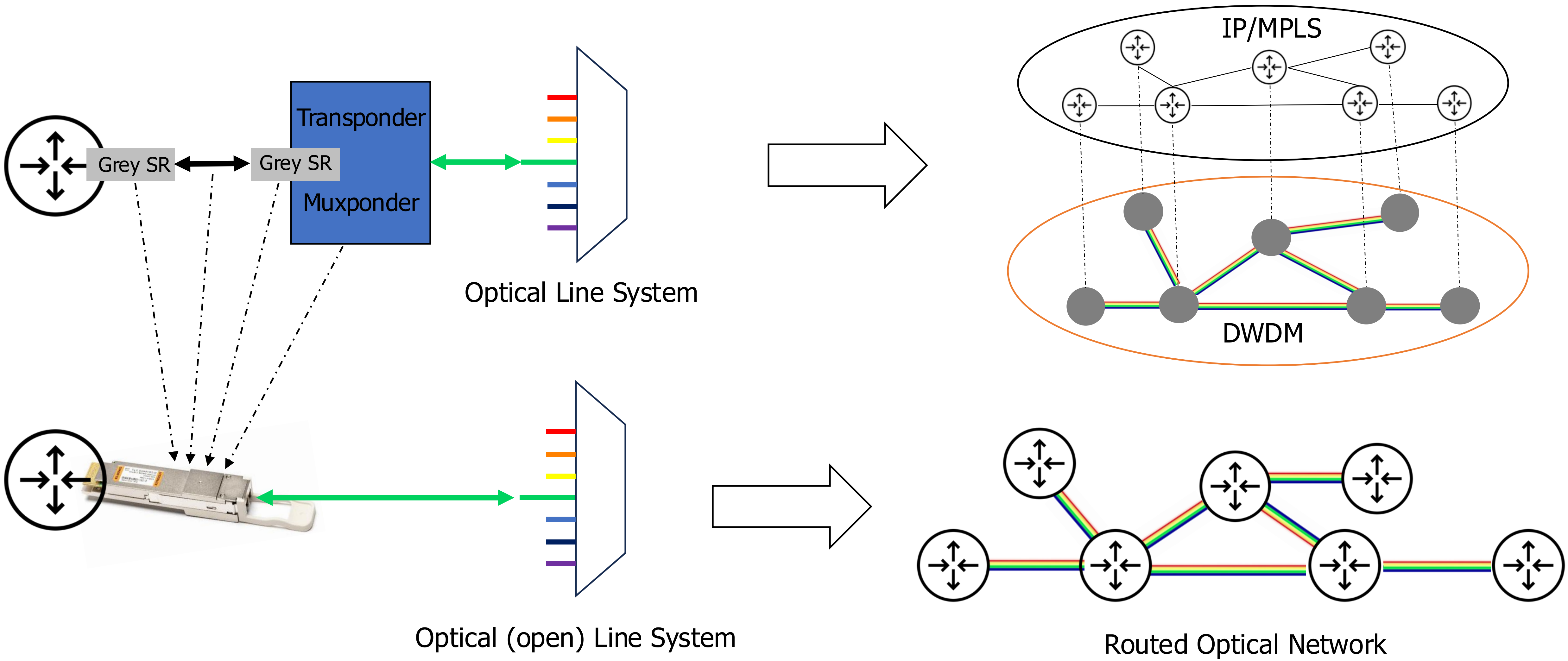
Optics 101
for
non-Optical (IP) folks

Tashi Phuntsho
[Technology Evangelist @FLEXOPTIX]
[Network Engineer/Trainer @NSRC]

Coherent Pluggables → IPoDWDM



Optical Power

Intensity of light→ *brightness*

Decibel (dB) is a log ratio between two values

-10dB: 1/10th of something, -**20dB**: 1/100th
10dB: 10x of something, **20dB**: 100x

Optical power expressed in **dBm**: *decibel relative to 1mW of power*

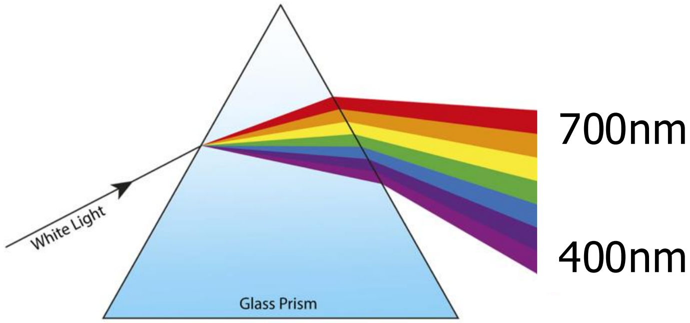
0dBm = 1mW

-10dBm = 0.1mW	**10dBm = 10mW**
-20dBm = 0.01mW	**20dBm = 100mW**

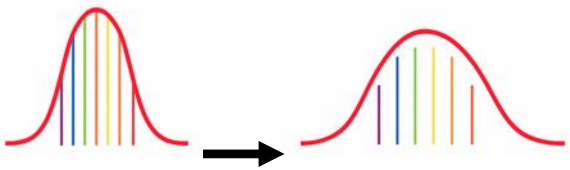
Chromatic Dispersion

Different colours (**λ**) of light travel at different speeds inside the fiber

- Longer wavelengths bend less → travel faster
- Arrive at different times at the destination!
  - Longer distance, bigger time difference ~ broaden
- This time difference (CD) is measured in ps/nm

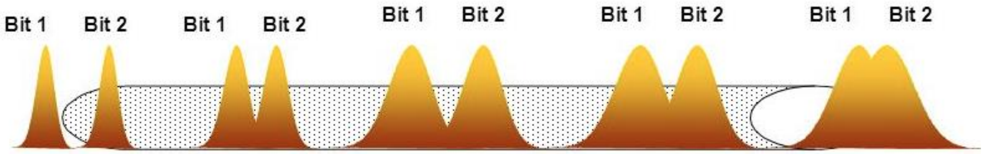


Source: KeyStageWiki



Problem with dispersion:

- As pulses becomes broader, they overlap each other
- Difficult to distinguish the two signals ~ *bit errors!*
- Limits the *bit rate*, or *distance* for a specific bit rate



Source: FOA

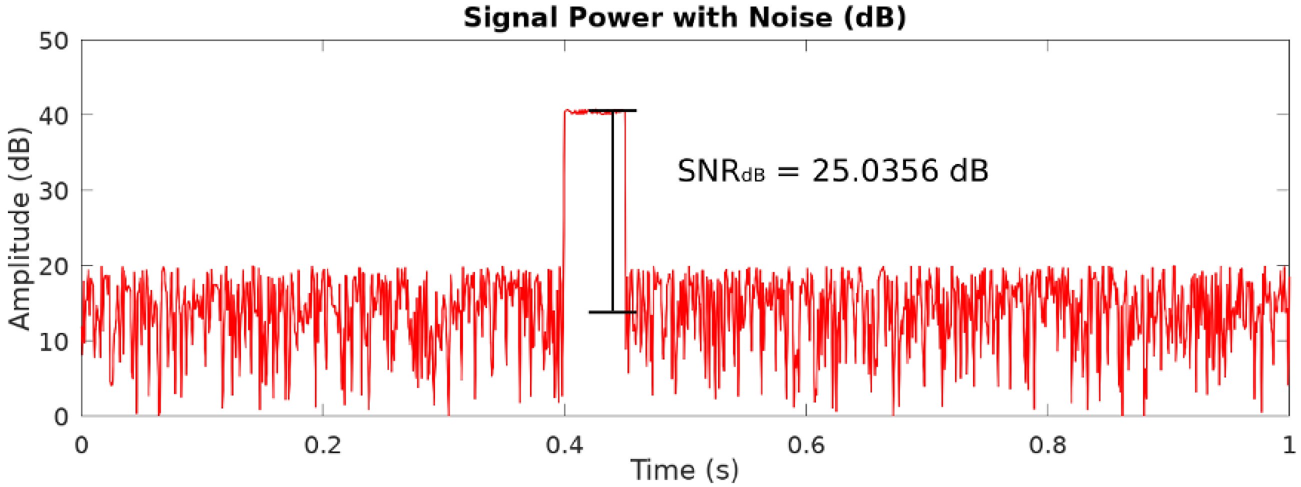
Signal Quality

(O)SNR (dB): Signal-to-Noise Ratio

- (log) ratio of *useful* signal power to *unwanted* noise power

→ Higher OSNR: cleaner signal, easier to detect!

