Advanced modulation techniques for NG EPON: duobinary

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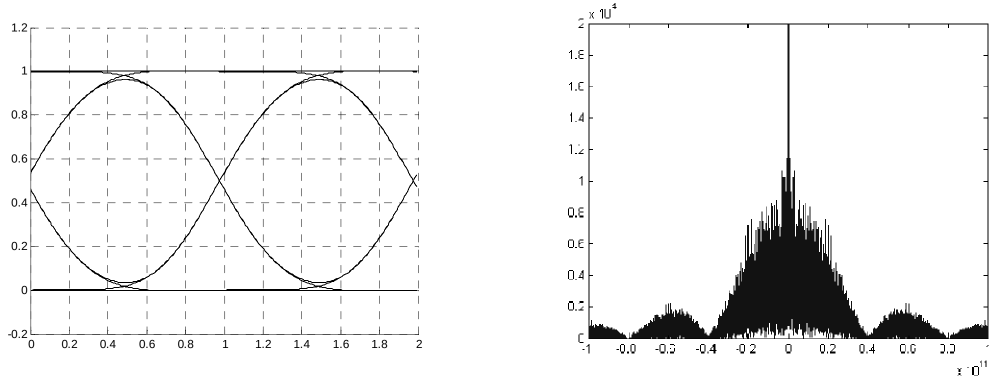
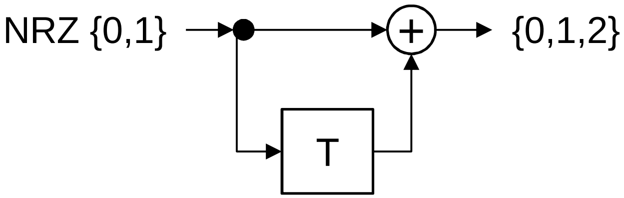
Duobinary modulation: reduces spectrum by half

