov17/

Keysight Optical Receiver Stress Test

CHALLENGES & AUTOMATION SW

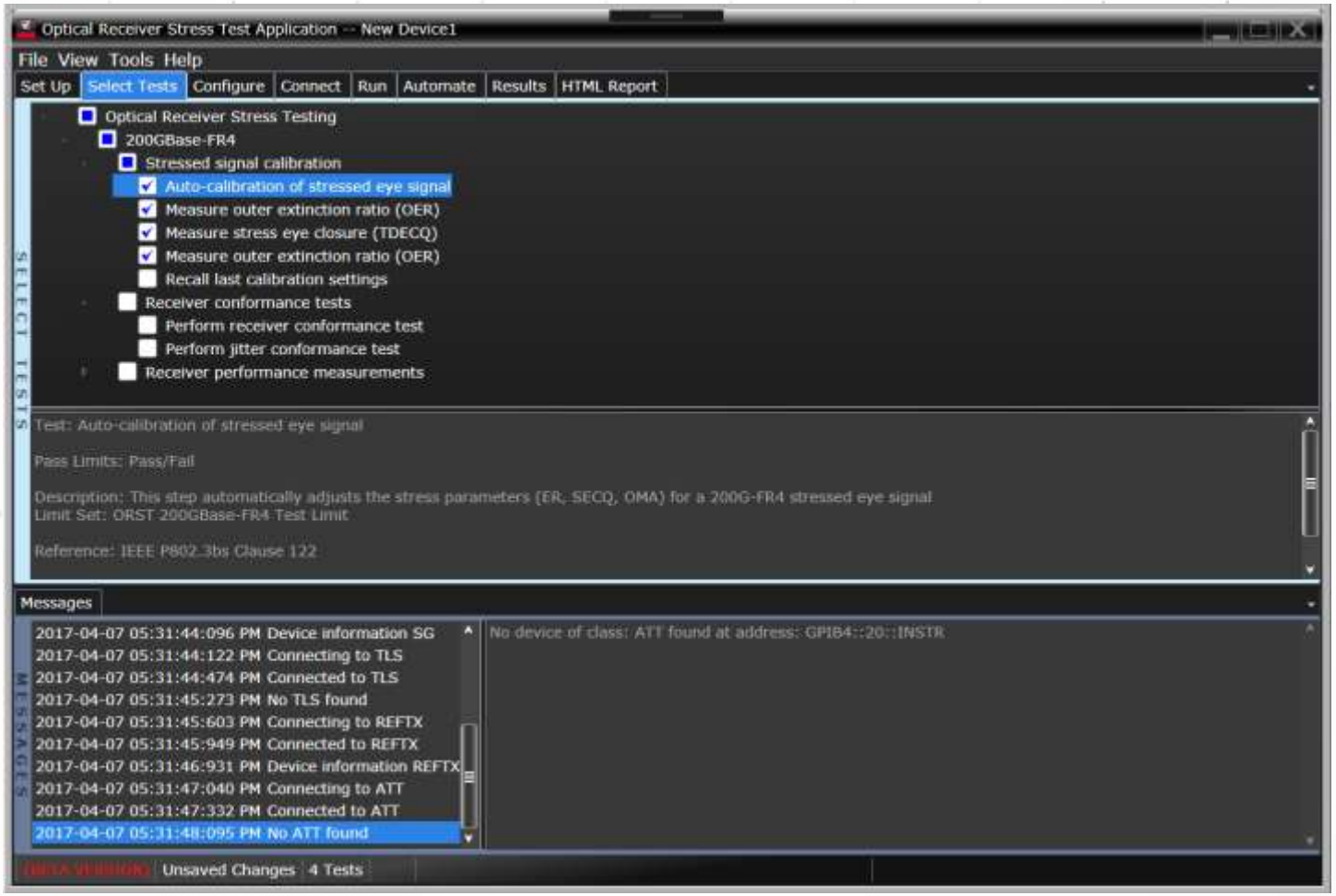
Challenges

- Calibration repeatiblity (accurate control of stress-mix)
- Stable stress signal calibration (Reference transmitter)
- Measurement accuracy (TDECQ algorithm)
- Tedious signal calibration (SW automation)



