400Gb/s is for Engineers and 1Tb/s is for Dreamers

Future Solutions for Tbit/s Ethernet

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Outline

- **Ethernet & Transport Technology**
- 100Gb/s Ethernet Technology
- Beyond 100Gb/s Ethernet Technology
- 100Gb/s Transport Technology
- Beyond 100Gb/s Transport Technology
- Conclusions

Ethernet and Transport Technology

- Historically, Ethernet rates lagged Transport rates, which enabled 10x rate Ethernet steps compared to 4x Transport rate steps, through leveraging of technology
- Since Ethernet and Transport rates are now aligned, it is more likely that both will take 4x rate steps
- Ethernet will continue to leverage Transport technology, which makes Transport a good window on future Ethernet approaches

Future Ethernet and Transport Rates

- IEEE and ITU-T are strongly committed to:
  - Full Ethernet and OTN compatibility
  - Avoiding transparency and networkability problems like in 10GbE transport over SDH or OTN
  - 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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- Ethernet & Transport Compatibility
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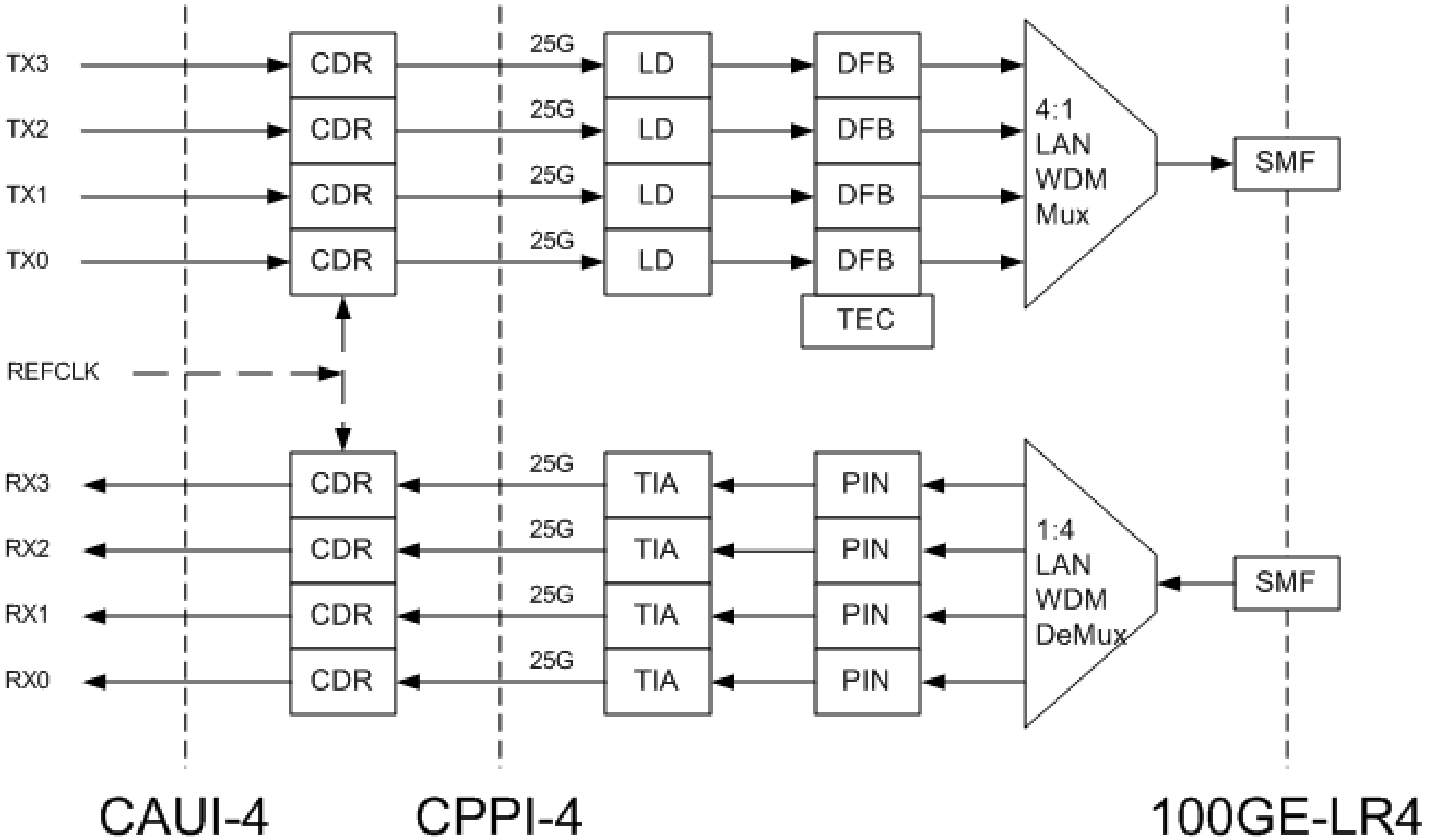
100GbE WDM SMF Transceiver