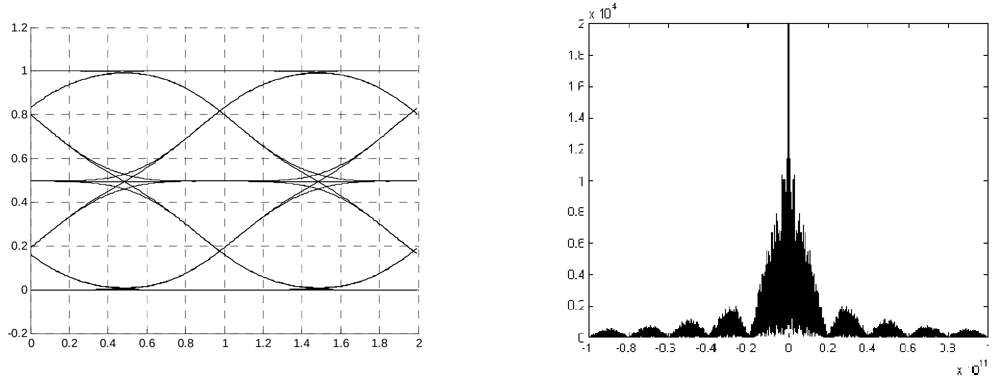
NRZ OOK

NRZ {0,1}

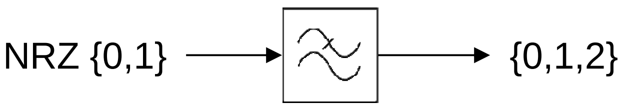


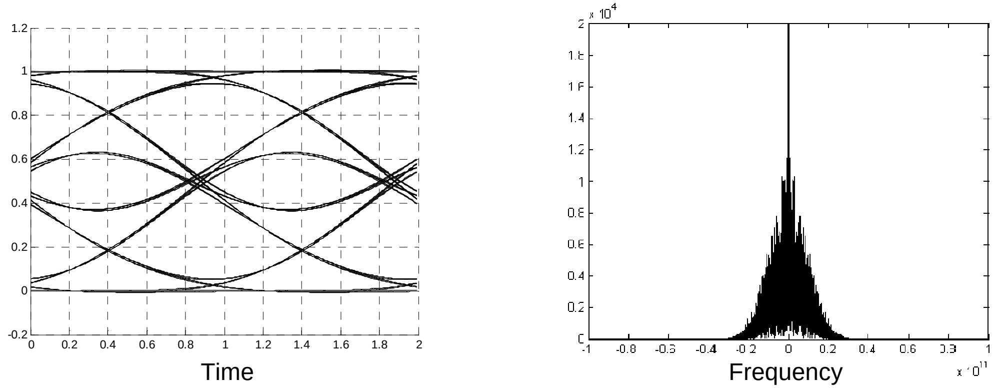
Duobinary*: delay and add filter





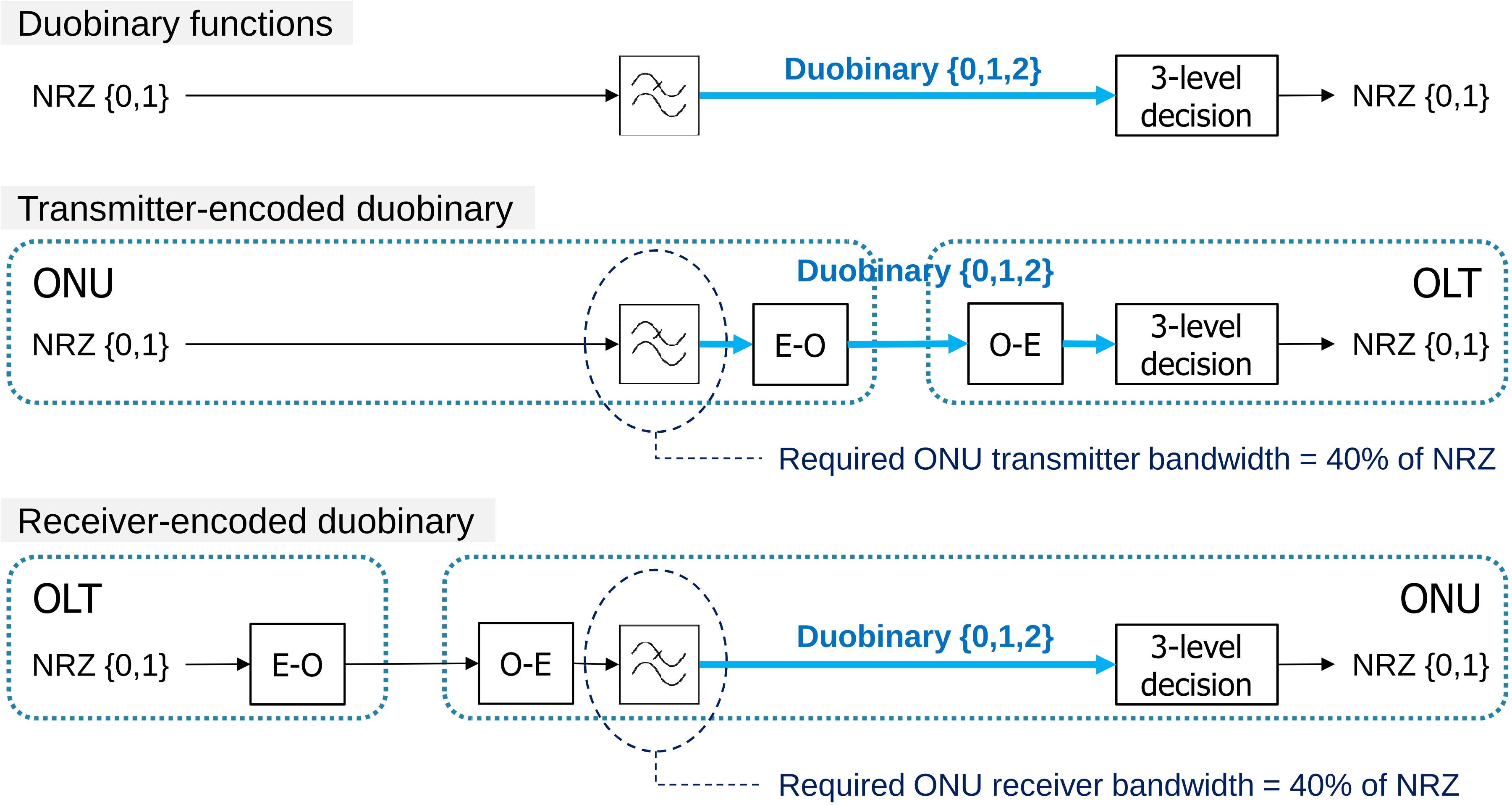
Duobinary*: low pass filter approximation