Keysight Optical Receiver Stress Test

SELECT TEST

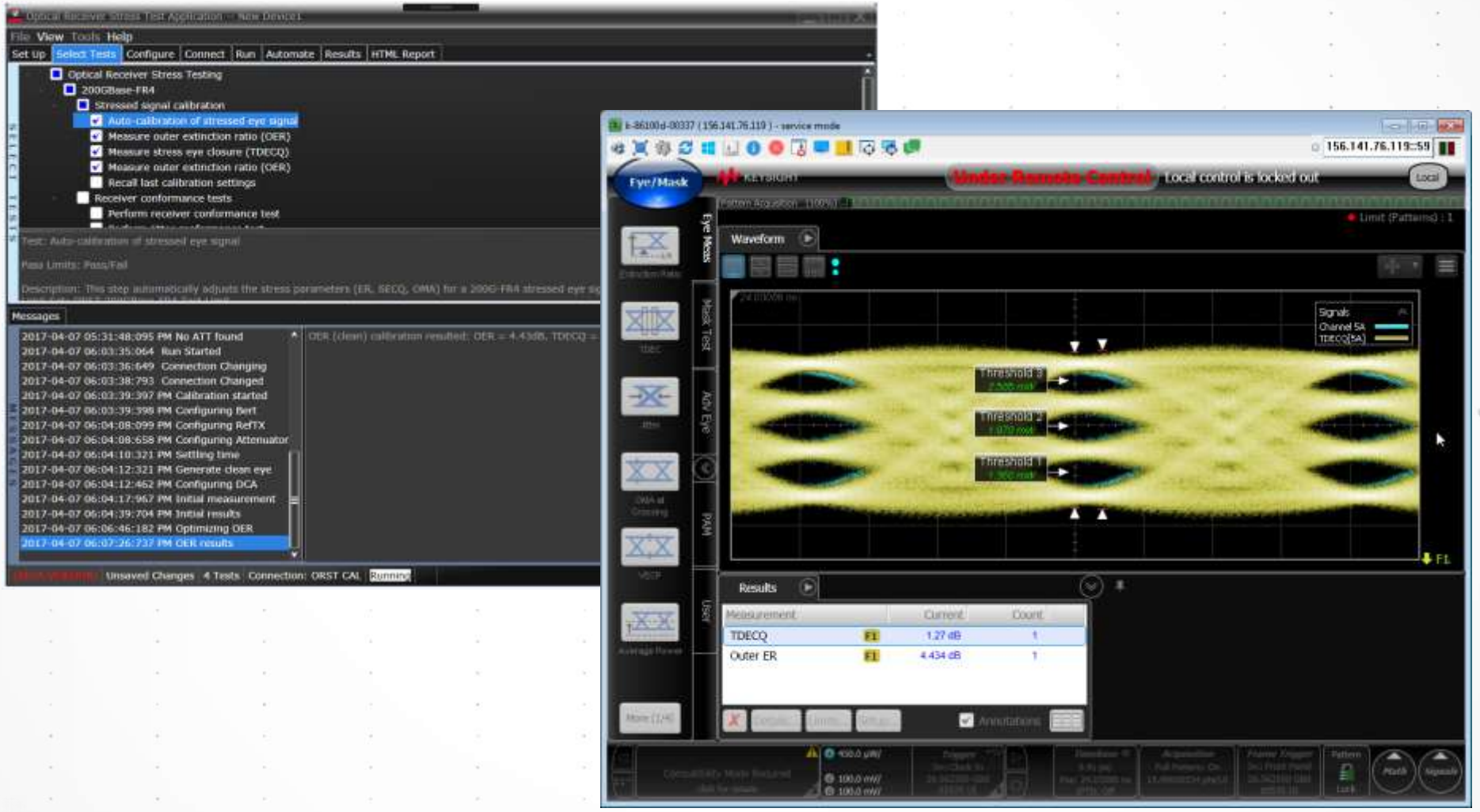


Keysight Optical Receiver Stress Test

CALIBRATION: INITIAL SECQ AND OER

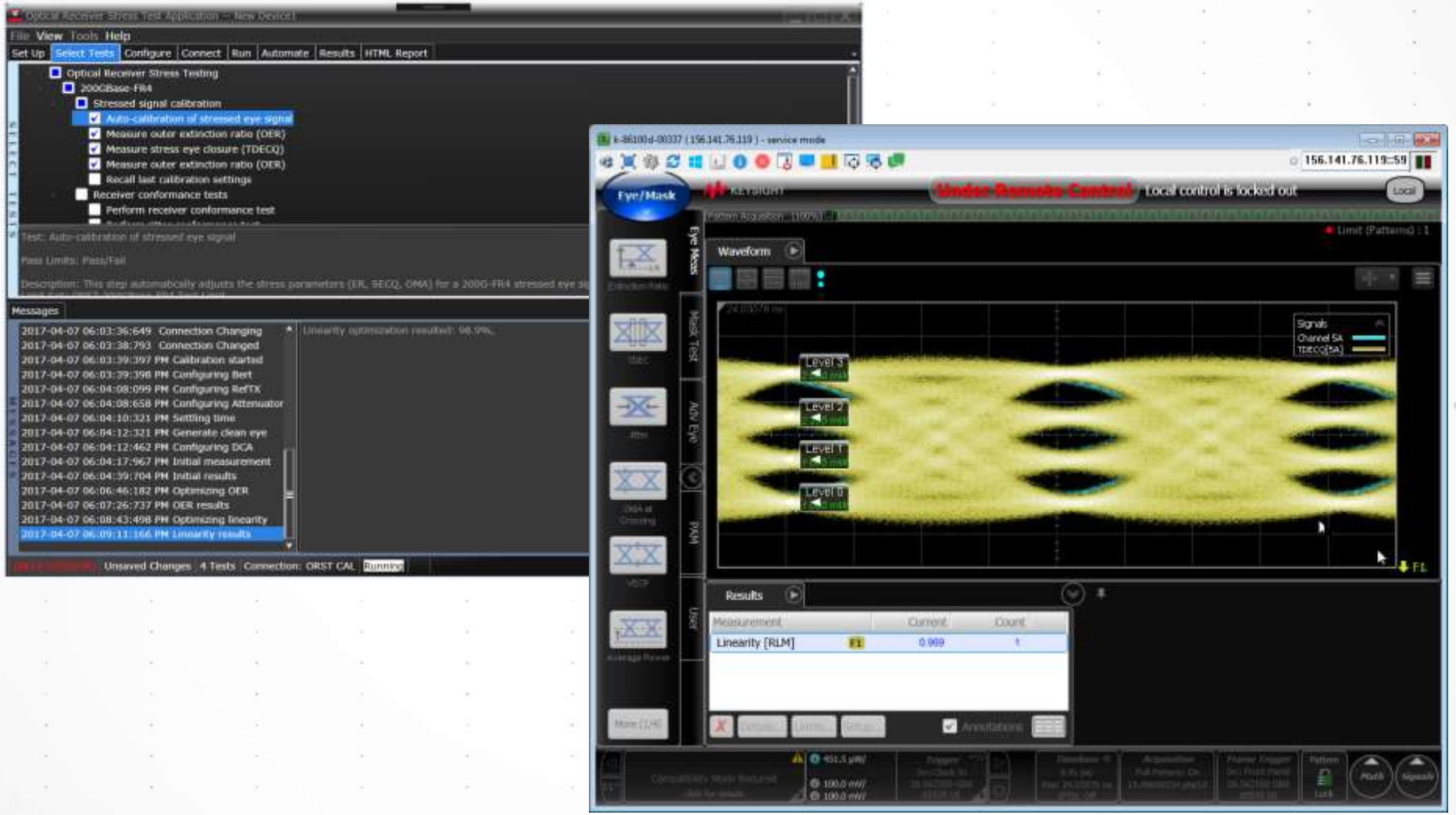
Keysight Optical Receiver Stress Test

CALIBRATION RUN: OER OPTIMIZATION



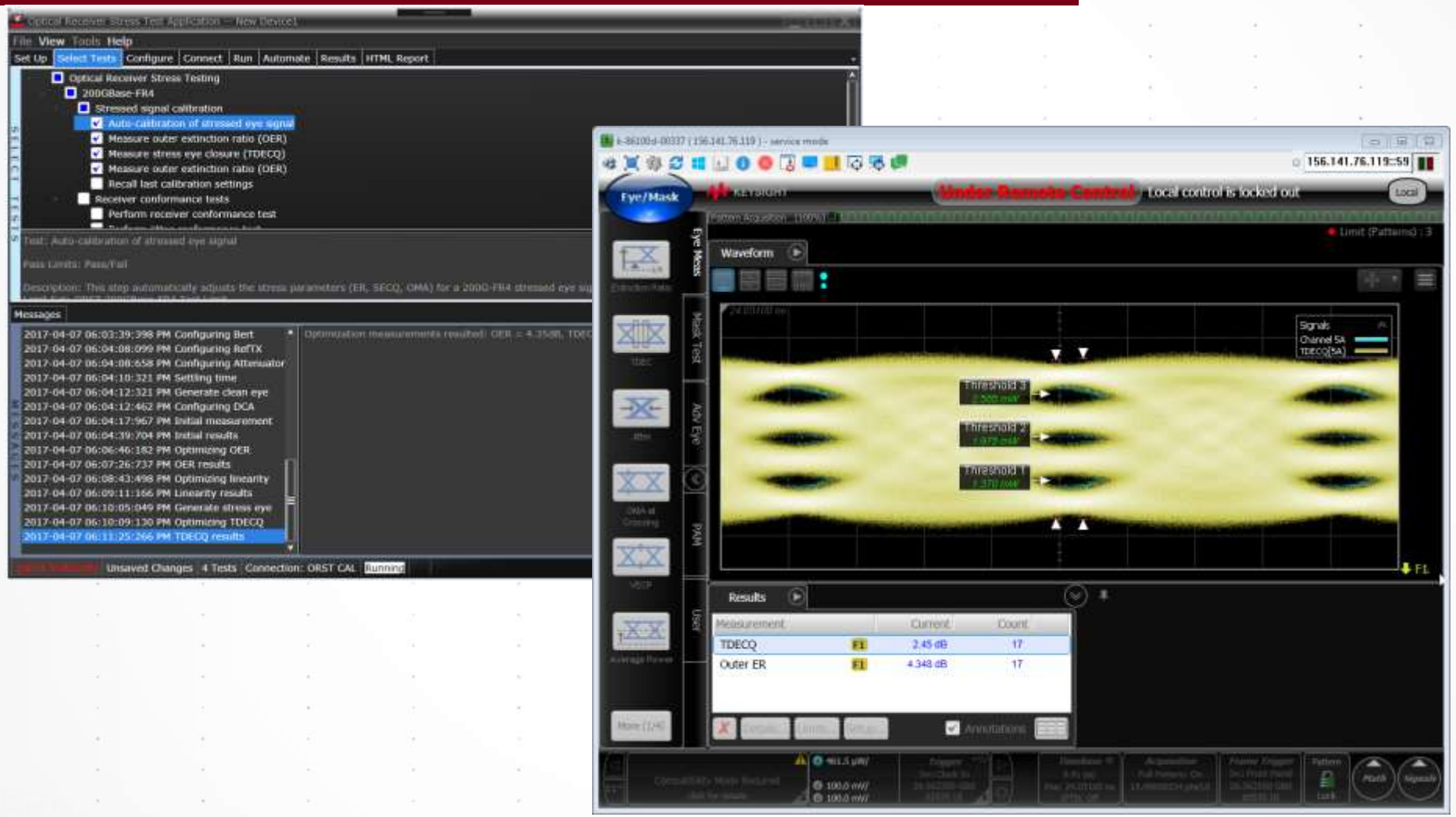
Keysight Optical Receiver Stress Test

CALIBRATION RUN: OPTIMIZE LINEARITY >96%



