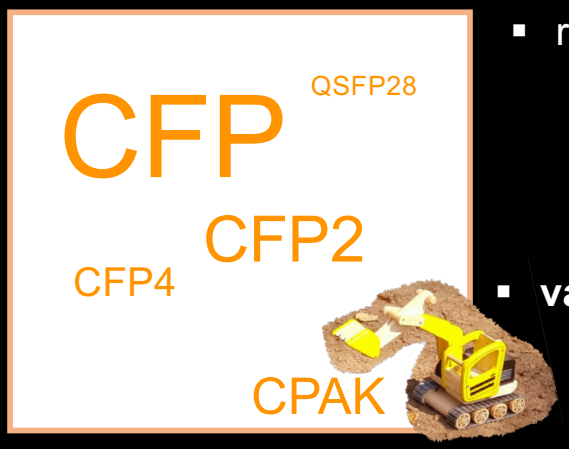
coherent optical transceivers

current capabilities and
future possibilities

Welcome - these slides are made by Thomas our CTO and Gerhard our Head of Product Development at FLEXOPTIX

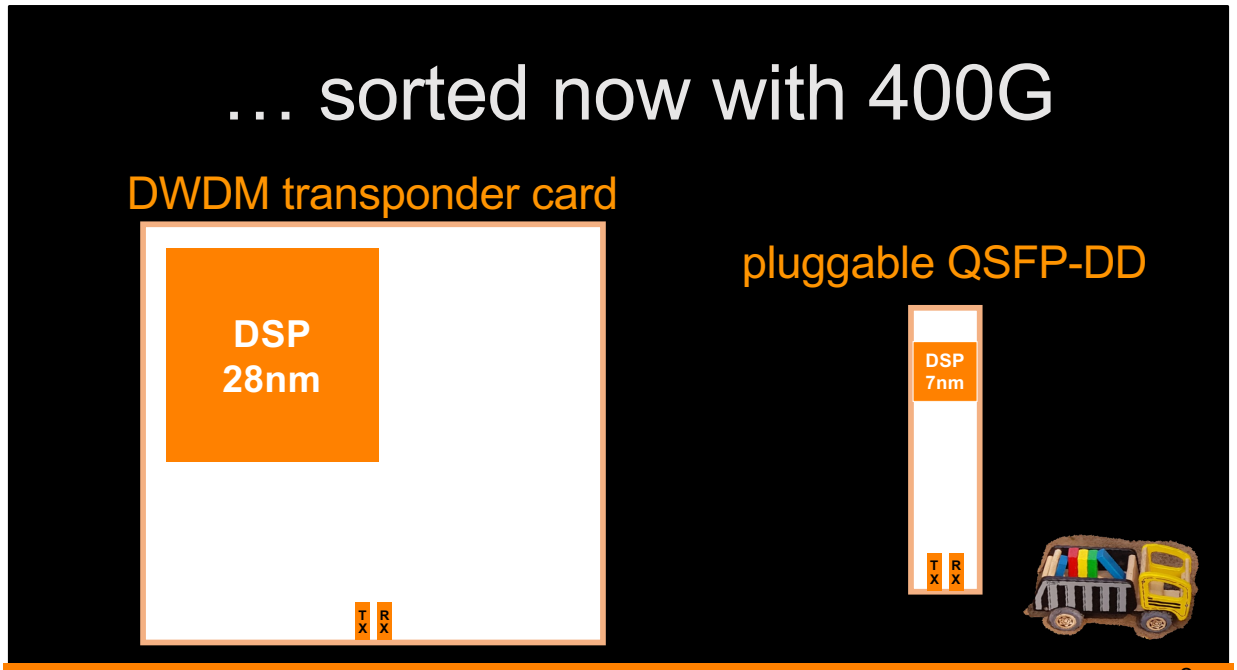
Coherent pluggable transceivers have been introduced with the speed of 400G. They will be a game changer in optical transmission and were coming to stay for a long time in networking. The Theory and practical usage / troubleshooting is addressed by this presentation.

100G ecosystem limits ...



- ratio of **power consumption** to formfactor
- focus on **inner datacenter links**
- **variation** of diverse hardware

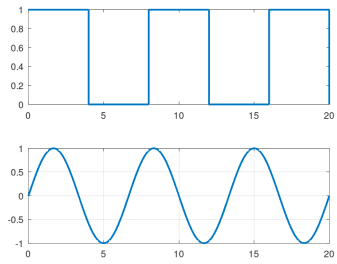
+ CFP provided a lot power (> 20Watt) but size was huge; implementation was very complicated. Not a lot adaopters of system manufacturers
+ CFP2 tried to catch up but never made it; CPAK was a Cisco proprietary solution
+ CFP4 never really launched
+ QSPF28 nice from factor, huge quantities but sadly only max. 5 Watt power consumption (incl. the switches and router did not provide enough power / cooling)



+ DSP have been arround for a while but latest chip manufacturing techniques and volume made small pluggables possible.
+ The DWDM transponder cards have been mainly used in metro and long haul transmission system and also for subsea links.
+ switching and routing hardware has sufficient power and cooling capabilities – see slide "analysis with the CLI" in the second part.
+ edge datacenters need high bandwidth interconnects between each other
+ only two formfactors – the widely used QSFP-DD and OSFP

Direct Detection Transceiver limits

With **higher** frequencies -> harder for Photodiodes to detect



Missed Opportunity: **Light** has more **Properties**

+ let's start with the challenges and problems with direct detection transceivers and higher frequencies.
+ only focusing on a frequency driven amplitude does miss further opportunities as photonic signal have more properties to observe; to do so a small system capable of doing more is needed to be build ...

