Is 1Tb/s Ready for Prime Time? Engineering Reality Check

Terabit Optical Ethernet

IEEE Photonics Society Summer Topical

Montreal, Canada

18 - 20 July 2011

Chris Cole

Ilya Lyubomirsky

chris.cole@finisar.com

Ilya.lyubomirsky@finisar.com

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Objective: Rain on 1Tb/s Parade

Unhappy 1Tb/s Researchers

Know Your Audience

- First version of this presentation was given at the Tera Santa Workshop in Tel Aviv on 13 April 2011
- Tera Santa is consortium of leading companies and universities in Israel backed by Israeli Office of the Chief Scientist with the objective to develop world's first Tb/s OFDM-based optical network
- The Workshop audience was unperturbed by being rained on
- This was later explained by Prof. Dan Sadot, Chairman, Electrical and Computer Engineering, Ben Gurion University (Tera Santa member):

  In Israel, as we are a relatively dry country, every type of rain is considered "blessing rain"

Outline

- **Ethernet & Transport Compatibility**
- 100Gb/s Ethernet Technology
- Beyond 100Gb/s Ethernet Technology
- 100Gb/s Transport Technology
- Beyond 100Gb/s Transport Technology
- Recommendations

10GbE and OTU2

- OTU2 defined by ITU-T → <u>~10.7Gb/s</u>
  - ~10Gb/s payload; SONET OC-192 or SDH STM-64
- 10GbE LAN and WAN subsequently defined by IEEE
  - 10GBASE-R LAN Physical Coding Layer: 10Gb/s data with 64B/66B encoding → <u>~10.3Gb/s</u> > 10Gb/s payload
  - 10GBASE-W WAN Interface Sub-layer defined to be compatible with 10Gb/s SONET and SDH → <u>~10Gb/s</u>
- 10GbE PHY ICs initially supported both LAN and WAN
  - required two separate processing cores; expensive
  - Not needed by vast majority of 10GbE users (data center operators) who only use LAN
- 10GbE LAN became the dominant interface

10GbE and OTU2, cont.

- 10GbE LAN Transport alternatives:
  - remove Preamble or IPG → <u>not transparent</u>
  - over-clock OTU2: OTU2e → <u>not networkable</u>
- Mess

4x 10GbE and OTU3

- OTU3 defined by ITU-T → ~43Gb/s
  - ~40Gb/s payload; SONET OC-768 or SDH STM-256
- 10GbE LAN is the dominant interface
- 4x 10GbE LAN → ~41.2Gb/s > 40Gb/s payload
- 4x 10GbE LAN Transport alternatives:
  - remove Preamble or IPG → not transparent
  - over-clock OTU3: OTU3e → not networkable
- Mess

40GbE and OTU3

- 40GbE LAN defined by IEEE → ~41.2Gb/s
- 40GbE PCS layer defined to have a small control word set to enable fixed trans-coding to OTU3
- 40GbE LAN Transport:
  - OTU3 → transparent and networkable
- No mess

100GbE and OTU4

- 100GbE LAN defined by IEEE → ~103Gb/s
- OTU4 initial proposals in ITU-T → ~160Gb/s & ~130Gb/s
  - Efficiently carry multiple 40Gb/s payloads
  - Inefficiently carry 100GbE payload
- OTU4 then defined by ITU-T → ~112Gb/s
  - Efficiently carries 100GbE payload
  - transparent and networkable
- No mess

Future Ethernet and Transport Rates

- IEEE and ITU-T are strongly committed to:
  - Full Ethernet and OTN compatibility
  - OTN support in Ethernet Specifications, ex. 40GbE
  - Efficient carrying of Ethernet over OTN, ex. OTU4
- OTU5 will be the next OTN rate after OTU4
  - OTU5 will be defined to efficiently carry next Ethernet rate after 100GbE
- OTU6 will be the following OTN rate after OTU5
  - OTU6 will be defined to efficiently carry following Ethernet rate

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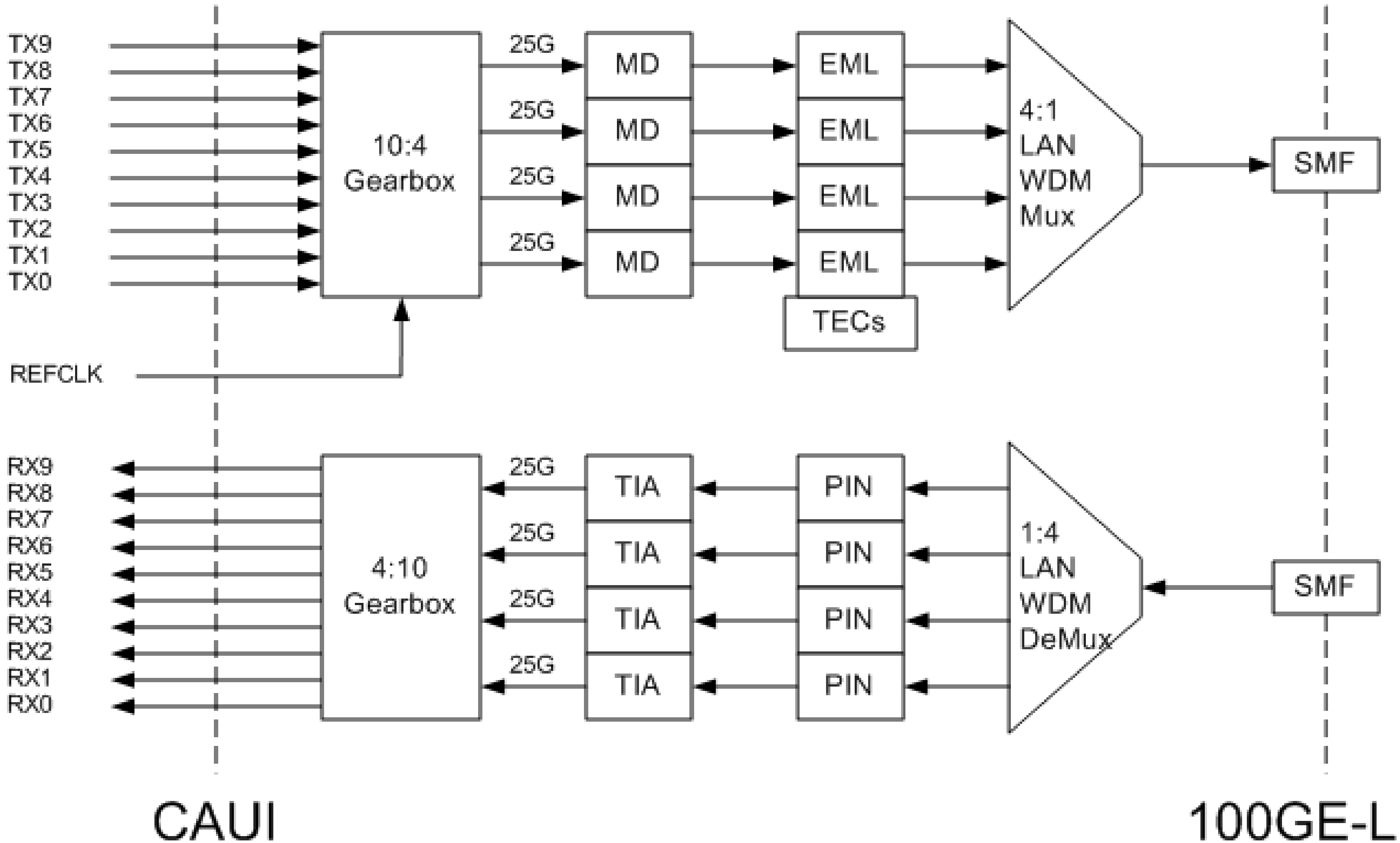
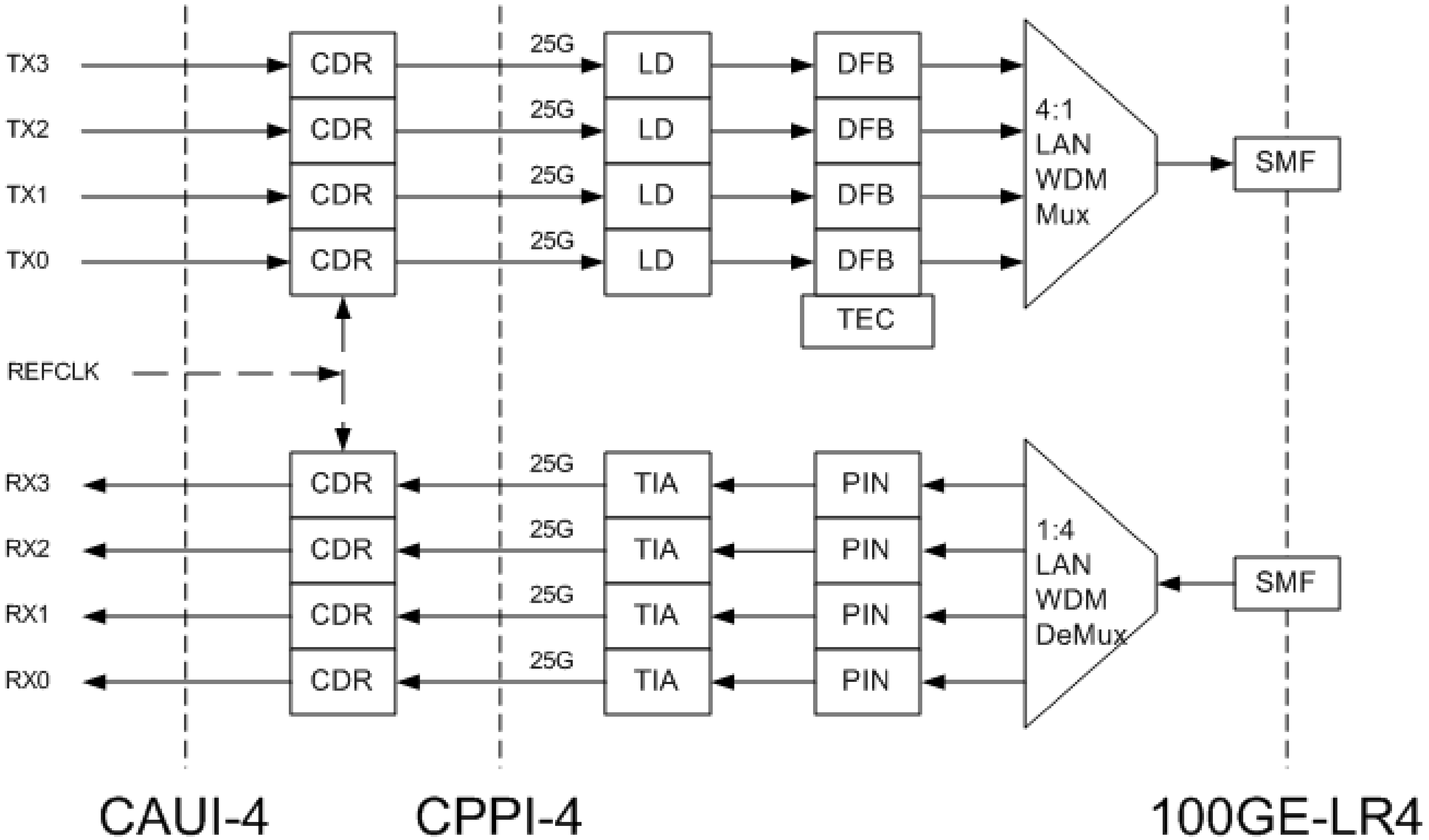
100GbE WDM SMF Gen1 Transceiver