Keysight Optical Receiver Stress Test

CALIBRATION RUN: OPTIMIZE SECQ

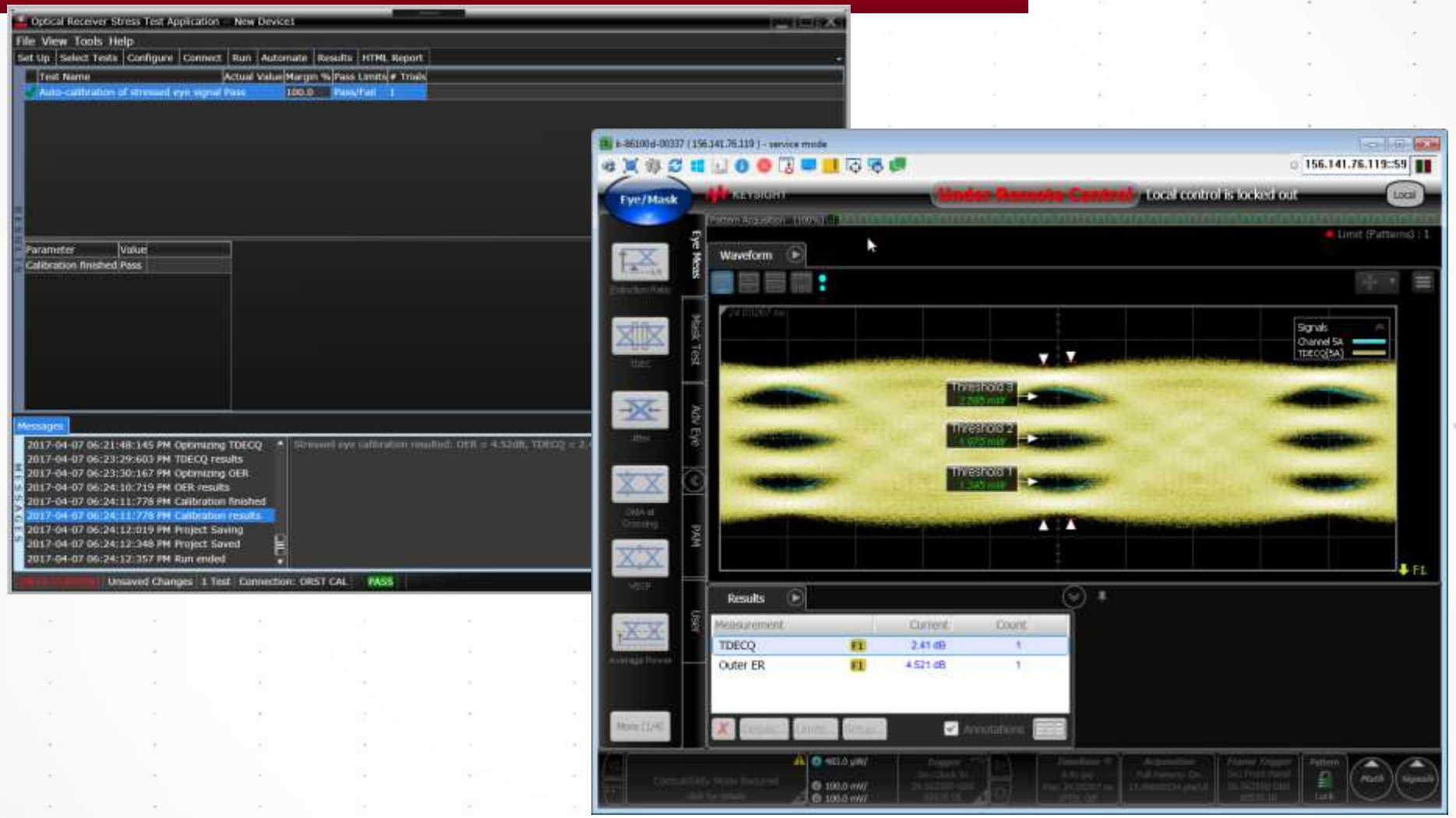


ORST for M8040A

400G ORST Solution - N4917BSCA

Keysight Optical Receiver Stress Test

CALIBRATION COMPLETED

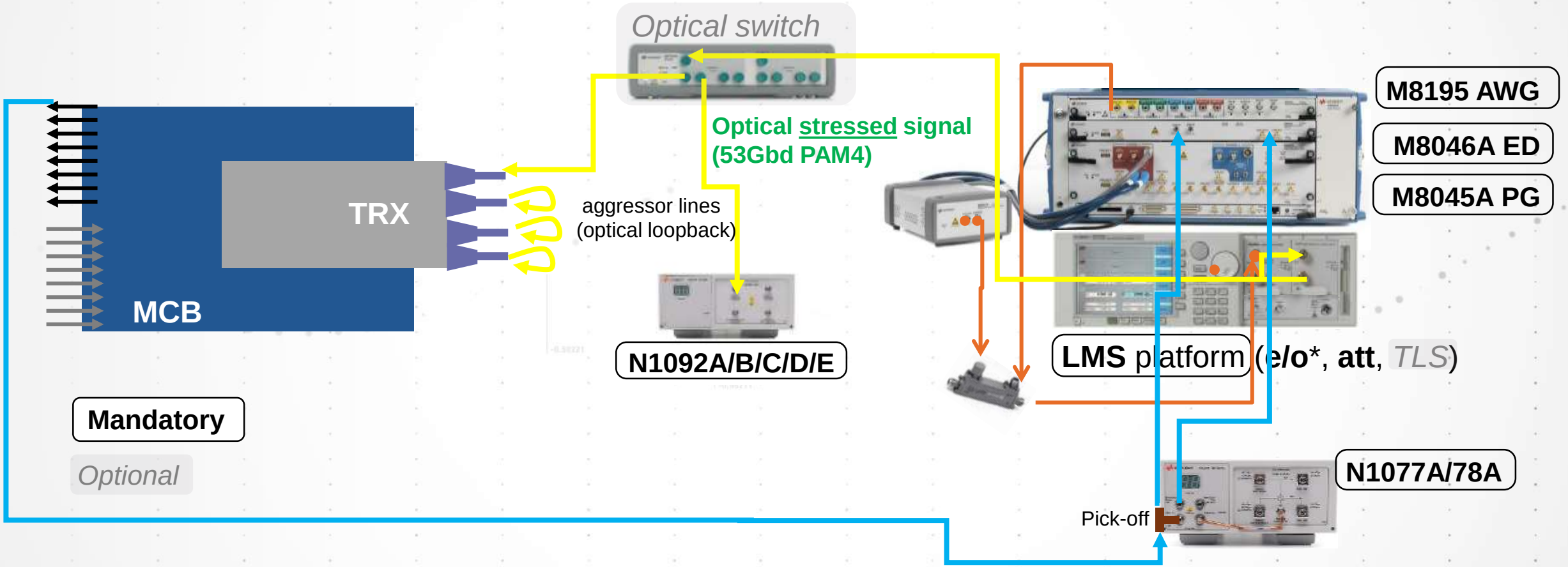


Agenda

- 100G & 400G TRX ecosystem
- Keysight TRX test solutions
- Optical Receiver Stress Test
- **DUT Test**

