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*

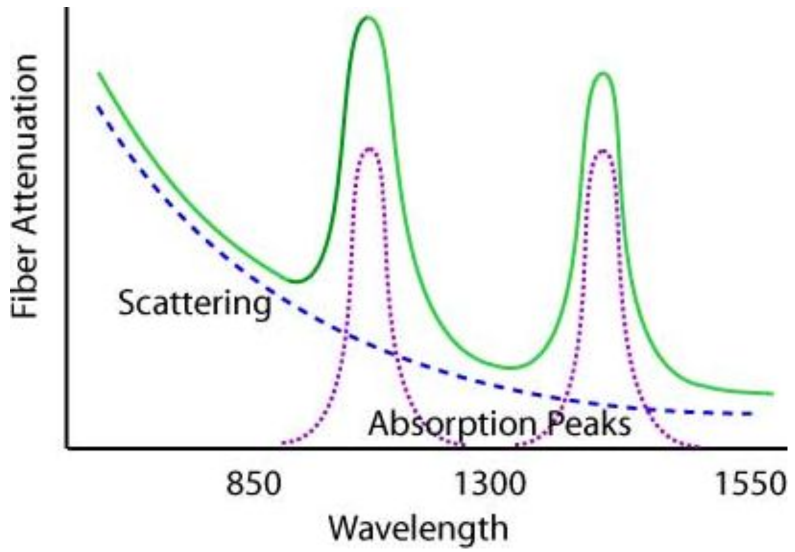
$$P(dBm) = 10\log_{10}(P_{mW}/1mW)$$

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

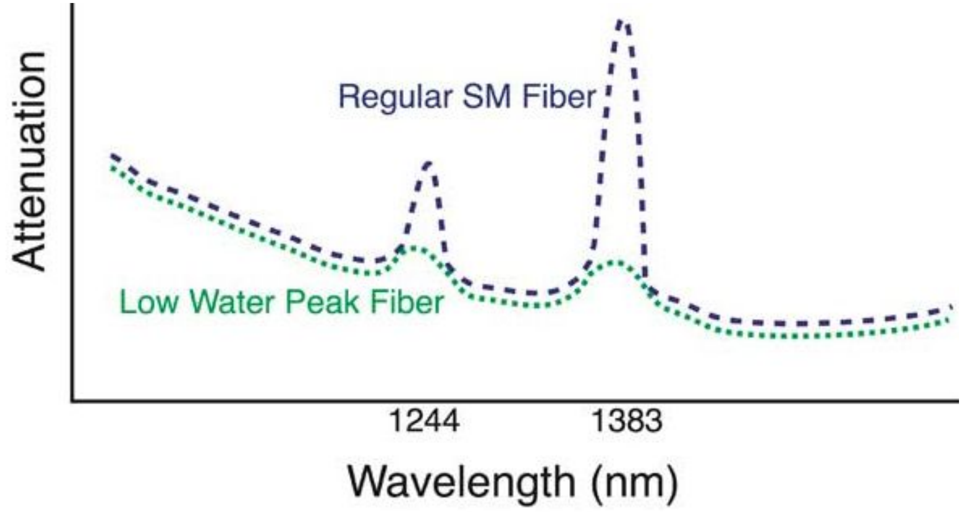
Attenuation

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)*



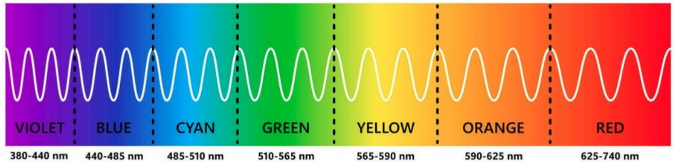
Source: https://foa.org/



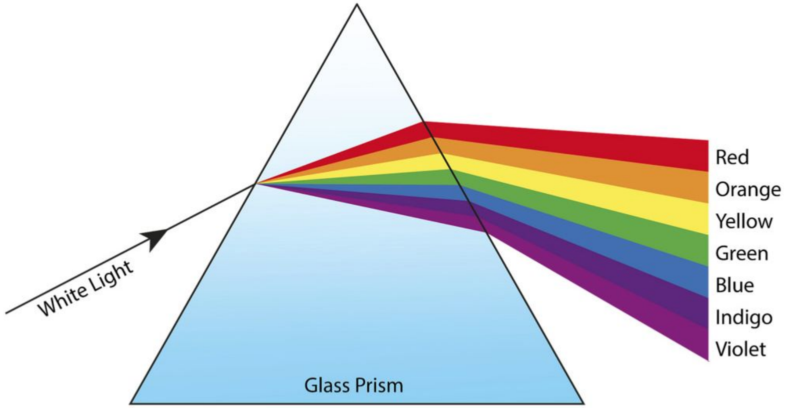
Chromatic Dispersion

Different colours (**f** or **λ**) of light 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

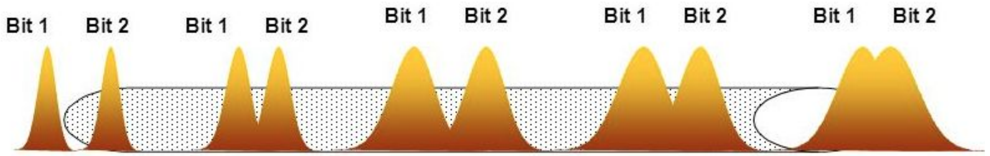


Source: KeyStageWiki

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 the **bit rate** or the **distance** for a specific bit rate

