1

Performance oriented DSP design for flexible coherent transmission

Abstract

We review the impact of DSP in terms of **performance** and **flexibility** in the data network. DSP has addressed the optimization of capacity against reach and power. Future DSP targets cost-reduction through flexible point-to-multi-point architectures.

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2

2

Outline

- Flexibility ?
- Background and History
- Coherent Transceivers
- Flexible Spectral usage
- Flexible DSP : Long filters and FFTs
- Flexible multi-format DSP
- Flexible Networks and sub-carriers
- Summary

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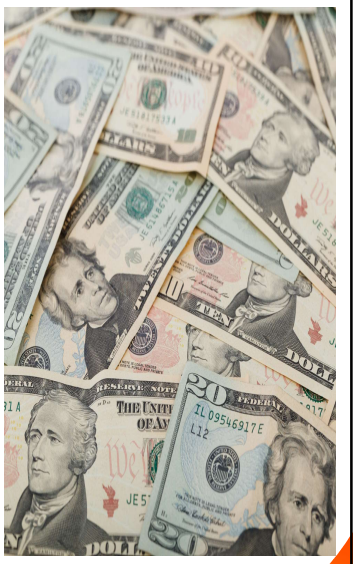
3

3

Why is flexibility of interest ?

- Lower inventory costs.
  - Same product for longhaul / Metro
- ASICs cost a lot to develop.
  - Share development costs
- Fibre bandwidth is a scarce resource
  - Maximise Capacity
  - Maximise Reach
- Cost-models / Easy upgrades
  - Same HW product but with SW switches
- Pluggable modules
  - Flexibility through multiple suppliers
  - Easy replacement



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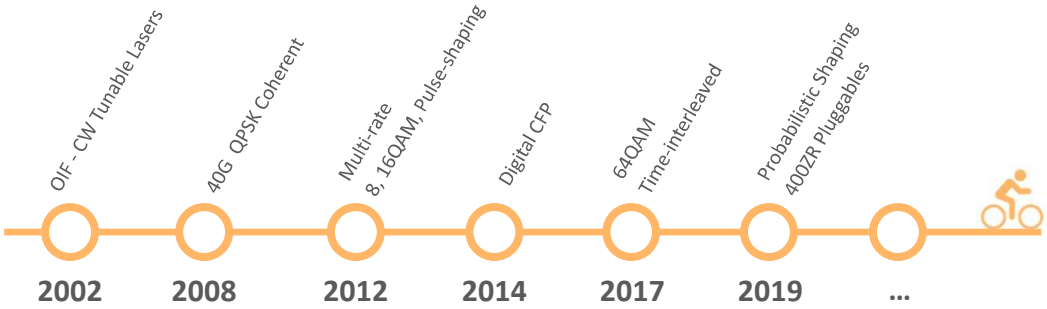
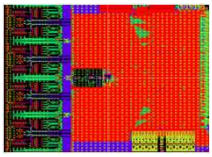
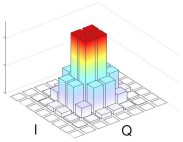
4

4

Timeline







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Coherent transceivers

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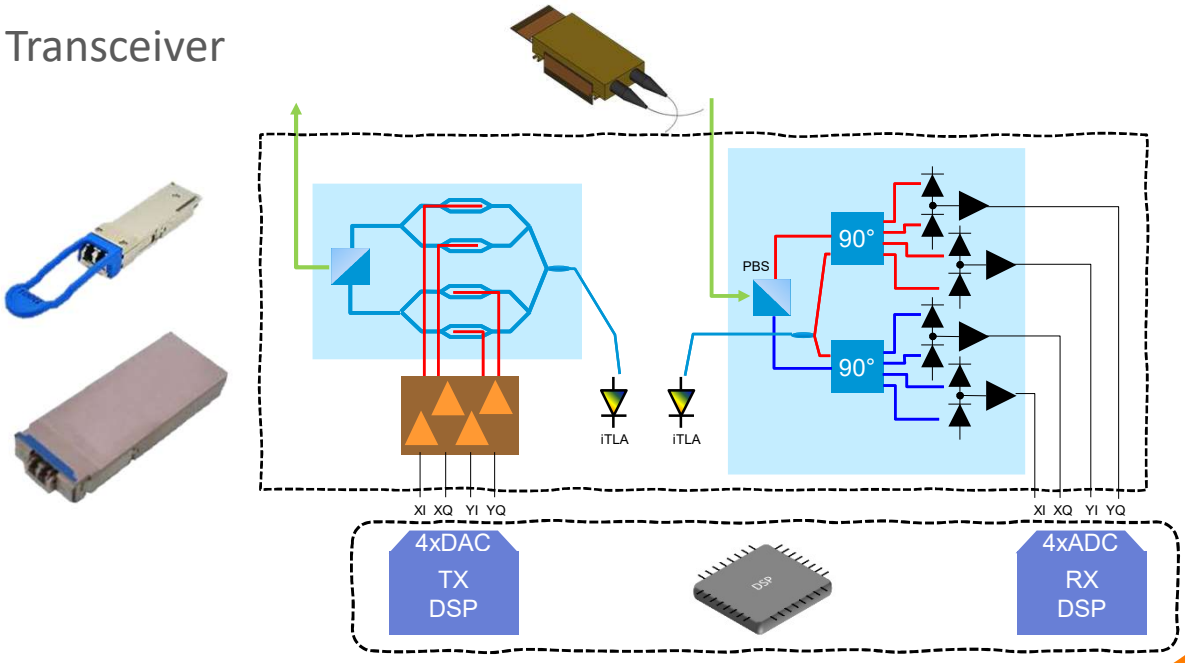
Transceiver



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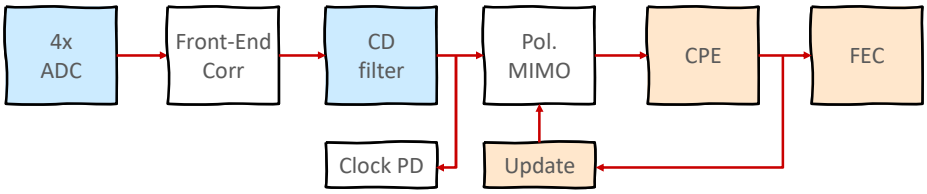
7

7

Line-side DSP



- Adding flexibility affects many parts of the design, and the power
- Modulation format
  - CPE/FEC/MIMO-update
  - Resolution, CD compensation
- Sampling-rate

S.J. Savory, "Digital filters for coherent optical receivers," Opt. Exp., vol. 16, no. 2, pp. 804-817, 2008
S. J. Savory, "Digital coherent optical receivers: Algorithms and subsystems, " IEEE J. Sel. Top. Quantum Electron., vol. 16, no. 5, pp. 1164 –1179, 2010.
M. Kuschnerov et al., "DSP for coherent single-carrier receivers," J. Lightw. Technol., vol. 27, no. 16, pp. 3614–3622, 2009.

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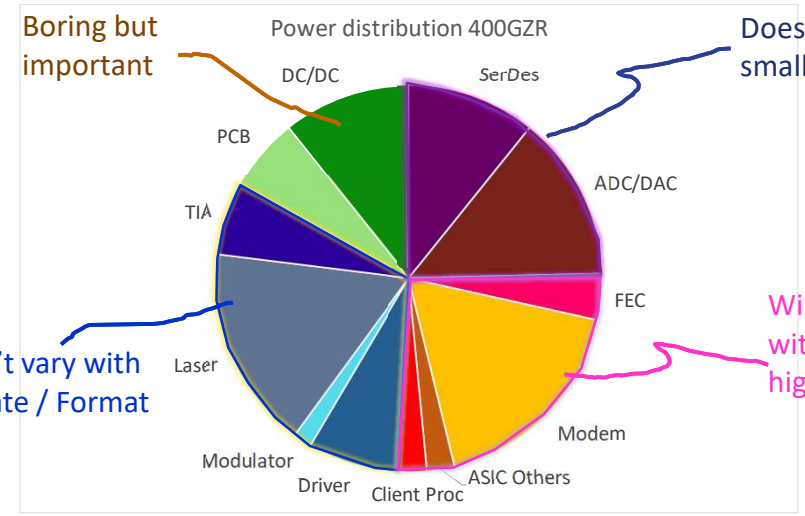
8

8

Power



based on "400ZR Modulation options" OIF2017.049.01
From ECOC Workshop 2018

- Module power dissipation limit
- Some power contributors do not change with capacity.

