Optical Time-Frequency Packing

M. Secondini[2], T. Foggi[1], F. Fresi[2], G. Meloni[1], A. Mastropaolo[2], F. Cavaliere [3], G. Colavolpe[4], E. Forestieri[2], L. Potì[1], R. Sabella [3] and G. Prati[1]

(1) CNIT
(2) Scuola Superiore Sant'Anna
(3) Ericsson Research Italia
(4) Parma University

outline

spectral efficient transmission

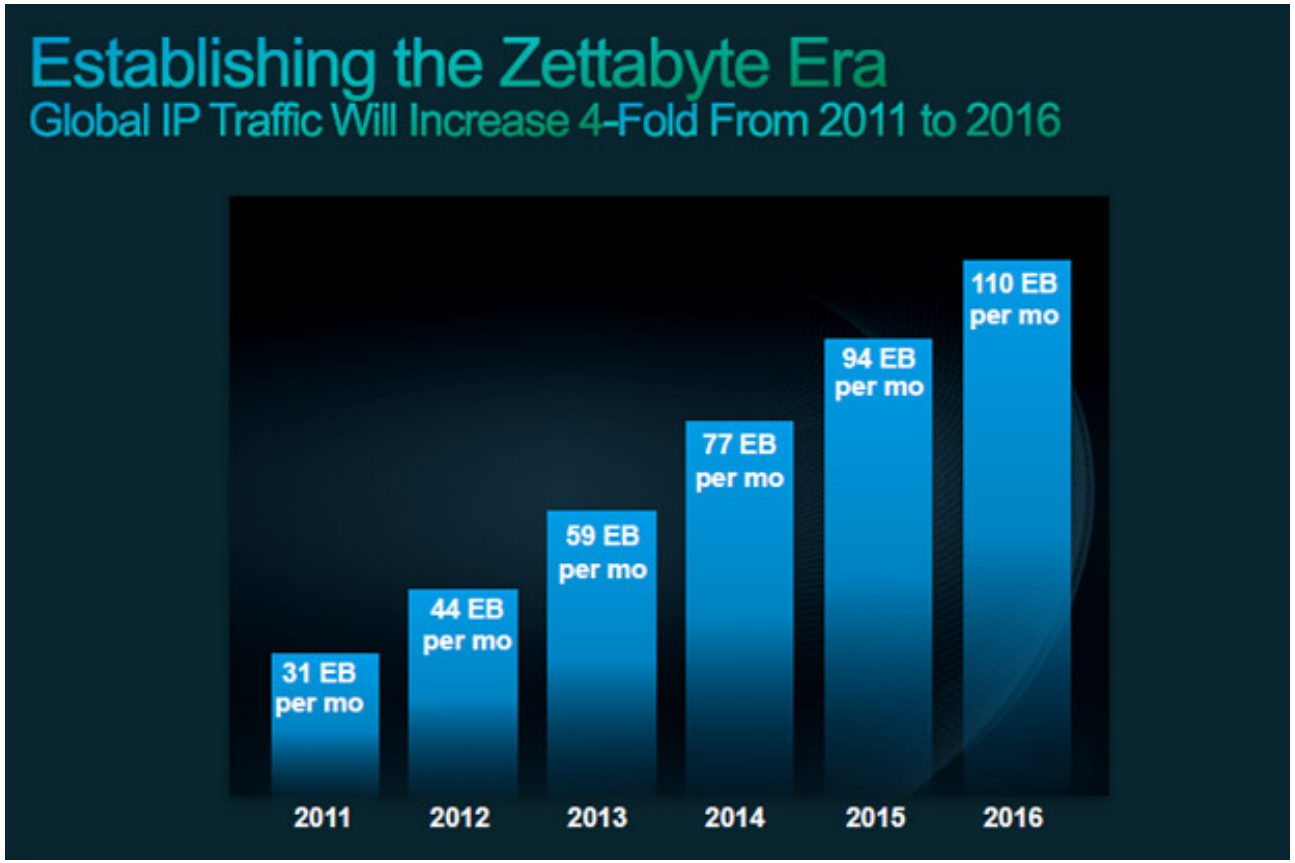
Time-Frequency-Packing

field trial description

The COFFEE Project

TFP vs NWDM

motivations

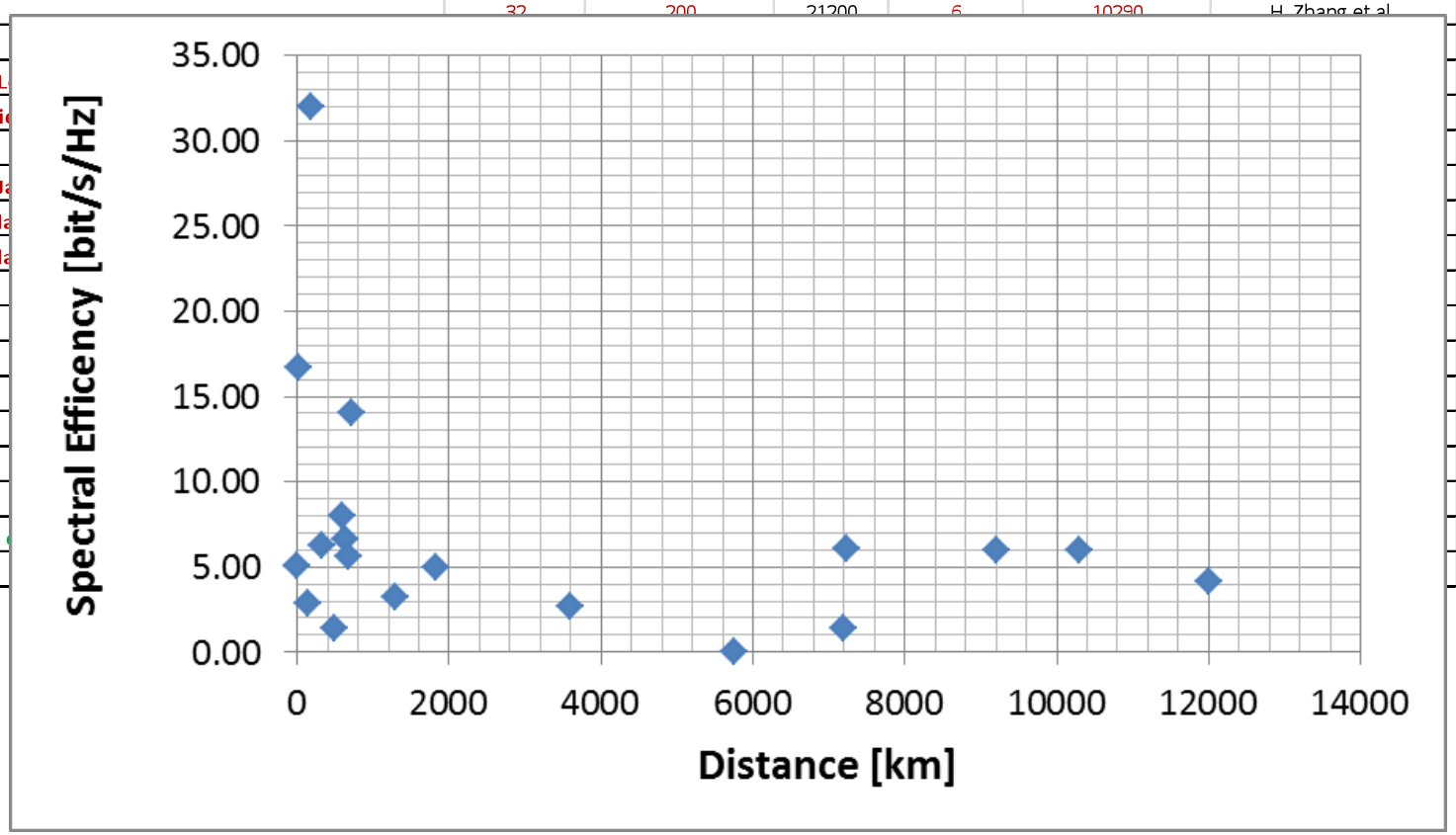


Exabyte per month

source: www.cisco.com

state of the art

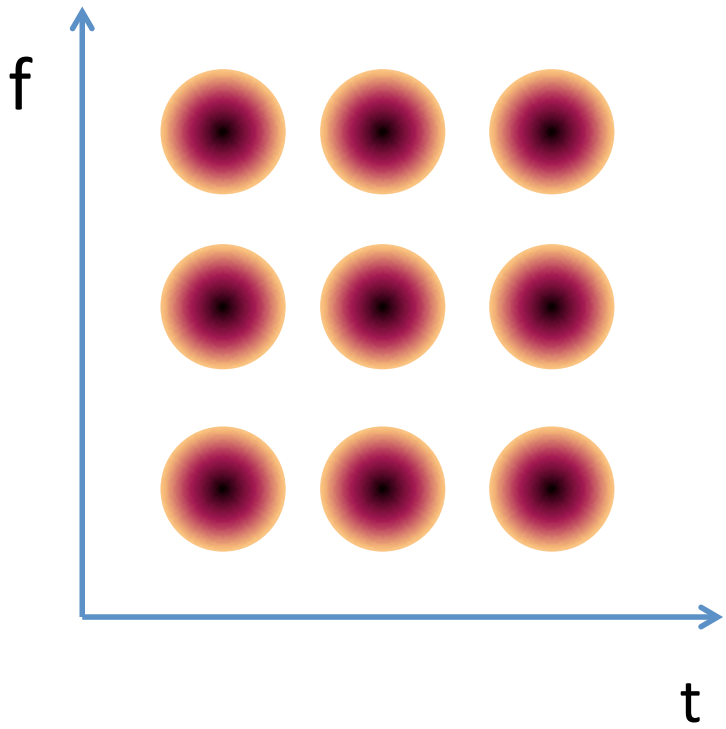
	Symbol Rate [Gbaud]	Bit rate [Gb/s] (single channel)	Capacity [Gbit/s]	Spectral Effi cency	Reached distance [km]	Reference	Reference
Verizon	24.8	120	40500	4.94	1822	A. Tanaka et al.	PDP5A.4 (OFC13)
Verizon	24.8		54200	6.6	634	A. Tanaka et al.	PDP5A.4 (OFC13)
TE SubCom	32	200	21200	6	10290	H. Zhang et al.	PDP5A.6(OFC13)
TE SubCom							PDP5A.6(OFC13)
Bell Labs ALU/UPC/L							PDP5a.1(OFC13)
Eindhoven/Nokia Si							OW11.5(OFC13)
NICT							OW1I.1(OFC13)
Tohoku University Ja							OTh4E.1(OFC13)
Alcatel Lucent Bell la							OTh4E.2(OFC13)
Alcatel Lucent Bell la							OTh4E.3(OFC13)
AT&T/OFS							OTu2B.4(OFC13)
NEC							JTh2A.37(OFC13)
CPqD							JTh2A.39(OFC13)
ZTE							JW2A.43(OFC13)
Xtera Communicati							JTh2A.42(OFC13)
Alcatel-Lucent							JW2A.40(OFC13)
NEC							NW4E.1(OFC13)
Research Insti tute							OTh4E.4(OFC13)
TE SubCom							OTu2B.3(OFC13)



spectral efficient transmission taxonomy

- Orthogonal transmission (no ISI, no ICI)
  - Multiple carriers separated in frequency but overlapping in time (e.g. Nyquist WDM)
  - Multiple carriers overlapped in frequency but separated in time (e.g. OFDM)
  - Multiple carriers overlapped in frequency but separated in codes (e.g. OCDMA)
- Non-orthogonal transmission

