Optics 101
for
non-Optical (IP) folks

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Optical Power

Intensity of light→ *brightness*

Decibel (dB) is a log ratio between two values

-10dB: 1/10th the signal, **-20dB**: 1/100th the signal…

- But 1/10th of what?

We need a reference for an absolute value

- In optics, that is **dBm**: *decibel relative to 1mW of power*

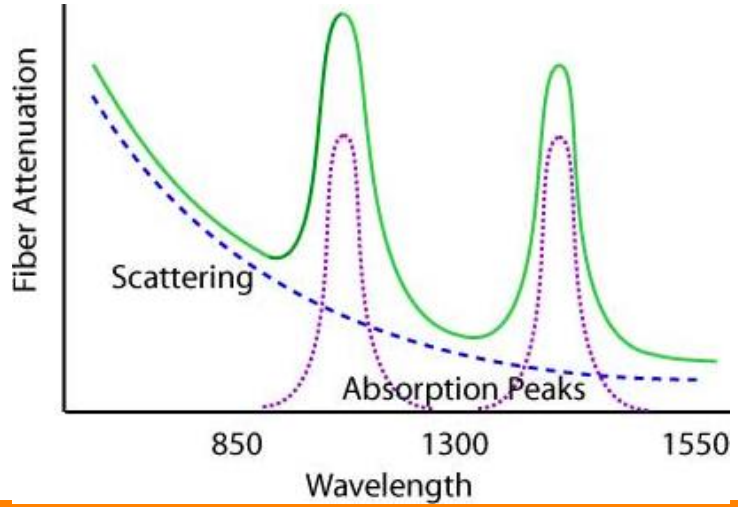
$$P(dBm)=10\log_{10}(P(mW)/1mW)$$

→ 0dBm = 1mW; 3dBm = 2mW; -10dBm = 0.1mW

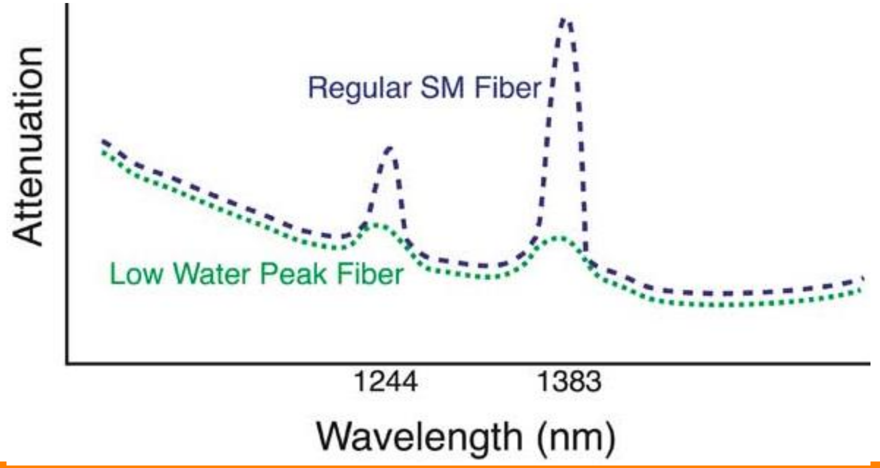
Attenuation

Energy lost as light travels through fiber – *attenuation*

- Attenuation coefficient: **dB/Km** (power loss per unit length)
- *Scattered* by imperfections in the fiber (*shorter λs*)
  - Some escape out of the core
  - Some travel back to the source (this backscatter is what your OTDRs see)
- *Absorbed* by residual OH+/dopants, dissipated as heat (*longer λs*)



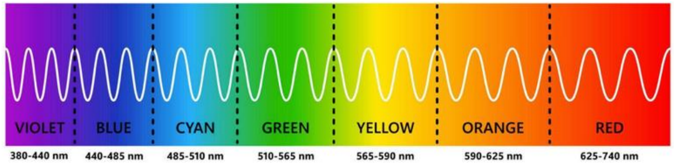
Source: https://foa.org/



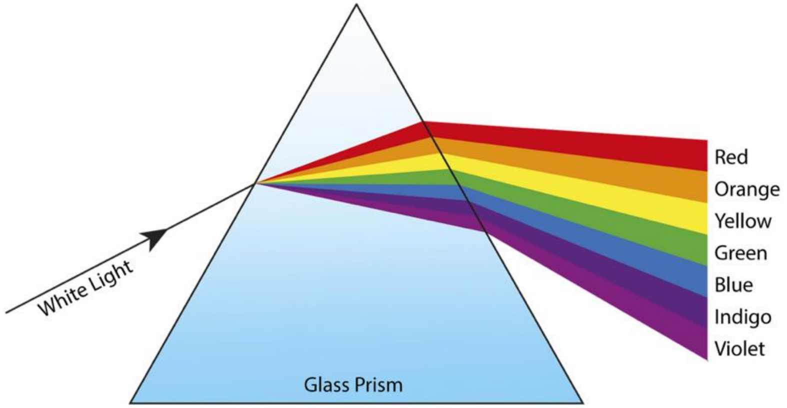
Chromatic Dispersion

Different colours of light (**f** or **λ**) travel at different speeds

- Longer wavelengths bend less → travel faster
- Longer the distance, bigger the time difference ~ **spread**
- CD measured in **ps/nm**



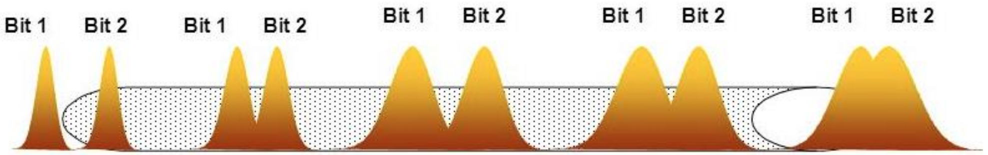
Source: VectEzzy



Source: KeyStageWiki

Problem with dispersion:

- As light pulse becomes wider, they *overlap each other*
- The receiver may not be able to recognize the two signals ~ ***bit errors!***
- Limits bit rate or the distance for a specific bit rate



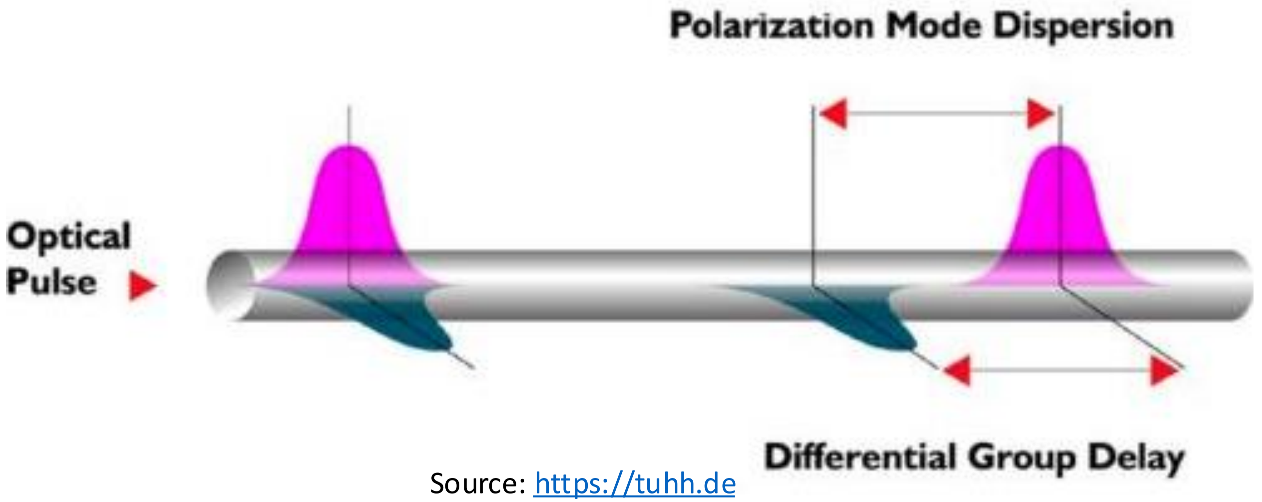
Source: https://foa.org/

Polarization Mode Dispersion

PMD is caused when light of one polarization arrives at different time than the other

- Usually caused by imperfections in the shape of fiber – cylindrical

- Broadens the light pulses → bit errors
- Measured as Differential Group Delay in **picoseconds (ps)**