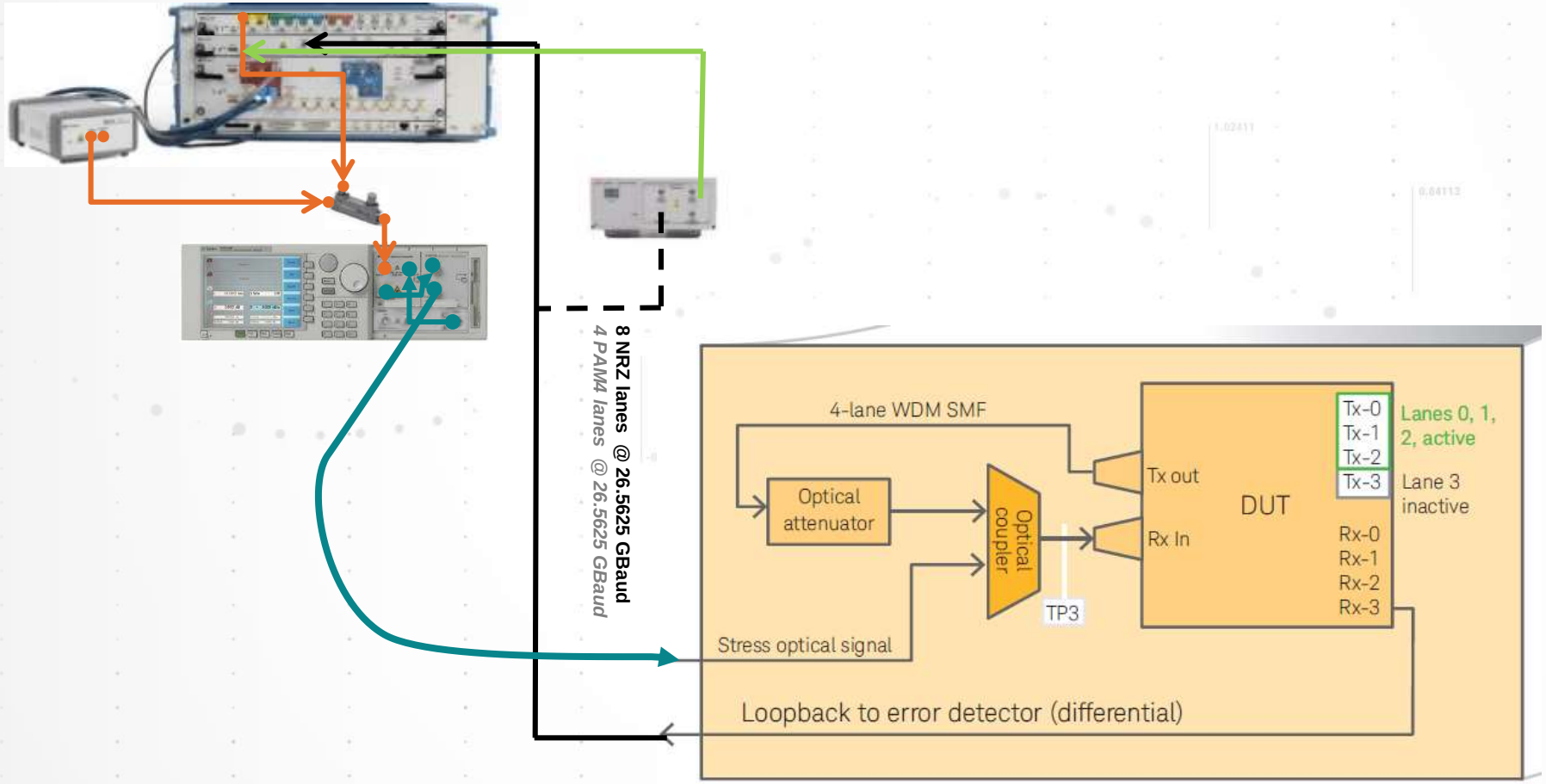
Optical Receiver Stress Test

HW SETUP FOR DR4



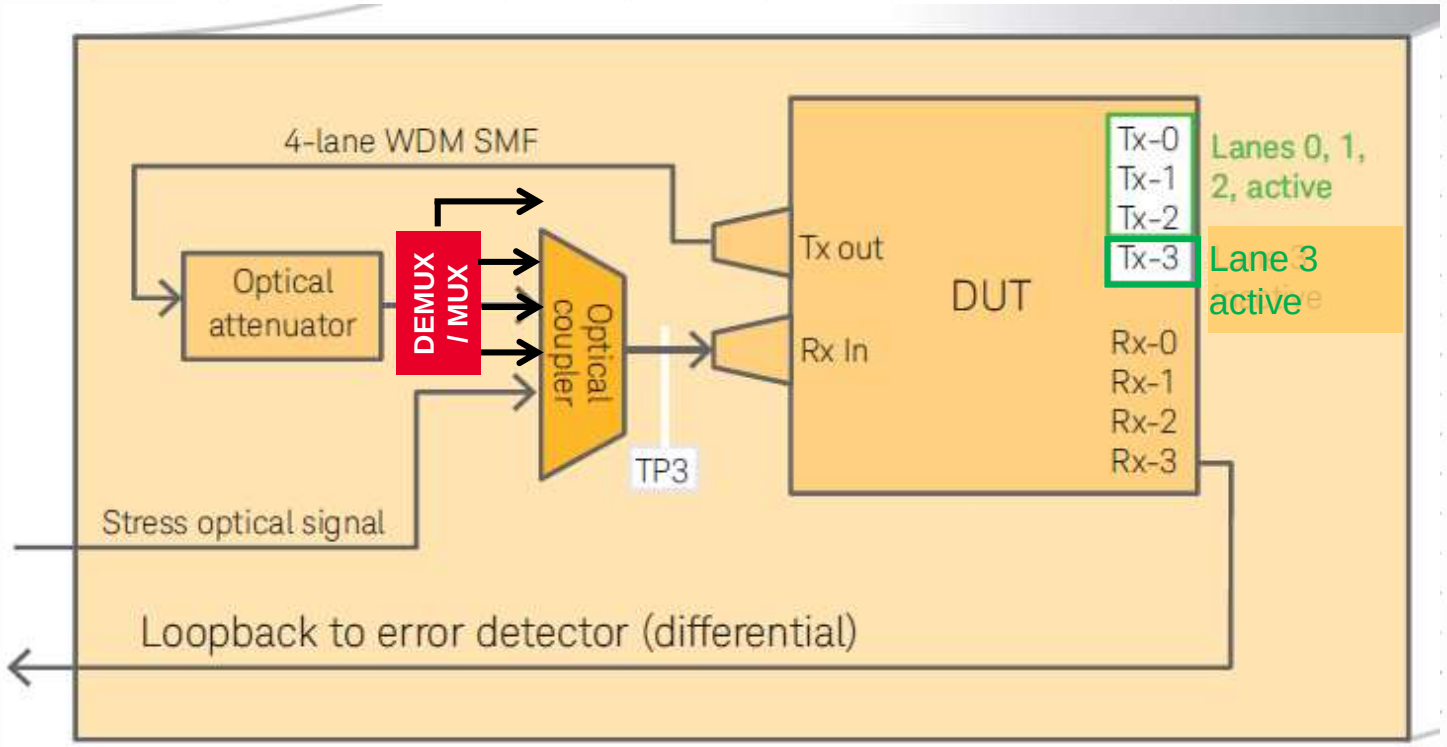
Optical Receiver Stress Test

MODULE PERFORMANCE MEASUREMENT

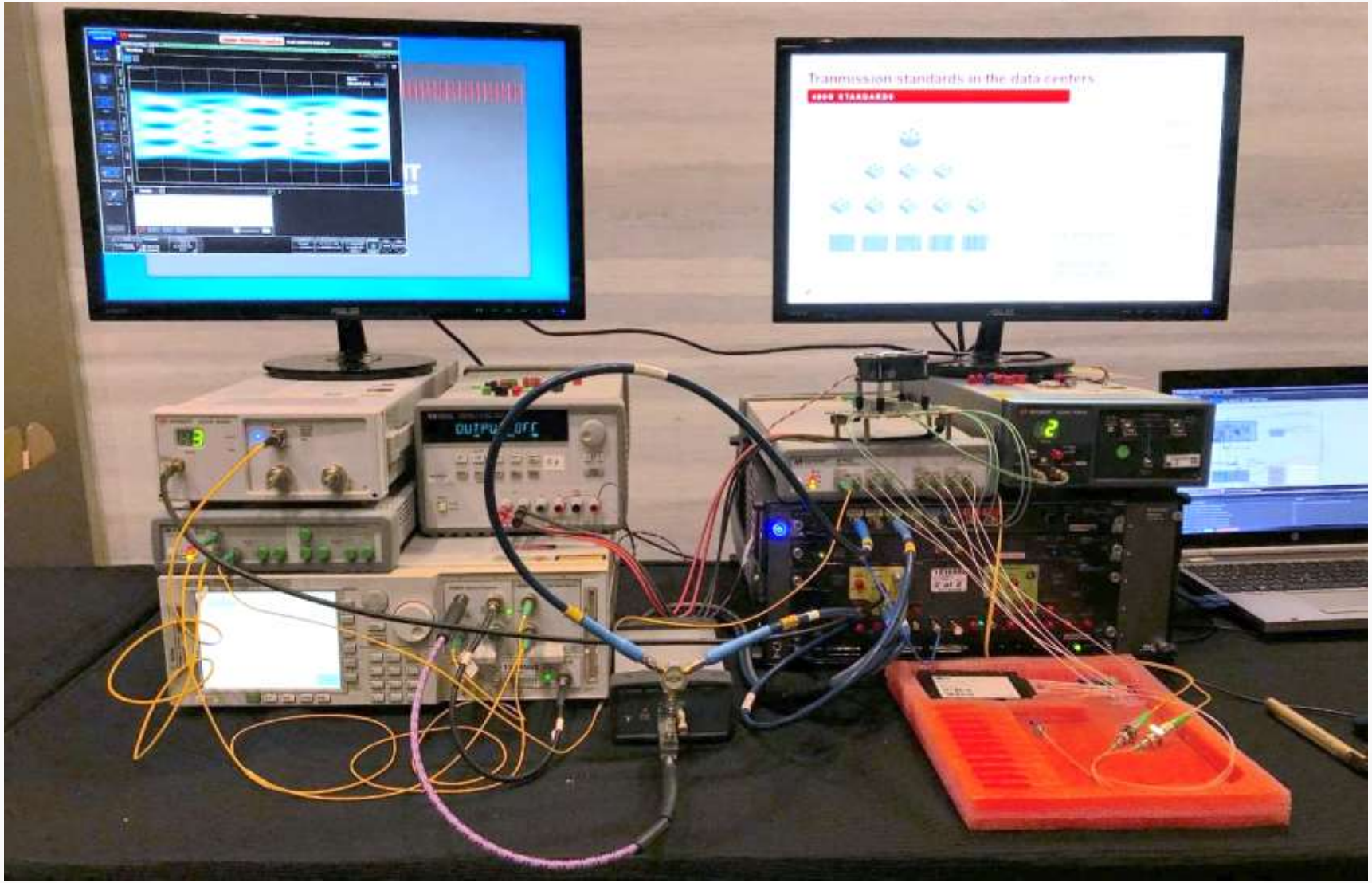


Optical Receiver Stress Test

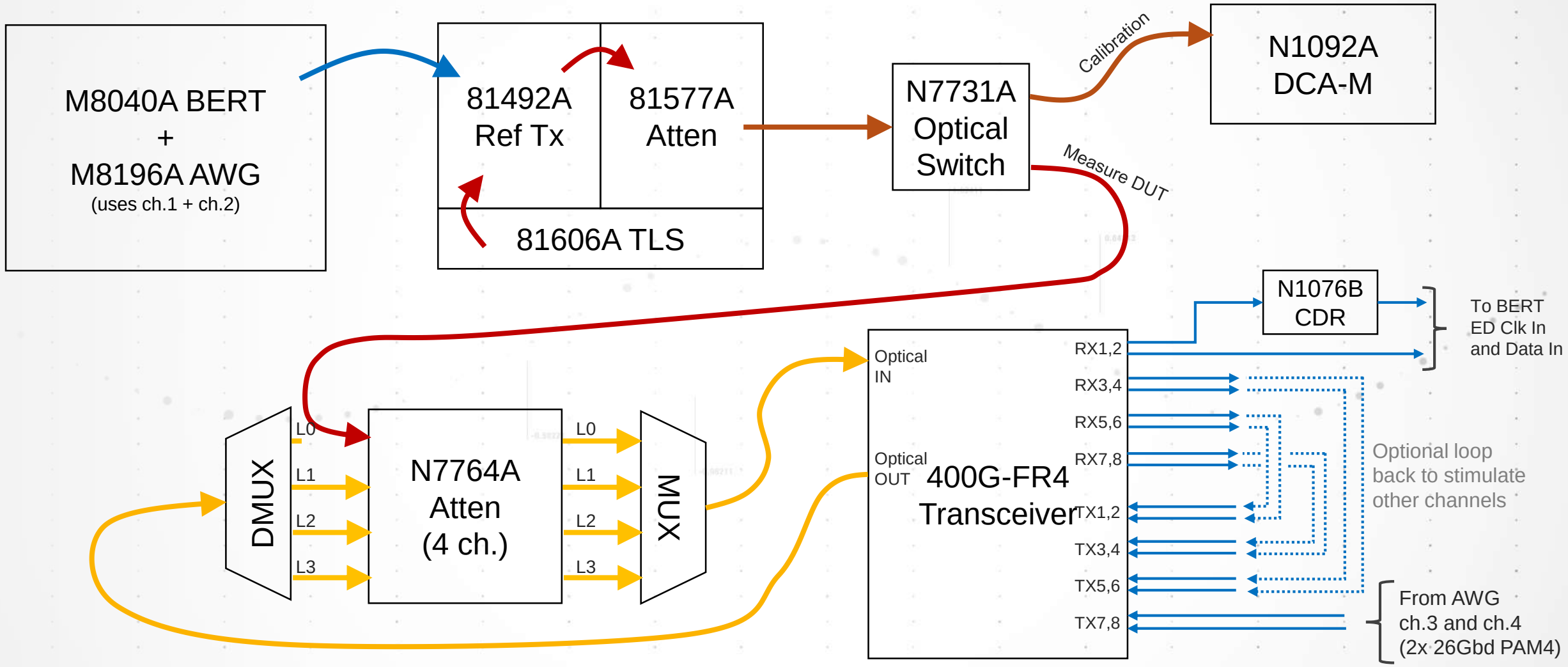
MODULE PERFORMANCE MEASUREMENT



ORST demo with 400G-FR4 DUT

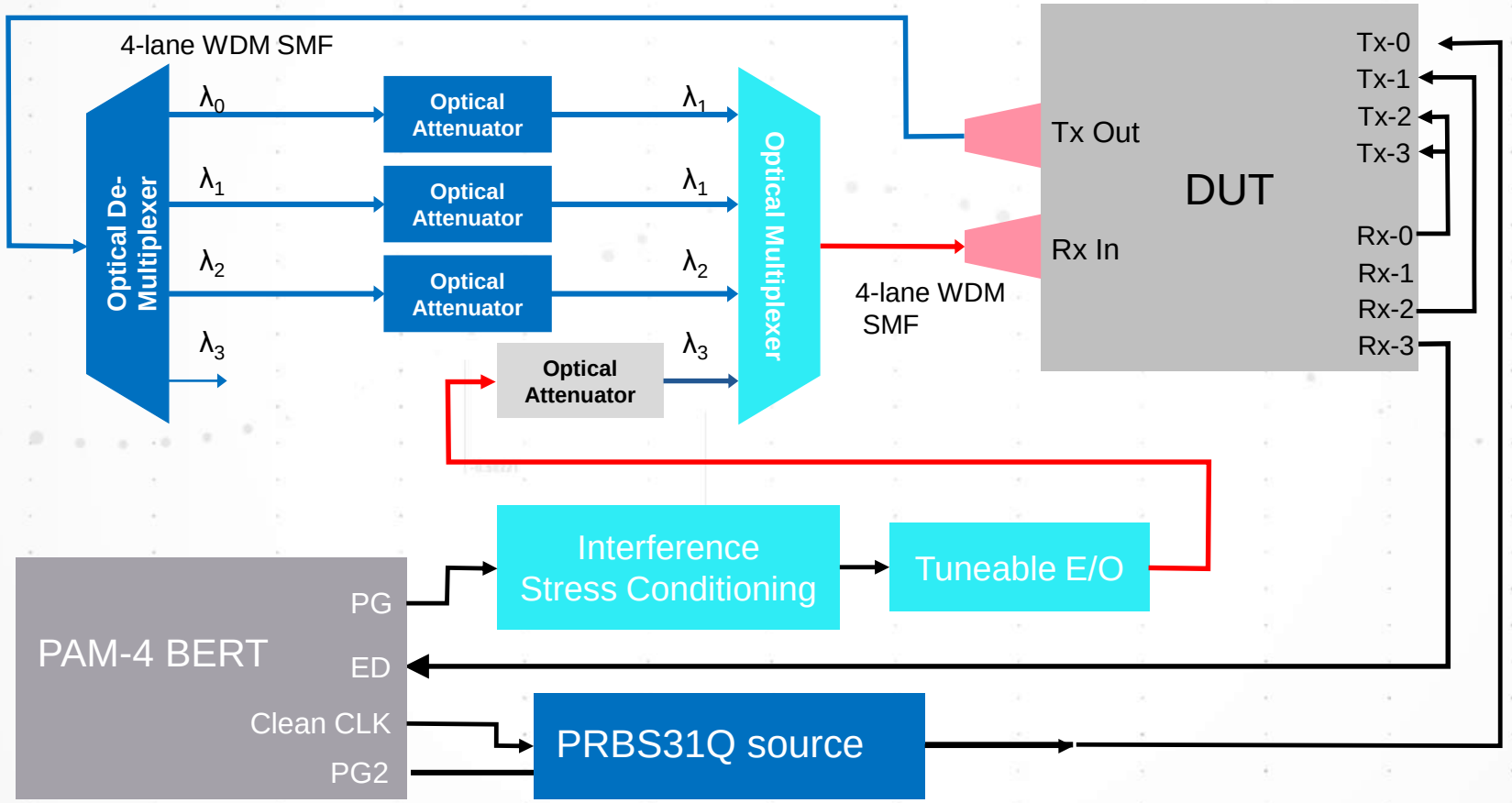


ORST demo setup



Optical Receiver Stress Test

GENERATING AGGRESSOR LANES



Part 2

400G Forward Error Correction

400G FEC 前向糾錯驗證

Joe Lin	2020.12.16
Project Manager / Keysight Technologies	

KEYSIGHT TECHNOLOGIES

Agenda

Introducing N4891A

Use-case #1: 400G functional test & manufacturing

Use-case #2: 400G FEC-aware Rx test (R&D and validation)

Introducing N4891A

With M8040A

Standalone

Affordable 400G interop. and manufacturing solution with uncompromised performance

Industry's first 400G FEC-aware Rx test solution for bullet-proofed design and modules qualification

Specifications

- **4 x QSFP-DD**
- **Per port BERT & FEC modes**
  - **PRBS**: 8 x 26.5625 Gbaud PAM4 lanes per QSFP-DD port
  - **KP4 FEC** RS(544,514)
    - 400GE
    - 200/100/50GE – *future SW upgrade (see roadmap)*