- *Long distance amplified links create noise → higher noise floor*



Source: Flexoptix

SNR = **0dB**

→ signal and noise power are same!

(O)SNR & Bit Errors

Bit Error Rate (BER) $= \dfrac{no.\,of\ error\ bits\ received}{no.\,of\ transmitted\ bits}$

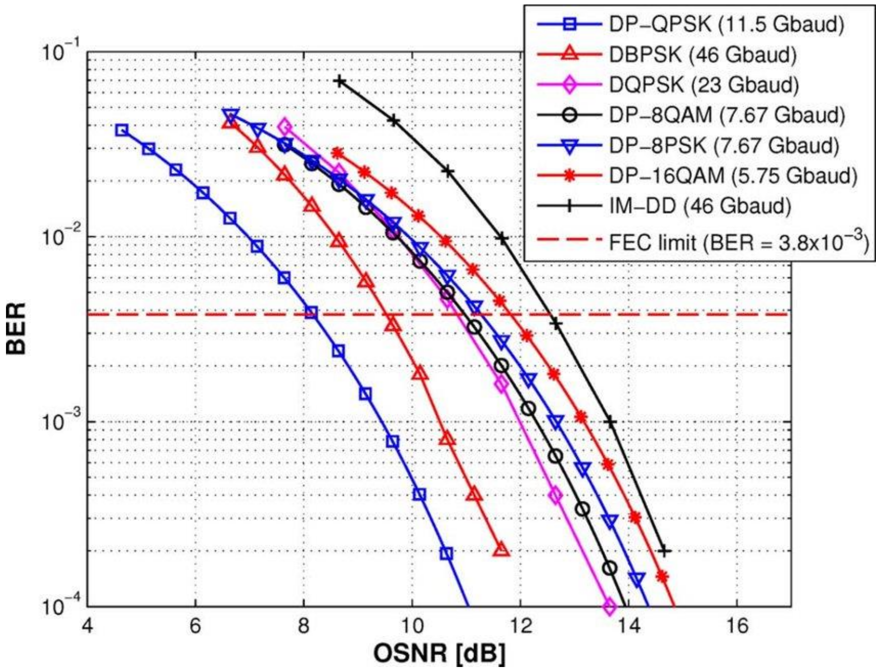
$\mathrm{BER} = 10^{-9}$

→ One error bit rx-ed for every 1 billion bits tx-ed!

(O)SNR directly affects BER:

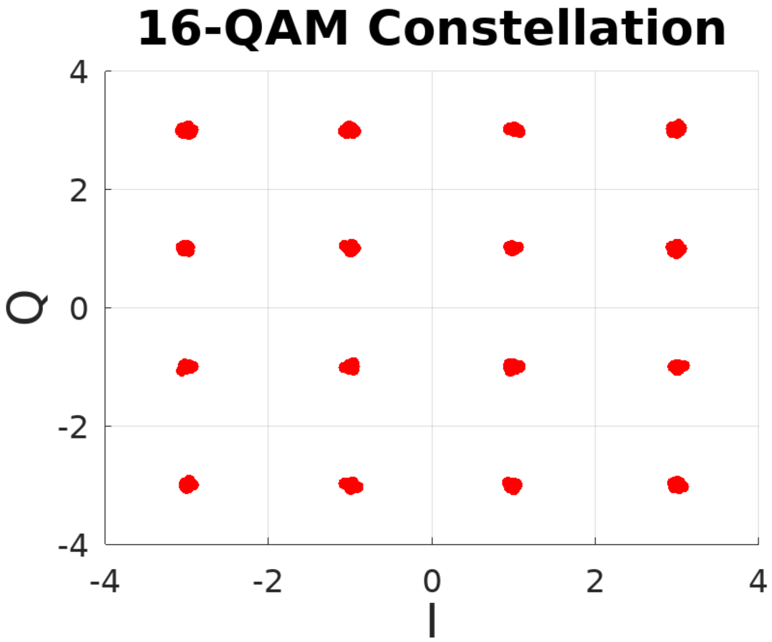
→ Higher OSNR: cleaner signal, easier to detect 0s and 1s → *Lower BER*