Source: FOA

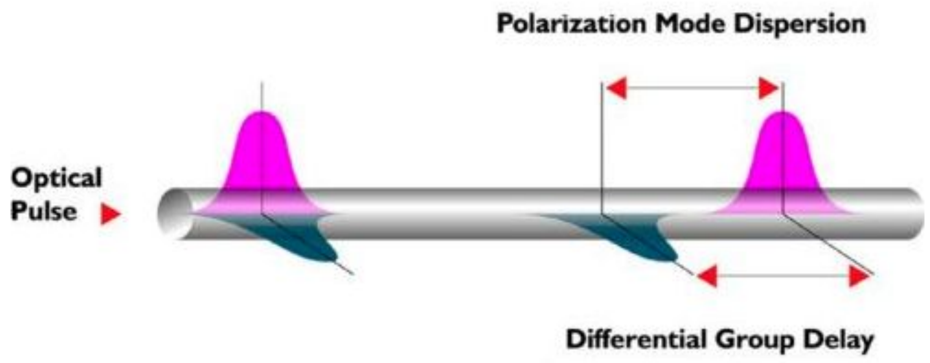


Polarization Mode Dispersion

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)**

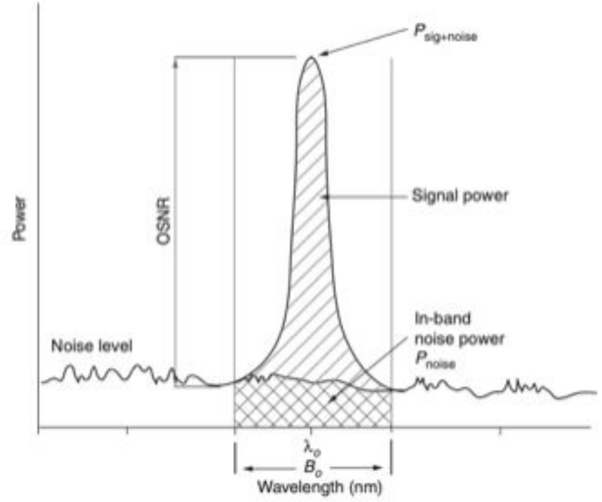


Source: https://tuhh.de

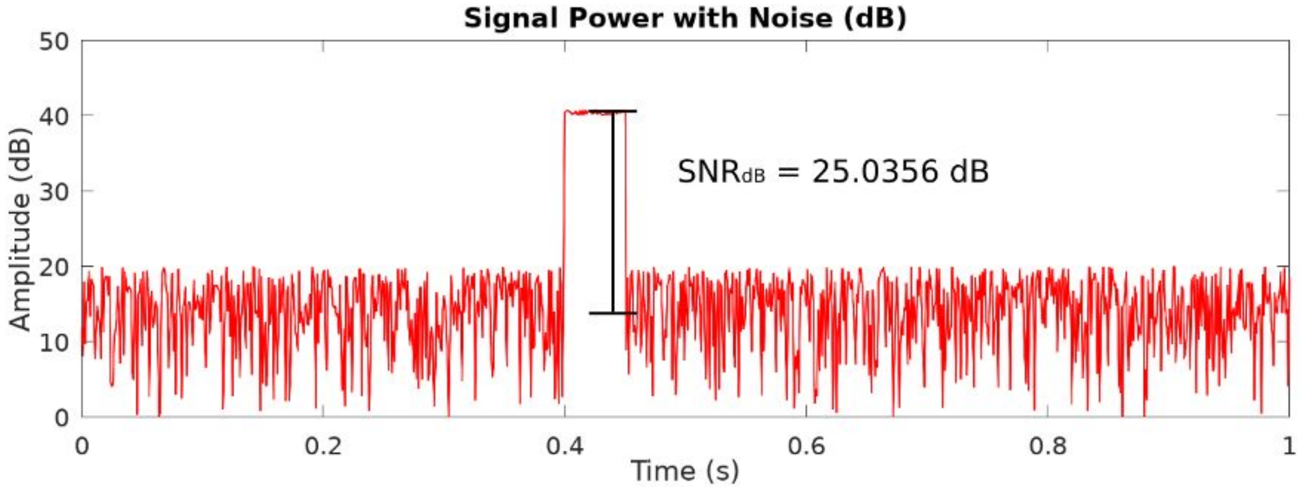
Signal quality

SNR (dB): Signal to Noise Ratio

- (log) ratio of signal power to noise power
- Higher the better!
- Long distance amplified links, you create 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

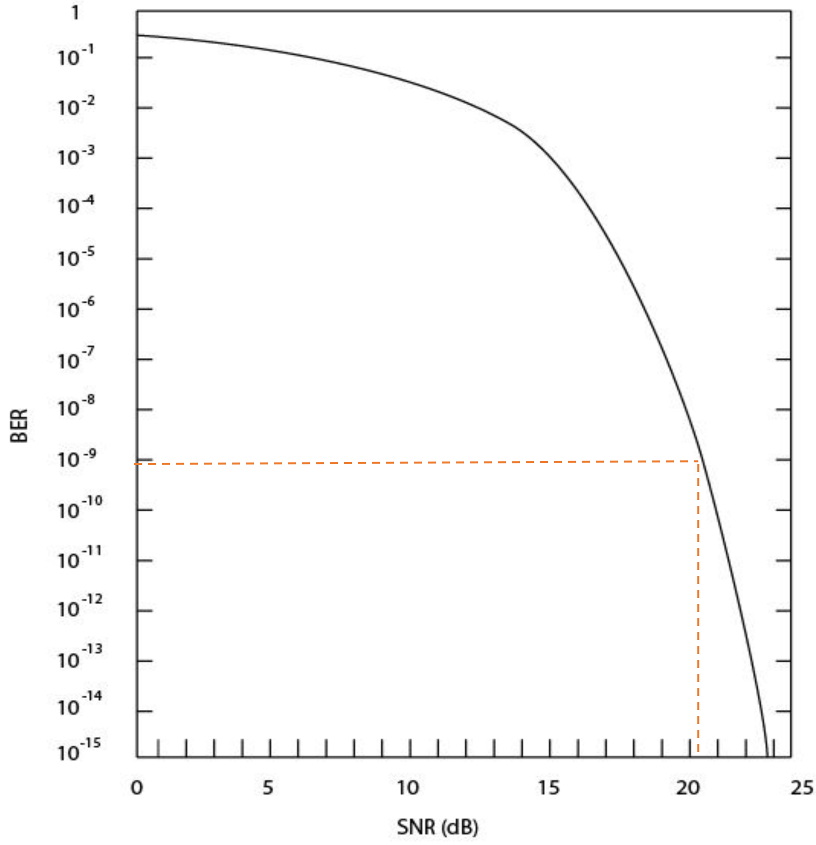
Bit Error Rate (BER) $= \dfrac{no.\,of\ error\ bits\ received}{no.\,of\ transmitted\ bits}$

Example: $\text{BER} = 10^{-9}$

→ *One error bit received for every 1 billion bits transmitted!*

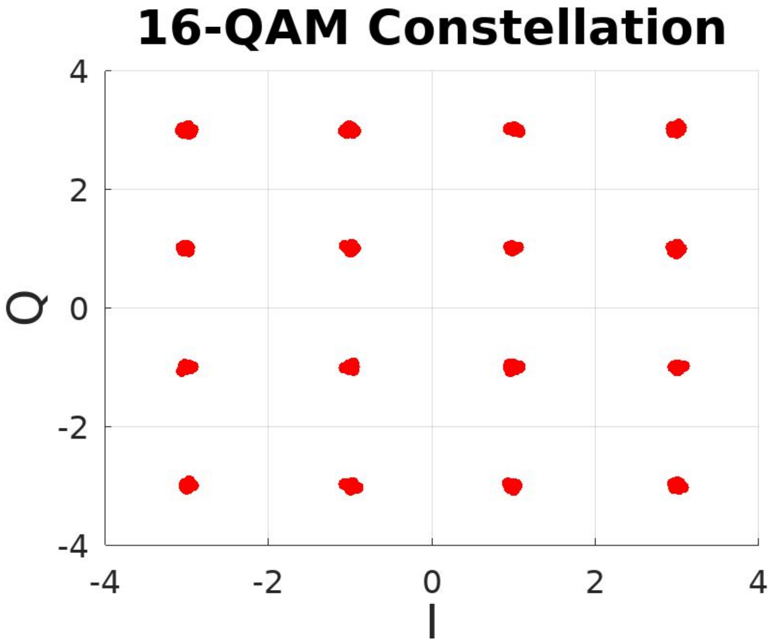
OSNR directly affects BER:

- *Better SNR, lower BER (and vice versa)*

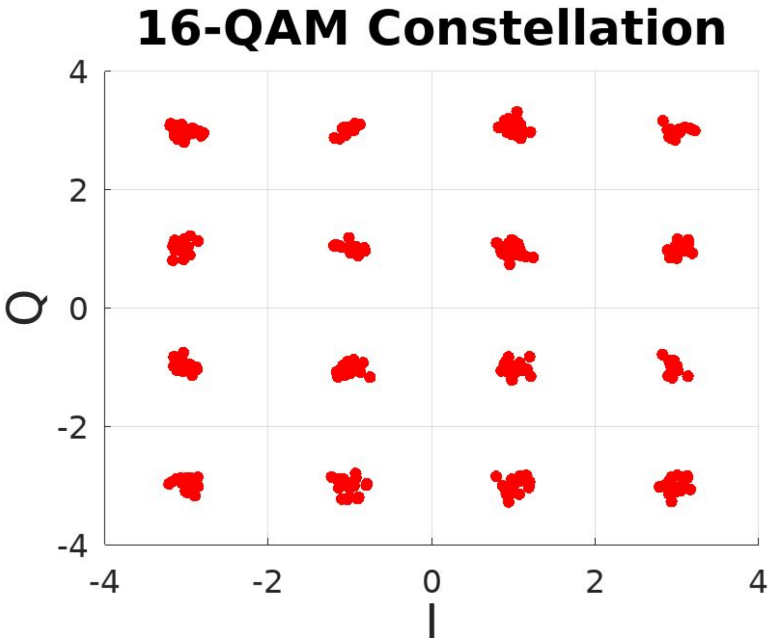


Source: FOSCO

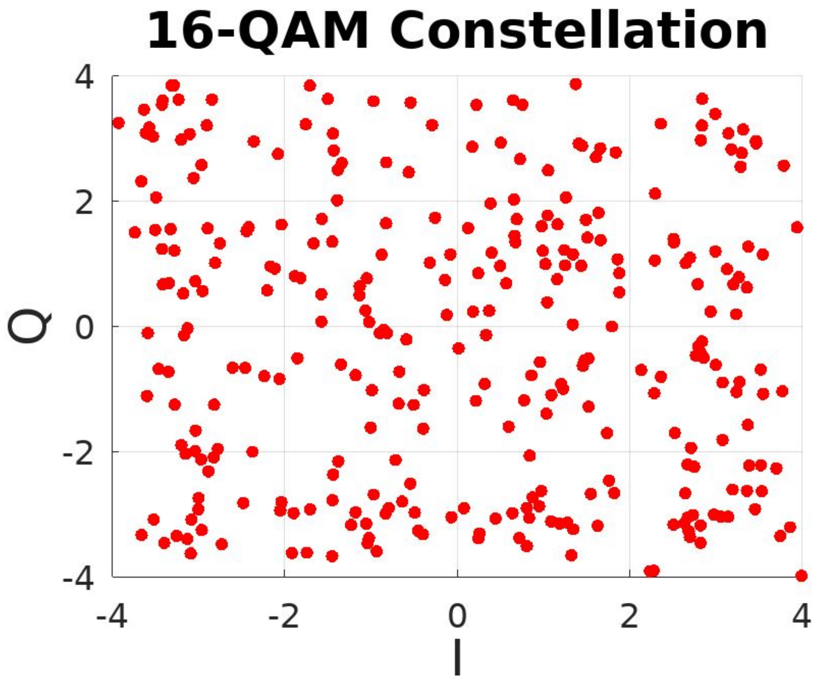
OSNR ☐ Phase and Amplitude errors



SNR = 30 dB



SNR = 20 dB



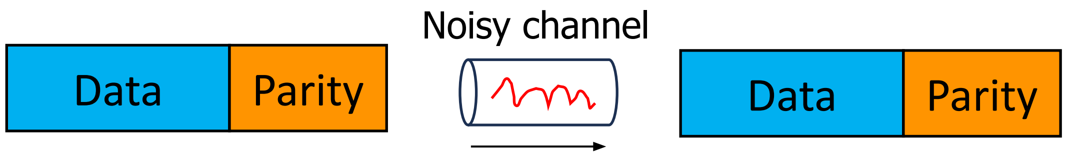
SNR = 5 dB

Source: Flexoptix

Forward Error Correction

FEC adds redundant (parity) bits to the transmitted data

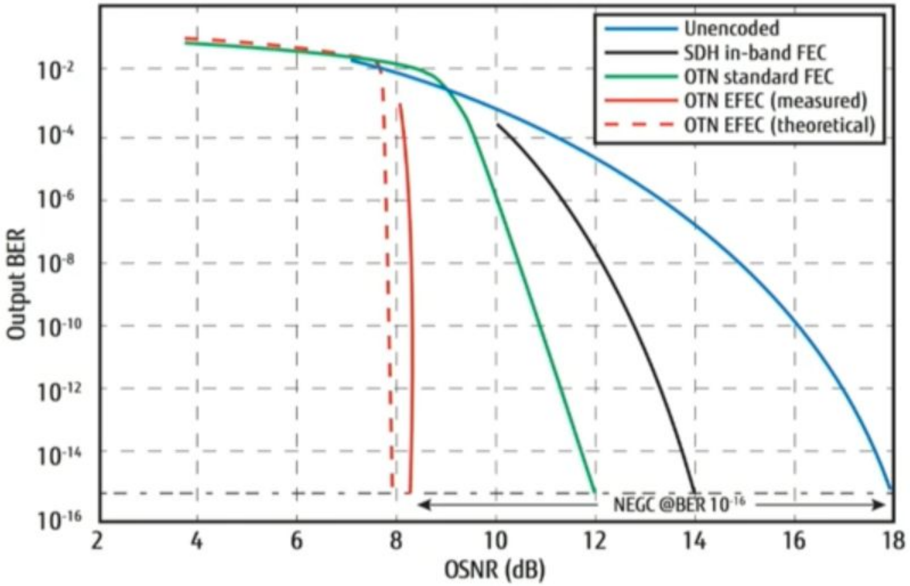
☐ contains enough info about the actual data, to reconstruct the original message at RX



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*

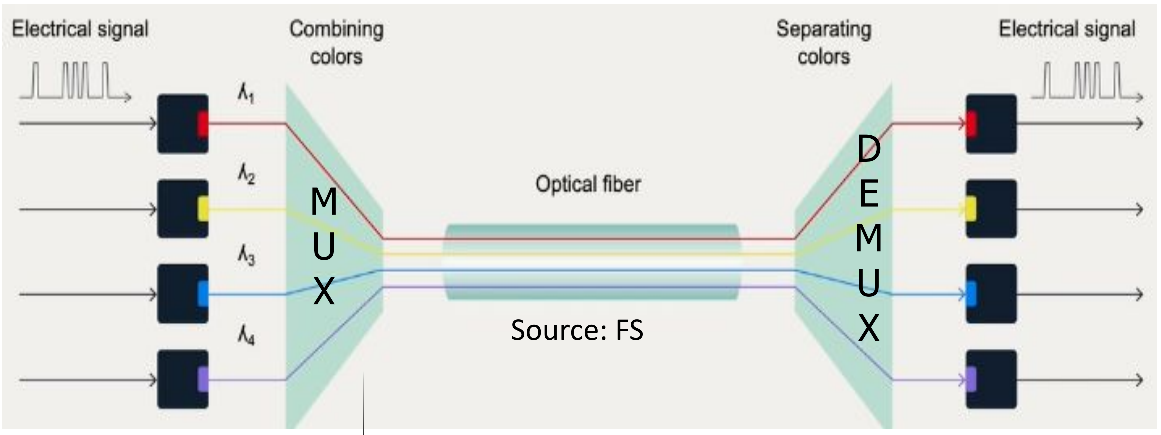


Coding gain with FEC (Source: ictbaike.com)

Wave Division Multiplexing (WDM)

Carry different colours (**λ**) of light on the same fiber

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

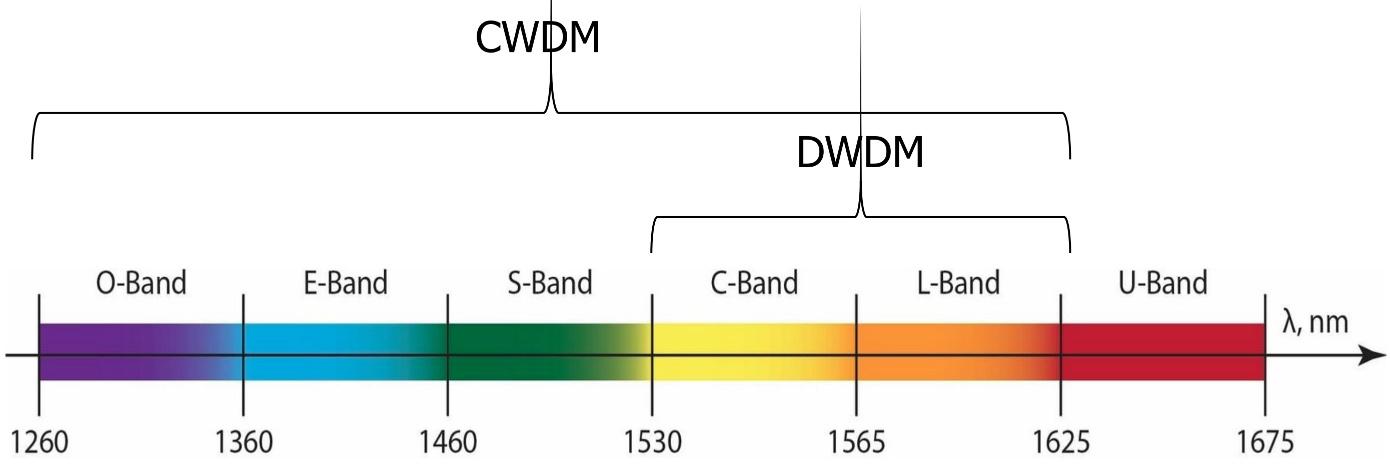


CWDM: Coarse WDM

- 20nm spacing (2500GHz)
  - 1470 -1610nm channels
  - **1270-1450nm with low water peak*