Direct Detection Transceiver limits

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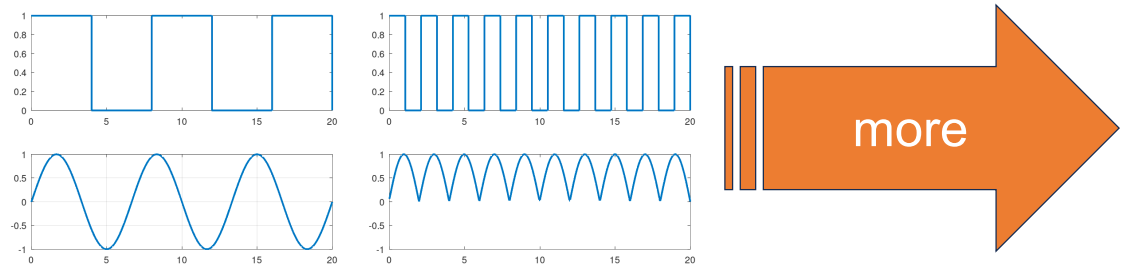

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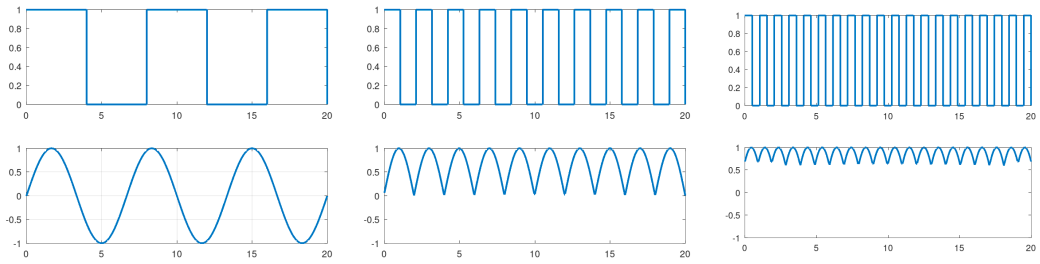
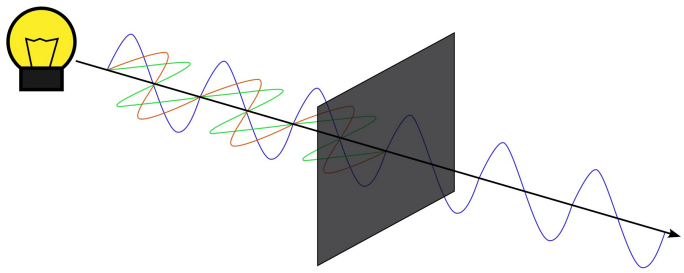


Missed Opportunity: **Light** has more **Properties**

+ let's start with the challenges and problems with direct detection transceivers and higher frequencies.
+ only focusing on a frequency driven amplitude (only 1bit/symbol for OnOff Keying modulation) does miss further opportunities as photonic signal have more properties to observe; to do so a small system capable of doing more is needed to be build ...

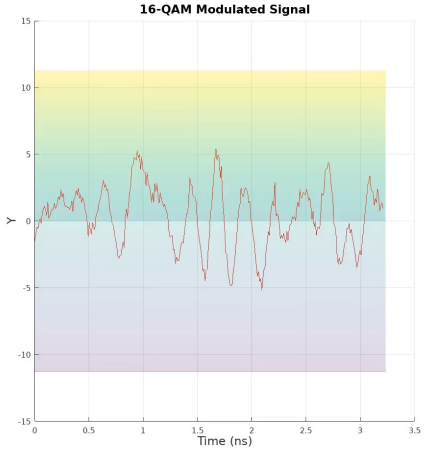
Main Properties of Photonic Waves

- Besides **Amplitude**, also **Phase** and **Polarisation**
- More properties per Carrier = Higher Bandwidth

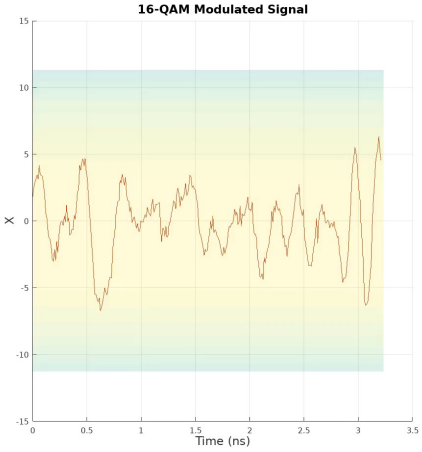


+ besides amplitude we can also send phase shifted wave. The first we look at is polarisation.
+ with a polarisation failter only certain directions are allowed and taken in consideration. We can use this to add more bits (higher density) per symbol to the transmission data. This is a very important characteristic for modulation.

