TQM analysis and results for 800GBASE-LR1

Kishore Kota – Marvell Semiconductor

P802.3dj Plenary Meeting, Montreal, Canada, July 2024

Introduction

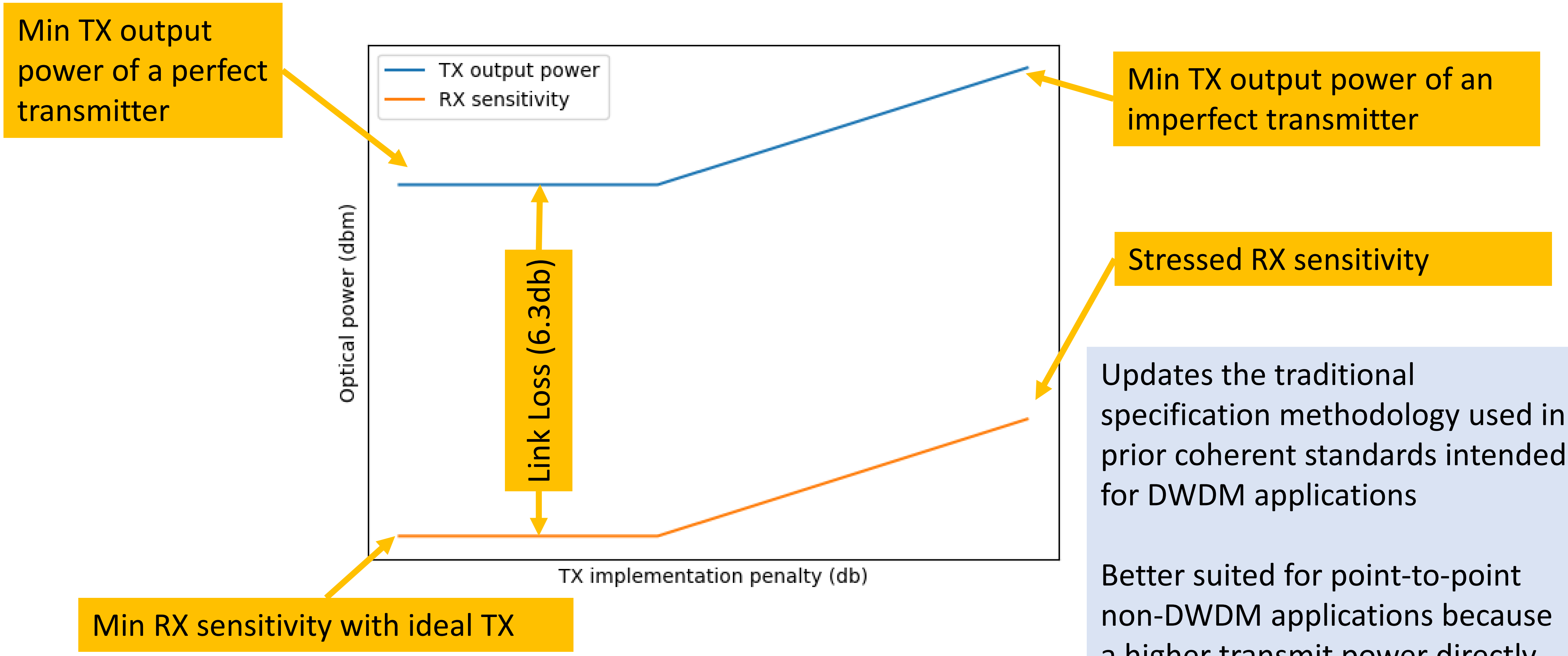
- kota_3dj_01a_2311 and kota_3dj_01a_2401 discussed the use of a transmit quality metric to specify TX output power and RX sensitivity specifications for 800GBASE-LR1
  - Same concept as TECQ in IMDD specifications

- 800GBASE-LR1 can benefit from such a specification methodology by allowing more options for implementors to lower complexity of coherent module designs

- T22-SG15-C-1214 and maniloff_3dj_02_2405 explored ways to define a transmit quality metric. "Transmitter Constellation Closure (TCC)" has been proposed as a TQM for coherent transmitters. This presentation uses the generic term "TQM" to refer to either of the proposals from the above references.

- OIF has collected interop data on 400G modules and was provided to 802.3 through a liaison. This presentation provides some results of processing the data that was provided in oif2023.502.00.zip

TQM based Specification Methodology



Updates the traditional specification methodology used in prior coherent standards intended for DWDM applications