DWDM: Dense WDM

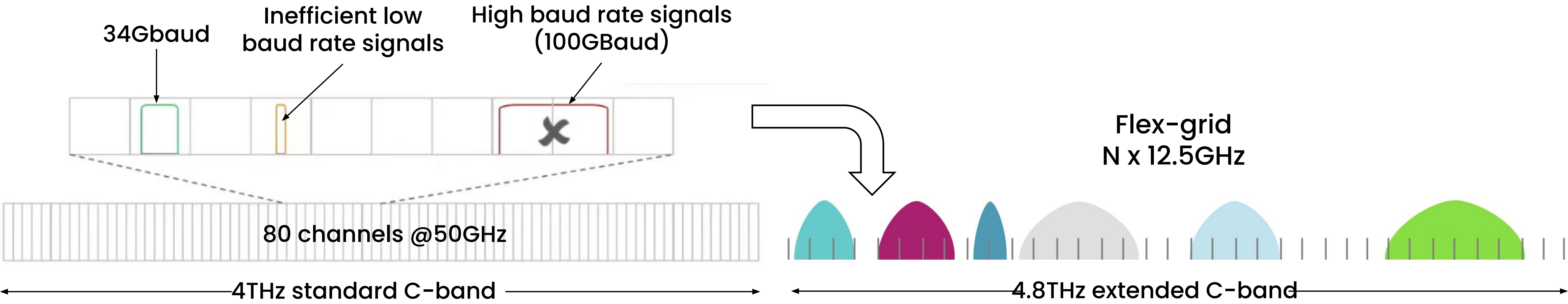
- Mostly in C-band (L-band being discussed)
  - 44/48 channels with 100GHz (0.8nm)
  - 64 channels with 75GHz (0.6nm)
  - 88/96 channels with 50GHz (0.4nm)



Flex Grid

Flexible frequency grid

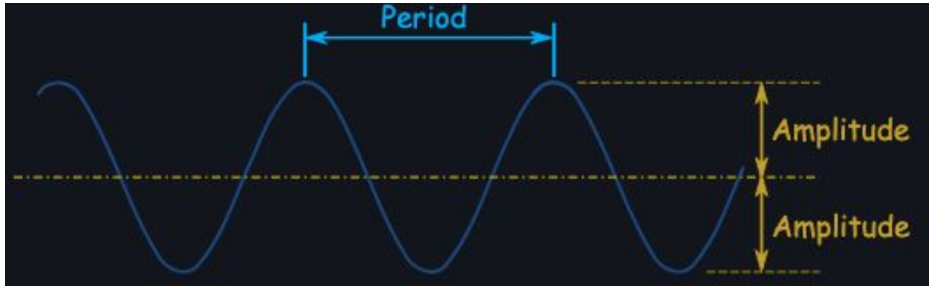
- Do away with the fixed grid (slots) approach
- Create flexible sized slots/channels (N x 12.5GHz)
- Each flexible slot can be rightsized for the signal it carries ☐ adaptive baud rates.
- Reduces "stranded' spectrum



Modulation

We still live in an analog world:

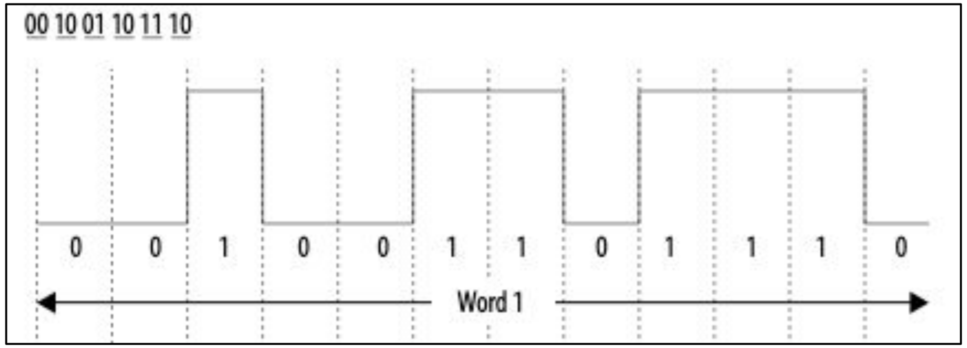
- Light ~ electromagnetic wave
- Digital signals (0,1) need to be encoded into analog waves



Source: MathIsFun

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

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

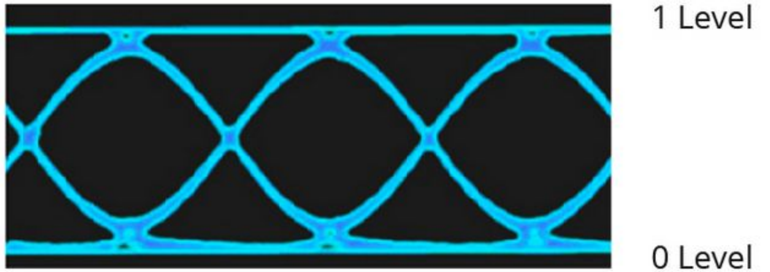


Source: Intel

Symbol (Baud) Rate & Bit Rate

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

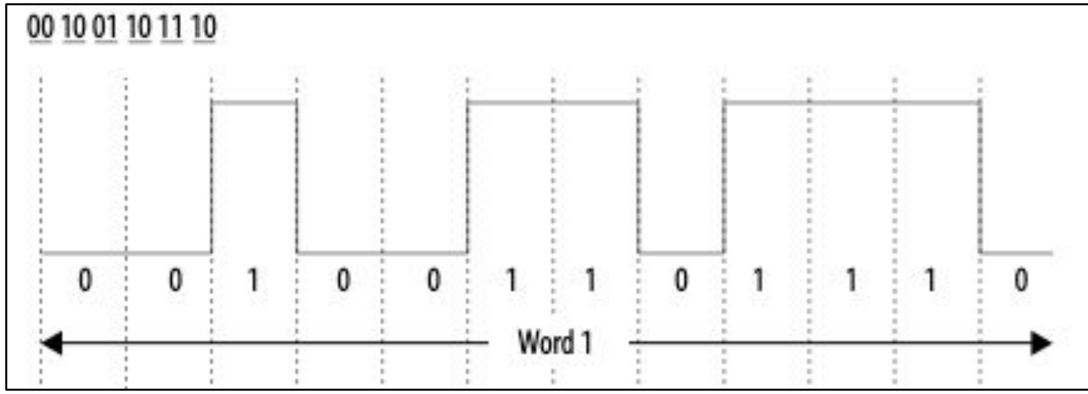
- *symbol rate per second*
- 10Gigabaud ~ flashing bright or dim 10 billion times/sec



NRZ: 1 bit per clock cycle

With NRZ (OOK/ASK)

- Encode 1 bit per symbol ☐ **symbol rate** equal to **bit rate**
  50 Gigabaud = 50 Gbit/s



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/wider channel sizes*

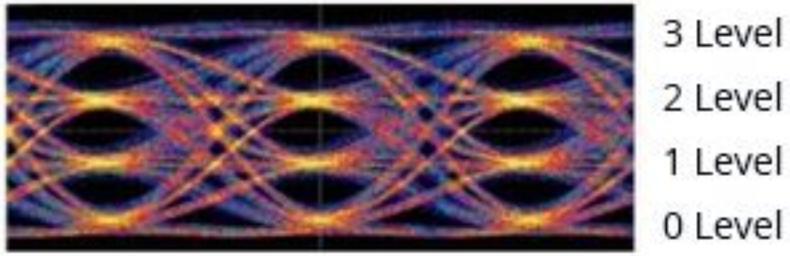
Source: Intel

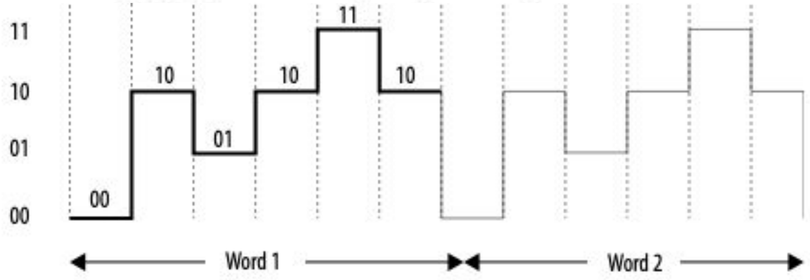
Higher data rates with baud limit?