100GBASE-ER4, 40km Transceiver places a SOA before the DeMux

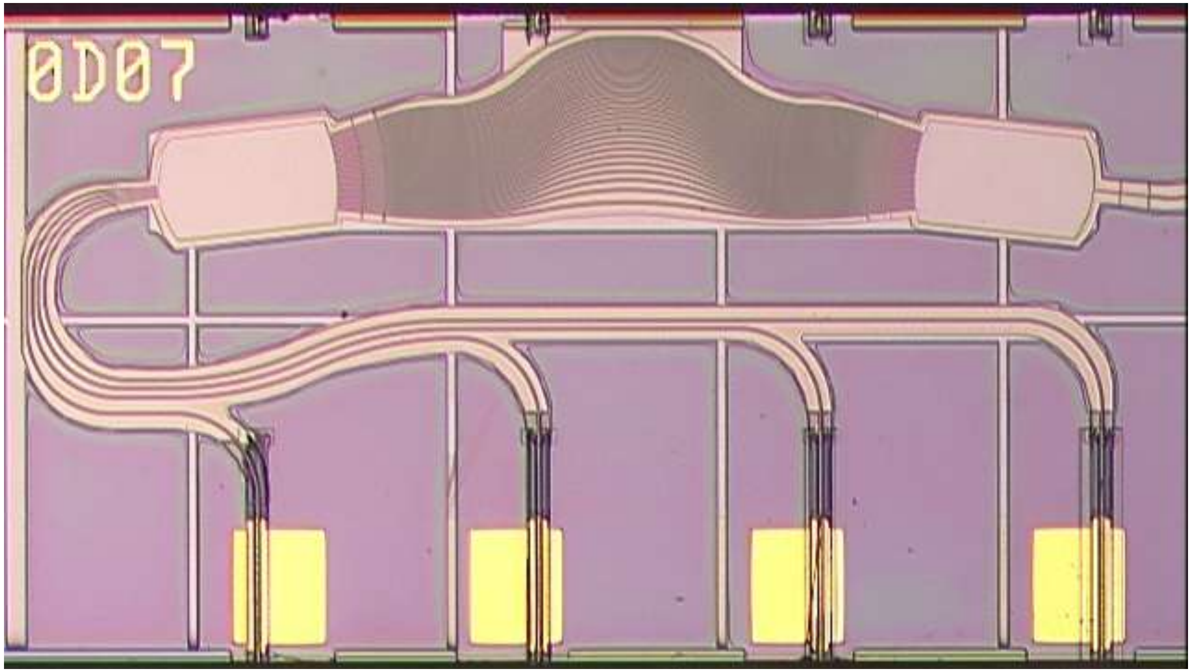
100GbE WDM SMF Gen2 Transceiver



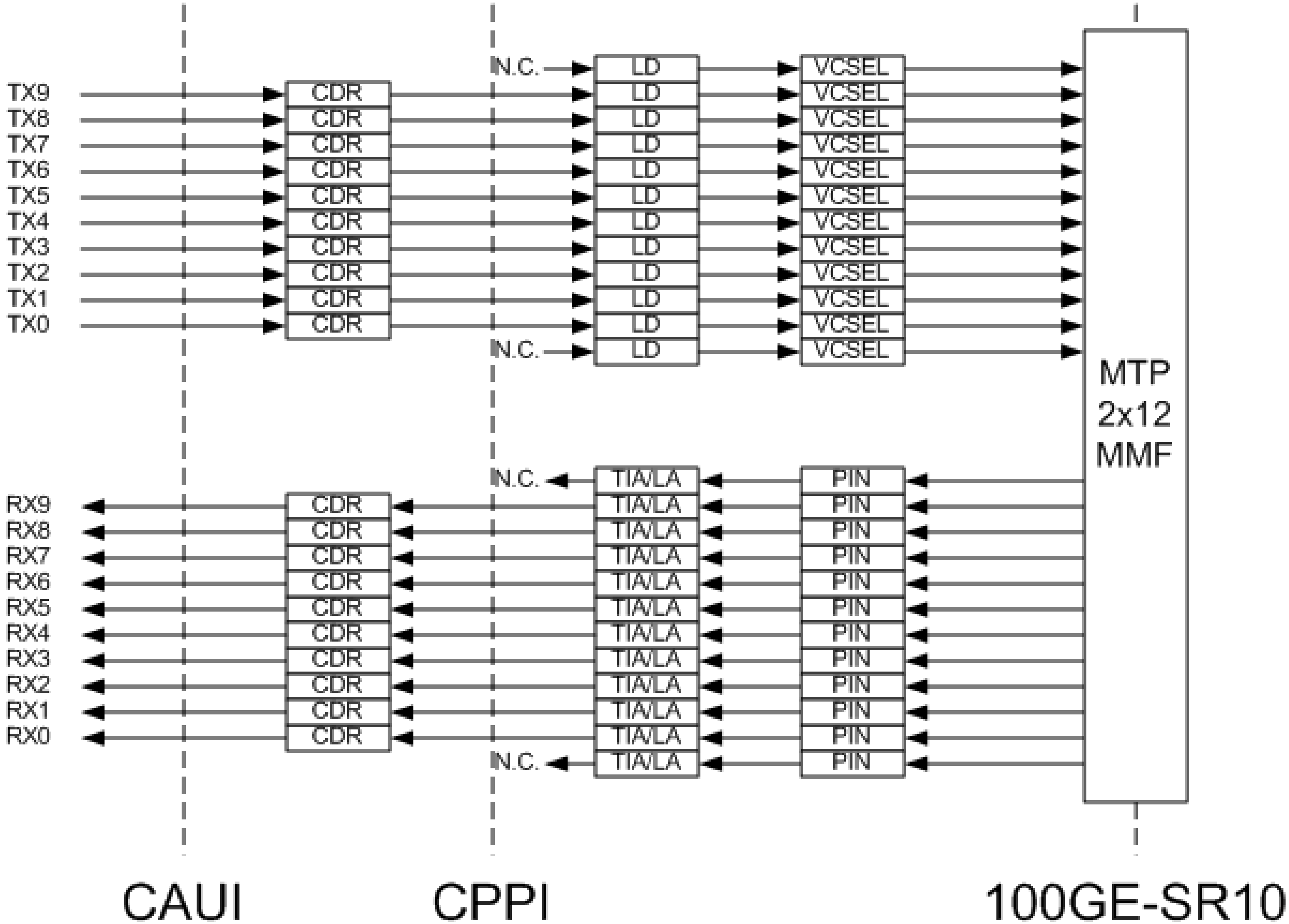
Long term, high volume architecture

100GbE WDM SMF Key Technology

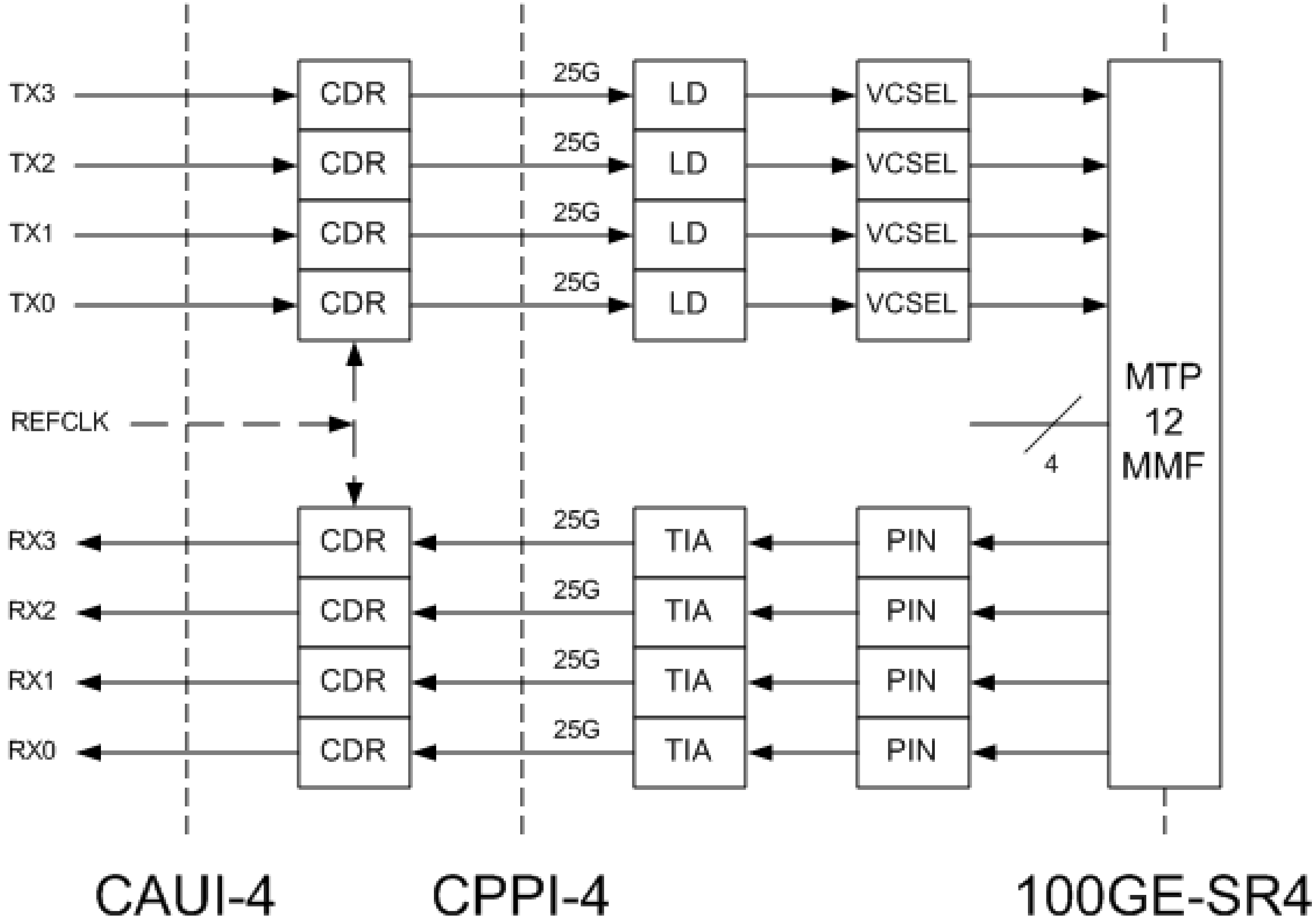
- High yield Photonic Integrated Circuit (PIC) WDM quad DFB array
- Ex. monolithic InP quad 1310nm band DFB laser array with AWG, 1.1mm x 2.4mm PIC, CyOptics Inc.