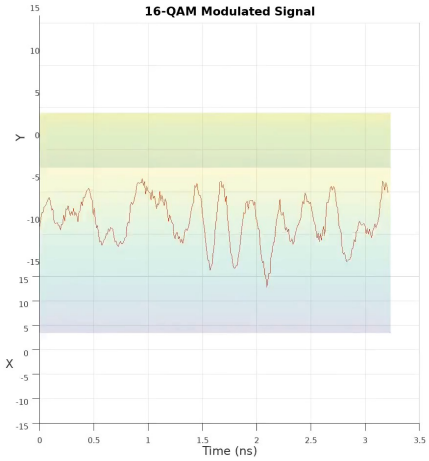
Polarisation Signal on X and Y Plane



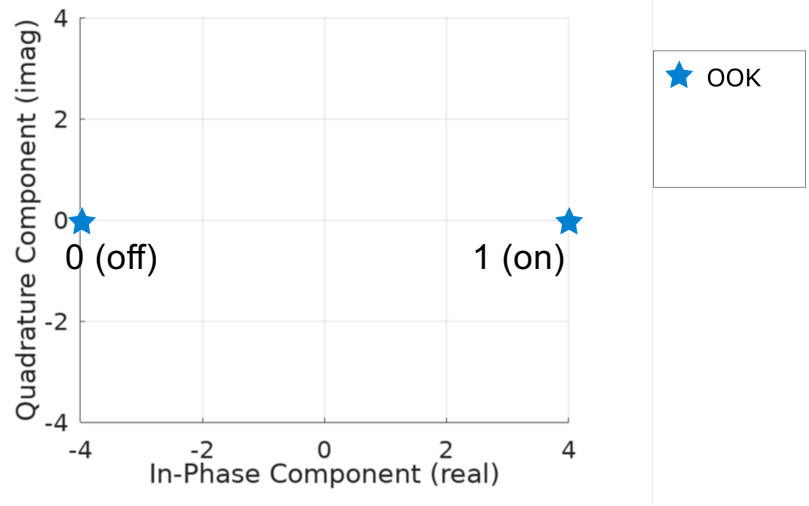
Polarisation Signal on X and Y Plane



Polarisation Signal on X and Y Plane



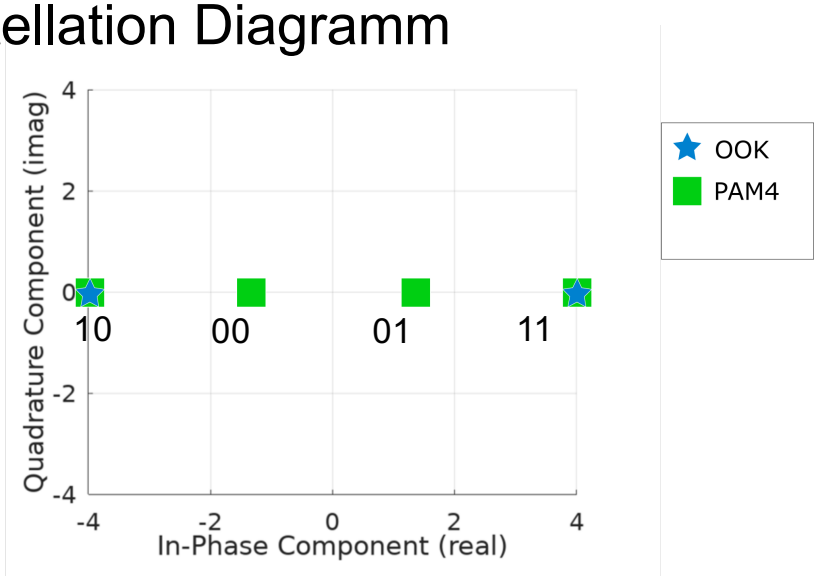
Constellation Diagramm



Considering on plane (either X or Y), a constellation provides a better overview for signales with many phases.

+ Now we see the NRZ (Non Return to Zero, an On-Off Keying variant) , which is not phase shifted, the values are kept on the In-Phase Axis

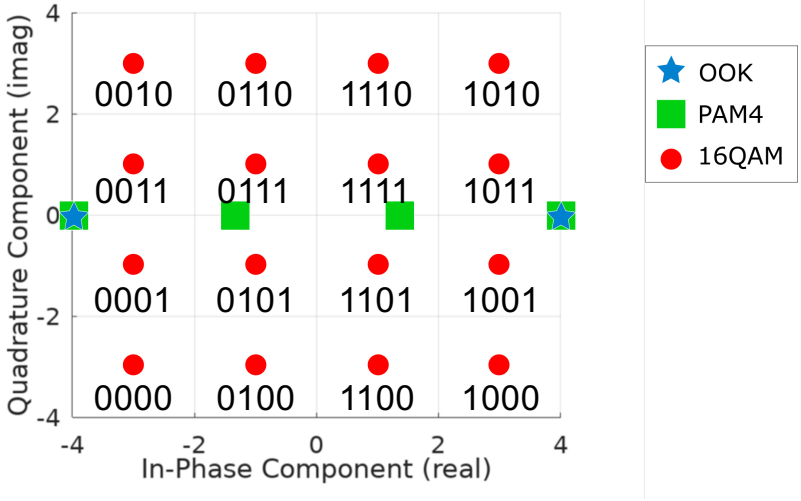
Constellation Diagramm



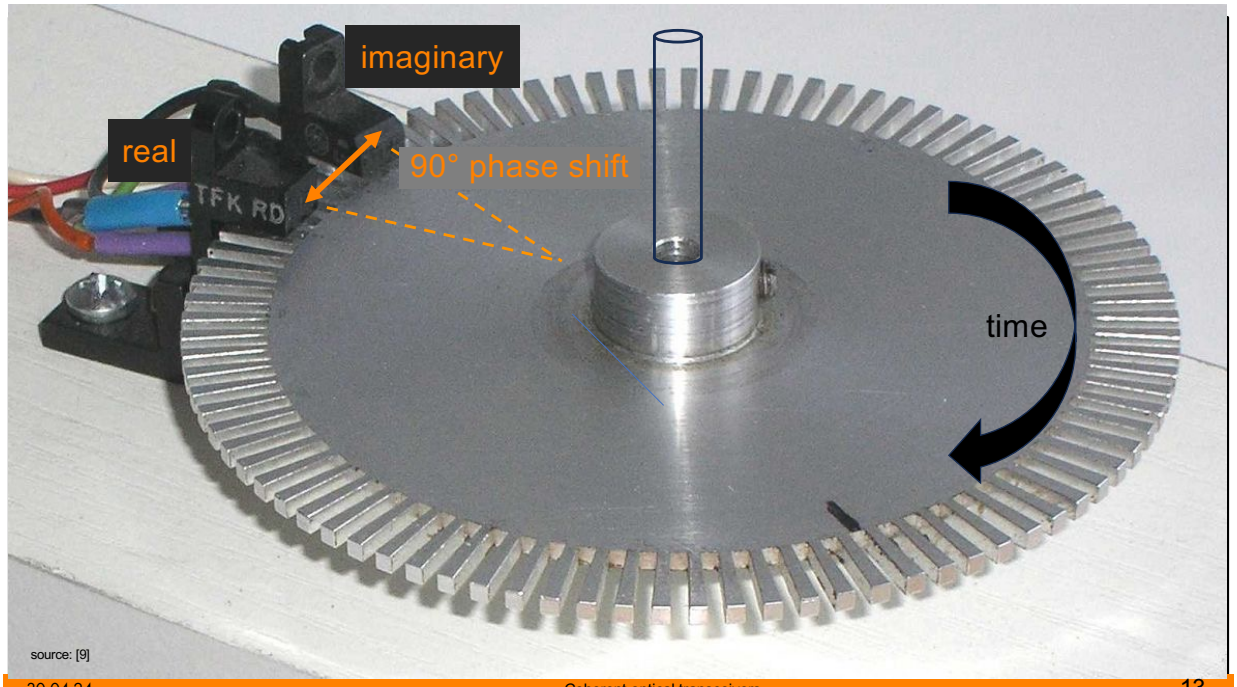
Same situation with PAM-4 (Pulse Amplitude Modulation with 4 Levels, 2bit/symbol) only has the In-Phase components (real), no imaginary part