→ Lower OSNR: noisier signal, harder to make out 0s and 1s → *Higher BER*

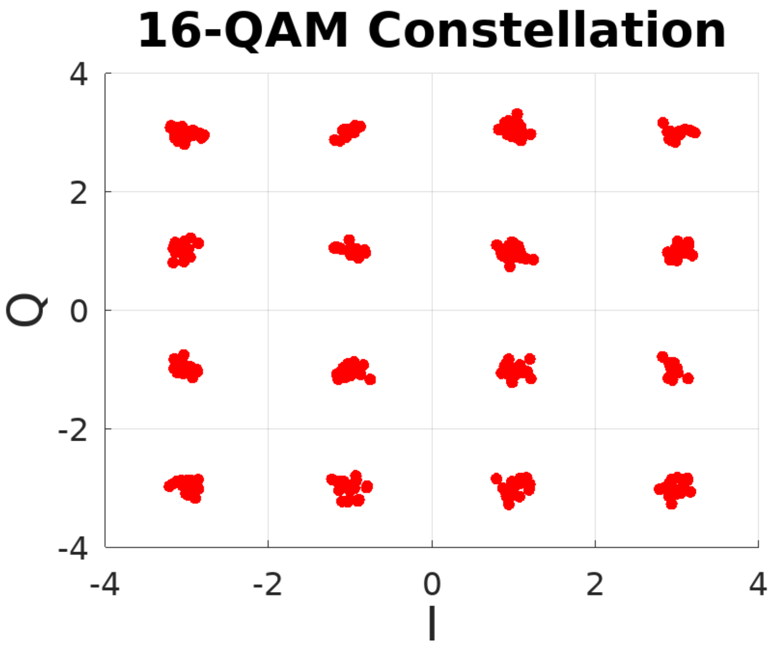


Source: ResearchGate

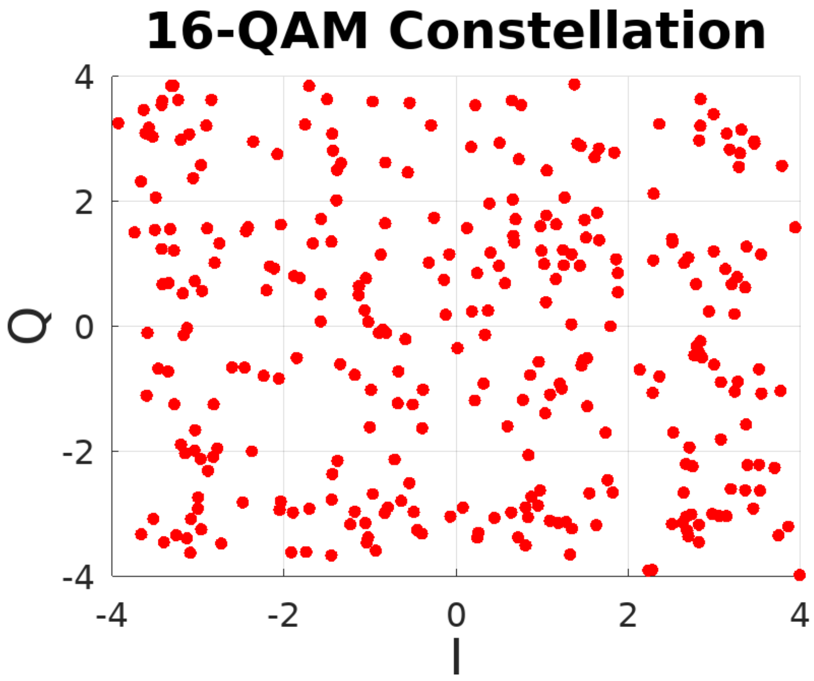
(O)SNR → Phase and Amplitude Errors



SNR = 30 dB



SNR = 20 dB



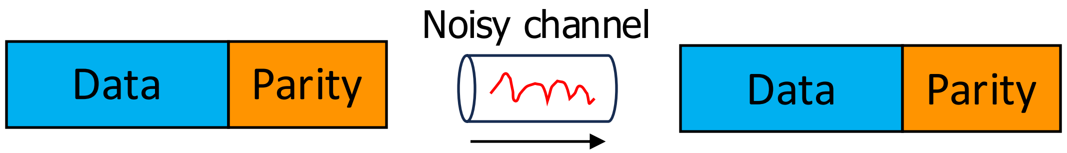
SNR = 5 dB

Source: Flexoptix

Forward Error Correction

FEC adds extra hints [redundant parity bits] to the transmitted data

→ Helps the receiver reconstruct the original message ~ without retransmission



Source: ChatGPT, Aug 6, 2025

In practice:

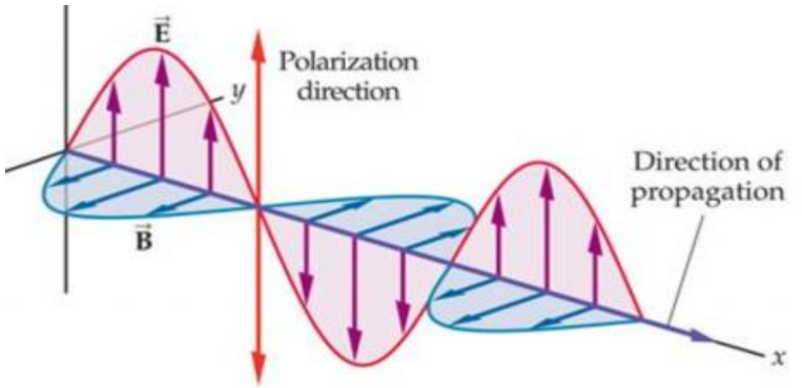
→Allows working with lower OSNR

→Go longer distance with bad signal/link quality!

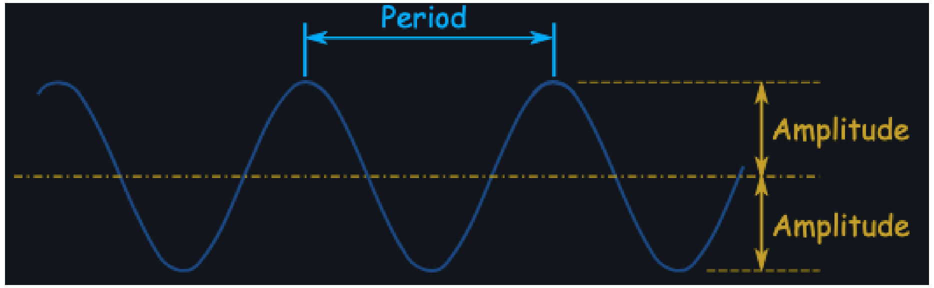
Modulation & Symbol (Baud) Rate

We still live in an analog world:

- Light → electromagnetic wave
- Digital signals (0,1) need to be encoded into analog waves



Source: Physics OpenLab



Source: MathIsFun

The rate at which we modulate a signal is "baud" rate

- *symbol rate per second*
- 10 Gigabaud (Gbaud) ~ flashing torch bright or dim 10 billion times/sec

Bit Rate & Baud Rate

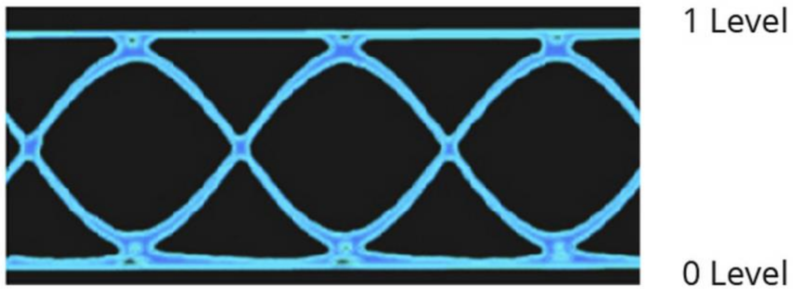
Optics began with the simplest coding schemes:

IM-DD (Intensity Modulation/Direct Detection)

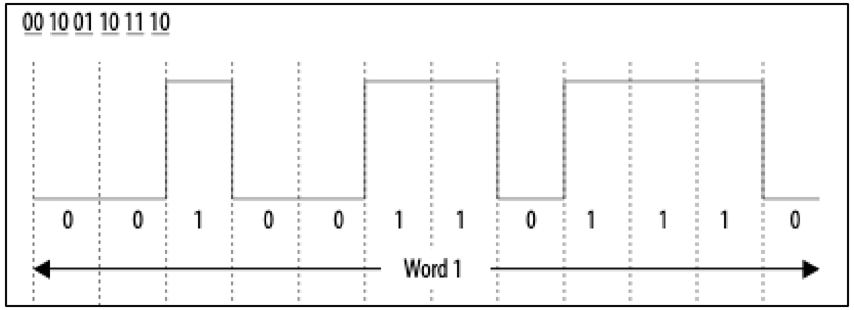
NRZ (ASK/OOK) most common

- amplitude/power of the optical wave is modulated!

- Encode one bit per transmitted symbol
  - High optical power (presence of light) - 1
  - Low optical power (absences of light) - 0



Source: Intel



Bit Rate = Baud x Modulation

Eg: 50Gbaud = 50 x 1 = 50Gbit/s

To achieve → Higher Bit Rates

Keep increasing the ***baud rate?***

- Higher baud rates *suffer due to dispersion at longer distances*
- Higher baud rates mean *wider channel sizes* → *more spectrum*

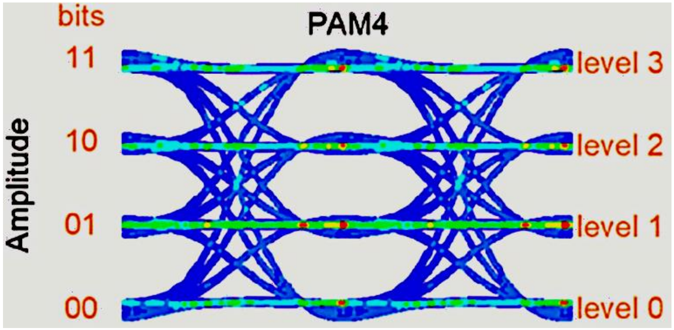
Higher Bit Rates **with Direct Detection**?