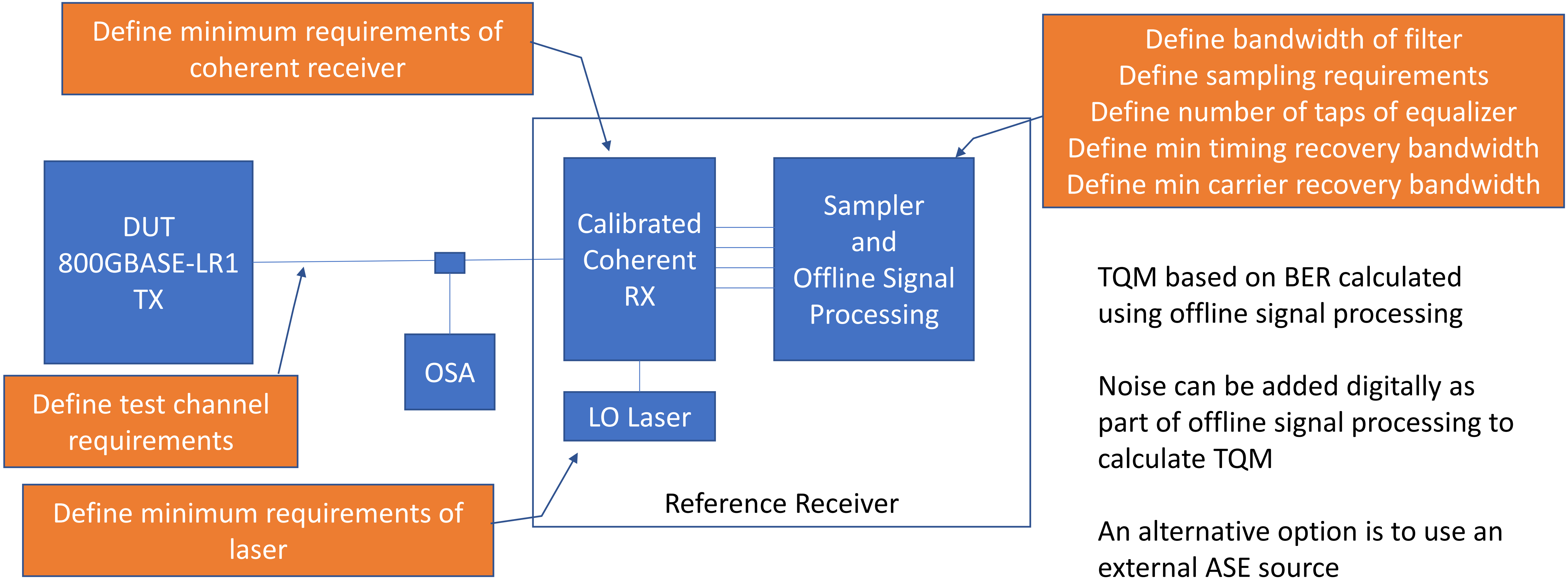
Better suited for point-to-point non-DWDM applications because a higher transmit power directly translates into link margin

What is a Transmit Quality Metric?

- Transmit quality metric estimates the BER penalty of the transmitter under test relative to an ideal transmitter measured at a reference receiver

- TQM will not predict the exact behavior of an arbitrary (unknown) receiver implementation!
  - A real receiver could see less penalty because an implementation may choose to use a receiver design which exceeds the capability of a reference receiver. For e.g. the real receiver might use a longer filter or a different sampling rate to improve performance relative to the reference receiver
  - Similarly, a real receiver could perform worse if aspects of the reference receiver aren't implemented. For e.g., TECQ reference receiver has perfect knowledge and can adjust sampling phase to minimize TECQ. A real receiver may not be able to match that.

Possible setup to measure TQM



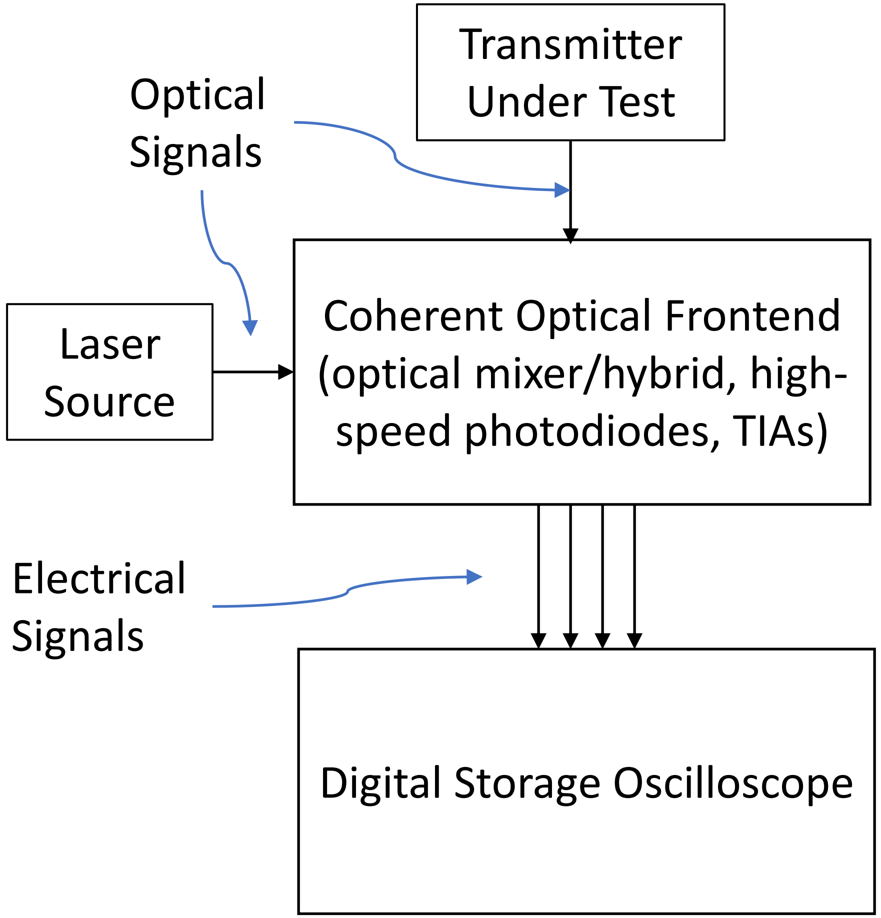
TQM based on BER calculated using offline signal processing

