Optical Telecommunications from megabits/s to petabits/s.

The big picture: so **highly simplified**, not covering all issues, no in depth maths, rounded figures, broad use of terminology.

If you want more detail or disagree, I will be around for questions and comments.

Dr. Robert Waegemans
invited by Electro Rent
ex-researcher University College London
System Consultant ADVA Optical Networks

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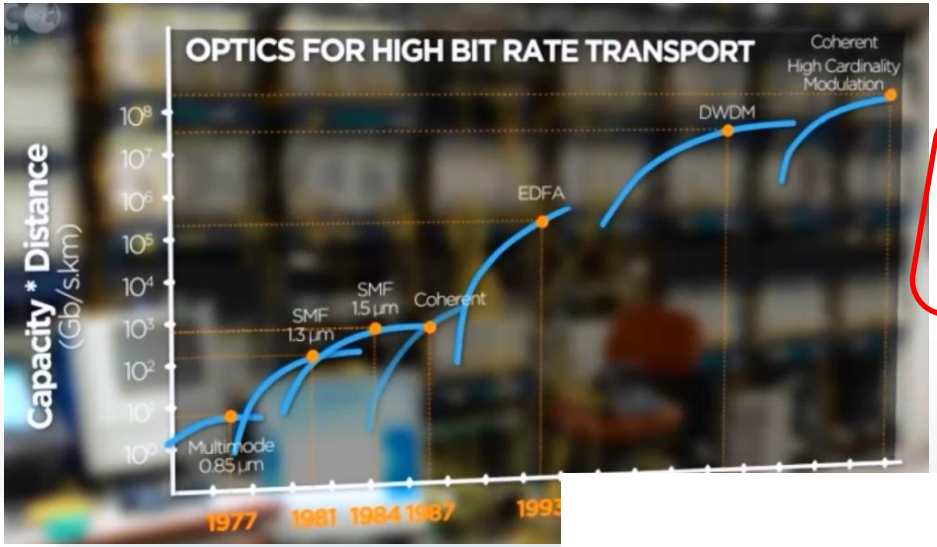
The past 40 years have been great for optics

search: “Clip 40th Edition ECOC “ url: http://youtu.be/TPXE0VxASn8

The setting



Let's focus 20 minutes on technical issue's limiting capacity and less on commercial aspects like cost !

ECOC 2014, Cannes - France
Th.1.2.1

How Will Optical Transport Deal With Future Network Traffic Growth?

Glenn Wellbrock[1], Tiejun J. Xia[2]

[1] Verizon, 2400 North Glenville Drive, Richardson Texas 75082, glenn.wellbrock@verizon.com
[2] Verizon, 2400 North Glenville Drive, Richardson Texas 75082, tj.xia@verizon.com

Abstract *Traffic will undoubtedly continue to grow, but it is important to put this into perspective. This presentation will categorize growth rates and propose cost effective solutions in Access, Metro and Long Haul without the need to replace existing fiber.*

Introduction

Network traffic will undoubtedly continue to grow in the foreseeable future due to ever increasing demand of emerging applications, such as peer-to-peer video sharing, machine-to-machine communications, ultra-high definition video, gaming, mobile data, etc. The overall global end

Given the high cost of replacement, an important question to global carriers is how long will the existing fiber infrastructure support the expected traffic growth and are there solutions on the horizon? Fortunately, Spatial Division Multiplexing (SDM) such as Multi-Core Fiber (MCF) and Few Mode Fiber (FMF) or Multi-

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- ~~Intro with video (2 slides)~~
- Systematic overview (9 slides)
- Selected Topics (5 slides)
- Conclusion (1 slide)

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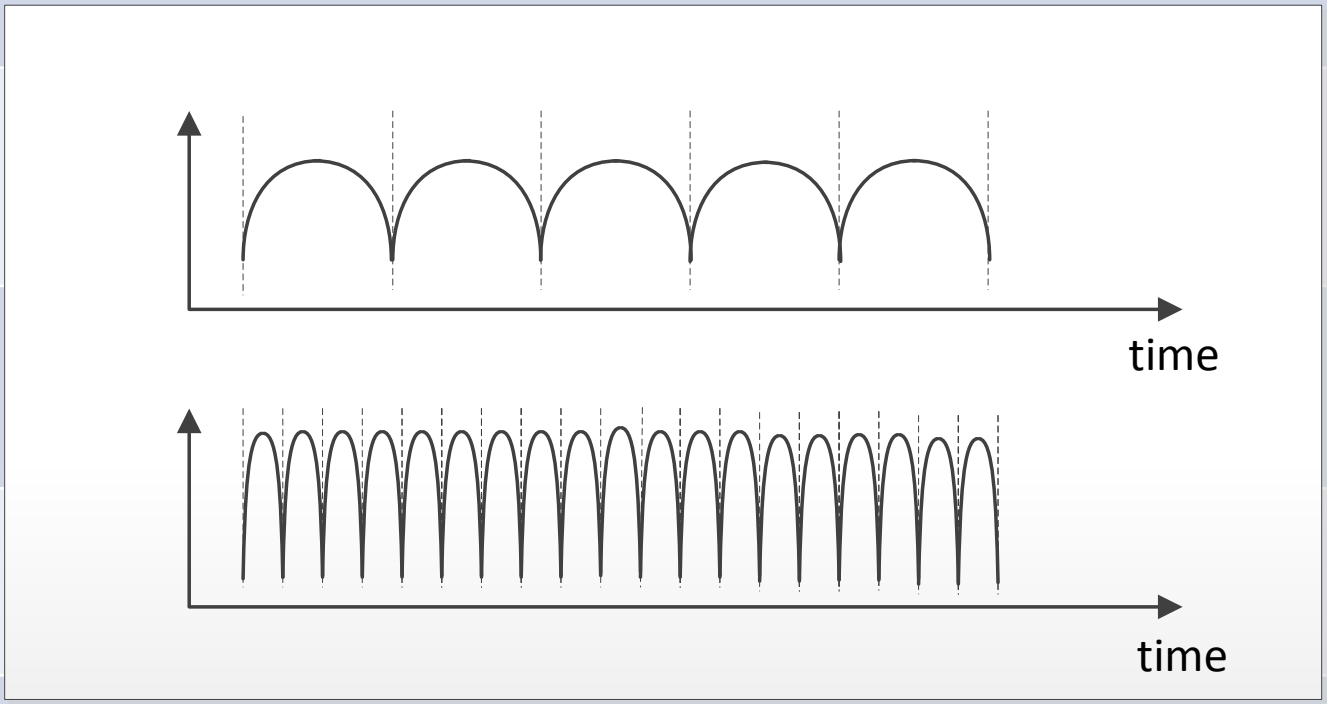
↑ capacity, 5 physical dimensions