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



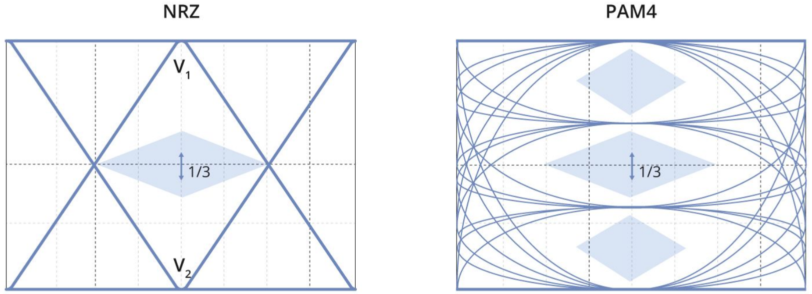


Source: FS

Example: 50 Gbaud

□ NRZ: 50 x 1 = 50 Gbps

□ PAM4: 50 x 2 = **100 Gbps**



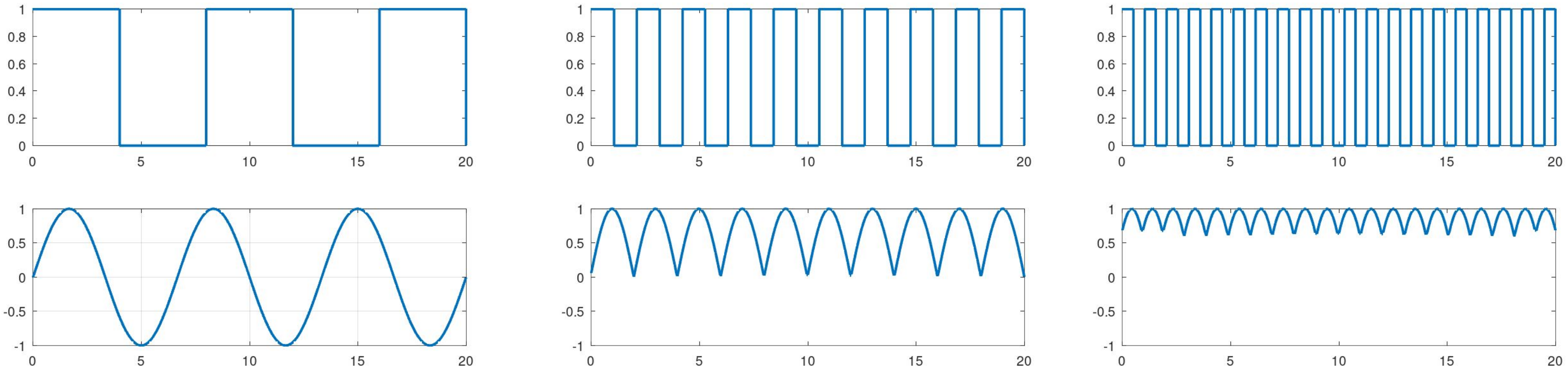
But the signal amplitude (eye) is 1/3rd (33%) of NRZ

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

Direct detection transceiver limits

At higher speeds (frequencies)

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



Source: Flexoptix

Higher data rates at longer distances?

Besides Amplitude, light also has other properties

- *More properties per carrier* ☐ *Higher the 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

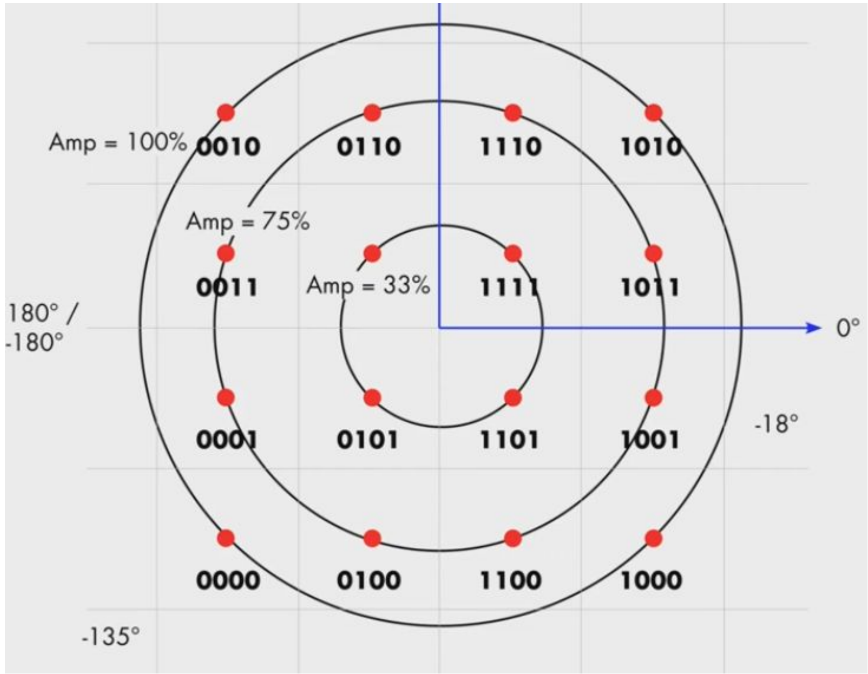
Phase & Amplitude □ Coherent

Quadrature Amplitude Modulation (QAM):