Noise can be added digitally as part of offline signal processing to calculate TQM

An alternative option is to use an external ASE source

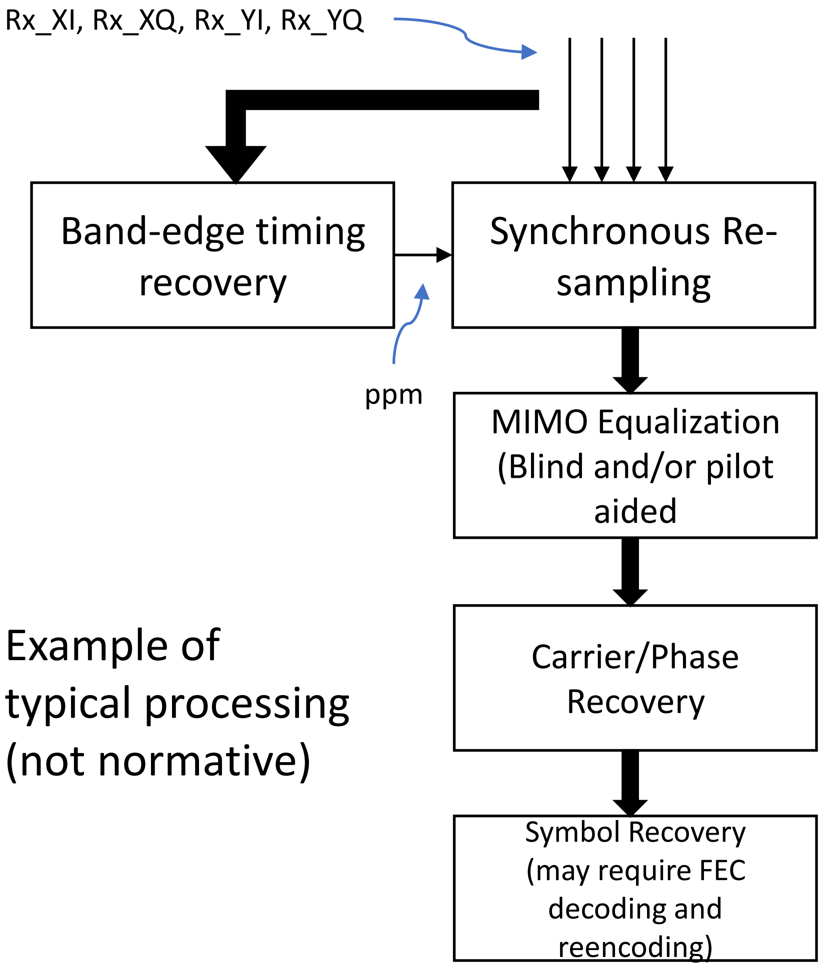
Coherent RX frontend: Optical to Electrical Conversion

- The coherent optical signal output of the transmitter under test is converted to a set of four electrical signals using a calibrated coherent optical front-end.
- Depending on the specific equipment used for the test, this may require the use of an external high quality laser source as the LO. External sources with laser linewidths ~100kHz will be sufficient for this measurement
- Such optical front-ends coupled with high speed scopes suitable for 800GBASE-LR1 are available from test vendors and commonly used during development.
- The optical front-ends need low noise and need to be well calibrated to ensure good matching: low gain/skew mismatches, low quadrature error, low noise and high bandwidth.
- The data provided by OIF was obtained using two such setups from different vendors for a number of 400G coherent modules provided by multiple module vendors.