Time	
Frequency	
Quadrature	
Polarization	
Spatial	

↑ capacity, 5 physical dimensions

Time	Increase symbol (pulse) rate
Frequency	
Quadrature	
Polarization	
Spatial	



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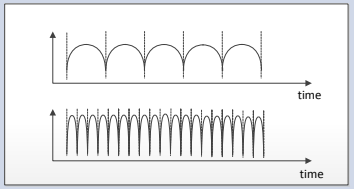
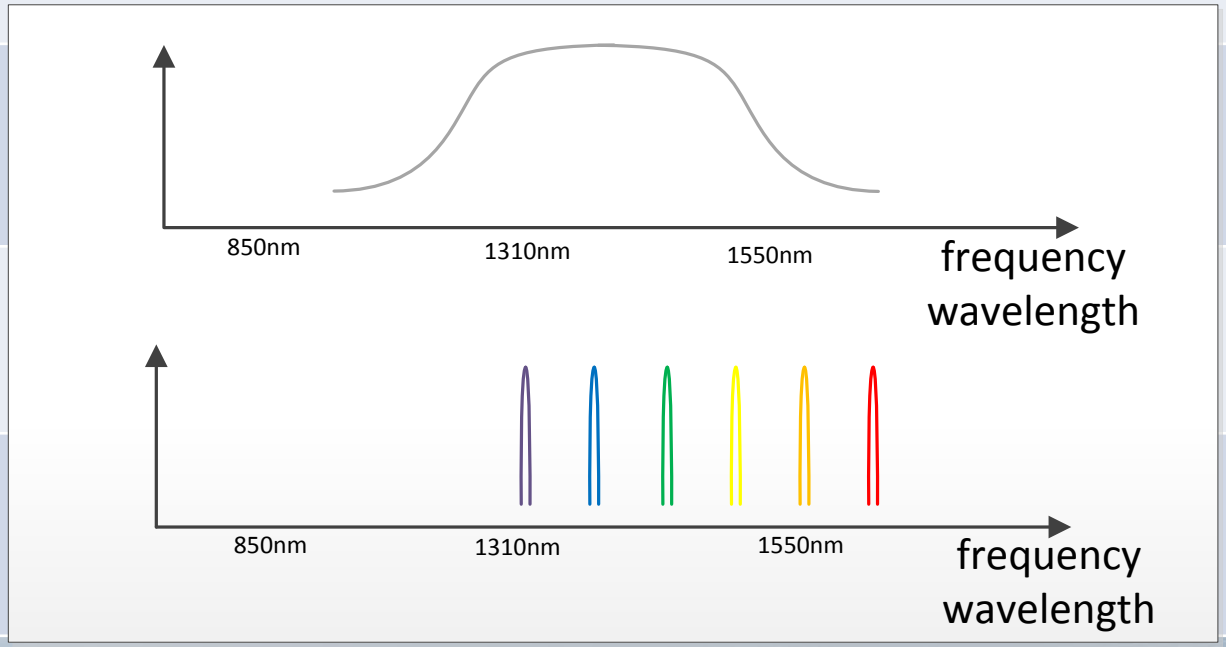
↑ capacity, 5 physical dimensions

Time	Increase symbol (pulse) rate 
Frequency	Use multiple channels in the optical spectrum (xWDM)
Quadrature	
Polarization	
Spatial	