100GbE Parallel MMF Gen1 Transceiver



100GbE Parallel MMF Gen2 Transceiver



Long term, high volume architecture

100GbE Parallel MMF Key Technology

- High yield Photonic Integrated Circuit (PIC*) parallel quad VCSEL array
- Ex. monolithic GaAs quad 850nm VCSEL array, 0.25mm x 1.0mm PIC, Finisar Corp.

* The "C" in PIC is a stretch since there are no optical connections.

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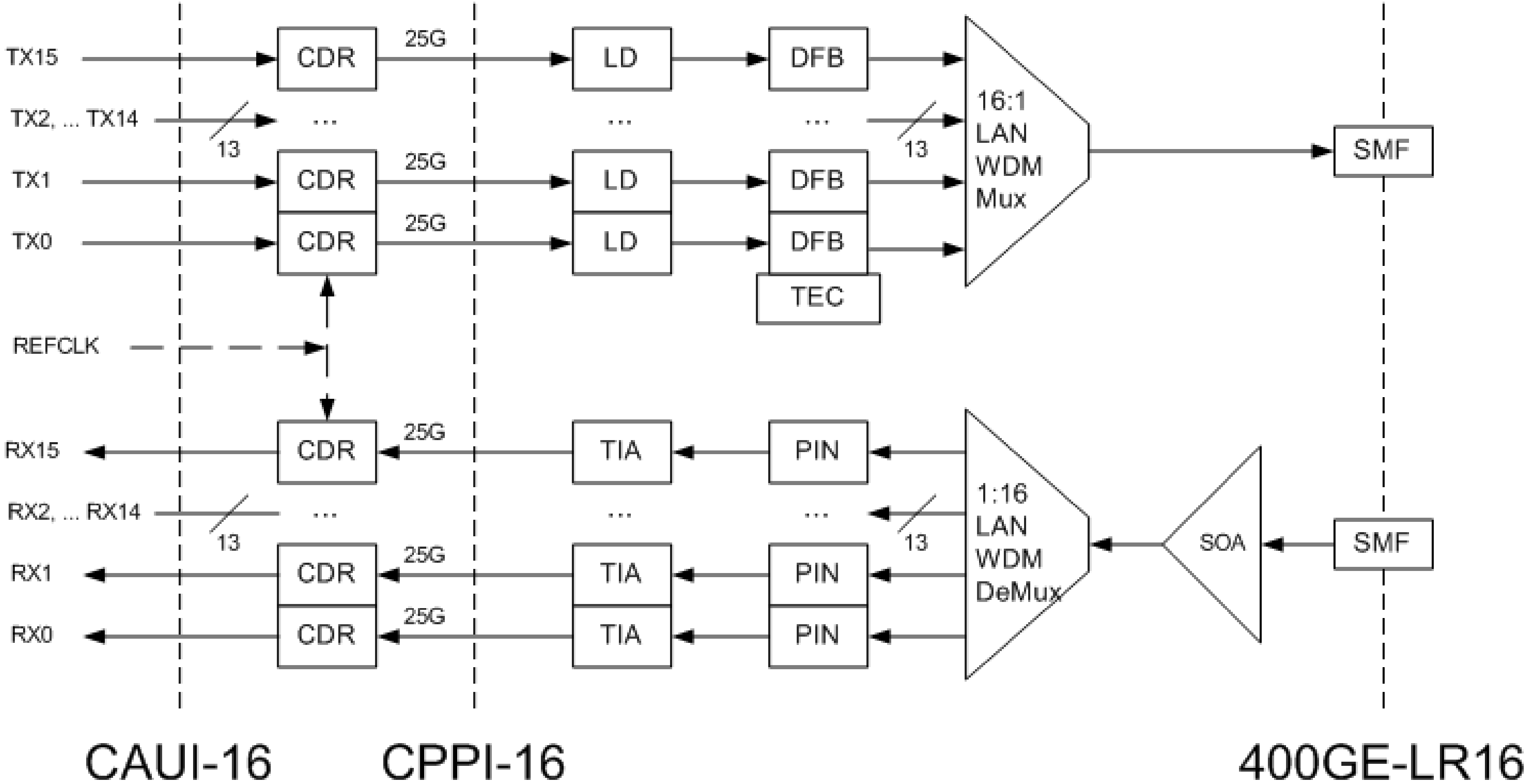
Beyond 100GbE Rate Requirements

- Requirements from end users
  - Provide meaningful data rate increase
  - Maintain parity with 100GbE bit/sec cost
- Requirements from developers
  - Leverage 100GbE R&D investment
  - Leverage ramping 100GbE product volumes
- Next data rate products should be based on 100GbE technology to control R&D and unit costs
- 400GbE meets these requirements
- Technology for above 400GbE (ex. 1TbE) does not exist, will require extensive R&D, and does not meet these requirements

400GbE WDM SMF Gen1 Transceiver



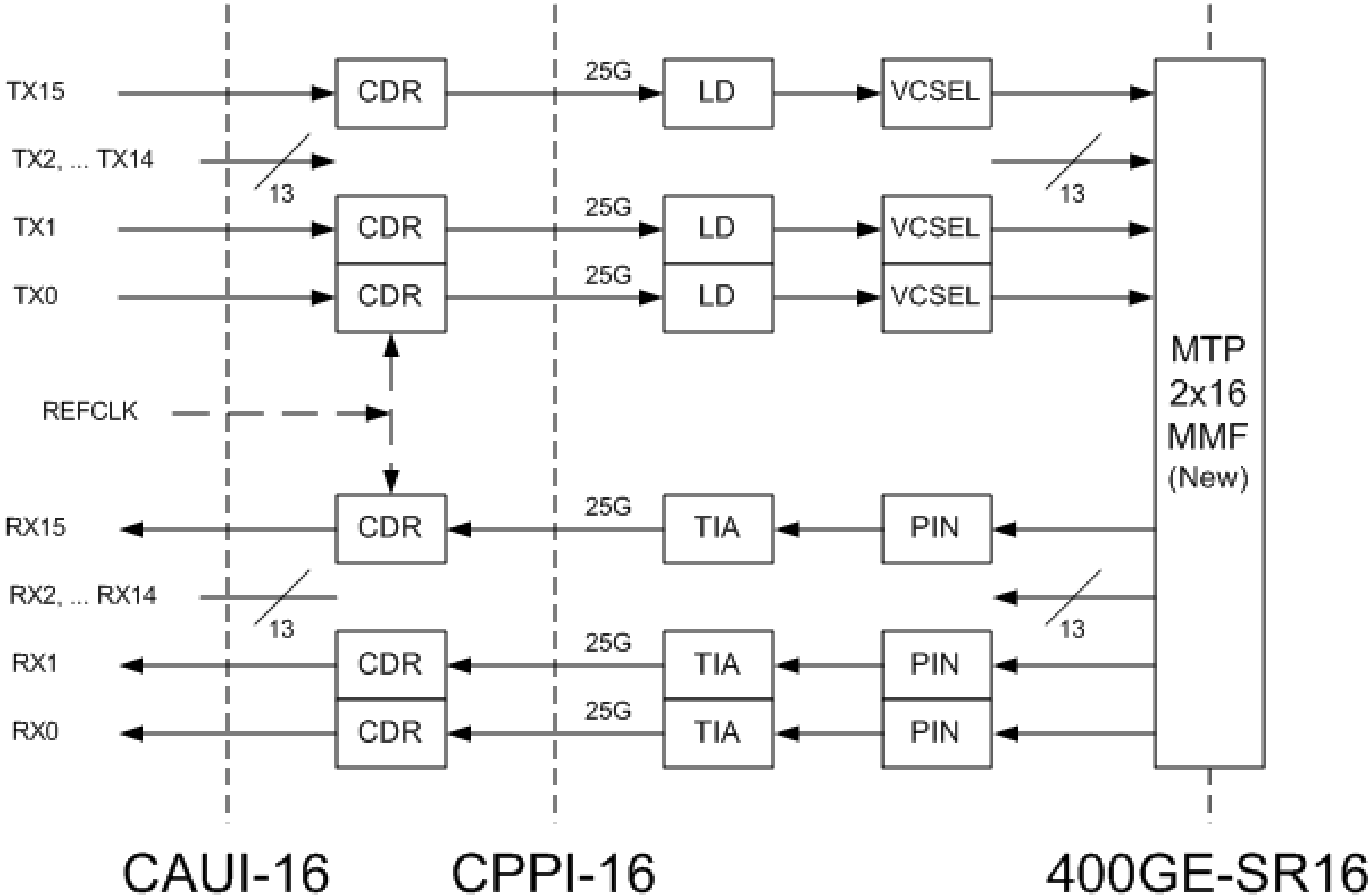
Different Gen2 architecture is required to support higher I/O density

400GbE WDM SMF λ Specifications

Lane	Center Frequency THz	Center Wavelength nm	Approximate Wavelength @nm
1330 band			
L33	225.8	1327.69	1328
L32	226.6	1323	1323
L31	227.4	1318.35	1318
L30	228.2	1313.73	1313
1310 band			
L23	**229**	**1309.14**	**1310**
L22	**229.8**	**1304.58**	**1305**
L21	**230.6**	**1300.05**	**1300**
L20	**231.4**	**1295.56**	**1295**
1290 band			
L13	232.2	1291.1	1292
L12	233	1286.66	1287
L11	233.8	1282.26	1282
L10	234.6	1277.89	1277
1270 band			
L03	235.4	1273.55	1275
L02	236.2	1269.23	1270
L01	237	1264.95	1265
L00	237.8	1260.69	1260