Offline Processing Step1: Extract transmitted symbol sequence

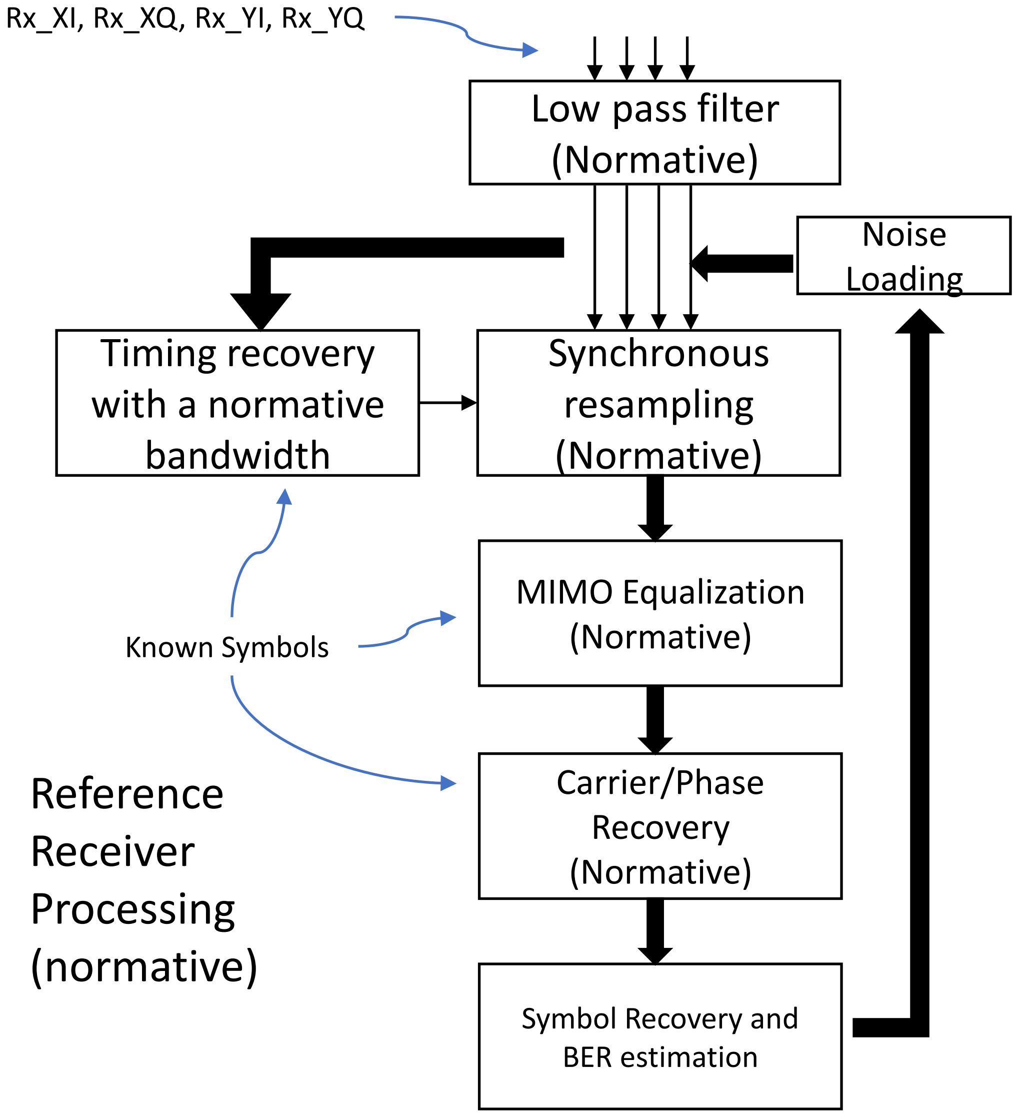
- Since TQM is intended to be based on BER measurements, the first step is to extract the uncorrupted symbol sequence corresponding to the waveforms captured using the scope
- The four received signals (Rx_xi/Rx_xq/Rx_yi/Rx_yq) available for the offline processing will in general contain an arbitrary mix of the Tx_xi/Tx_xq/Tx_yi/Tx_yq signals (See Fig 184-2) since the polarization at the receive optical front-end is arbitrary relative to the transmitter. In addition, the symbol frequency offset and LO offset will be non-zero relative to the transmitter under test.
- Any appropriate procedure is acceptable for this step. An example of such processing will is shown using some form of band-edge timing recovery to extract the symbol timing, blind and/or pilot aided MIMO equalization, and carrier frequency/phase recovery to extract the transmit symbols.
- Either a test pattern (such as SSPRQ) or a fully compliant FEC encoded signal can be used for the test. A test pattern would allow recovery of the symbol sequence without requiring implementation of the deinterleavers and FEC decoding steps.
- The OIF data was captured in normal mode without the use of test patterns. However, recovery of the exact sequence is still possible through FEC decoding followed by re-encoding the recovered bits.



Example of typical processing (not normative)

Offline Processing Step2: Noise vs BER of normative Reference Receiver

- Next step of the TQM calculation will require the use of normative reference receiver and digital noise loading to calculate the SNR vs BER characteristic of the transmitter under test.
- The reference receiver should be capable of correcting for receiver imperfections but not transmit imperfections (with possible exceptions).
- If it is determined that certain transmit specifications should be relaxed as part of the standard (for e.g. to enable better yields or manufacturablity for high volume applications), it would then be acceptable to define the reference receiver to handle such impairments
- Note that the description of the reference receiver in the standard does not have to be "practical" as long as it is understood that practical receiver DSP implementations with similar performance are feasible
- For e.g. it would be ok to use known symbols from step 1 to assist the timing recovery, MIMO equalization and carrier recovery steps in the reference receiver



TQM Calculation

- TCC calculation is shown below (See Q. Fan & X. Liu, TH2A.26, OFC 2024)
  - $TCC(dB) = 10\log_{10}\left(\frac{\sigma_{ideal}^2}{\sigma_{TUT}^2+\sigma_s^2}\right) + 10\log_{10}\left(\frac{p_{unfiltered}}{p_{filtered}}\right)$
- The alternative $\nabla RSNR_{TX}$ is described in [maniloff_3dj_02_2405]
  - $\nabla RSNR_{TX} = 10\log_{10}\left({}^{RSNR_{vase}}/_{RSNR_{th}}\right)$
- Although the description and treatment is different, both metrics are equivalent is $RSNR_{th}$ corresponds to an ideal receiver