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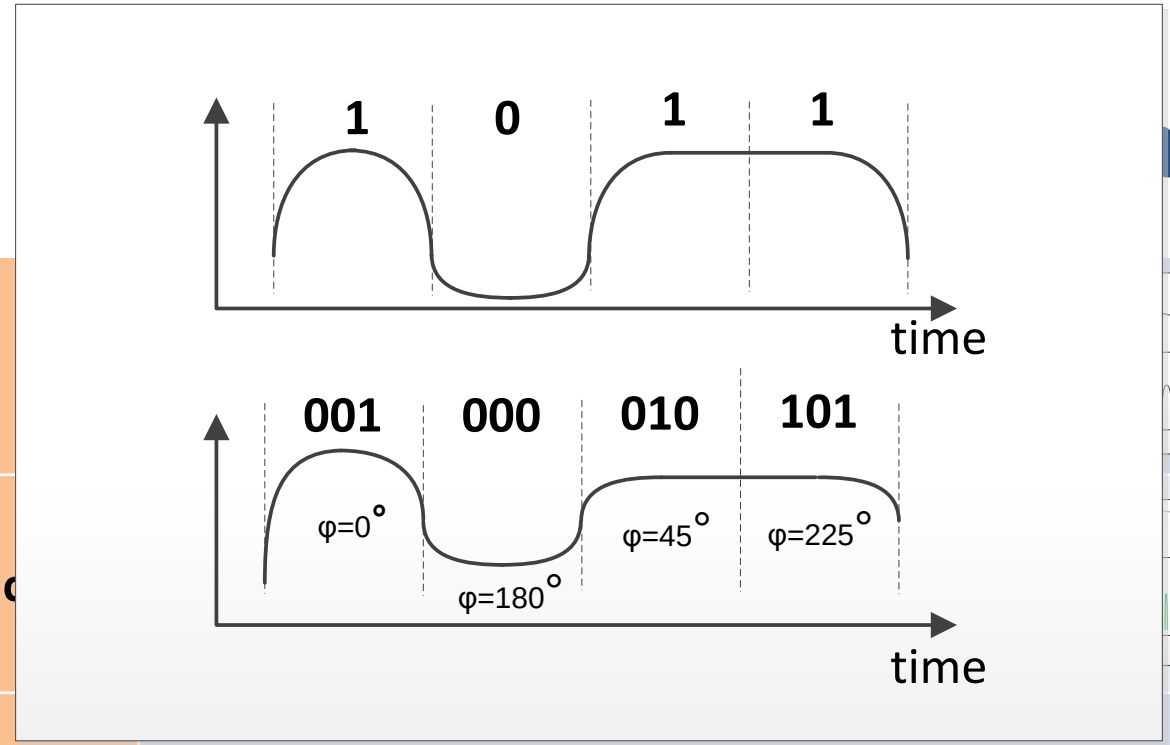
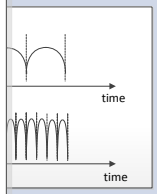
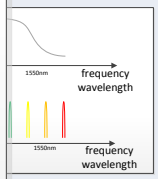
↑ nsions



Time	
Frequenc	
Quadrature	Send multiple bits in 1 symbol.
Polarization	
Spatial	

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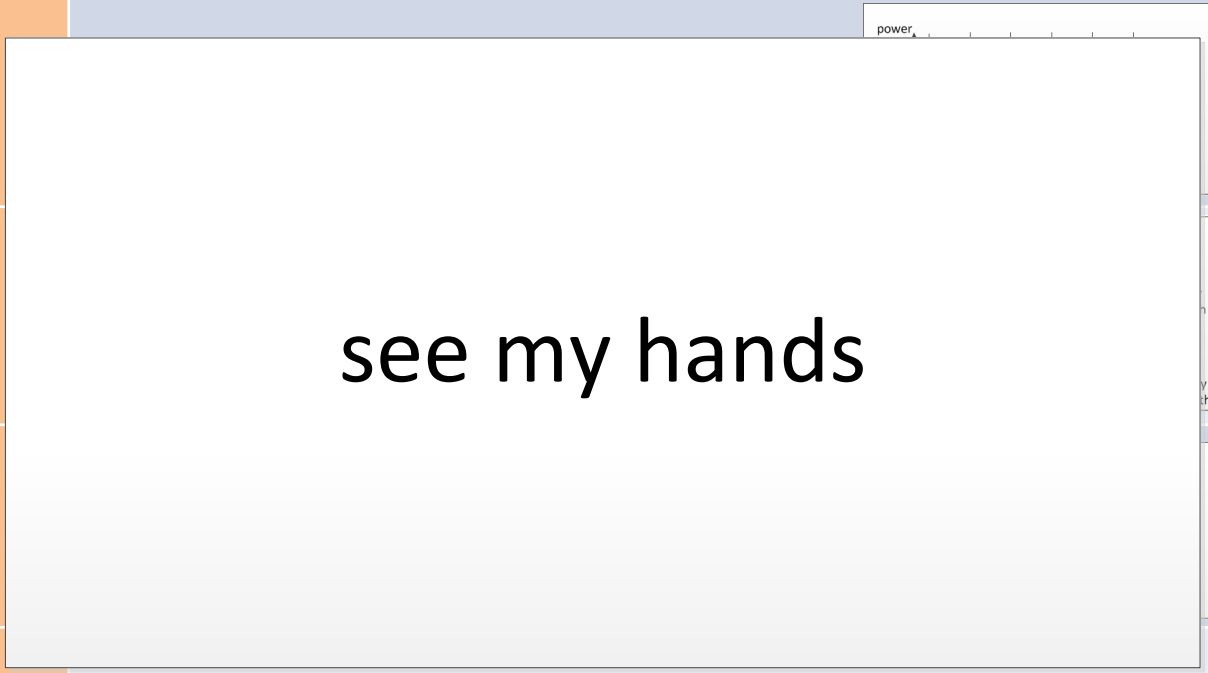
↑ capacity, 5 physical dimensions

Time	 see my hands
Frequency	
Quadrature	
Polarization	2 polarization states
Spatial	