- **PHY characteristics**
  - User-controlled Tx de-emphasis
  - Rx Auto-adaptive (CTLE, FFE, DFE)
  - Baud rate 26.5625 GBaud +/- 100 ppm
  - PRBS mode: PRBS31Q, PRBS23Q, PRBS20Q, PRBS13Q, PRBS9Q, PRBS7Q, SSPRQ (Tx only)
- **Measurements**
  - BERT mode: per lane Raw BER
  - FEC mode: pre FEC BER, FLR, error distribution across FEC code word, error density across all lanes
  - Common management Interface Spec (QSFP-DD MSA)

Agenda

Introducing N4891A

Use-case #1: 400G functional test & manufacturing

Use-case #2: 400G FEC-aware Rx test (R&D and validation)

N4891A – Functional & Interop Testing

E.G. LOOPBACK FUNCTIONAL AND RX SENSIVITY TEST

Key Measurements per QDD port

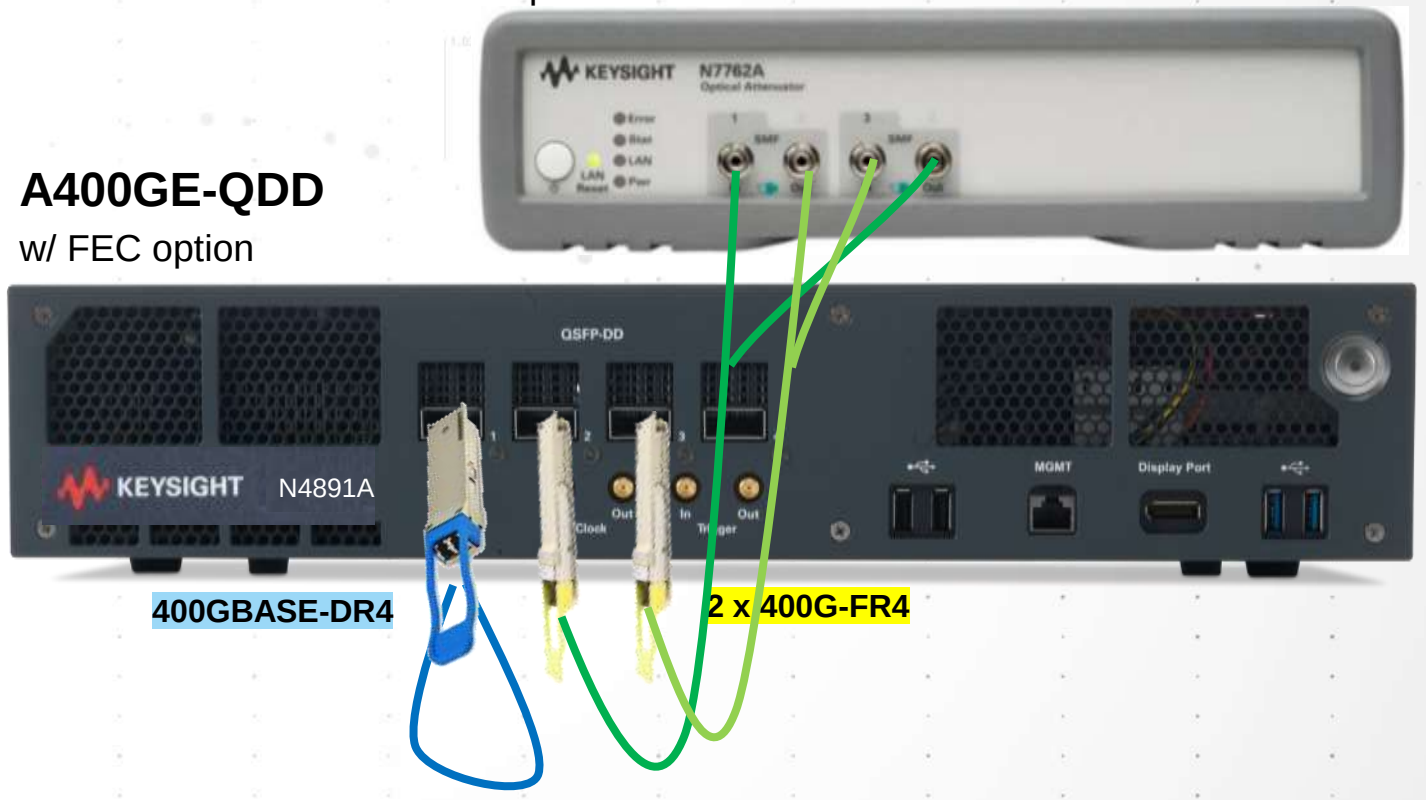
- **BERT mode (PRBS)**
  - Per lane raw BER
  - Rx sensitivity
- **FEC mode**
  - pre FEC BER, FLR,
  - error distribution across FEC code word, error density across all lanes

N7762A

Optical attenuator

A400GE-QDD

w/ FEC option



N4891A – 400G Manufacturing

E.G. PILOT MANUFACTURING FOR 400G-FR4

N1092A-40

Sampling scope with 56Gbaud integrated CDR

N4891A

N77xxB

Optical switch and attenuator

Key Measurements

- **Tx test**
  - TDECQ (SSPRQ), OMA
  - functional test w/ reference Rx
- **Rx test**
  - Rx sensitivity (PRBS & FEC)
  - Loopback or golden DUT

Agenda

Introducing N4891A

Use-case #1: 400G functional test & manufacturing

Use-case #2: 400G FEC-aware Rx test (R&D and validation)

Characterizing Error Mechanisms

IEEE 802.3bs/cd

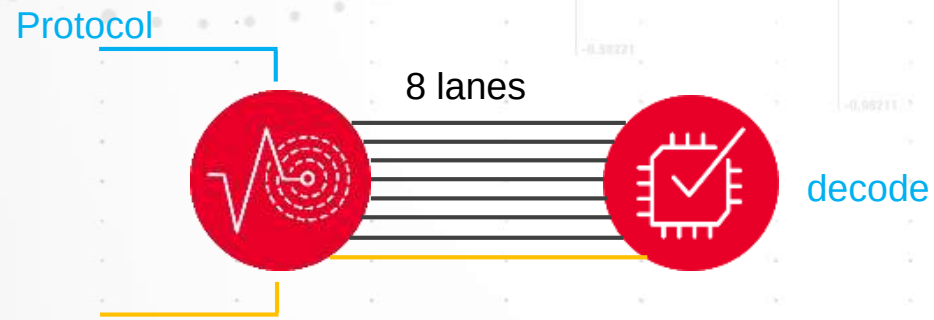
121.1.1 Bit error ratio

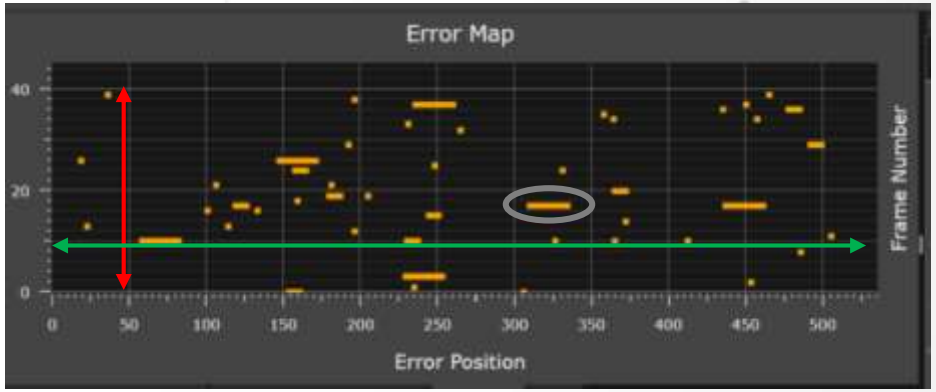
The bit error ratio (BER) when processed according to Clause 120 shall be less than 2.4×10^{-4} provided that the error statistics are sufficiently random that this results in a frame loss ratio (see 1.4.223) of less than 1.7×10^{-12} for 64-octet frames with minimum interpacket gap when processed according to Clause 120 and