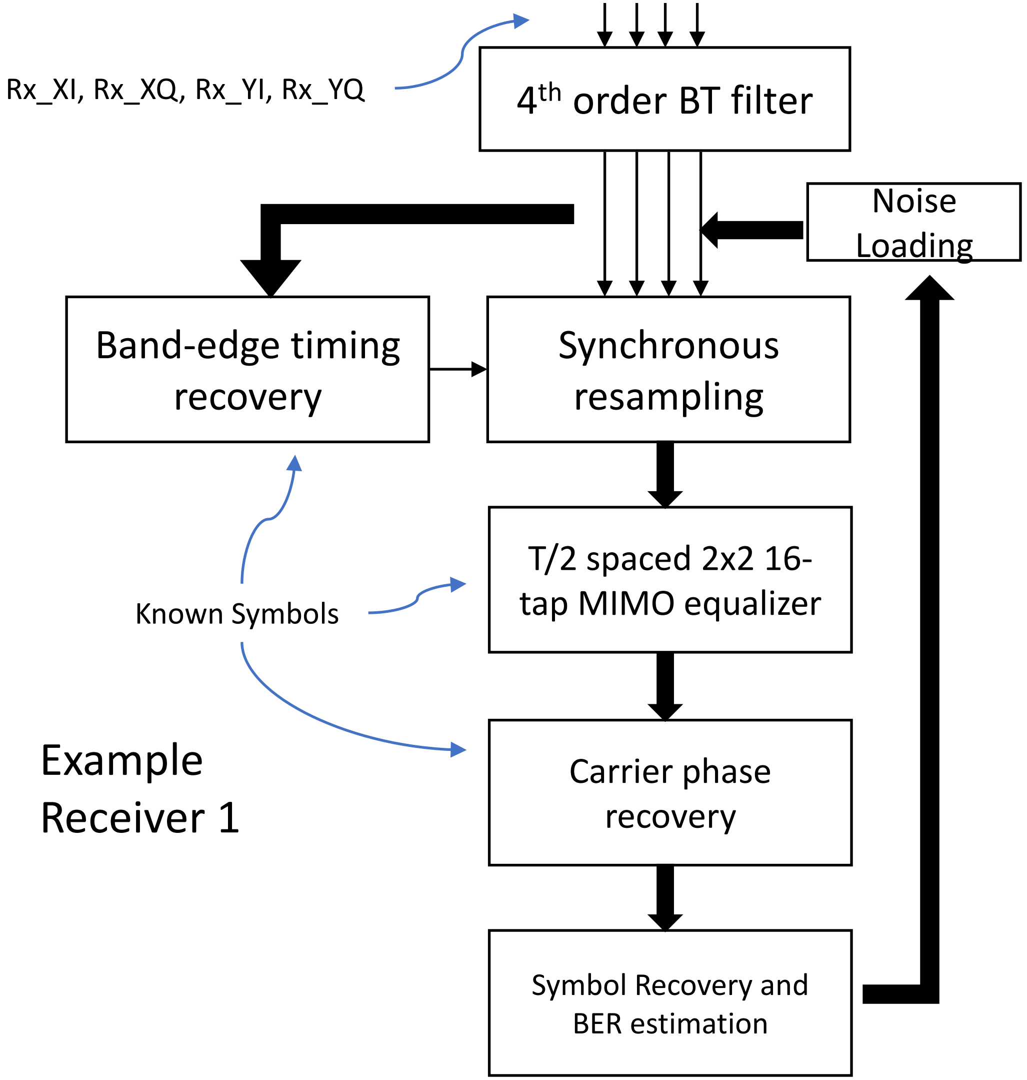
Comments on the OIF data

- The "preECOC2023" data provided via liaison in oif2023.502.00.zip is used in this presentation
- The data was collected from multiple modules in a standard 400ZR+ mode labelled "Vendor_A" to "Vendor_J"
  - Symbol rate is 60.1318GHz and modulation is DP-16QAM
  - The line side FEC is OFEC with a BER threshold of 2×10^{-2}
  - A line side framing includes pilot symbols inserted once every 32 symbols using the outermost constellation points
- Data files were captured using two different setups from different test vendors (labelled in this presentation as TestVendor_1 and TestVendor_2)
  - Datafiles contain approximately 161k or 33k samples at ~92GHz or 100GHz rate
  - No separate scope noise measurements are available
  - Data for some modules available only from one setup
  - Unclear whether the vendor labels in the two test setups are the same. Assuming the labelling is not the same pending confirmation.

Results from Example Receiver 1 (Preliminary)

- $\nabla RSNR_{TX}$ (in dB) calculated per maniloff_3dj_02_2405
  - $RSNR_{vase}$ is the SNR threshold calculated relative to signal power at BT4 input at BER threshold
  - $RSNR_{th}$ = 12.7dB (for 2e-2 BER threshold)
- Calibrated scope noise measurements unavailable to exclude impact of test equipment