Long term, high volume architecture

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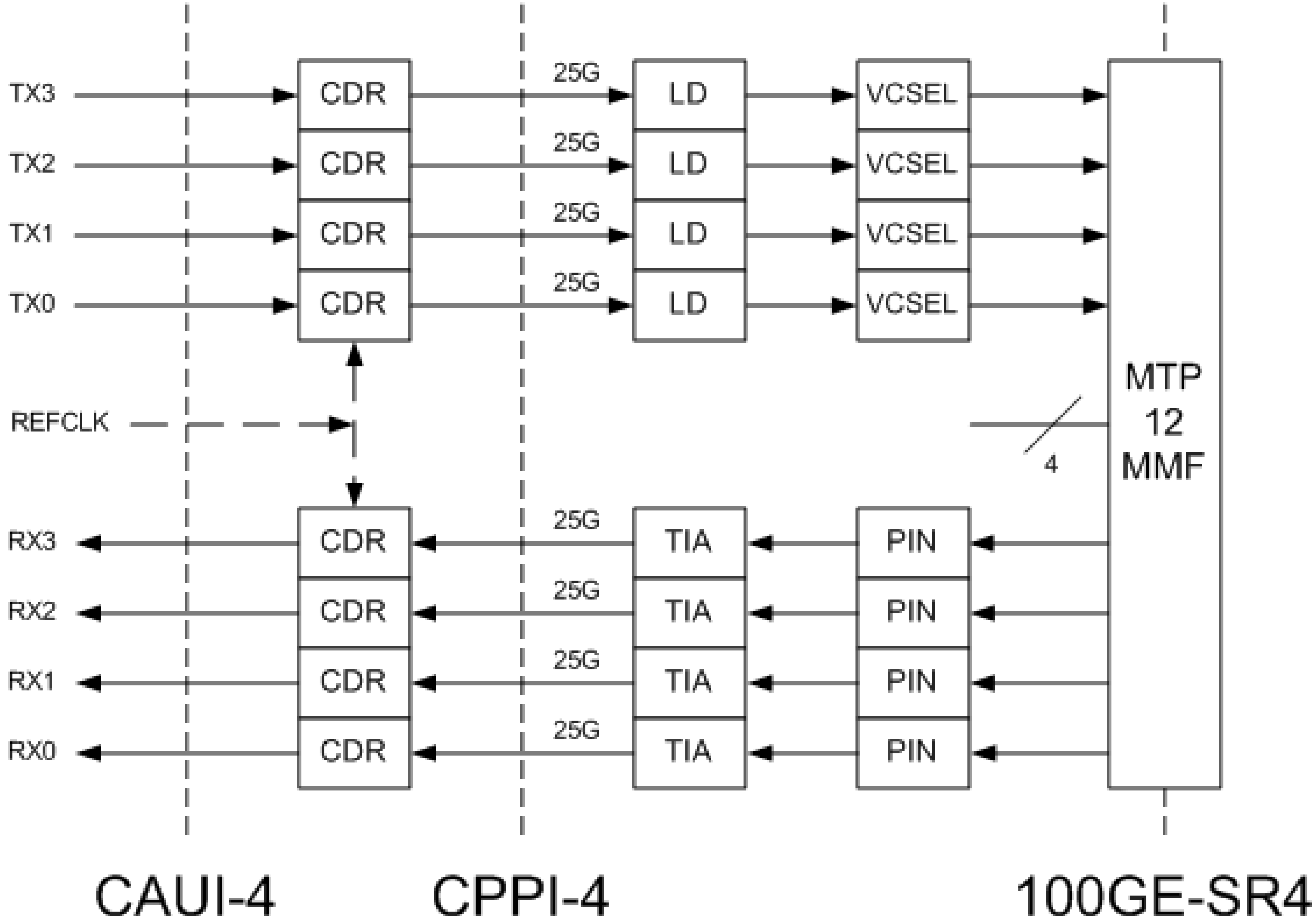
100GbE Parallel MMF Transceiver



Long term, high volume architecture

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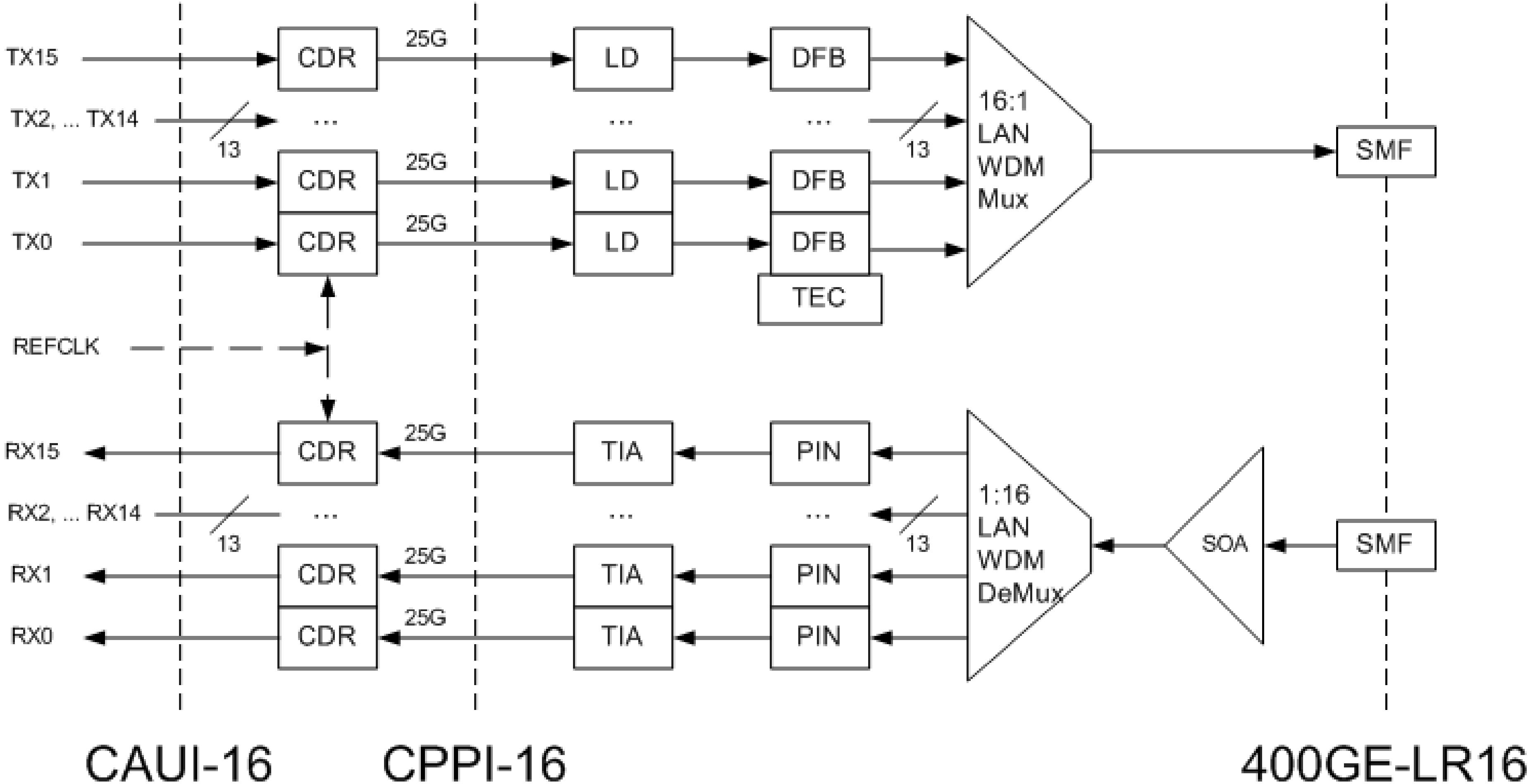
Beyond 100GbE Rate Requirements