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9

9

Flexible Spectral Usage

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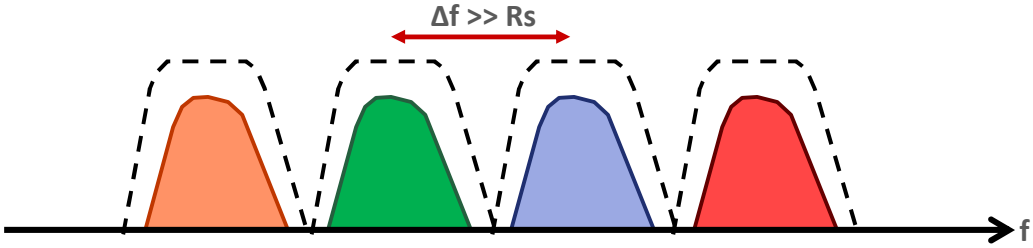
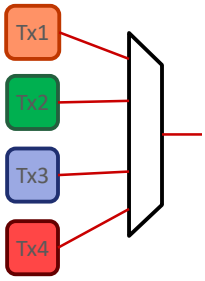
Flexible Spectral Usage





- AWG filter to combine wavelengths
- Wasted bandwidth
- Fixed channel spacing

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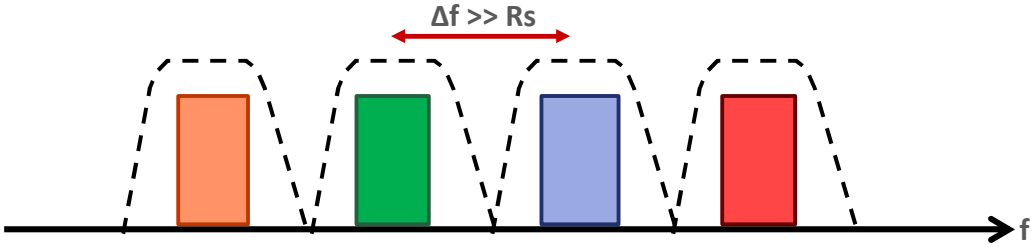
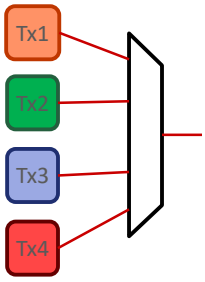
11

11

Flexible Spectral Usage





- Nyquist pulse shaping narrows the transmitted spectrum

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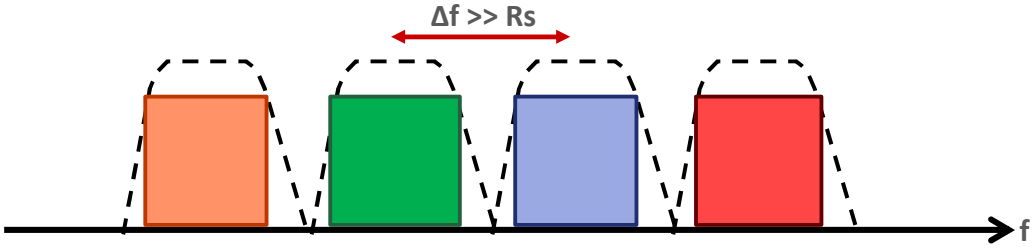
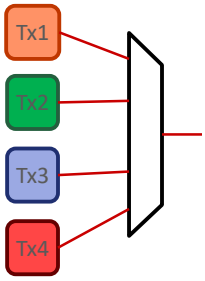
12

12

Flexible Spectral Usage





- Nyquist pulse shaping narrows the transmitted spectrum
- Higher line-rates can pass through same filters

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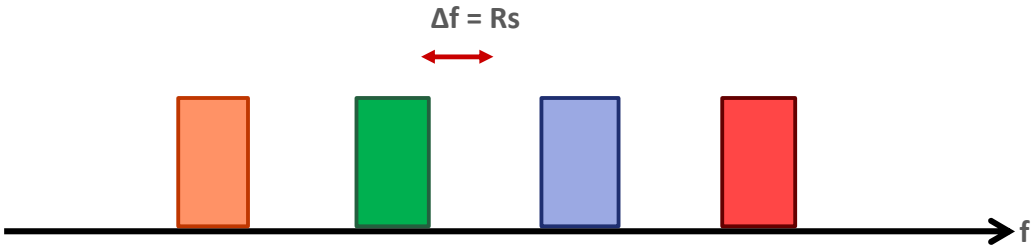
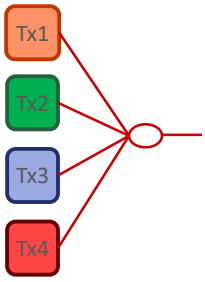
13

13

Flexible Spectral Usage





- Nyquist pulse shaping narrows the transmitted spectrum
- Higher line-rates can pass through same filters
- Cheaper combiners can be used
- Spectrum can be packed into “Super-Channels”

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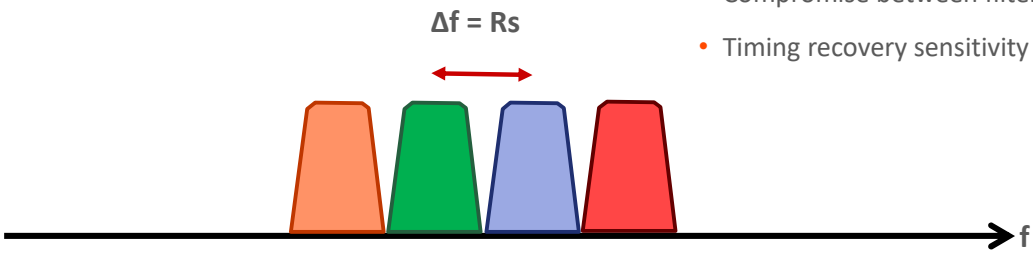
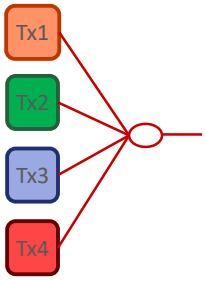
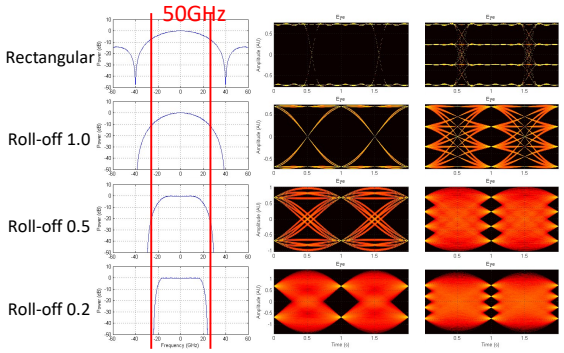
14

Flexible Spectral Usage

- Compromise between filter length
- Timing recovery sensitivity







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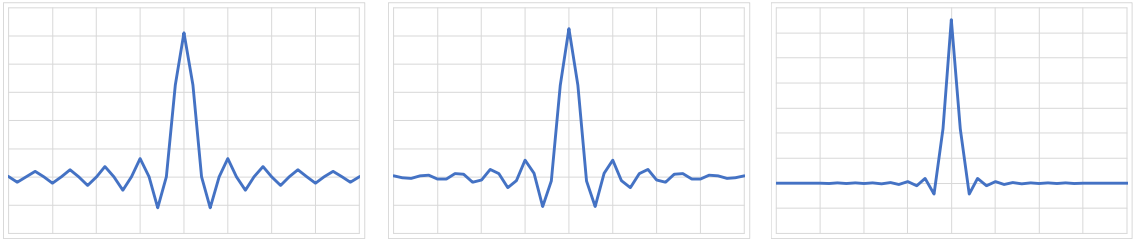
15

15

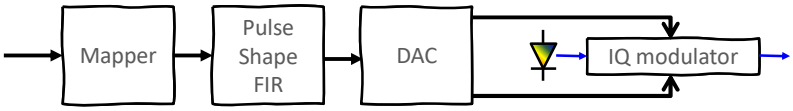
Flexible Spectral Usage :: DSP requirements

RRC pulse shapes for 2x Oversampling



RRC 0.01 RRC 0.2 RRC 1.0

- Sharper frequency responses require longer impulse lengths
  - Long FIR filters



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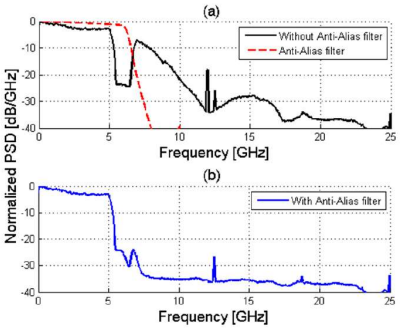
16

16

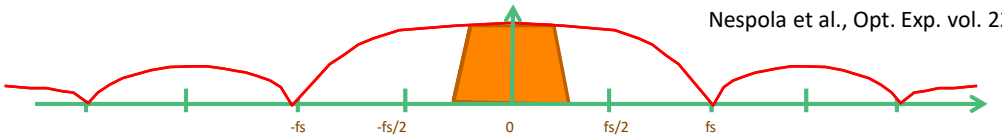
Anti-aliasing filters

Discrete Time → DAC → Continuous Time

2 samples/sym



Nespola et al., Opt. Exp. vol. 22, p. 1796, 2014



- Aliasing can occur in DAC (as in ADC)
- If DAC BW is infinite, there will be an infinite no. copies of our discrete signal x sinc function.
- Filtering is required to remove these copies.
  - No interference from neighbouring channels

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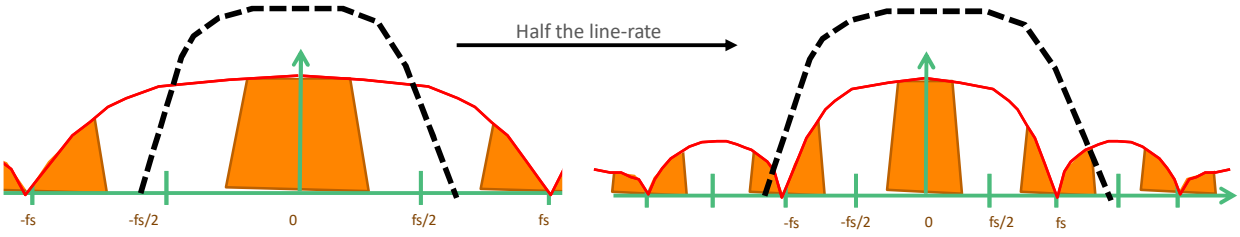
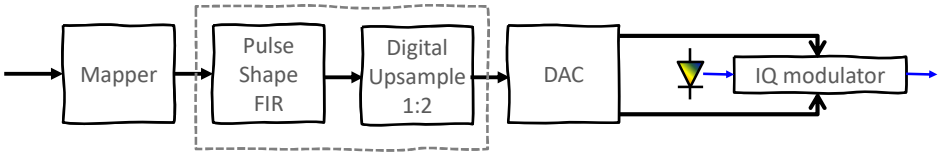
17