PAM4 (Pulse Amplitude Modulation 4-level)

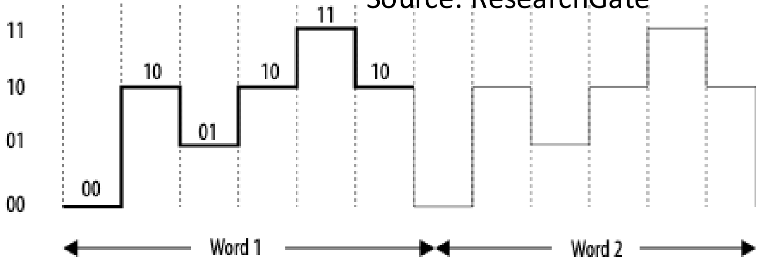
- encode 2 bits per symbol ($2^2=4$)

Bit Rate = Baud x Modulation

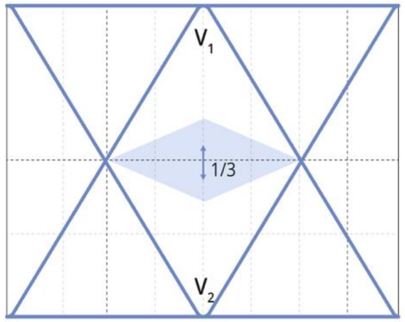
→ Eg: 50Gbaud = 50 x 2 = 100Gbit/s



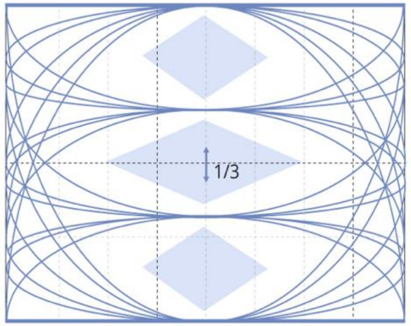
Source: ResearchGate



NRZ



PAM4



But the signal amplitude (eye):

- 1/3rd of NRZ
- Sensitive to noise → *lower OSNR* → *higher bit errors*
- Not suitable for longer distances

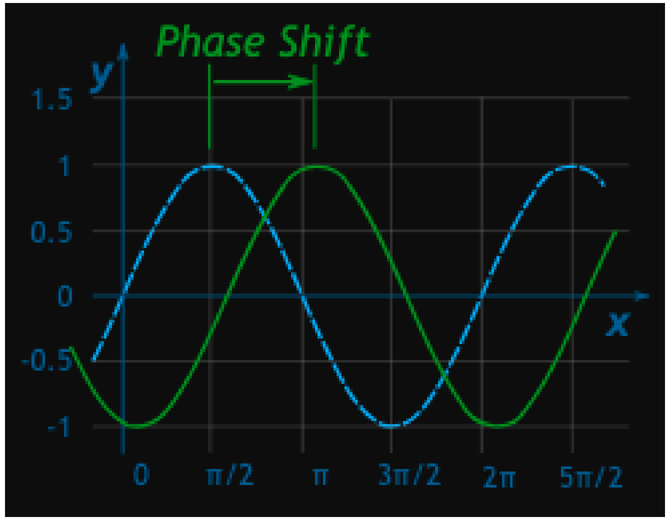
Higher Data Rates **@longer distances**?

Besides Amplitude, light also has other properties

- More properties per carrier (to encode data) → Higher the data rate

Phase

- Position of light wave in its cycle.
- We can use amplitude and phase shifts → encode more bits per symbol.



Source: https://mathsisfun.com

Phase & Amplitude

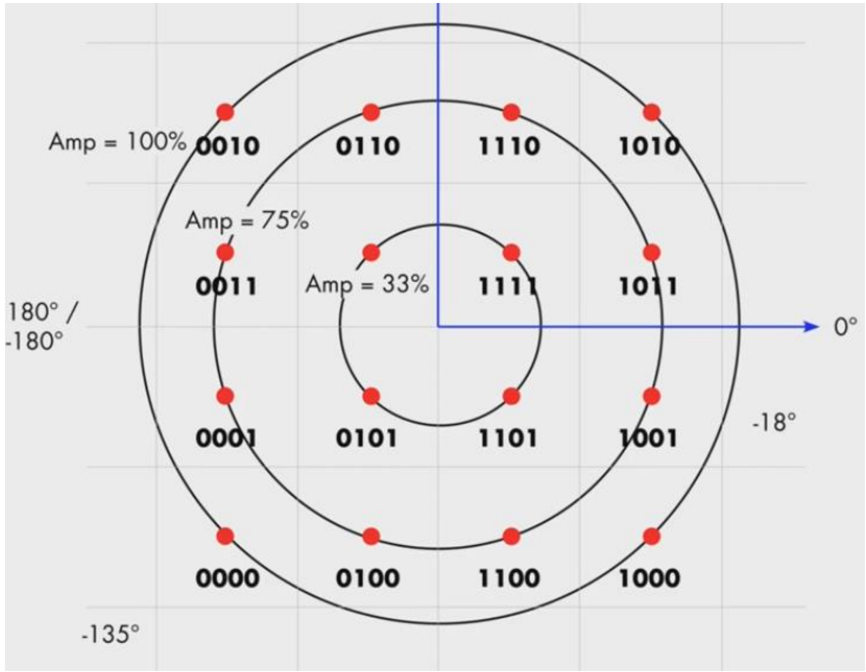
Quadrature Amplitude Modulation (QAM):

- Modulates the *amplitude* of two carrier signals → *out of phase by 90º*

16QAM

- 16 different amplitude and phase angle to encode data

[2^4 ~ encode 4 bits per symbol]