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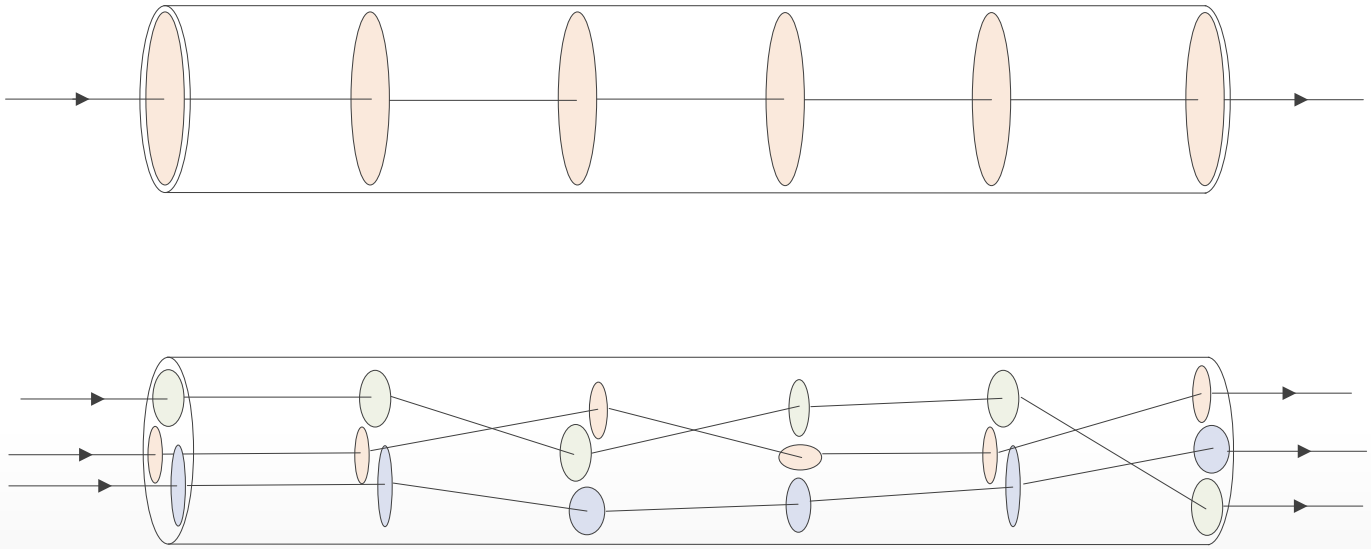
↑ capacity, 5 physical dimensions

Time	
Frequency	
Quadrature	
Polarization	2 polarization states
Spatial	Parallel routes (ribbon fibre ?)



see my hands

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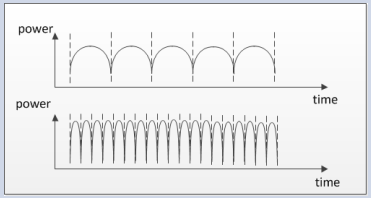
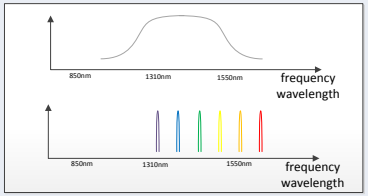
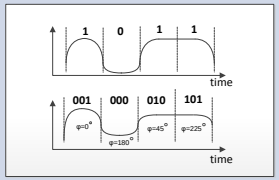
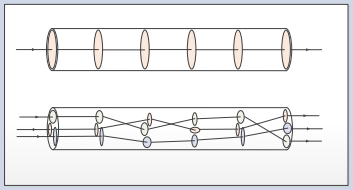
↑ capacity, 5 physical dimensions

Time	Increase symbol (pulse) rate	
Frequency	Use multiple channels in the optical spectrum (xWDM)	
Quadrature	Send multiple bits in 1 symbol.	
Polarization	2 polarization states	see my hands
Spatial	Parallel routes (ribbon fibre ?)	

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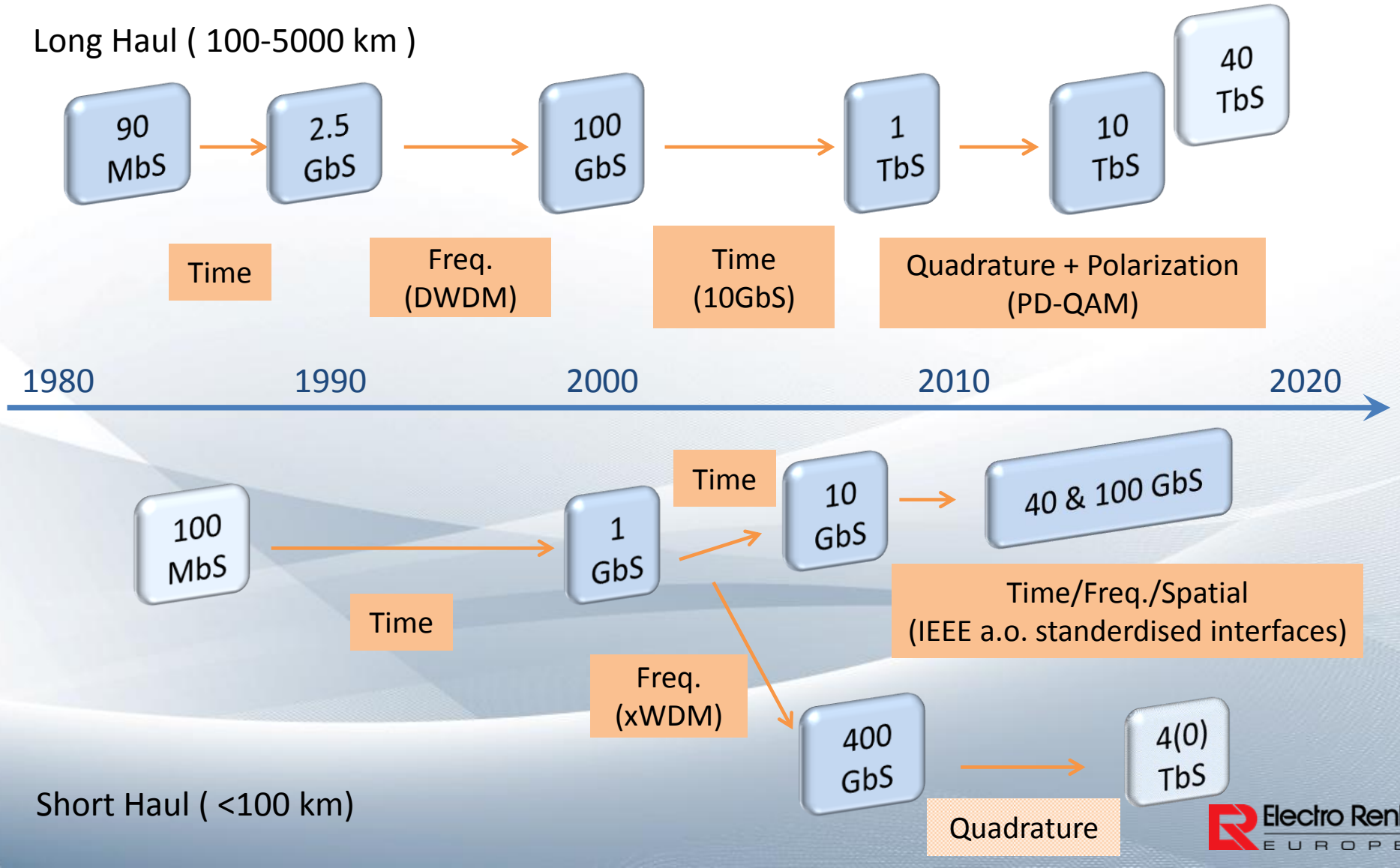
History of optical capacity in 1 slide