- Modulates the *amplitude* of two carrier waves/signals □ *out of phase by 90º*

16QAM

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

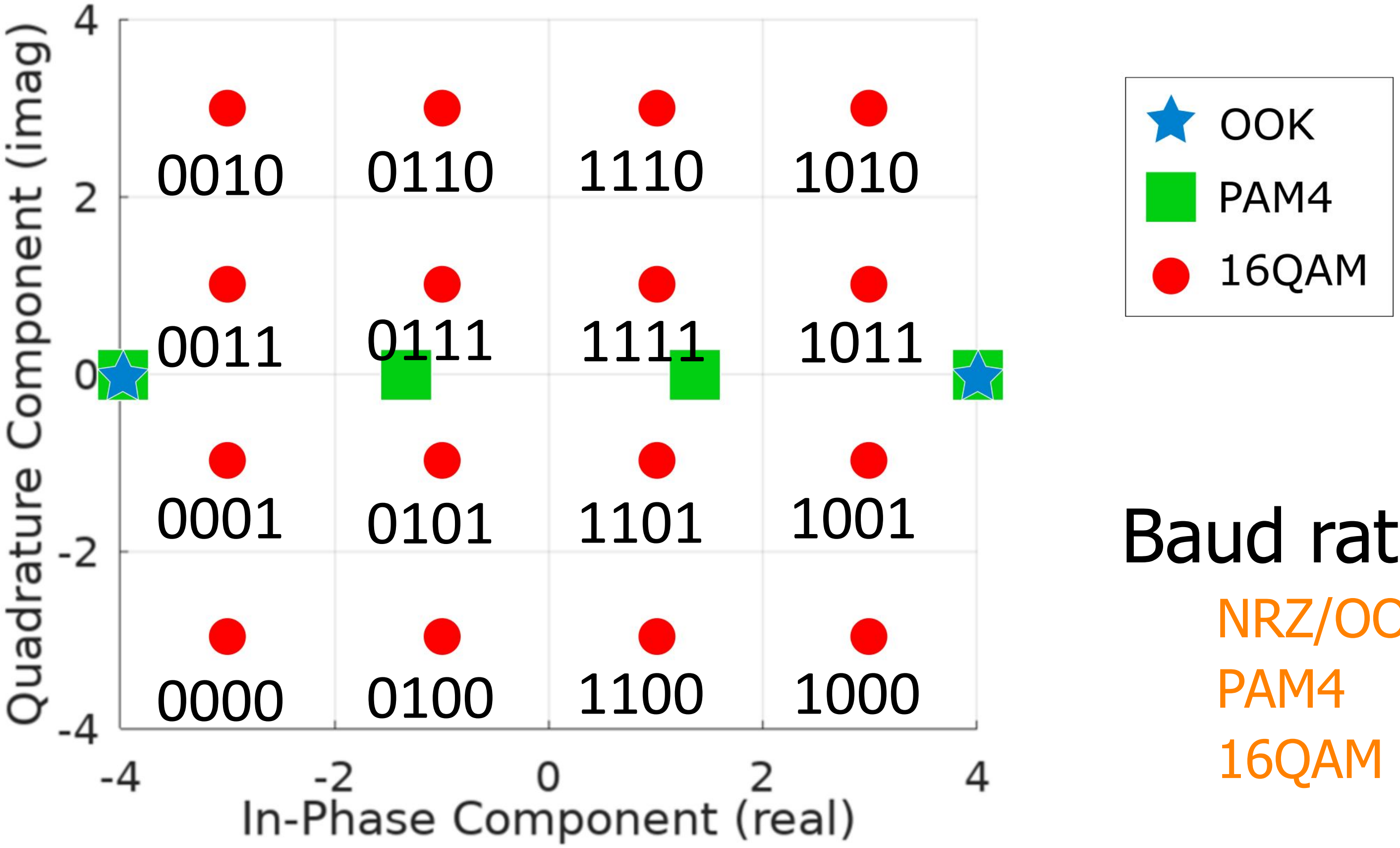


Source: Flexoptix

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

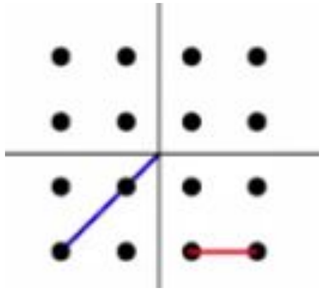
NRZ/OOK : 1 x 50 = **50 Gbit/s**

PAM4 : 2 x 50 = **100 Gbit/s**

16QAM : 4 x 50 = **200 Gbit/s**

Why not higher order modulations?

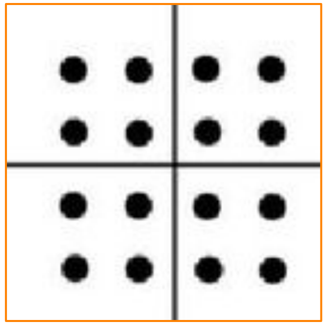
- The distance between symbols determines the *immunity to noise*
- The distance to the origin determines the required *signal power*



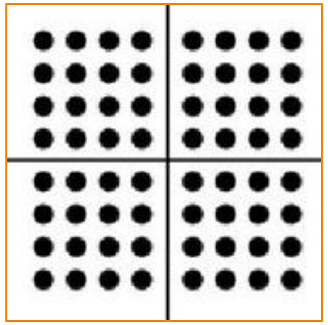
If we want the energy of constellation to remain the same, the points on the constellation must be closer together

☐ *More susceptible to noise (lower OSNR levels)*

☐ *Limits the distance/reach*



16-QAM



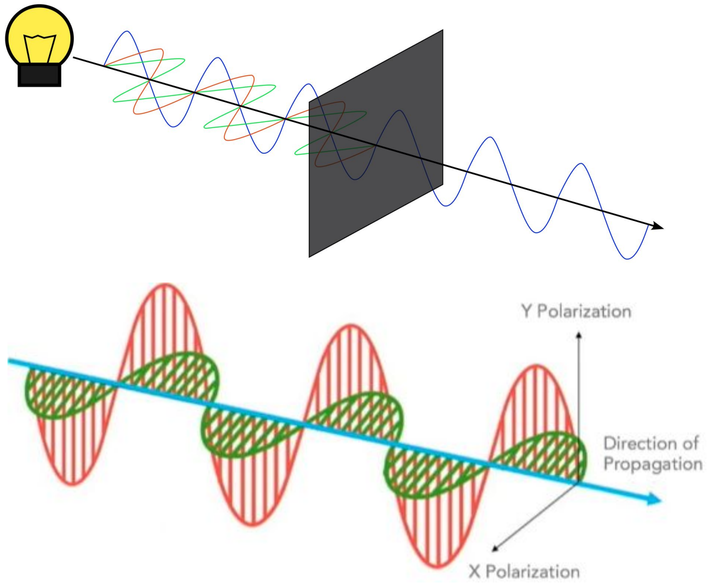
64-QAM

Polarization

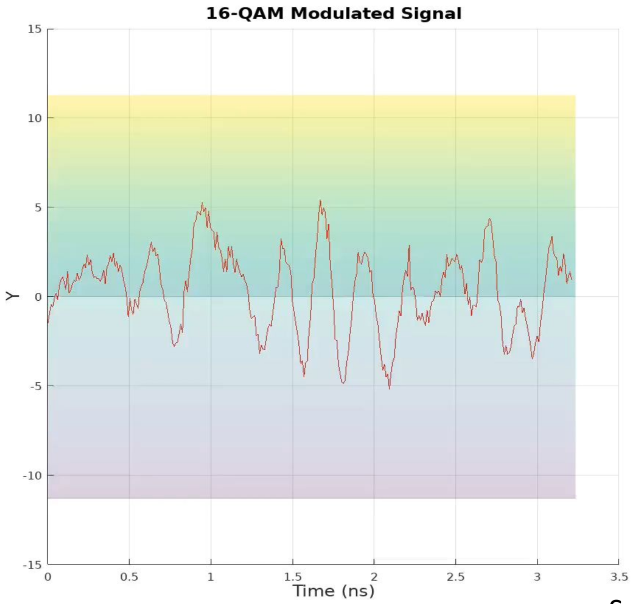
Light ~ electromagnetic wave

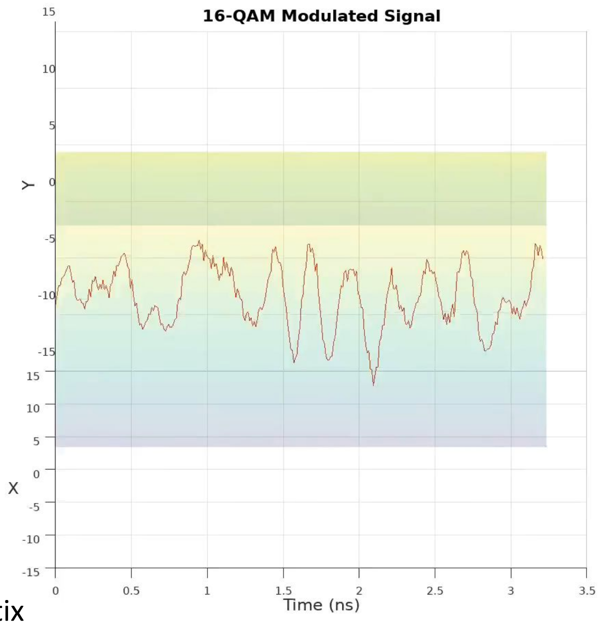
Besides Amplitude & Phase, we can also use **Polarization**

- Send two independent orthogonal waves – do not interfere – **double the bit rate!**
- Modern DSPs - compensate for impairments in the fiber (polarization drifts)



Source: Science Facts





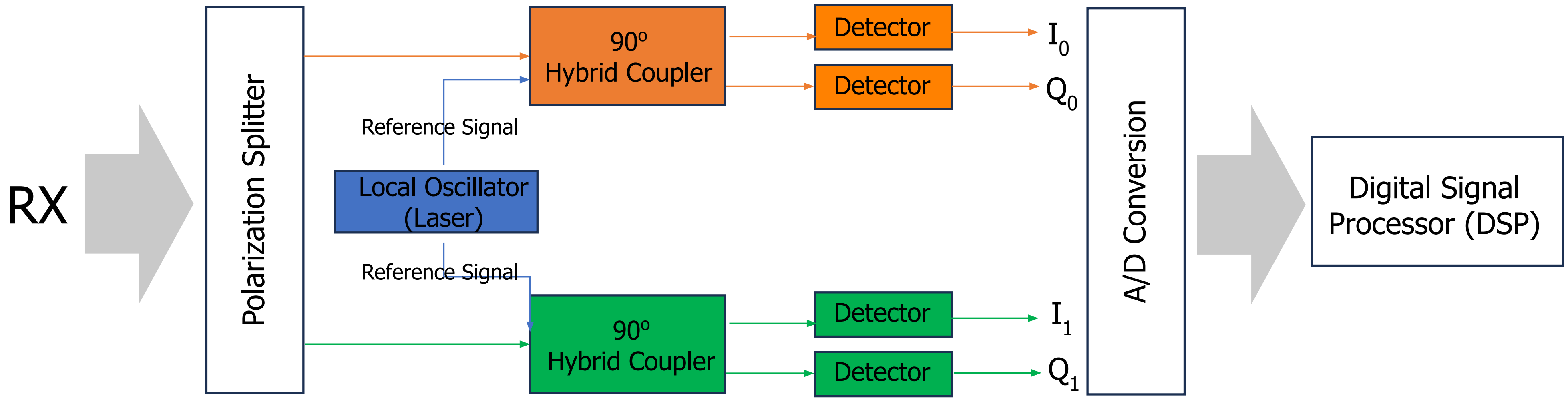
Source: Flexoptix

Coherent Detection

Direct detection receivers: can ONLY detect the intensity (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

