Tutorial

Next Generation Optical Access Technologies

Peter Vetter – Bell Labs, Alcatel-Lucent
ECOC, Amsterdam, September 18th, 2012

Inputs from:
Romain Brenot, Ed Harstead, Ron Heron, Thomas Pfeiffer, Wolfgang Poehlmann, Joe Smith, Dora van Veen

Outline

- Introduction
- TDM-PON
- TWDM-PON
- WDM-PON
- OFDM-PON
- Comparison
- Summary

PON: Passive Optical Network
NG-PON: Next Generation PON
TDM: Time Division Multiplexing
TWDM: Time and Wavelength Division Multiplexing
WDM: Wavelength Division Multiplexing
OFDM: Orthogonal Frequency Division Multiplexing

Outline

- Introduction
  - PON basics
  - Optical access roadmap
  - Uses for NG-PON
- TDM-PON
- TWDM-PON
- WDM-PON
- OFDM-PON
- Comparison
- Summary

PON: Passive Optical Network
NG-PON: Next Generation PON
TDM: Time Division Multiplexing
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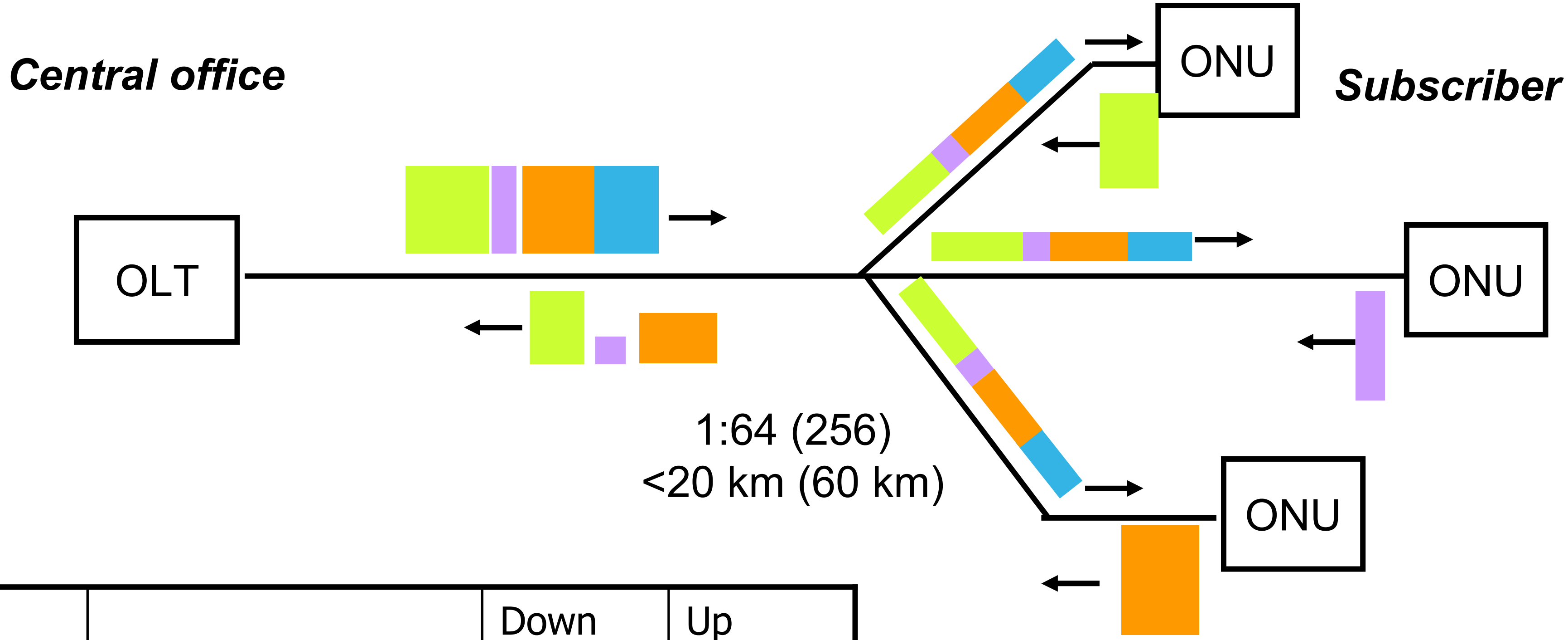
WDM: Wavelength Division Multiplexing
OFDM: Orthogonal Frequency Division Multiplexing

TDM/TDMA PON Basics



		Down (Gbit/s	Up (Gbit/s)
FSAN ITU-T	BPON (G.983)	0.622	0.155
	GPON (G.984)	2.5	1.25
	XG-PON1 (G.987)	10	2.5
IEEE	EPON (802.3ah)	1.25	1.25
	10G-EPON (802.3av)	10	1 or 10

OLT: Optical Line Termination
ONU: Optical Network Unit
TDMA: Time Division Multiple Access
FSAN: Full Service Access Network
BPON: Broadband PON
GPON: Gigabit-capable PON
XG-PON: 10-Gigabit-capable PON
EPON: Ethernet PON

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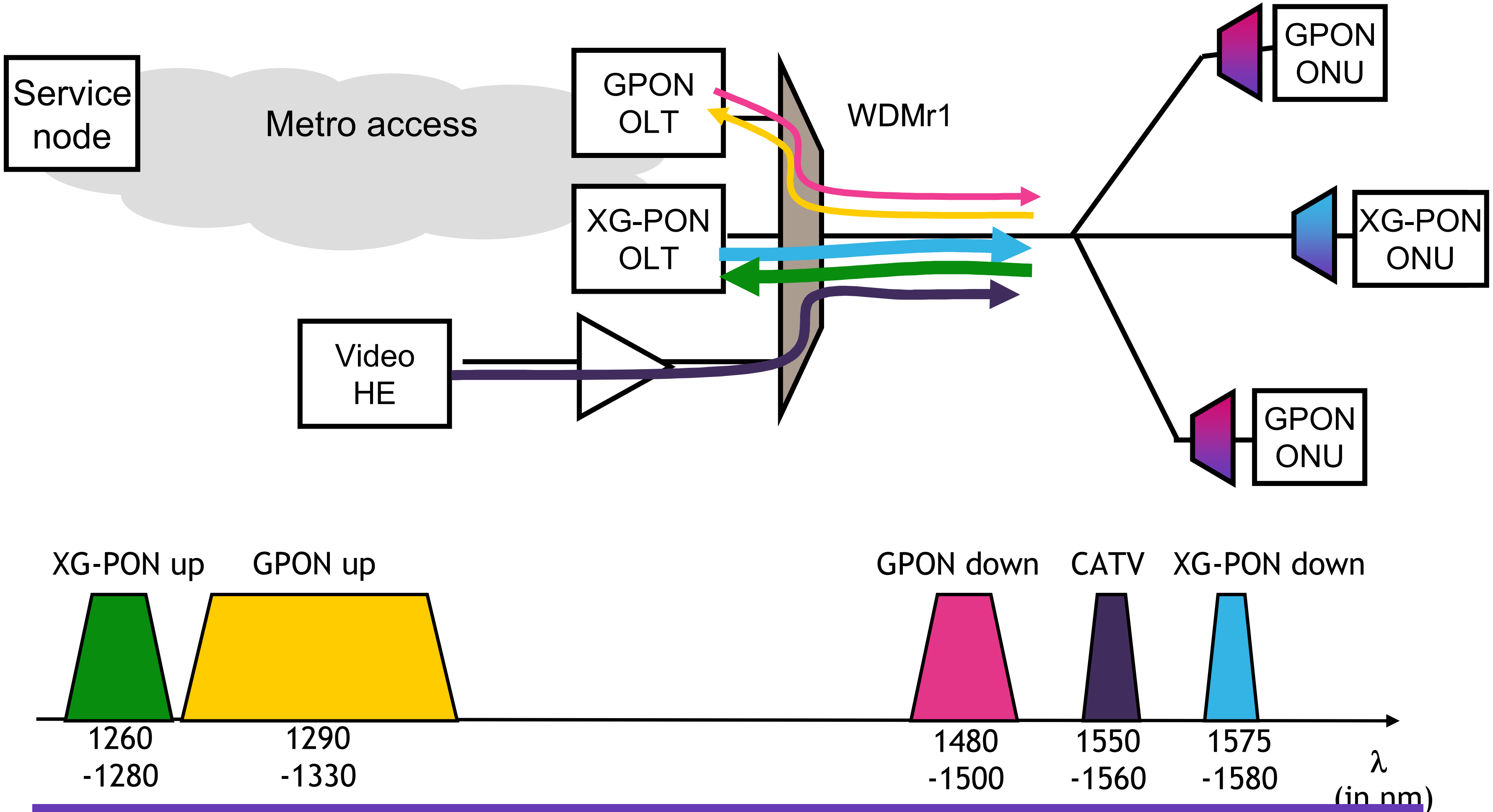
Wavelength-plan and Coexistence (FSAN)



Future NG-PON2 solutions should co-exist with existing standards

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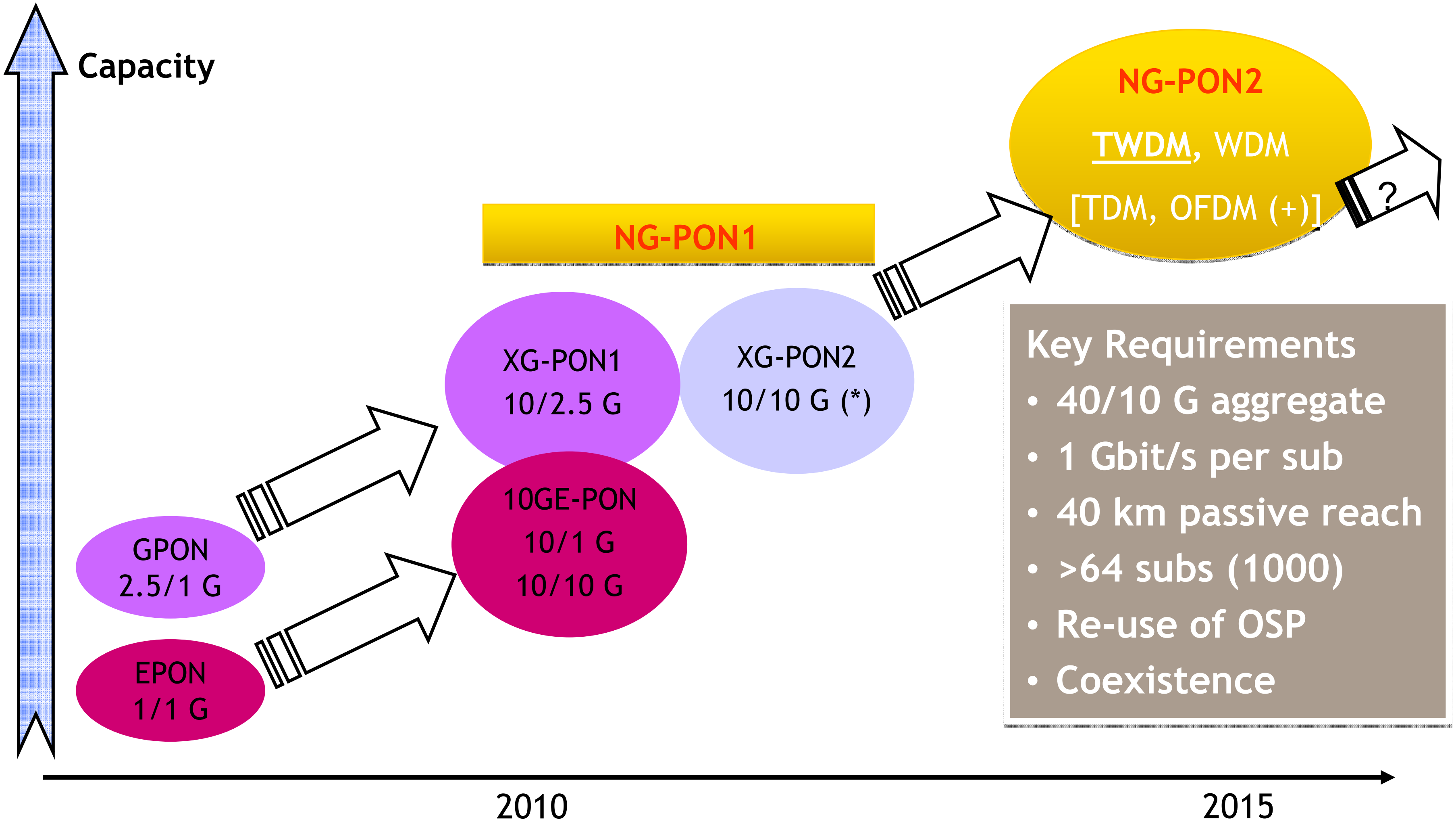
PON Standardization Roadmap