17

Anti-aliasing filters and flexible line-rate





- Analogue anti-aliasing filters tend to be fixed
- Just changing DAC sampling rate leads to aliasing noise
- Digital resampling preferred, with DAC rate constant

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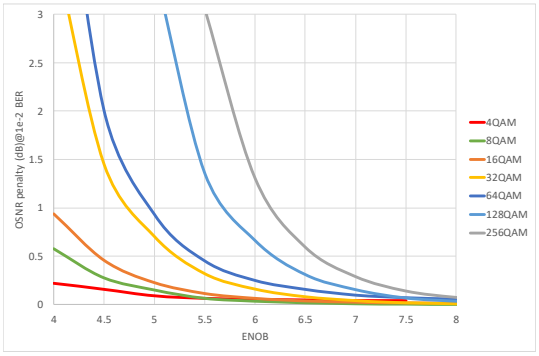
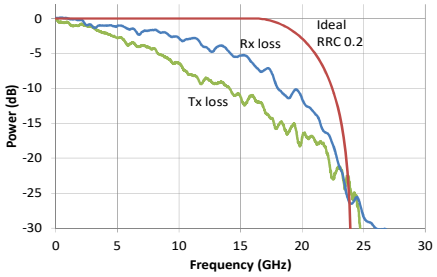
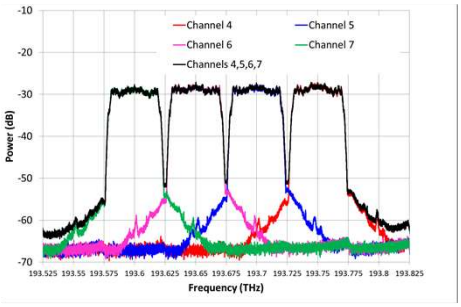
18

18

ADC/DAC resolution







- QPSK → 16-QAM → 64-QAM : +1 bit per step
- >5.5 Effective Number of Bits (ENOB) required for 64-QAM
- ENOB needs to be chosen for highest order modulation
- Sampling rate needs to be chosen for highest line-rate
  - At least 2x bandwidth of input signal (Roll-off important)
- Anti-aliasing filters need to suppress image spectrum
- Filtering losses can be compensated digitally at expense of ENOB

Fludger et al., Paper Th1B.3, OFC2016

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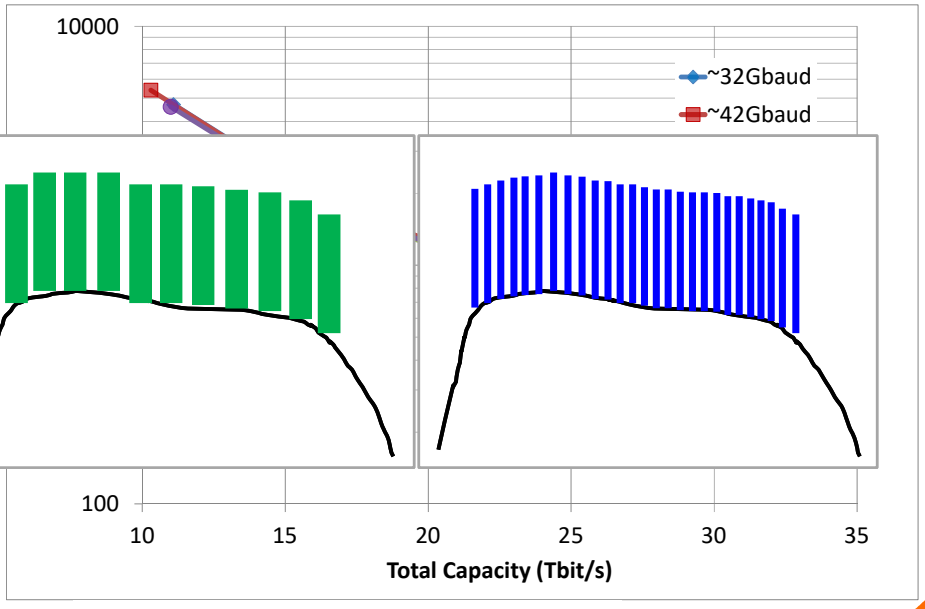
19

19

Baudrate & Format

- Reach vs Capacity same
  - Some NL benefit with low
- Less boxes for same capa
- device cost (chip + optics same or increase margina



GN model simulations for 100km spans of NDSF, 0.2dB loss, 5dB NF EDFA

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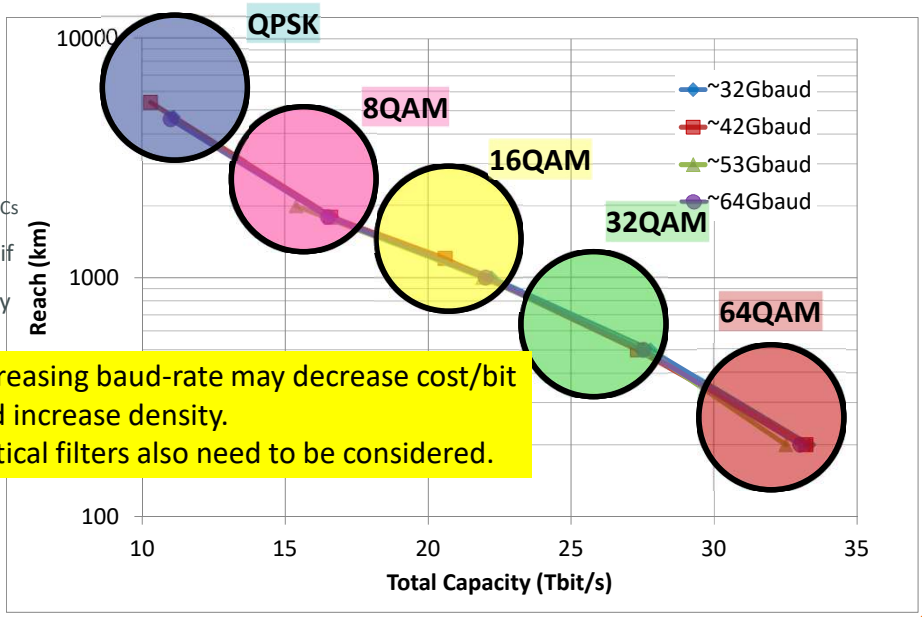
20

20

Baudrate & Format

- Reach vs Capacity same
  - Some NL benefit with low BW SCs
- Less boxes for same capacity if
- device cost (chip + optics) stay same or increase marginally



Increasing baud-rate may decrease cost/bit and increase density.
Optical filters also need to be considered.

GN model simulations for 100km spans of NDSF, 0.2dB loss, 5dB NF EDFA. Capacity not subtracting overhead

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21

21

Notes on variable line-rate

- Higher line-rate decreases the number of boxes
- Potentially decrease the cost/bit.
- Compatibility with existing optical filters
- Lowering the line-rate doesn't use full potential of the hardware
- VCXO control for fine tuning.
- Wide tuning (96, 64, 32 Gbaud) better done digitally
  - Anti-aliasing of neighbour channels
  - Tuning range of PLL in ADC/DAC
  - Fixed interpolation filters may be employed.

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22

22

Flexible DSP
Long filters and FFTs

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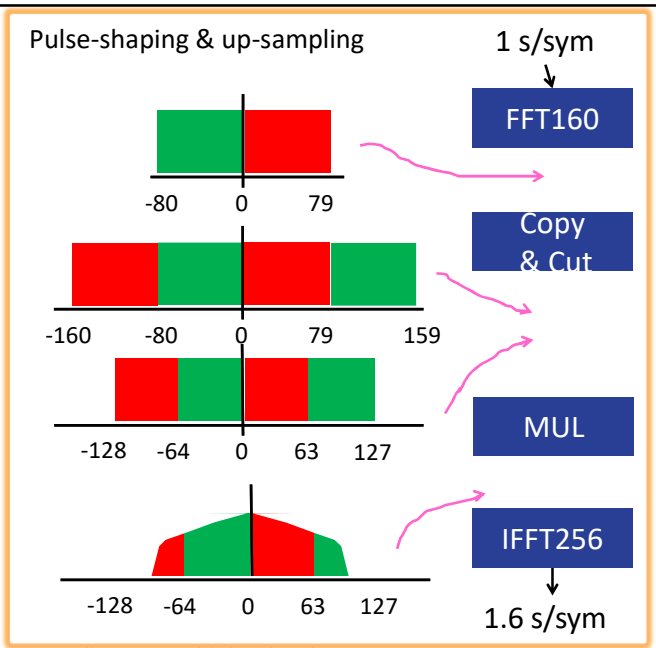
23

FFT applications

1. DMT / SC transmission
   FFT + IFFT < 300mW for 256SC in 28nm CMOS [1]
2. Up/ Down-sampling [2]
3. Convolution
   - Long filters



[1] I. Dedic, "Implementation of DMT transceiver for 400GbE 2km and 10km PMD using 4 wavelengths", http://www.ieee802.org/3/bs/public/14_07/dedic_3bs_01a_0714.pdf
[2] C.R.S. Fludger, T.Duthel, et al., "1Tb/s Real-Time 4x40Gbaud DP-16QAM Superchannel using CFP2-ACO Pluggables over 625 km of Standard Fibre", Paper Th1B.3, OFC2016

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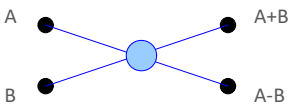
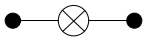
24