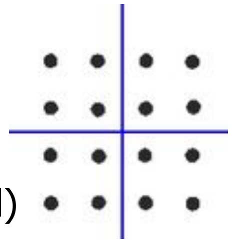


Reference: NPTEL-NOC IITM

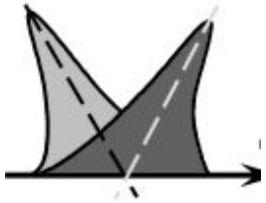
Bit rate = Baud x Modulation x Polarization

50 Gbaud

*60 Gbaud (75GHz channel)



200 Gbit/s



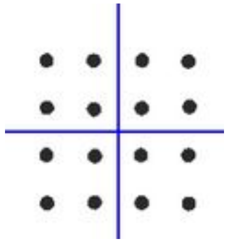
400 Gbit/s

*480 Gbps

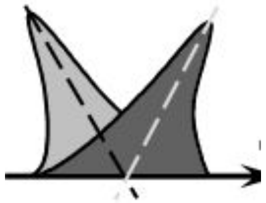
16-QAM

DP-16QAM

100 Gbaud

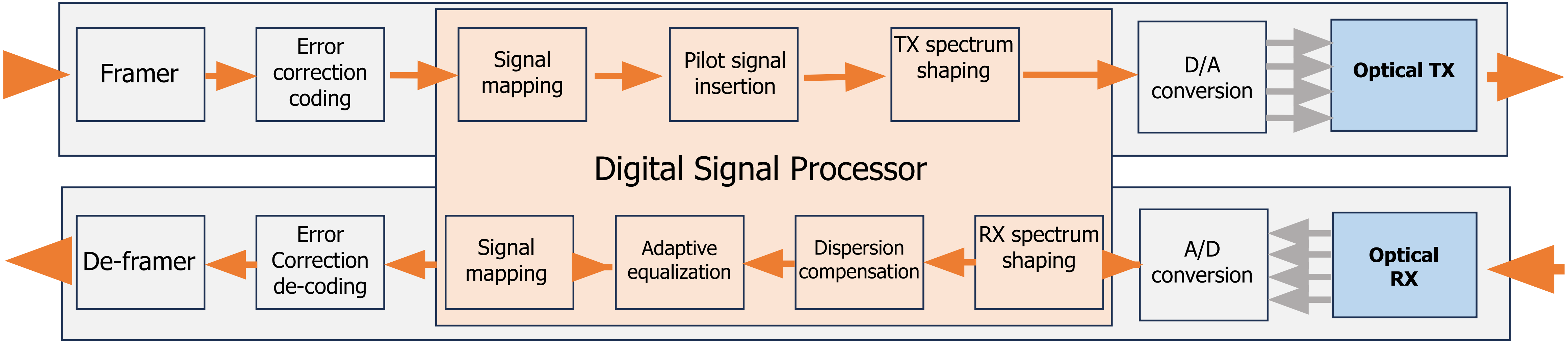


400 Gbit/s



800 Gbit/s

DSP – "Heart" of Coherent Optics

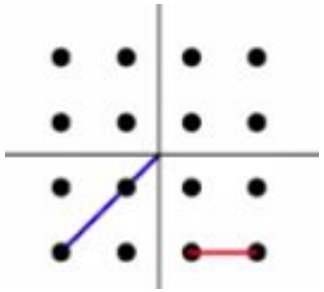


Source: Effect Photonics

- 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

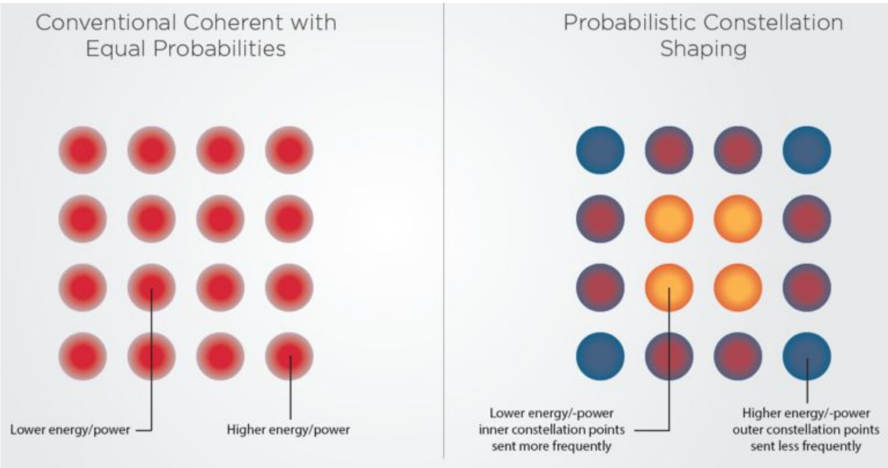
- The distance between symbols determines the *immunity to noise*
- The distance to the origin determines the required *signal power*



In a typical 16-QAM modulation in coherent transceivers:

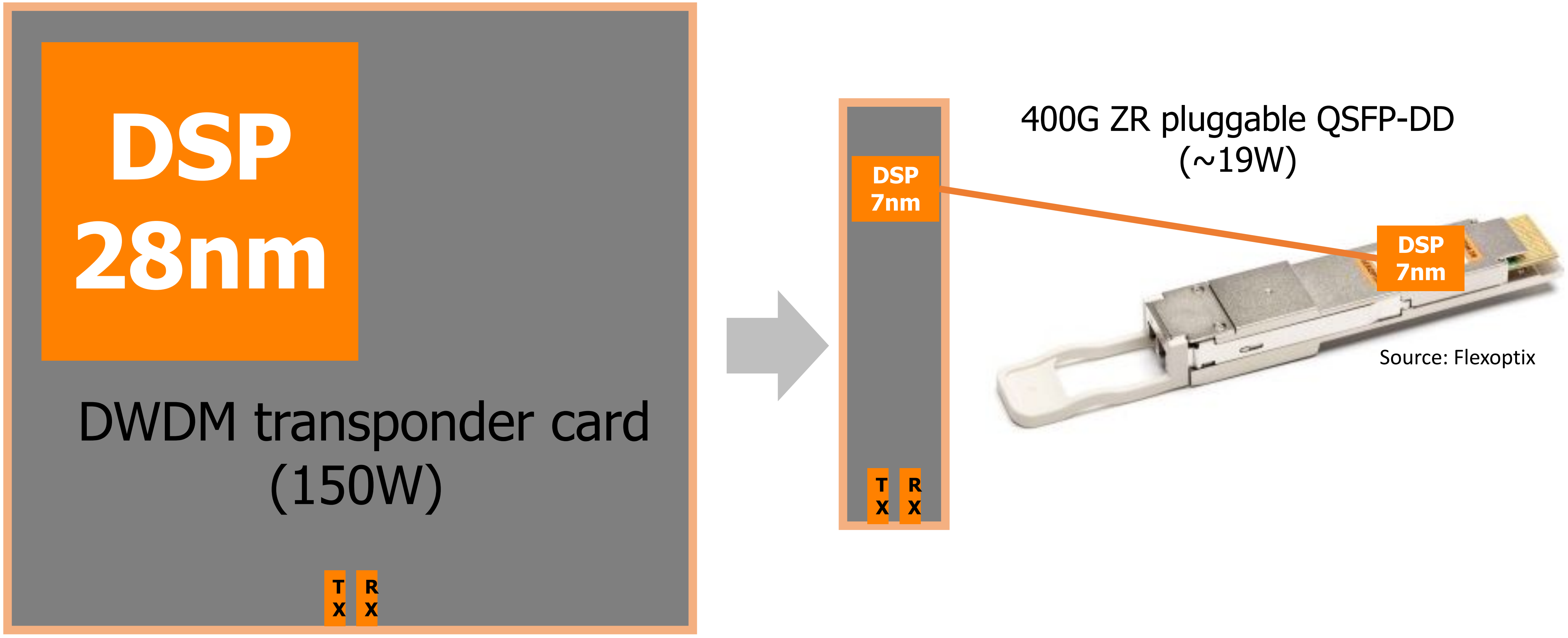
- each constellation point - same probability of being used
  - outer points (require more power) have same probability as inner ones, that need less power