Ref.: FSAN / ITU-T G.984 *G.987* *G.ngpon2*
IEEE 802.3ah *802.3av*

(*) Not a standard

(+) No longer considered

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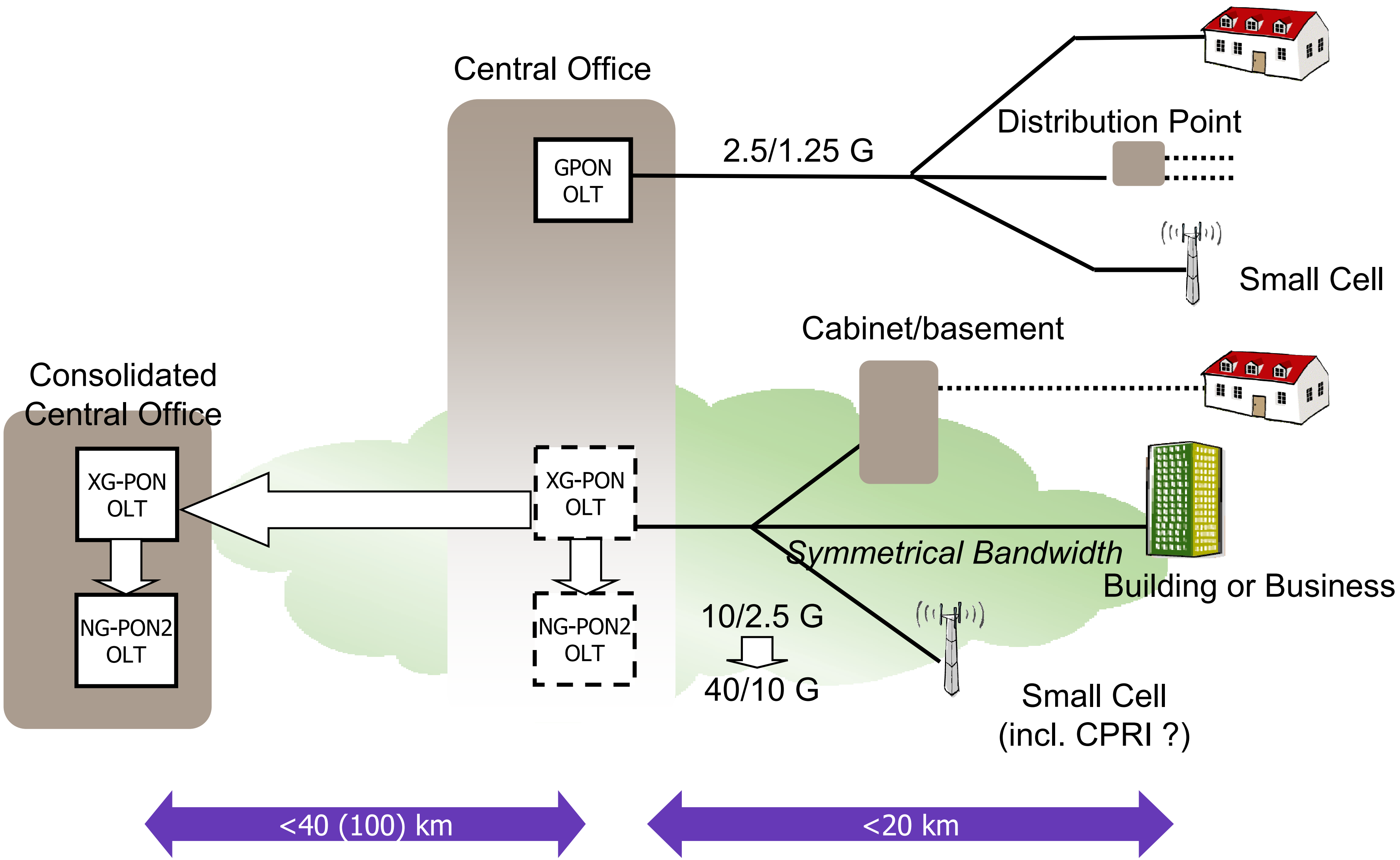
OSP: Outside Plant

Uses for NG-PON



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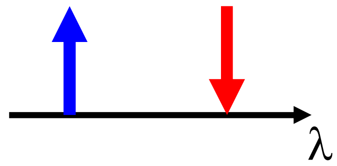
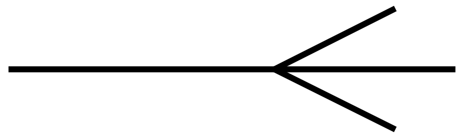
CPRI: Common Public Radio Interface

Outline

- Introduction
- TDM-PON
  - 10 Gbit/s upstream TDMA
  - Energy efficiency improvements
  - 40 Gbit/s downstream
- TWDM-PON
- WDM-PON
- OFDM-PON
- Comparison
- Summary





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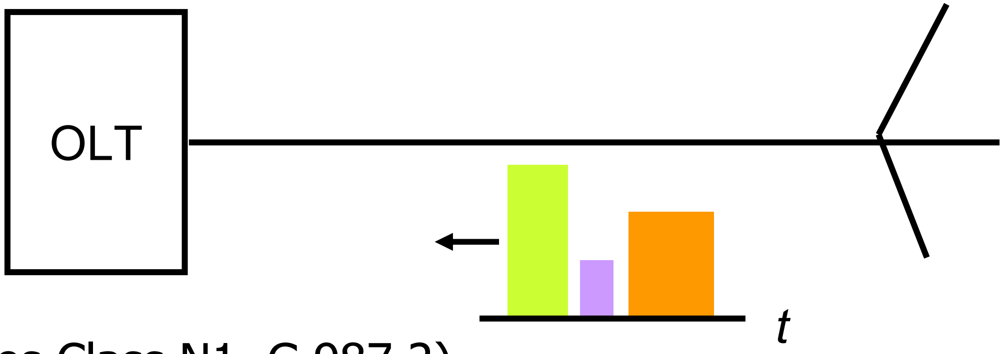
TDMA 10G upstream



- Challenges
  - Dynamic range >20.5 dB
  - Rx sensitivity <-27.5 dBm (assumes Class N1, G.987.2)
  - Minimal preamble for gain and time lock-in
- Standard solution available for 10G-EPON, but continued research. E.g.:

- *Ref.: S. Yoshima, J. Nakagawa et al.,* ***ECOC 2012 (Invited, Tu.1.B.3)***
  - Dual rate 10.3/1.25 Gbit/s
  - -30.7 dBm for 10G (BER 1e-3)
  - Sync time: 240 ns
- *Ref.: Y. Xin, X.Z. Qiu et al.,* ***ECOC 2012 (Tu.1.B.5)***
  - -30.5 dBm for 10G (BER 1e-3), 30 dB dynamic range
  - Gain settling time: 60 ns
- *Ref.: D. van Veen et al. OFC 2011:*
  - Full system demonstration 10/10 G XG-PON2 (Not spec. in standards)

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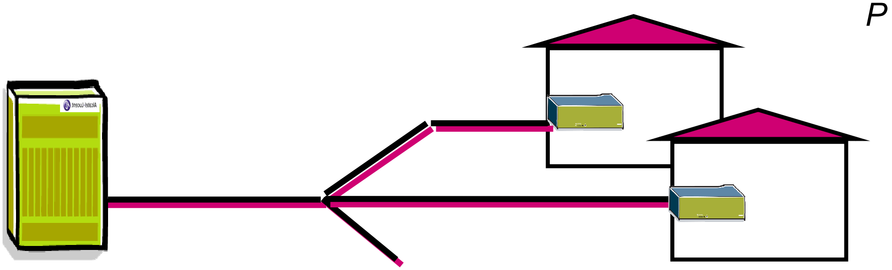
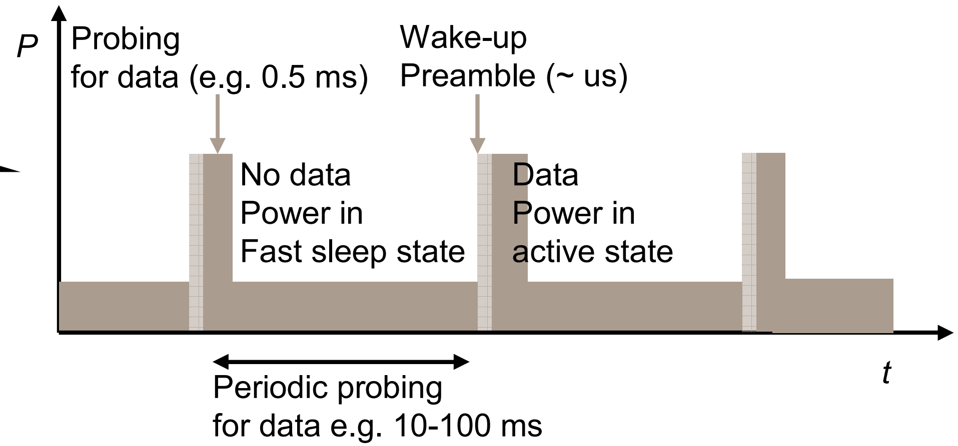
Power Saving by Sleep Mode in ONU

- Doze – state: Rx path remains awake to check for data
- Sleep – state: Rx and Tx are asleep;
  - Periodic probing to check for data
  - Transmission of data during periodic awake time
- Ref. e.g.:
  - ***J. Kani, ECOC 2012, (Invited Mo.2.B.3)***
  - *M. Fiamengo, B. Skubic, ECOC 2011 (8.C.3)*
  - *FSAN G.987.3 for XG-PON; G.984 sup.45 for GPON – SIEPON for IEEE EPON*





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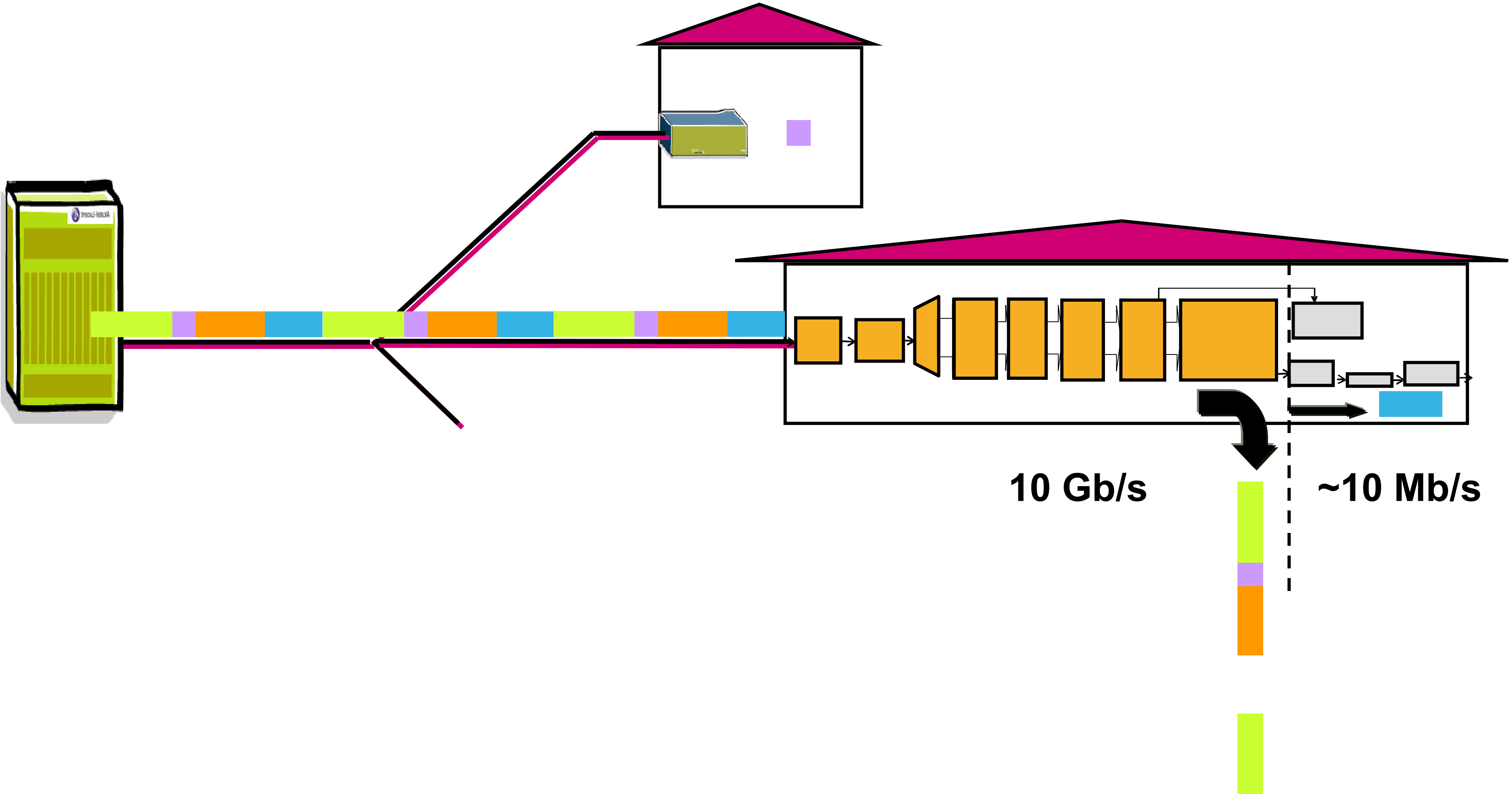
Standard XG-PON