- 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



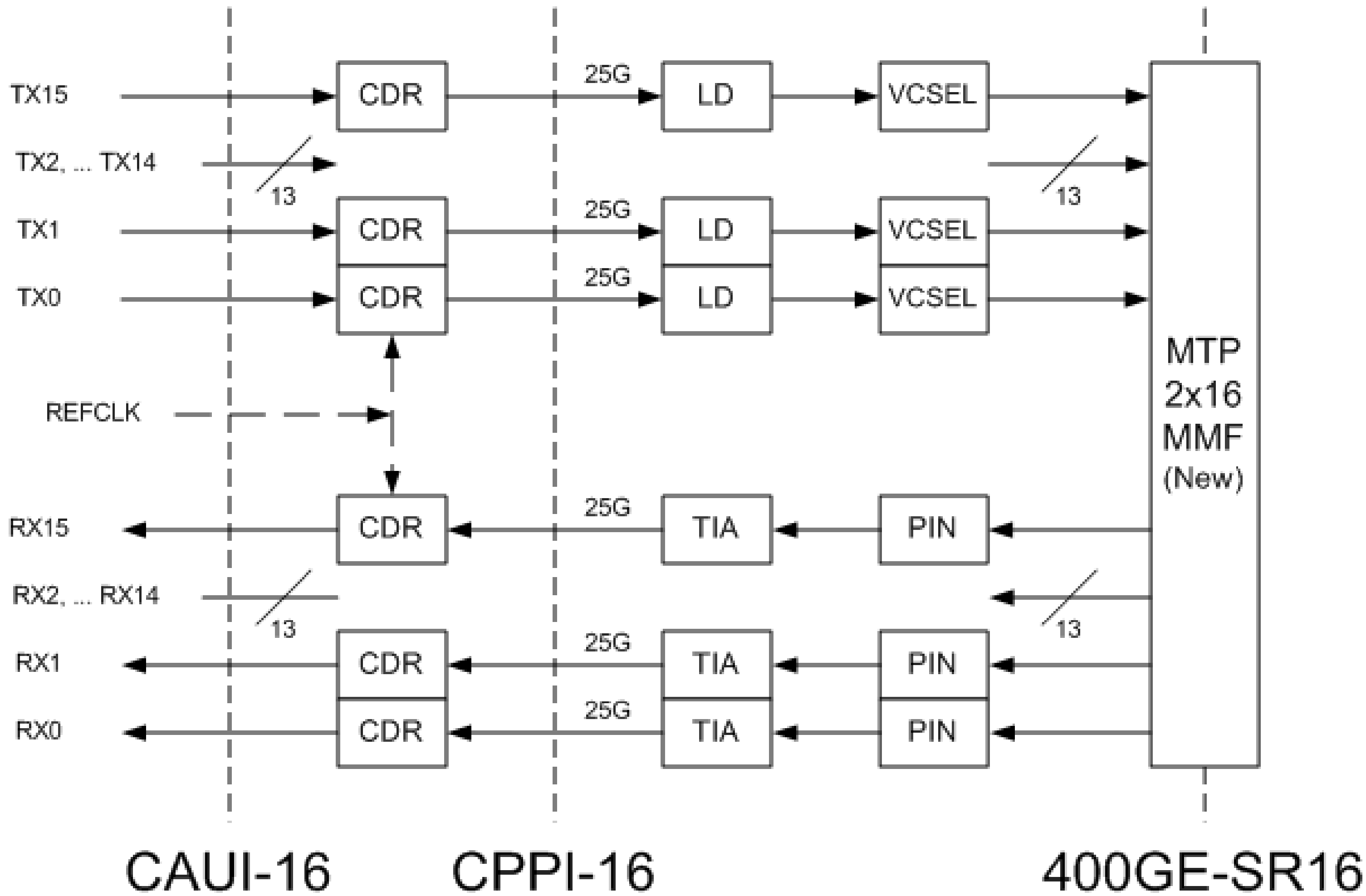
Different Gen2 architecture is required to support higher I/O density

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

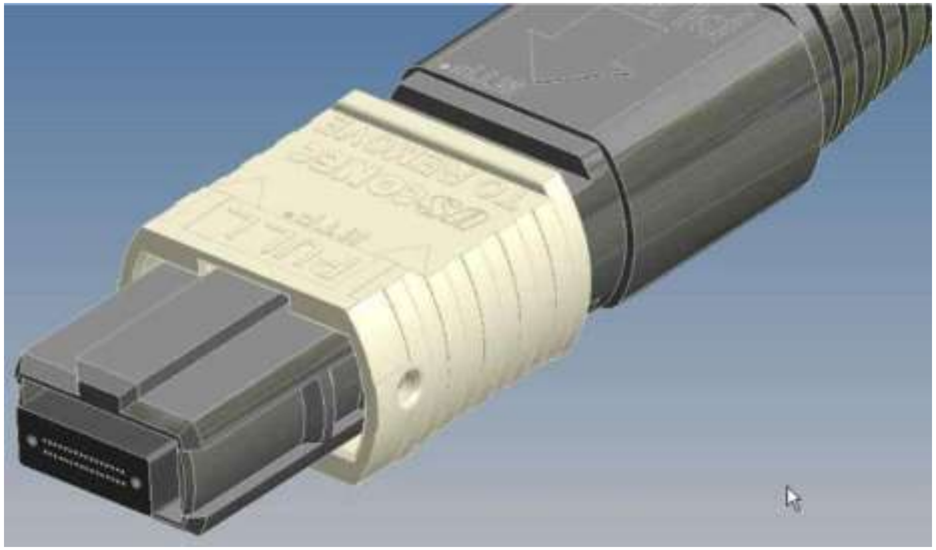
← 1310nm band 100GbE WDM specification defined in IEEE 802.3ba

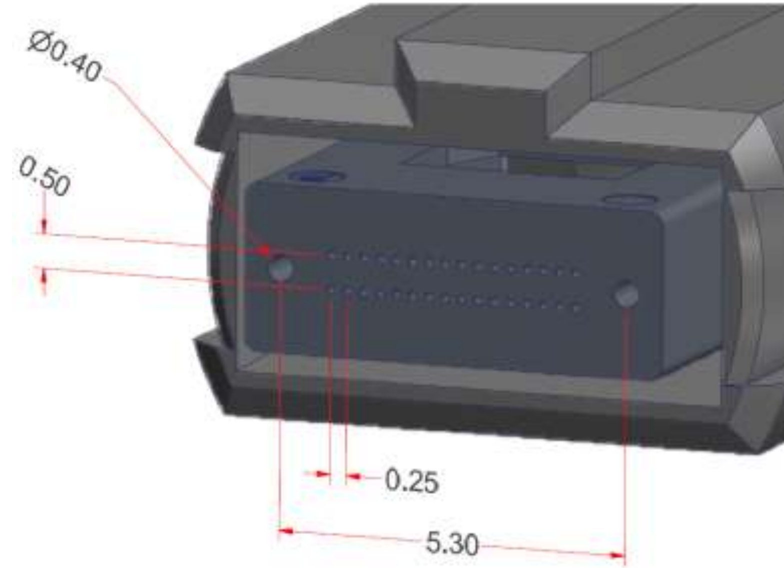
400GbE Parallel MMF Gen1 Transceiver



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 Rate Alternatives

- 1TbE
  - 2.5x is a small BW increase from 400GbE
  - unlikely to justify a huge investment
- 1.2TbE
  - 3x is a small BW increase from 400GbE
  - unlikely to justify a huge investment
  - 3 is an odd number
- 1.6TbE
  - 4x is a traditional BW increase from 400GbE
  - Sufficient to justify a huge investment
  - NRZ, PAM-N impractical because of too many channels
  - Complex Modulation is only feasible alternative
  - No technology exists that can be commercialized
  - Excellent long term research opportunity