Source: https://tuhh.de

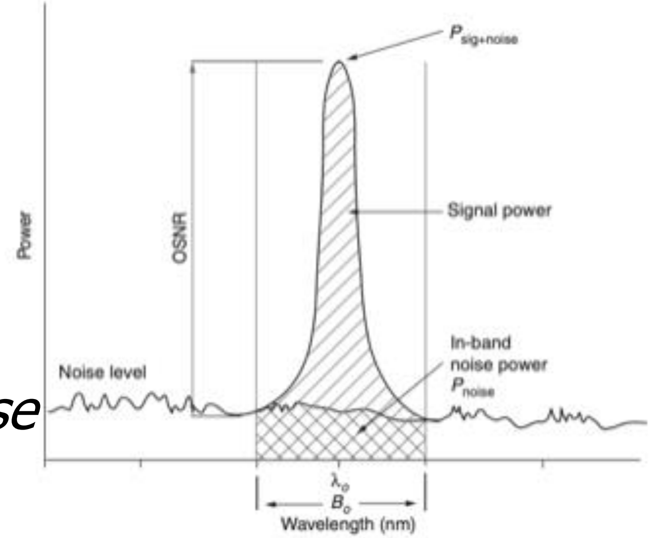
Signal quality?

SNR (dB):

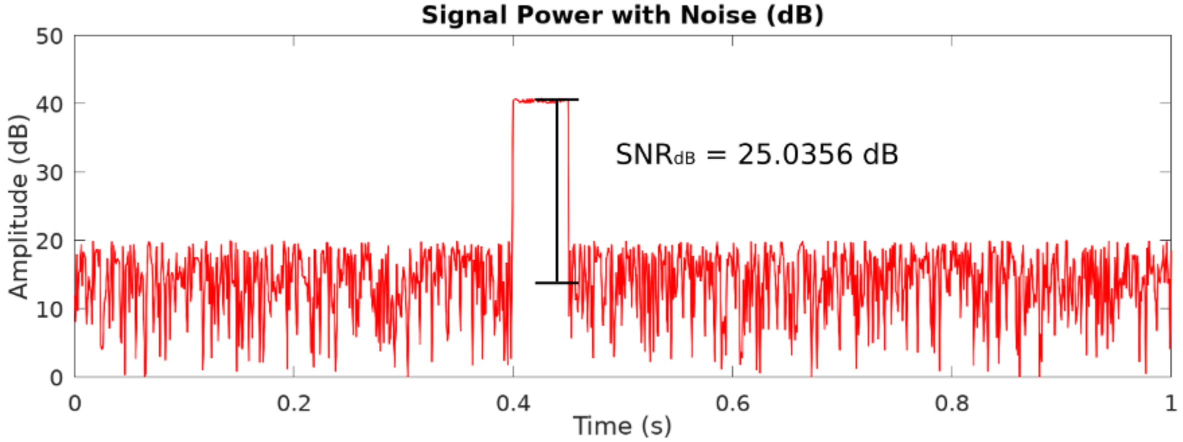
- log ratio of signal power to noise power

  $OSNR(dB) = 10\log_{10}(Signal\ power/Noise\ power)$

- *Higher the better!*
- Long distance amplified links, you amplify noise too → *higher noise floor*



Source: https://mapyourtech.com



Source: Flexoptix

SNR = **0dB**

- signal and noise power are same!
  → cannot detect/recover at RX

SNR & Bit Errors

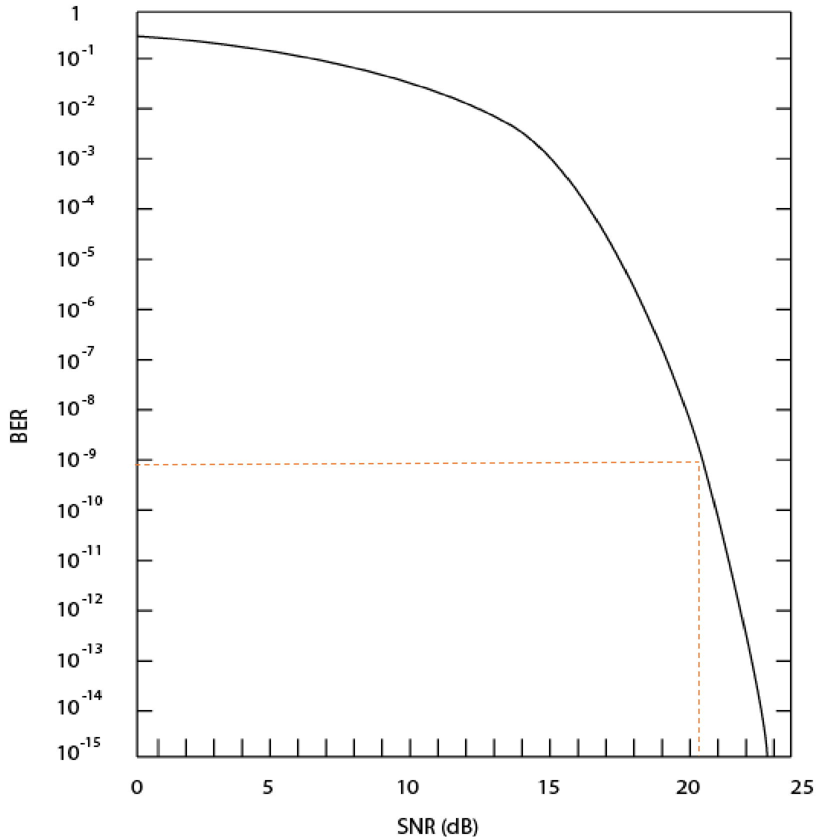
Bit Error Rate (BER) $= \frac{no.of\ error\ bits\ received}{no.of\ transmitted\ bits}$

Example: $\mathrm{BER} = 10^{-9}$
→ *One error bit received for every 1 billion bits transmitted!*

OSNR directly affects BER: $BER = (\frac{2}{\pi SNR})^{½}\, e^{-(SNR/8)}$

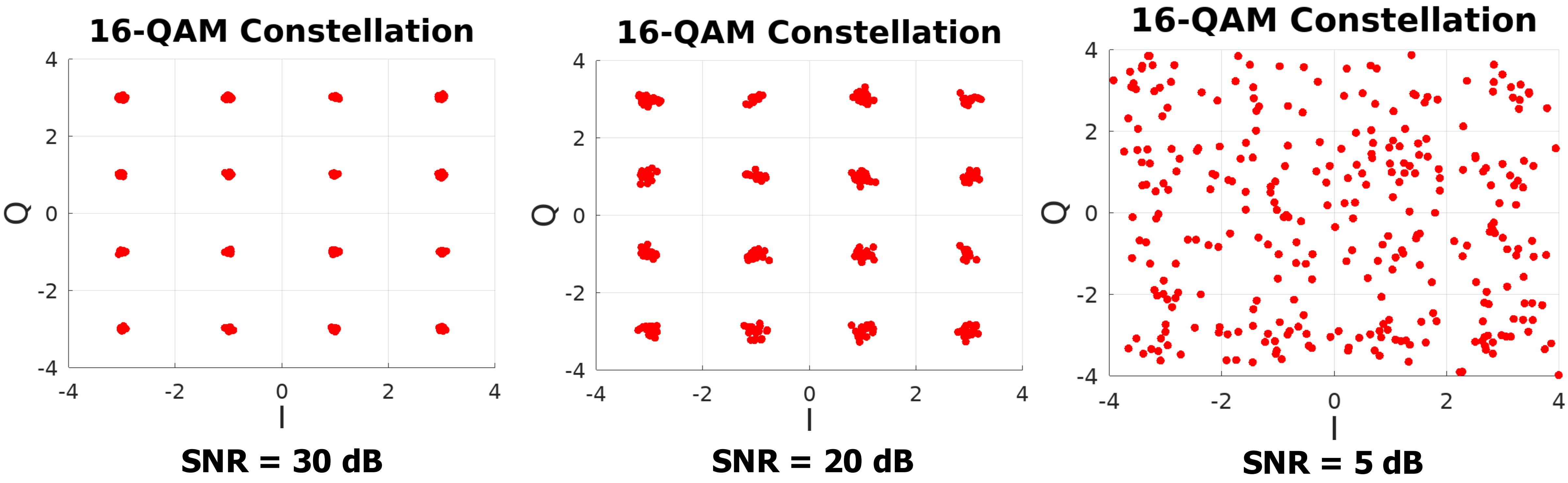
→ *As the SNR improves, BER decreases (and vice versa)!*