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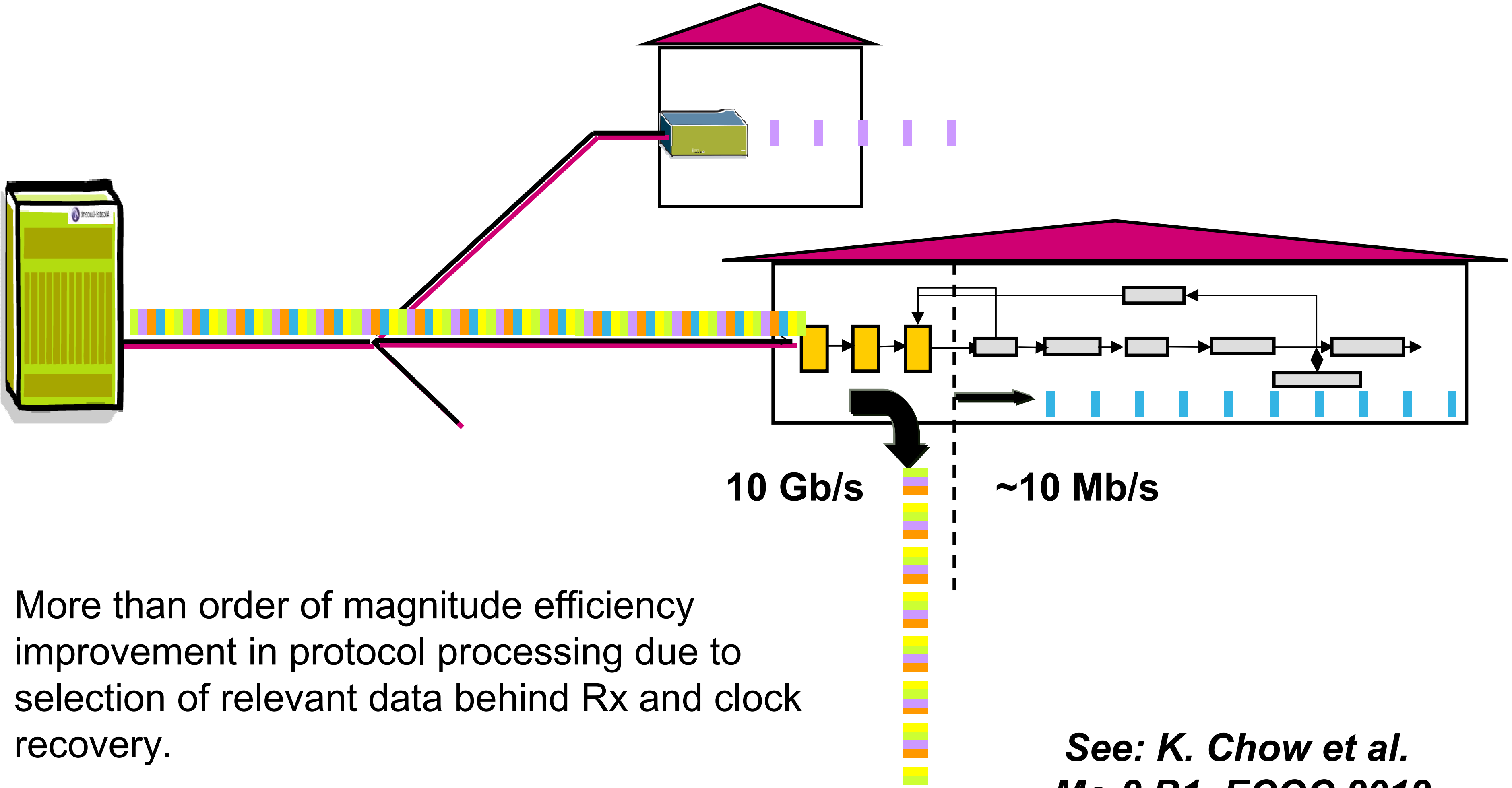
Bit-Interleaving PON



More than order of magnitude efficiency improvement in protocol processing due to selection of relevant data behind Rx and clock recovery.

Even more important for high bit rates (10-40G)

See: K. Chow et al. Mo.2.B1, ECOC 2012

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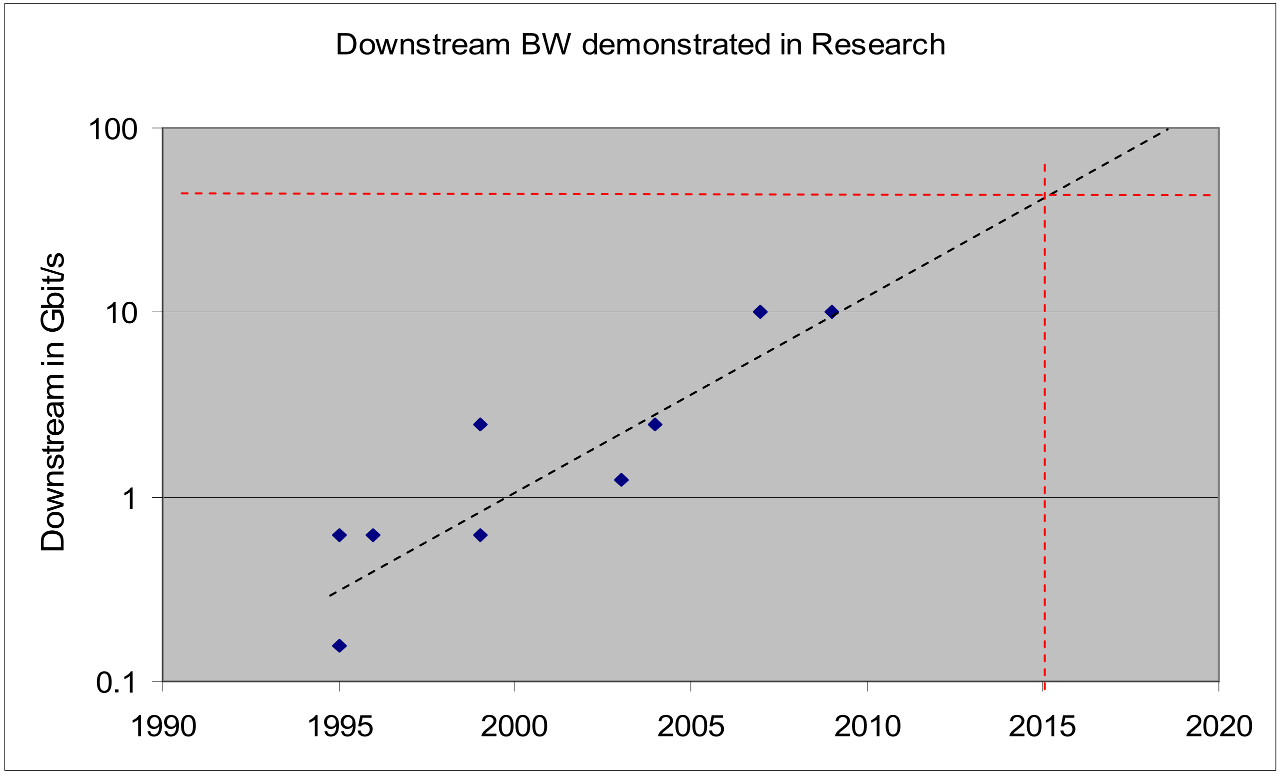
Is there life for TDM beyond 10G ?

Historical trend: TDM PON has overcome two main challenges without aid of WDM

- Higher speed electronics, aided by Moore's Law
- More optical power to sustain SNR

Can this be repeated for 40 Gbit/s?



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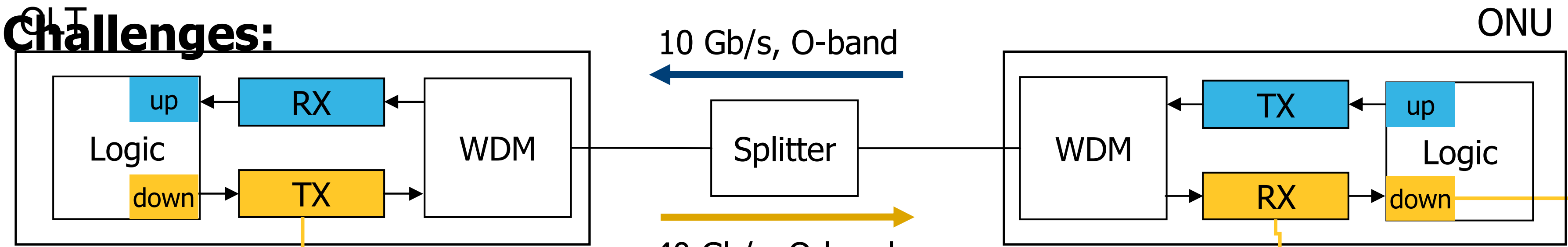
XLG-PON (40G/10G TDM PON)

- Maintain all the benefits of TDM PON, including
  - most flexible bandwidth allocation
  - colorless ONU
- Complementary to TWDM evolution

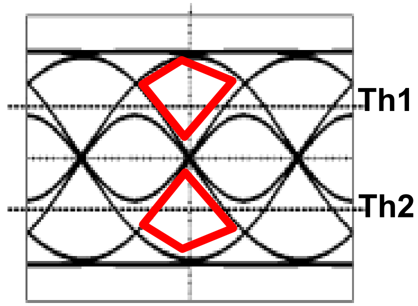
Cf.: 25G DB with 7 GHz APD
D. van Veen, Tu.3.B.1, ECOC 2012

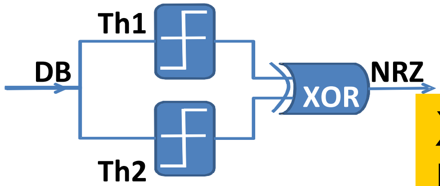
Challenges:



Chromatic dispersion at 40G
- Select low dispersion 1.3µm wavelength (“O-band”)
- Duo-binary mitigates CD by 3x

Maintain SNR at 40G
- Integrated EML + SOA
- Efficient FEC (e.g. LDPC)





Rx bandwidth limitations
- Current APD ~10Gbit/s (8GHz)
- Research on 20GHz APD e.g. by III-V labs
- Duo-binary modulation allows for 40G signal with 20GHz APD

Power and size of electronics
- Bit interleaving allows for ONU electronics at user rate

XLG-PON: 40G-capable PON
LDPC: Low Density Parity Check
CD: Chromatic Dispersion
DB: Duobinary

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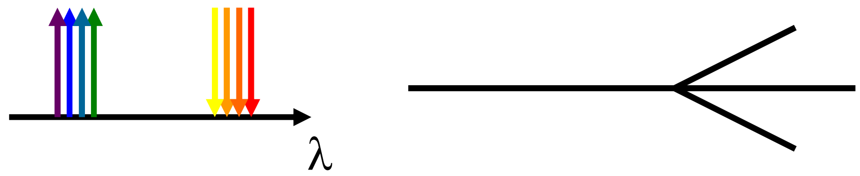
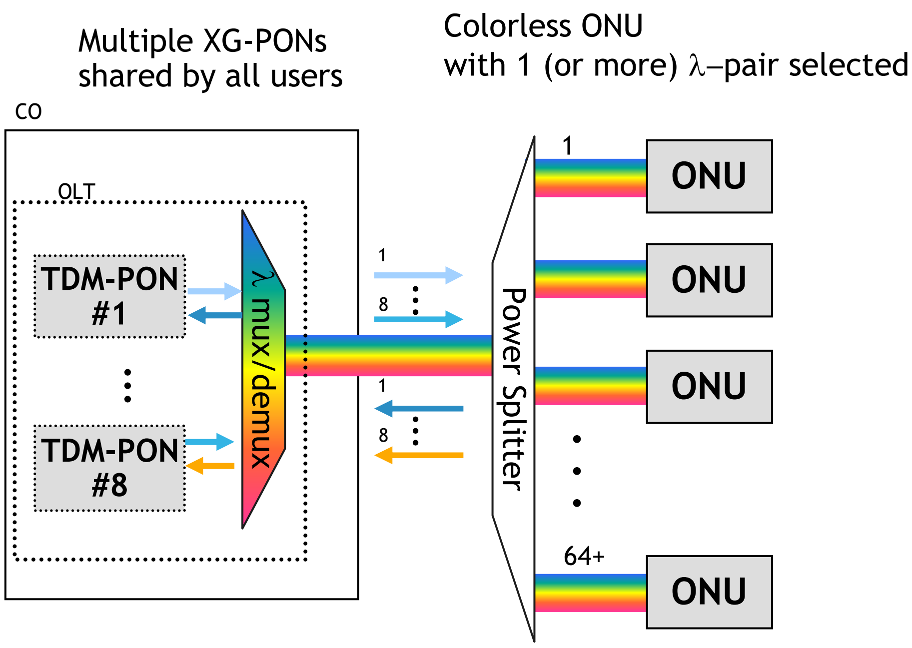
- Introduction
- TDM-PON
- TWDM-PON
  - Basic architecture
  - TWSDM-PON
  - Coexistence
- WDM-PON
- OFDM-PON
- Comparison
- Summary