Constellation Diagramm

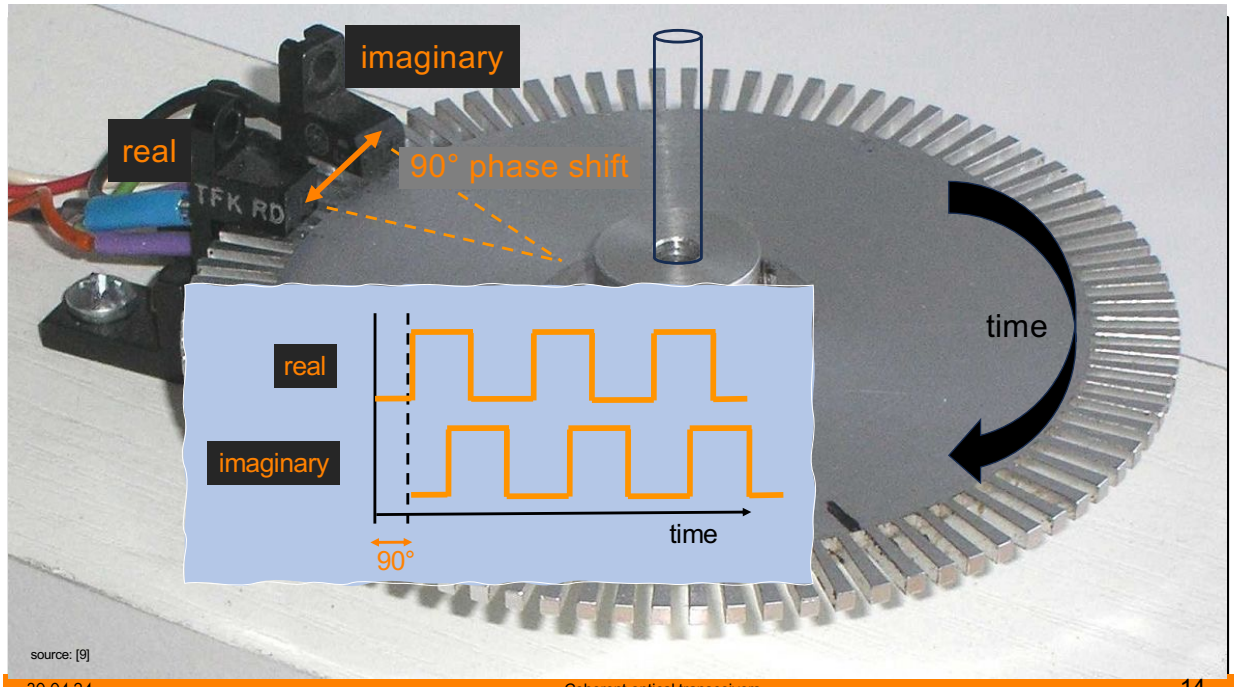
90° phase shifted amplitude



+ And the 16 QAM (Quadrature Amplitude Modulation), 16 because 16 symbols. And instead of watching a time windows, we just scatter for every symbol to the complex plane wherever it belongs.
Talking about real and imaginary number, in terms of signal modulation we just use In-Phase (0 degrees) and Quadrature (90 degrees). As you can see in case of 16 QAM there always is an amplitude and phase angle given that belong to the given symbol.
16QAM: 4bit/symbol
+ amplitude measurement with two samples, shifted by ¼ Wavelength to get real and imaginary number; see optical rotary encoder as mechanical solution



+ Rotary optical encoder in the analog world to represent QAM, the slices in the disc encode 1s
+ Phase shift by 90° due position of the photo sensor and the corresponding frequency; the higher the frequency the closer both photo sensor need to be placed keeping the same phase shift of 90°



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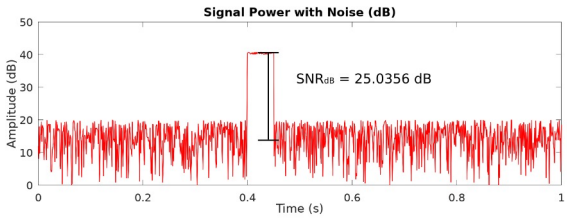
Measuring Signal Quality

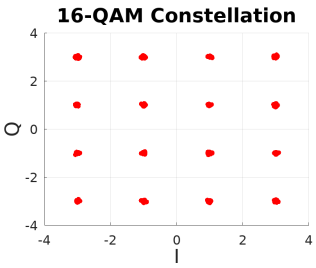
- **SNR** = Signal-to-Noise-Ratio
- Convenience of using decibels for **small** and **large** values
- (e)SNR vs OSNR:

  electrical vs **optical**

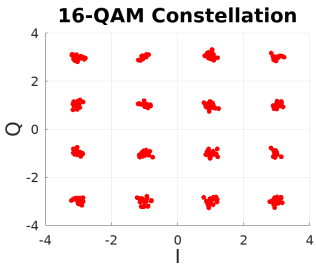


SNR is the ratio between the desired signal and the noise. Analog world example is a presentation. If the audience is quiet you can hear the speaker quite good, the SNR is quite high. If the audience is loud the SNR gets worse (e.g. also applies to a cheering soccer stadium)
For signal quality we define two properties from different worlds:
+ for people with focus on control circuits there is SNR: The higher the better (see the peak of the signal in the diagramm)
+ there is a relationship between the Bit Error Rate (BER)and SNR; SNR does influences how good or bad the BER will be at the end.

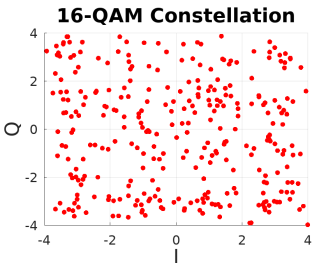
Phase and Amplitude Errors



SNR = 30 dB



SNR = 20 dB



SNR = 5 dB

NOTE: Polarisation Error not considered

Comparing SNR values between 30, 20 and 5dB; you can clearly see which signal can still be recovered properly and which are properly lost.
Bit Error Ratio and SNR as correlated values to measure, but what more complex statistics. What for example if you want to know the error distribution of your probes. Standard deviation, median, mean values.