☐ PCS uses lower power inner points more frequently



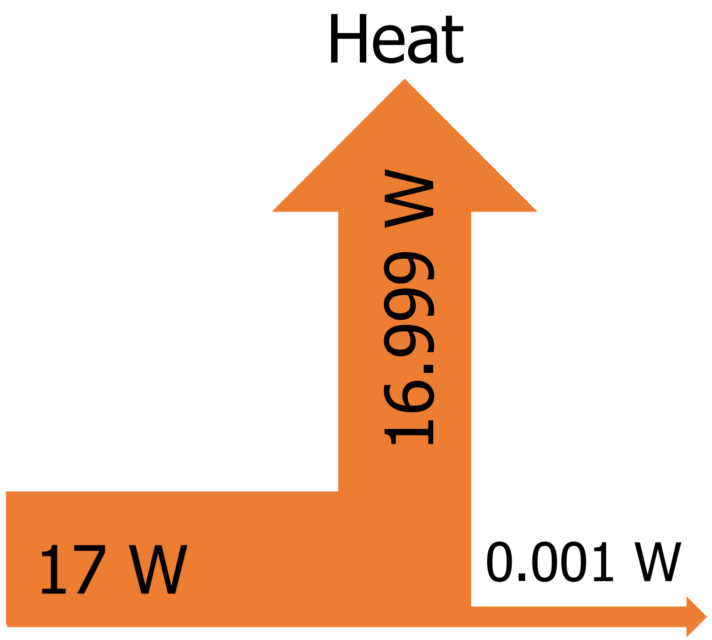
Source: Effect Photonics

☐ Coherent Pluggable Optics



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	-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



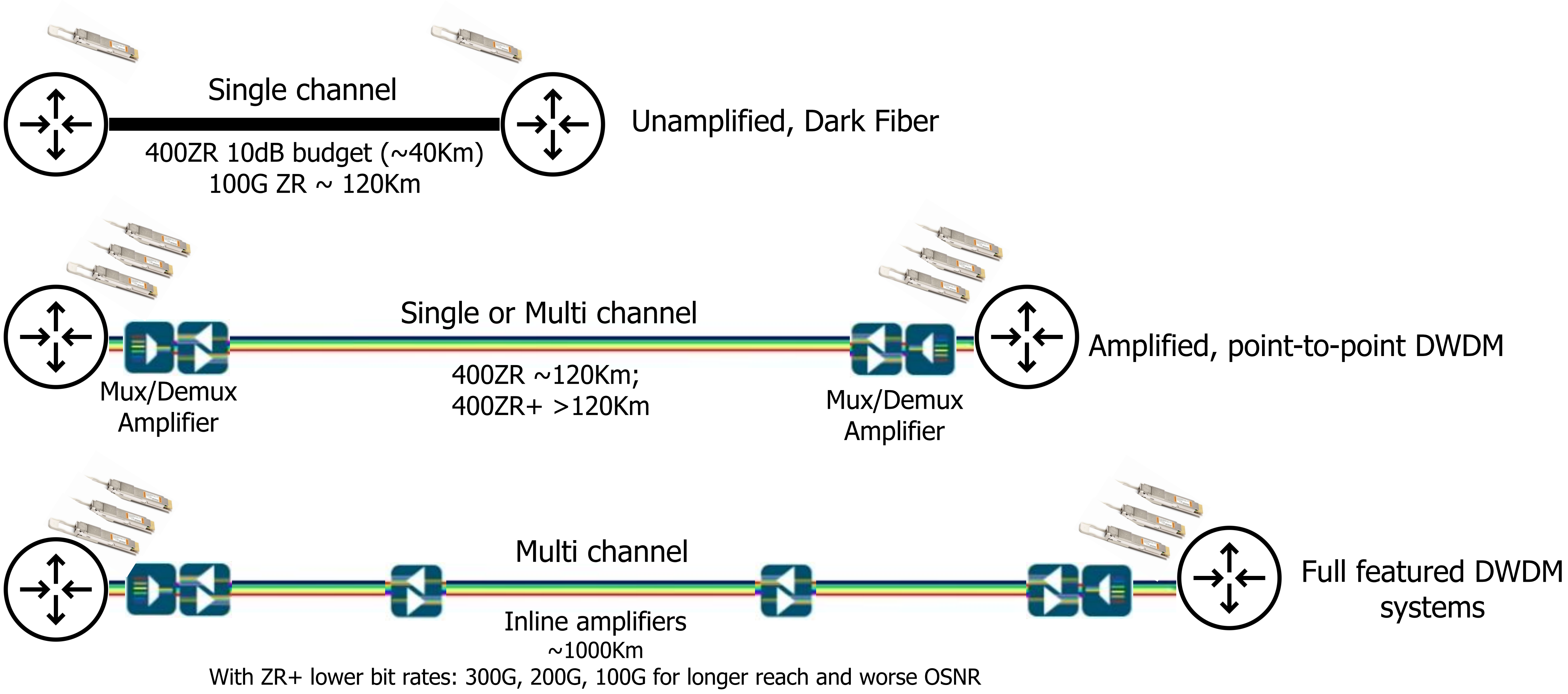
Source:
Flexoptix & DE-CIX 400G ZR test 2023

Visibility of optical transport parameters on Routers

```
Nokia 7950 XRS# show port 8/1/c7
...

===============================================================================
Coherent Optical Module
===============================================================================
Cfg Tx Target Power:   1.00 dBm                  Present Rx Channel  : 23
Cfg Rx LOS Thresh  : -23.00 dBm                  Cfg Rx Channel      : 23

Disp Control Mode  : automatic                   Sweep Start Disp    : -25500 ps/nm
Cfg Dispersion     :      0 ps/nm                Sweep End Disp      :   2000 ps/nm
CPR Window Size    : 32 symbols                  Rx LOS Reaction     : squelch
Compatibility      : openZrpOfec1
Cfg Tx Power Min   : -22.90 dBm                  Cfg Tx Power Max    :   4.00 dBm

Cfg Alarms         : modflt mod netrx nettx hosttx
Alarm Status       :
Defect Points      :

Rx Q Margin        :    2.4 dB                   Chromatic Disp      :    220 ps/nm
SNR/OSNR X Polar   :   17.4 dB / 34.4 dB         Diff Group Delay    :      2 ps
SNR/OSNR Y Polar   :   17.4 dB / 34.4 dB         Pre-FEC BER         : 1.213E-03

Module State       : ready
Tx Turn-Up States  : init laserTurnUp laserReadyOff laserReady
                     modulatorConverge outputPowerAdjust
Rx Turn-Up States  : init laserReady waitForInput adcSignal opticalLock
                     demodLock
===============================================================================
```

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

Coherent Pluggables ☐ IPoDWDM



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

Real world example:

Source: Daniel Melzer, DE-CIX

Nokia SR-OS and 400G ZR Transceiver

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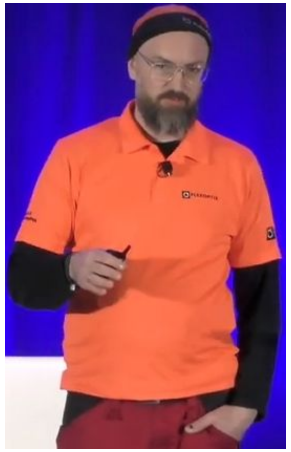

Source: Thomas Weible, Flexoptix

=

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)
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