Example:
→ To achieve a $BER = 10^{-9}$ the equation predicts an SNR ~ $21dB$



Source: FOSCO

OSNR → Phase and Amplitude errors

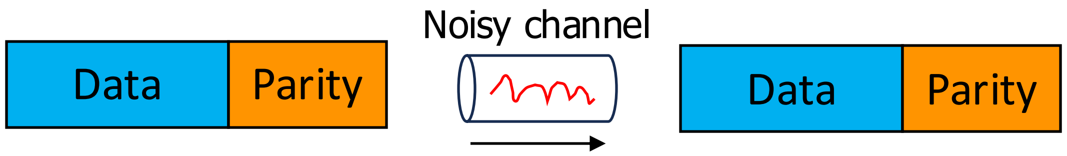


Source: Flexoptix

Forward Error Correction

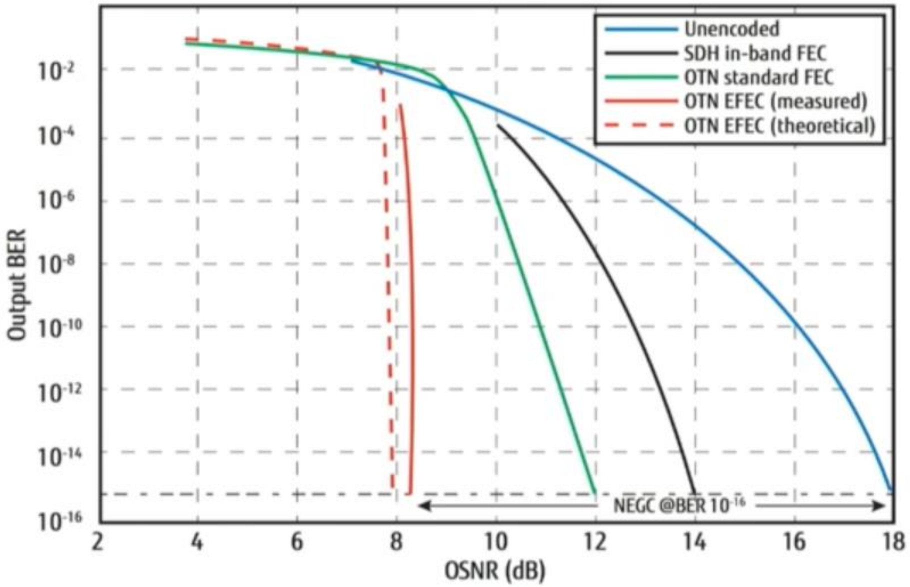
FEC adds redundant/extra (parity) bits to the transmitted data

→ contains enough info about the actual data, to reconstruct the original message at RX



In practice:

- Allows working with lower OSNR → go longer distance with bad signal quality!
  - Example: padding 10.3Gbps link to 11Gbps (~7% padding), extend the signal from 80Km to 120Km
- *Sacrifice bandwidth for reach*

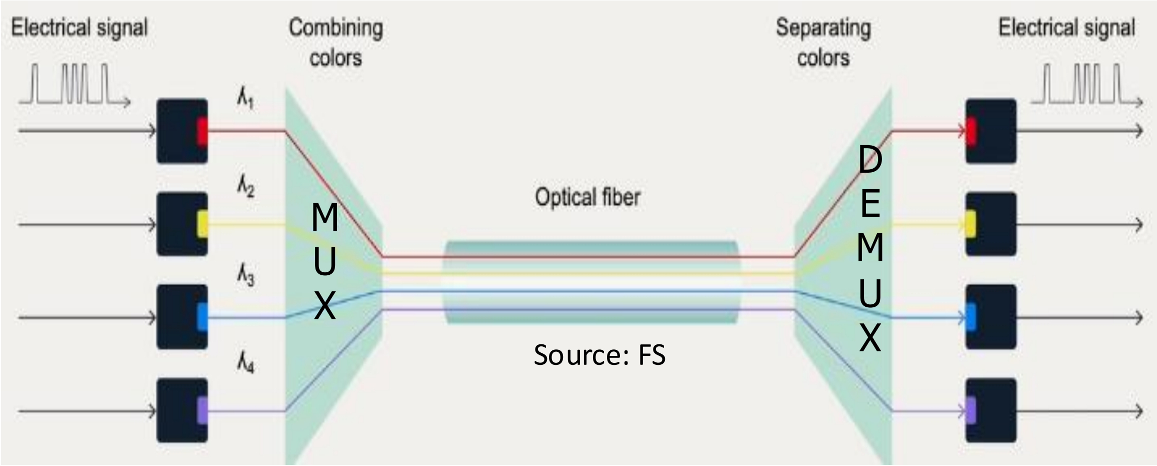


Coding gain with FEC (Source: ictbaike.com)

Wave Division Multiplexing (WDM)

Carry different colours of light on the same fiber

- Parallel transmission of data streams - on different wavelengths - without interference!

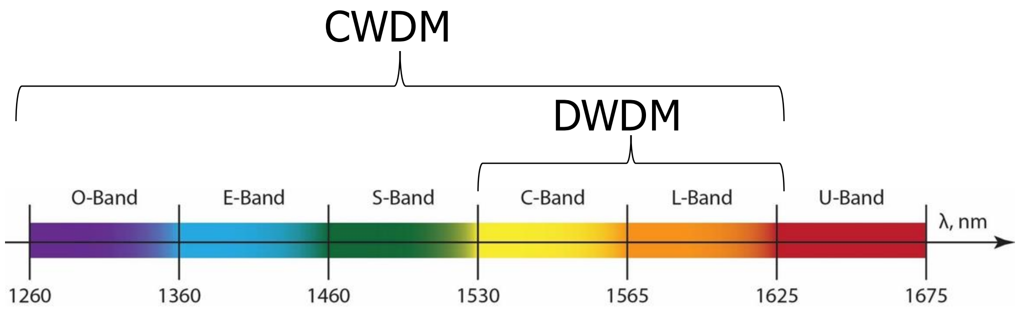


CWDM: Coarse WDM

- 20nm spacing
  - 1470-1610nm channels (*1270-1450nm with low water peak)*

DWDM: Dense WDM

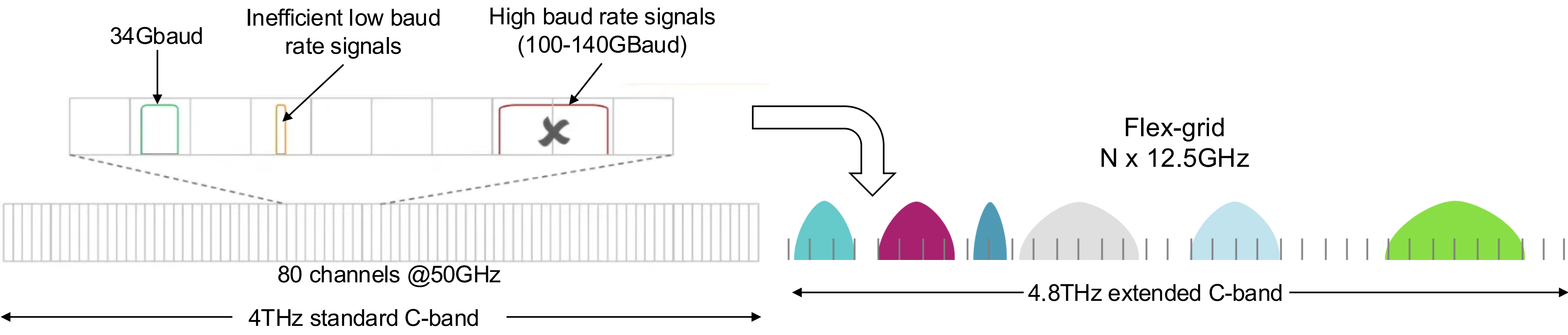
- Mostly in C-band (L-band being discussed)
- 0.1nm(12.5Ghz), 0.2nm(25GHz), 0.4nm(50GHz), 0.8nm(100GHz)
  - 40 channels with 100GHz (0.8nm)
  - 80 channels with 50GHz (0.4nm)



Flex-Grid

Flexible frequency grid

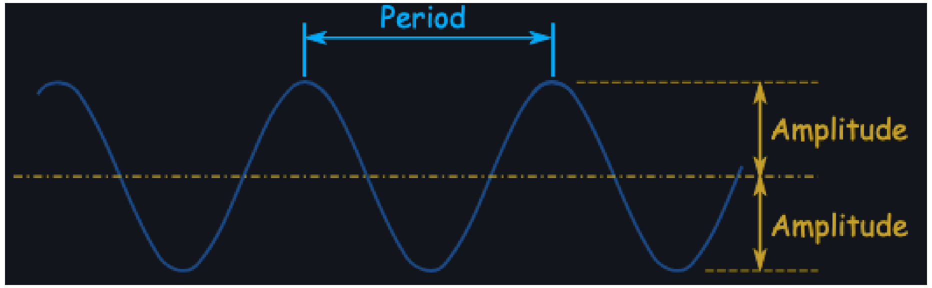
- Do away with the fixed grid (slots) approach
- Create flexible sized slots (N x 12.5GHz)
- Each flexible slot can be rightsized for the signal (baud rate) it is carrying!
- Reduces "stranded' spectrum ~ supports adaptive baud rates.