NOKIA SR-OS and 400G ZR Transceiver

source:Daniel Melzer; DE-CIX

+  =

source: https://www.flexoptix.net/en/d-co164hg-2-yt.html

terrific coherent workshop with

DE CIX

together with Daniel Melzer from DE-CIX we did a great workshop understanding the Nokias CLI output – this was in October 2023

config with the CLI

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

===============================================================================
QSFP-DD Connector
===============================================================================
Description        : -
Interface          : 8/1/c7
FP Number          : 2                         MAC Chip Number  : 3
...
Breakout           : c1-400g
RS-FEC Config Mode : None

Transceiver Data

Transceiver Status : operational
Transceiver Type   : QSFP-DD                   DCO              : Enabled
Model Number       : 3HE16564AARA01  NOK  INUIAPHHAA
TX Laser Wavelength: 1558.983 nm               Present Channel  : 23
                                               Configured Chann*: 23
Laser Tunability   : flex-tunable
Config Freq (MHz)  : 0                         Min Freq(MHz): 191300000
Oper Freq(MHz) :192300000                      Max Freq(MHz): 196100000
Fine Tune Range    : 6000 MHz                  Fine Tune Resolu*: 1 MHz
Supported Grids: 100GHz 75GHz 50GHz 25GHz 12.5GHz 6.25GHz
Diag Capable       : yes
Number of Lanes    : 1
Connector Code     : LC                        Vendor OUI       : 20:20:20
Manufacture date   : 2021/12/12                Media            : Ethernet
...
```

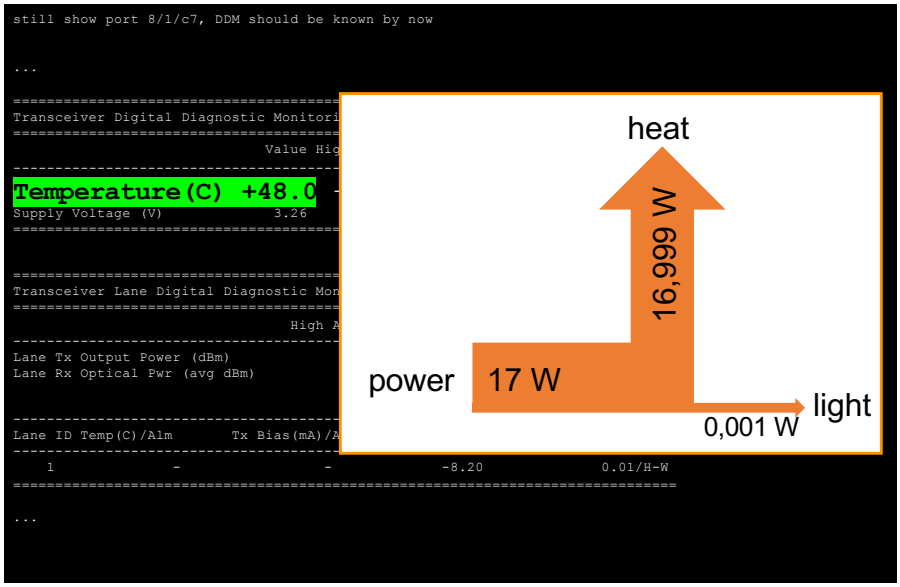

A fully tunable DWDM transceiver. Currently tuned at Channel 23 (192,30 GHz)

analysis with the CLI

```
still show port 8/1/c7, DDM should be known by now

...

================================================================================
Transceiver Digital Diagnostic Monitoring (DDM)
================================================================================
                            Value High Alarm  High Warn   Low Warn  Low Alarm
--------------------------------------------------------------------------------
Temperature(C)  +48.0 +80.0 +75.0 +15.0 -5.0
Supply Voltage (V)           3.26      3.46       3.43       3.17       3.13
================================================================================


================================================================================
Transceiver Lane Digital Diagnostic Monitoring (DDM)
================================================================================
                                 High Alarm   High Warn    Low Warn   Low Alarm
--------------------------------------------------------------------------------
Lane Tx Output Power (dBm)             0.00       -2.00      -13.00      -14.00
Lane Rx Optical Pwr (avg dBm)          2.00        0.00      -21.02      -23.01


--------------------------------------------------------------------------------
Lane ID Temp(C)/Alm       Tx Bias(mA)/Alm   Tx Pwr(dBm)/Alm   Rx Pwr(dBm)/Alm
--------------------------------------------------------------------------------
    1             -                 -             -8.20             0.01/H-W
================================================================================

...
```


1. DDM should be implemented by now and your NMS is capturing this data
2. Monitor the temperature – refer to "unsupported" platforms as such a transceiver can draw up to 17 Watt per port. With 30 ports you end up with roughly 500 Watts for the optical transmission.

analysis with the CLI



Only a very small portion of the electrical energy is used for the optical side. The major part is converted into heat, as this simple Sankey Diagram shows

the interesting part

```
still show port 8/1/c7, now it becomes tricky

...

================================================================================
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
================================================================================
```


these are the coherent specific parameters in the CLI

RX Channel

```
still show port 8/1/c7, the receiver requires its own laser

...

===============================================================================
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
```

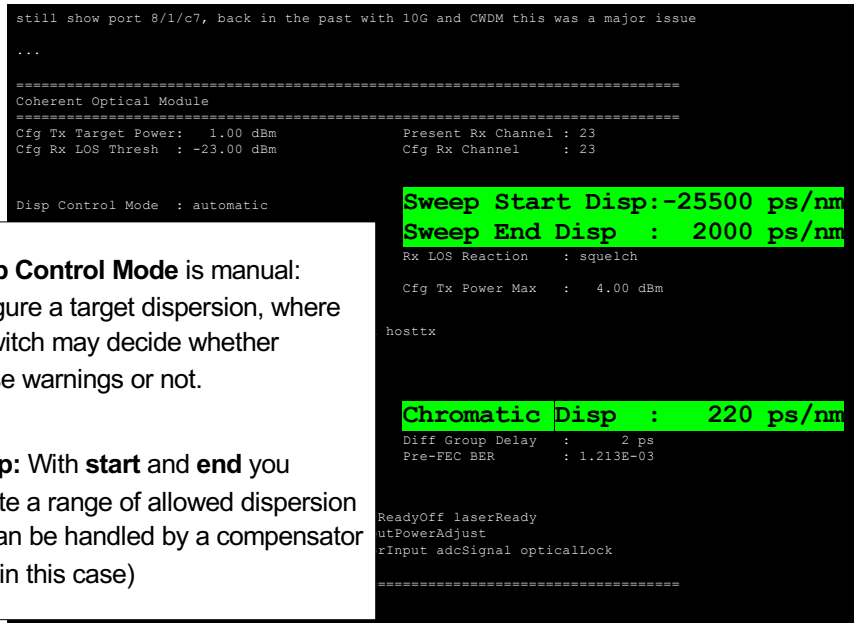
required to establish the link, no sweeping