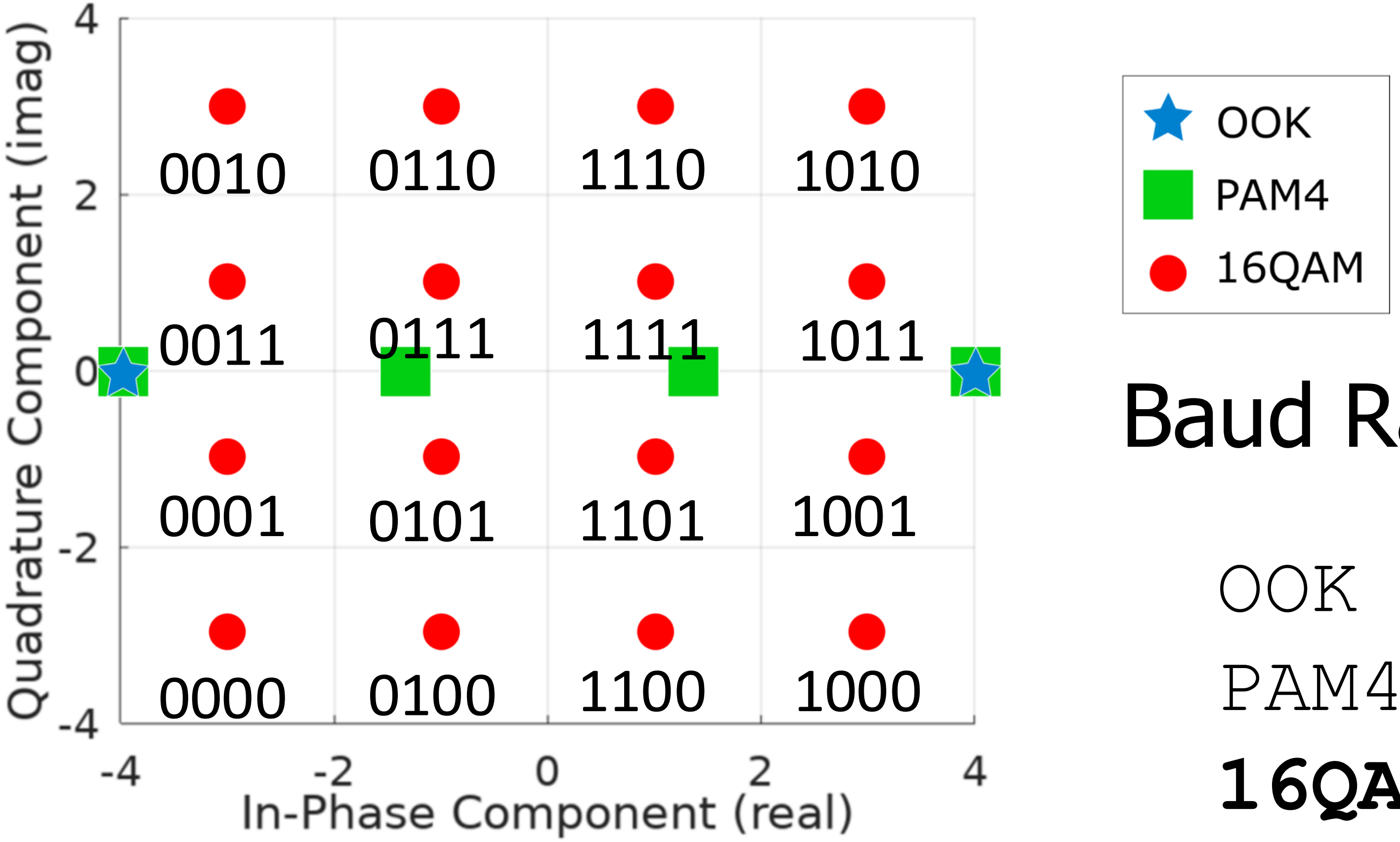


Source: Flexoptix

1111 0101 0010

Amp	Phase	Data
33%	45º	1111
33%	-135º	0101
100%	135º	0010

Bit Rate = Baud x Modulation



Source: Flexoptix

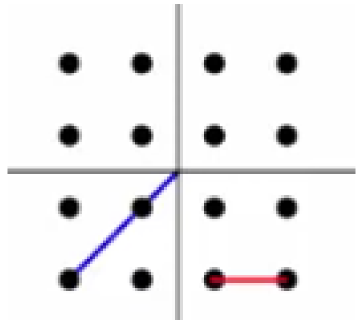
Baud Rate: 50Gbaud

```
OOK   :50x1 = 50Gbit/s
PAM4  :50x2 = 100Gbit/s
16QAM :50x4 = 200Gbit/s
```

Higher (*and higher*) order Modulations?

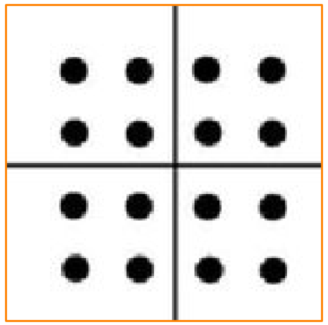
→The distance between symbols determines the *immunity to noise*

→The distance to the origin determines the required *signal power*

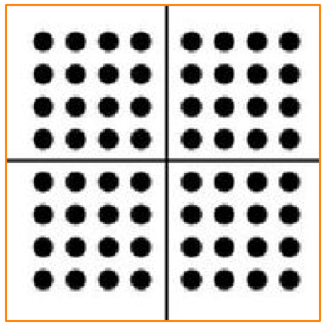


If energy of constellation to remain same, the points must be closer:

- More susceptible to noise (lower OSNR→ higher BER)
- Limits the distance/reach



16-QAM



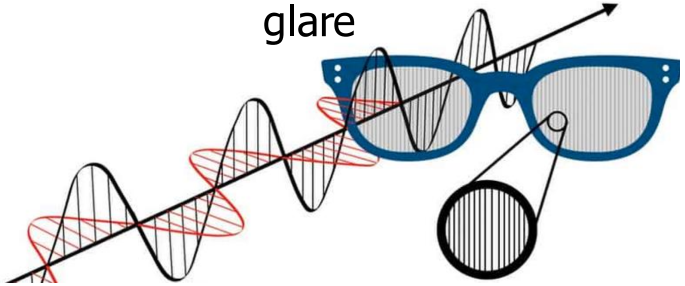
64-QAM

Hmm.. then what?

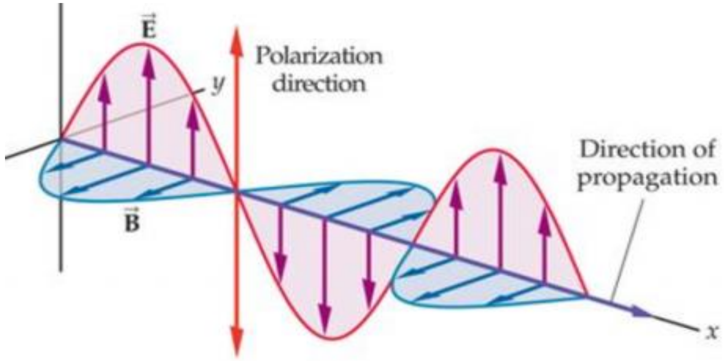
Besides Amplitude & Phase, we can also use **Polarization**

→ Direction of the Electric field (E)

Polarized lens filters out the reflected horizontal light ~ glare

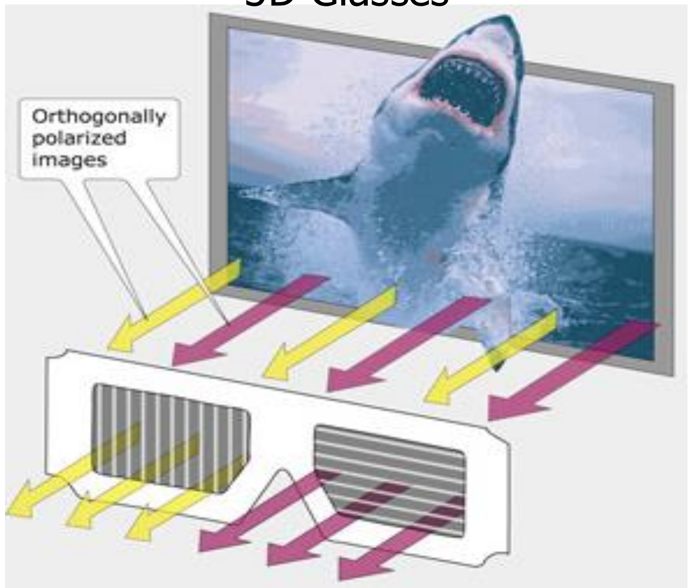


Source: Progressive Glasses



Source: Physics OpenLab

3D Glasses



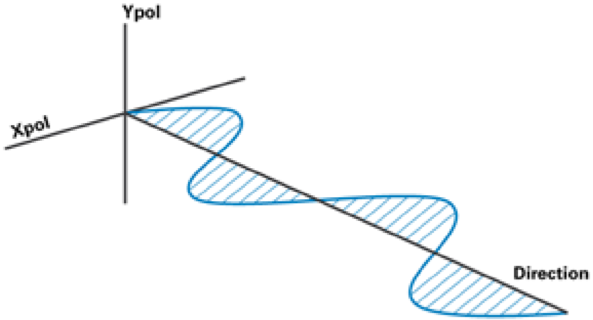
Source: Cable Wholesale

Polarization → Coherent Optics

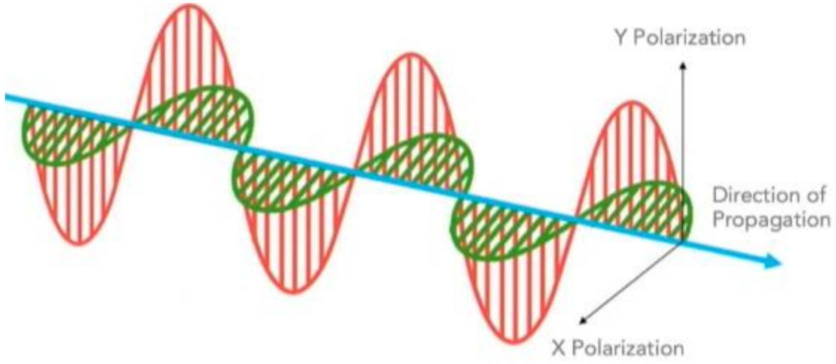
Send two independent orthogonal polarized waves

- Do not interfere → double the bit rate!