OIF-CEI 4.0

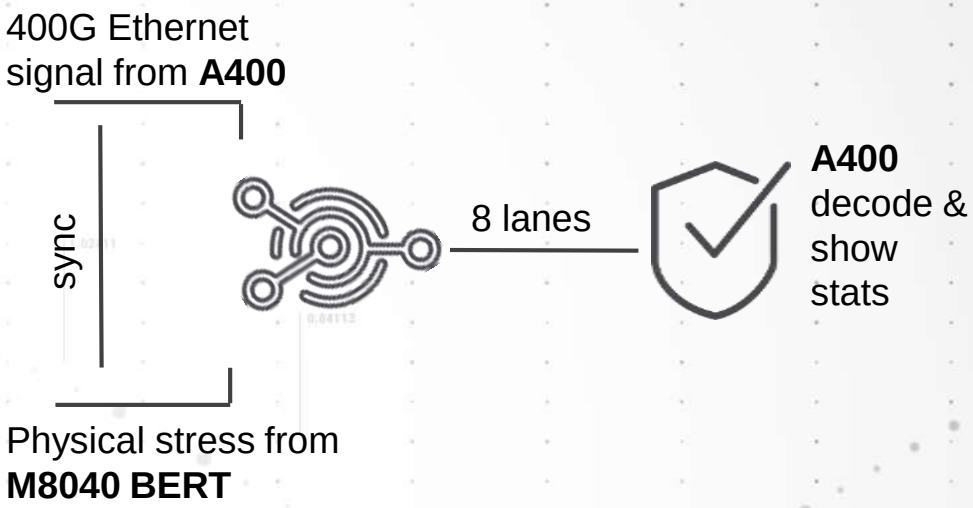
Capable of achieving a raw Bit Error Ratio (BER) of 10^{-6} or better per lane. FEC is assumed to be used to achieve a corrected BER of 10^{-15} or better per lane. The baud rate includes the overhead required for FEC. The definition of FEC is outside the scope of this IA (see Appendix 16.D).

But different jitter types have different effects on TDECQ, BER **and FEC**





FIRST & ONLY FEC-Aware Electrical / Optical Stress Testing



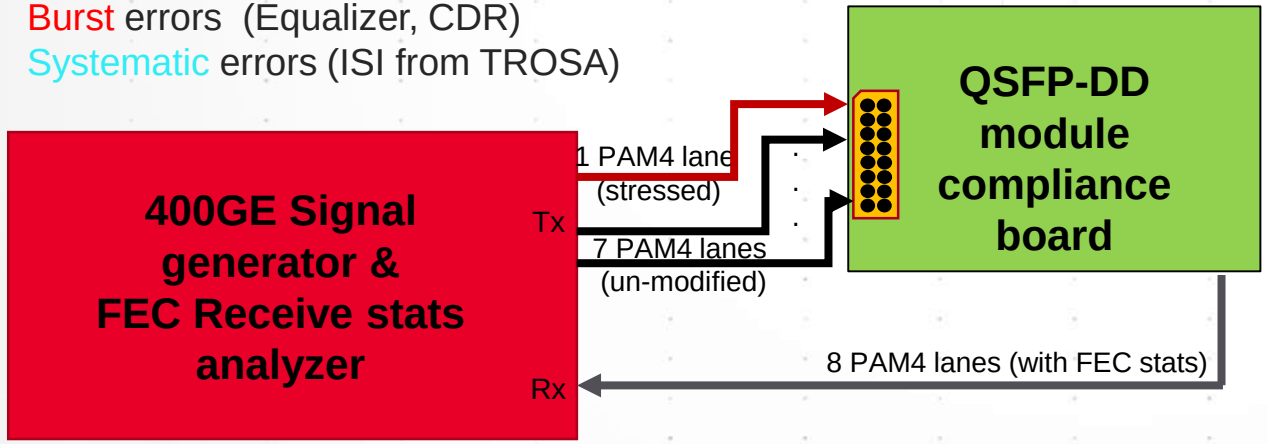
Synchronizes FEC lanes from 2 sources (N4891A & M8040A) seamlessly

Loki injects analog stress onto (1) 50G PAM4 lane

See real-time impact on FEC performance with N4891A Receive Stats (Port 4)

400GAUI-8 - Characterizing Error Mechanisms

- Randomly distrusted errors (noise)
- Burst errors (Equalizer, CDR)
- Systematic errors (ISI from TROSA)



A Physical Lane	B PCS Lane Marker Lock	I FEC Corrected Bit
Totals		
0		1.02e-004
1		6.81e-005
2		1.06e-009
3		6.83e-009
4		1.09e-009
5		3.53e-010
6		1.81e-009
7		2.84e-008
8		5.68e-010
9		1.11e-010
10		6.06e-009
11		1.29e-009
12		9.40e-009
13		6.27e-008
14		1.68e-009
15		3.20e-008

Below FEC limit

FEC Frame Loss Ratio	9.96e-010
pre FEC Bit Error Rate	1.75e-005
FEC Codeword with 0 error	11,222,349
FEC Codeword with 1 error	724,583,051
FEC Codeword with 2 errors	125,727,391
FEC Codeword with 3 errors	26,741,564
FEC Codeword with 4 errors	6,356,835
FEC Codeword with 5 errors	1,627,784
FEC Codeword with 6 errors	442,411
FEC Codeword with 7 errors	125,802
FEC Codeword with 8 errors	36,891
FEC Codeword with 9 errors	11,517
FEC Codeword with 10 errors	3,496
FEC Codeword with 11 errors	1,030
FEC Codeword with 12 errors	377
FEC Codeword with 13 errors	91
FEC Codeword with 14 errors	39
FEC Codeword with 15 errors	8
FEC Uncorrectable Codewords	6
FEC Transcoding Uncorrectable Events	6
Transmit Arp Gratuitous	0
Transmit Arp Reverse	0

FEC has no margin!