24

FFTs in ASICs

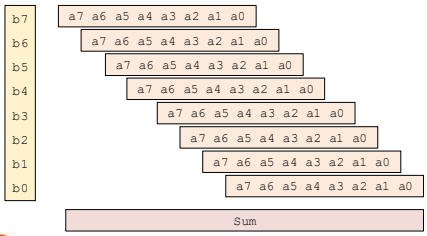


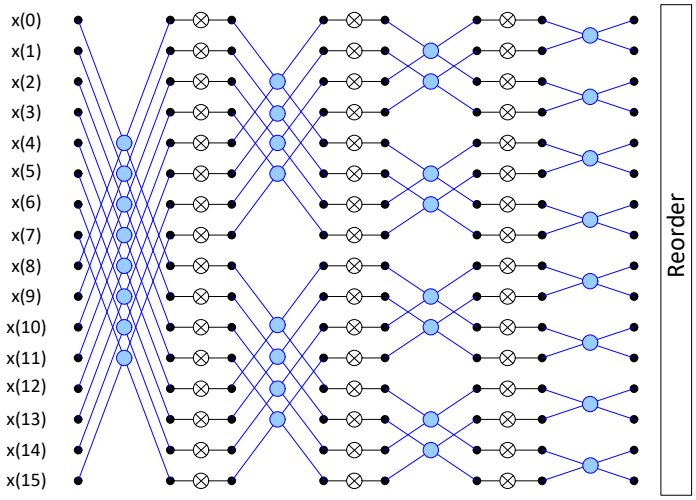


$W_{k,N}=e^{-j2\pi k/N}$

Often trivial such (1,-1,j,-j)

Multipliers are shift-compare and add





- Twiddle factors are fixed and often trivial
- Complex multiplications $\frac{N}{2}log_2(N)$ → in ASIC $\frac{N}{4}log_2(N)$

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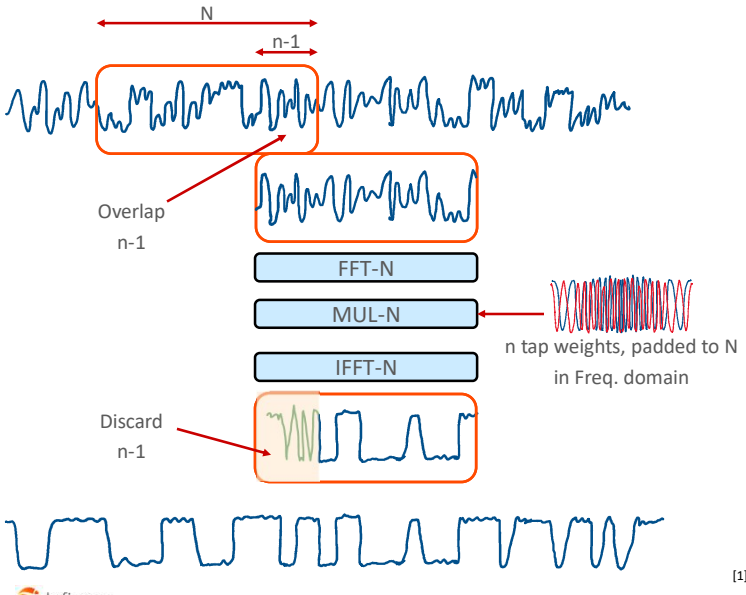
25

Fast convolution with Overlap-Save method



- n tap weights
- FFT length N
- Mathematically equivalent to convolution if impulse length constrained to n
- Overlap to overcome cyclic properties of FFT.
- N samples processed in parallel

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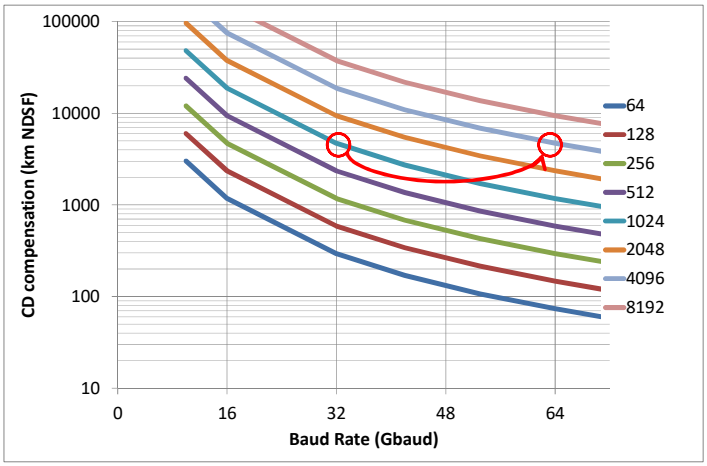
[1] J.C. Geyer, "Efficient Frequency Domain Chromatic Dispersion Compensation in a Coherent Polmux QPSK Receiver", OFC2010

26

CD compensation and baud-rate



- Impulse length and length of compensation filter scales quadratically with CD
- Low baud-rates give large CD tolerance

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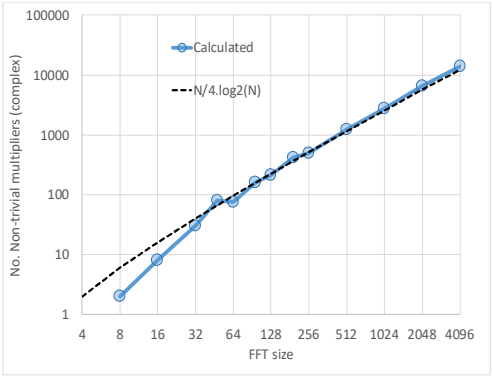
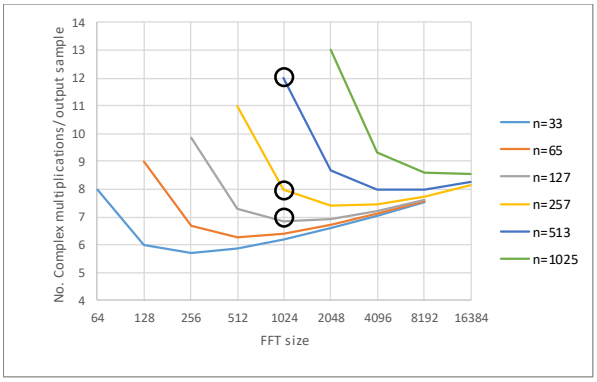
27

27

What about flexibility ?

FFT N	
N-(n-1) Samples processed	n-1 samples overlap





- Want to save power for short-reach (low CD), higher power for long-reach (high CD)
- Keep hardware the same (FFT size) and vary the no. tap weights (overlap ratio)
- But larger FFTs consume more chip area and wiring becomes difficult
- Impact of quantization noise: Double FFT size → +0.5bit resolution required
- Have to design resolution for highest order modulation format.
- Note that flexibility doesn't give the optimum for all applications

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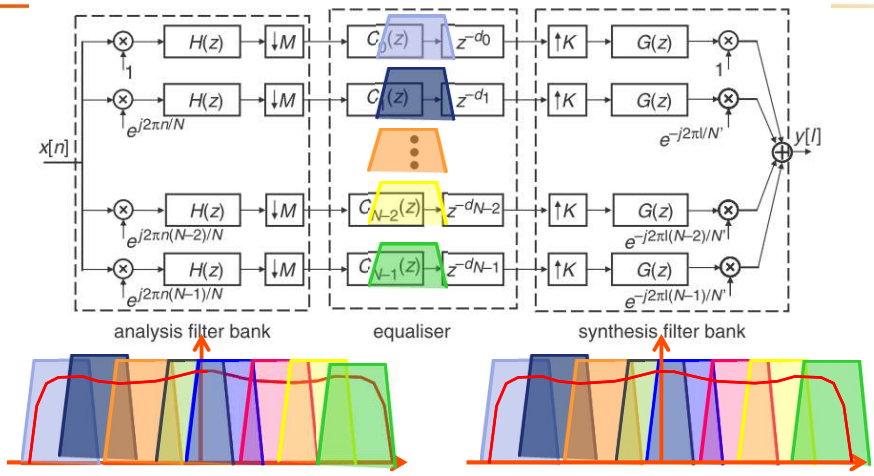
28

28

Sub-band filtering

e.g.
K.P. Ho, "Subband equaliser for chromatic dispersion of optical fibre," Electron. Lett., 45, p. 1224 (2009).



- Analysis filter – Splits signal into sub-band using prototype filter
- Separate equalisers for each sub-band (Time shifts for group delay)
- Synthesis filter bank – Joins sub-bands

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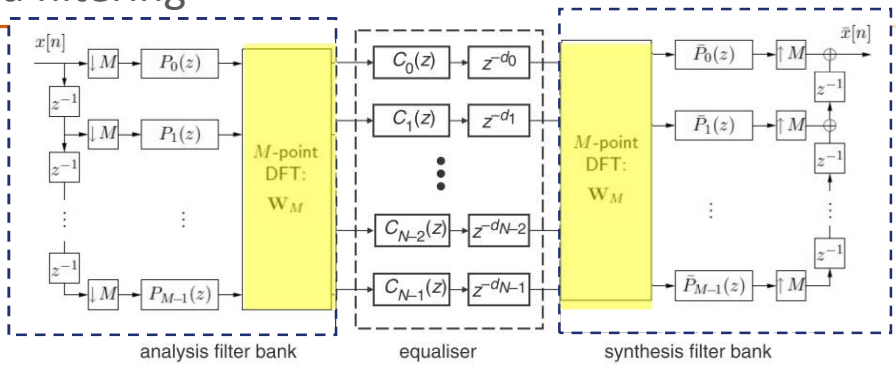
29

29

Sub-band filtering



- Polyphase implementation (DFTs) are an efficient way of performing downsampling
- Equaliser can be in time or frequency domain (FFT, filter, IFFT)

F.J. Harris, *C. Dick, M. Rice,* "Digital Receivers and Transmitters Using Polyphase Filter Banks for Wireless Communications", IEEE Trans. Microwave Theory and Techniques, vol. 51, no. 4, Apr. 2003, pp. 1395-1412.