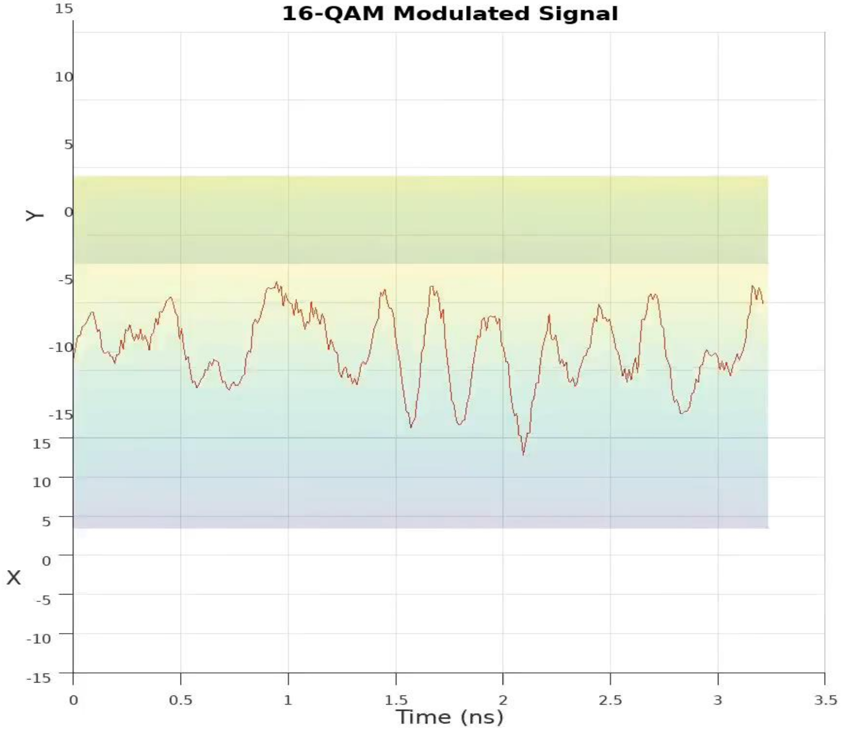
Single Polarization



Dual Polarization



Source: Shape Science



Source: Flexoptix

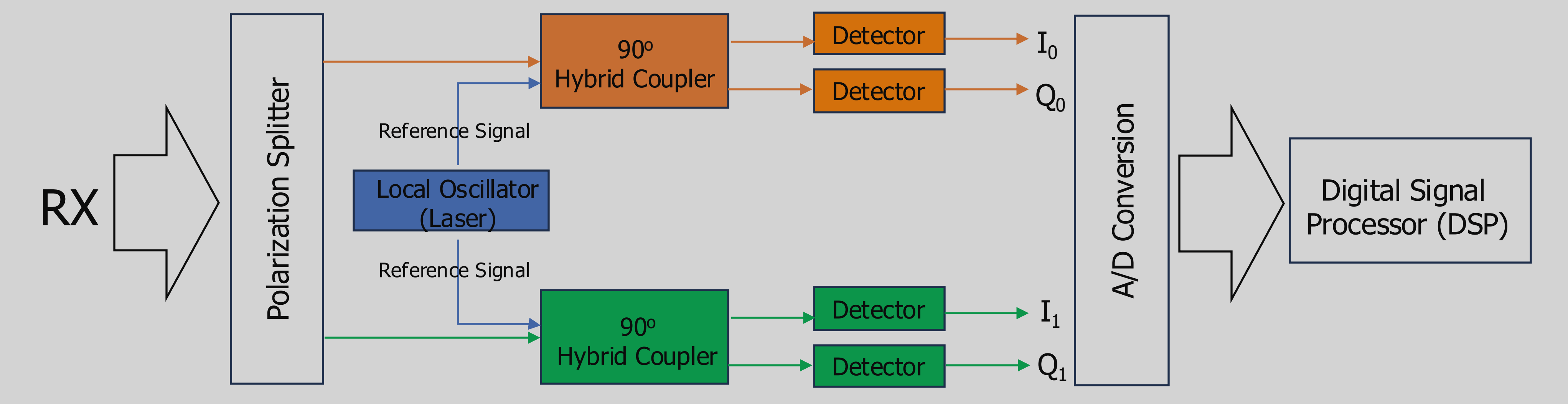
How to Decode?

Recap: direct detection receivers can ONLY detect the intensity/amplitude changes!

Need Coherent Receivers:

- Signal detection improved (gain) using a local oscillator (laser)
- The reference signal is mixed *coherently* with the incoming signal

  → Reconstruct the Amplitude and Phase information per polarization



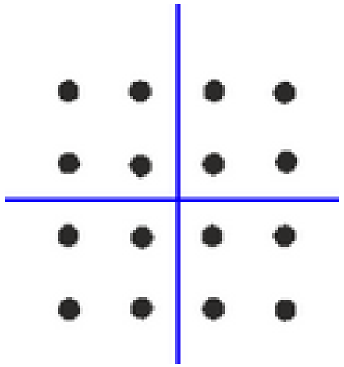
Reference: NPTEL-NOC IITM

Bit Rate = **Baud** x **Modulation** x **Polarization**

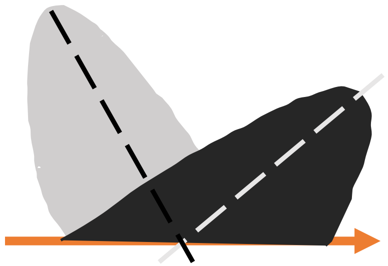
16-QAM

DP-16QAM

50 Gbaud



200 Gbit/s



400 Gbit/s

60 GBd
(75GHz)

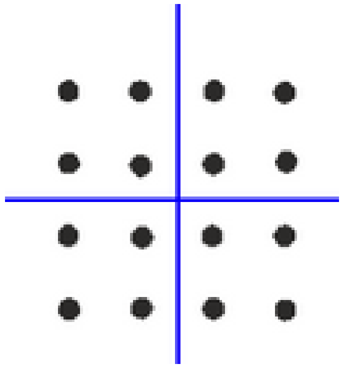
240Gbit/s

480Gbit/s
(400GbE~ 425Gbit/s)

Bit Rate = **Baud** x **Modulation** x **Polarization**

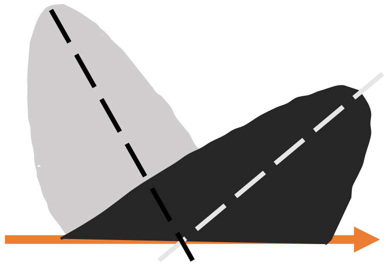
118 GBd
(150GHz)