TWSDM-PON: Time and Wavelength-Set Division Multiplexing PON

TWDM-PON

- 4 λ x 10G capacity
- Reuse of TDM-PON technology
- Compatible with existing OSP
- Limited tuning range required
  - Allows for lower cost tuning solution than in pure WDM-PON
- **Primary solution for NG-PON2**



Ref.: e.g. T. Koonen et al. TOBASCO, ComMag. 1997
P. Iannone et al. OFC2011 (PDP)
W. Poehlmann et al. ECOC 2011 (We.9.C.1)
Y. Ma, F. Effenberger et al. OFC2012 (PDP5D.7), ***ECOC2012 (Invited Tu.4.B.1)***

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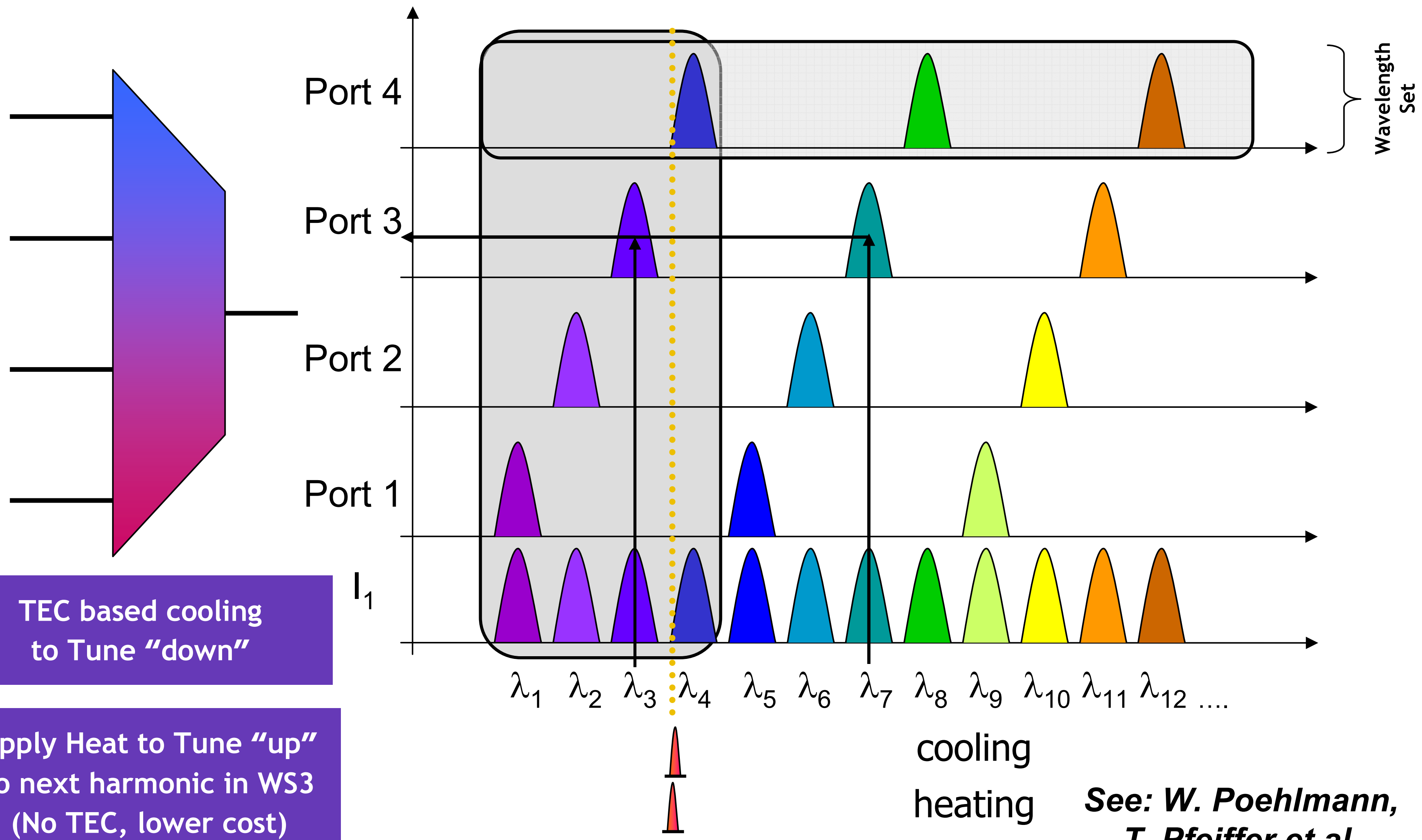
Concept of *W*avelength ***S*et** *D*ivision *M*ultiplexing

4 wavelength sets WS1 – WS4 in cyclic AWG, 50GHz grid



TEC based cooling to Tune "down"

Apply Heat to Tune "up" to next harmonic in WS3 (No TEC, lower cost)

AWG: Arrayed Waveguide Grating

See: W. Poehlmann, T. Pfeiffer et al.
ECOC 2011 (We.9.C.1)
ECOC 2012 (Tu.4.B.2)

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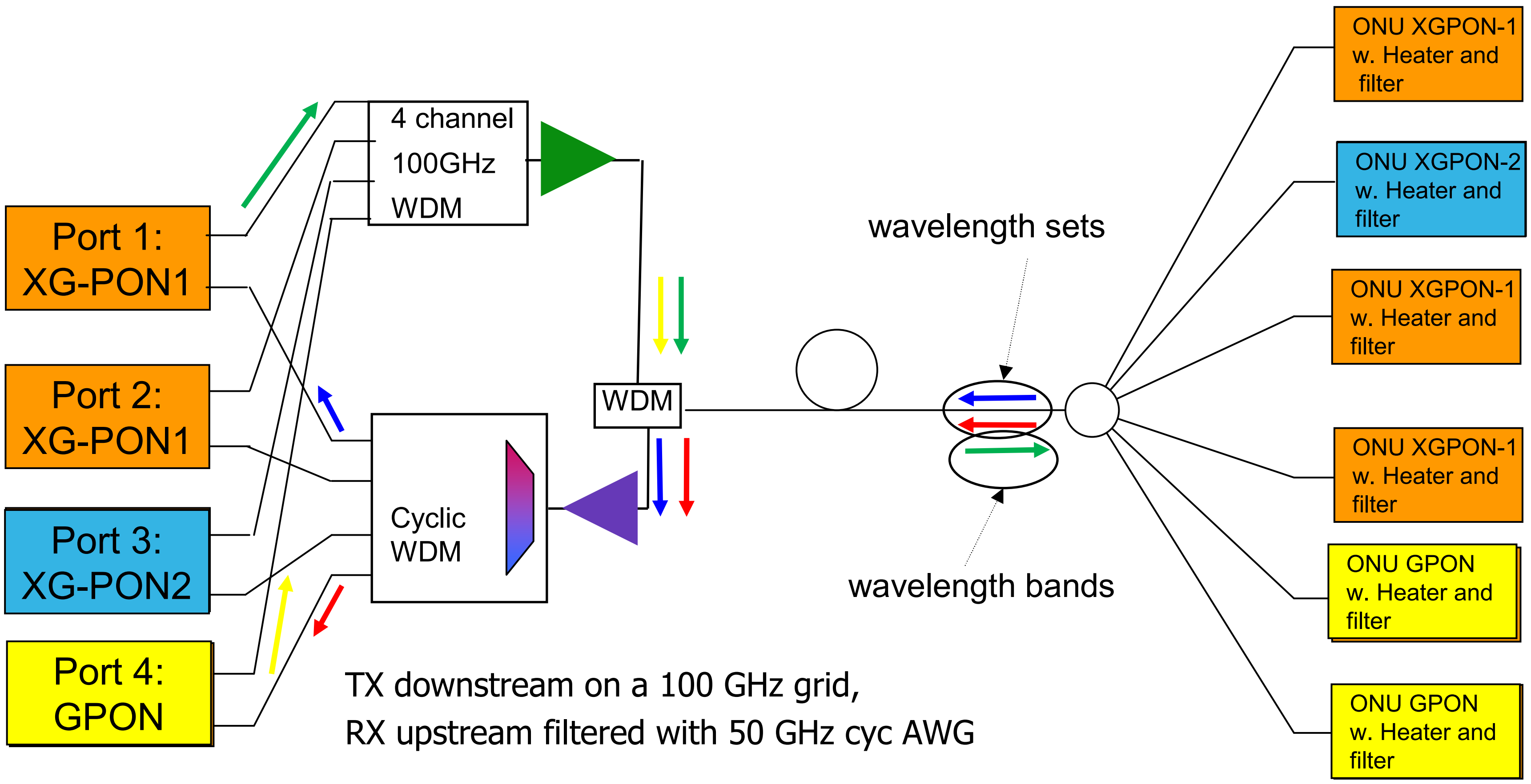
TWDM PON System



ONU: Tuneable Tx + Tuneable filter

- **A straight-forward way to get 40/10G by 4 x XG-PON1**
- **Possible for multi-provider sharing**
- **Stacking of different standards: GPON, XG-PON1, XG-PON2**

Tuneable Rx e.g.: R.Murano et al.. ECOC 2012 (We.2.B.3)

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Power saving at OLT with TWDM-PON

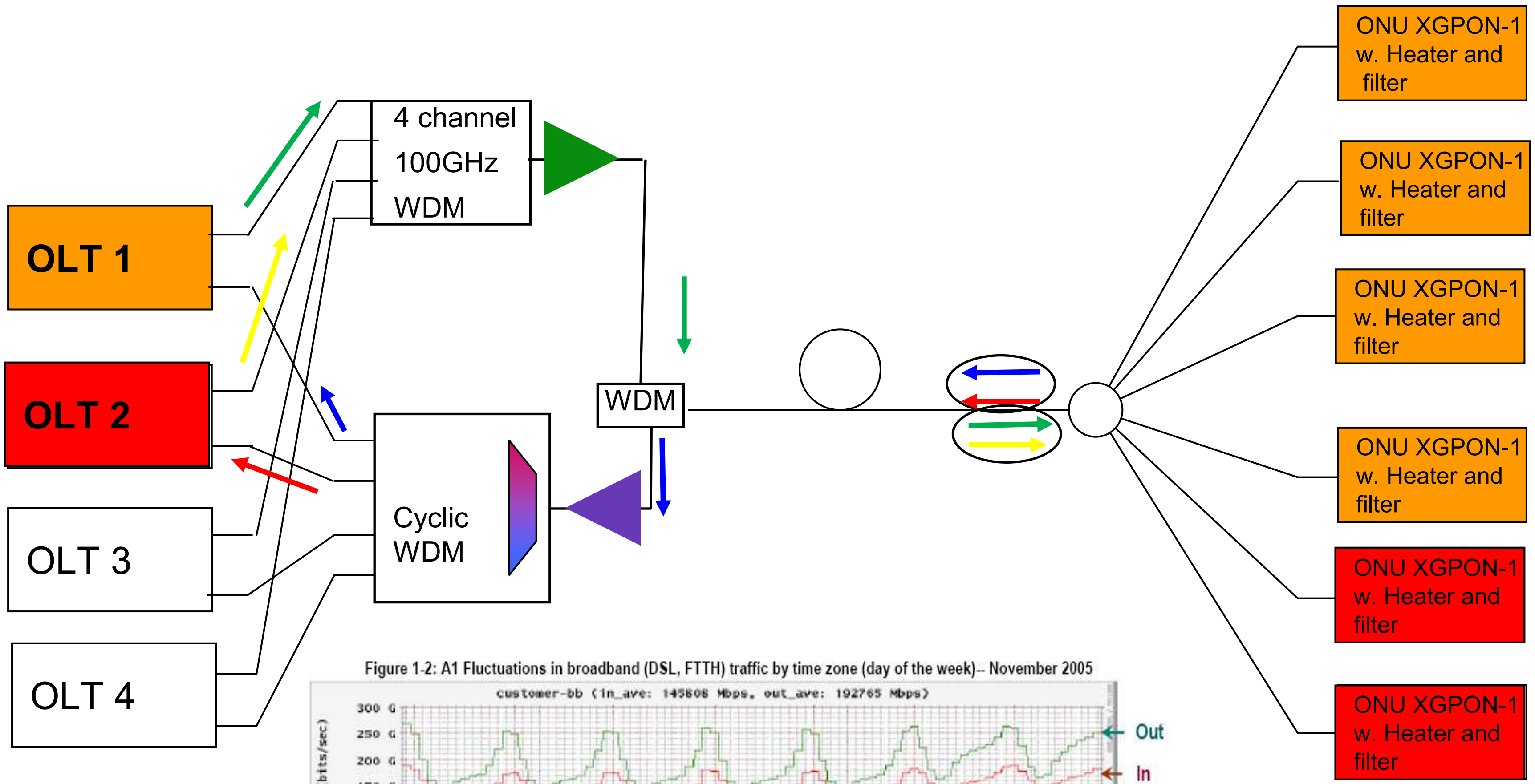
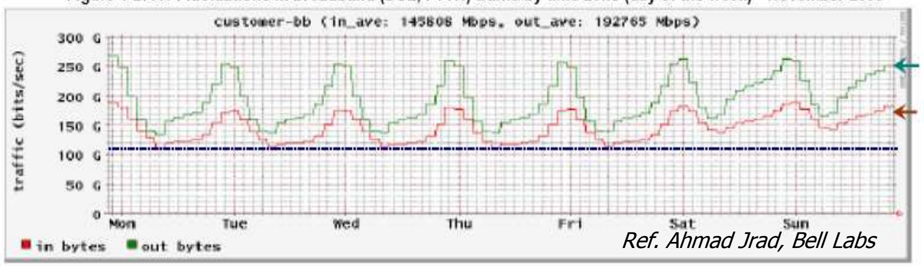