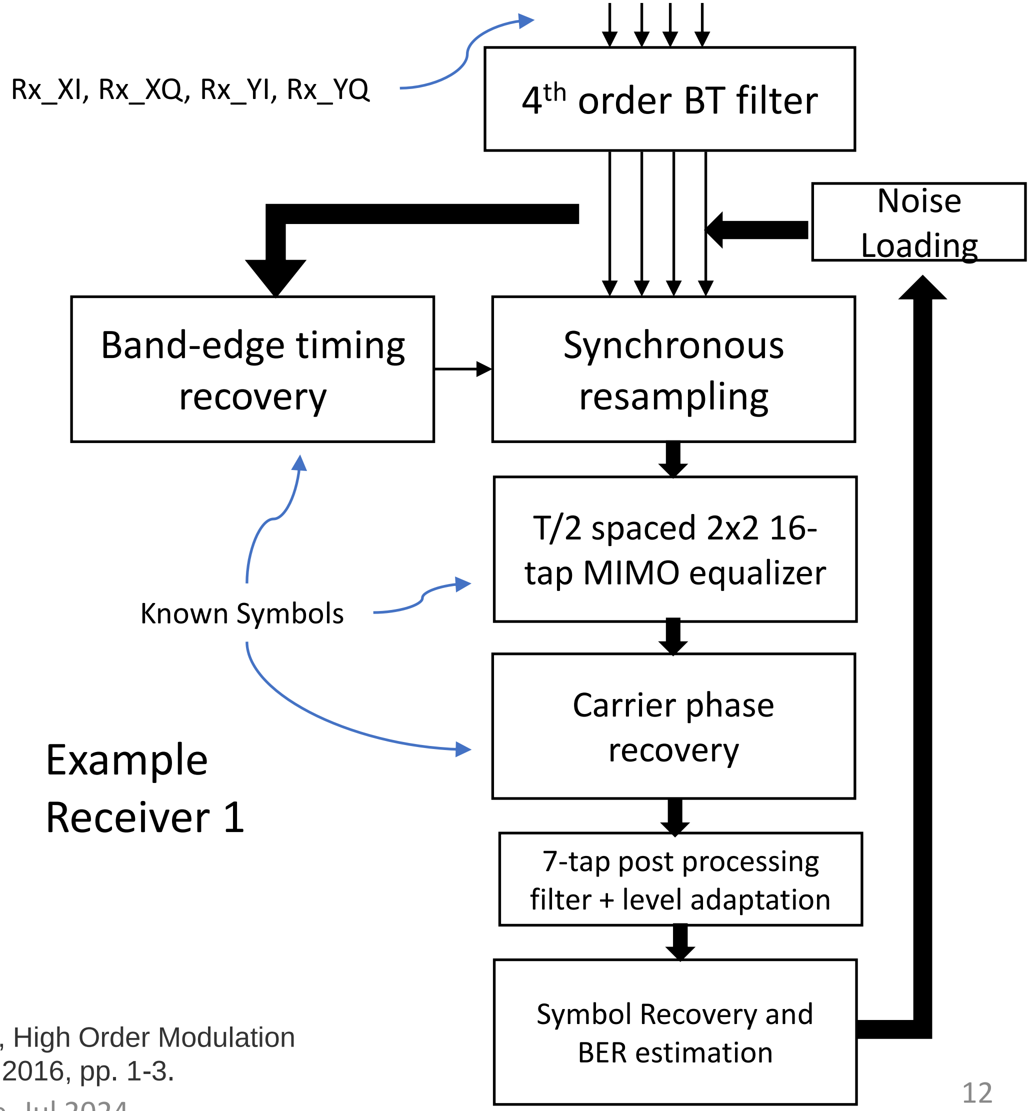
Test Vendor 1		Test Vendor 2	
Module	**$\nabla RSNR_{TX}$(dB)**	**Module**	**$\nabla RSNR_{TX}$(dB)**
A	1.5	A	2.2
B	1.7	B	1.7
C	1.6		
		D	3.2
		E	4.7
F	2.7	F	3.5
G	2.8	G	3.2
H	3.3	H	3.7
I	2.7	I	3.0
J	5.3	J	3.6



Results from Example Receiver 2 (Preliminary)

- Receiver 2 includes an additional post processing filter to handle some TX impairments‡
- preECOC2023 data from OIF liaison

Test Vendor 1		Test Vendor 2	
Module	$\nabla RSNR_{TX}$(dB)	**Module**	$\nabla RSNR_{TX}$(dB)
A	1.5	A	2.0
B	1.6	B	1.5
C	1.4		
		D	2.8
		E	4.1
F	2.6	F	3.0
G	2.6	G	3.2
H	2.9	H	3.1
I	2.4	I	2.7
J	4.4	J	3.1