  Single/Multiple carriers, which may overlap in frequency



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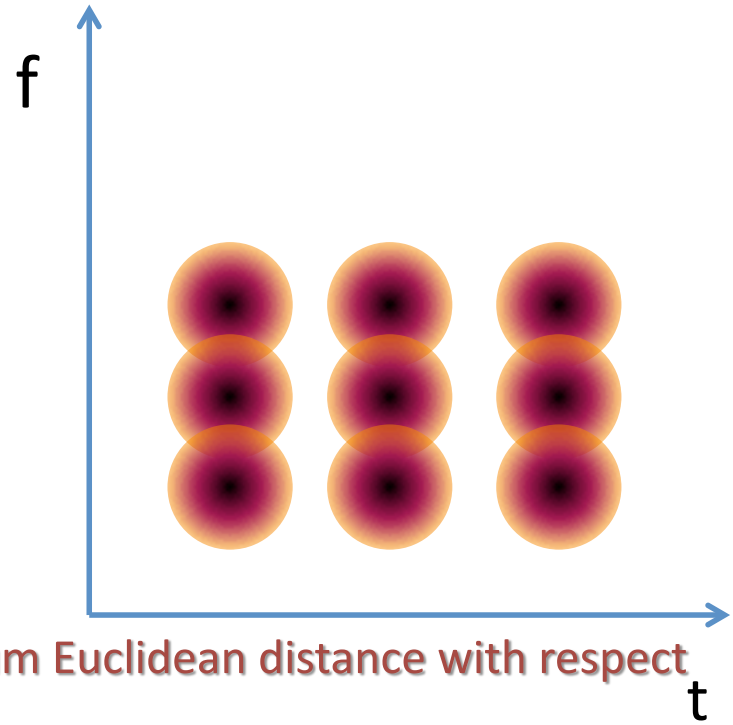
- Non-orthogonal transmission

  Single/Multiple carriers, which may overlap in frequency and/or time



Faster-Than-Nyquist (FTN) [1]

Design criterion: no reduction of the minimum Euclidean distance with respect to the Nyquist case

Time-Frequency-Packing (TFP) [2]

Design criterion: maximum spectral efficiency with a design constrained receiver complexity

[1] F. Rusek and J. B. Anderson, "The two dimensional Mazo limit," in Proc. IEEE International Symp. Inform. Theory, Sept. 2005
[2] G. Colavolpe, T. Foggi, A. Modenini, and A. Piemontese, "Faster-than-Nyquist and beyond: how to improve spectral efficiency by accepting interference," OSA Opt. Express, vol. 19, pp. 26600-26609, December 2011.

underlying Information theory

Info

SE=

F= fre

T=tim

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inter

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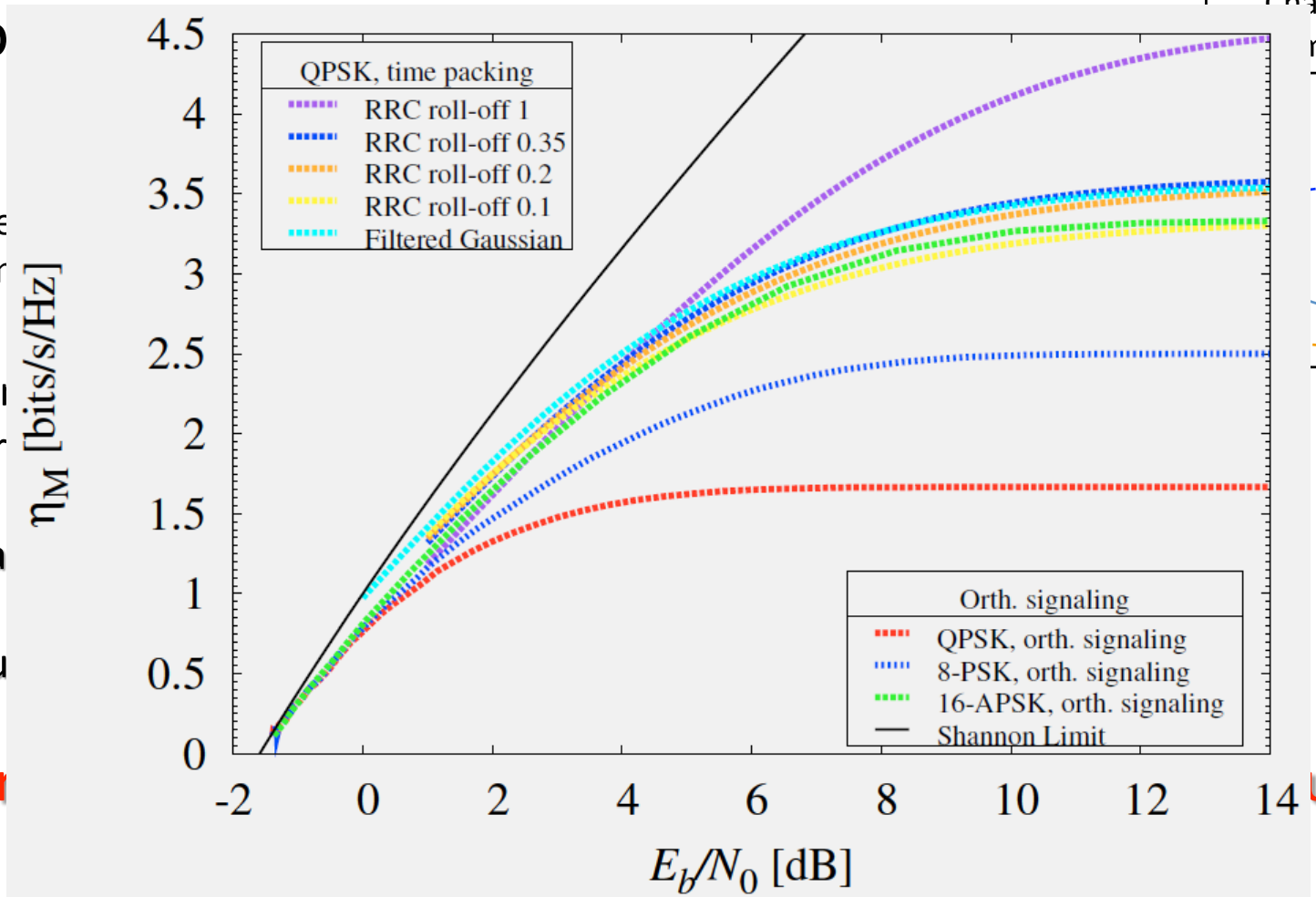
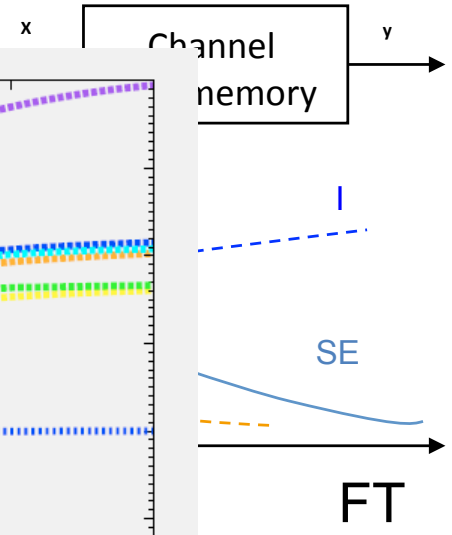
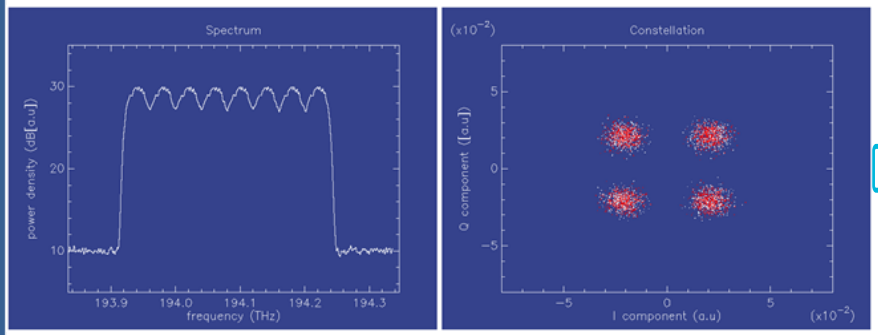




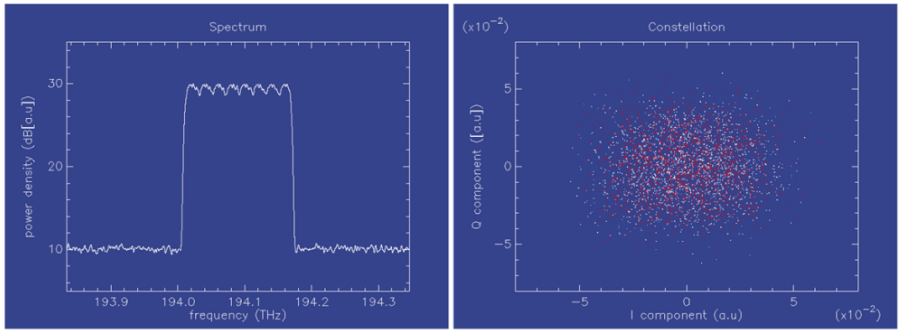
und !

time packing example

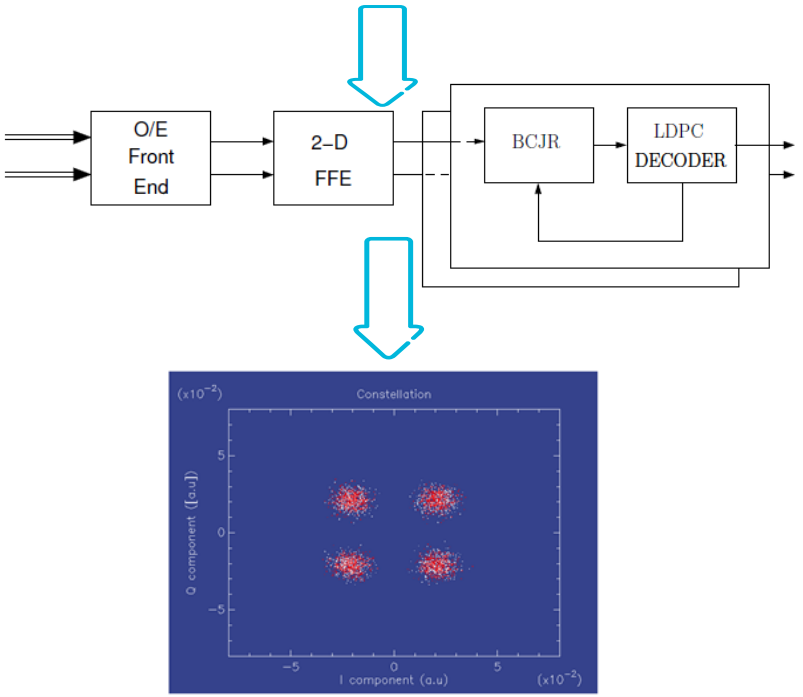
conventional orthogonal QPSK transmission



time packed non-orthogonal signaling



- At the Tx the carriers are LDPC encoded, narrow filtered and ultra-densely spaced in frequency
- At the Rx, a conventional coherent front end is followed by an equalizer, a trellis BCJR decoder and a LDPC decoder
- BCJR and LDPC blocks iteratively exchange information until the correct bit sequence is detected
- A light outer FEC can easily compensate for LDPC error floors

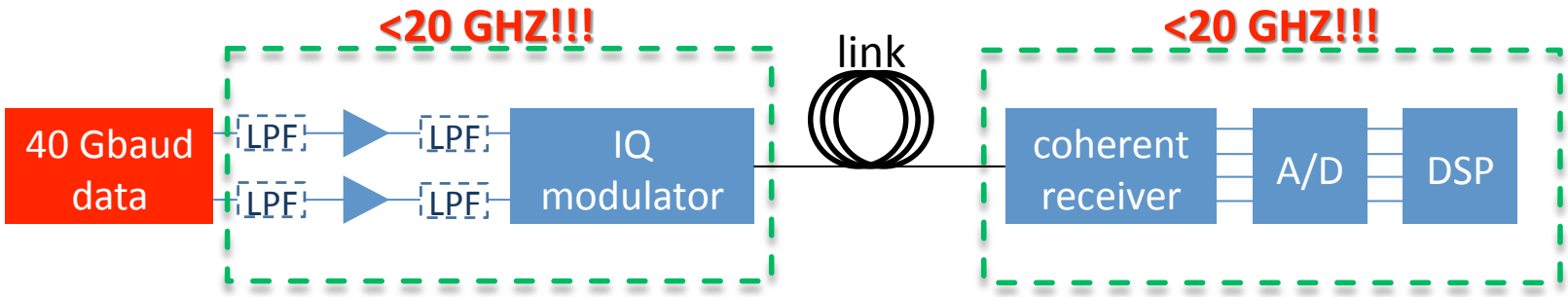


why Time-Frequency-Packing

- Compared to **OFDM**
  - No cyclic prefix, less sensitive to phase noise, more resilient to non-linearities, modular and scalable
- Compared to **Nyquist WDM**
  - Similar technology but more spectral efficient (lower cut-off frequency)
- Compared to traditional "**Faster than Nyquist**"
  - Receiver complexity fixed by design to enable implementation

two additional benefits:

1. **flexibility** (adaptive code rate)
2. lower electronic and optoelectronic **bandwidth** requirements (power consumption)



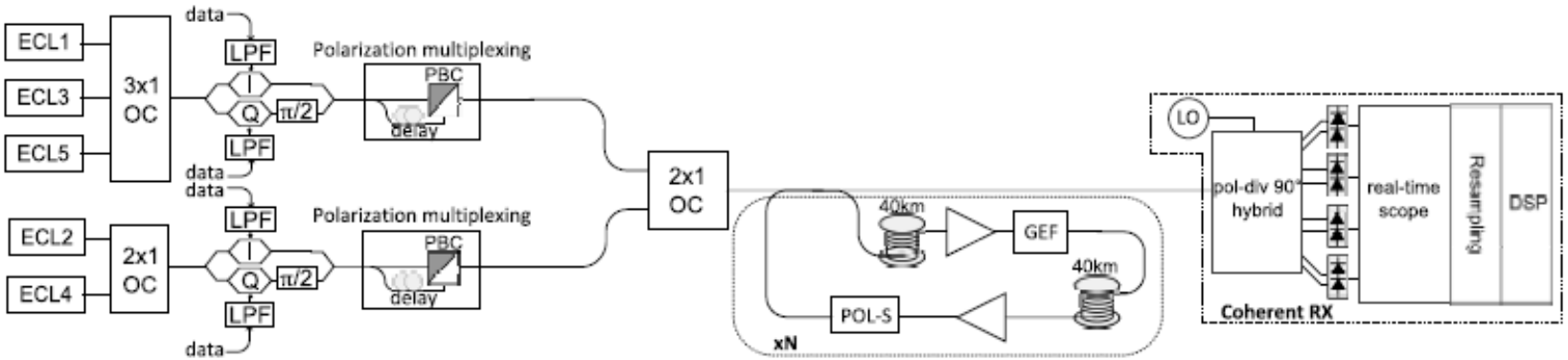
How TFP works

- Set the desired input constellation (e.g., QPSK) and detector complexity

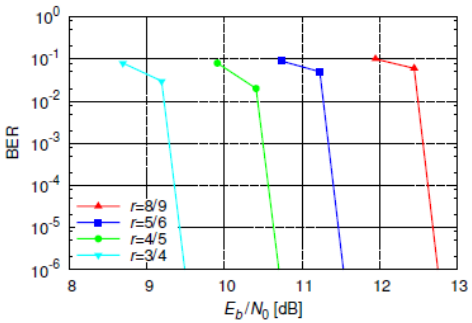
- Find the optimum time and frequency spacing which provides the maximum achievable SE

- Select a proper code to approach as close as desired the achievable SE

Experimental demonstration

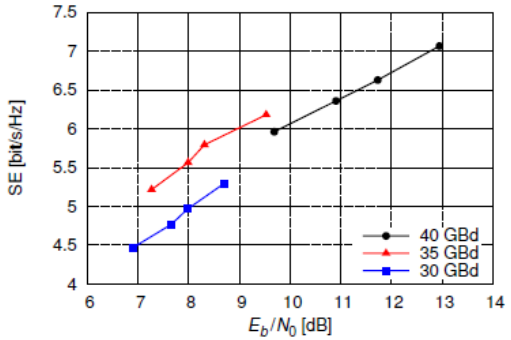


Experimental setup

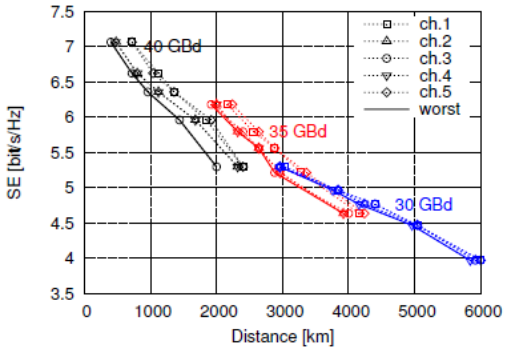


Experimental back-to-back performances of the TFP system : BER 40 GBd DP-QPSK

[3] arXiv:1411.6892



Experimental back-to-back performances of the TFP system : Achieved SE with 40 GBd, 35 GBd and 30 GBd DPQPSK

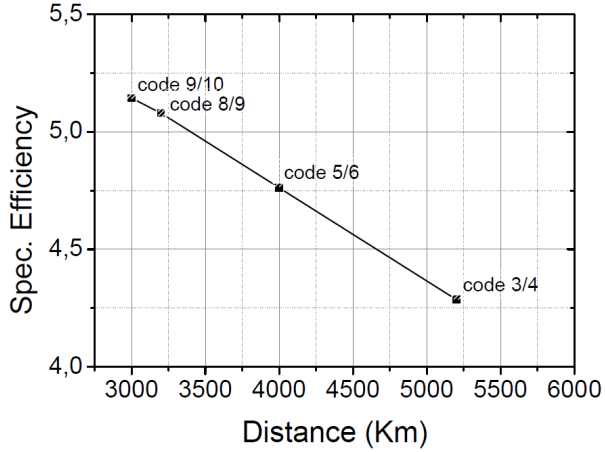


Experimentally achieved SE vs reached distance with 40 GBd, 35 GBd and 30 GBd DPQPSK

Time-Frequency-Packing in long haul

developed by CNIT, Scuola Superiore Sant'Anna, and Ericsson [3-4]

- Long reach combined with high spectral efficiency
- Highly modular architecture enabling energy efficient aggregation of parallel data flows
  - More spectral efficient and simpler than OFDM (no phase synch, less overhead, simple ADC)
- Ultra Long Haul
  - > 5000 km demonstrated in lab with SMF, not achievable with 16QAM
- SW adaptable line rate for easy traffic planning and protection
  - 62% distance increase (5200 km) possible with 15% reduced line rate – demonstrated in lab

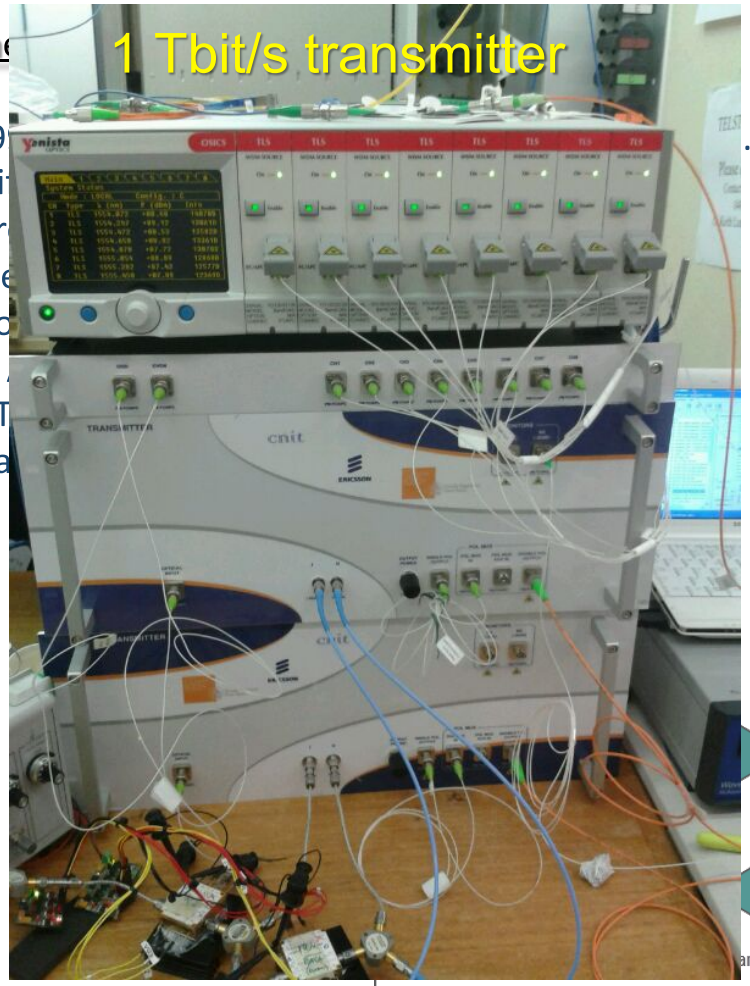


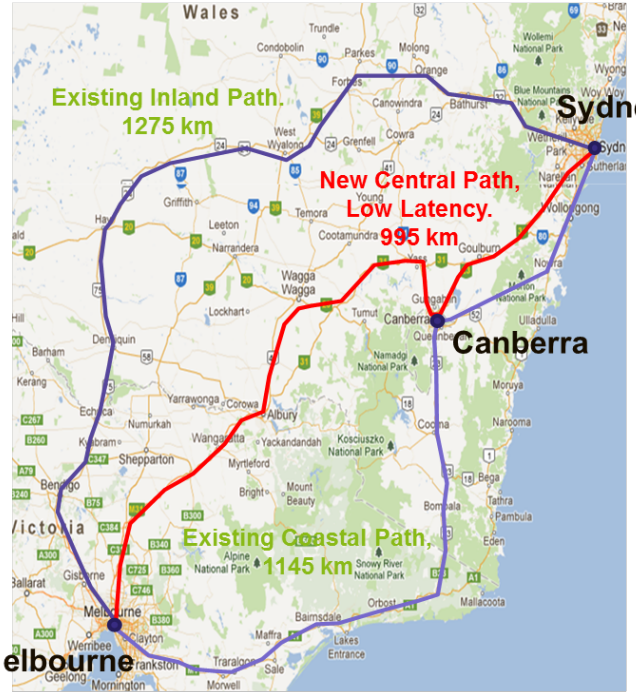
[3] L. Potì, G. Meloni, G. Berrettini, F. Fresi, M. Secondini, T. Foggi, G. Colavolpe, E. Forestieri, A. D'Errico, F. Cavaliere, R. Sabella, G. Prati, "Casting 1 Tb/s DP-QPSK Communication into 200 GHz Bandwidth", ECOC 2012, June 2012, Amsterdam.
[4] G. Colavolpe, T. Foggi, A. Modenini, and A. Piemontese, "Faster-than-Nyquist and beyond: how to improve spectral efficiency by accepting interference," OSA Opt. Express, vol. 19, pp. 26600-26609, December 2011.