Figure 1-2: A1 Fluctuations in broadband (DSL, FTTH) traffic by time zone (day of the week)-- November 2005



See also e.g.: H. Saito et al. ECOC 2012 (Tu.4.B.5)

OLT ports and lambda can be turned on/off according to expected traffic load

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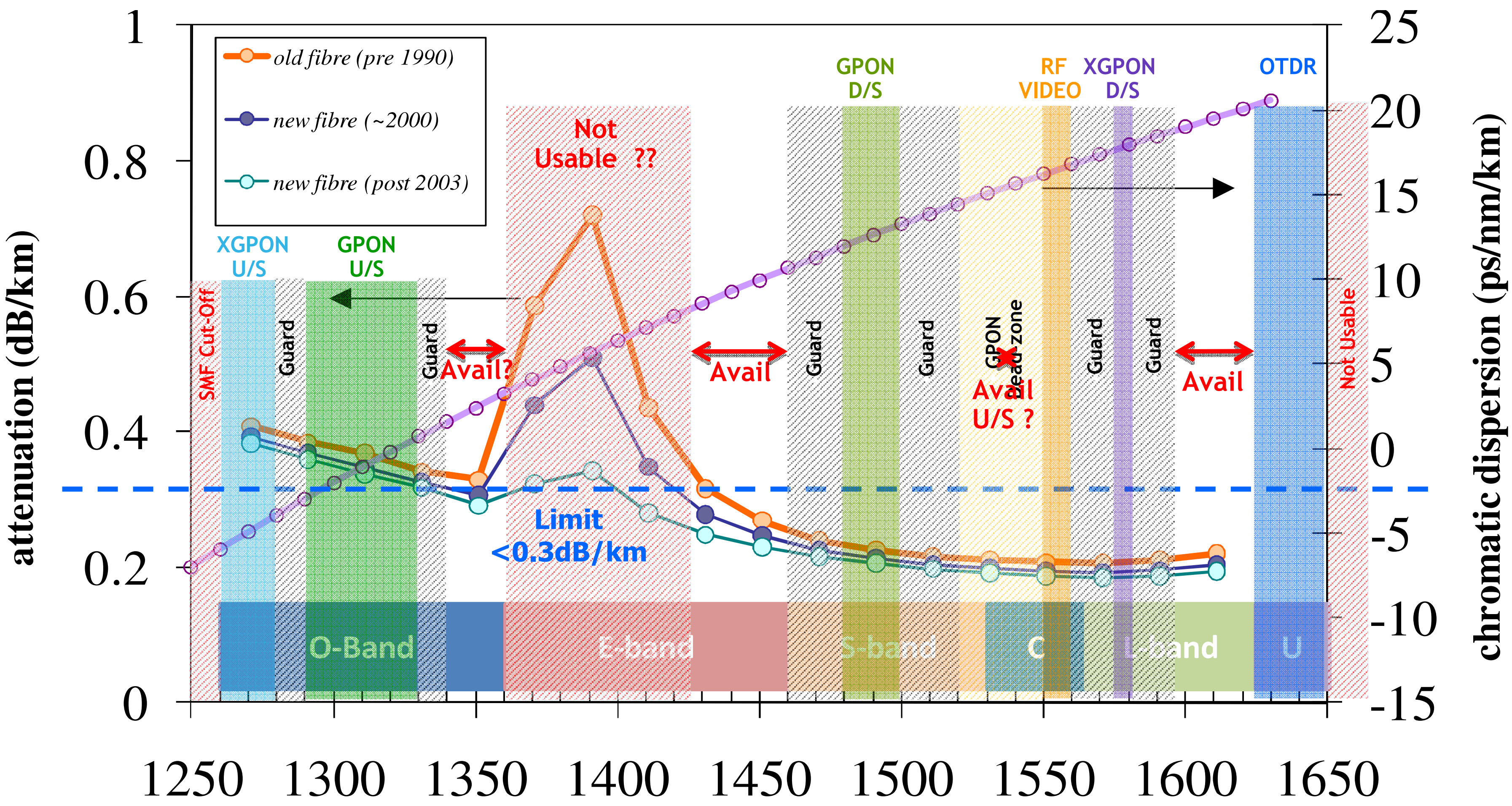
Coexistence options for TWDM-PON



Subject of on-going debate in FSAN

Courtesy: J. Smith, Alcatel-Lucent

OTDR: Optical Time Domain Reflectometry
RF: Radio Frequency Video
D/S: Downstream
U/S: Upstream

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- TDM-PON
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- WDM-PON
  - Tuneable ONU
  - RSOA architectures
  - Coherent WDM-PON
- OFDM-PON
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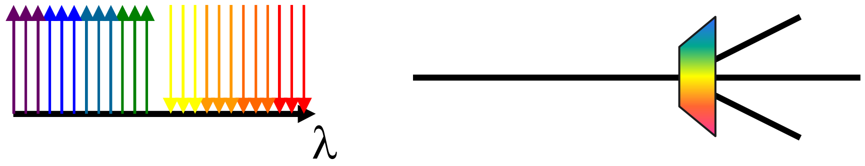

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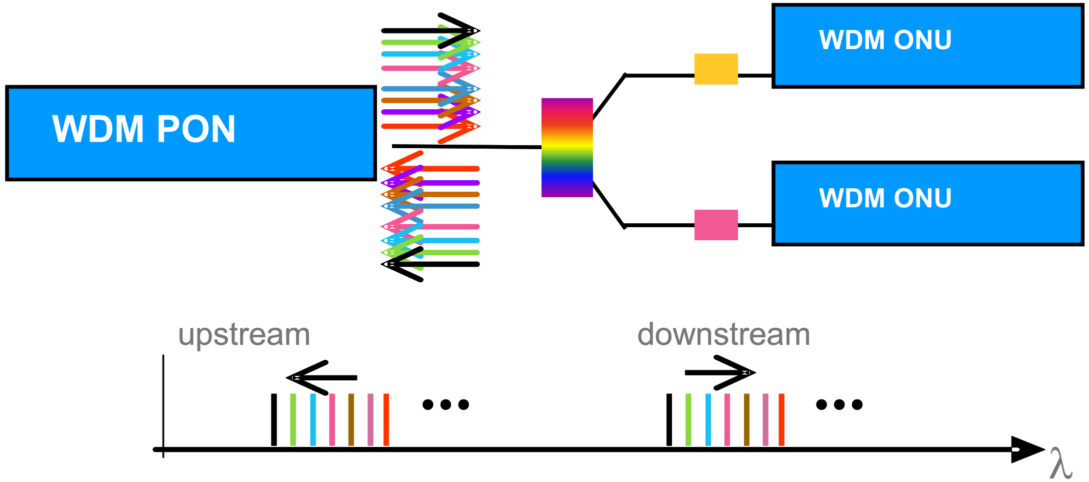
RSOA: Reflective Semiconductor Optical Amplifier

WDM-PON

- Wavelength (pair) per subscriber
- WDM (AWG) instead of passive splitter reduces required optical budget
- 1G (-10G) per subscriber
- **Optional overlay for NG-PON2 in FSAN**
- Challenges:
  - "colorless" ONU
  - Low cost optical components



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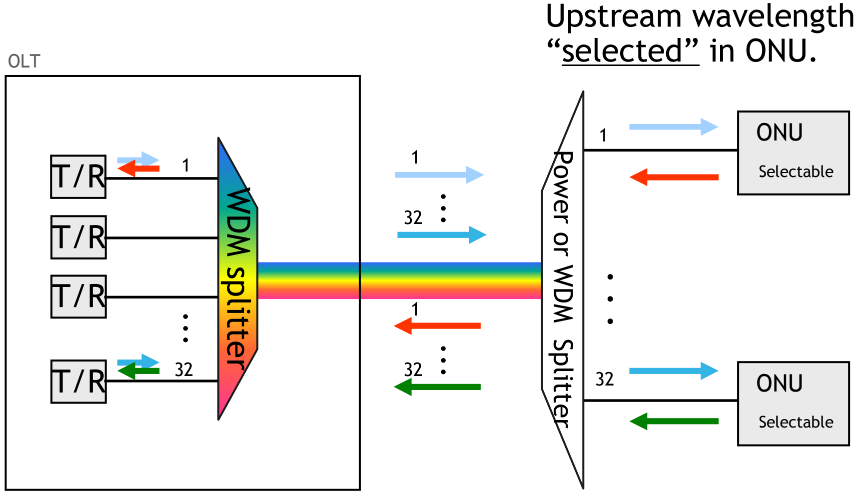
Main approaches for "colorless" ONU Tx

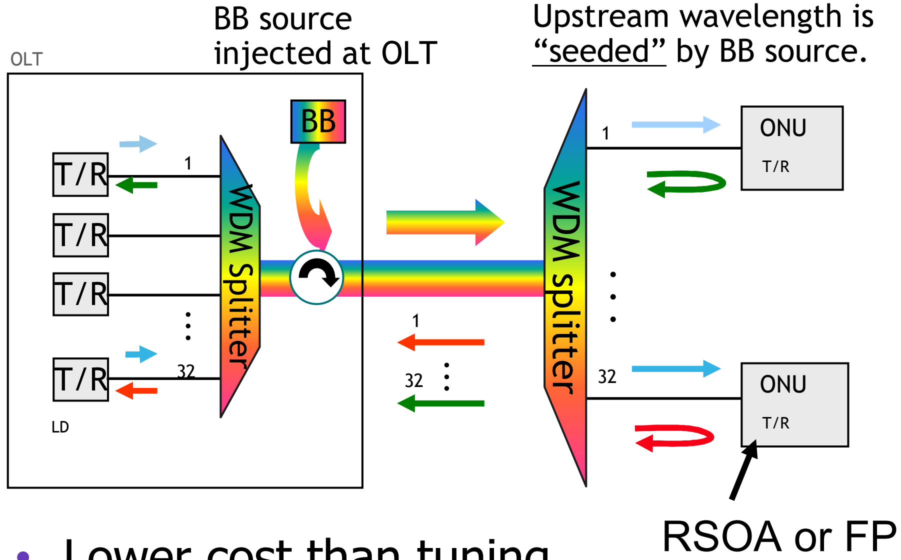
Tuneable laser



- Ideal technical solution
- Large optical budget
  - 60km (with AWG WDM splitter)
  - Also passive splitter possible
- Feasible 1 -10Gbit/s
- But complex and expensive components for tuneable lasers

(Note: λ-selection is sufficient)

Remotely-modulator WDM-PON



- Lower cost than tuning
- Smaller optical budget
  - Only works with WDM splitter
- Modulation limited to 2.5 Gbit/s
- Large chirp due to gain modulation
- Requires seeding source in OLT
- Reflection noise