What limits us ?

In theory, if you can infinitely increase signal power, then there is no limit on the capacity. (Shannon)

Time	**Components** (+ optical effects a.e. dispersion, + electronics, +...) 28 GBaud now used for 100GbS, 30-50 GBaud possible, 100 GBaud very challenging
Frequency	**Usable (amplifiable) spectrum** (+ attenuation, +...) For LH we already use full C-L band, for SH we can grow (Maybe we can use it more efficient)
Quadrature	**Noise** (+ complexity, + cost, + maximal power, +...) Currently used to ↑ LH & SH capacity
Polarization	**Only 2** polarization states exist Cost of fibre/filter versus capacity gain
Spatial	Fibre & component **science & technology** .... A lot of academic R&D ongoing

Some detail in next slides

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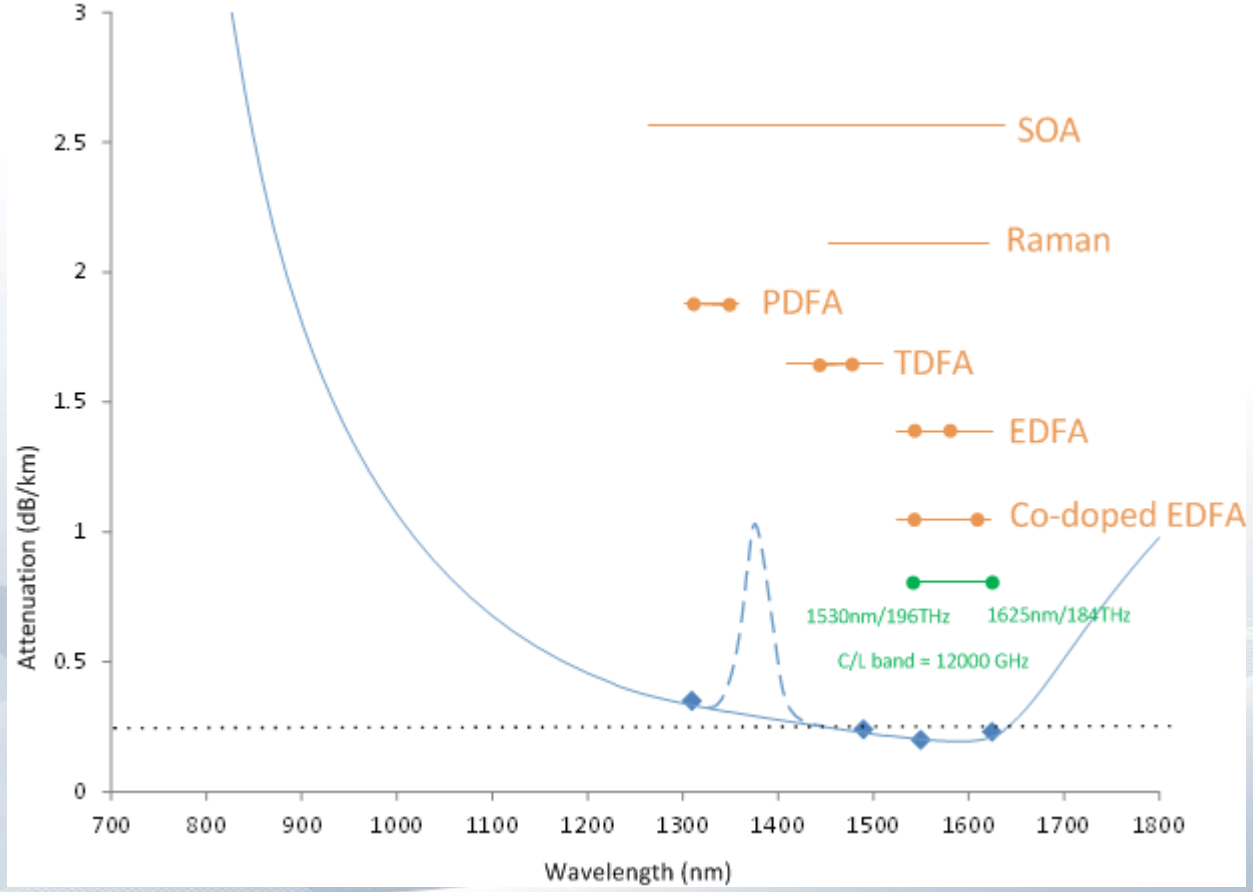
- ~~Intro with video (2 slides)~~
- ~~Systematic overview (9 slides)~~
- Selected Topics (5 slides)
  - Bandwidth versus loss/amplification
  - Time relates to frequency: FFT[f(t)]=f’(f)
  - Quadrature and noise
  - Spatial multiplexing
  - A setup at petabits/s
- Conclusion (1 slide)