16-QAM



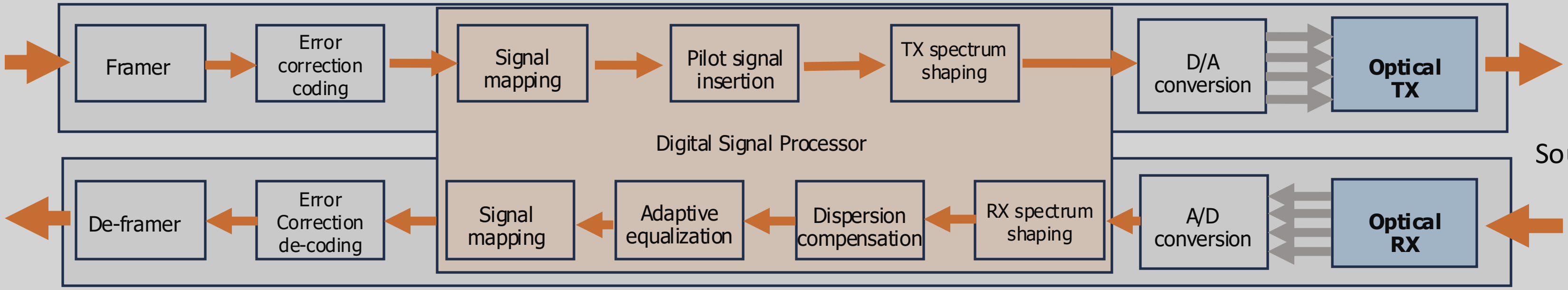
472 Gbit/s

DP-16QAM



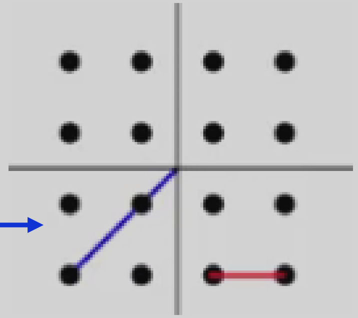
944 Gbit/s
(800GbE ~ 850Gbit/s)

DSP makes it possible!



Source: Effect Photonics

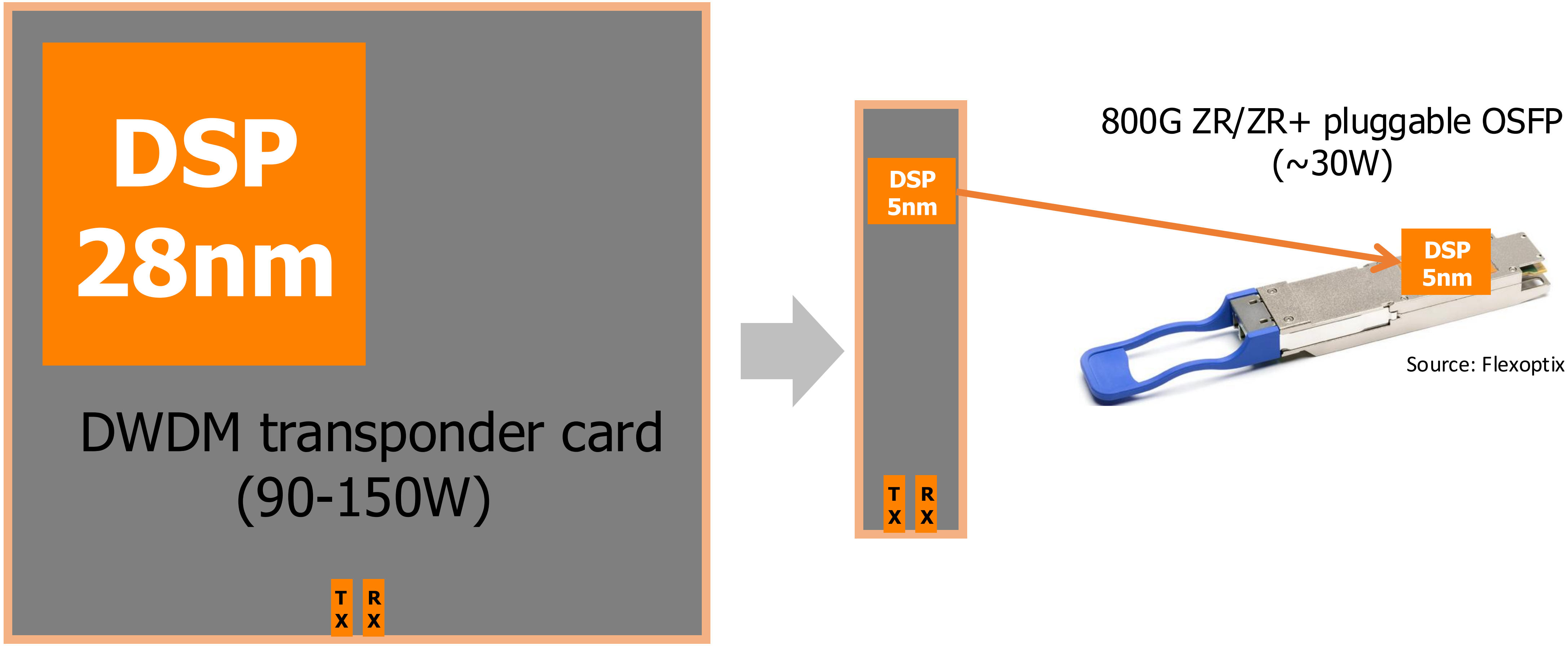
- Signal mapping:
  - encode data into/decode data from → amplitude, phase and polarization
  - Pilot signal insertion
- Error Corrections, Dispersion compensation
- (Probabilistic) Constellation shaping