Ref: R. Brenot, Bell Labs, Invited APC 2011
R. Heron, Alcatel-Lucent

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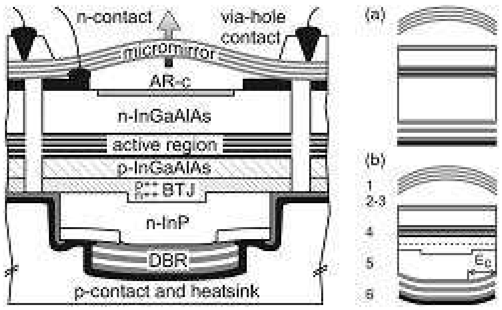
WDM-PON
Tuneable lasers

- **Device challenges:**
  - Tuning range: 40 nm
  - Low cost: A-thermal (no TEC)
  - Wavelength stability (mode hops)
  - Complexity (yield, cost)
- **System:**
  - Protocol for λ–setting
    Current wavelength ?
    Target wavelength ?
  - Wavelength tuning without interference of other users

- Example Technologies:
  (1) External cavity: e.g. MEMS VCSEL by *P. Debernardi et al., JQE, April 2008*
  (2) DS-DBR: e.g. *S. H. Lee, A. Wonfor, M. Wale et al., ECOC2010 (Mo.1.B.2)*
  (3) SG Y-branch: e.g. *M. Roppelt, J.P. Elbers, et al. OFC 2012 (OW1B.4)*



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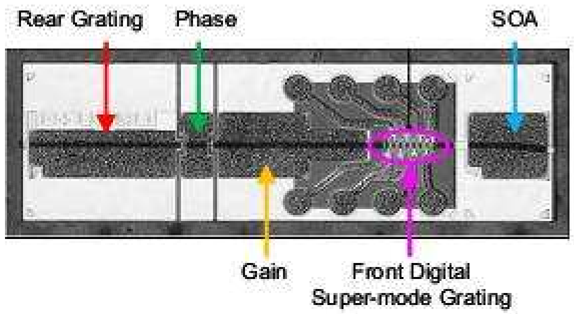

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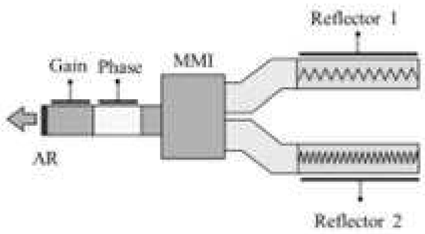

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TEC: Thermo-Electric Cooling

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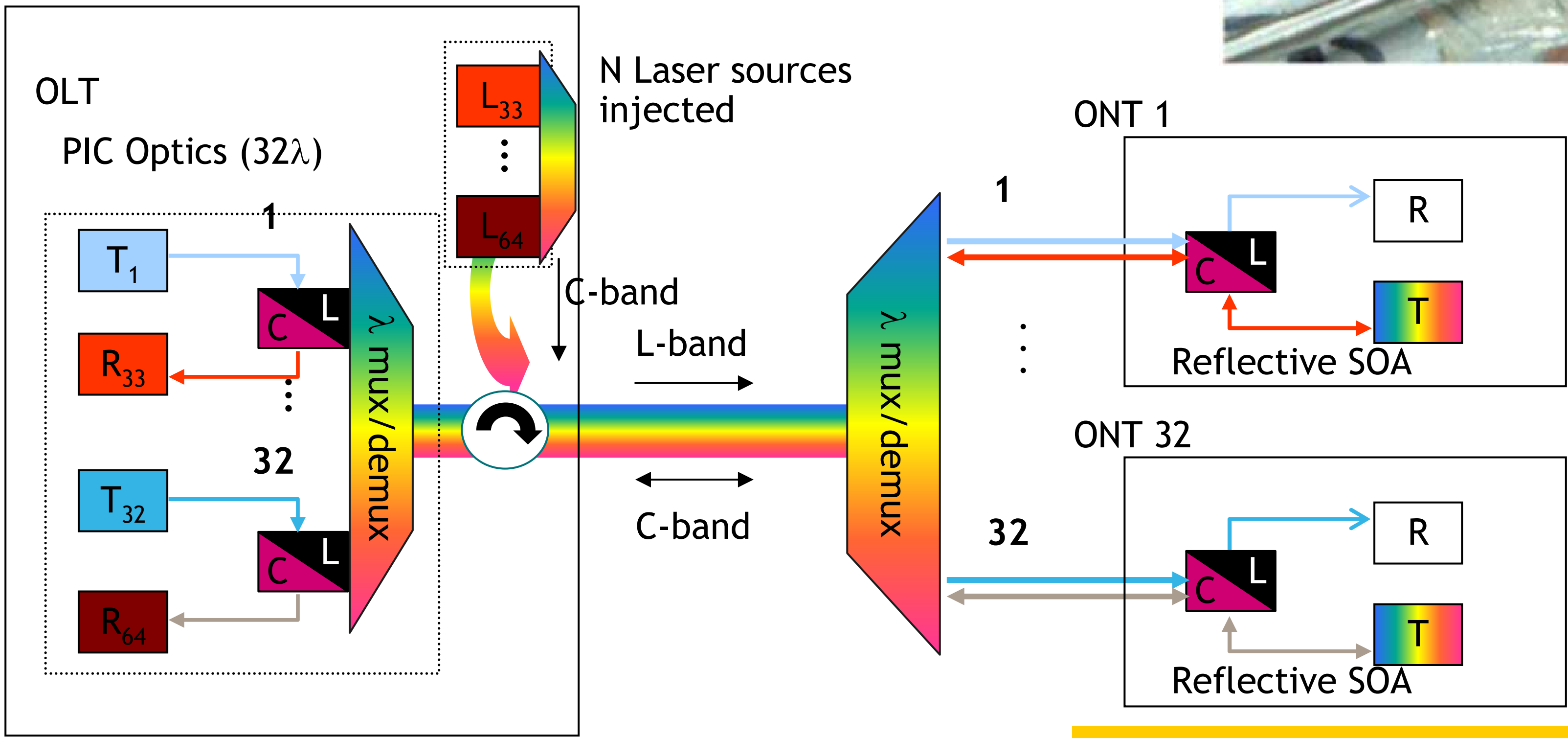
WDM-PON with remote modulation
1. Laser seeding

- From the OLT:
  - Optical budget limited to **25 dB**
  - Strong RBS impairment; cost of one laser at CO per ONU



RBS: Rayleigh BackScattering
CO: Central Office
PIC: Photonic Integrated Circuit
T: Transmitter
R: Receiver

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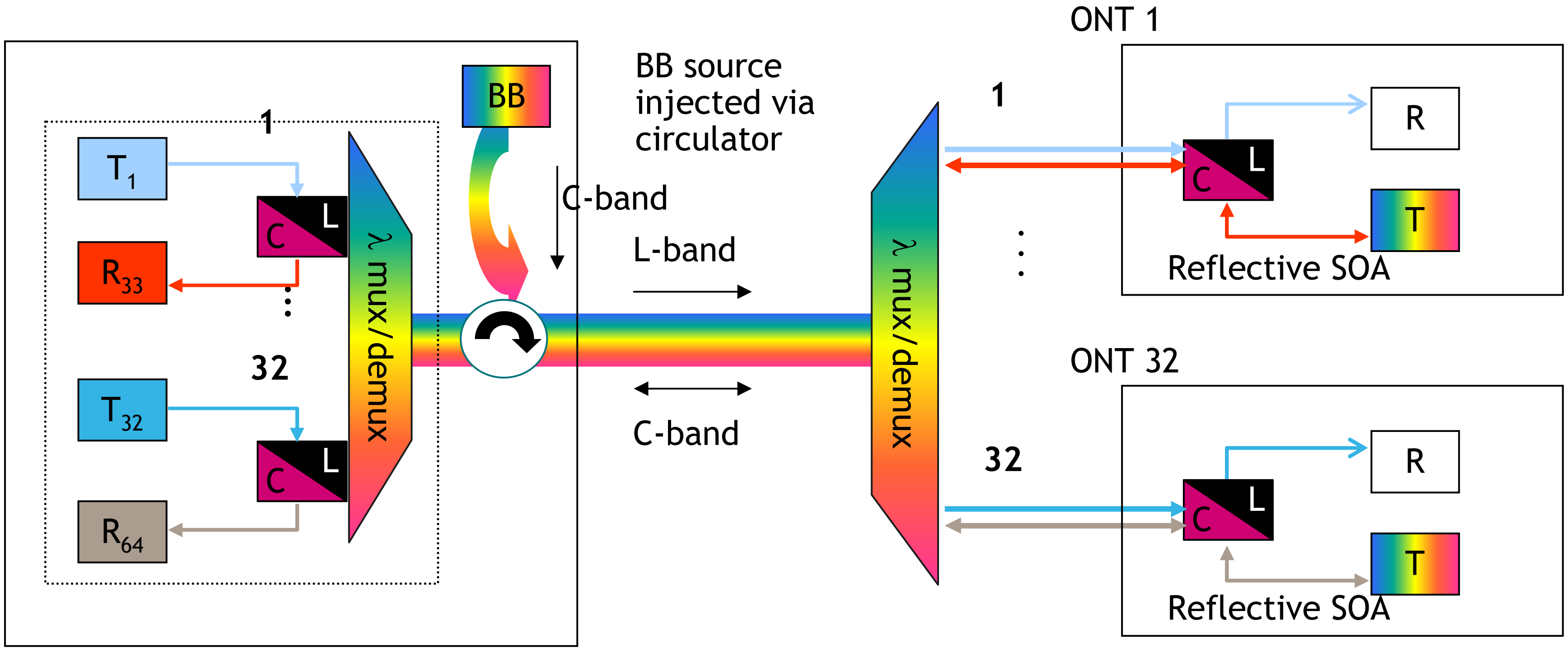
WDM-PON with remote modulation
2. Spectrum sliced WDM-PON

- BB source seeding by EDFA
- Main issue : ASE noise



E.g. J.Y. Kim et al., ECOC 2012 (We, 1.B.4)

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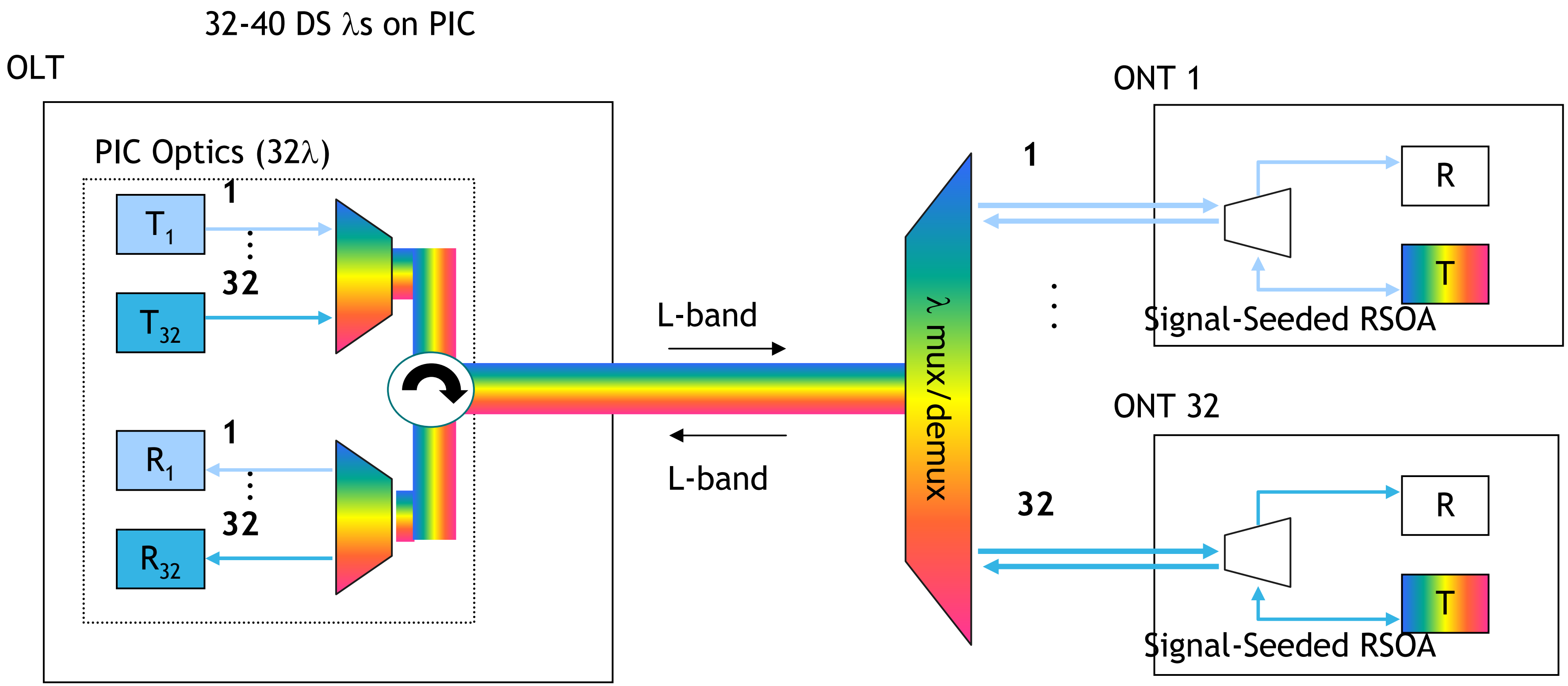
WDM-PON with remote modulation
3. Wavelength reuse