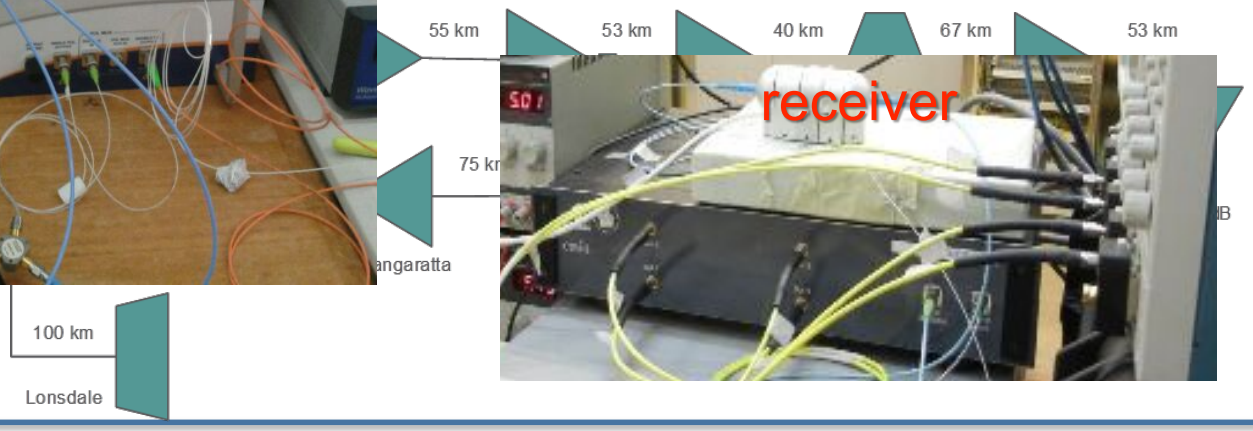
field trial description

Melbourne

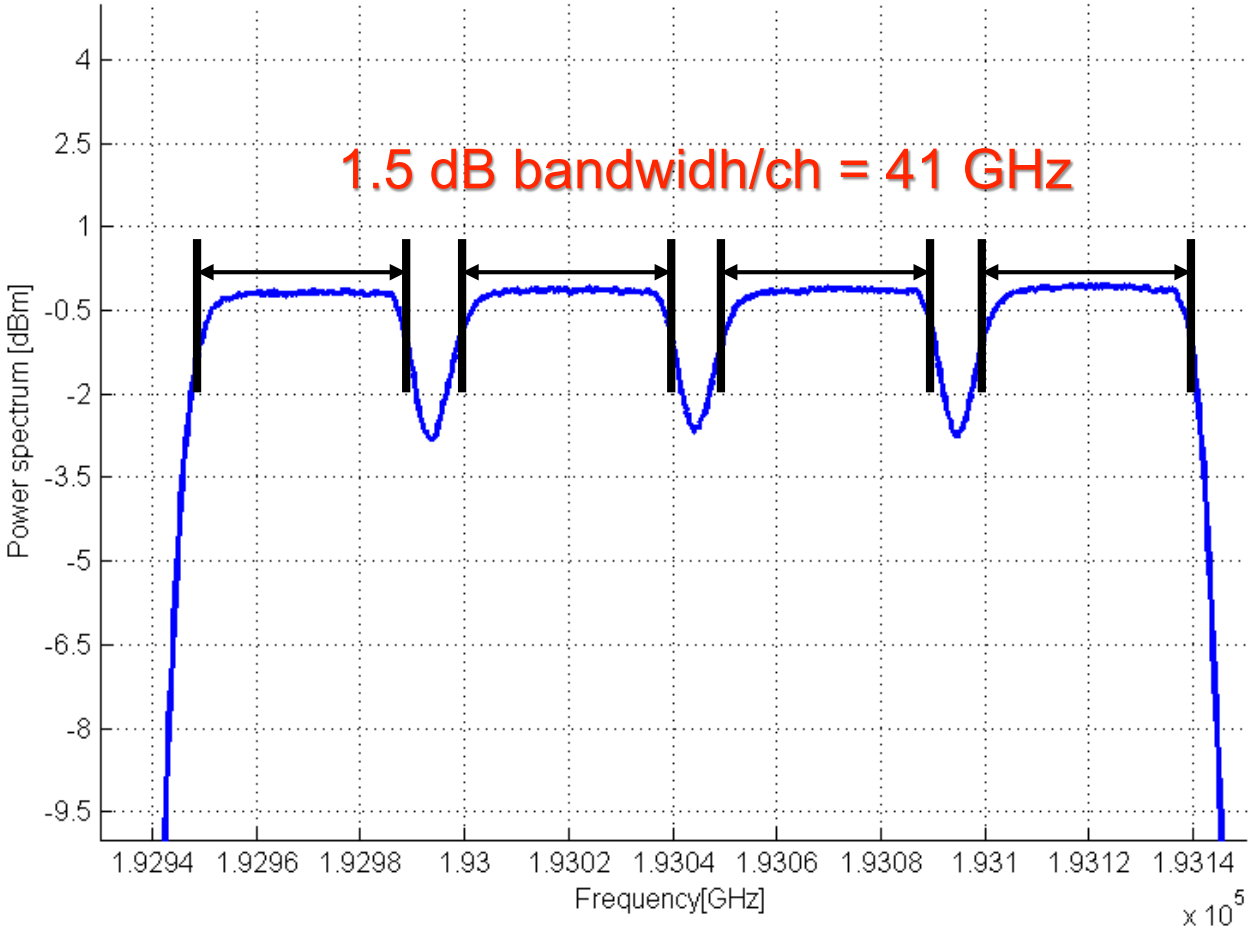
- Approx 9
- 13 Ampli
- ~500 fibr
- Recover e
- Utilise Co
- Increase
- Provide T
- Provide a





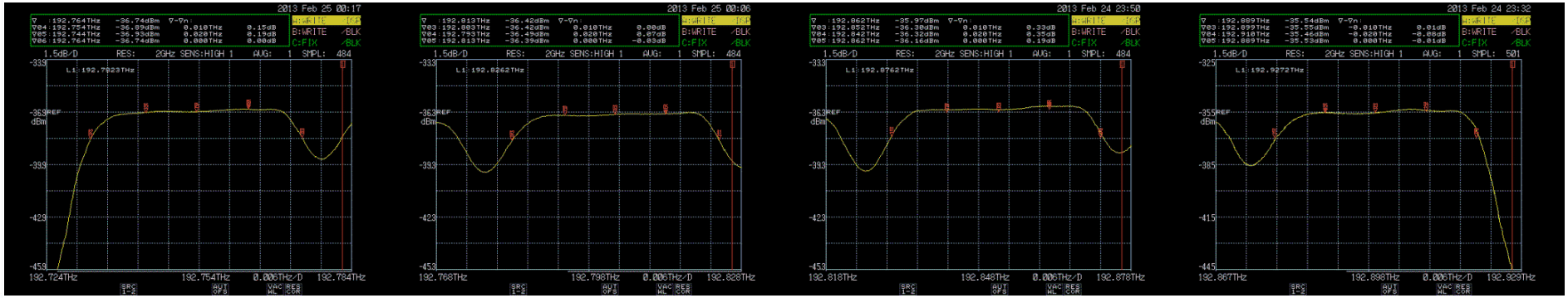


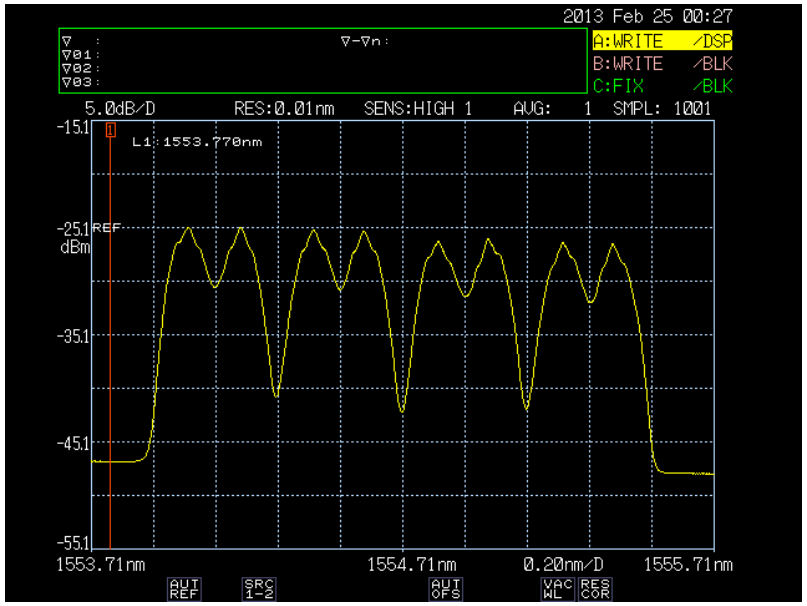
WSS characterization



superchannel 3dB bandwidh = 194.3 GHz

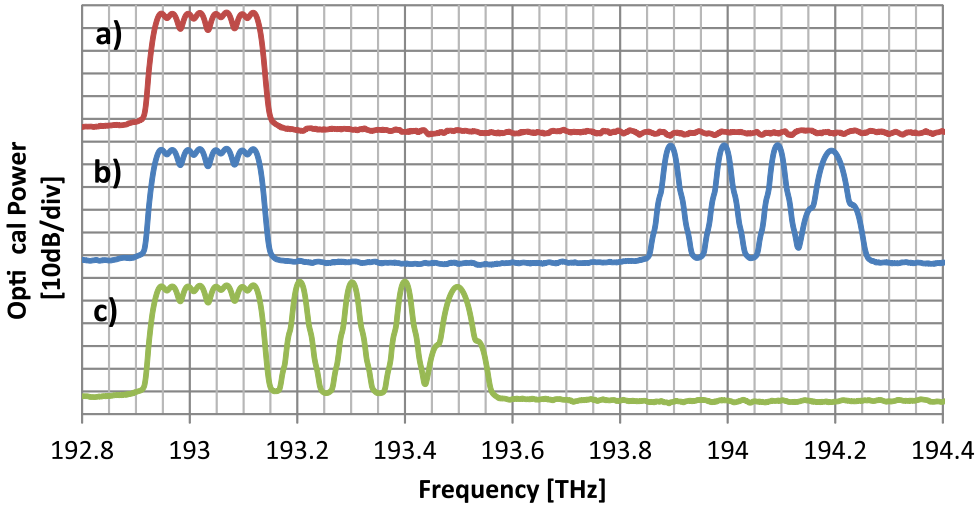
channel allocation

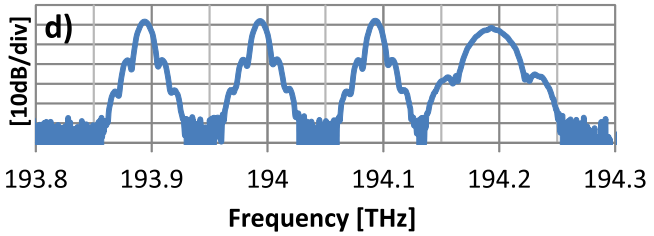


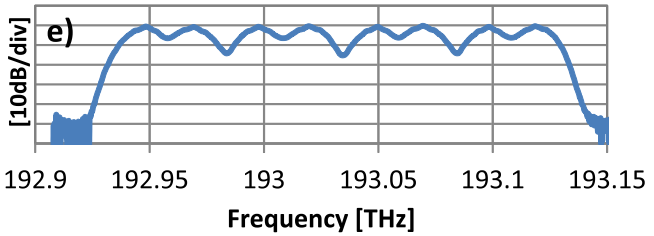


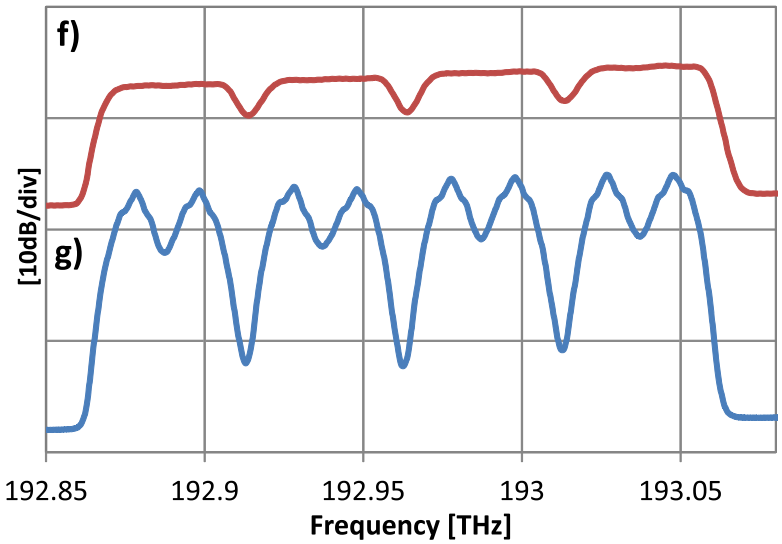
3dB bandwidh = 194.3 GHz
channel separation = 20 GHz