Modulation

We still live in an analog world:

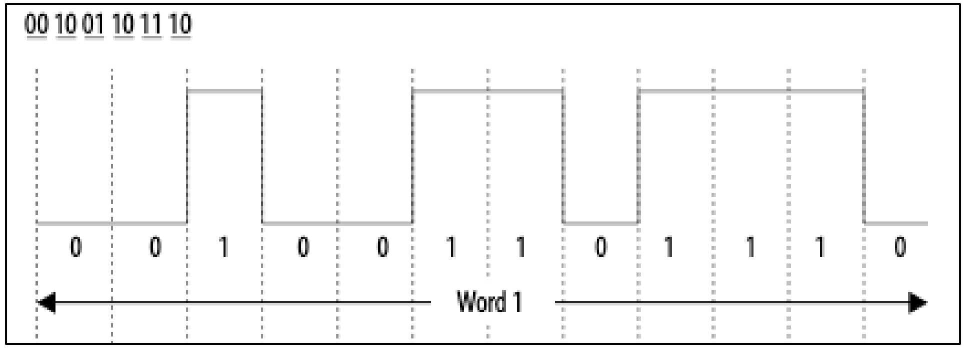
- Light ~ electromagnetic wave
- Digital signals (0,1) need to be encoded into analog waves



Source: MathIsFun

Optical transport began with the simplest coding schemes: **IM-DD** *Intensity Modulation (Direct Detection)*

- NRZ (non-return-to-zero) most common
  - ASK (amp shift keying) ~ OOK (On/Off keying)
  - amplitude/power of the optical wave is modulated!
- Each transmitted *symbol encoded with one bit*
  - Lower optical power for 0
  - High optical power for 1

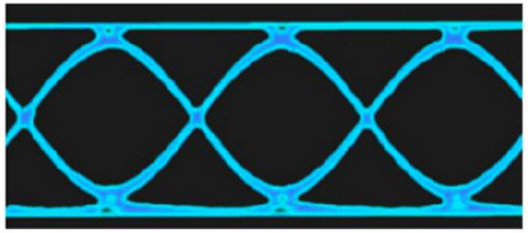


Source: Intel

Symbol Rate & Bit Rate

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

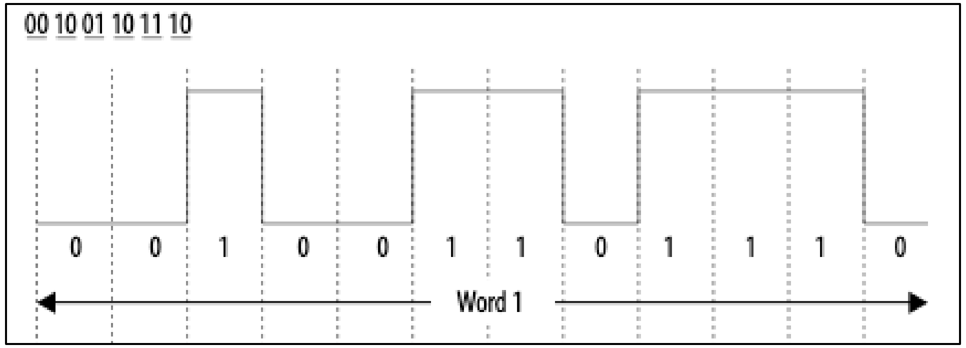
- *symbol rate per second*
- 10Gigabaud ~ flashing bright or dim 10 billion times/sec



NRZ: 1 bit per clock cycle

With NRZ (OOK/ASK)

- the **symbol rate** is equal to the **bit rate**
  → 10Gigabaud = 10Gbit/s



Source: Intel

Scaling the baud rate can only go so far:

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

Higher data rates with baud limit?

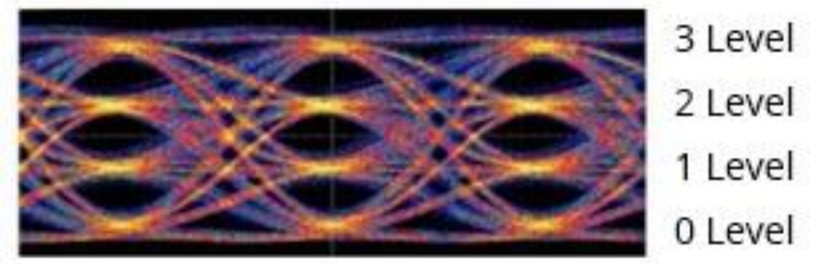
How do we get higher data rates with direct detection?

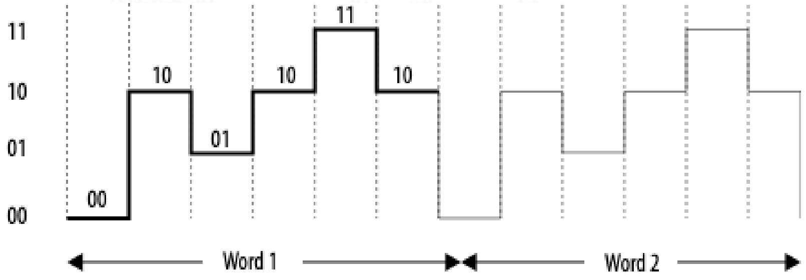
PAM4: Pulse Amplitude Modulation 4-level

- encodes *2 bits per symbol* ($2^2=4$)

- for the same baud rate, *bit rate* is 2x that of NRZ

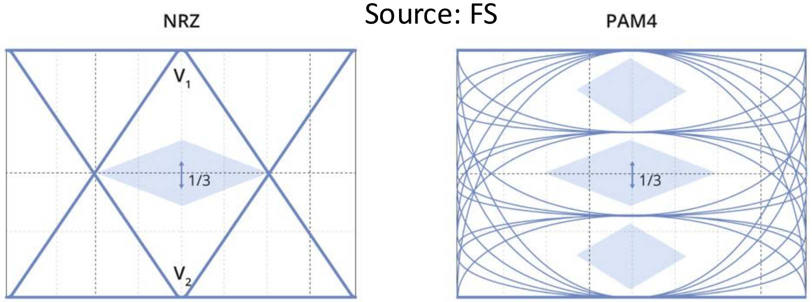
Example: 50Gbaud → NRZ: 50x1 = 50Gbps, but PAM4: 50x2 = 100Gbps





But the signal amplitude (eye) is 1/3rd (33%) of NRZ

- Sensitive to noise → lower *SNR* → higher bit errors
- Not suitable for longer distances (> 40km)