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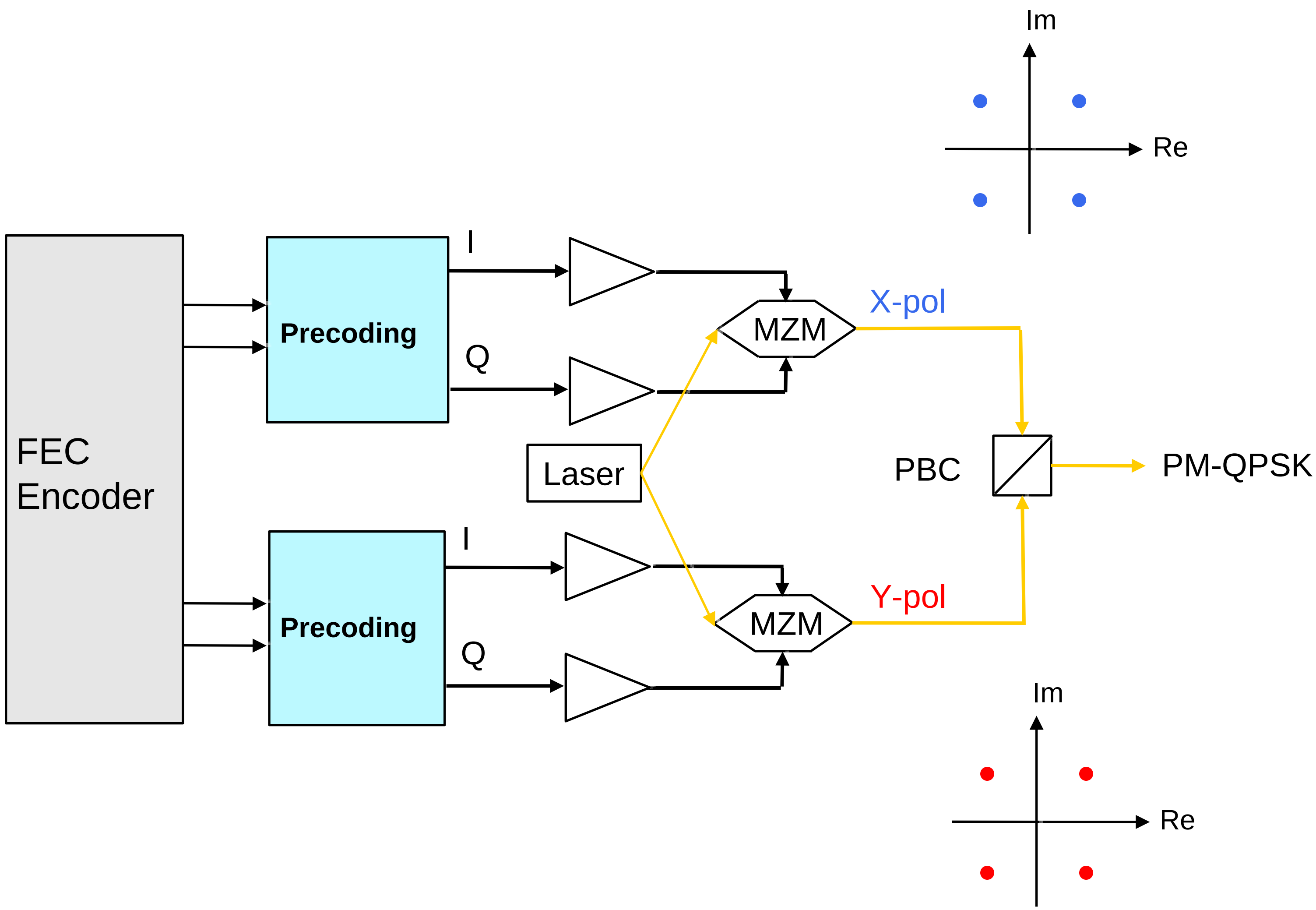
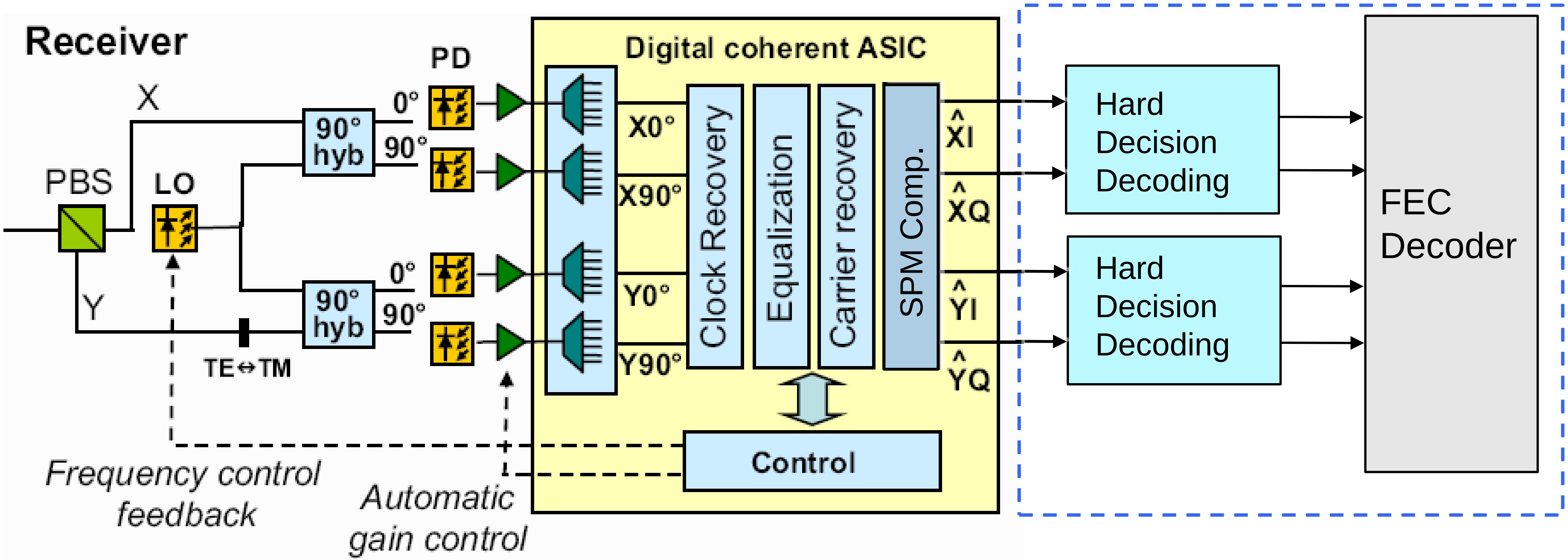
PM-QPSK TX