input and output spectra

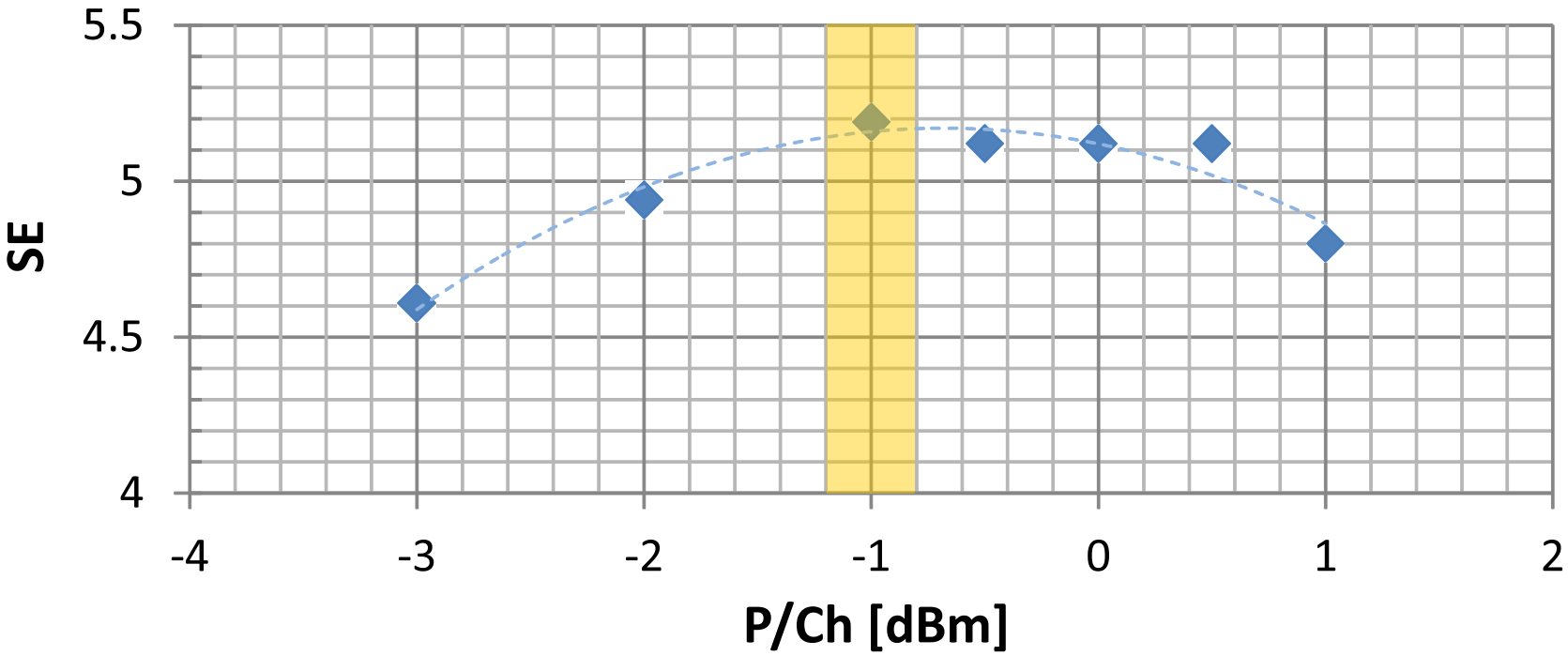




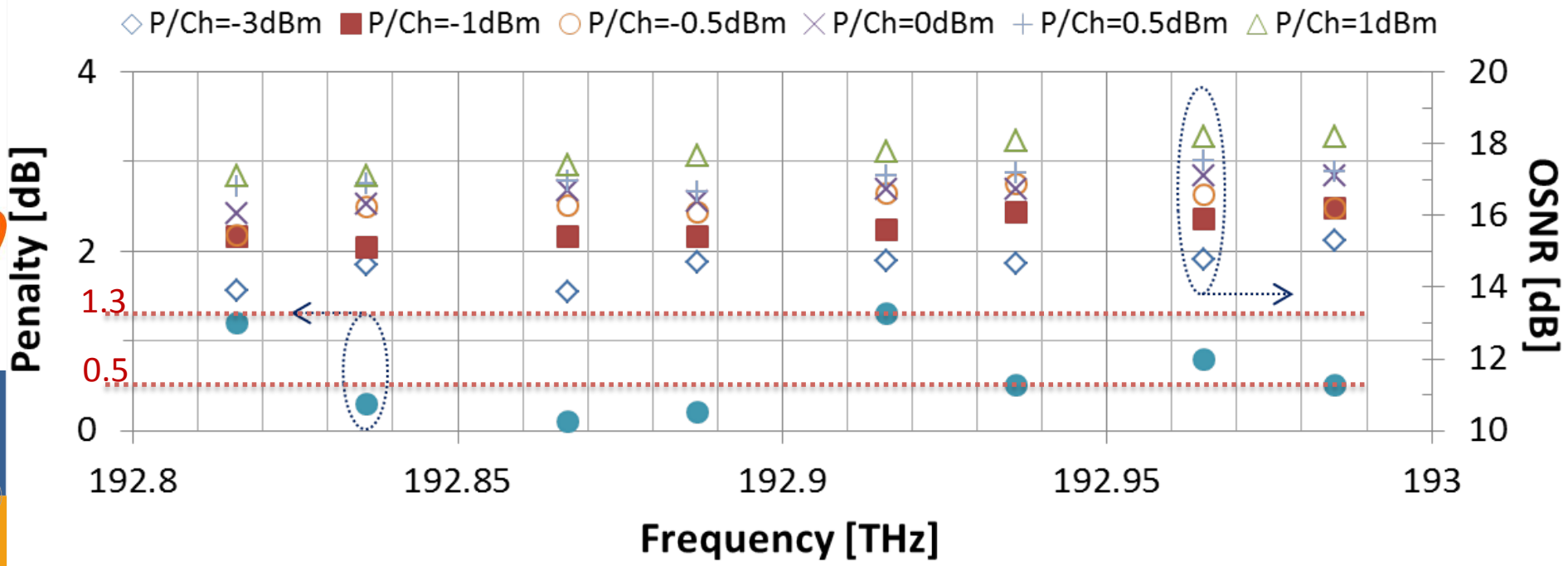




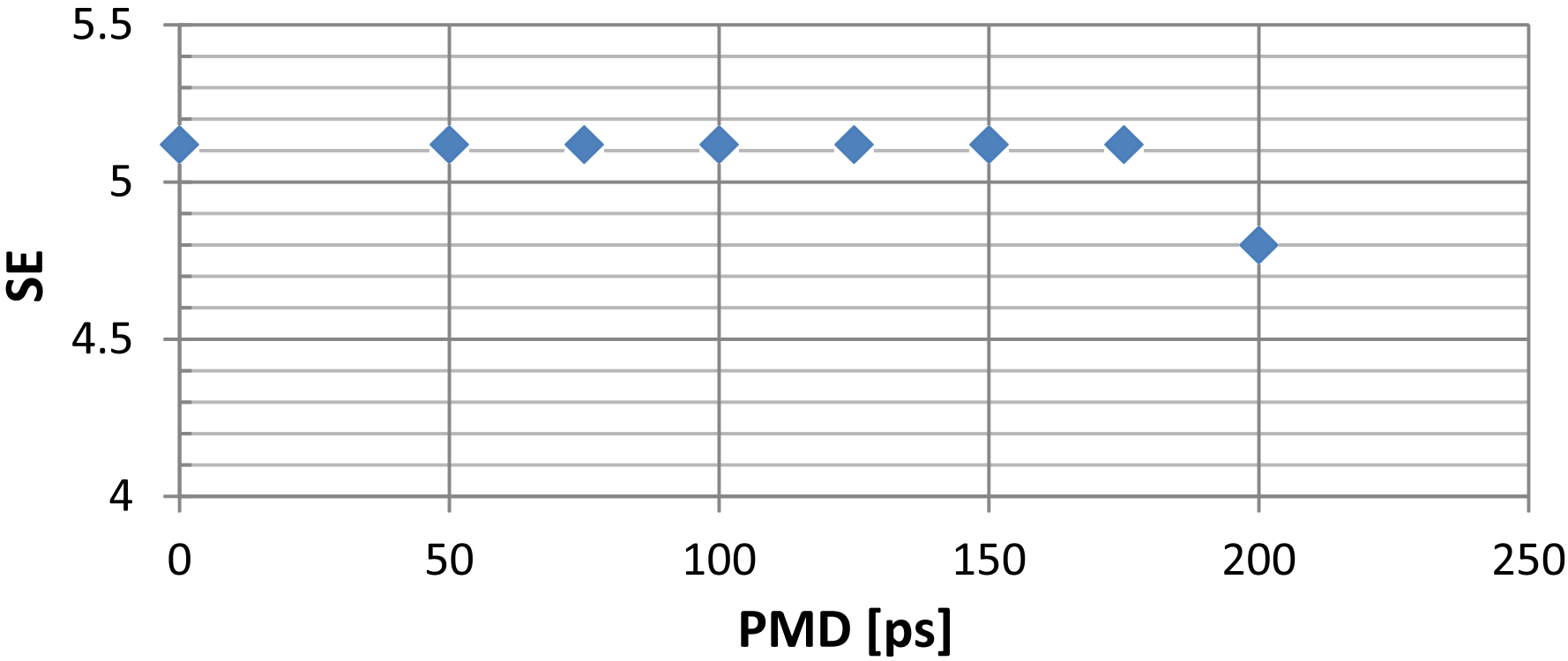
power optimization



power penalty

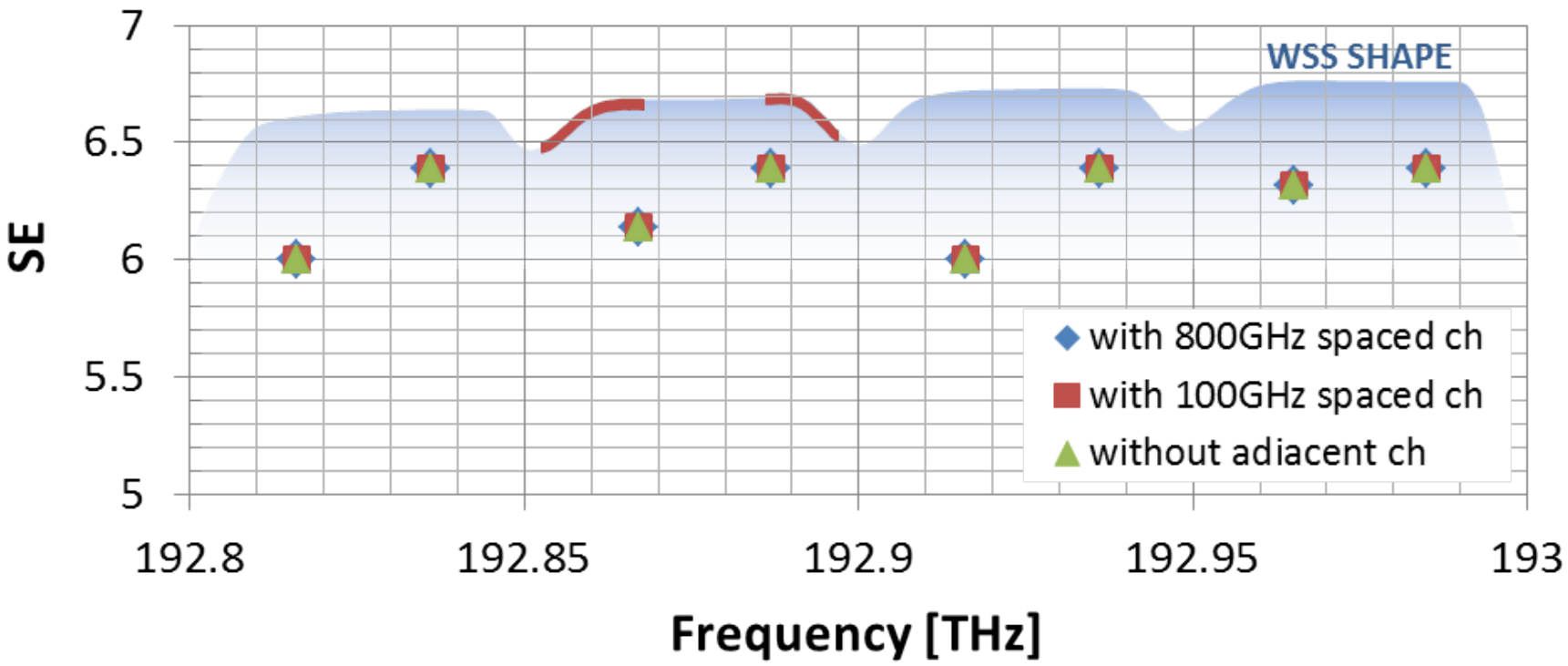


PMD penalty

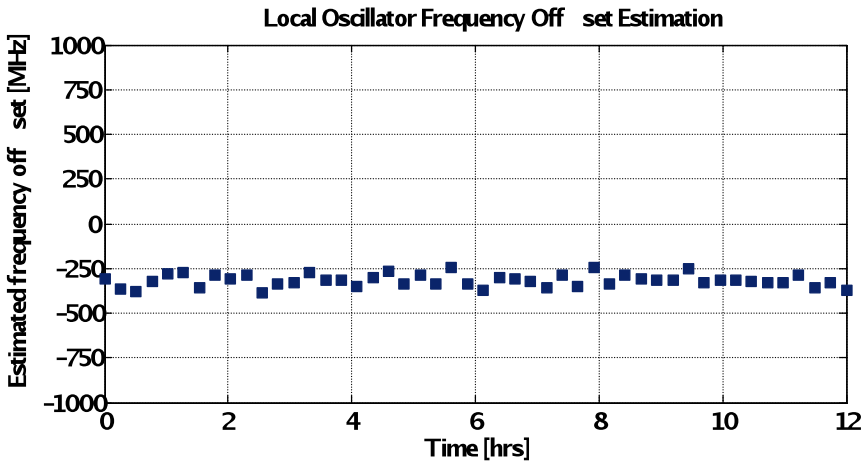


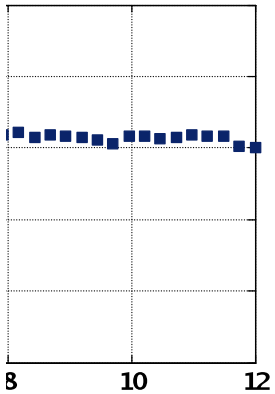
- No penalty up to 170 ps additional DGD
- 5% SE drop with 200 ps