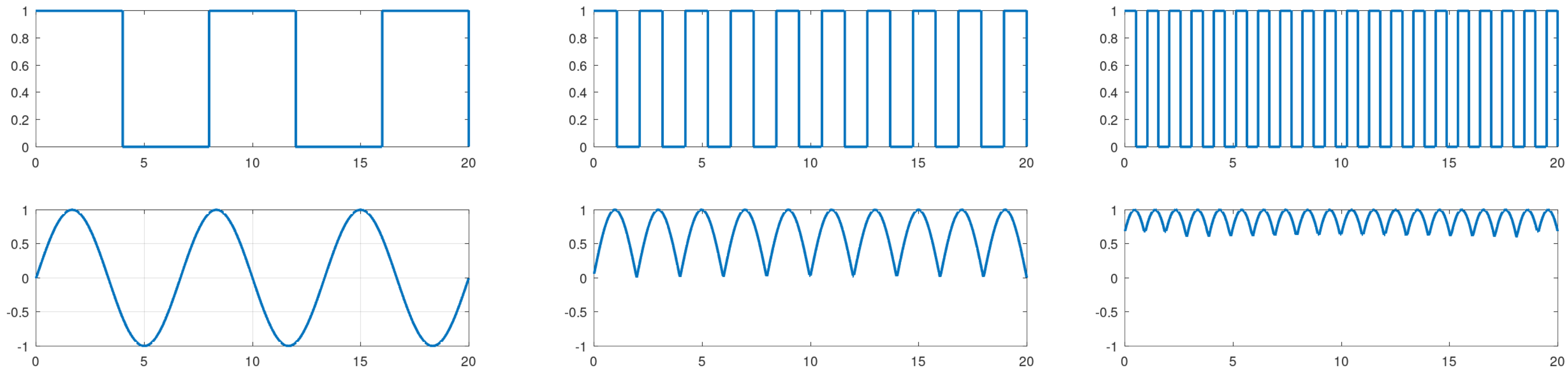


Source: FS

Direct detection transceiver limits

At higher speeds (frequencies)

- Dispersion effects cause → pulses to get closer together and start overlapping
- Difficult for photodiodes to correctly detect each pulse at the RX



Higher data rates at longer distances?

Besides Amplitude, light also has other properties

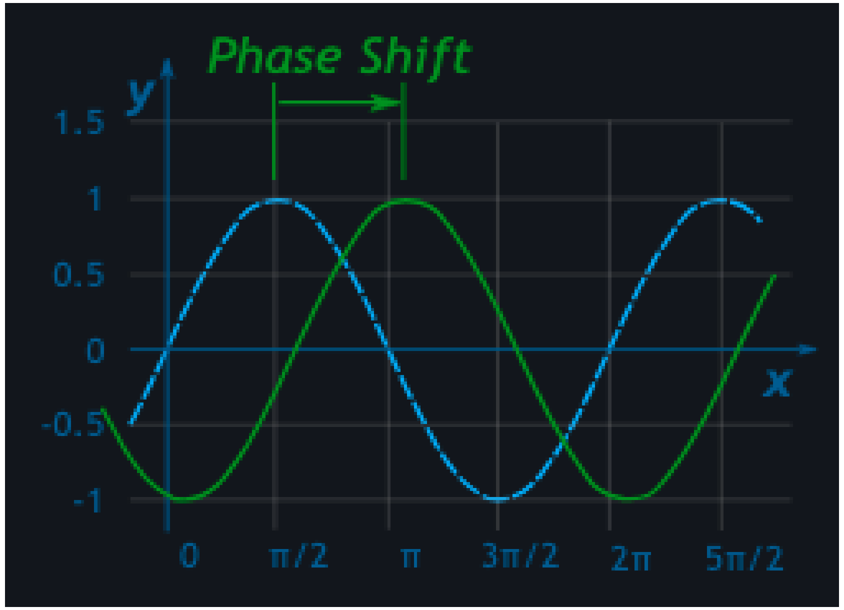
- *More properties per carrier → Higher data rate*

Phase

- We can combine *amplitude* and *phase shifts* to encode more bits per symbol.

➔ Coherent waves:

- *same frequency* and a *constant phase difference*



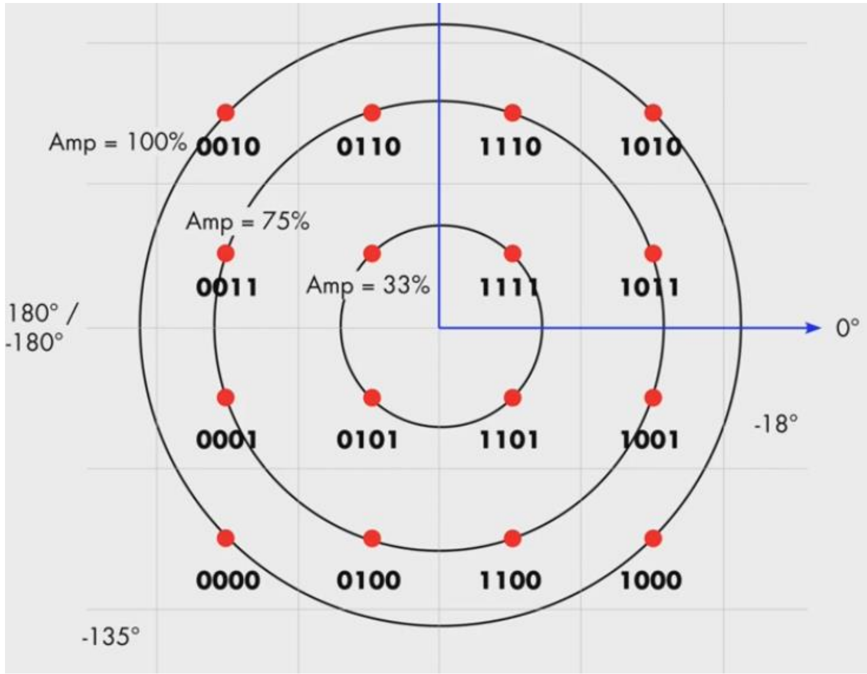
Source: https://mathsisfun.com

Phase & Amplitude → Coherent

QAM: Modulates the *amplitude* of two carrier waves/signals → *out of phase by 90°*

16QAM

- encodes 4 bits per symbol
  - 16 level modulation
- For every symbol there is an → amplitude and phase angle