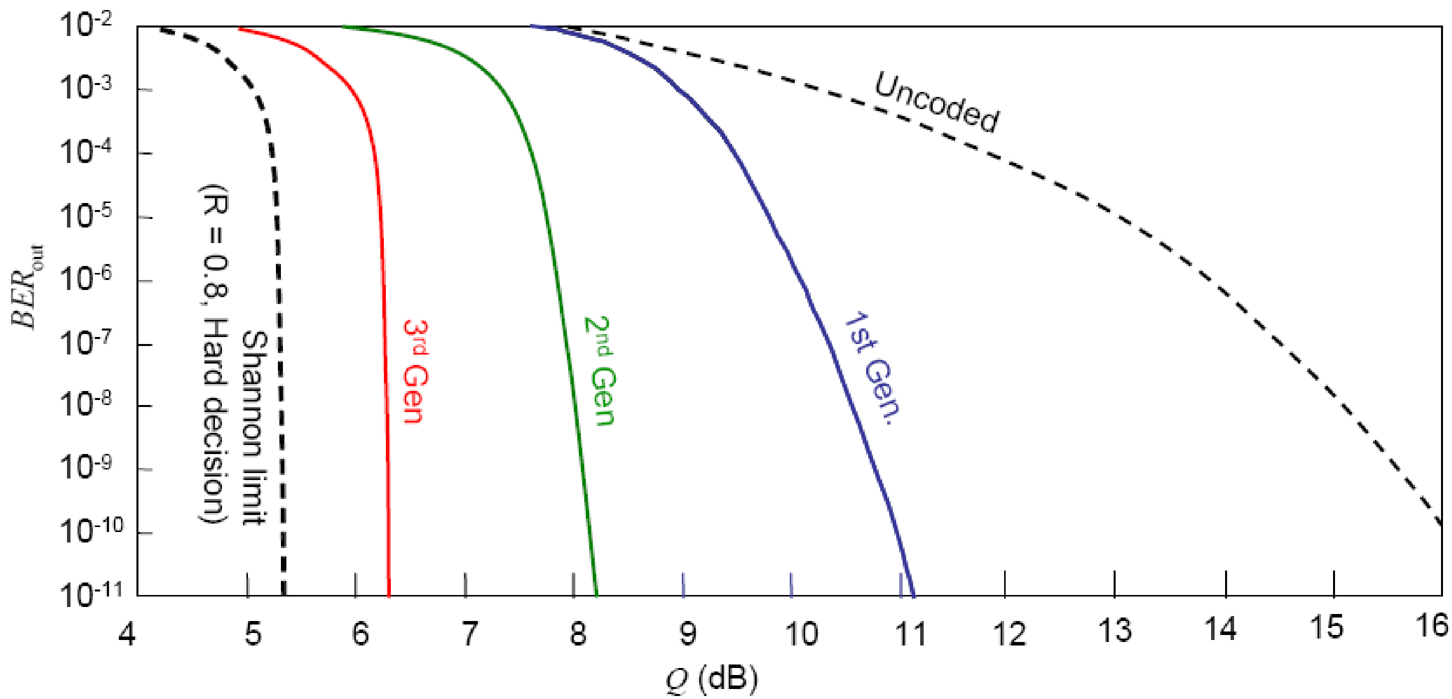
FEC
Encoder
Precoding
Precoding
I
Q
I
Q
Laser
MZM
MZM
X-pol
Y-pol
PBC
PM-QPSK
Im
Re
Im
Re

PM-QPSK RX



SD FEC is an alternative to HD FEC

OTU4 Coding Alternatives 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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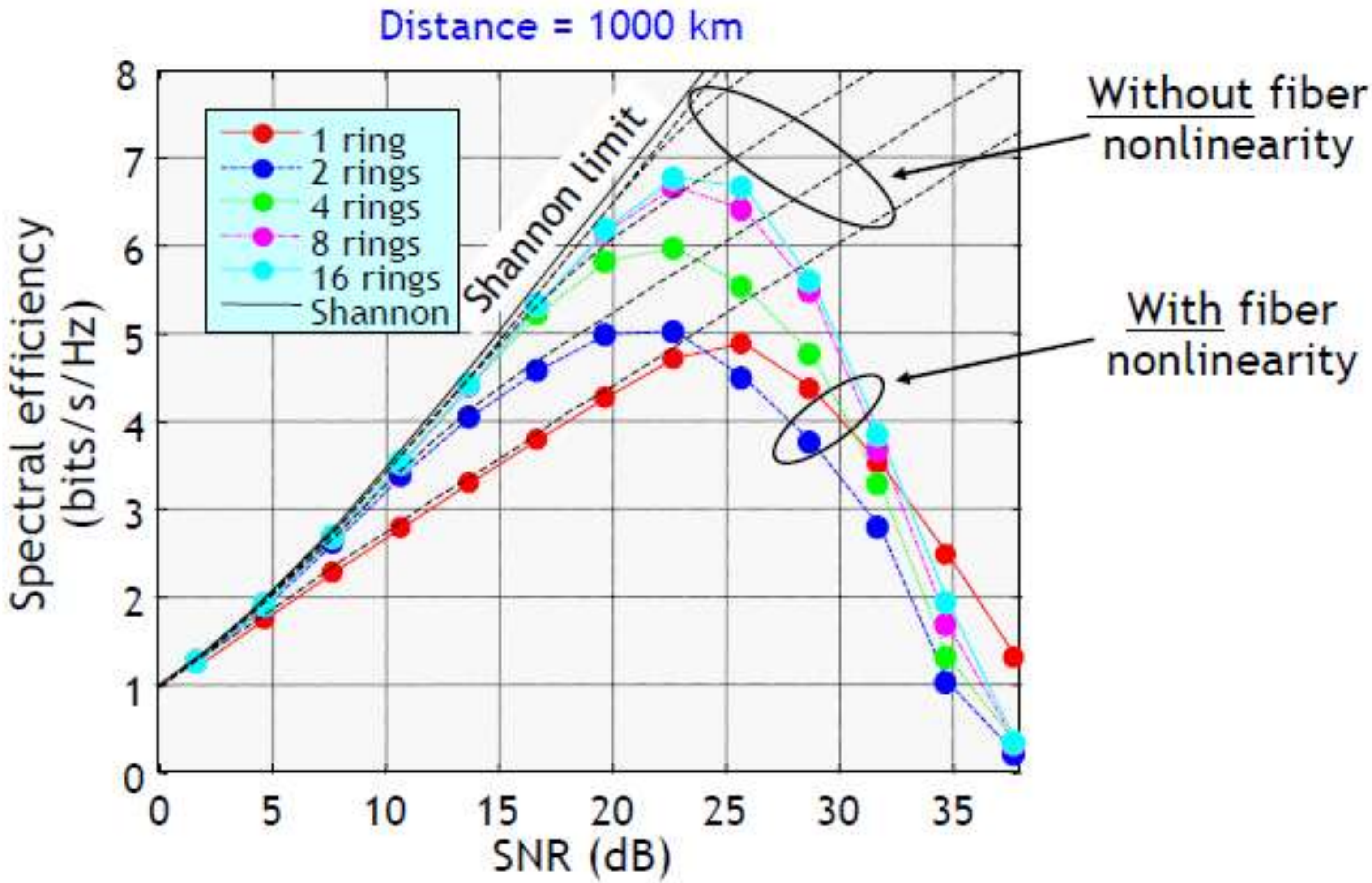
Deployed SMF Spectral Efficiency Limits