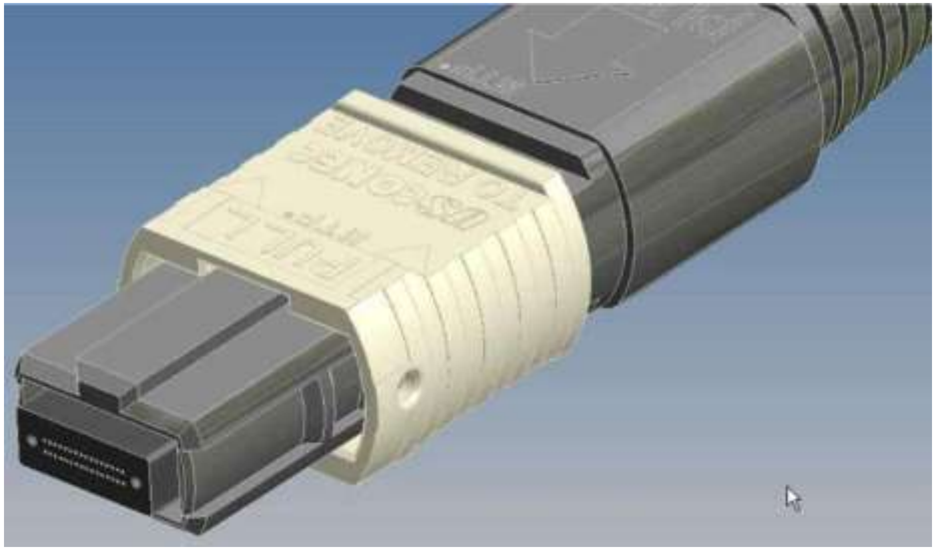
← 1310nm band 100GbE WDM specification defined in IEEE 802.3ba

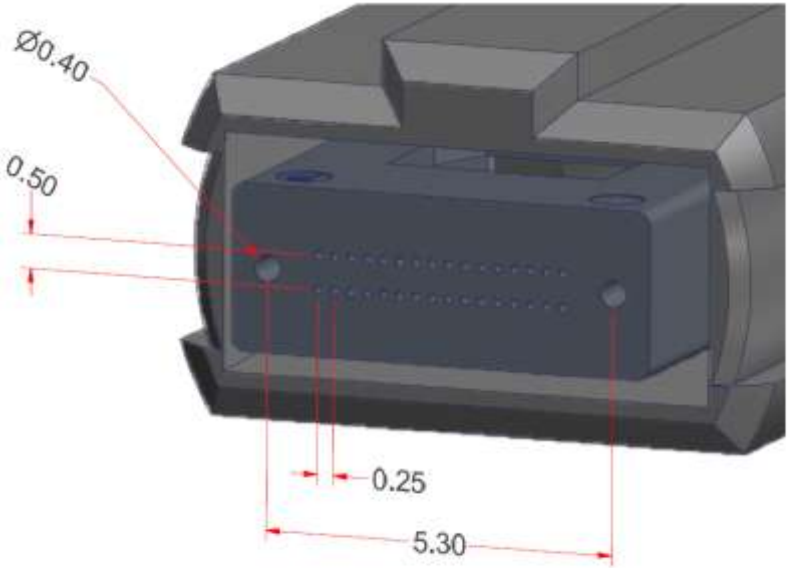
400GbE Parallel MMF Gen1 Transceiver



Different Gen2 architecture is required to support higher I/O density

400GbE MTP Connector Specifications





- USCONEC Proposal
- Same core technology as originally developed by NTT Laboratories researchers T. Satake and colleagues
- Same critical dimensions as existing MTP connectors
- Width increased to support 2x16 fibers

400GbE Transceiver Alternatives

- On/Off modulation
  - 16 x 25Gb/s NRZ lasers (VCSEL and DFB) baseline
  - Linear extension of 100GbE technology
  - Only requires process yield improvements
  - <u>Benchmark against which to measure other proposals</u>
- Multi-level amplitude modulation
  - Ex. 8 x 50Gb/s PAM-N lasers (VCSEL and DFB)
  - Coding DSP (ex. TCM)
  - Multiple implementation and SNR challenges
- Complex (amplitude and phase) modulation
  - Ex. 4 x 100Gb/s PM-QPSK (MZM)
  - Coherent DSP
  - No technology exists that can be commercialized

Beyond 400GbE Alternatives

Following after 400GbE:

- 1TbE ?
  - 2.5x is a small increase from 400GbE
  - unlikely to justify a huge investment
  - unlikely to meet bandwidth growth demands
- 1.2TbE ?
  - 3x is a small increase from 400GbE
  - unlikely to justify a huge investment
  - 3 is an odd number
- 1.6TbE ?
  - 4x increase from 400GbE (same as 10GbE to 40GbE)
  - Sufficient increase to justify a huge investment

1.6TbE Transceiver Alternatives

- 64 x 25Gb/s NRZ lasers
  - Not practical
  - Too many channels
- 32 x 50Gb/s PAM4 lasers
  - Not practical
  - Too many channels
- Complex (amplitude and phase) modulation
  - Only feasible alternative to control channel count
  - Ex1. 16 x 100Gb/s PM-QPSK (MZM)
  - Ex2.   8 x 200Gb/s PM-16QAM (MZM)
  - Requires complex CMOS ICs and PICs
  - No technology exists that can be commercialized
  - Excellent opportunity for long term academic research

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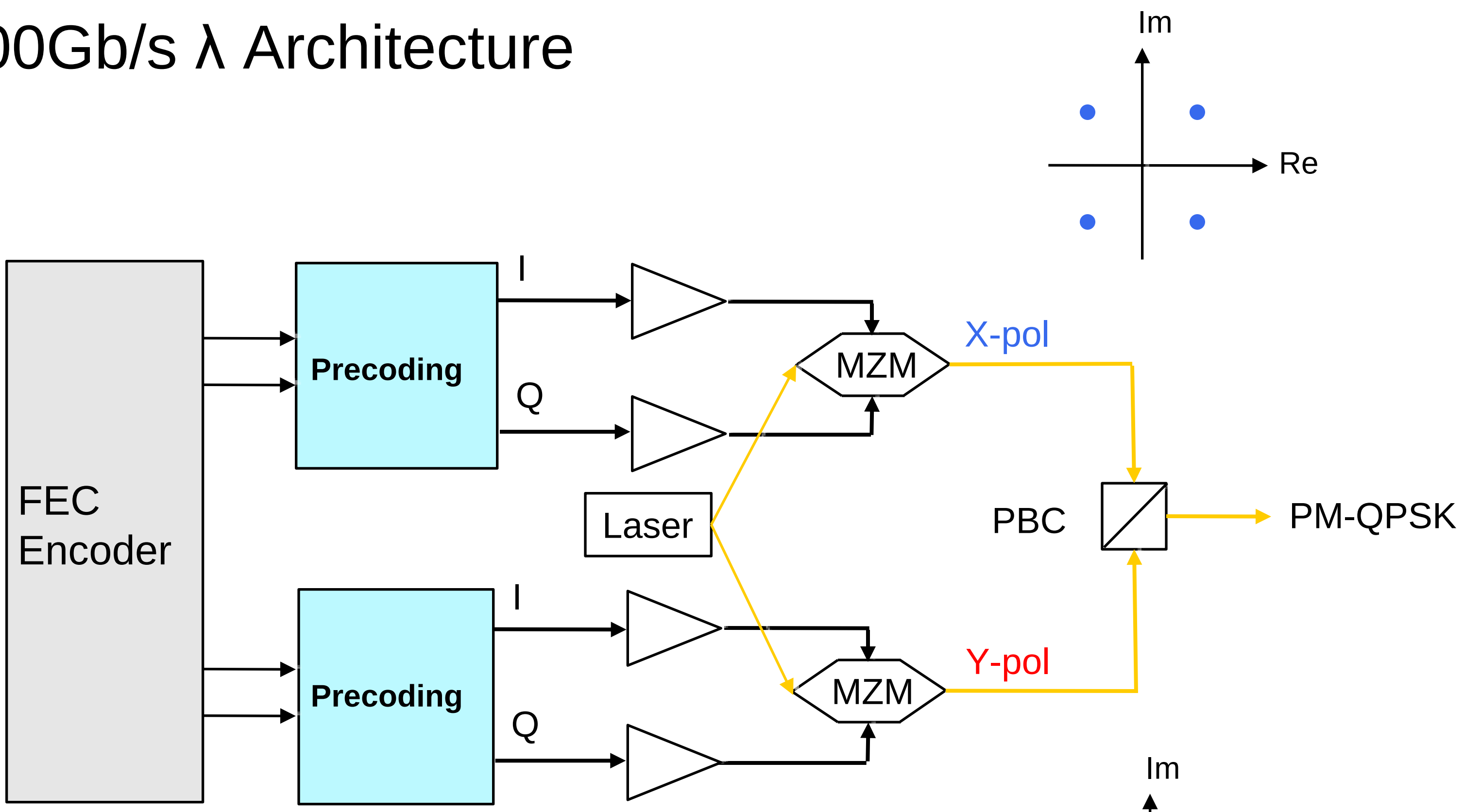
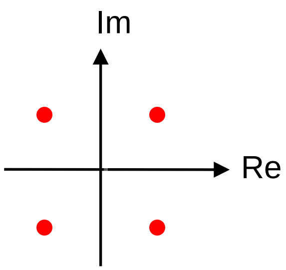
OTU4 28GBd PM-QPSK TX