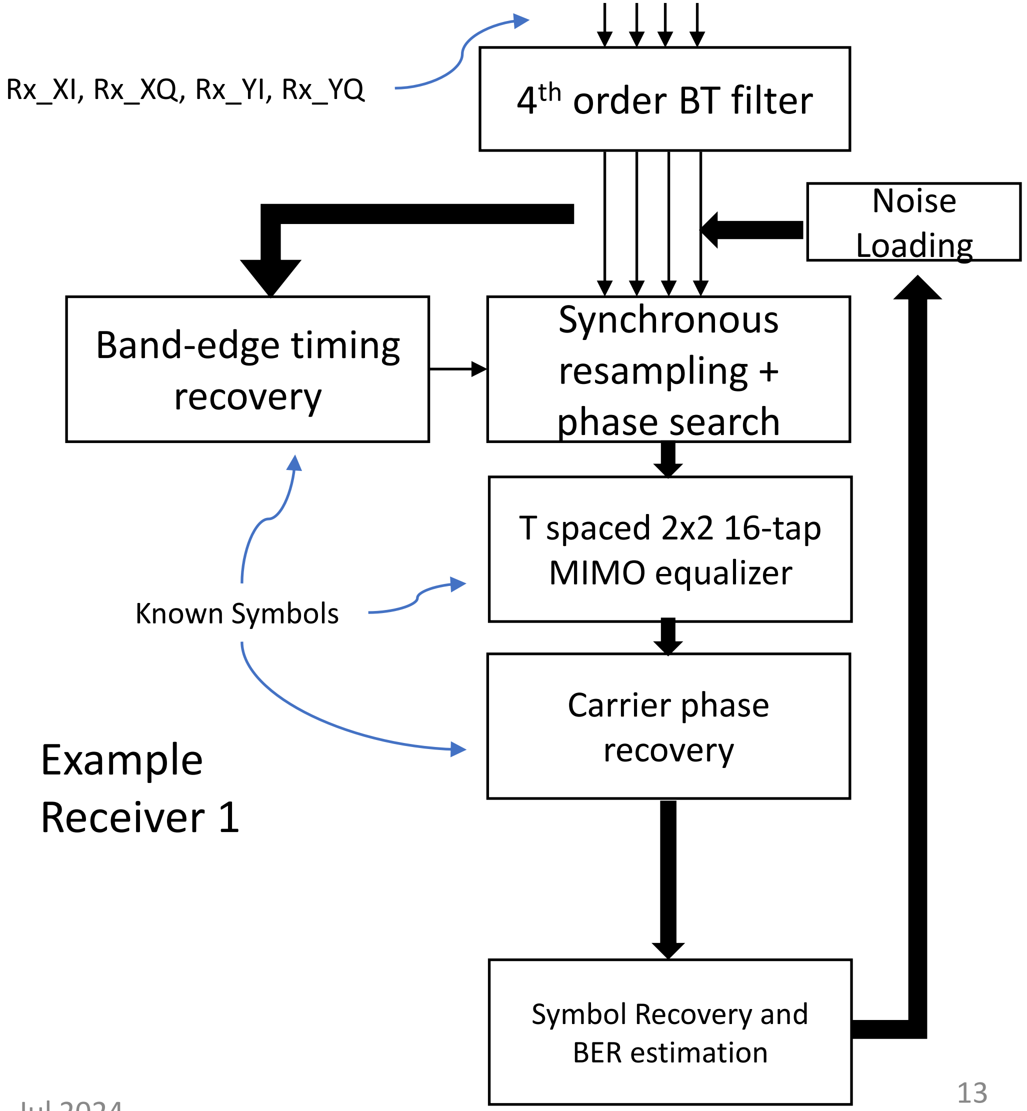


‡C. R. S. Fludger and T. Kupfer, "Transmitter Impairment Mitigation and Monitoring for High Baud-Rate, High Order Modulation Systems," *ECOC 2016; 42nd European Conference on Optical Communication*, Dusseldorf, Germany, 2016, pp. 1-3.

Results from Example Receiver 3 (Preliminary)

- Receiver 1 with T-spaced equalizer coupled with a sampling phase search
- preECOC2023 data from OIF liaison

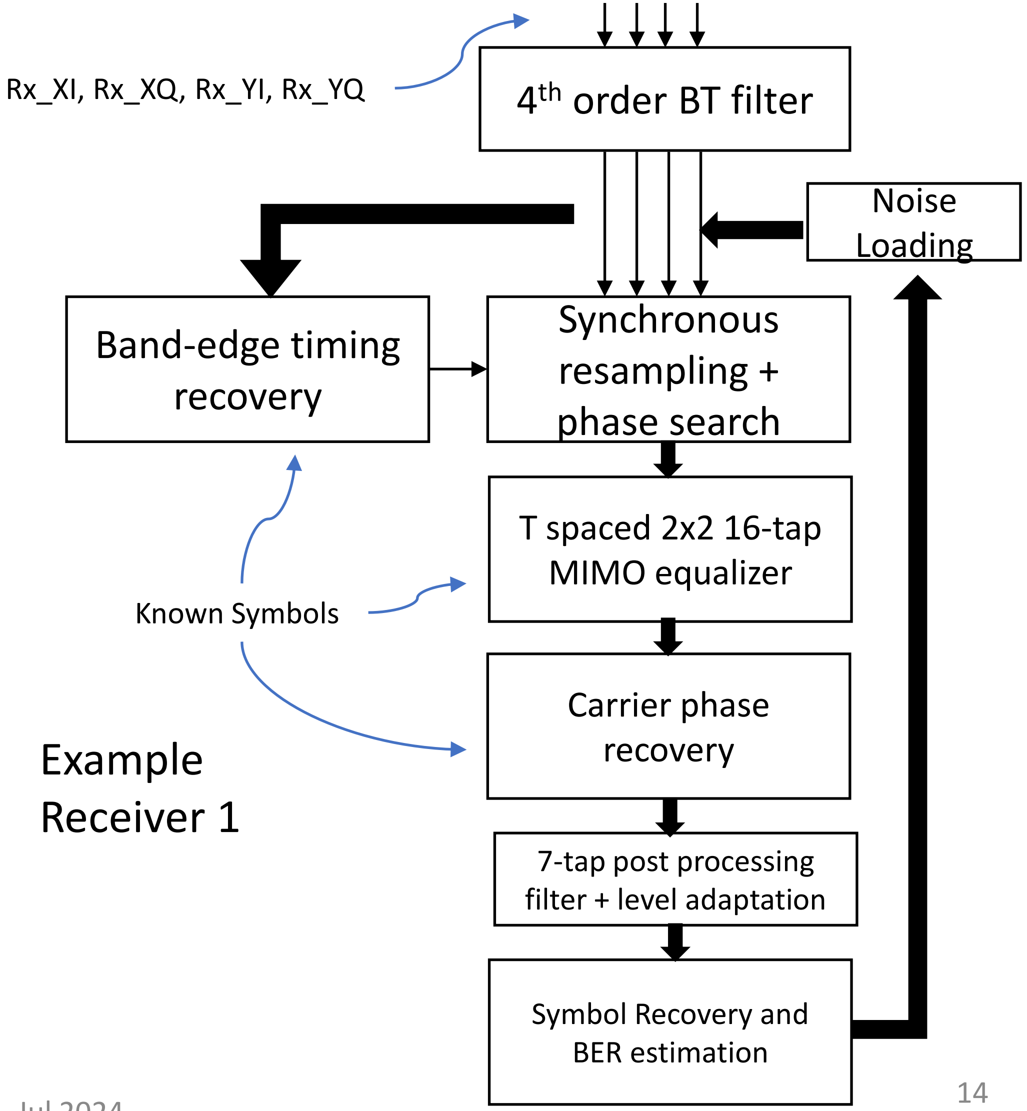
Test Vendor 1		Test Vendor 2	
Module	$\nabla RSNR_{TX}$(dB)	Module	$\nabla RSNR_{TX}$(dB)
A	1.9	A	1.9
B	3.4	B	1.5
C	1.4		
		D	2.4
		E	*
F	4.4	F	3.6
G	3.0	G	*
H	4.9	H	*
I	*	I	4.2
J	*	J	3.4