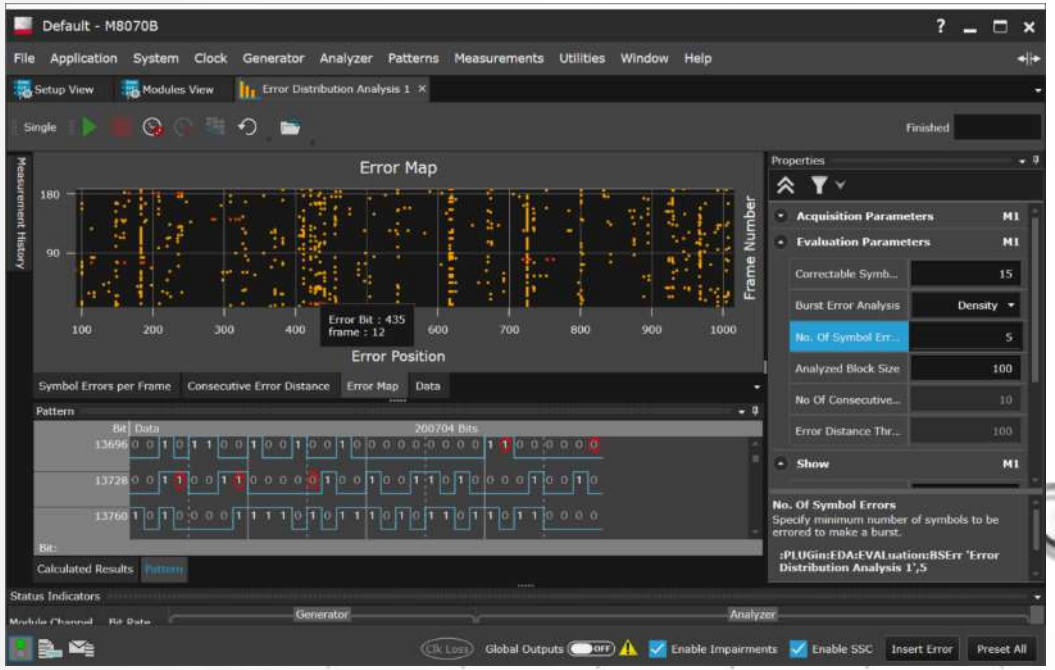
FLR target failed

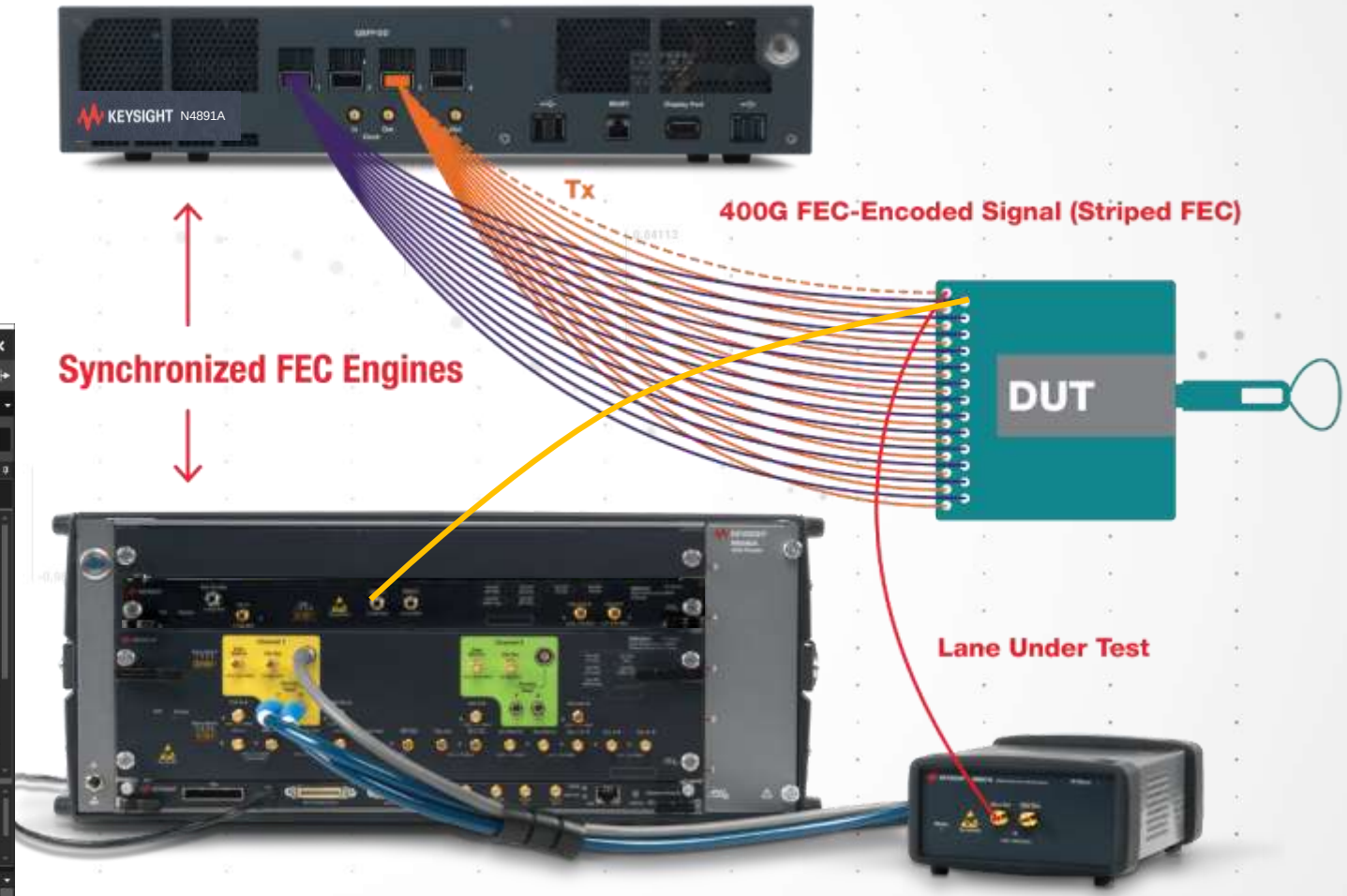
N4891A – FEC-aware Compliance Testing

400GAUI-8 // PHY CHIP OR GEARBOX

Multi-lane analysis

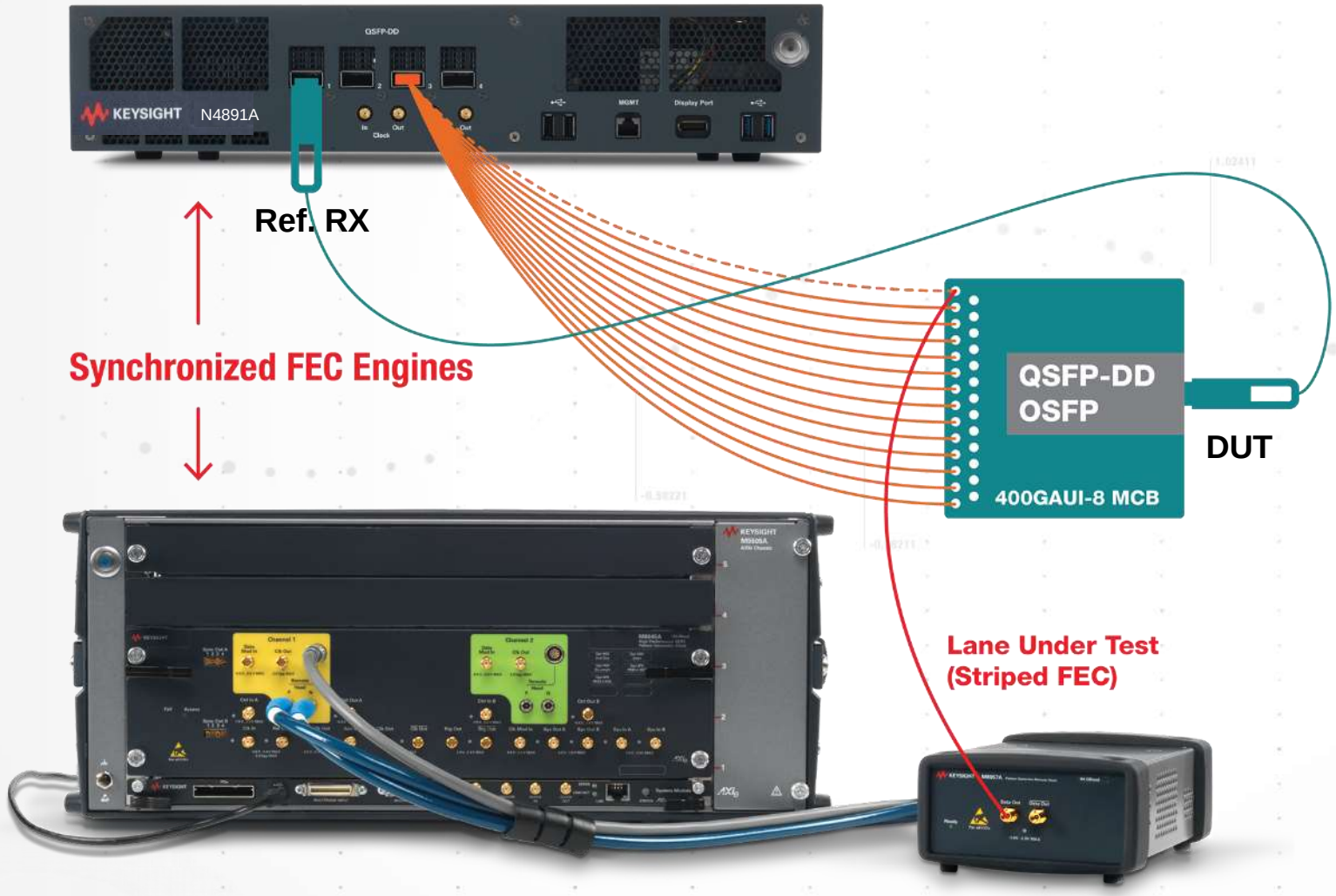
Tx & Rx test
- Post FEC (FLR)
- Pre-FEC BER on all lanes (KP4 or PRBS mode)





N4891A – FEC-aware Compliance Testing

400GAUI-8 // OPTICAL TRANSCEIVER MODULE



- ✓ **Jtol measurements**
  - Post FEC (FLR)
  - Pre-FEC
- ✓ **Sensitivity measurement**
- ✓ **Rx (FEC) and Tx test (PRBS)**
- ✓ PMDs agnostic
- ✓ Compliance testing for
  - OIF-CEI 56G-VSR
  - IEEE 802.3bs
- ✓ configuration w/ internal loopback possible

N4891A – FEC-aware Compliance Testing

400G PMD // 400GBASE-FR8

Synched
FEC engines

WDM MUX/DEMUX

Optical Lane under test
(striped FEC)

Optical Receiver Stress Test
- Receiver sensitivity
- Jitter tolerance
- BER, FLR, FEC margin

N4891A – FEC-aware Compliance Testing

400GAUI-8 INTERFACE

- **Error analysis with stripped FEC**
  - **one stress lane**
  - Two stress lanes - *future SW upgrade*
  - **seven aggressor lanes**

- **Compliant with**
  - IEEE 400GAUI-8 specifications
  - 200GAUI-4 & 100GAUI-2 - *future SW upgrade*

  - IEEE 400GBASE-FR8/-LR8/(-SR8) specifications
  - 400GBASE-DR4/-(FR4) - *future SW upgrade*
  - 200GBASE-FR4/-LR4 - *future SW upgrade*
  - 100GBASE-DR- *future SW upgrade*

Unique combination of

BERT platform & protocol tester

Detect design issues affecting FEC performance early in the design or qualification process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