1x 100Gb/s λ Architecture

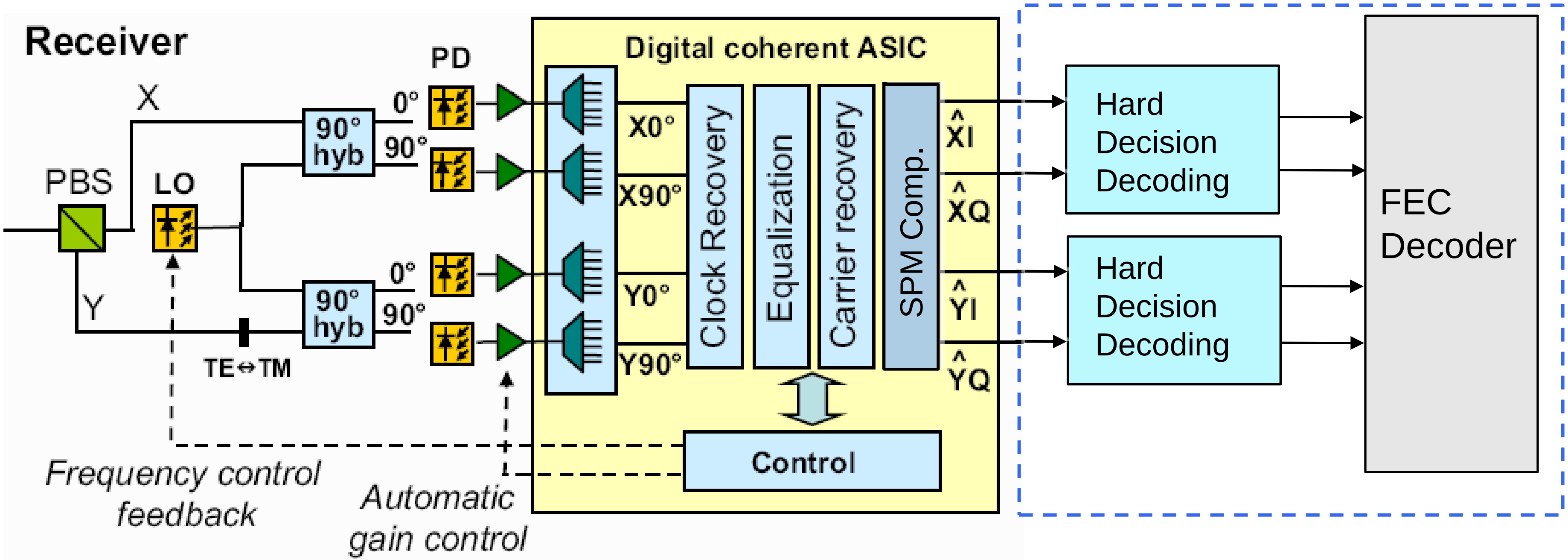


Soft Decision (SD) FEC requires 32Gbd TX



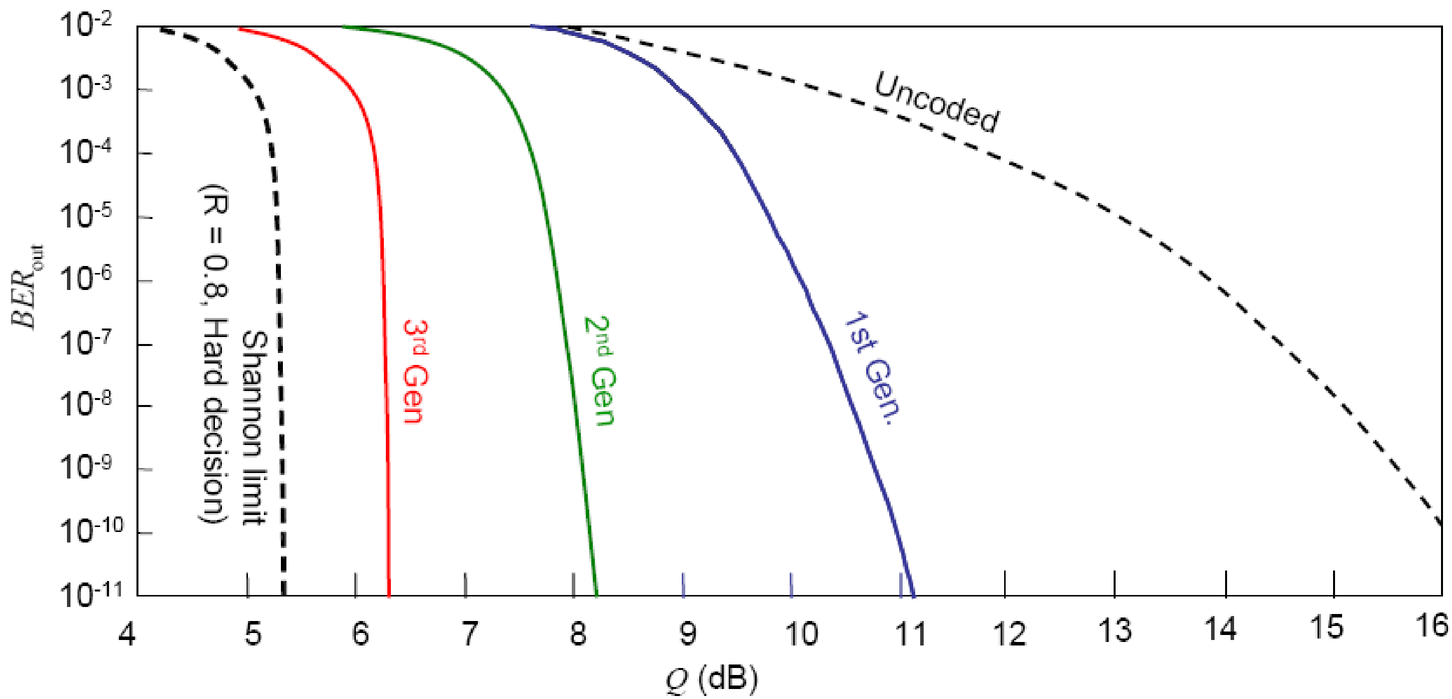
OTU4 28GBd PM-QPSK RX

1x 100Gb/s λ Architecture



SD FEC requires 32Gbd RX

OTU4 OSNR Limited BER



Year	2003	2000	1993
Coding Scheme	Block Turbo Code LDPC	Concatenated RS, BCH	RS(255,239)
Net Coding Gain (@ 10^{-13})	~10dB	7~9dB	5.8dB

T. Mizuochi, “Next Generation FEC for Optical Communications,” OFC’08, Tutorial, San Diego, CA, 24-28 Feb. 2008

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OTN Spectral Efficiency Limits

- OTU4 rate: ~112Gb/s
- OTU4 technology: 100Gb/s in 50GHz: ~2bits/sec-HZ
- Theoretical capacity of standard SMF: ~8bits/sec-HZ

  (P. Mitra, J. Stark, Bell Labs, "Nonlinear limits to the information capacity of optical fiber communications," *Nature*, Sept. 2001)
- Practical equipment and fiber limit for standard SMF over typical LH distances (1000km or longer): ~4bits/sec-HZ

  (P. Anslow, Ciena, "Optical Line Technologies for Rates above 100G ," Joint ITU-T/IEEE Workshop, Geneva, May 2010)
- 2x left for improving spectral efficiency for LH applications,

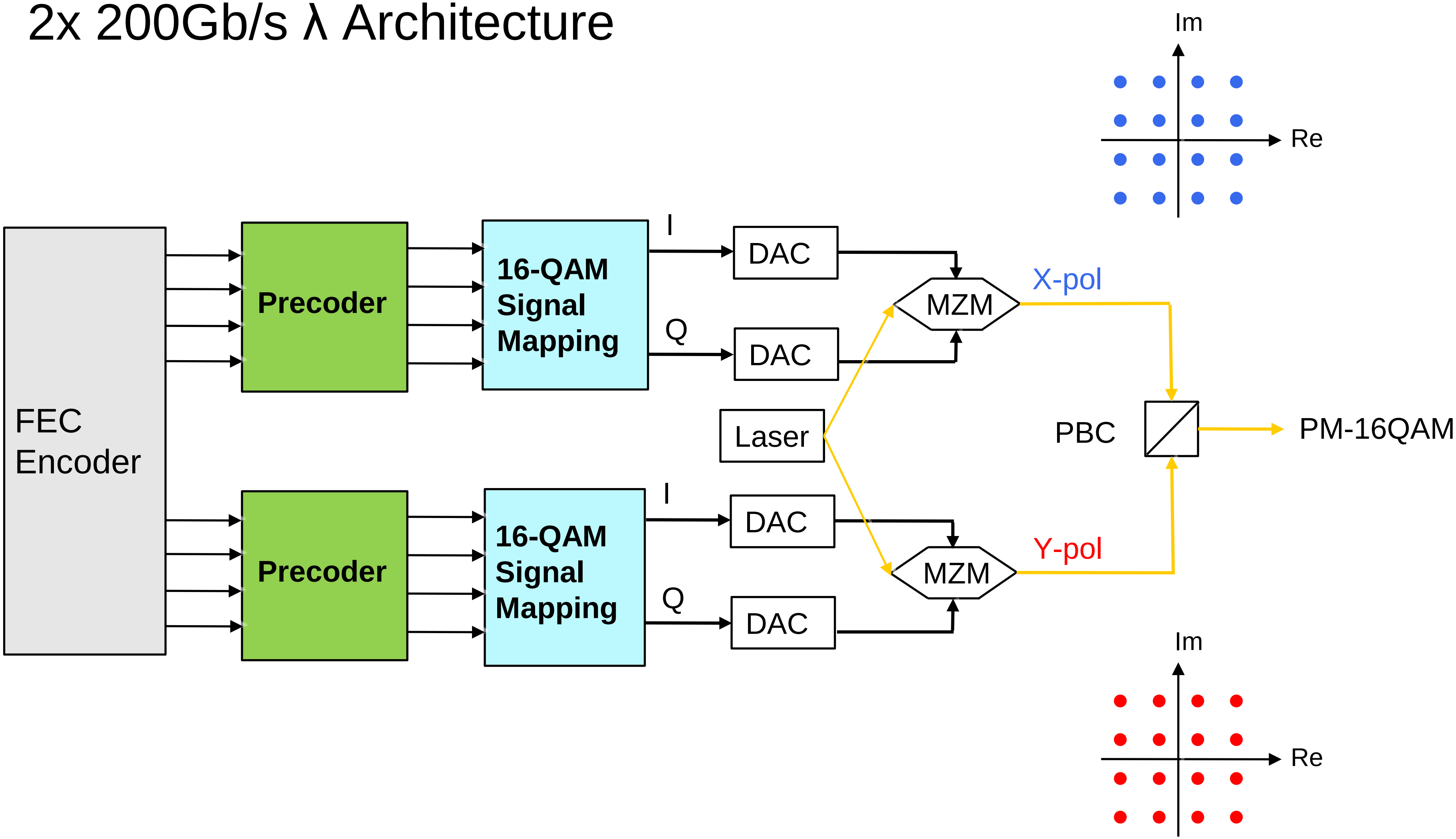
  ex. 400Gb/s in 100GHz: ~4bits/sec-Hz

OTU5 Rate

- 400GbE rate = ~412Gb/s
- To efficiently carry 400GbE, OTU5 = ~450Gb/s
- 20% SD FEC transport rate = ~500Gb/s
- 100GHz channel bandwidth gives ~2x spectral efficiency increase over OTU4
- Maintains 4x traditional OTN rate jump, ex. OTU2 to OTU3
- Allows extending OTU4 DP-QPSK technology
- Higher OTU5 rate has no spectral efficiency benefits ex.1Tb/s only increases bandwidth