- Reduced #lasers, Higher # channels, but RBS and remodulation impairments



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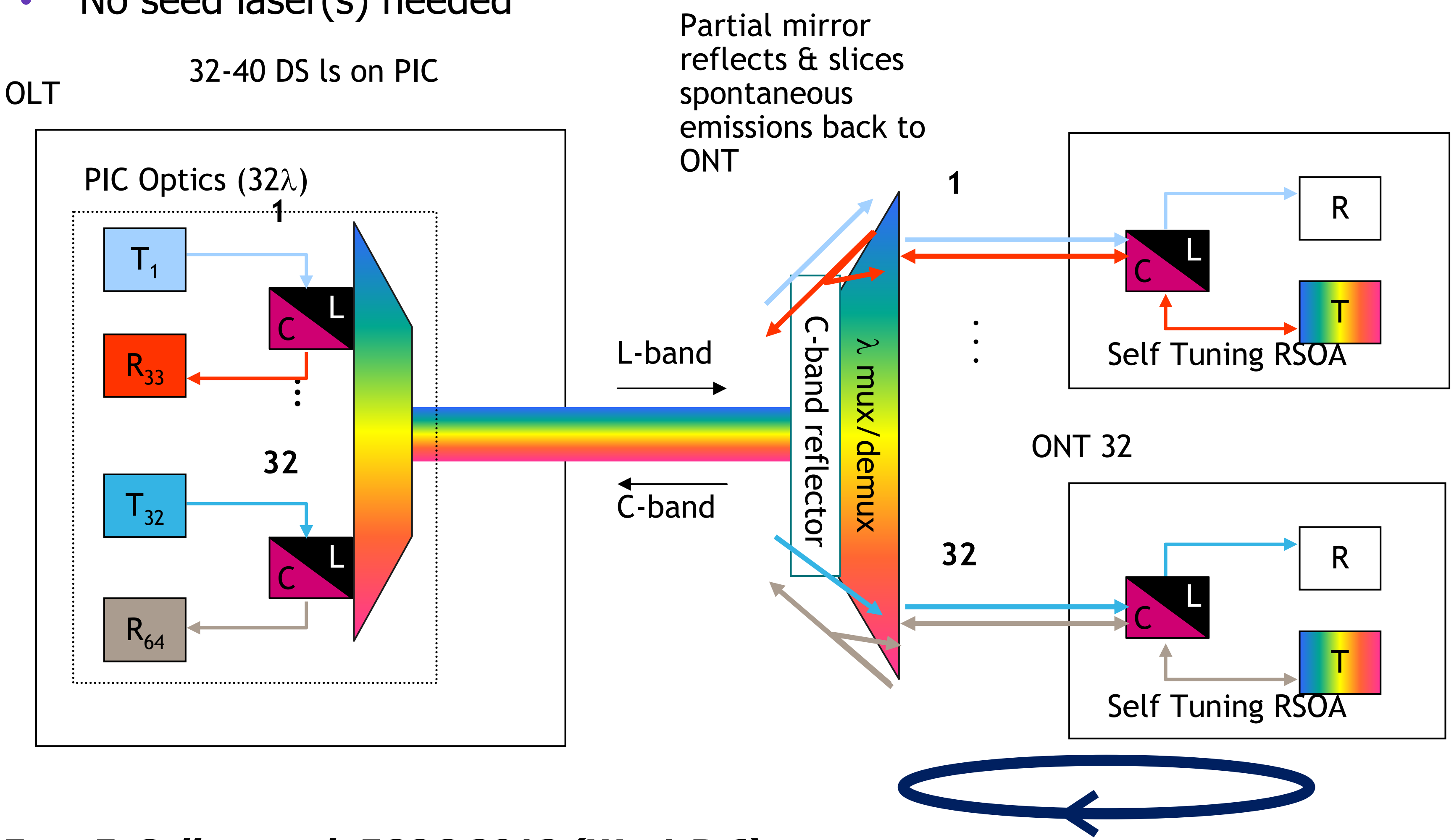
4. Self-seeding WDM-PON

- Wavelength "self-configured" by port in AWG
- No seed laser(s) needed



E.g.: F. Saliou et al, ECOC 2012 (We.1.B.6)

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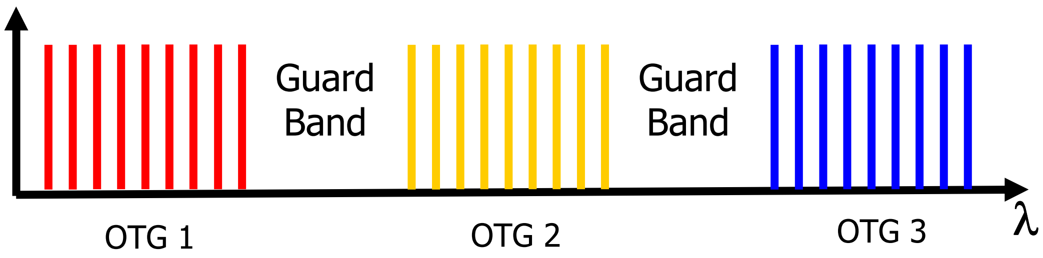
Coherent WDM-PON

- **Improved optical budget and channel density, but expensive**

(Ref.: S. Smolorz, H. Rohde et al., OFC2011, PDP D4)

- **UDWDM-PON**
  - One Laser is modulated with up to 10 carriers - 3 GHz spacing
  - 50 GHz per OTG
  - Scalable with multiple OTG
  - 1Gbit/s DQPSK symmetrical bandwidth per subscriber
  - Heterodyne detection: -46 dBm Rx sensitivity
    - 40 km, 256 channels over passive plant
  - Colorless ONU: tuneable ECL as LO
  - Expensive – requires photonic integration to reduce cost



Also Coherent WDM-PON at ECOC 2012:
e.g. We.1.B.1, We.1.B.3, We.2.B.2, PDP

OTG: Optical Transmission Group
ECL: External Cavity Laser
LO: Local Oscillator

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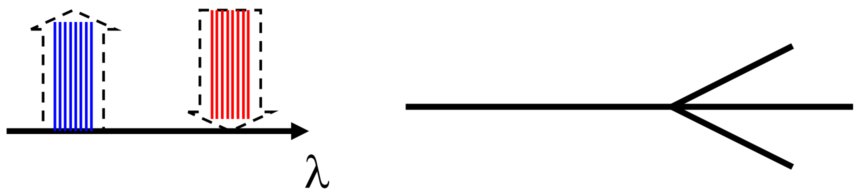

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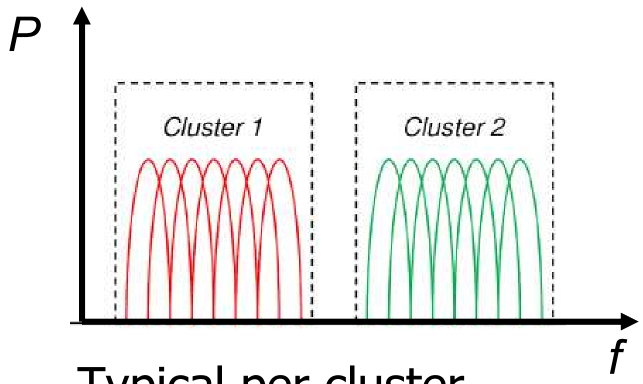
OFDM-PON



Typical per cluster
16-256 OFDM subcarriers
16 QAM

Potential benefits for access:

- High single carrier rate (High spectral density)
  - 40-100 Gbit/s demonstrated
- Dispersion tolerance suited for long reach (100 km)
- Subcarrier frequency as multiple access dimension
  (can be further combined with time and wavelength)
- ONU needs to process only subset of spectrum and can operate at lower rates
- Ability to adjust link capacity power consumption to temporal traffic demands

But

- Complex…

Ref. e.g.: N. Cvijetic et al., NEC LA, e.g. OFC2011, OMG3

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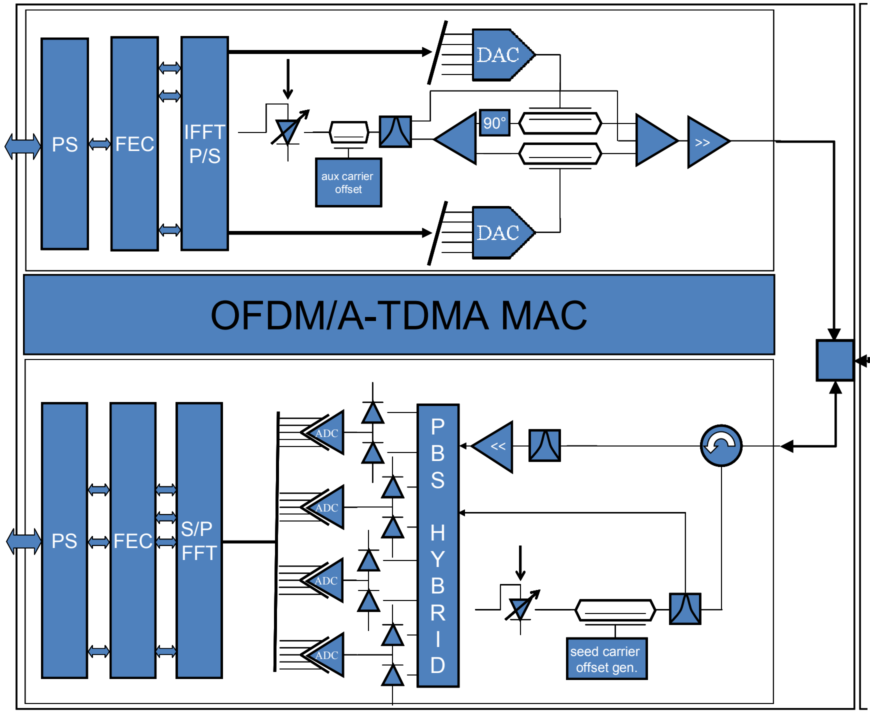
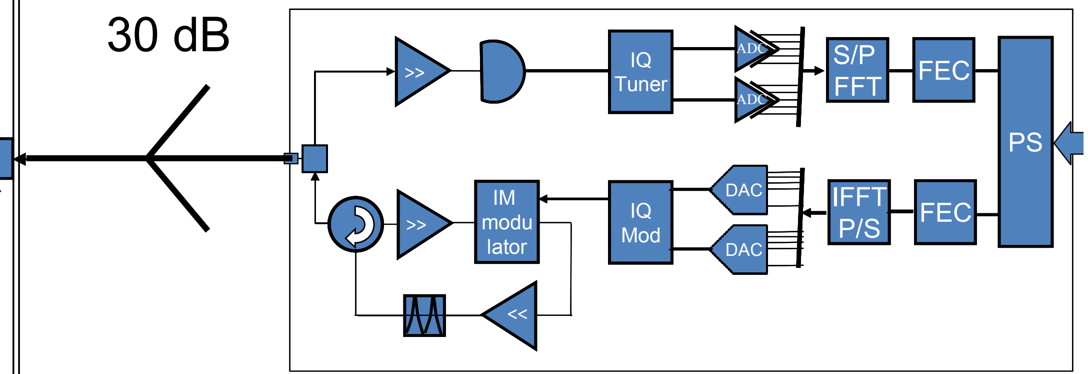
Asymmetrical Coherent OFDM-PON





ONU Cost improvements

Downstream: Direct Detection

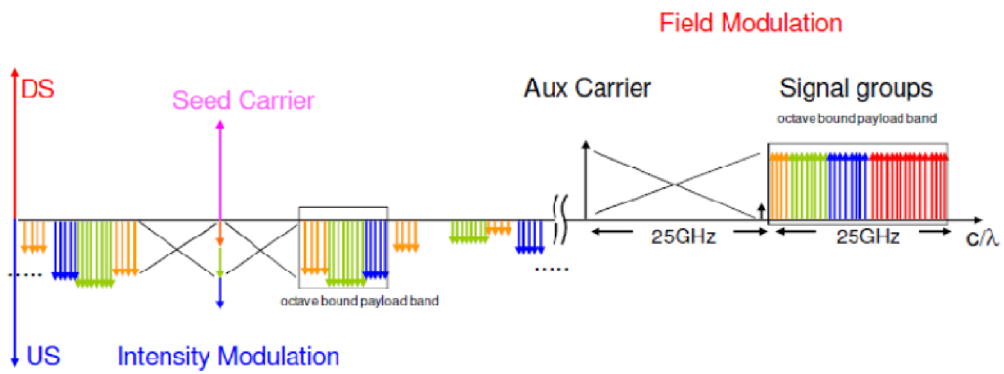
Upstream: Intensity Modulation

Subset of subcarriers

OLT Downstream: Field Modulation

Upstream: Coherent Detection

Ref.: H. Krimmel, T. Pfeiffer, et al.
FP7-Accordance



DAC: Digital to Analog Conversion
ADC: Analog to Digital Conversion
(I)FFT: (Inverse) Fast Fourier Transform