T. Source: R.-J. Essiambre, et. al., "Capacity Limits of Fiber-Optic Communication Systems," Tutorial, OFC'09

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OTN Spectral Efficiency

- OTU4 rate: ~112Gb/s
- OTU4 technology: 100Gb/s in 50GHz: ~2bits/sec-HZ
- Practical equipment and fiber limit for standard SMF over typical LH distances (1000km or longer): ~4bits/sec-HZ

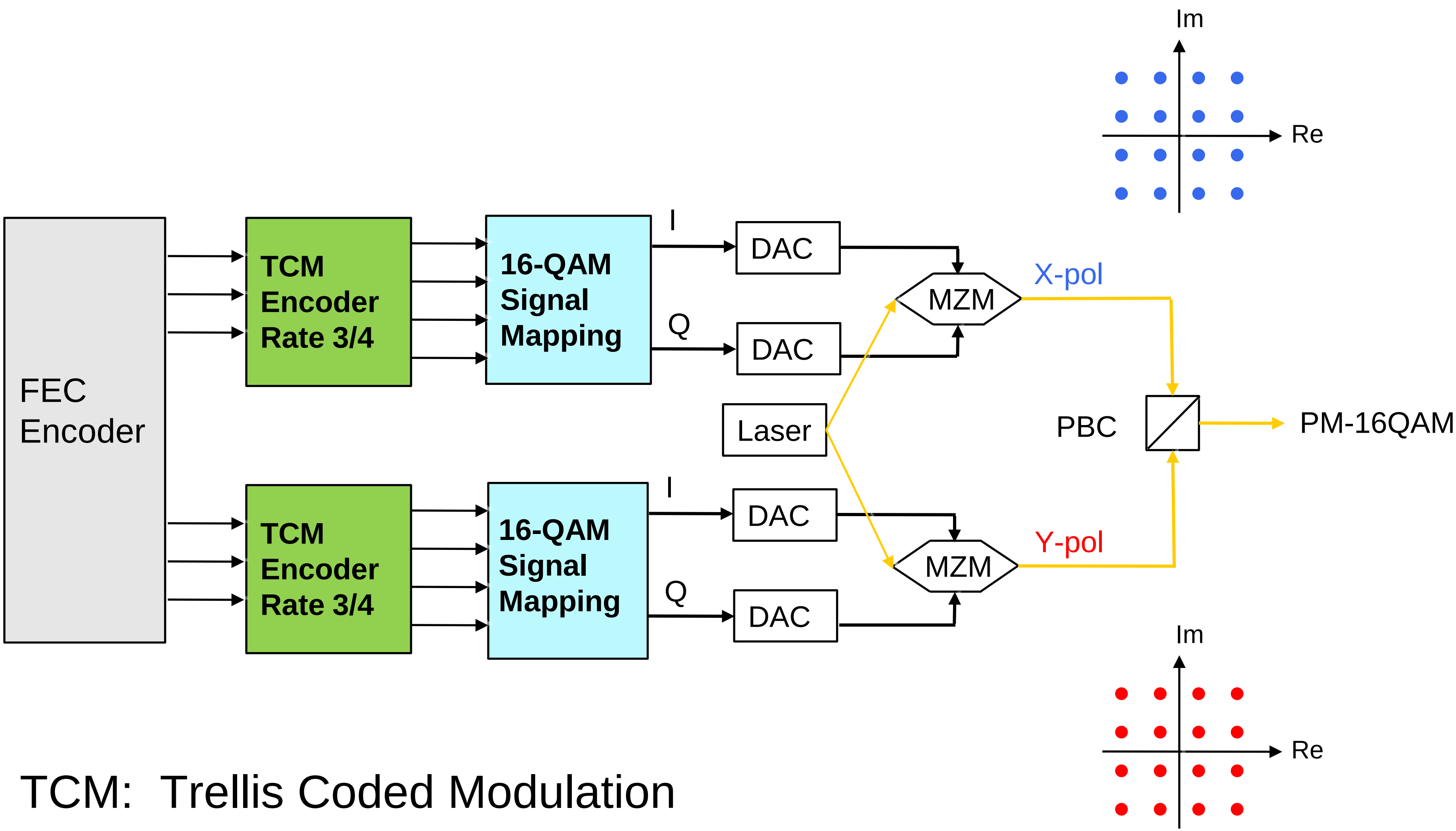
  (P. Anslow, Ciena, "Optical Line Technologies for Rates above 100G ," Joint ITU-T/IEEE Workshop, Geneva, May 2010)
- 2x left for improving spectral efficiency for LH applications,