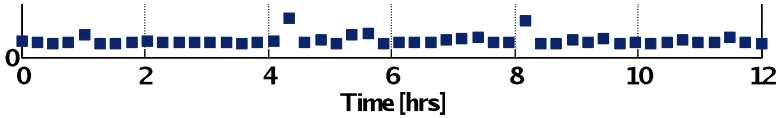
SE and xtalk with 40G and 100G

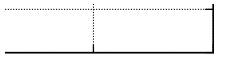


Long term test

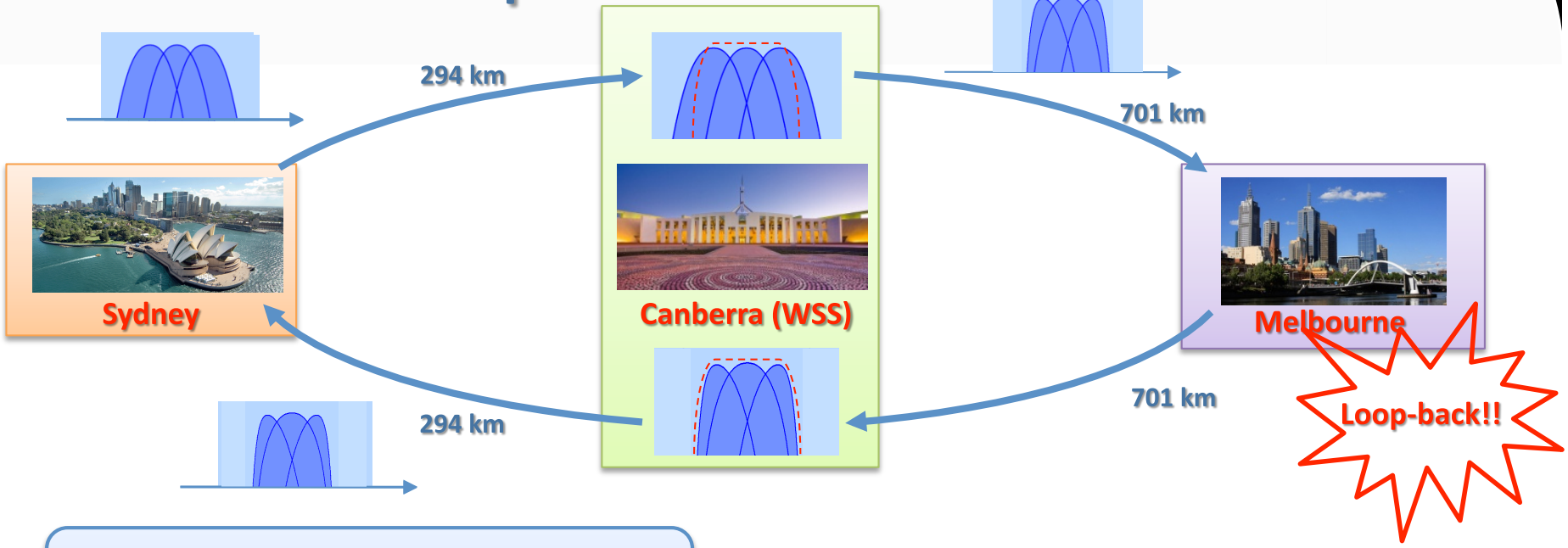








1990km – loop back



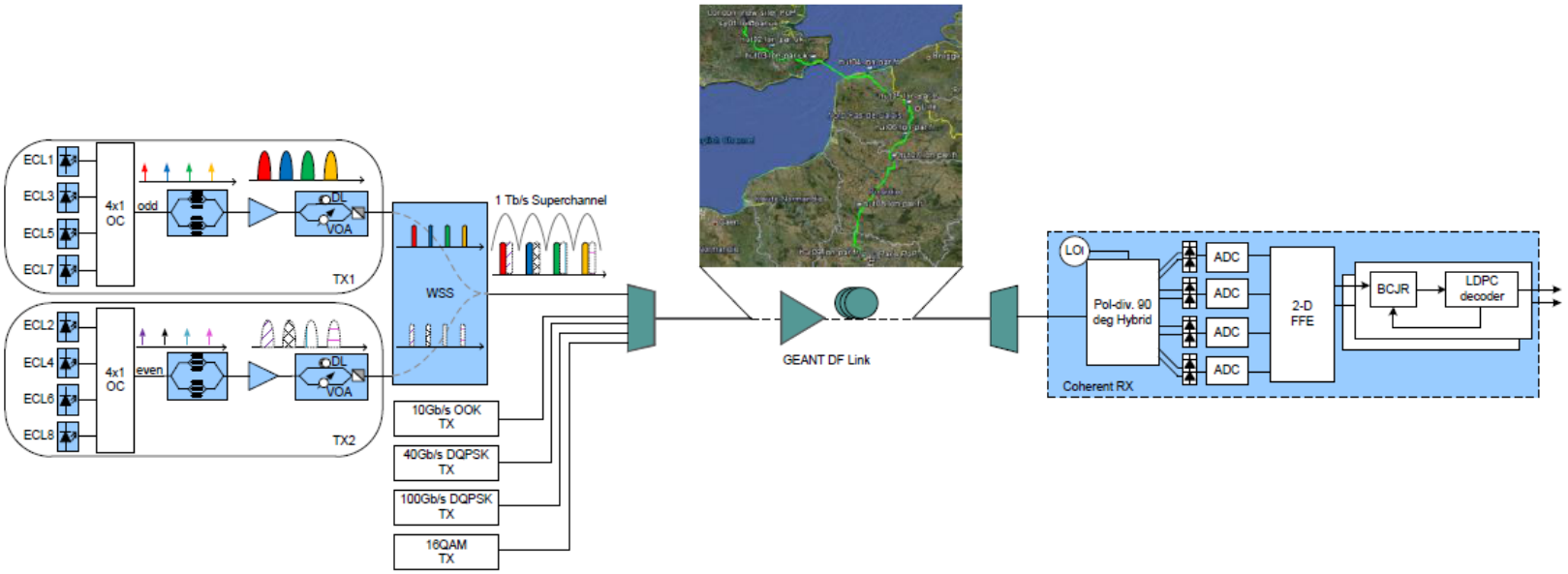
- **Single sub-channel**
  - P=1dBm
  - OSNR= 14.8 dB
  - SE= 7.1
  - BW=18 GHz
  - code rate 4/5
  - Rate=40GHz
  - information rate = 128 Gb/s

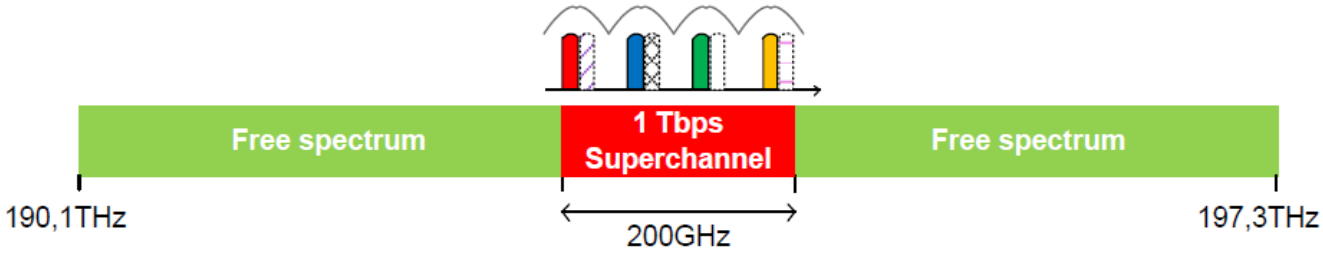
- **Three adjacent channels**
  - P/ch= 1dBm
  - OSNR= 14.6 dB
  - BW/ch=18 GHz
  - SE= 4.7
  - total BW= 60 GHz
  - code rate= 2/3
  - rate= 35 GBaud
  - information rate= 280 Gb/s

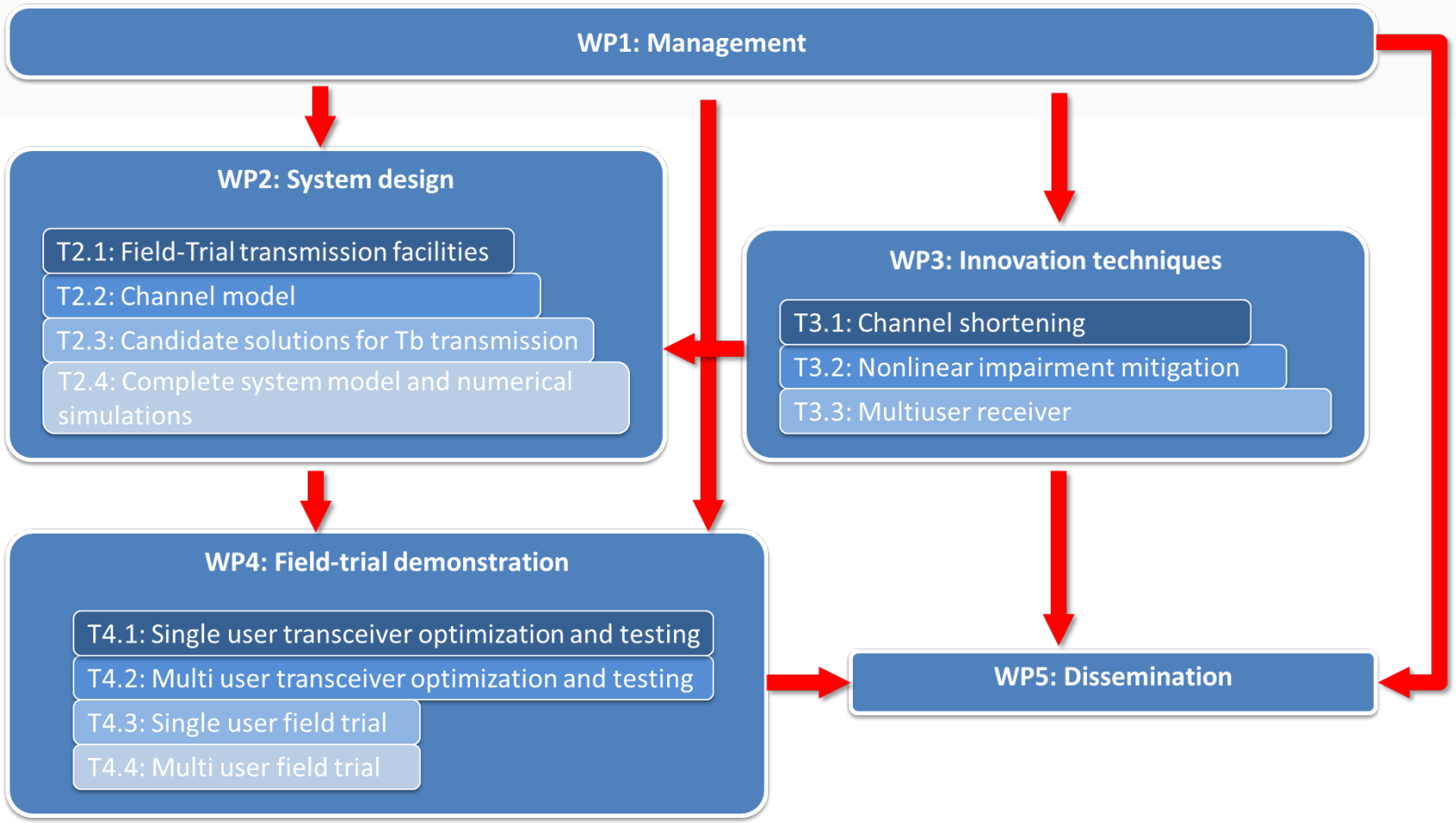
conclusions

- **Time-Frequency-Packing** has been introduced
- 1Tbit/s field trial transmission over **995 km**
- sub-channel **SE between 6 and 6.5** have been measured for all 8 channels
- a total minimum information rate of **1.0084 Tb/s** within 194.3 GHz have been transmitted
- nonlinear propagation effects have been minimized
- PMD tolerance up to 170 ps verified
- **compatibility** with existing **40 and 100 Gb/s** channel **confirmed**
- long term stability evaluated within 12 hours
- loopback measures **(1990km)** single sub-channel and three interfering sub-channels SE= 4.7, information rate=280 Gb/s over 18GHz