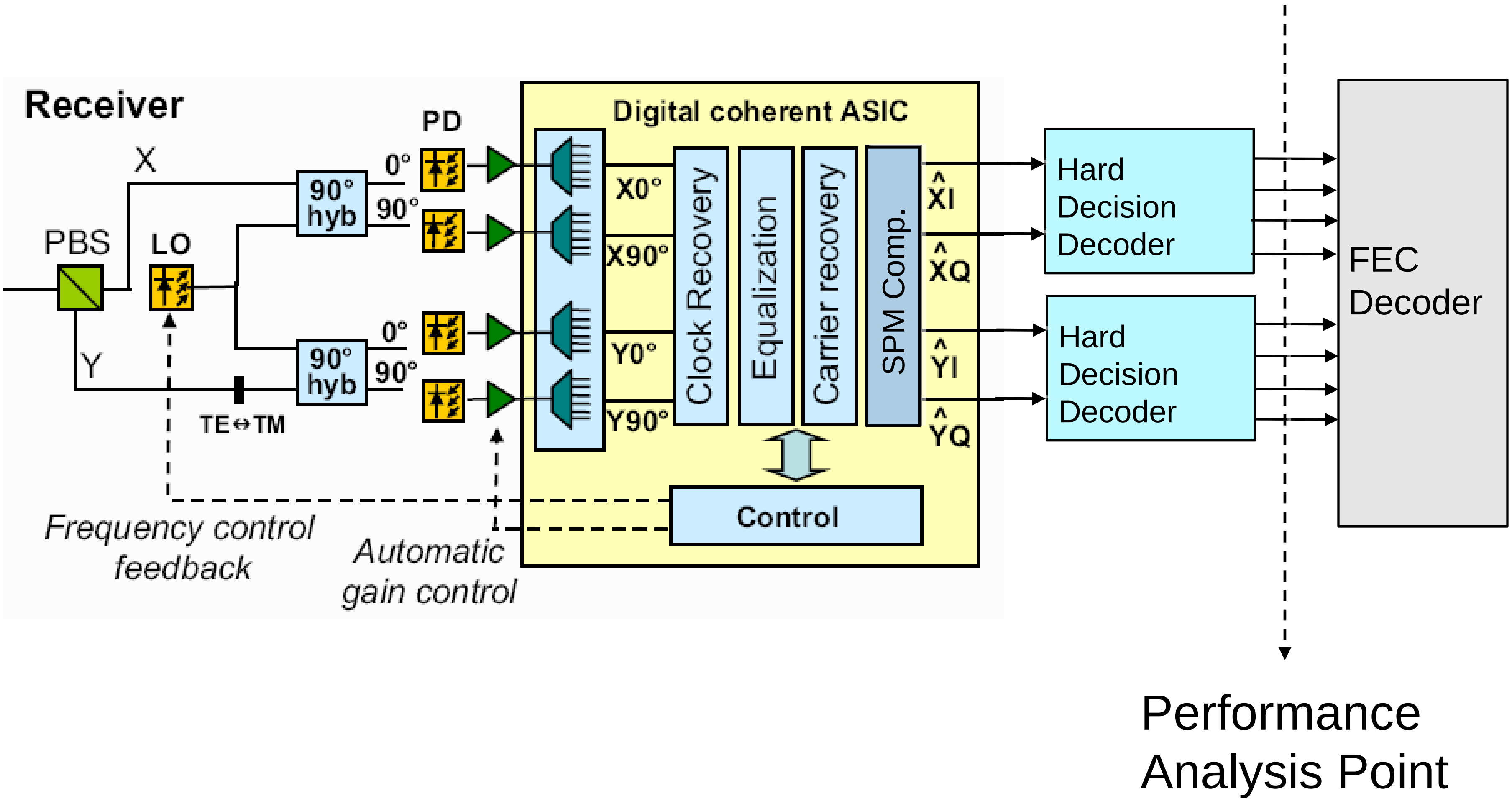
OTU5 28GBd PM-16QAM TX (1 of 2)

2x 200Gb/s λ Architecture

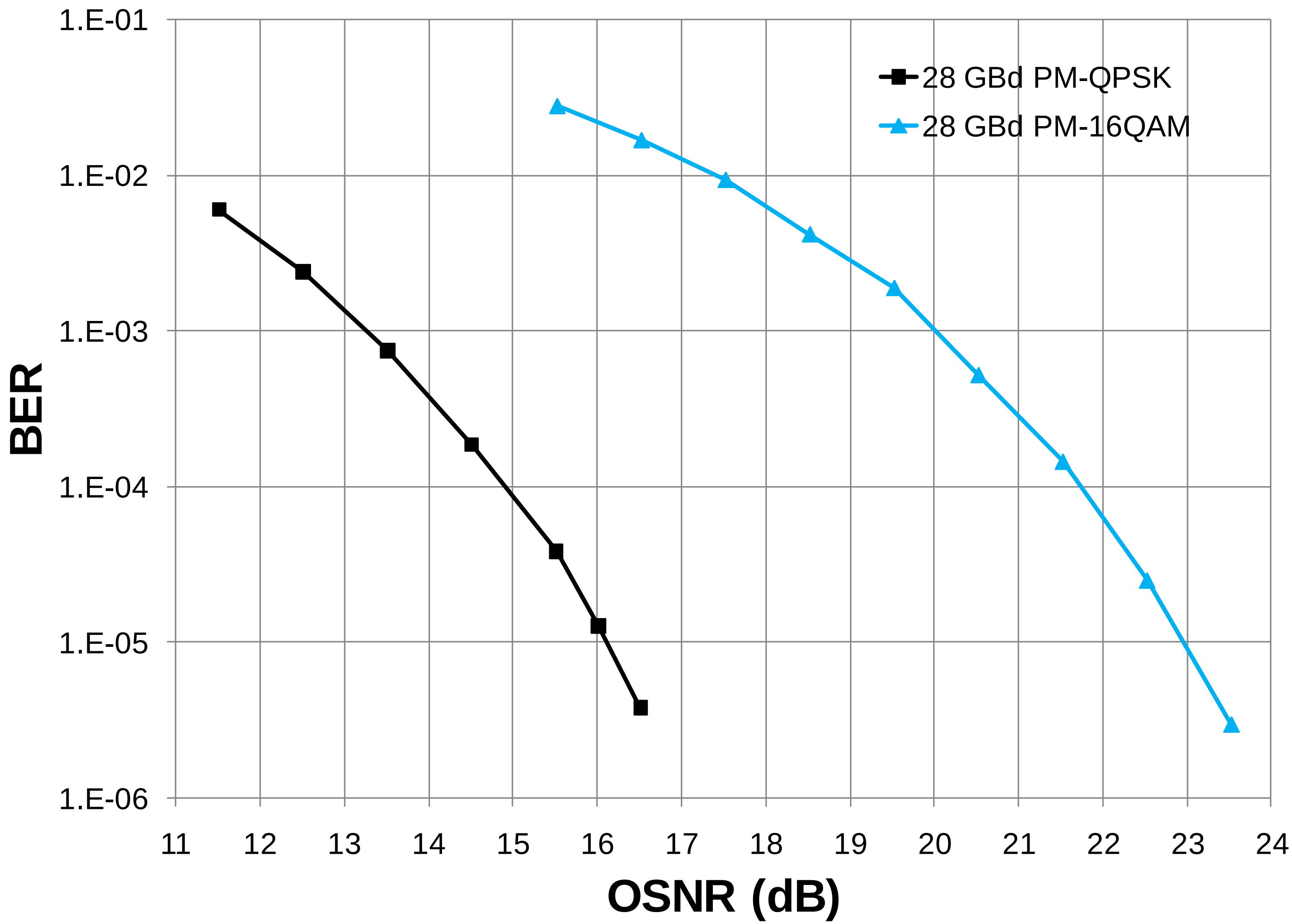


OTU5 28GBd PM-16QAM RX (1 of 2)

2x 200Gb/s λ Architecture



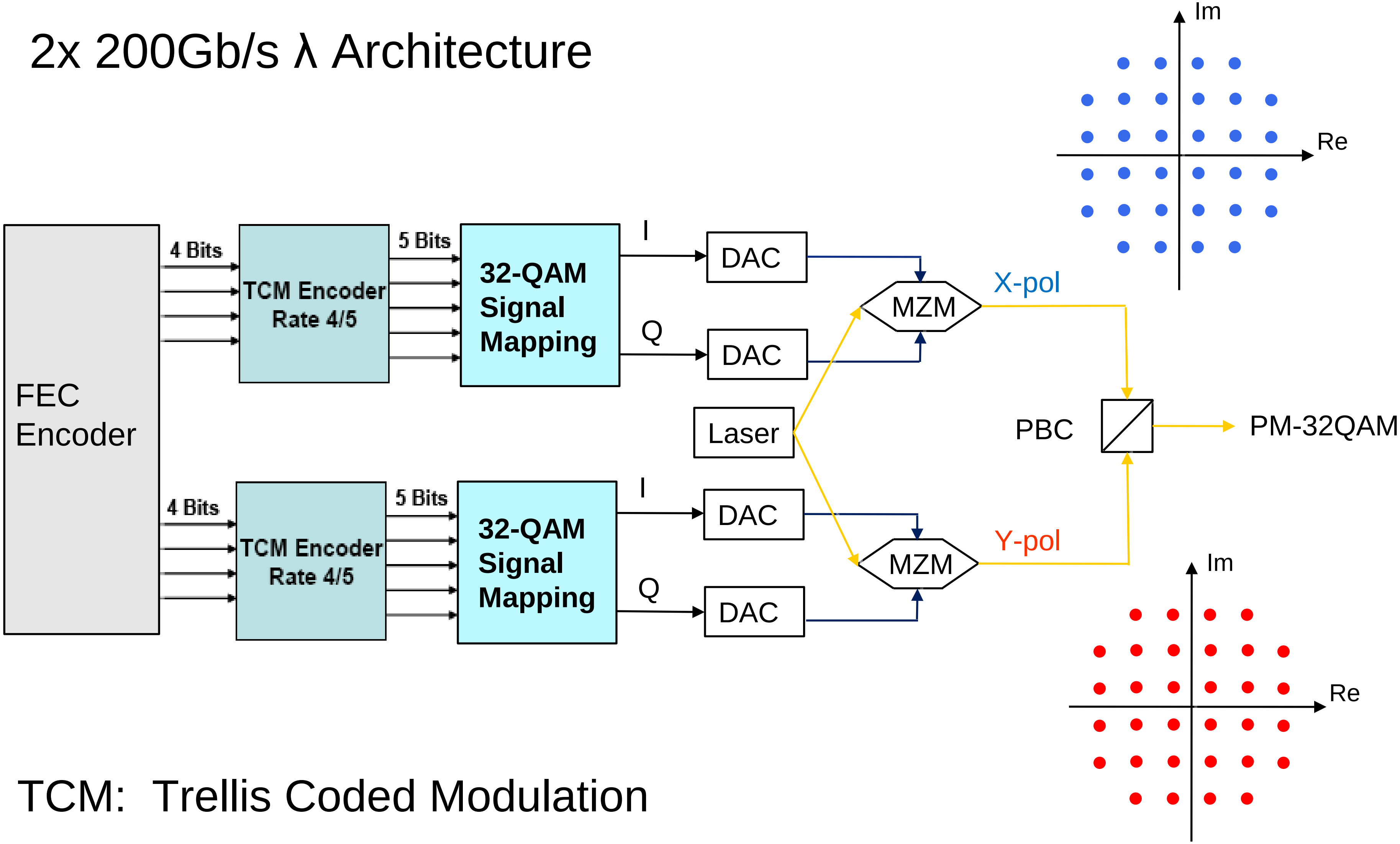
OTU5 28GBd PM-16QAM BER



Linear analysis of 224Gb/s λ in 50GHz channel with ASE noise

OTU5 28GBd PM-TC-32QAM TX (1 of 2)