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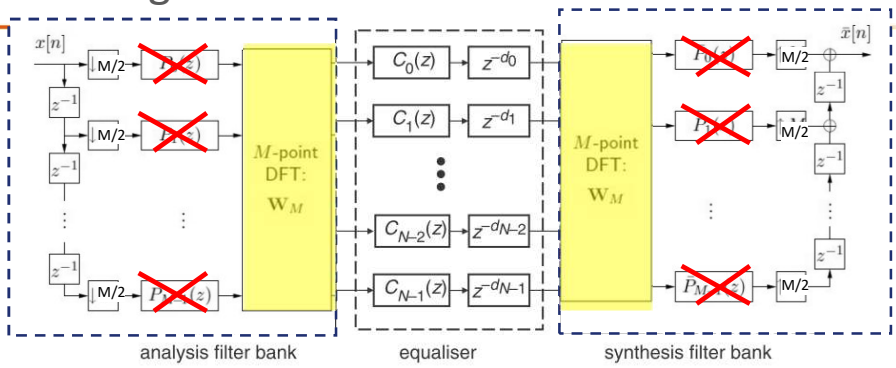
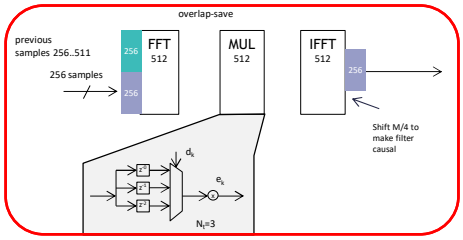
30

30

Sub-band filtering



- Simplified prototype filter
- Equivalent to frequency domain overlap-save
- Flexible number of delays



I.Slim, A.Mezghani, L.G. Baltar, J.Qi, F.N. Hauske, and J.A. Nossek, "Delayed Single -Tap Frequency-Domain Chromatic-Dispersion Compensation," Photon. Technol. Lett. 25, pp. 167–170 (2013).

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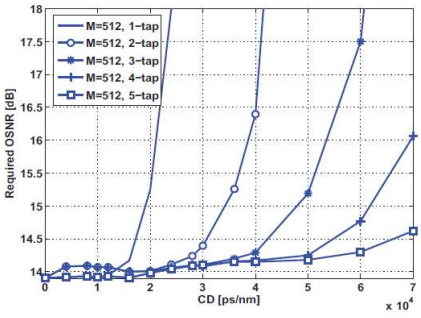
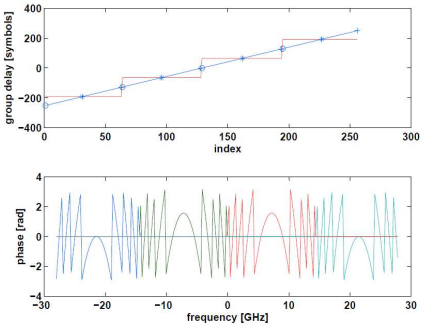
Sub-band filtering





- Phase errors at stitch points
  - Accumulative penalties
  - Worse for higher order modulation formats

I.Slim, A.Mezghani, L.G. Baltar, J.Qi, F.N. Hauske, and J.A. Nossek, "Delayed Single -Tap Frequency-Domain Chromatic-Dispersion Compensation," Photon. Technol. Lett. 25, pp. 167–170 (2013).

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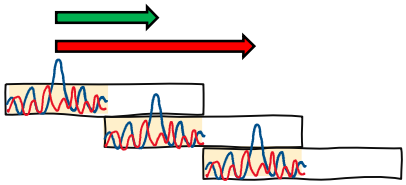
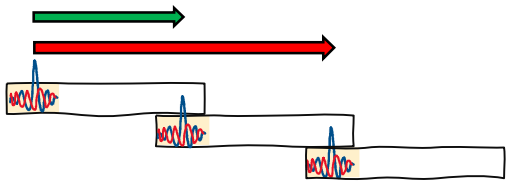
Sub-band filtering

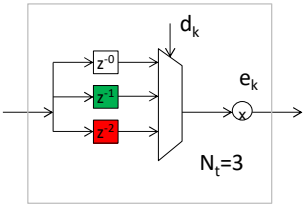
e.g. 50% Overlap



e.g. 25% Overlap



- Phase errors at stitch points
  - Accumulative penalties
  - Worse for higher order modulation formats
- Only works for n>(N/2)



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33

33

Flexible Capacity/Reach

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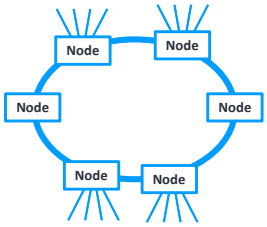
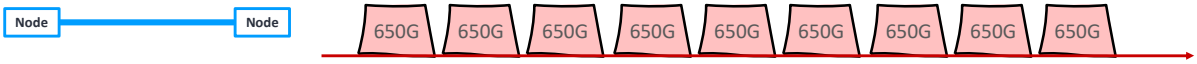
34

Network view



- Fibre is a scarce resource
- Bandwidth shared between different customers
- Different capacities + Link lengths

- Link length fixed
- Maximise Capacity



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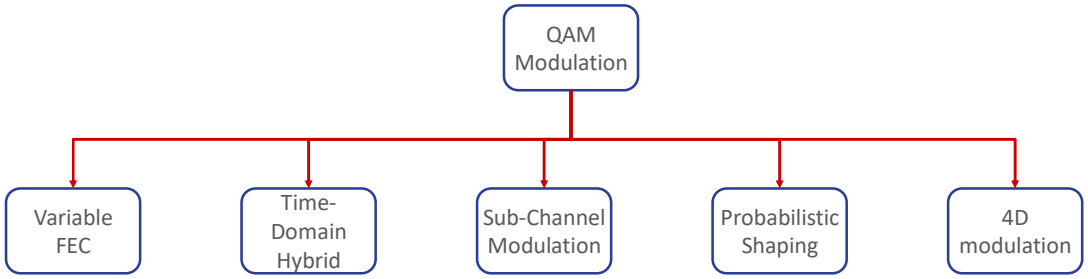
35

Options for variable Capacity / Reach



Variable FEC	Time-Domain Hybrid	Sub-Channel Modulation	Probabilistic Shaping	4D modulation
SNR gain vs overhead	Time multiplexing	Freq. multiplexing	Different symbol probabilities	Set partitioning / super-symbols
- Different codes for best results	**+ Reuse of existing HW**	**+ Reuse of existing HW** **+ Some NL gain**	**+ SNR gain** **+ Fine granularity** **- Implementation tricky**	**+ Can use standard QAM symbols**
		Fischer et al., JLT, vol. 32, p. 2886, 2014	Buchali et al. JLT Vol.34, No.7, 2016 Boecherer et al. JLT vol.37. no.2, 2019	Fischer et al., JLT, vol. 32, p. 2886, 2014

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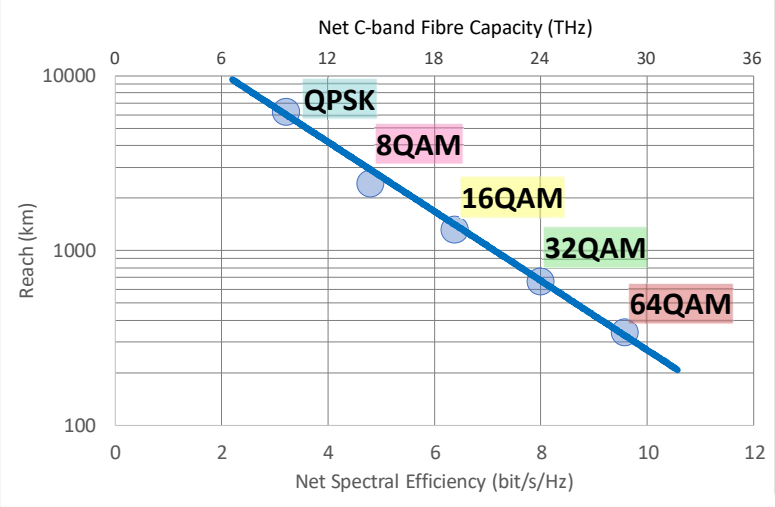
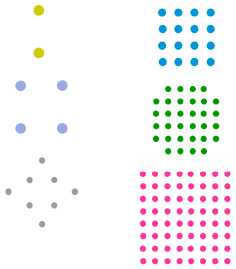
36

Flexible capacity



- Capacity can be traded against reach
- QAM modulation formats offer fixed granularity



32Gbaud RRC1.05, Nyquist transmission, Nx 100km SMF fibre, EDFA 5dB NF. Capacity for 3THz shown.
EGN model from Poggiolini et al., JLT, vol. 34, p. 458, 2017

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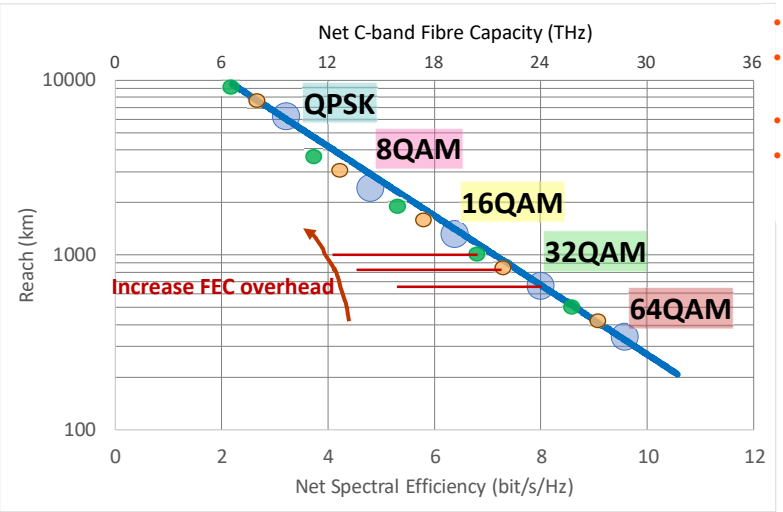
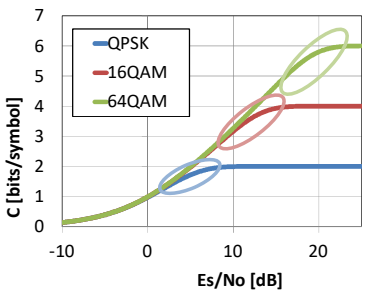
37