The COFFEE Project

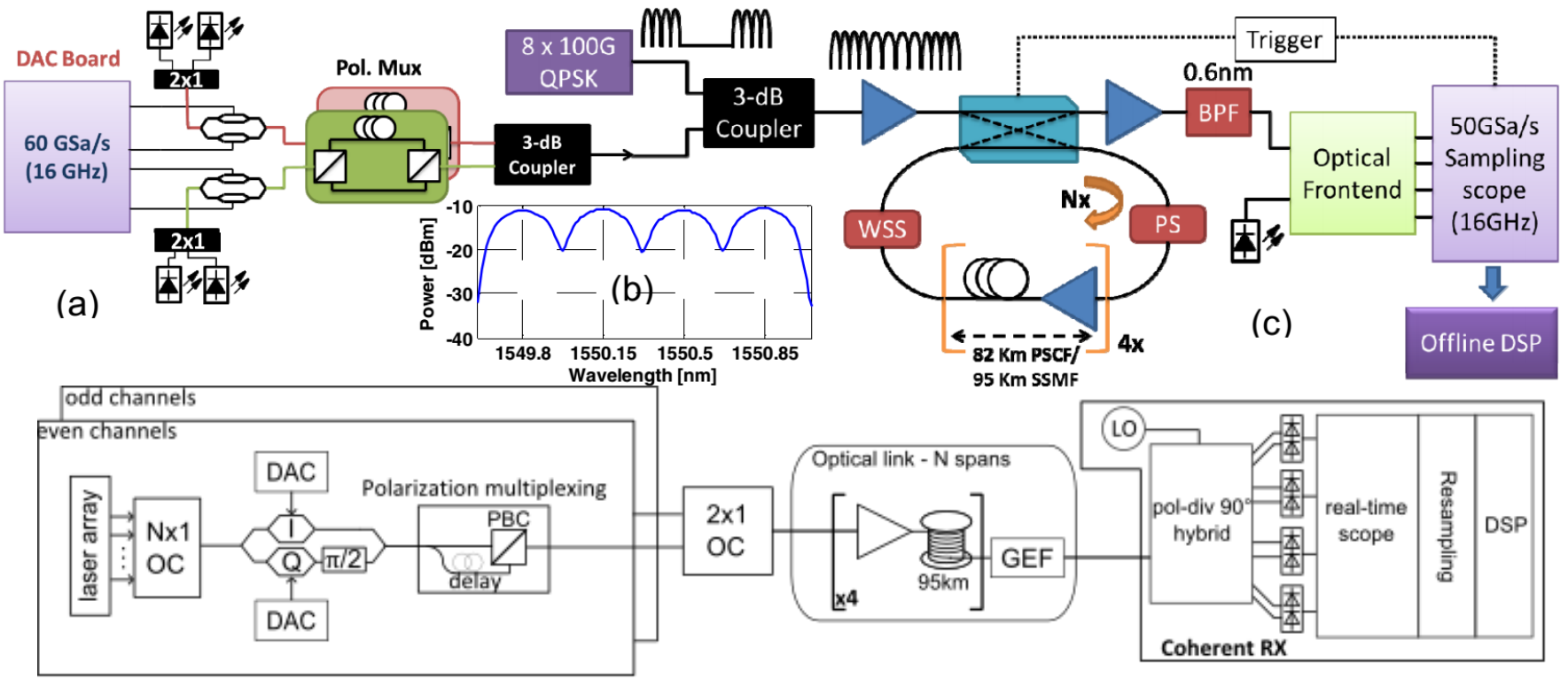






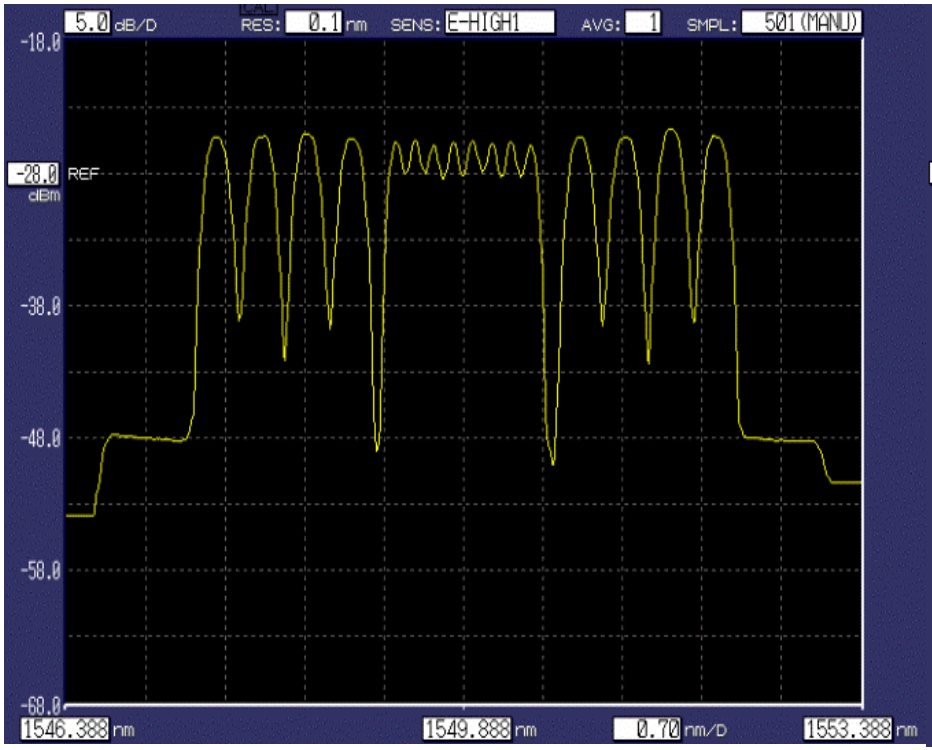
Field trial Milano-Finkenstein loop back ~ 643x2 km starting half of January

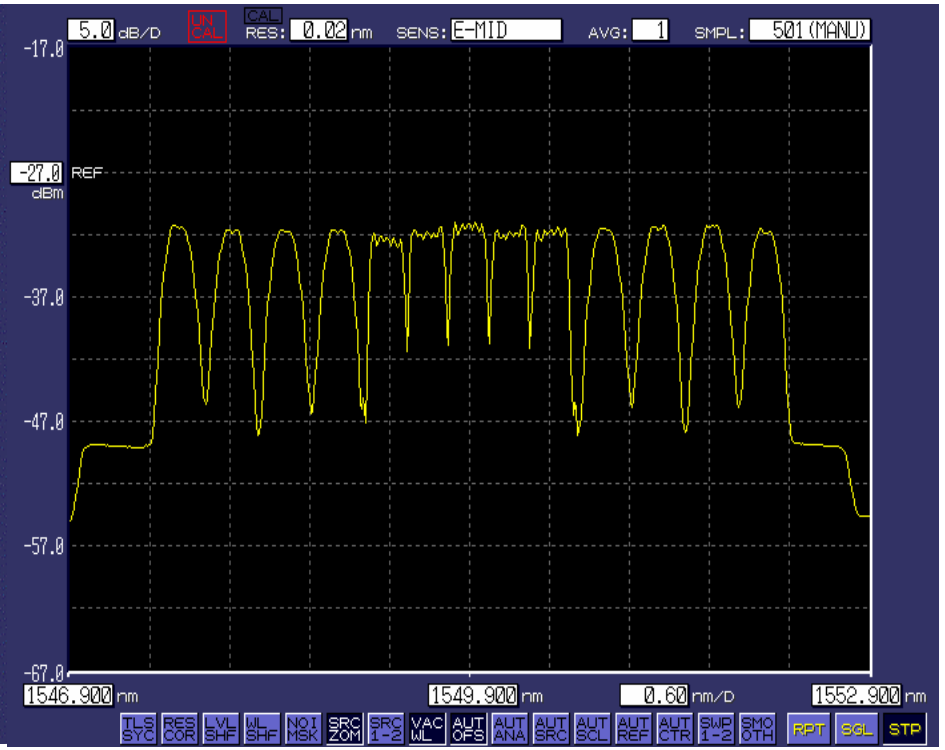
TFP vs NWDM


DAC Board
60 GSa/s
(16 GHz)
2x1
2x1
Pol. Mux
8 x 100G
QPSK
3-dB
Coupler
3-dB
Coupler
(a)
Power [dBm]
-10
-20
-30
-40
1549.8
1550.15
1550.5
1550.85
Wavelength [nm]
(b)
WSS
Nx
PS
4x
82 Km PSCF/
95 Km SSMF
Trigger
0.6nm
BPF
Optical
Frontend
50GSa/s
Sampling
scope
(16GHz)
Offline DSP
(c)
odd channels
even channels
laser array
Nx1
OC
DAC
DAC
I
Q
π/2
Polarization multiplexing
PBC
delay
2x1
OC
Optical link - N spans
x4
95km
GEF
LO
pol-div 90°
hybrid
real-time
scope
Resampling
DSP
Coherent RX