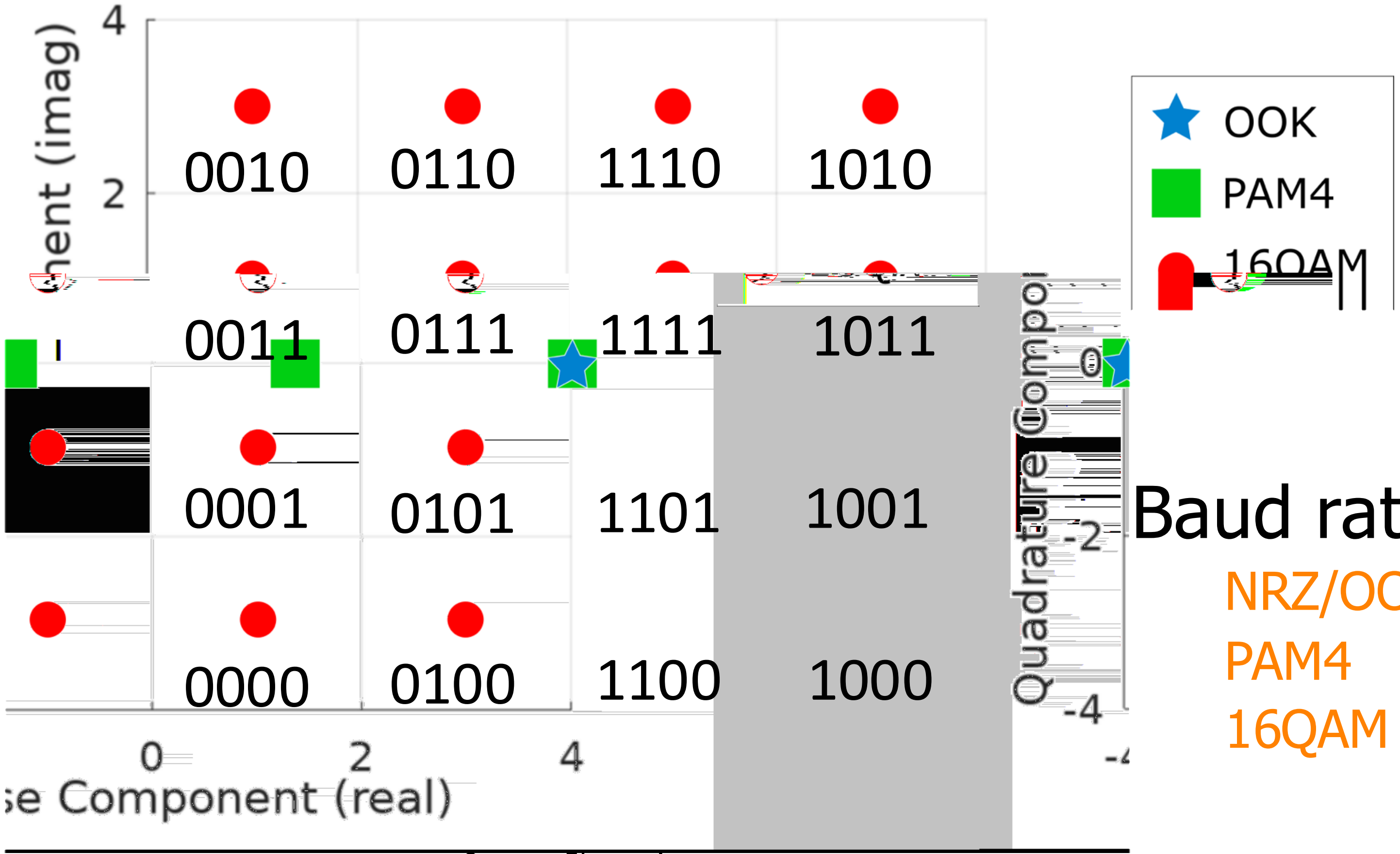


Source: Flexoptix

1111 0101 0110

Amp	Phase	Data
33%	45°	1111
33%	-135°	0101
75%	135°	0110

Bit rate = Baud x Modulation



Source: Flexoptix

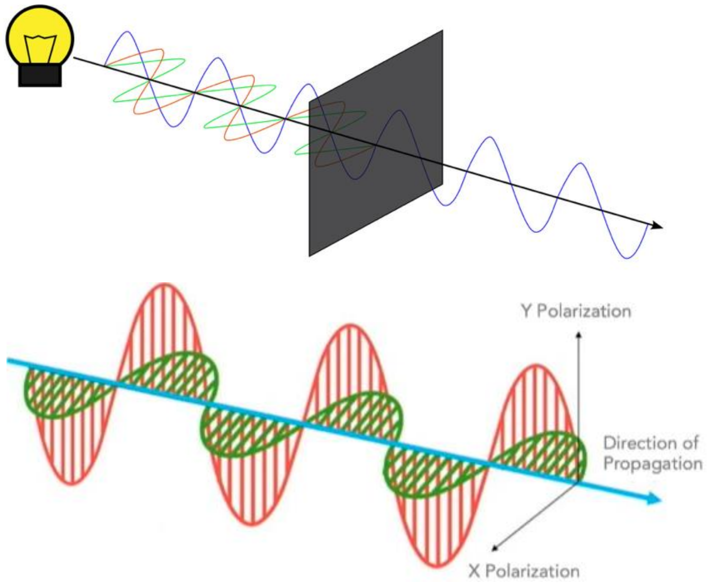
Baud rate: 50Gbaud

NRZ/OOK	: 1 x 50 = 50Gbit/s
PAM4	: 2 x 50 = 100Gbit/s
16QAM	: 4 x 50 = 200Gbit/s

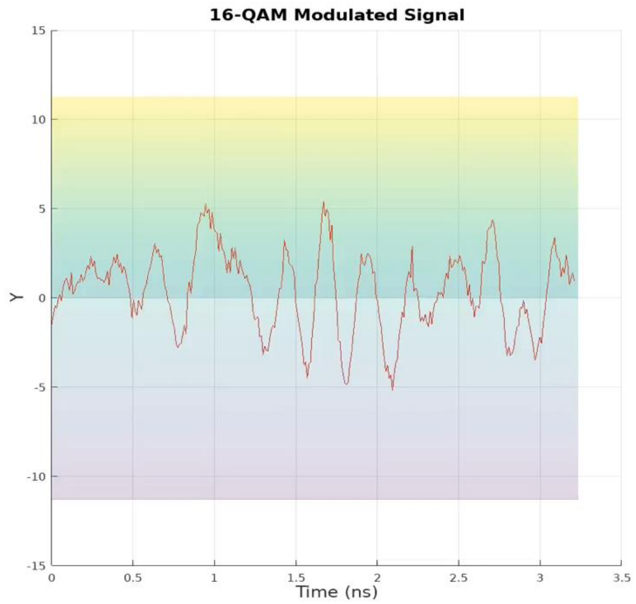
Polarization

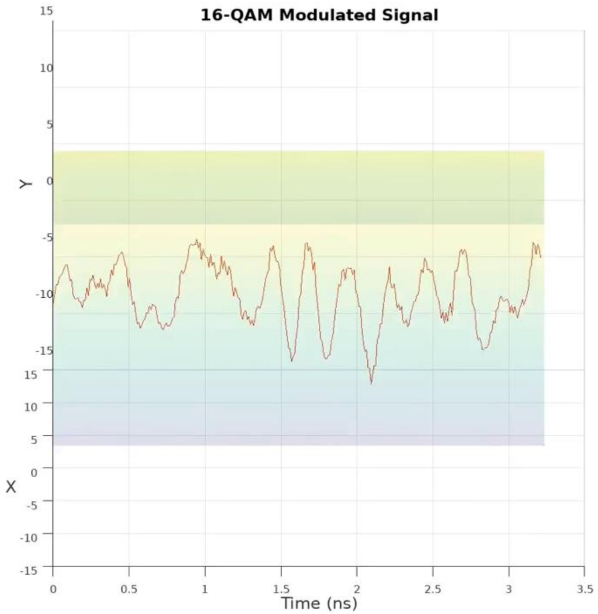
Light ~ electromagnetic wave

- Send two independent orthogonal waves – do not interfere with each other
- Modern DSPs - compensate for impairments in the fiber (polarization drifts)



Source: Science Facts



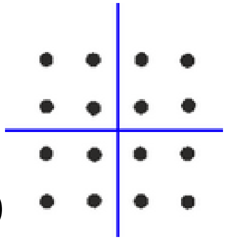


Source: Flexoptix

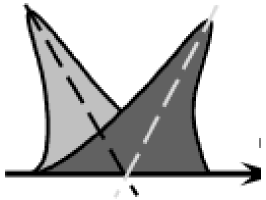
Bit rate = Baud x Modulation x Polarization

50Gbaud

*60Gbaud (75GHz channel)



200Gbit/s

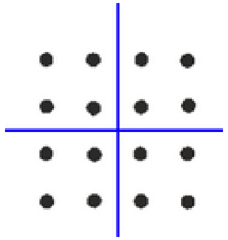


400Gbit/s

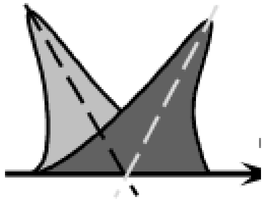
16-QAM

DP-16QAM

100Gbaud



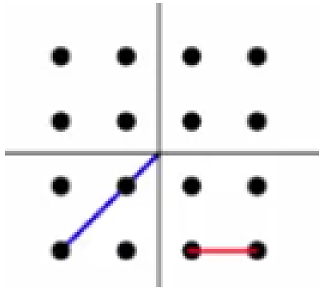
400Gbit/s



800Gbit/s

Why not higher order modulations?

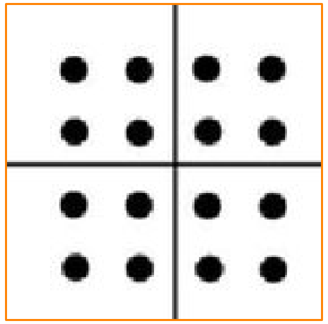
- The distance between symbols determines the *immunity to noise*
- The distance to the origin determines the required *signal power*



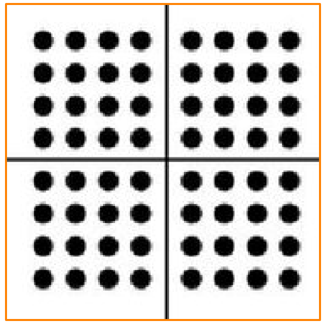
If we want the energy of constellation to remain the same, the points on the constellation must be closer together