  ex. 400Gb/s in 100GHz for OTU5: ~4bits/sec-Hz

OTU5 Rate

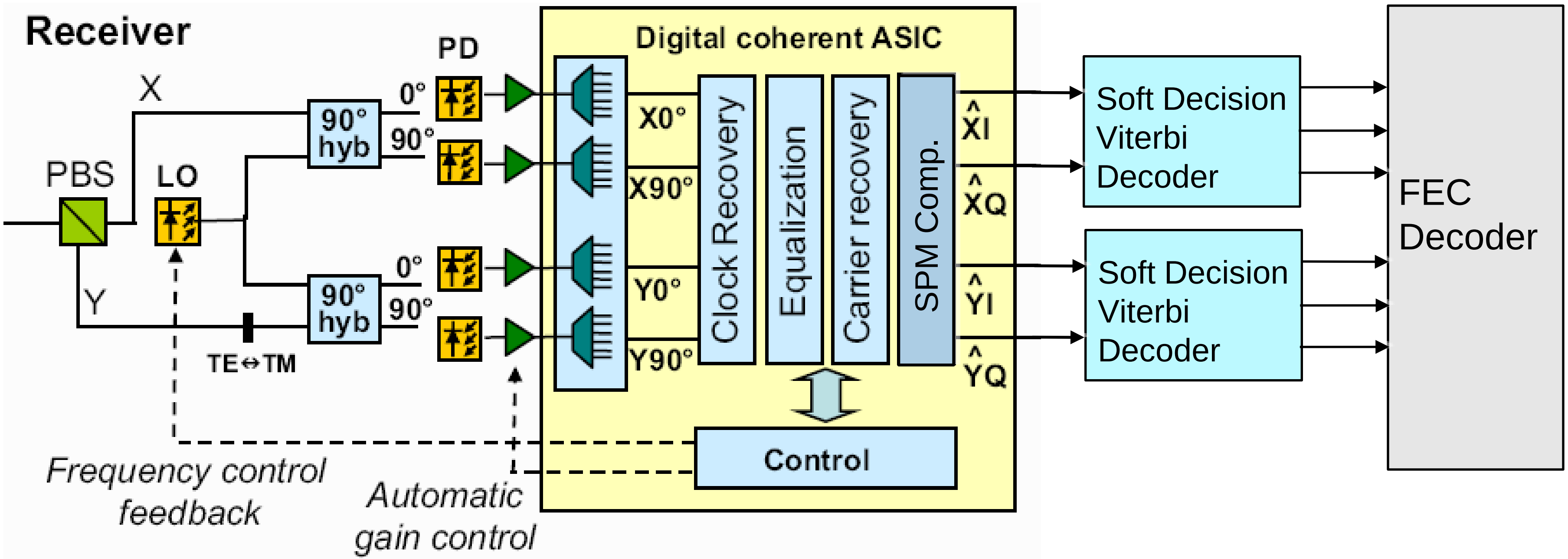
- 400GbE rate = ~412Gb/s
- To efficiently carry 400GbE, OTU5 = ~450Gb/s
- 20% SD FEC transport rate = ~500Gb/s
- 100GHz channel bandwidth gives ~2x spectral efficiency increase over OTU4
- Maintains 4x traditional OTN rate jump, ex. OTU2 to OTU3
- Allows extending OTU4 DP-QPSK technology
- Higher OTU5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