Bandwidth versus loss/amplification



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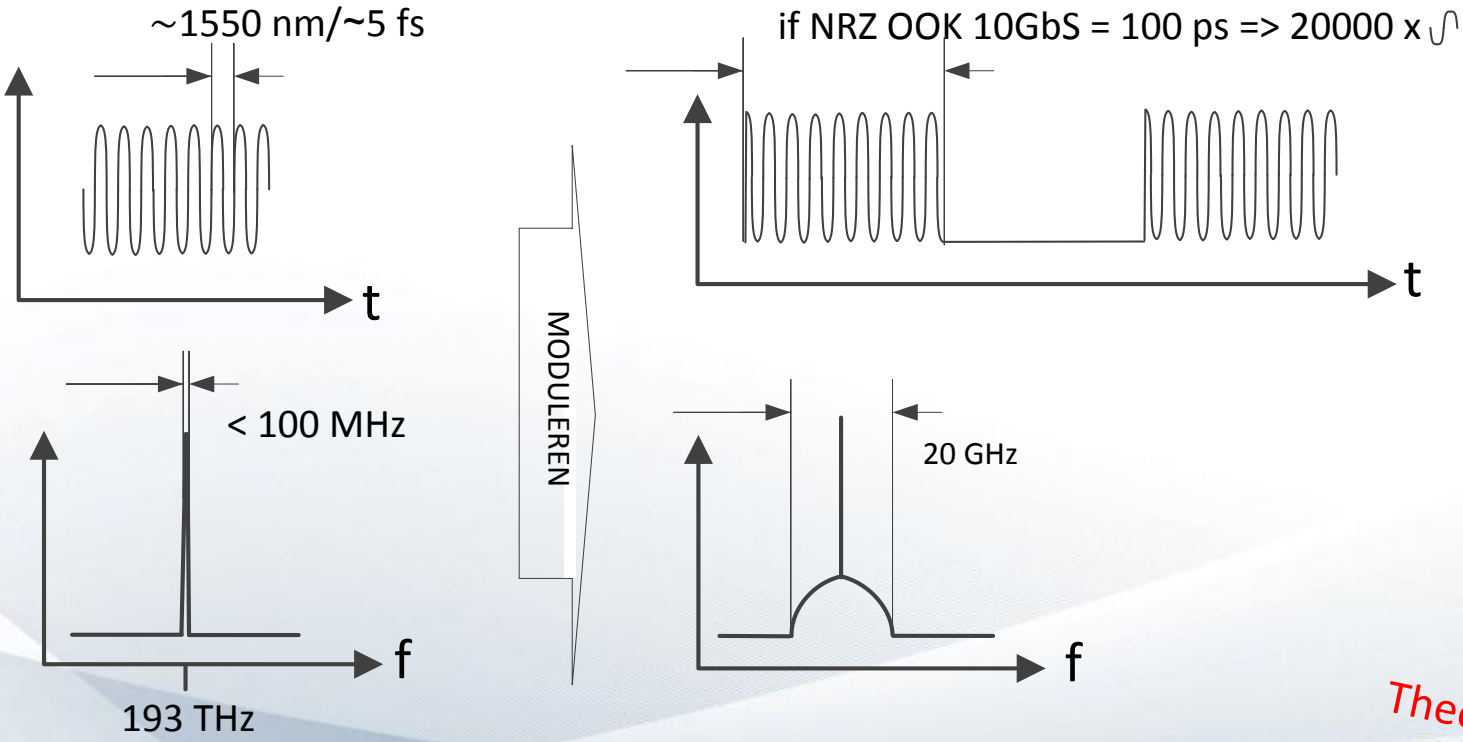
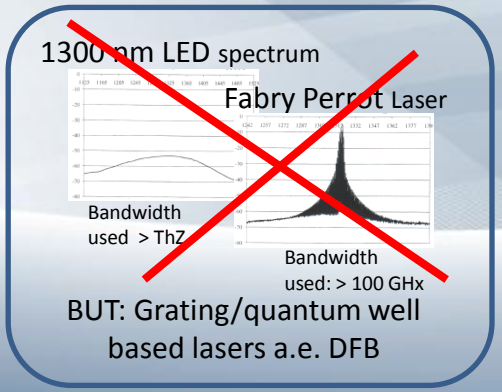
Time relates to frequency: FFT[f(t)]=f'(f)





Theoretical Values !

Format	Bitrate	Baud rate	Bandwidth	Efficiency
NRZ OOK	10 GbS	10 GBd	20 GHz	0.5 b/s/Hz
NRZ OOK	100 GbS	100 GBd	200 GHz	0.5 b/s/Hz
PD-QPSK	100 GbS	25 GBd	50 GHz	2 b/s/Hz
PD-64QAM	400 GbS	25 GBd	50 GHz	8 b/s/Hz