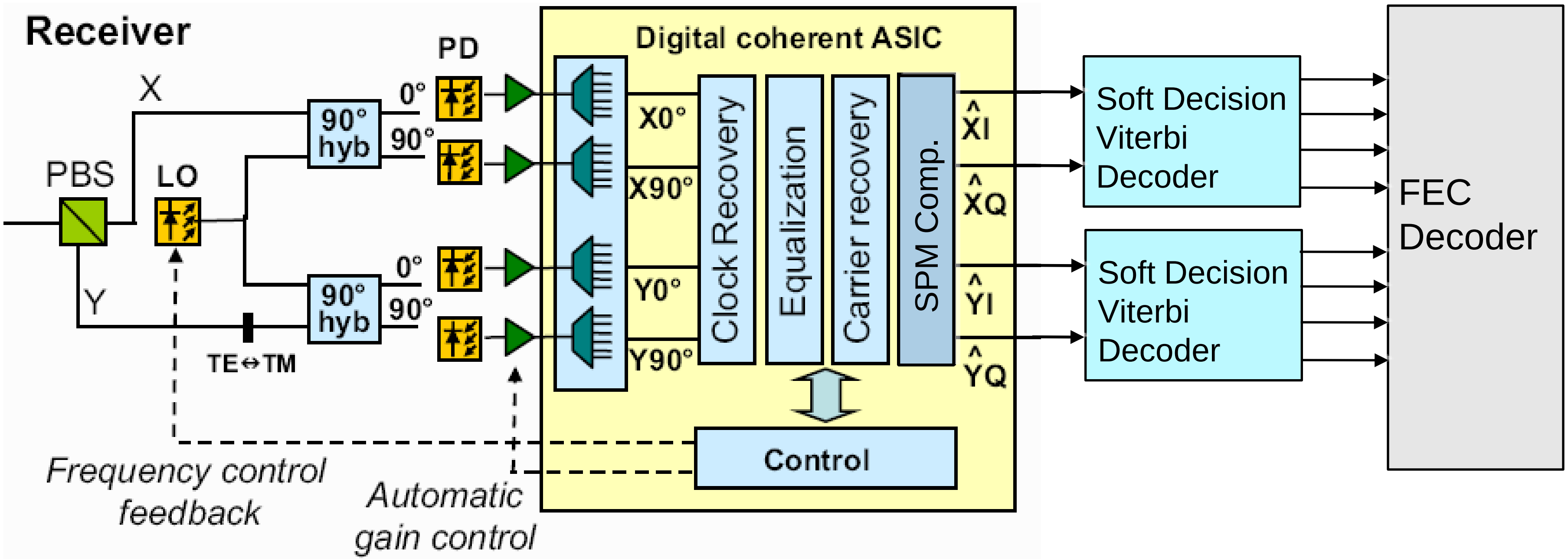
2x 200Gb/s λ Architecture



TCM: Trellis Coded Modulation

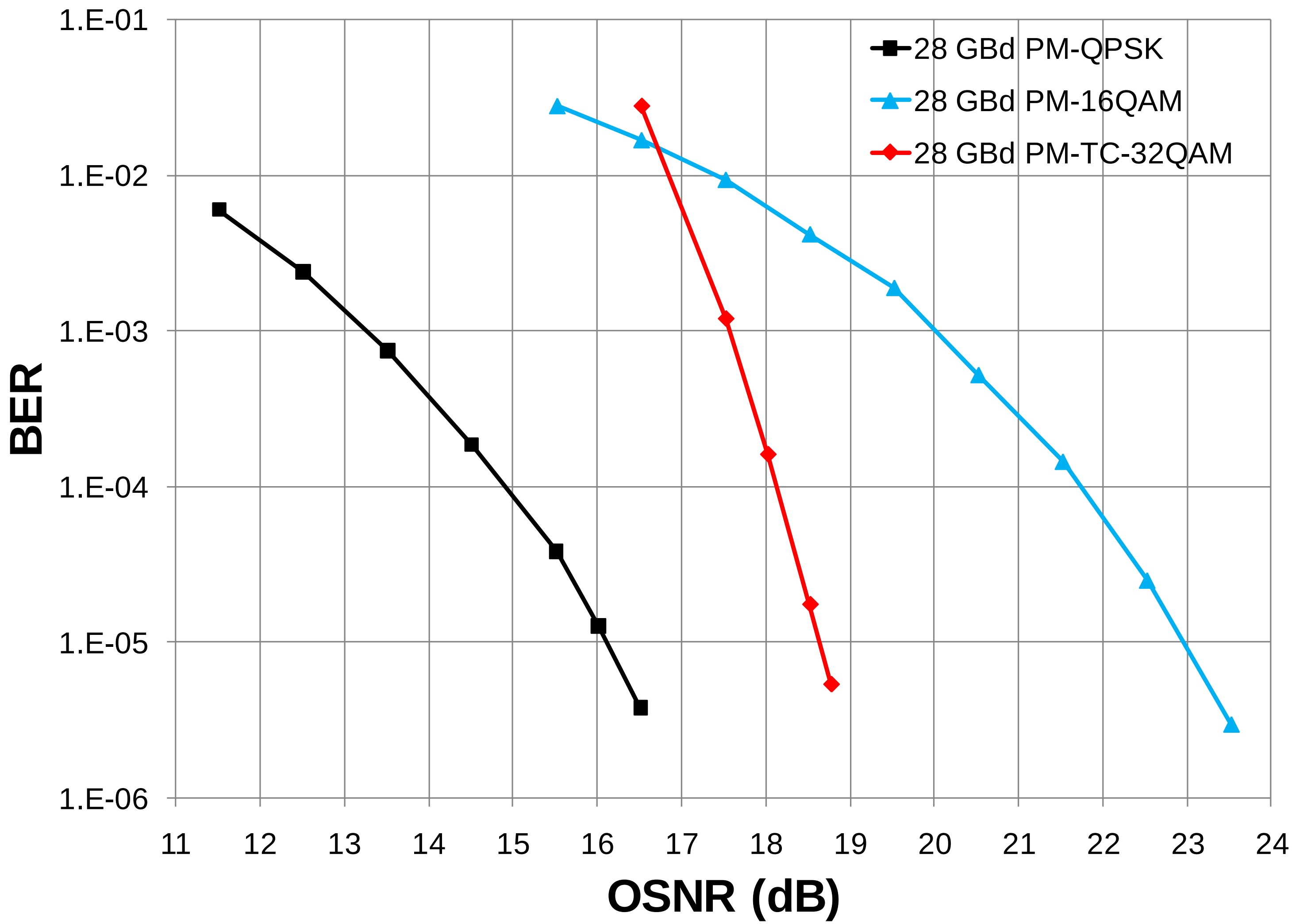
OTU5 28GBd PM-TC-32QAM RX (1 of 2)

2x 200Gb/s λ Architecture



PM-QPSK → PM-TC-8PSK to improve 100Gb/s OSNR proposed in: M. Magarini, et al., "Concatenated Coded Modulation for Optical Communication Systems," IEEE Photonics Technology Letters, v.12, no.16, 15 Aug. 2010