NWDM and TFP – Spectra

- Spectra of NWDM and TFP over link with 8×100 Gb/s commercial Coriant QPSK

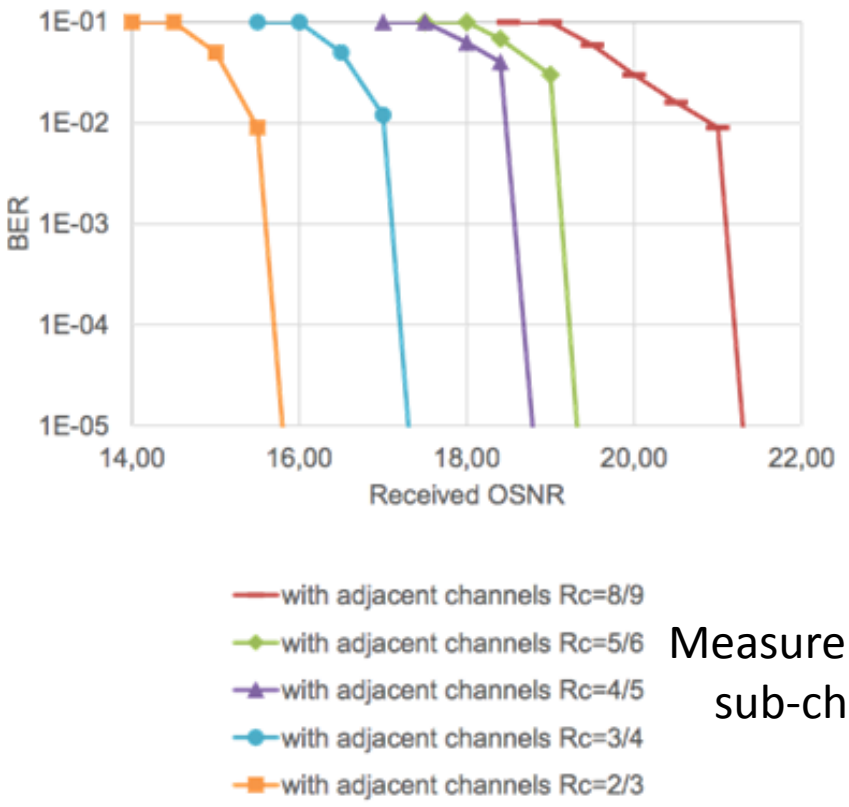




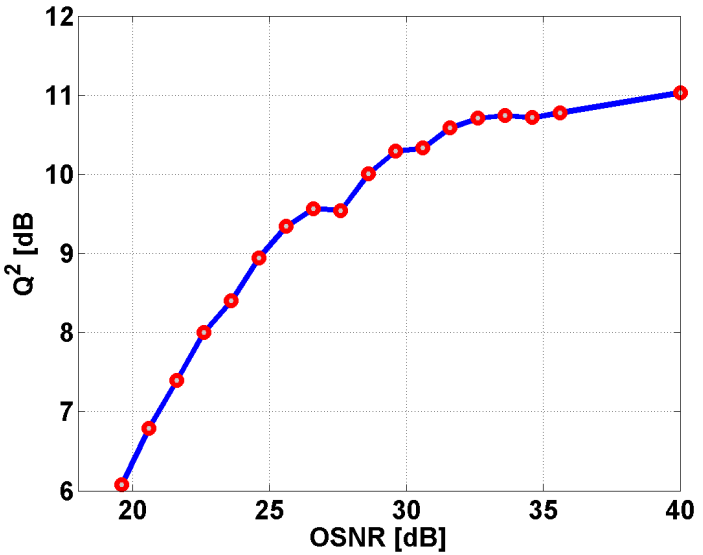
Information$_{rate}$ = 40Gbaud * 2quadratures * 2Pol * 8 carriers/(1+OH) ≈ 1.28 Tb/s
OH = 28% taking into account FEC, pilot, framer synchronization

NWDM and time-frequency packing B2B

TFP (QPSK, 40 Gbaud, 8 subcarriers)

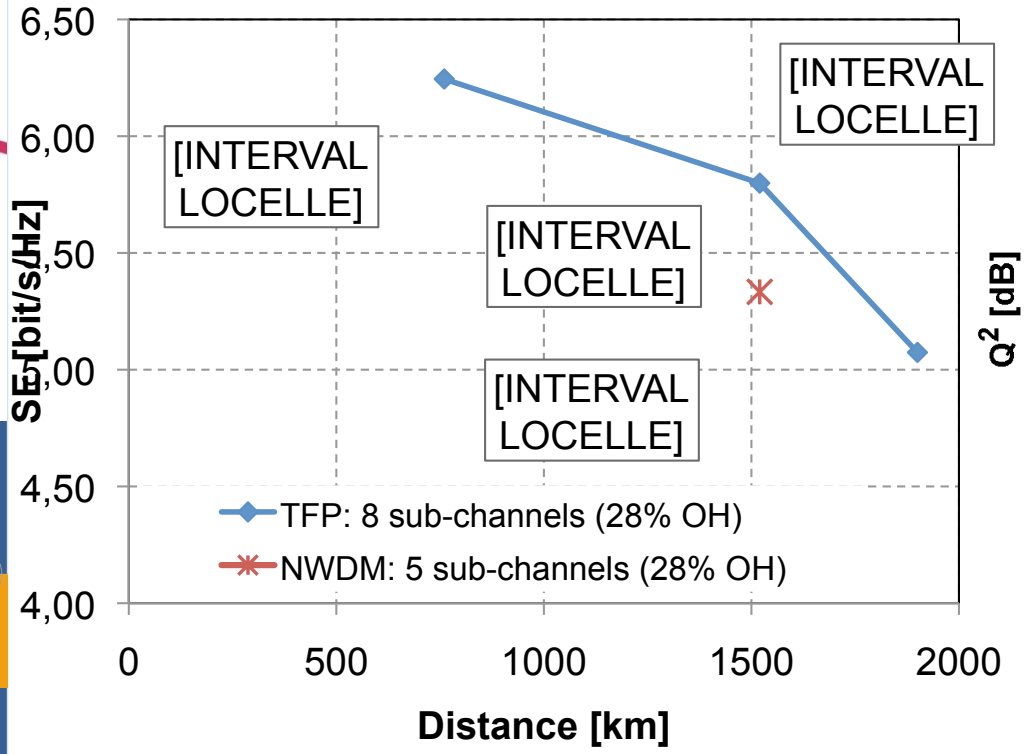


NWDN (16QAM, 32 Gbaud, 5 subcarriers)

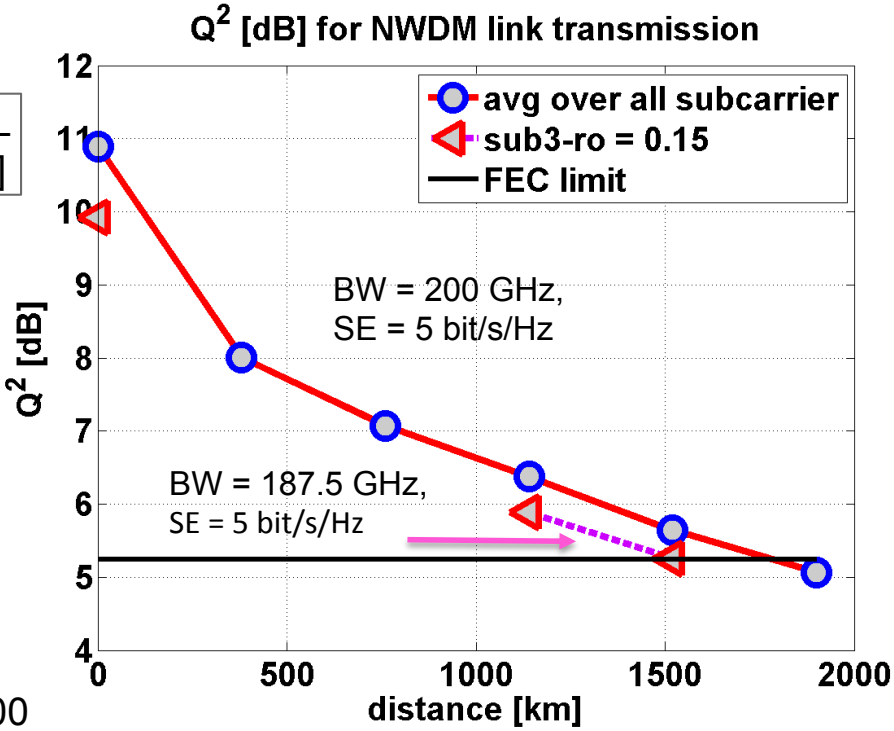


Measure on the central sub-channel out of three

NWDM and TFP – Transmission



TFP: performance in Spectral efficiency as function of distance and spectral occupancy



TFP (QPSK, 40 Gbaud, 8 subcarriers)

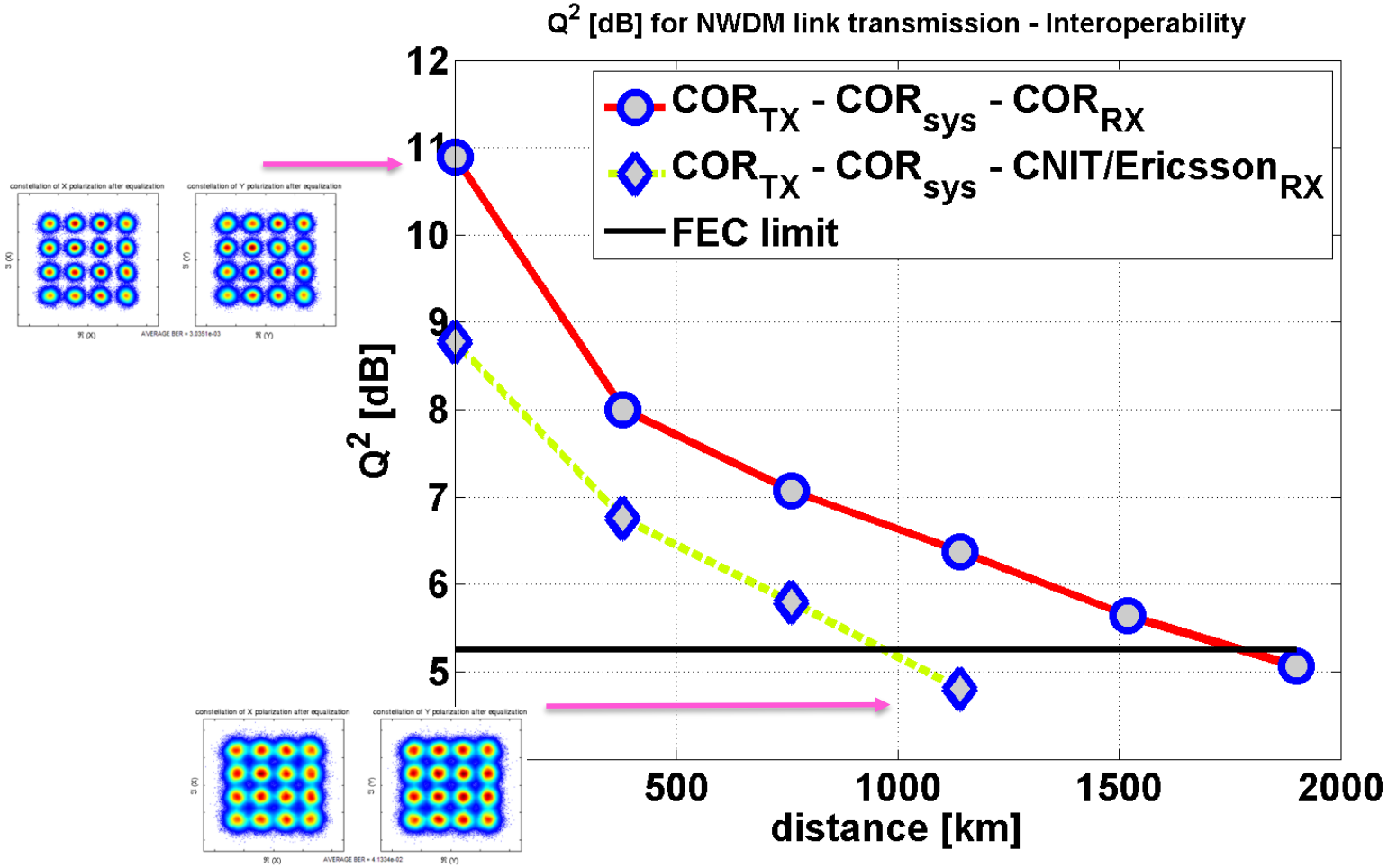
BVT interoperability experiment

- Experiment carried out at Munich at CORIANT labs.
- NWDM based PM-16QAM and PM-QPSK transmission with Coriant TX and CNIT / Ericsson coherent RX
- Objective: demonstrate a first level of transmission interoperability at pre-FEC (BER < BER_{TH}) with $BER_{TH} = 3.4 \times 10^{-2}$

- Successfully demonstrated in b2b and over link, although we some lost in performance

First level of BVT interoperability

TX Coriant 32GBaud PM-16-QAM over Coriant system, received by CNIT / Ericsson RX



conclusions

1 Tb/s

Bandwidth [GHz]	# slots (12.5 GHz)	distance [km]
200	16	2000
187.5	15	1800
175	14	1500
162.5	13	800
150	12	?
100	8	??

single-user receiver

multi-user receiver

cnit

ISTITUTO
DI TECNOLOGIE DELLA
COMUNICAZIONE,
DELL'INFORMAZIONE
E DELLA
PERCEZIONE

Scuola Superiore
Sant'Anna

thank you!

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