37

Flexible capacity



- Capacity can be traded against reach
- QAM modulation formats offer fixed granularity
- FEC Overhead can traded against capacity
- Often more than 1 FEC included in an ASIC



A. Ghazisaeid et al., "52.9 Tb/s Transmission over Transoceanic Distances using Adaptive Multi-Rate FEC", Paper PD3.4, ECOC2014

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38

38

Variable FEC

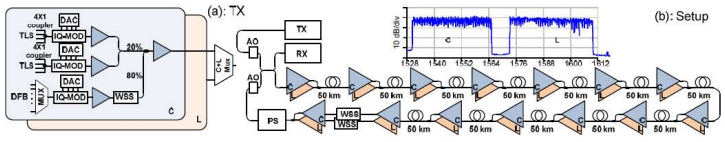
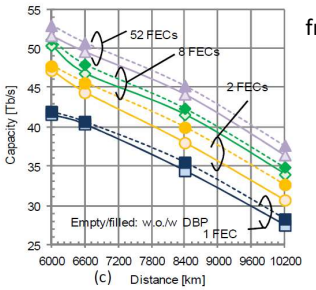
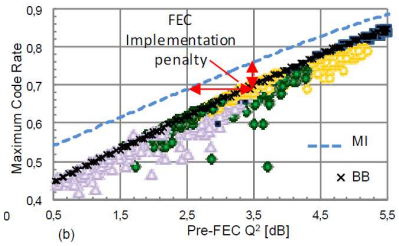


Fig. 1: The setup, a): transmitter, b) the recirculation loop: DAC: digital-to-analog convertor, IQ-MOD: IQ-modulator, TLS: tunable laser source, DFB: distributed feedback laser, AO: acousto-optic switch, WSS: wavelength selective switch, PS: synchronous polarization scrambler. Inset: signal spectrum at TX output.



from [1]

- Keep high-order modulation format
  - 16QAM [1] / SPC-BICM [2]
- FEC overhead varied to achieve reach
- Capacity reduction for longer reaches
- FEC complexity ~ CD comp. [3]
- DBP complexity ~ 20-30x CD comp[1]



[1] A. Ghazisaeid et al., "52.9 Tb/s Transmission over Transoceanic Distances using Adaptive Multi-Rate FEC", Paper PD3.4, ECOC2014
[2] H.Zhang et al., "Coded Modulation and Approaching Nonlinear Shannon Limit", ECOC 2014, Paper Tu4.3.3
[3] M. Kuschnerov, et al., "Energy Efficient Digital Signal Processing", OFC2014, Th3E.7

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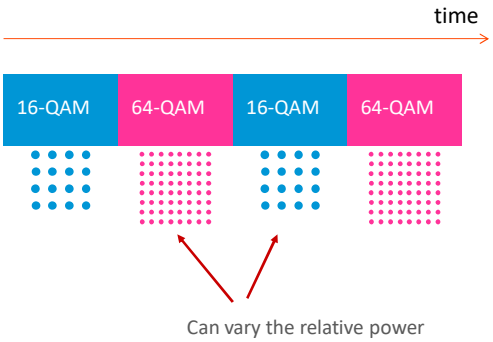
39

39

Time-domain Hybrid Formats

32Gbaud
(20% FEC)

Capacity	BPSK	QPSK	16QAM	64QAM
300				4
275			1	3
250			2	2
225			3	1
200			4	
175		1	3	
150		2	2	
125		3	1	
100		4		
75	2	2		
50	4			



- DSP is designed for each discrete format
- Variable capacity achieved by time interleaving symbols
- Granularity important
  - Not every capacity increase is useful !

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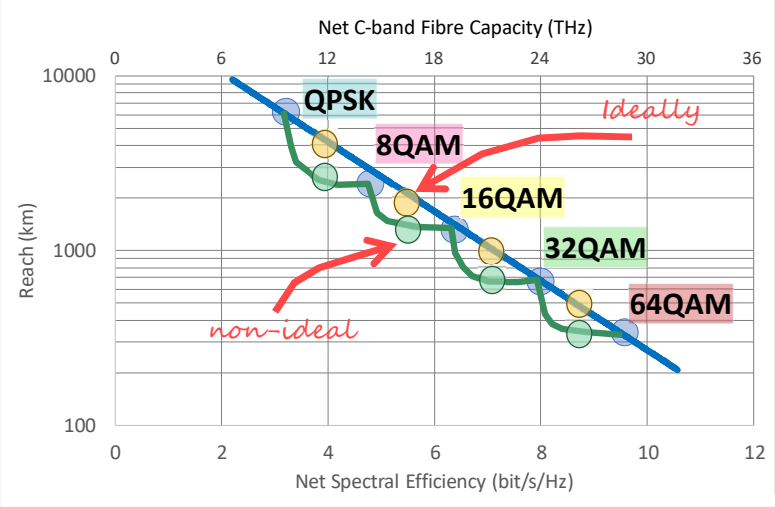
40

40

Flexible capacity



- Capacity can be traded against reach
- QAM modulation formats offer fixed granularity
- Interleaving can provide intermediate rates
- Only valuable if a reach improvement is seen.

32Gbaud RRC1.05, Nyquist transmission, Nx 100km SMF fibre, EDFA 5dB NF. Capacity for 3THz shown.
EGN model from Poggiolini et al., JLT, vol. 34, p. 458, 2017

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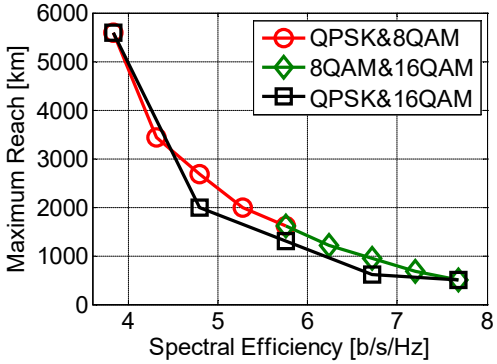
41

41

Time-domain Hybrid Formats



McGill

Superchannel:

- data rates from 576 Gb/s to 1.15 Tb/s
- spectral efficiencies from 3.84 b/s/Hz to 7.68 b/s/Hz
- Transmission distances from 5600 km to 500 km

from :Q.Zhuge et al., "Time Domain Hybrid QAM Based Rate-Adaptive Optical Transmissions Using High Speed DACs", Paper OTh4E6, OFC2013

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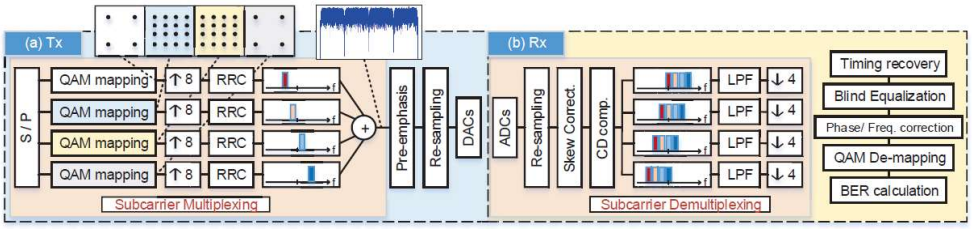
12

42

42

Sub-carriers – interleaving in frequency domain



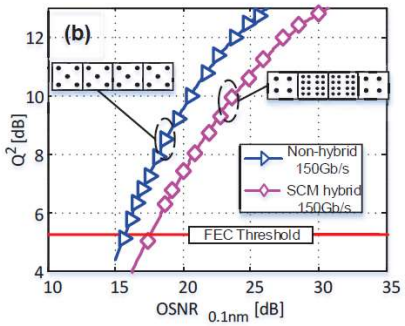


Table I: Various SCM hybrid QAM formats and achievable data-rates and SE for 37.5GHz spectral grid.

Symbol-rate	SCM hybrid QAM scheme (QAM order of each subcarrier)	Net Data-rate	SE (bit/s/Hz)	Max # of WSSs at FEC threshold	Max Reach [km]
32GBd	4-4-4-4	100Gb/s	2.67	11	1045
32GBd	4-8-8-4	125Gb/s	3.33	11	1045
32GBd	4-16-16-4	150Gb/s	4.00	11	1045
32GBd	8-8-8-8	150Gb/s	4.00	7	665
32GBd	8-16-16-8	175Gb/s	4.67	7	665
32GBd	16-16-16-16	200Gb/s	5.33	4	380

T.Rahman et al., Tu3K.5, OFC2016

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43

43

Flexible multi-format DSP

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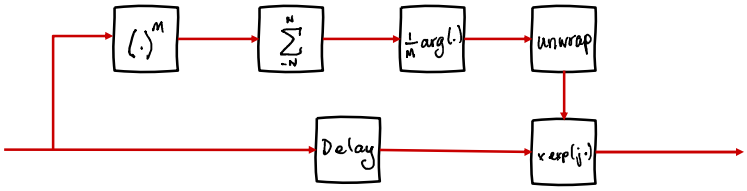
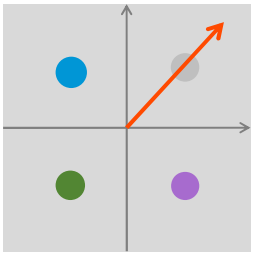
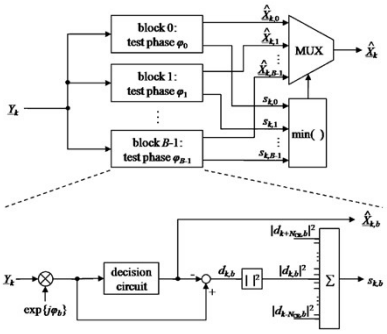
44