*These are 3-level “electro” duobinary modulations, not to be confused with optical duobinary

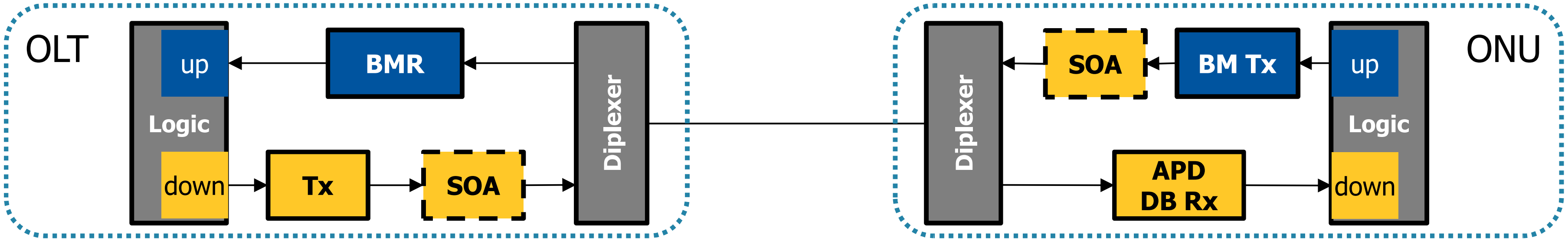
Partitioning duobinary functions in TDM PON



Can get 25 Gb/s symmetric transmission with 10 Gb/s components in the ONU!

Can get 40 Gb/s symmetric transmission with 25 Gb/s components in the ONU!

25 and 40 Gb/s TDM PON optical architecture



Downstream

Bit rate	Modulation	OLT Tx	ONU APD DB Rx
25 Gb/s	Receiver-encoded duobinary	25 Gb/s	7 GHz (10 Gb/s)
40 Gb/s		40 Gb/s	11 GHz (<25 Gb/s)

Upstream

Bit rate	Modulation	OLT BMR	ONU BM Tx
10 Gb/s	NRZ	10G EPON BMR	10G EPON DML
25 Gb/s	Transmitter-encoded duobinary	12.5 GHz APD Rx	7 GHz Tx (10 Gb/s)
40 Gb/s		20 GHz p-i-n Rx + SOA	11 GHz EML Tx (<25 Gb/s)

Re-use 10G EPON

10 Gb/s components

Piggyback on 40GBASE-FR, etc.

Piggyback on 100GBASE-ER4

Technology exists

25 Gb/s NRZ upstream might also be possible, for future study

Estimated TDM PON OLT launch power requirements.