- D/A conversion (vice-versa), etc

Noise-cancelling headphones ~ also auto-translates and corrects mistakes ☺

→ Coherent Pluggable Optics

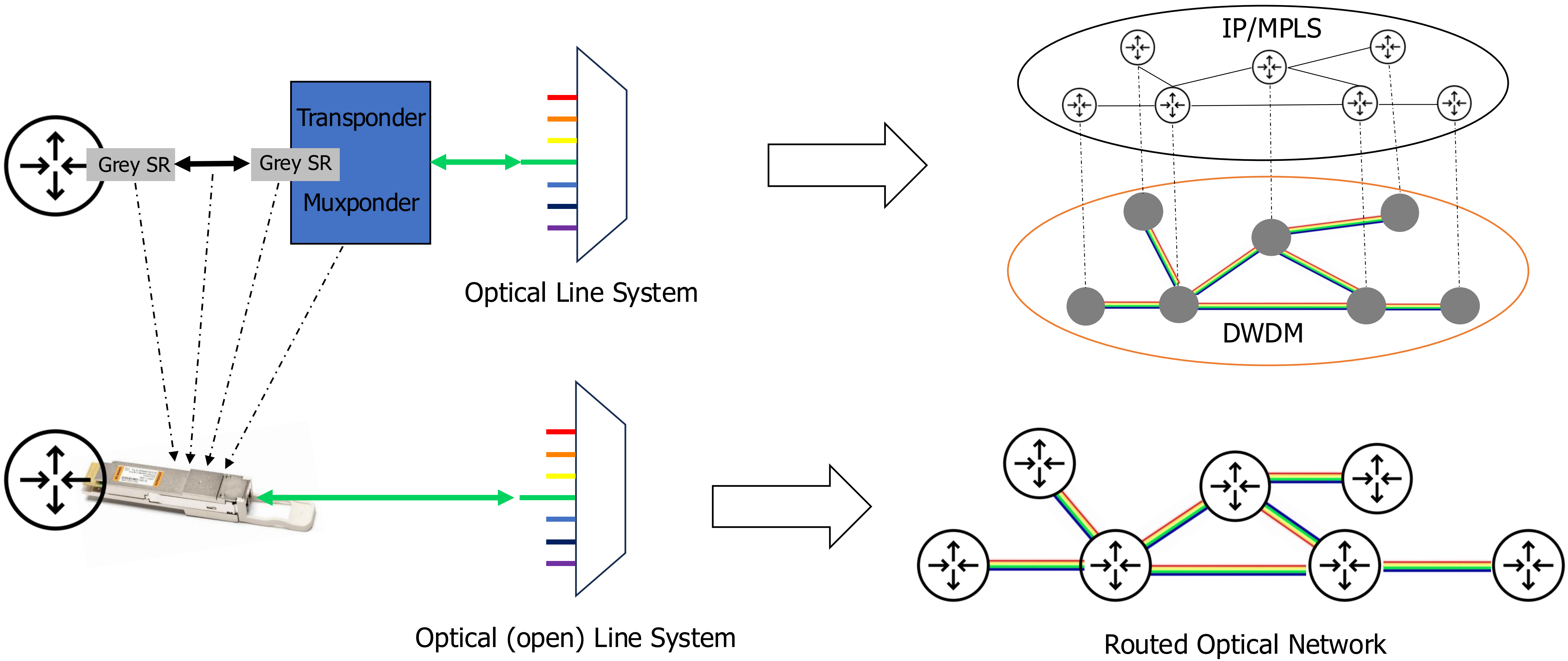


```
Current Interval [04:27:17 Mon Oct 20 2025 - 04:40:23 Mon Oct 20 2025]

Parameter           MIN          AVG          MAX
------------------------------------------------
CD(Short)[ps/nm]    1132.00      1134.57      1137.00
DGD[ps]             2.00         2.73         3.00
RX PWR[dBm]         -10.10       -8.58        -7.59
TX PWR[dBm]         -4.03        -3.99        -3.95
OSNR[dB]            26.30        26.63        26.90
RX CHAN PWR[dBm]    -13.04       -11.19       -9.93
ESNR[dB]            15.30        15.58        15.70
LASER BIAS[mA]      223.09       223.09       223.09
FREQ OFF[Mhz]       404.00       419.92       436.00
SOP RATE[krad/s]    0.00         0.00         0.00
PDL[dB]             0.40         0.50         0.60
SOPMD[ps^2]         39.00        58.35        84.00

EC BITS   : 3841784457486
UC WORDS  : 17794933

Parameter           MIN        AVG        MAX
---------------------------------------------
PREFEC BER          6.18e-03   6.66e-03   7.50e-03
POSTFEC BER         0.00e+00   0.00e+00   0.00e+00
Q FACTOR[dB]        7.70       7.83       7.90
Q MARGIN[dB]        0.70       0.91       1.00
```

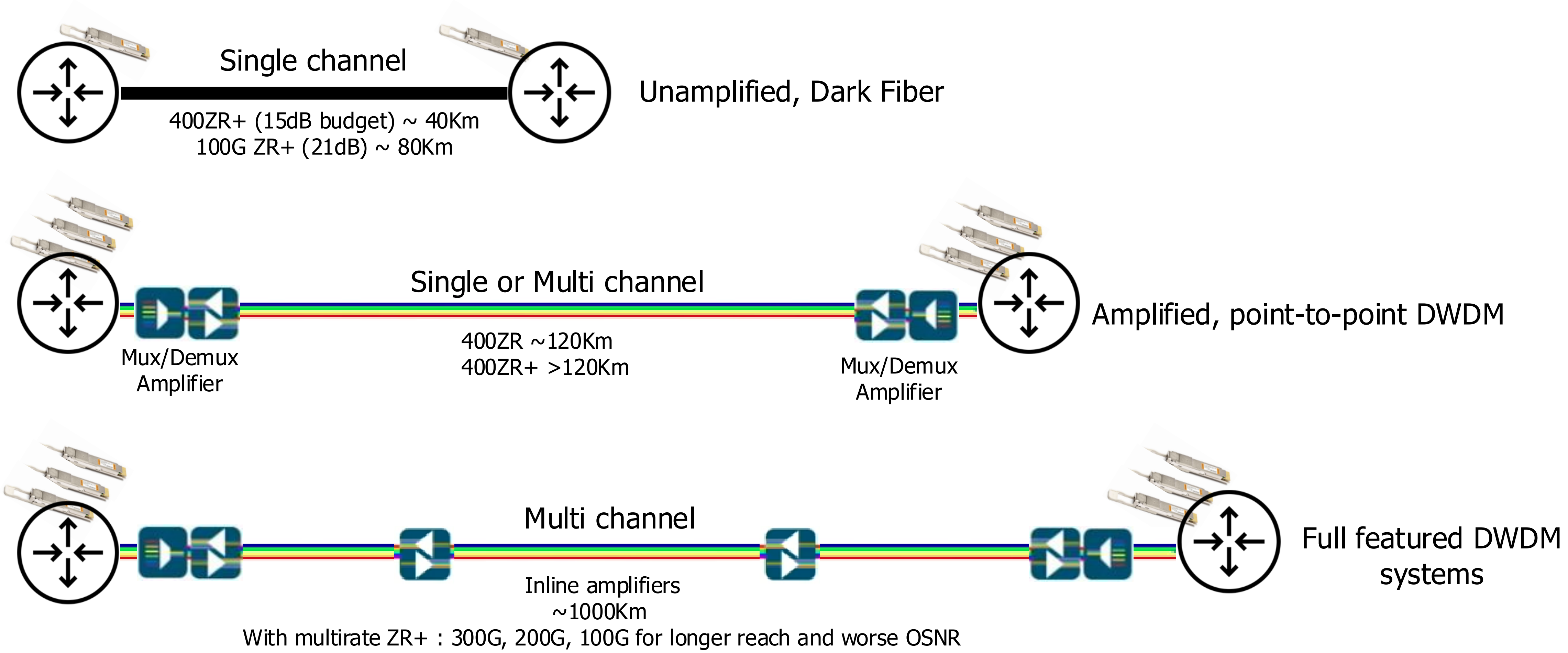
Visible on Routers & Switches

Source:
DrukREN 400G ZR+ test (October 2025)

Coherent Pluggables → IPoDWDM



Coherent Pluggables → IPoDWDM



Source: https://www.flexoptix.net/en/blog/400g-zr

OIF 400ZR and OpenZR+ MSA

	OIF 400ZR	OpenZR+ MULTI-SOURCE AGREEMENT
Reach	~120Km	> 120Km
Client	400GbE Only	100-400GbE multirate
Application	Campus, Metro	DCI, Regional, Long-haul
FEC	C-FEC	oFEC
Max Power	~15-20W	~18-20W
Form factor	QSFP-DD/OSFP	QSFP-DD/OSFP
Max TX power	-6dBm	-10dBm/0dBm
Min RX sensitivity	-12dBm	-12dBm
CD tolerance	2400 ps/nm	20000 ps/nm
PMD tolerance	10 ps	20 ps
OSNR tolerance	26dB	24dB


LESS
CONFUSION
MORE
CLARITY

Reference

1. “Coherent optical transceivers - current capabilities and future possibilities”, Thomas Weible & Gerhard Stein - Flexoptix, CSNOG (February 2024)
2. “Everything You Always Wanted to Know About Optical Networking – But Were Afraid to Ask”, Richard Steenbergen - Petabit Scale, NANOG89 (October 2023)
3. OIF-400ZR-01.0 - https://www.oiforum.com/wp-content/uploads/OIF-400ZR-01.0_reduced2.pdf
4. What are FEC and PCS, and Why do They Matter? https://effectphotonics.com/insights/what-are-fec-and-pcs-and-why-do-they-matter/
5. What's inside a coherent DSP – EffectPhotonics https://effectphotonics.com/insights/whats-inside-a-coherent-dsp
6. 400G ZR Operation Modes – FLEXOPTIX https://www.flexoptix.net/en/blog/400g-zr
7. “Managing Digital Coherent Optics on Routers”, Phil Bedard – Cisco, NANOG87 (February 2023)