PM-TC-16QAM TX



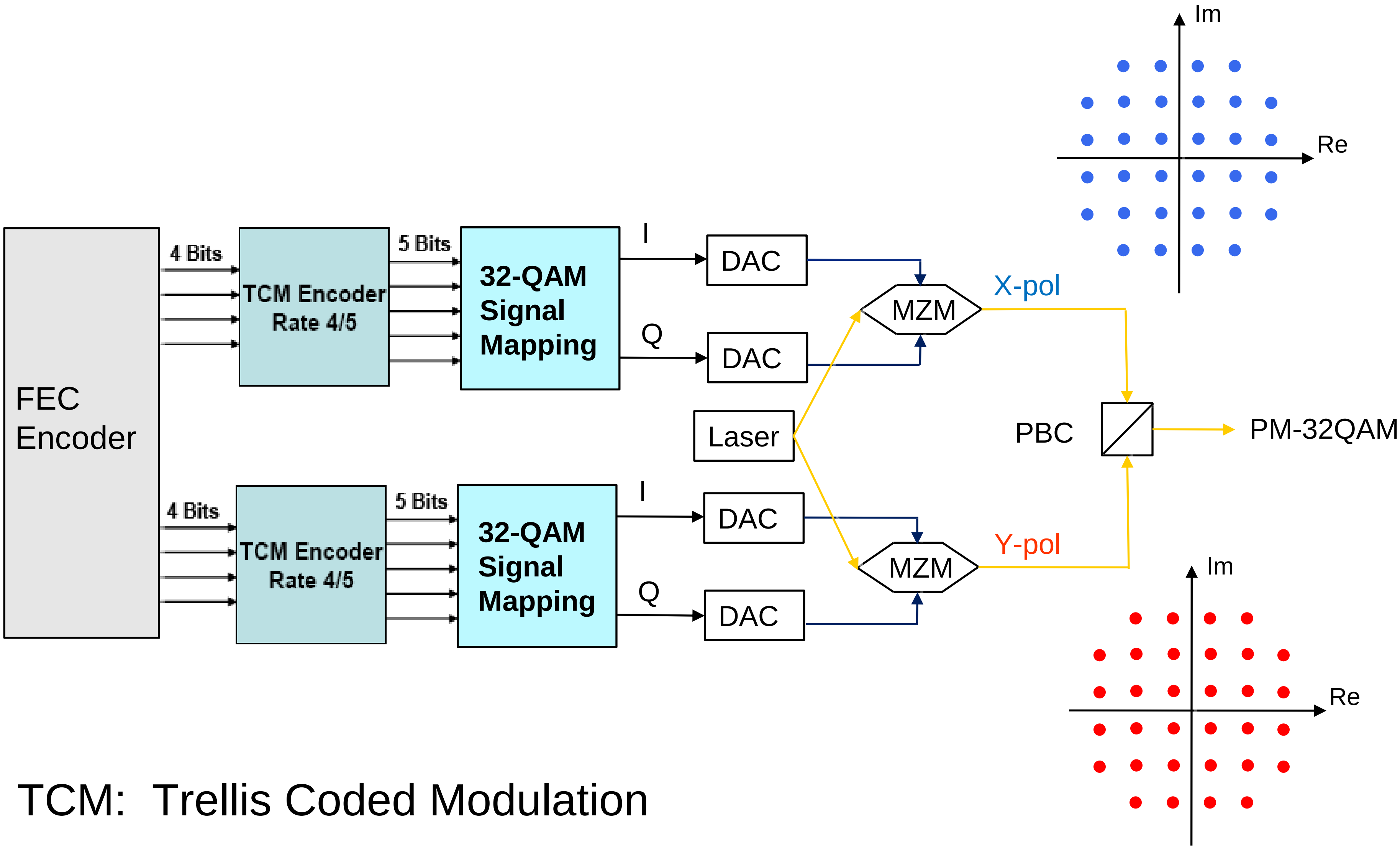
TCM: Trellis Coded Modulation

PM-TC-16QAM RX



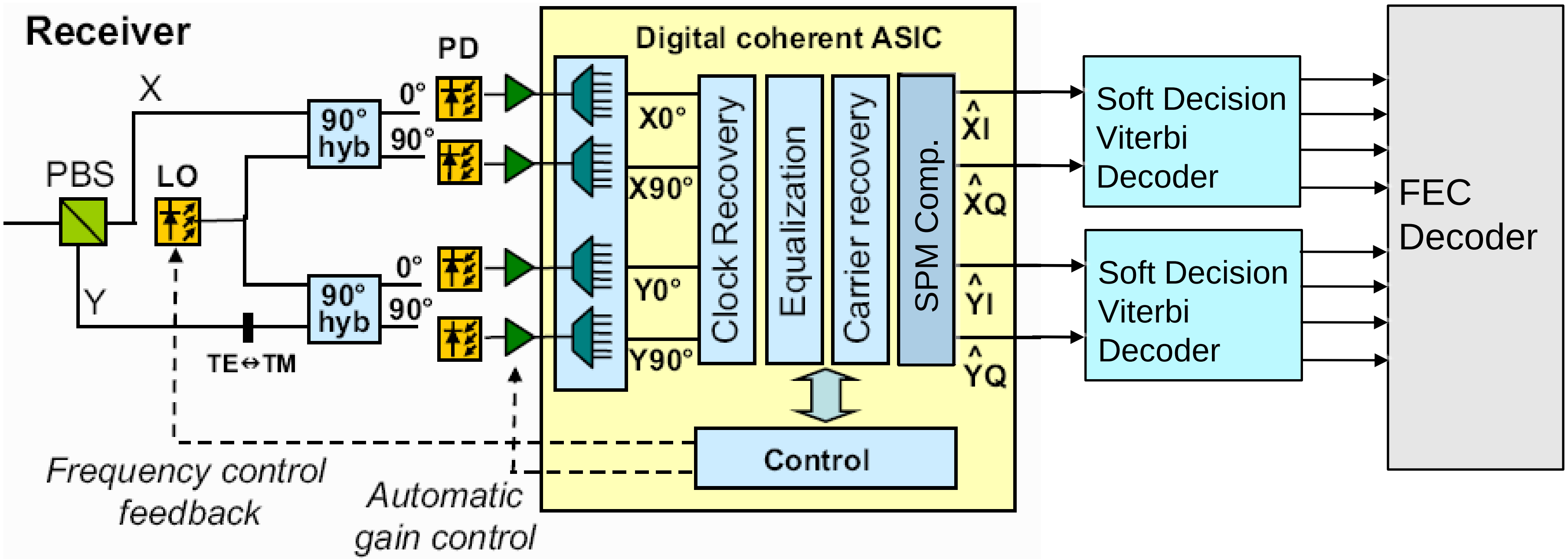
PM-QPSK → PM-TC-8PSK to improve 100Gb/s OSNR proposed in: M. Magarini, et al., "Concatenated Coded Modulation for Optical Communication Systems," IEEE Photonics Technology Letters, v.12, no.16, 15 Aug. 2010

PM-TC-32QAM TX

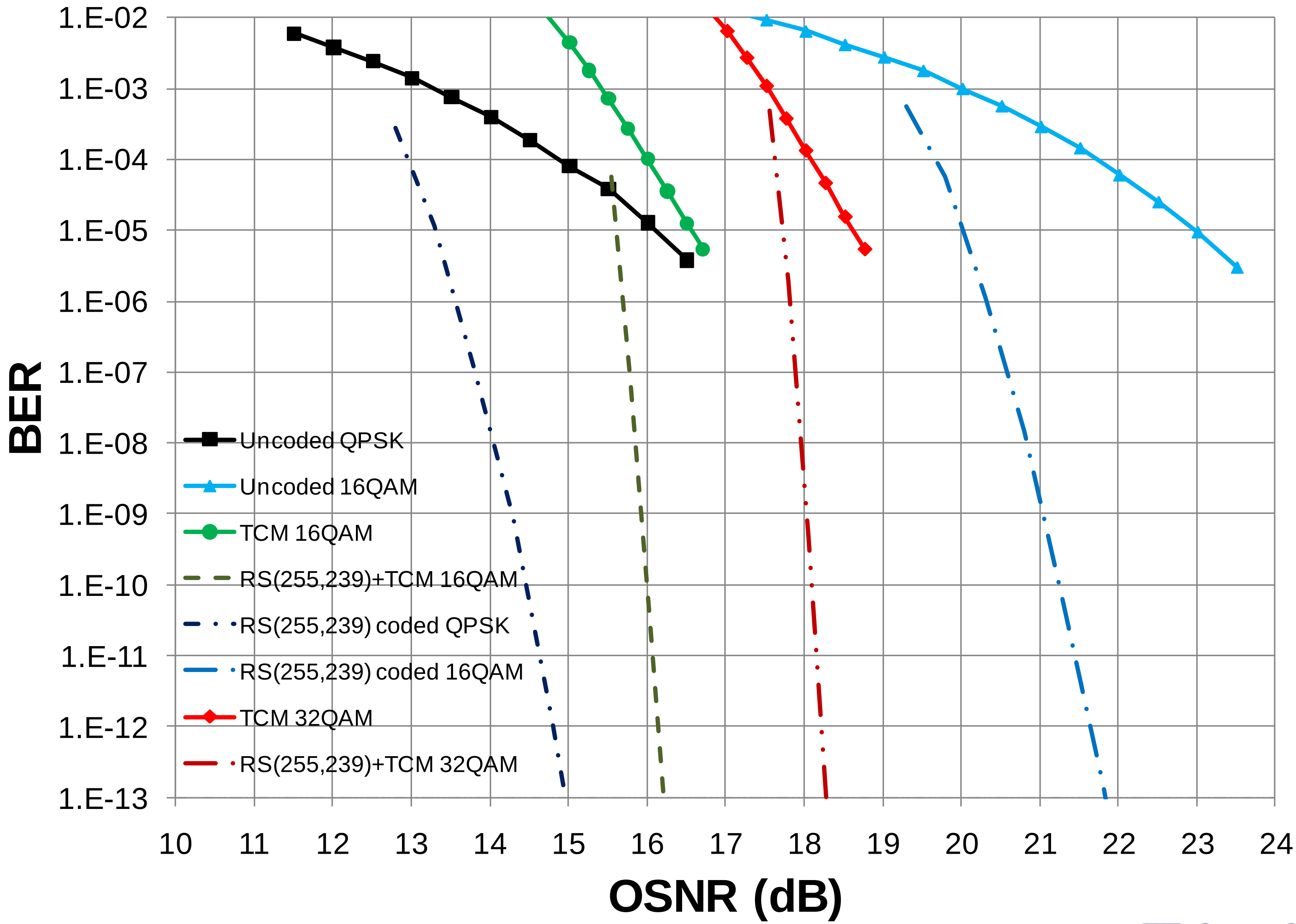


TCM: Trellis Coded Modulation

PM-TC-32QAM RX



OTU5 Modulation Alternatives BER



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400Gb/s OTU5 Alternatives Summary

Alternative	channel BW per λ GHz	Rate GBaud	Spectral Efficiency bits/sec-Hz	ΔOSNR* BER=1.e-12 dB
single 112 Gb/s λ PM-QPSK	50	28	2	0
dual 224 Gb/s λ PM-16QAM	50	28	4	6.8
dual 224 Gb/s λ PM-TC-32QAM	50	28	4	3.4
quad 112 Gb/s λ PM-TC-16QAM	25	18.7	4	1.3

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

Conclusions

Next Ethernet and OTN (OTU5) rate is likely to be ~400Gb/s

- Focus engineering development on ½Tb/s technologies
- Extend 100GbE 4x26GBd NRZ Technology
- Double OTN spectral efficiency to 4bits/sec-Hz by extending 4x28GBd PM-QPSK Technology

Following Ethernet and OTN rate is preferably ≥1.6Gb/s

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

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

- Excessive engineering objective
- Insufficient research objective

If you are going to dream, how about 10Tb/s as an objective?