→ *More susceptible to noise (need better OSNR levels)*

→ *Limits the distance/reach*



16-QAM



64-QAM

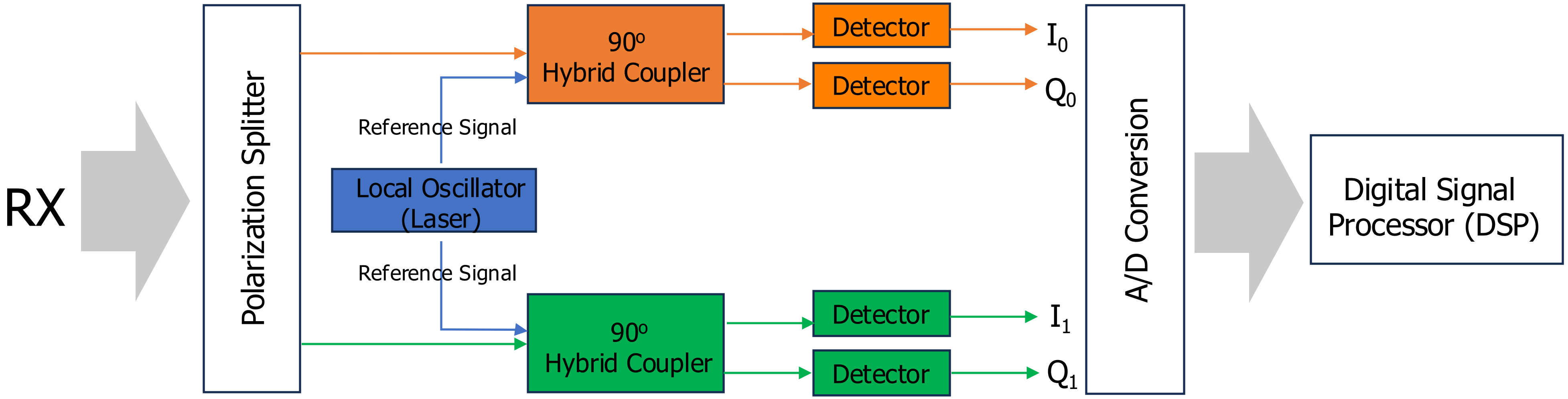
Coherent Detection

Direct detection receivers: can only detect the amplitude changes

Coherent Receiver:

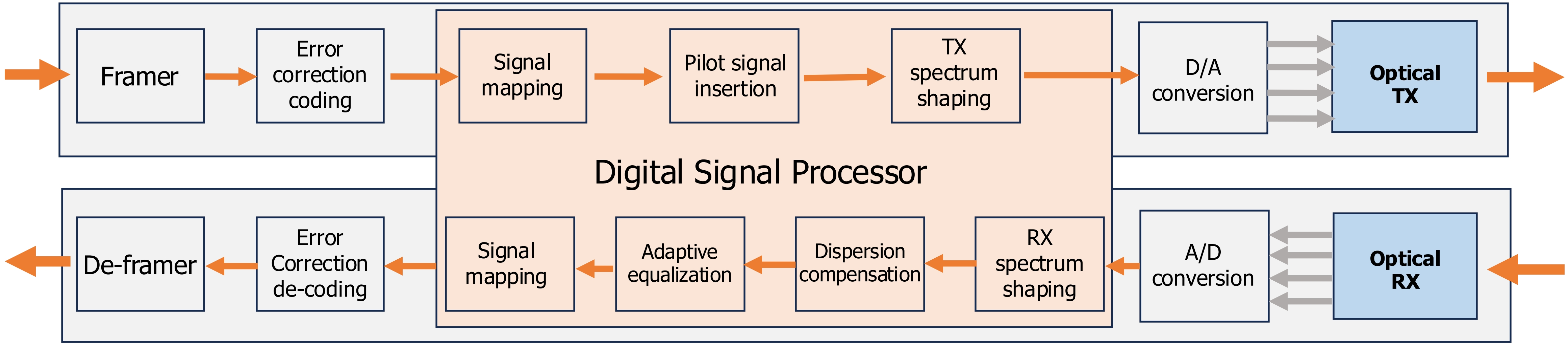
- Signal detection improved (gain) using a local oscillator (laser)
- The reference signal is mixed *coherently* with the incoming signal

→Reconstruct the Amplitude and Phase information per polarization



Reference: NPTEL-NOC IITM

DSP – heart of coherent optics

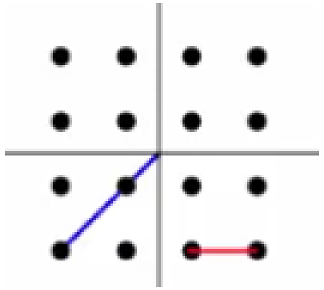


Source: Effect Photonics

- Signal mapping:
  - encoding data into and decoding data from → amplitude, phase and polarization
- Error corrections
- Dispersion compensation
- Probabilistic constellation shaping
- D/A conversion (vice-versa), etc…

Probabilistic Constellation Shaping

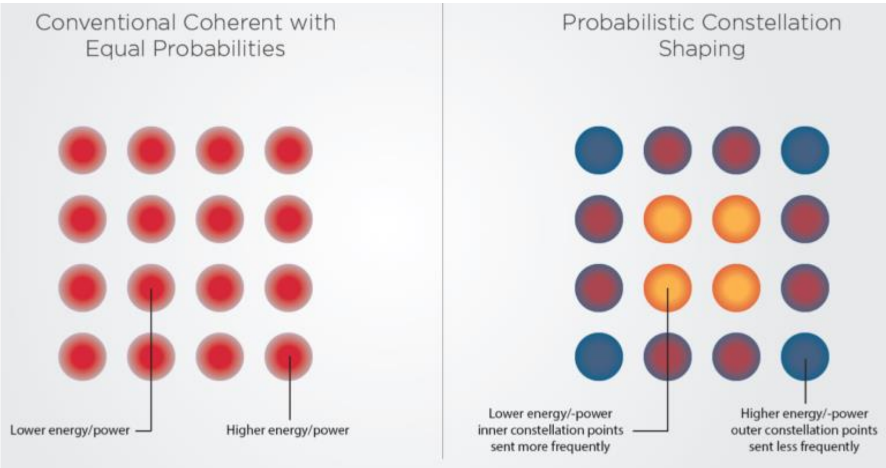
- The distance between symbols determines the *immunity to noise*
- The distance to the origin determines the required *signal power*



In a typical 16-QAM modulation in coherent transceivers:

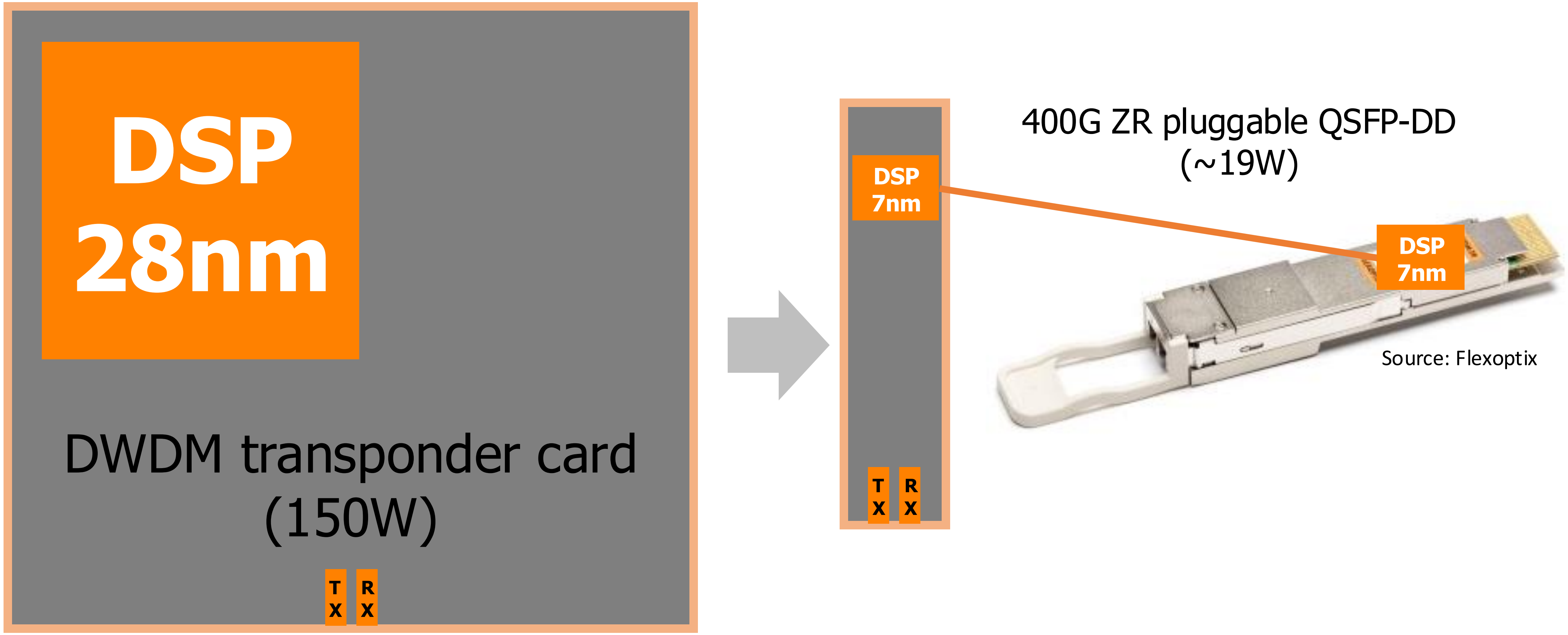
- each constellation point has the same probability of being used
  - outer points (require more power) have same probability as inner ones, that need less