Carrier Phase Estimation



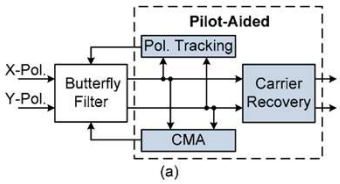


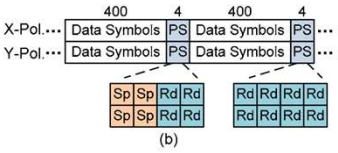
- Viterbi-and-Viterbi
  - Relies on symmetry of modulation format
  - Modulation format dependent
- Blind-phase search
  - Various test phases calculated
  - Decision circuit used to select lowest square error
  - Modulation format dependent

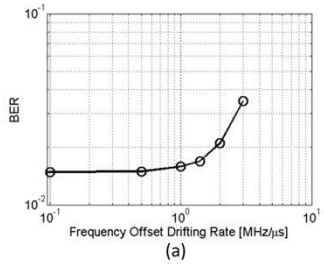


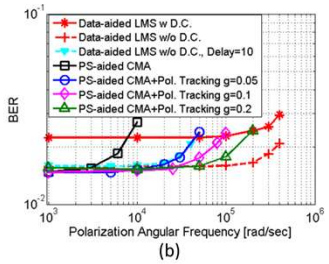
[1] T. Pfau et al., "Hardware-Efficient Coherent Digial Receiver Concept with Feedforward Carrier Recovery for M-QAM constellations", Journal of Lightwave Technology, Vol.27, No.8, April 15, 2009

Pilot Symbol based DSP



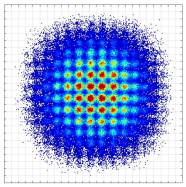




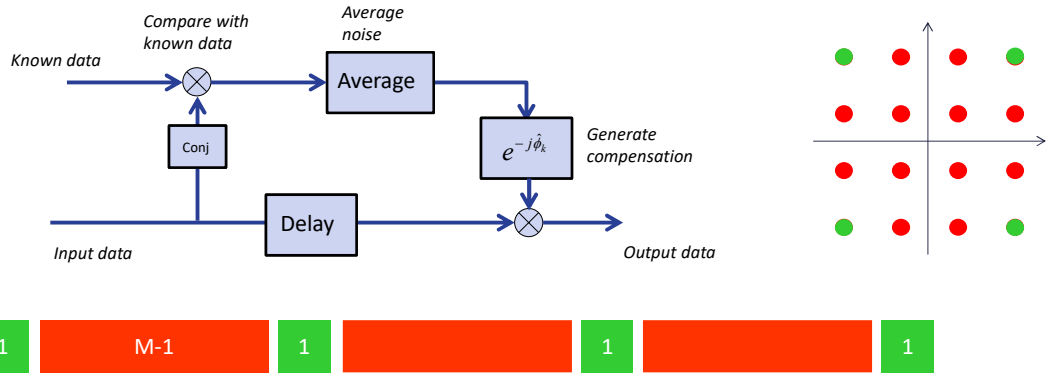


Zhuge et al. Optics Express, vol. 22, p. 2278, 2014

- Blind algorithms are often not really blind
  - Different CPE required for each modulation format
- Pilot symbols DSP is relatively simple.
  - Can ignore payload symbols !
- Pilots need to be random
- Absolute phase CPE
- Useful if the constellation looks like:



Pilot based / Training based

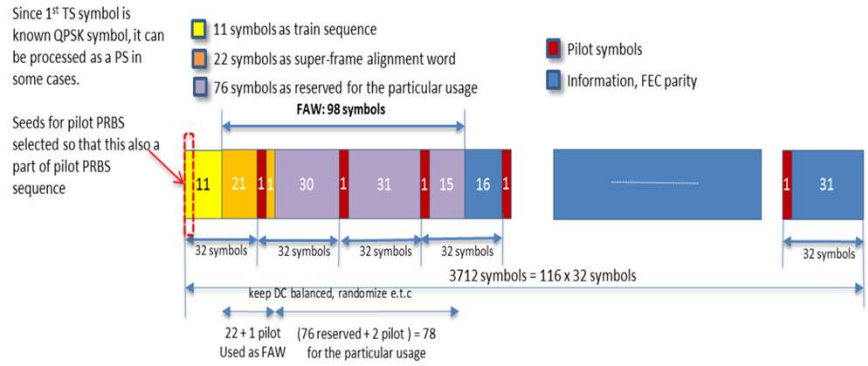


- Independent of modulation format
- What to do when there is no training data ?
- Extra overhead increases line rate

400ZR

- Frame defined with header, training sequences and pilot symbols

From OIF, 400ZR specification



Flexible Networks and sub-carriers

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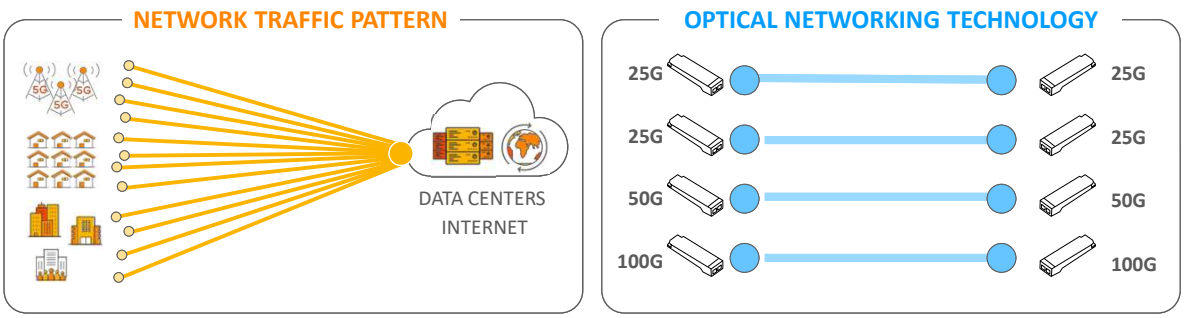
49

Flexibility in the network

For 50+ years, the industry has been
USING A POINT TO POINT TECHNOLOGY FOR A POINT TO MULTI-POINT APPLICATION



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50

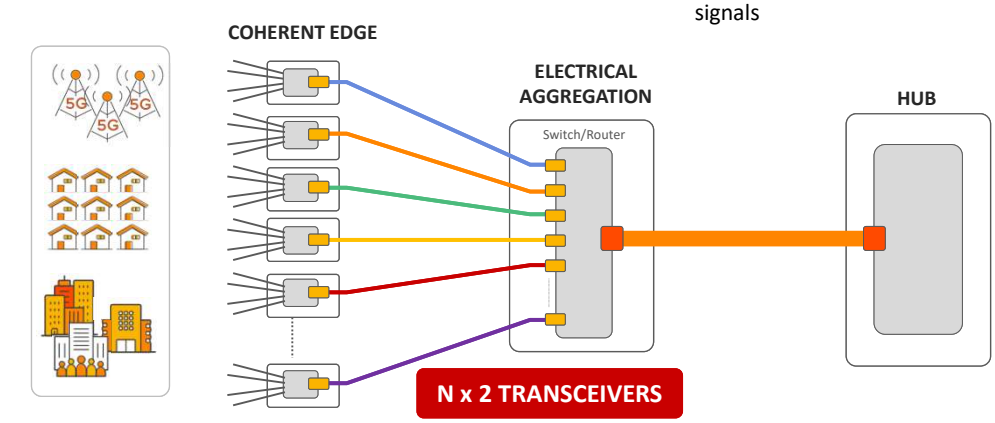
50

Flexibility in the network

For 50+ years, the industry has been
USING A POINT-TO-POINT TECHNOLOGY FOR A POINT-TO-MULTIPOINT APPLICATION

INTERMEDIATE AGG devices/locations with **N x 2 TRANSCEIVERS** required to "up-speed" signals

Upgrades require **RIP AND REPLACE OF BOTH ENDS** (OpEx, time, truck rolls)



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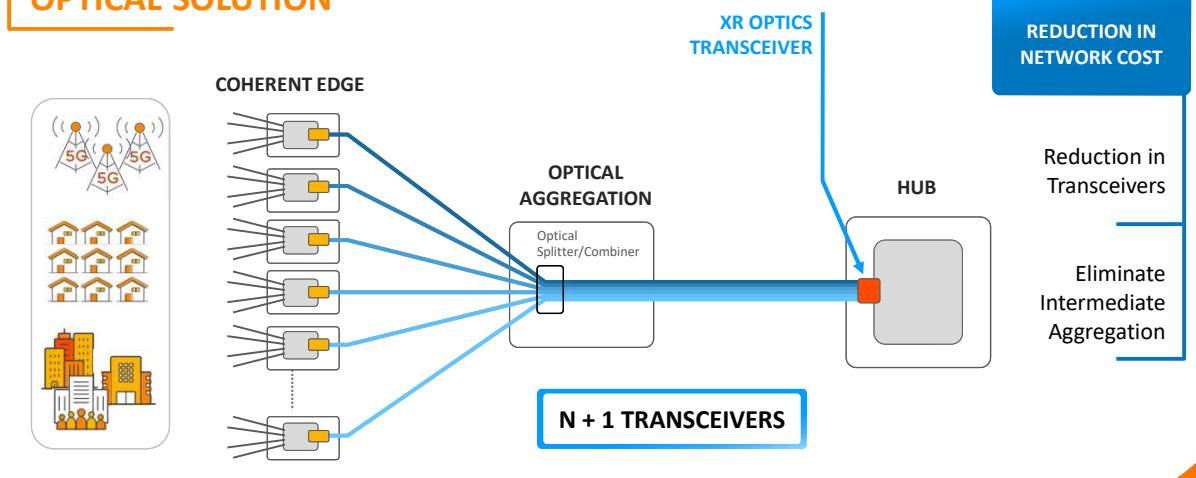
51