```
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
===============================================================================
```


+ center frequence of the Optical Local Oscillator (OLO). The OLO is a laser – either a dedicated one or taken from TX. This is required to gather the desired signal from the carrier

+ this is a new approach. In the past with 10G tunable DWDM only TX required tuning – RX took basically "all".

Chromatic Dispersion (CD)

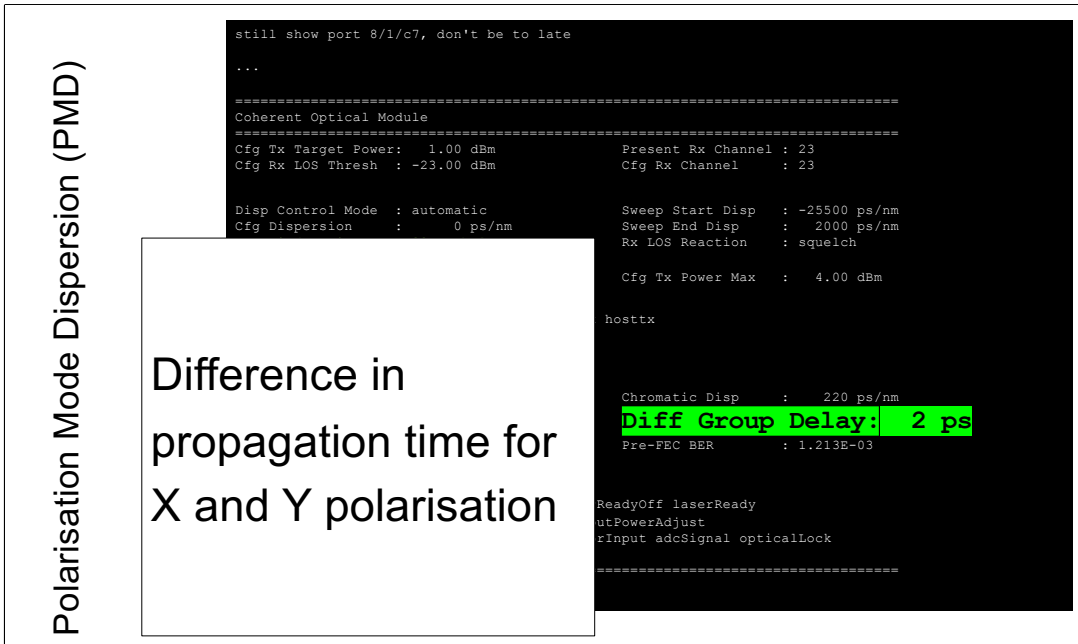


If **Disp Control Mode** is manual:
Configure a target dispersion, where the switch may decide whether to raise warnings or not.

Sweep: With **start** and **end** you indicate a range of allowed dispersion that can be handled by a compensator (DSP in this case)

+ CD is the change of the variance while the signal (propagation speed is either decelerated or accelerated) is traversing the fiber. Very well known back in the days when operating 10G CWDM networks. 1310nm window (O-band) was not an issue but longer wavelength in the L-Band arround 1610nm had significant issues with CD on longer spans.
+ the DSP can sweep through a certain range and identify / measure the propagation swift / chromatic dispersion
+ the CLI output is based on a 15km of fiber span (10ps/nm/km) - some offset of 70-80ps/nm (still unknown where they are coming from as they are showed even at a back-to-back link which has 0ps/nm)

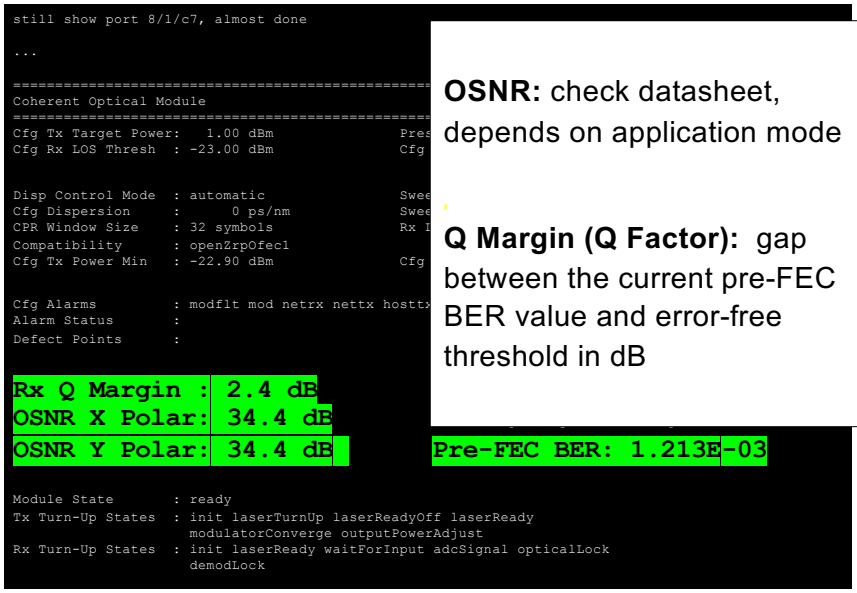
Polarisation Mode Dispersion (PMD)



Difference in propagation time for X and Y polarisation

+ DGD is a characteristic of the fiber and influences the two polarziations (X and Y).
+ typically a QSFP-DD 400G OIF 400ZR can compensate up to 10ps. Please check its datasheet.

Signal-to-Noise Ratio (SNR)



OSNR: check datasheet, depends on application mode

Q Margin (Q Factor): gap between the current pre-FEC BER value and error-free threshold in dB

+ Rx Q Margin is defined by Nokia. Industry calls it Q Factor
+ Typical OIF 400ZR transceiver can handle OSNR of up to 26dB

+ a back-to-back look like this:

Rx Q Margin	: 4.1 dB	Chromatic Disp	: 80 ps/nm
SNR/OSNR X Polar	: 28.2 dB / 29.7 dB	Diff Group Delay	: 3 ps
SNR/OSNR Y Polar	: 28.2 dB / 29.7 dB	Pre-FEC BER	: 5.180E-04

+ Error Vector Magnitude:

1. EVM (error vector magnitude; the intuitive approach of taking the distance of a measured point from the closest ideal constellation point.)
2. SNR (von EVM abgeleitet, auch MER genannt)
3. BER (vorhergesagt durch EVM)

Compatibility / Application Mode

```
still show port 8/1/c7, !??