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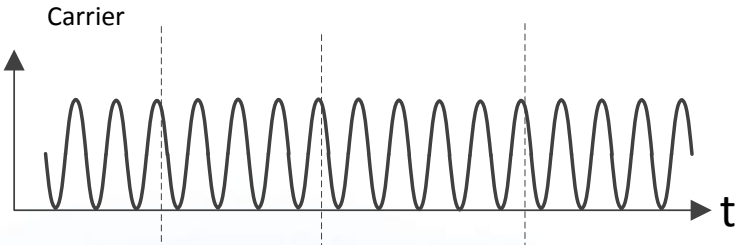
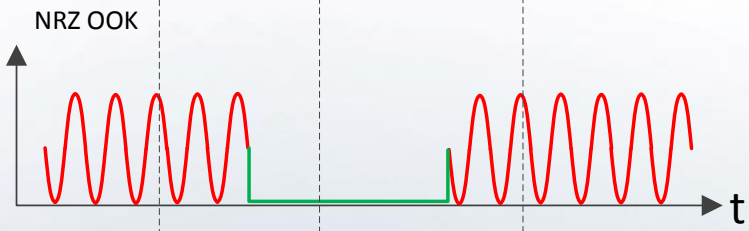
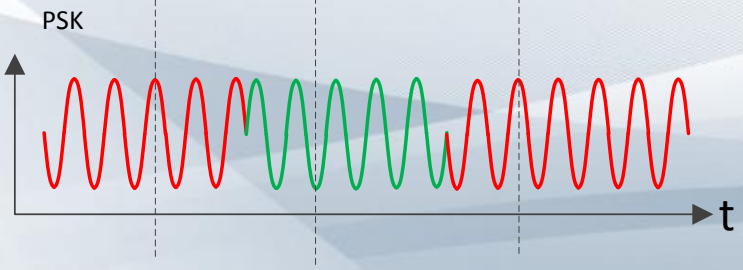
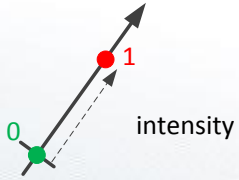
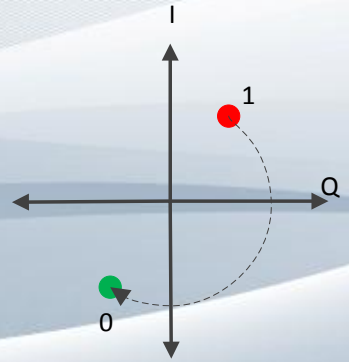
Quadrature and noise

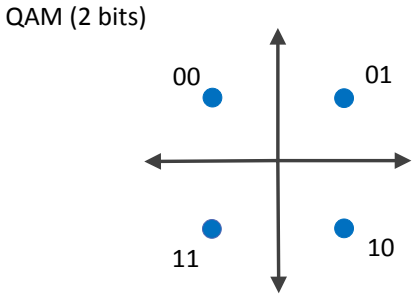


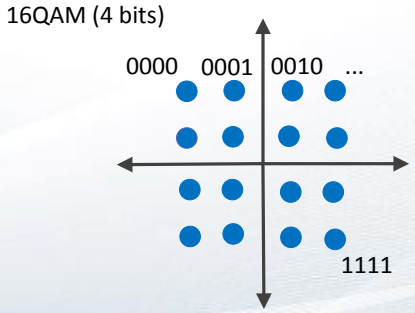


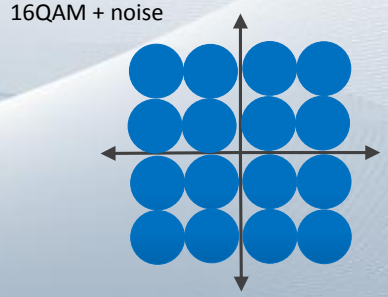












And now I should show relation noise – distance but time ....

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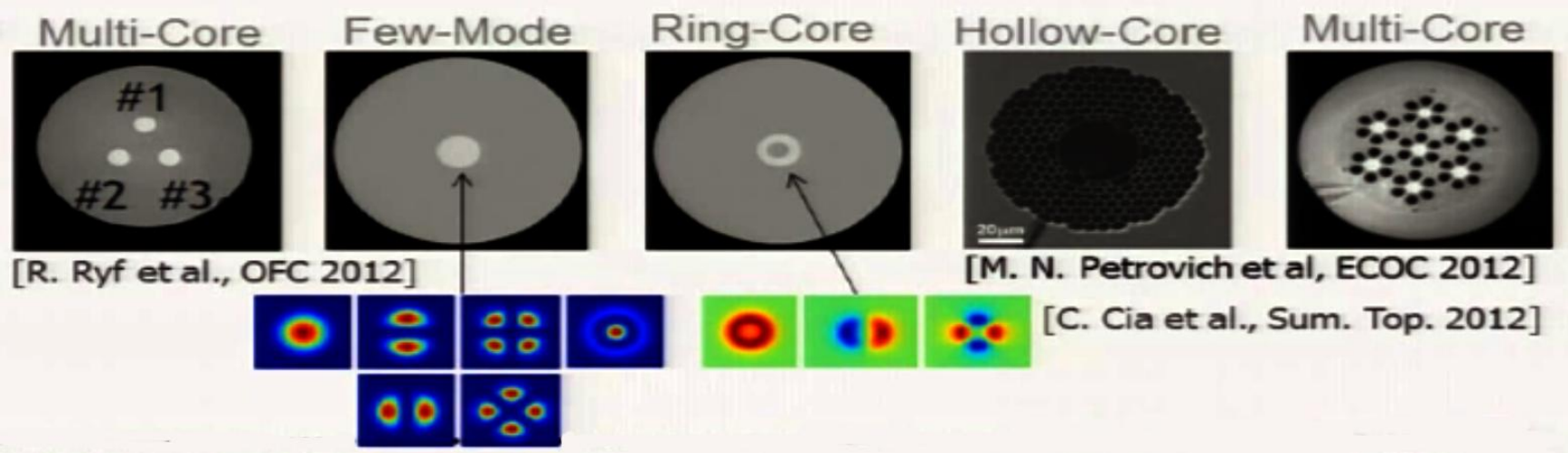
Spatial multiplexing

Multiple solutions:



Key issues:

- Interference between the cores/modes results in requirement for MIMO signal processing.
- We want components that handle all cores/modes together.