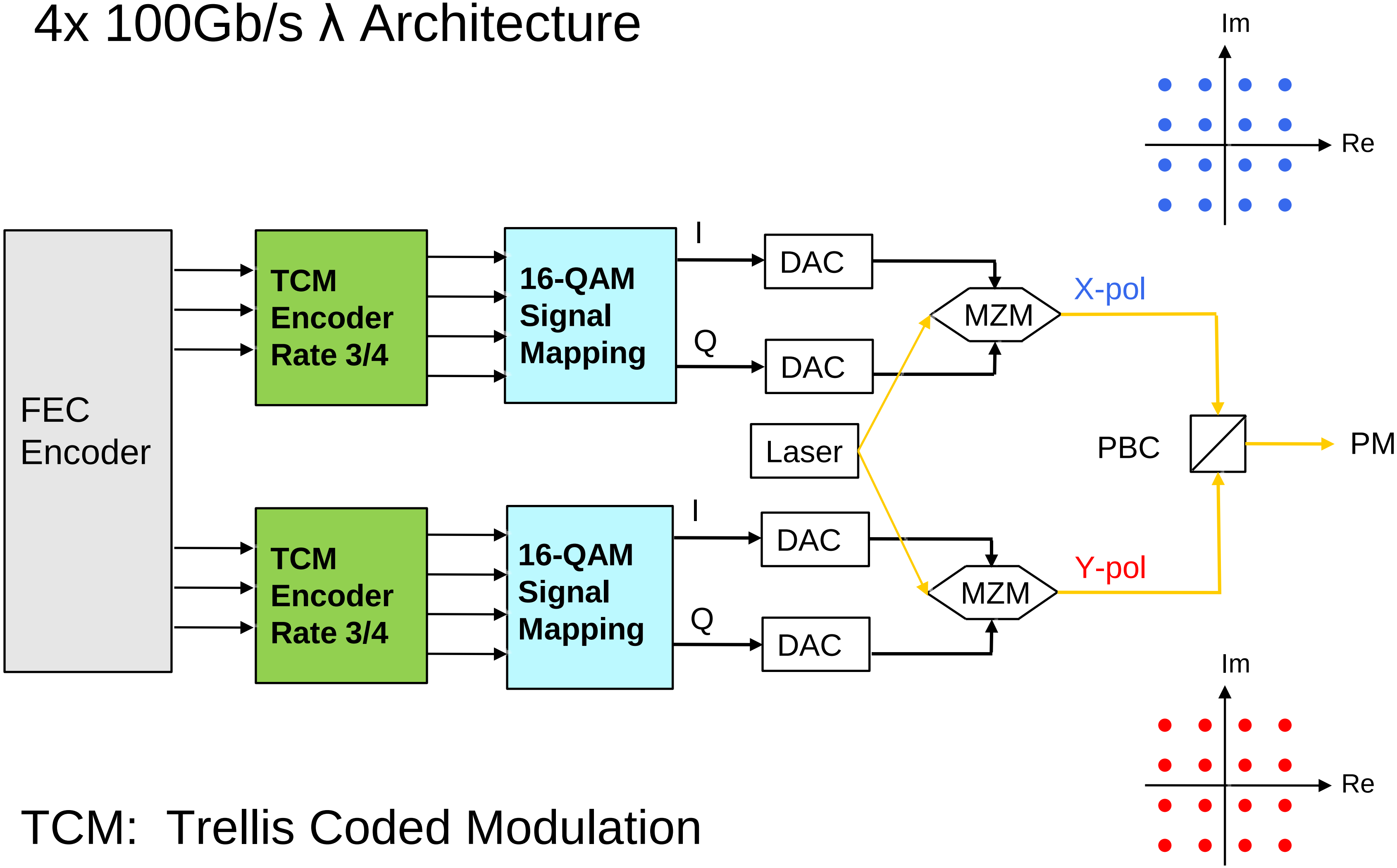
OTU5 28GBd PM-TC-32QAM BER



Linear analysis of 224Gb/s λ in 50GHz channel with ASE noise

OTU5 18GBd PM-TC-16QAM TX (1 of 4)

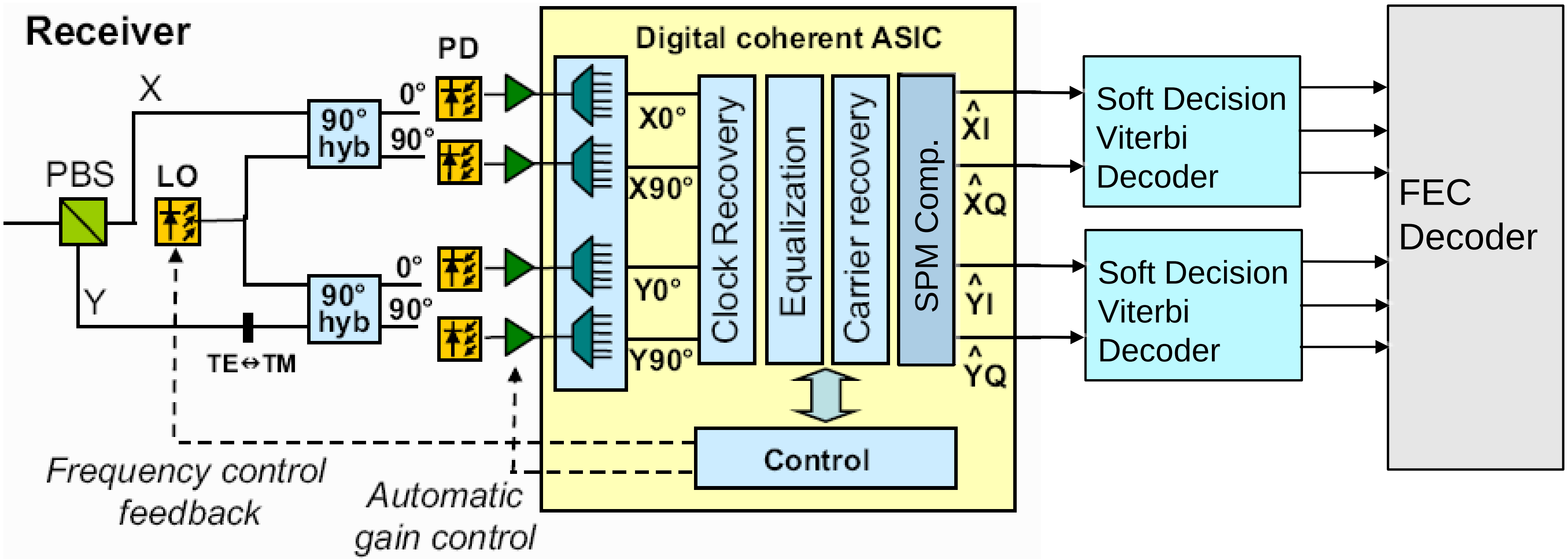
4x 100Gb/s λ Architecture



TCM: Trellis Coded Modulation

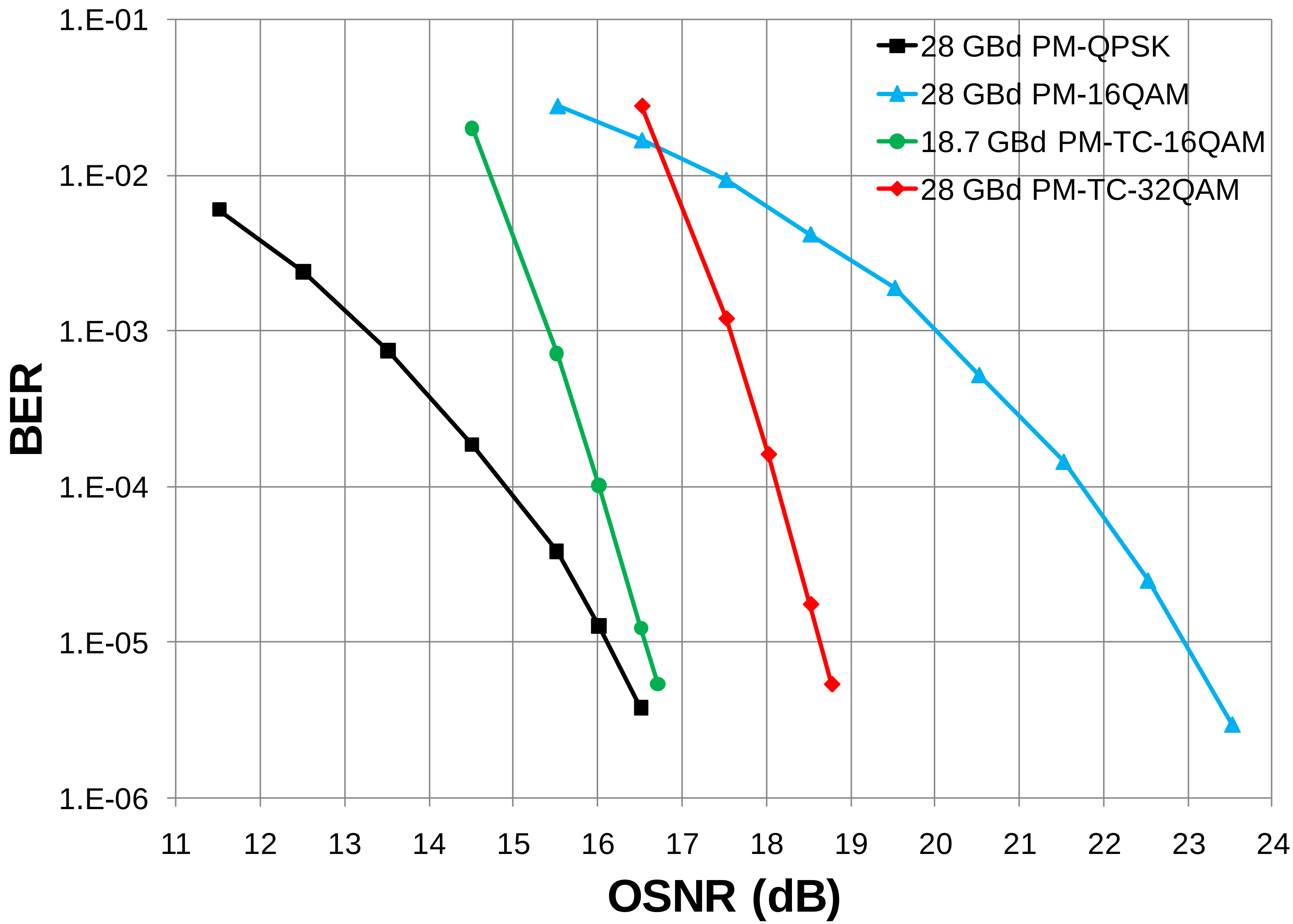
OTU5 18GBd PM-TC-16QAM RX (1 of 4)

4x 100Gb/s λ Architecture



Sub-carrier TCM to improve OSNR proposed in: X. Liu, et al., “Transmission of 44-Gb/s Coherent Optical OFDM Signal with Trellis-Coded 32-QAM Subcarrier Modulation,” OFC’10, San Diego, CA, 21-25 Mar. 2010

OTU5 18GBd PM-TC-16QAM BER



Linear analysis of 112Gb/s λ in 25GHz channel with ASE noise

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OTU5 400Gb/s Alternatives Summary

Alternative	Per λ channel BW GHz	Rate GBaud	Spectral Efficiency bits/sec-Hz	ΔOSNR* pre-FEC BER=1.e-3 dB
single 112 Gb/s λ PM-QPSK	50	28	2	0
dual 224 Gb/s λ PM-16QAM	50	28	4	6.7
dual 224 Gb/s λ PM-TC-32QAM	50	28	4	4.3
quad 112 Gb/s λ PM-TC-16QAM	25	18.7	4	2.1

* At constant 50GHz channel AOP without non-linear constraints

OTN Rate Beyond OTU5

- OTU5 = ~450Gb/s to efficiently carry 400GbE
- OTU6 will efficiently carry following Ethernet
- If following Ethernet is 1.6TbE, OTU6 = ~1.8Tb/s
- 20% SD FEC transport rate = ~2Tb/s
- Spectral efficiency will only increase with new type of fiber or fundamentally different approaches to the SMF channel
- Technology for transport rates above 500Gb/s (ex. 1Tb/s) does not exist and will require extensive R&D

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Recommendations

Next Ethernet and OTN (OTU5) rates are likely to be ~400Gb/s

- Focus engineering development on 500Gb/s
- Double OTN spectral efficiency to 4bits/sec-Hz
- Extend 100GbE and OTU4 28GBd PM-QPSK technology

Following Ethernet and OTN rates are preferably $\geq$1.6Gb/s

- Focus fundamental research on at least 2Tb/s
- Quadruple OTN spectral efficiency to at least 8bits/sec-Hz
- Invent new modulation, DSP, device and fiber technology

There will be no ~1Tb/s Ethernet or OTN rates

- Neither a good engineering or research objective

Conclusion

1Tb/s Researchers praying for guidance