→ PCS uses lower power inner points more frequently



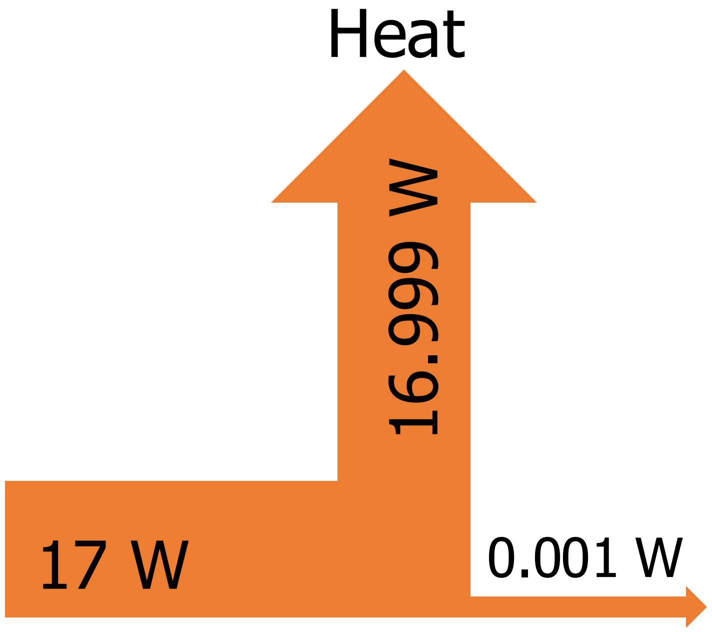
Source: https://effectphotonics.com

→ Coherent Pluggable



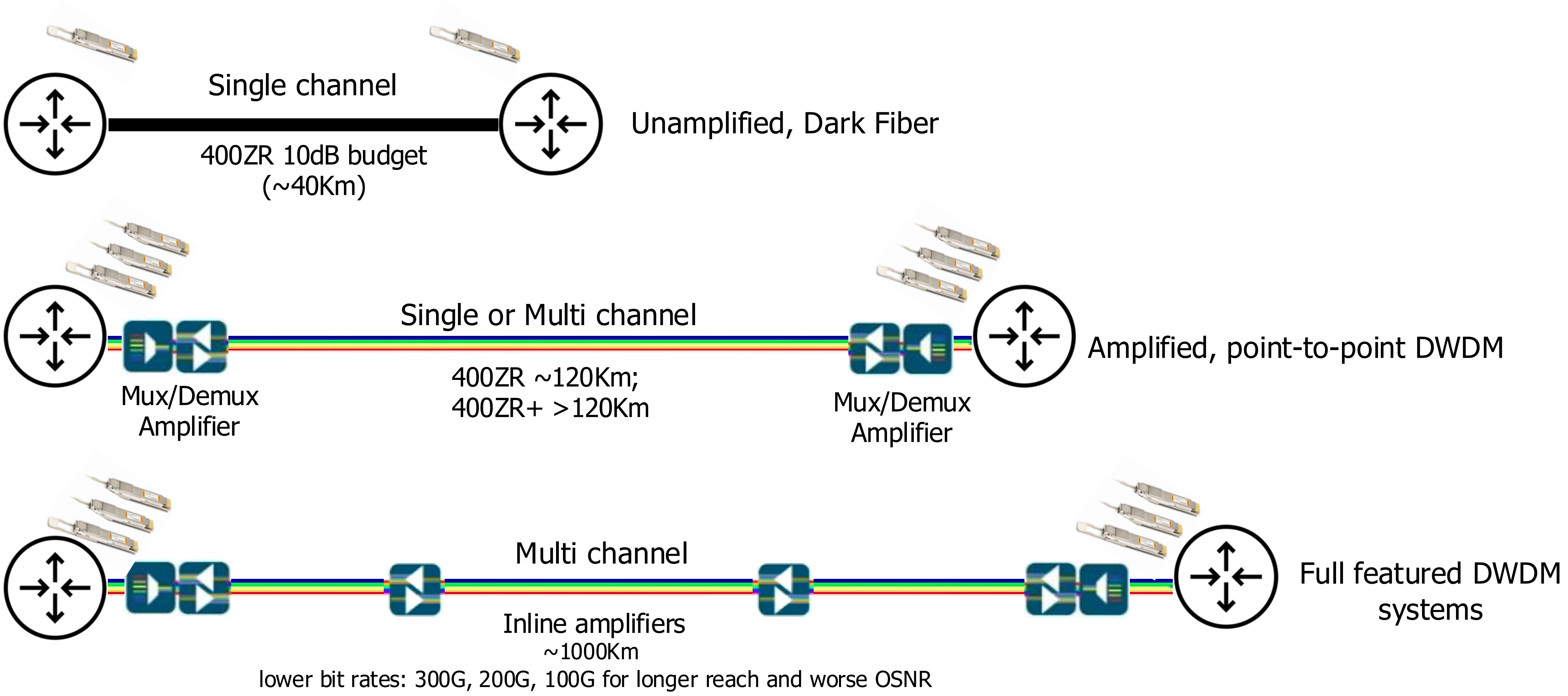
OIF 400ZR and OpenZR+

	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	-6 dBm	-10 dBm
Min RX sensitivity	-12 dBm	-12 dBm
CD tolerance	2400 ps/nm	20000 ps/nm
PMD tolerance	10 ps	20 ps
OSNR tolerance	26 dB	24 dB



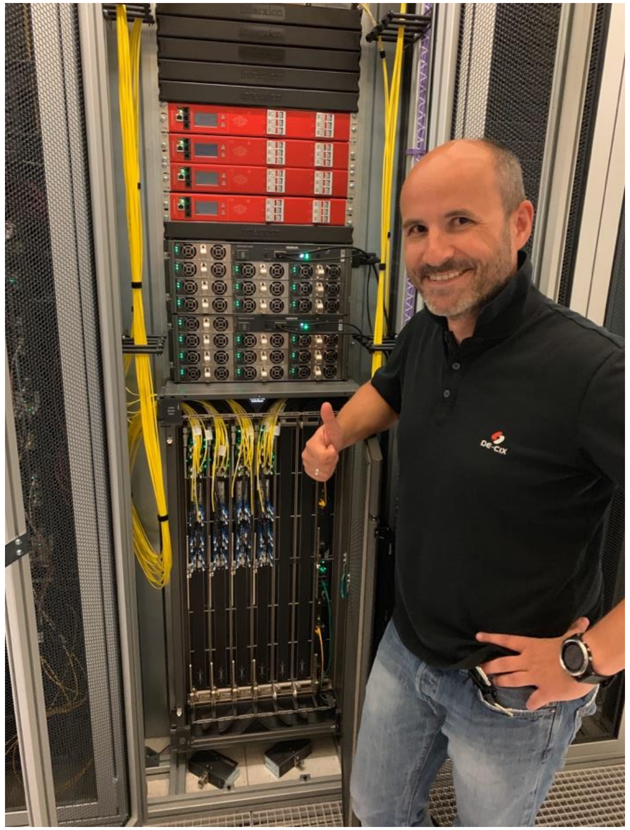
Source:
Flexoptix & DE-CIX 400G ZR test 2023

Coherent optics → IPoDWDM



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

NOKIA SR-OS and 400G ZR Transceiver



Source: Daniel Melzer, DE-CIX

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Source: Thomas Weible, Flexoptix

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Terrific coherent workshop with

DE CIX

Reference: NANOG90 https://www.youtube.com/watch?v=XaQb1yKiOTM&list=LL&index=39

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)