A setup at petabits/sec

Th.3.C.1.pdf ECOC Postdeadline Papers © 2012 OSA

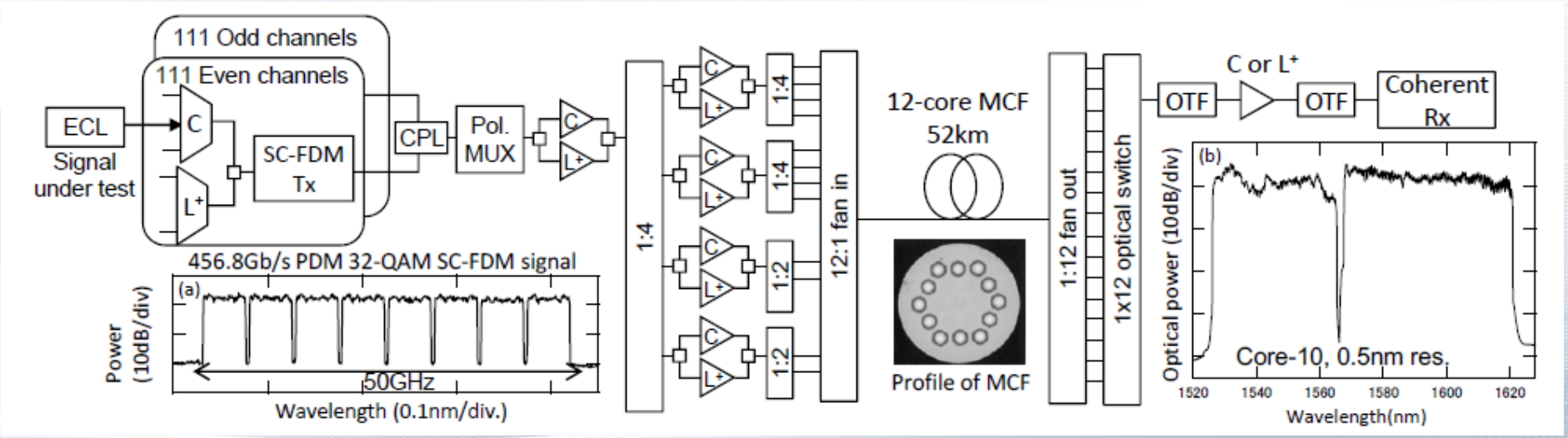
1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) Crosstalk-managed Transmission with 91.4-b/s/Hz Aggregate Spectral Efficiency

H. Takara[(1)], A. Sano[(1)], T. Kobayashi[(1)], H. Kubota[(1)], H. Kawakami[(1)], A. Matsuura[(1)], Y. Miyamoto[(1)], Y. Abe[(2)], H. Ono[(2)], K. Shikama[(2)], Y. Goto[(3)], K. Tsujikawa[(3)], Y. Sasaki[(4)], I. Ishida[(4)], K. Takenaga[(4)], S. Matsuo[(4)], K. Saitoh[(5)], M. Koshiba[(5)], and T. Morioka[(6)]

[(1)] NTT Network Innovation Laboratories, NTT Corporation, [(2)] NTT Photonics Laboratories, NTT Corporation, [(3)] NTT Access Network Service Systems Laboratories, NTT Corporation, [(4)] Fujikura Ltd, [(5)] Hokkaido University, [(6)] Technical University of Denmark, takara.hidehiko@lab.ntt.co.jp

Abstract *We demonstrate 1.01-Pb/s transmission over 52 km with the highest aggregate spectral efficiency of 91.4 b/s/Hz by using low-crosstalk one-ring-structured 12-core fiber. Our multi-core fiber and compact fan-in/fan-out devices are designed to support high-order modulation formats up to 32-QAM in SDM transmission.*

OCIS codes: (060.2330) Fiber Optics Communications; (060.2360) Fiber optics links and subsystems



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- ~~Intro with video (2 slides)~~
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- ~~Selected Topics (5 slides)~~
- Conclusion (1 slide)

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Conclusion ?

Long haul (>100km)

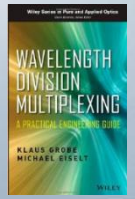
- Current ‘commercial’ technology limits us to around 40 TbS/fp.
- What will deliver the next step ? - New technology like Spatial Multiplexing ?
  - Incremental improvements in other areas ?
  - More efficient usage ?
- Interesting research space to watch while the 10-40 TbS systems come to market.

Short haul (<100km)

- Lots of possibilities available before we reach our technical limit.
- Current technology can deliver higher capacities than available for LH.
- The big question is cost, cost and cost !!!
- Will this cost issue result in a similar technology mix as long haul or ... ?

If you want to know more there are papers and books on these subjects a.e.:

- from ‘Bell Labs’ : “René-Jean Essiambre *et All,* Capacity Limits of Optical Fiber Networks, Journal Of Lightwave Technology, Vol. 28, No. 4, February 15, 2010”
- from a colleague at ADVA: “ Klaus Grohe, Michael Eiselt, Wavelength division multiplexing, Wiley, 2014”



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Acronyms/Symbols

ECOC	European Congress on Optical Communications
peta	10^{15} or 1000 tera
exa	10^{18} or 1000 peta
WDM	wavelength division multiplexing
φ	phase
SH	Short Haul (my definition: in general <100km)
LH	Long Haul (my definition: in general >100km upto 5000km)
nm	nanometer (10^{-9} meter)
fs	femtosecond (10^{-15} second)
ps	picosecond (10^{-12} second)
MbS	megabits per second
GbS	gigabits per second
TbS	terabits per second
NRZ-OOK	None Return to Zero - On Off Keying
PSK	Phase Shift Keying
PD-QPSK	Polarization Diverse - Quadrature Phase Shift Keying
PD-QAM	Polarization Diverse - Quadrature Amplitude Modulation
SOA	Semiconductor Optical Amplifier
EDFA	Erbium Doped Fibre Amplifer
TDFA	Thulium Doped Fibre Amplifier
PDFA	Praseodymium Doped Fibre Amplifier
fp	fibre pair
MIMO	Multiple Input Multiple Output