Results from Example Receiver 4 (Preliminary)

- Receiver 2 with T-spaced equalizer coupled with a sampling phase search
- preECOC2023 data from OIF liaison

Test Vendor 1		Test Vendor 2	
Module	$\nabla RSNR_{TX}$(dB)	Module	$\nabla RSNR_{TX}$(dB)
A	1.9	A	1.8
B	3.2	B	1.4
C	1.3		
		D	2.1
		E	*
F	4.0	F	3.4
G	3.0	G	*
H	4.4	H	*
I	*	I	3.9
J	*	J	*



Example Receiver 1

Extension of TECQ to 800GBASE-LR1 (1/2)

PAM4 TECQ	Coherent TQM (suggestions from kota_3dj_01a_2401)	Recommendation
Each lane tested individually	All lanes simultaneously	All lanes simultaneously
SSPRQ Test pattern on lane under test to stress the timing recovery	Same pattern might be useable for coherent	Test pattern from oif2023.070.04 or normal mode
Worst case optical return loss with splitter, variable reflector	May not be necessary for coherent	Not necessary
Worst RIN by adjusting polarization of reflection	May not be necessary for coherent	Not necessary
4th order Bessel-Thompson filter at half symbol rate	Same filter should be ok	4^{th} order BT, 3dB 61.8GHz
Channel with worst-case CD and return loss, minimum IL and minimum DGD	Carry over the same concept without CD because it is a linear impairment for coherent. Use fixed polarization but adjust for worst case	Measurement without CD. TBD on polarization adjustment
Scope noise is measured without signal but using same settings to use in the calculation	Use same concept for coherent	Adjust using calibrated scope noise (e.g. see TCC)

Extension of TDECQ to coherent (2/2)

PAM4 TDECQ/TECQ	Coherent TQM (from kota_3dj_01a_2401)	Recommendation
Noise is added as part of calculation to determine largest amount of noise for desired BER target	Use same concept of adding noise to calculated level of noise required to reach desired BER target	Add noise as part of calculation
BER of receiver is estimated indirectly by calculating noise sigma from histograms of the measured eye	Propose to measure BER directly by comparing bits to ideal bits. Since coherent BER threshold is 1e-2 instead of 2.4e-4 this does not require long captures	Use BER to calculate TQM
Reference receiver consists of fixed-length (5-taps) symbol rate equalizer, CD with specified bandwidth (4MHz)	Reference receiver will consist of fixed-length symbol rate (?) equalizer, carrier recovery and timing recovery	See next slide
CDR with specified bandwidth in hardware or software	CDR with specified bandwidth in software. Capture length needs to be long enough to be consistent with the chosen clock recovery bandwidth	Recommend CDR bandwidth of ~3MHz in spec
Sampling phase is optimized to minimize TDECQ	Sampling phases of each channel will need to be individually optimized (in software)	Optimize sampling phase
PAM levels adapted to optimize TDECQ calculation	Needs more discussion	Optimize levels
Ideal signal with measured OMAouter is used as the reference	Ideal signal with measured signal power can be used as the reference	Use signal power at input

Proposed Reference Receiver

- Timing Recovery
  - Similar to PAM4 systems, a high timing recovery bandwidth (around 3MHz) is desired to ensure robust performance in small form-factor modules
- MIMO Equalizer
  - A symbol-rate equalizer with optimal phase selection
  - 2x2 complex MIMO
  - Equalizer length – approximately 16 taps
  - Equalizer adaptation algorithm itself can be left out of the standard similar to the TECQ/TDECQ procedure
- Carrier Frequency/Phase recovery
  - Data aided carrier recovery with averaging over approx. 16 symbols
- Approx 7-tap post filter and PAM4 level adjustment in each dimension
  - The filter is important in 800GBASE-LR1 specification to handle IQ-skew from transmitter
  - Level adjustment is required to relax TX lane-to-lane power imbalance specifications

Summary

- Proposing adoption of TCC/ $\nabla RSNR_{TX}$ (in dB) as TQM
- Proposing additional parameters of TQM procedure
- Publishing results of TQM processing of data provided by OIF

Thank you!