Outline

- Introduction
- TDM-PON
- TWDM-PON
- WDM-PON
- OFDM-PON
- Comparison
- Summary

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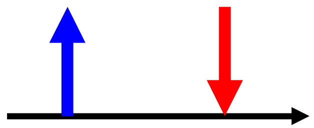
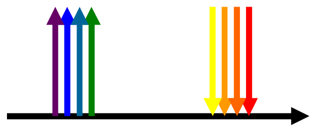
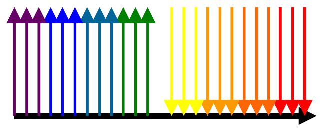
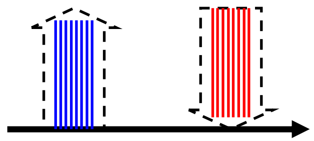
Comparison

	TDM 	TWDM 	WDM 	OFDM 
Rate (Down/Up)	40/10G	4x (10/2.5G)	Nx(1/1)G	40/10G
Optical budget	31 dB	37.5 dB	29-43 dB	30-36.5 dB
Split	64 (*)	64 (*)	80	64 (*)
Reach	<40 km (°)	<40 km	<20-60 km	<100 km
System maturity Cost (L ↔ H)				
Power OLT Power ONU				

(*) typical split for passive split PON – actual split is trade off with reach within optical budget
(°) dispersion limit – actual reach is trade off with split within optical budget

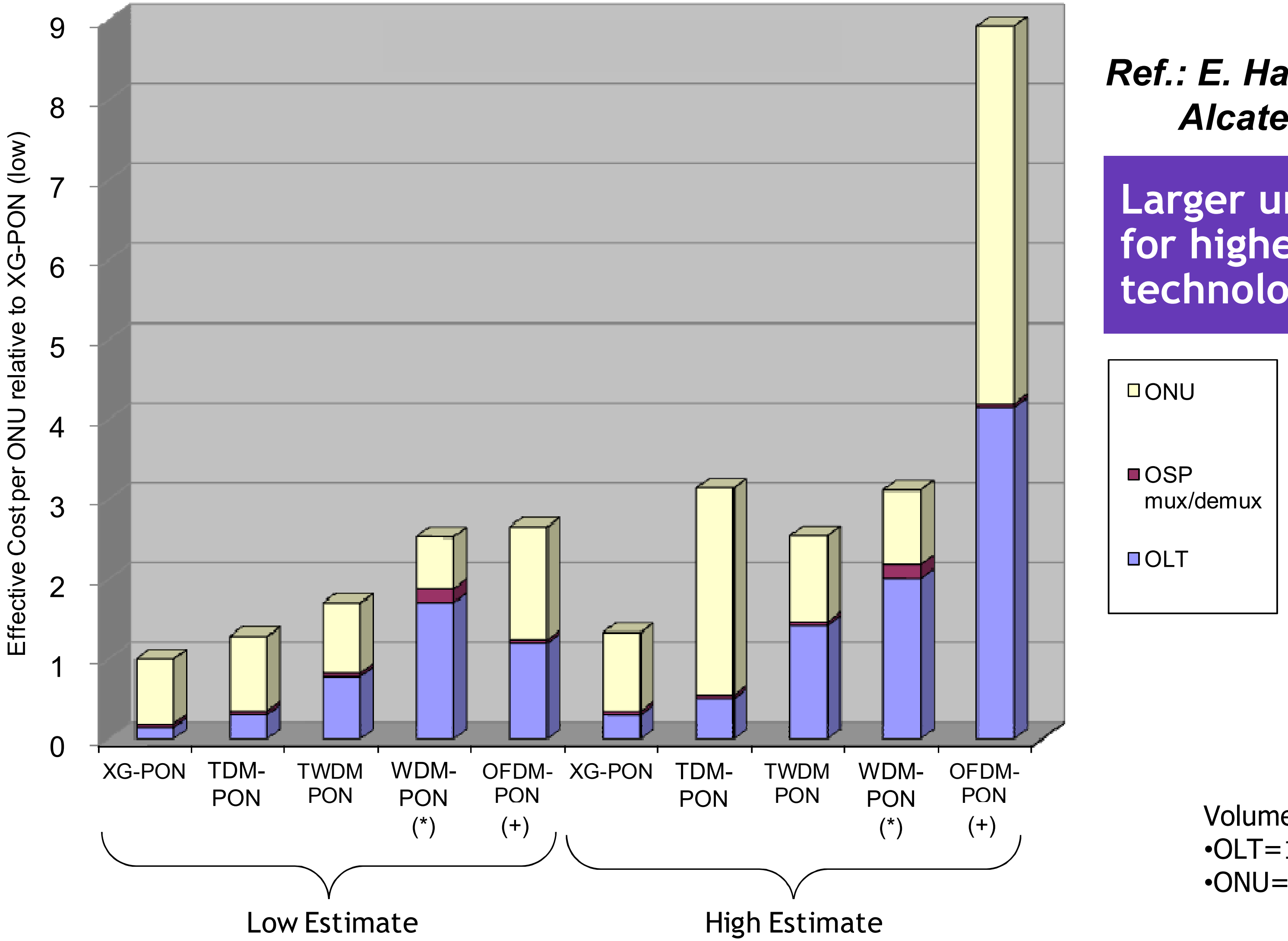
Comparative studies - See also e.g.: FSAN NG-PON2 White Paper; FP7-OASE

Cost comparison 40/10G NG-PON2 (year 2015)

Effective cost per subscriber (16 ONU connected per OLT)

Ref.: E. Harstead et al., Alcatel-Lucent

Larger uncertainties for higher risk technologies



Volumes:
- OLT=10k
- ONU=100k

(*) Self-seeded PON used as example case
(+) Asymmetrical OFDM PON used as example case

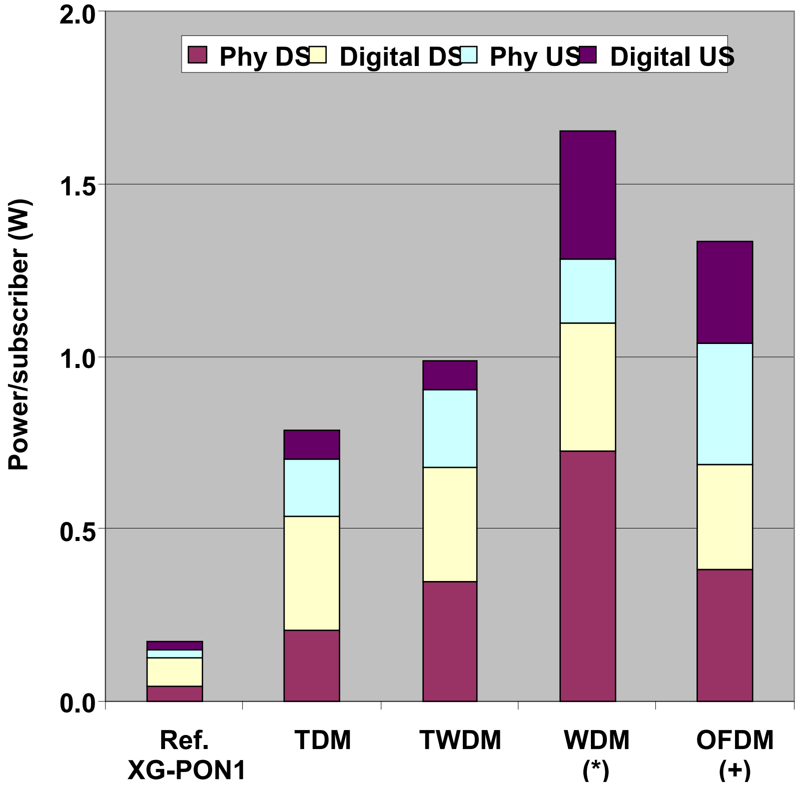
Power consumption

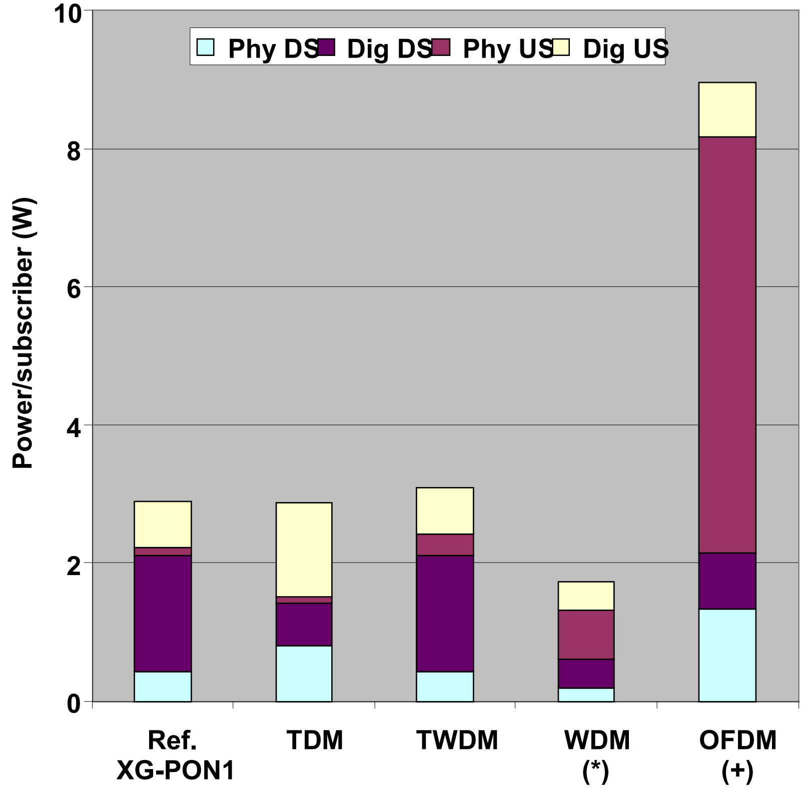
OLT power per subscriber (1:32)

- TDM-PON: higher rate optics
- TWDM-PON: optics x4
- WDM-PON: Tx/Rx per subs
- OFDM: large (OA, DAC/ADC, (I)FFT)

ONU

- TDM-PON: bit interleaving for 40G D/S
- TWDM: similar to XG-PON + tuning
- WDM-PON: low (1 Gbit/s)
- OFDM: large (OA for U/S); subset of carriers reduced DAC/ADC and (I)FFT



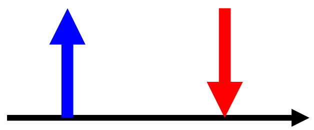
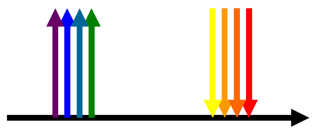
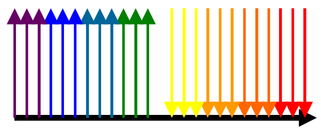
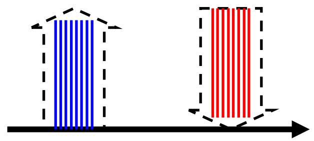


(*) Self-seeded PON used as example case

(+) Asymmetrical OFDM PON used as example case

OA: Optical Amplfication

Comparison

	TDM	TWDM	WDM	OFDM
				
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Split	64 (*)	64 (*)	80	64 (*)
Reach	<40 km (°)	<40 km	<20-60 km	<100 km (°)
System maturity Cost (L ↔ H)	Research $ ↔ $$$	Development $ ↔ $$	Development $$ ↔ $$$	Research $$ ↔ $$$$
Power OLT Power ONU	Low Medium	Low Medium	High Low	Medium High

(*) typical split for passive split PON – actual split is trade off with reach within optical budget
(°) dispersion limit – actual reach is trade off with split within optical budget

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Summary

- TWDM-PON primary solution for FSAN NG-PON2
  - Optional WDM-PON overlay
  - Other technologies have their merits,
    but higher risk in 2015 time frame (target of FSAN NG-PON2)
  - NG-PON uses expected for wireline and wireless backhaul, business
- Future research directions
  - Low cost technologies within existing standards framework
    (components, systems)
  - Reduce operational cost
  - Support multi-provider and multi-service (business, residential, backhaul)
  - Green access solutions (in central office, remote node, and at subscriber)
  - New long-term concepts beyond standards
    (needs compelling advantage over standard solution and at lower cost)

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