51

Flexibility in the network

COHERENT POINT-TO-MULTIPOINT OPTICAL SOLUTION



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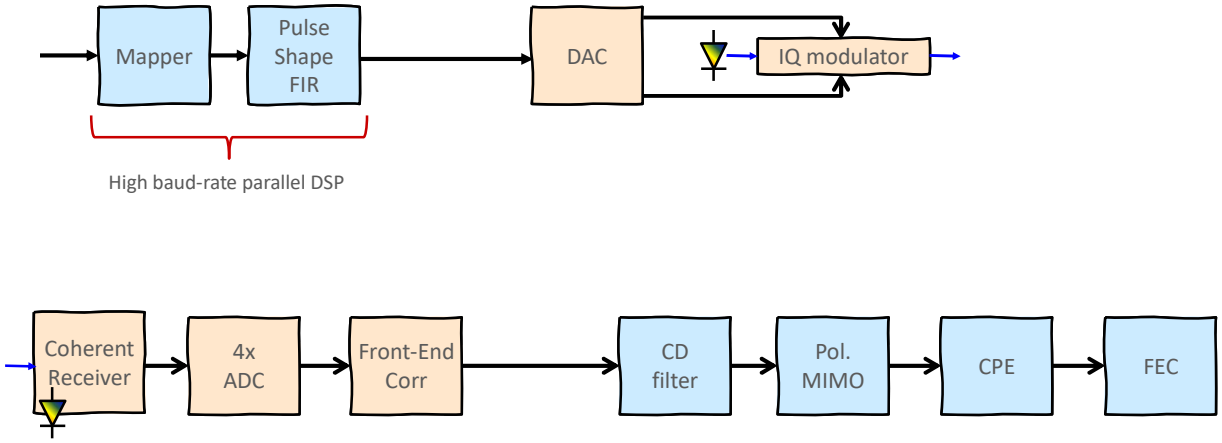
52

52

Single-channel



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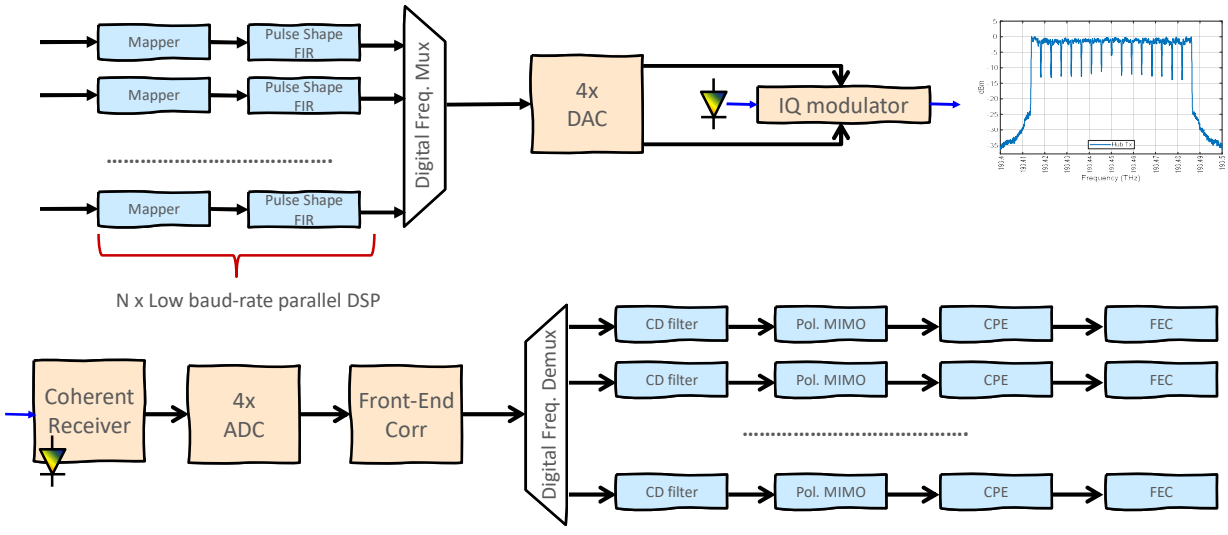
53

53

Multiple Sub-channels



- ASIC capacity can be tailored to application and number of sub-carriers

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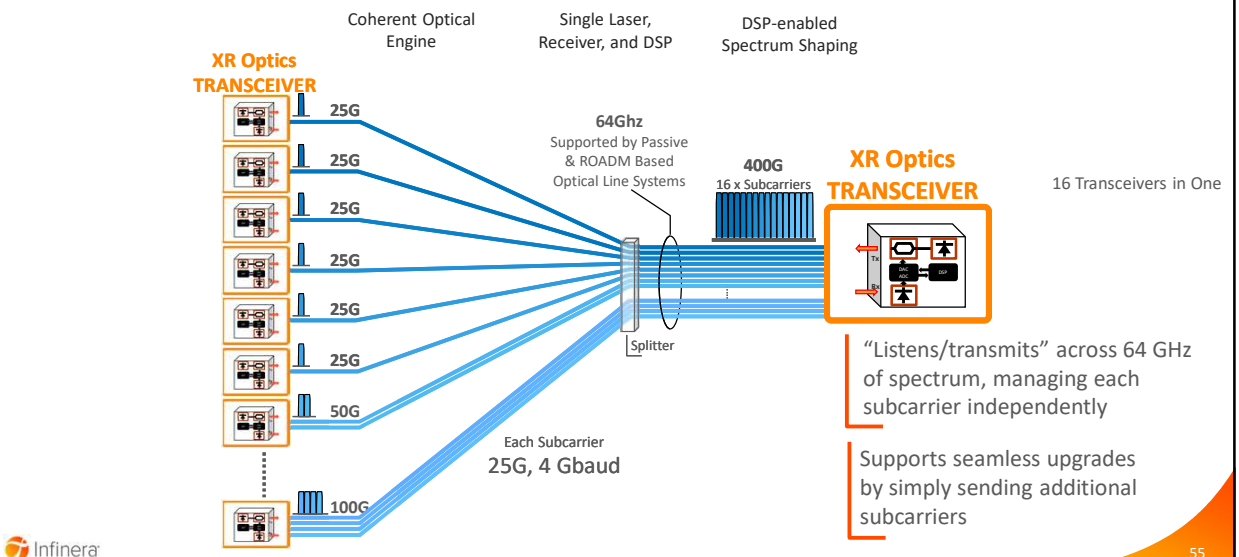
54

54

Transforming Point-to-Multipoint Aggregation

POINT-TO-MULTIPOINT SUBCARRIER-BASED TRANSCEIVER TECHNOLOGY



16 Transceivers in One

"Listens/transmits" across 64 GHz of spectrum, managing each subcarrier independently

Supports seamless upgrades by simply sending additional subcarriers

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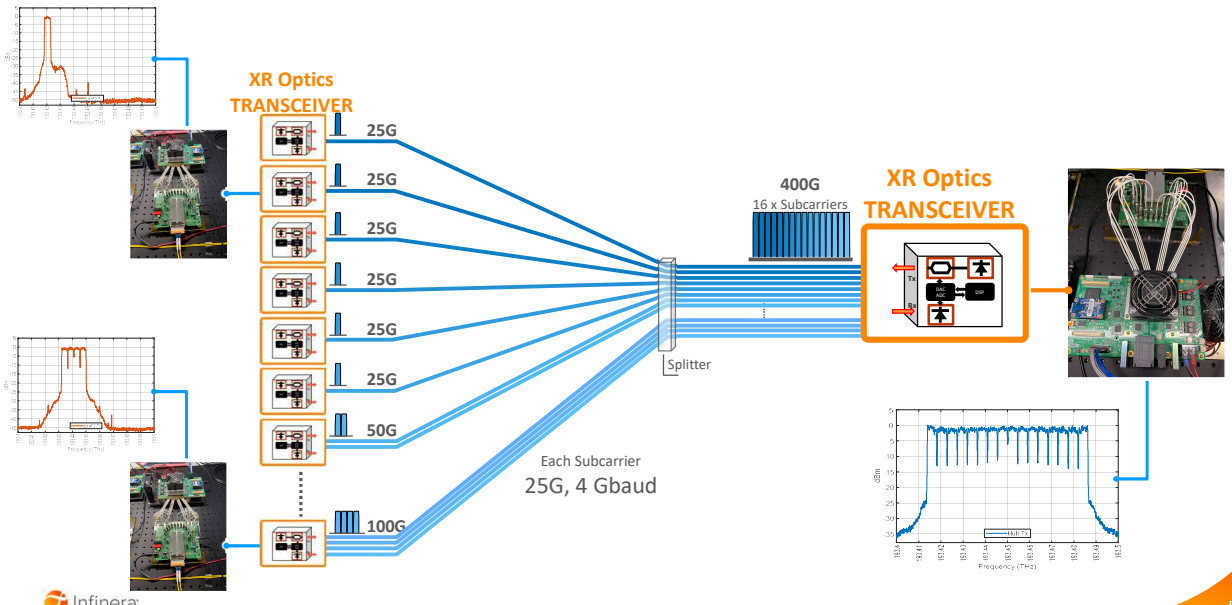
55

55

Point-to-Multi-point experiment



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56

56

Summary

57

Summary

- **Flexibility offers cost optimisation : OPEX / CAPEX**
- Capacity / Reach
- Return-on-Investment
  - ASIC development
- Inventory and replacements costs
  - Pluggable multi-application modules
- Reduction in network elements / complexity

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58

58