...

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Compatibility:  openZrpOfec1
Cfg Tx Power Min    : -22.90 dBm             Cfg Tx Power Max   :   4.00 dBm
```
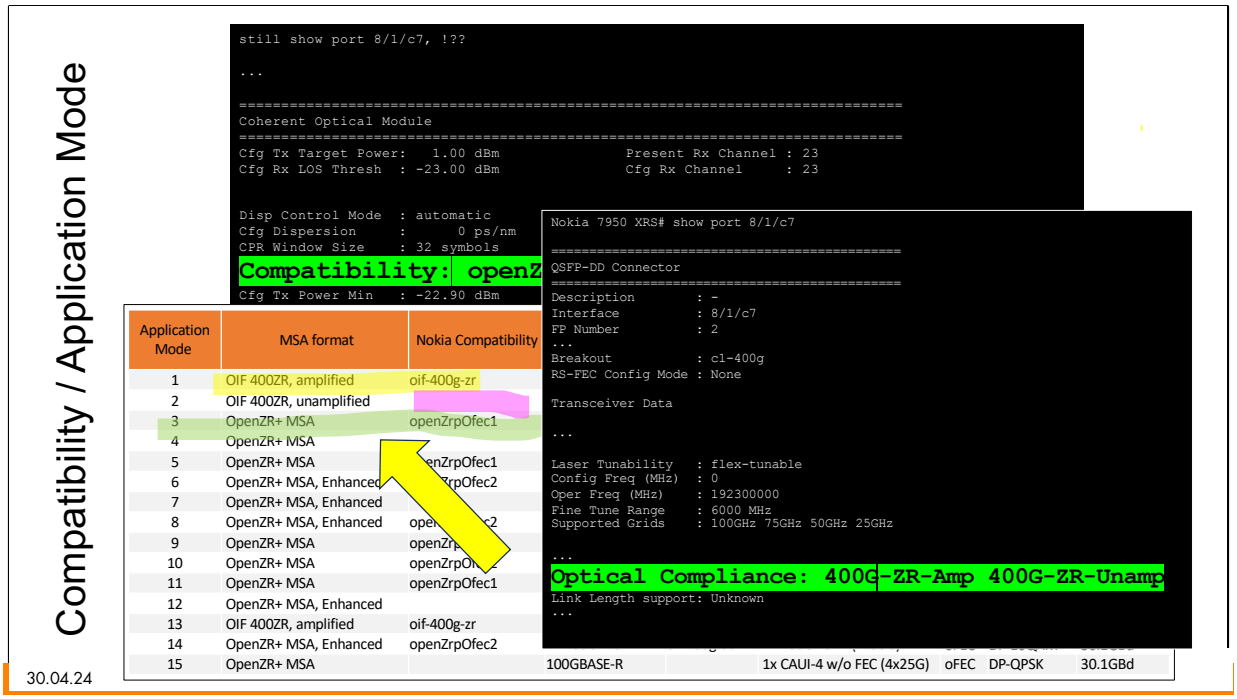

Application Mode	MSA format	Nokia Compatibility	Host format	Nokia Config	Electrical interface	FEC	Modulation	Line Symbol Baud Rate
1	OIF 400ZR, amplified	oif-400g-zr	400GBASE-R	c1-400g	1x 400GAUI-8 (8x 50G)	CFEC	DP-16QAM	59.8GBd
2	OIF 400ZR, unamplified		400GBASE-R		1x 400GAUI-8 (8x 50G)	CFEC	DP-16QAM	59.8GBd
3	OpenZR+ MSA	openZrpOfec1	400GBASE-R	c1-400g	1x 400GAUI-8 (8x 50G)	oFEC	DP-16QAM	60.1GBd
4	OpenZR+ MSA		2x 200GBASE-R		2x 200GAUI-4 (4x 50G)	oFEC	DP-16QAM	60.1GBd
5	OpenZR+ MSA	openZrpOfec1	4x 100GBASE-R	c4-100g	4x 100GAUI-2 (2x 50G)	oFEC	DP-16QAM	60.1GBd
6	OpenZR+ MSA, Enhanced	openZrpOfec2	400GBASE-R	c1-400g	1x 400GAUI-8 (8x 50G)	oFEC	DP-16QAM	60.1GBd
7	OpenZR+ MSA, Enhanced		2x 200GBASE-R		2x 200GAUI-4 (4x 50G)	oFEC	DP-16QAM	60.1GBd
8	OpenZR+ MSA, Enhanced	openZrpOfec2	4x 100GBASE-R	c4-100g	4x 100GAUI-2 (2x 50G)	oFEC	DP-16QAM	60.1GBd
9	OpenZR+ MSA	openZrpOfec1	2x 100GBASE-R	c2-100g-aui2	2x 100GAUI-2 (2x 50G)	oFEC	DP-QPSK	60.1GBd
10	OpenZR+ MSA	openZrpOfec2	1x 100GBASE-R	c1-100g-aui2	1x 100GAUI-2 (2x 50G)	oFEC	DP-QPSK	30.1GBd
11	OpenZR+ MSA	openZrpOfec1	3x 100GBASE-R	c3-100g	3x 100GAUI-2 (2x 50G)	oFEC	DP-8QAM	60.1GBd
12	OpenZR+ MSA, Enhanced		3x 100GBASE-R		3x 100GAUI-2 (2x 50G)	oFEC	DP-8QAM	60.1GBd
13	OIF 400ZR, amplified	oif-400g-zr	4x 100GBASE-R	c4-100g	4x 100GAUI-2 (2x 50G)	CFEC	DP-16QAM	59.8GBd
14	OpenZR+ MSA, Enhanced	openZrpOfec2	2x 100GBASE-R	c2-100g-aui2	2x 100GAUI-2 (2x50G)	oFEC	DP-16QAM	30.1GBd
15	OpenZR+ MSA		100GBASE-R		1x CAUI-4 w/o FEC (4x25G)	oFEC	DP-QPSK	30.1GBd

+ SR-OS23.10.R1: openZrpOfec1 (according Nokia CLI reference guide it is called "open-zr-ofec1"
+ a 400G coherent transceiver does support more than just plain 400G; there are so called "application modes" and you can choose between 10 – 15 different application modes, e.g. 2 x 200G or 4 x 100G operations. This depends on the DSPs firmware capabilities and implementation.



+ Inconsistent – compatibility is set to openZrpOfec1 although the transceiver supports only OIF 400 ZR amplified and unamplified

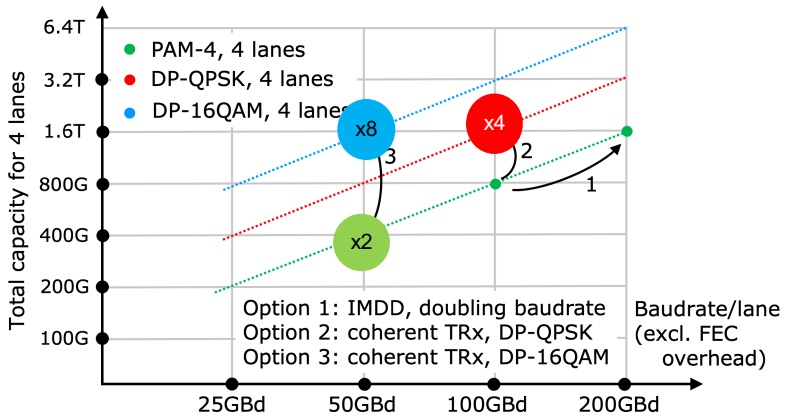
+ SR-OS23.10.R1 has the following optical compliance:

1. ZR400-OFEC-16QAM
2. ZR300-OFEC-8QAM
3. ZR200-OFEC-QPSK
4. ZR100-O

OIF 400ZR vs. OpenZR+ MSA optical parameters

	OIF 400ZR	OpenZR+ MSA	
		60LA	60HA
max. TX power	-6 dBm	-10 dbm	0 dBm
min. RX power	-12 dBm	-12 dBm	-12 dBm
CD Tolerance	2,400 ps/nm	20,000 ps/nm	
PMD Tolerance	10 ps	20 ps	
OSNR Tolerance	26 dB	24 dB	

more bandwidth for 800G, 1.6T or 3.2T with coherent



source: [1]

+ Result: with pure compute power of the DSP we can increase bandwidth multiple times.

+ diagramm : reference is 50Gbaut NRZ; the initial situation is 100Gbit/s (PAM-4 modulation with 50Gbaud) on 4 lanes = 400GBit. (x2); Modulation is an important key to increase bandwidth

+ different datarate based on formfactors:

1. 400G used PAM-4 on 8 lanes (each running 50Gbit/s PAM-4) modulation and doubles the symbol rate to 2 bits/symbol; applies to QSFP-DD and OSFP; QSFP112 has 4 lanes each handling up to 100Gbit/s PAM-4
2. 800G uses PAM-4 on 8 lanes (each running 100Gbit/s PAM-4); there are plans to run 200Gbaud per lane for 1,6T (8 lanes); QSFP-DD800 or OSFP
3. 1.6T based on OSFP-XD has 16 lanes each handling up to 100Gbit/s

+ with DP-16QAM on the optical path you get 4 bits/symbol x 2 polarizations (x8) with 50Gbaud = 400Gbit/s per lane (4 lanes = 1,6T)

Want to learn for yourself?

Your switch gear
\+ our coherent optics
= **less hickups, more knowhow**

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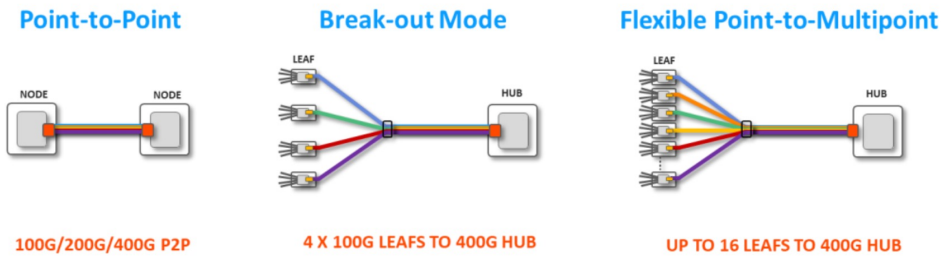
gerhard.stein@flexoptix.net

We are happy to do more testing in different gear of various vendors.
Feel free to contact us: thomas.weible@flexoptix.net and gerhard.stein@flexoptix.net

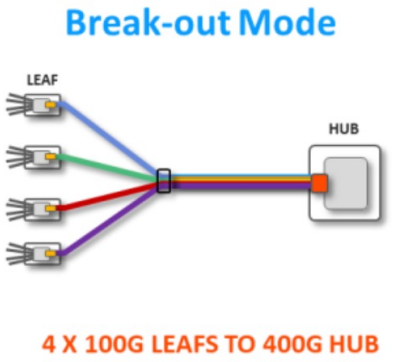
Outlook: OpenXR 16 x 25Gbit/s via DSCM



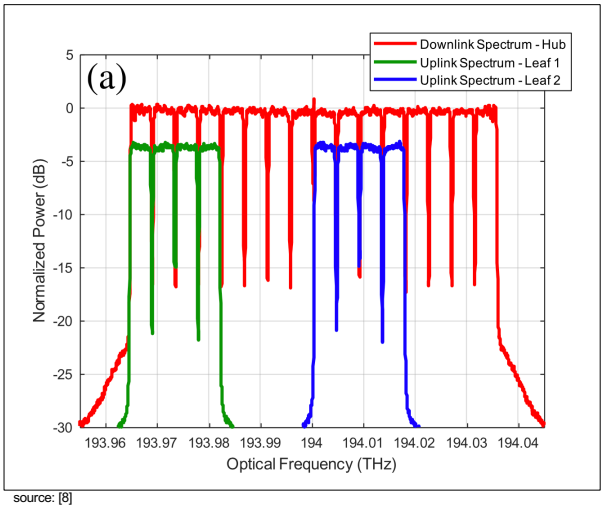
source: [7]

Flexible Point-to-Multipoint: make full use of the DSP capabilities to generate different channels and distinguish between them
OpenXR is another forum of vendors like OpenZR+ and OIF

Outlook: DSCM (Digital SubCarrier Multiplexing)



source: [7]



source: [8]

note: only the spectrum for 2 x 100G is shown in the diagramm

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