		25 Gb/s down	40 Gb/s down	25 Gb/s up	40 Gb/s up*
10GBASE-PR(X) EPON Rx sensitivity		-29.5 dBm (U4)		-29 dBm (D4)	
Changes to account for high speed transmission					
Sustain SNR #1: 2-level → 3-level		+3 dB			
Sustain SNR #2: wider receiver bandwidth		0 dB	2 dB	2.5 dB	4.5 dB
Penalty: suboptimal duobinary encoding		+1.5 dB			
Factor in improved LDPC FEC coding gain		- 1 dB		0 dB	
Projected Rx sensitivity (b-to-b)		-26 dBm	-24 dBm	-22 dBm	-20 dBm
Optical path penalty (20 km, incl. 1 dB CD penalty)		+1.5 dB			
Required minimum launch powers		OLT		ONU	
PR-10 loss budget	+20 dB	-4.5 dBm	-2.5 dBm	-0.5 dBm	1.5 dBm
PR-20 loss budget	+24 dB	-0.5 dBm	1.5 dBm	3.5 dBm	5.5 dBm
PR-30 loss budget	+29 dB	4.5 dBm	6.5 dBm	8.5 dBm	10.5 dBm
PR-40 loss budget	+33 dB	8.5 dBm	10.5 dBm	12.5 dBm	14.5 dBm

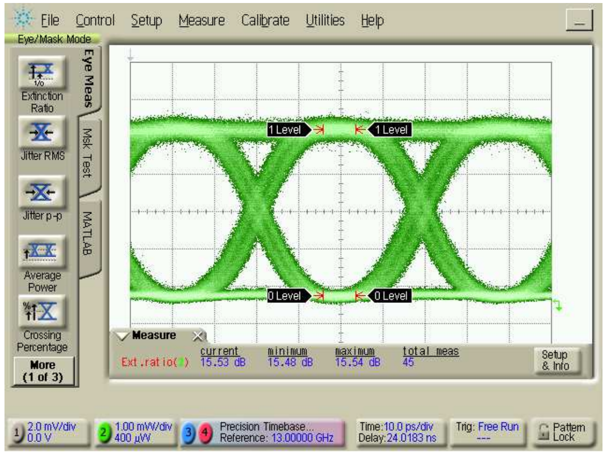
Within capability of commercial DMLs/EMLs

a combination of DML and/or TEC might eliminate need for SOA

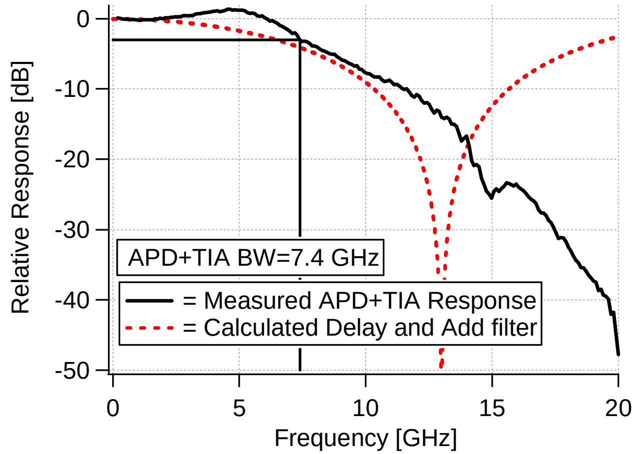
Within capability of commercial SOAs

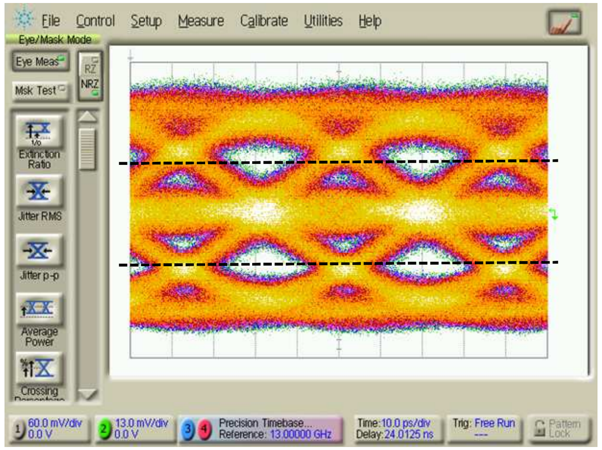
*we assume p-i-n + SOA sensitivity equivalent to APD

26 Gb/s experiment using standard 10 Gb/s APD
Downstream receiver-encoded duobinary

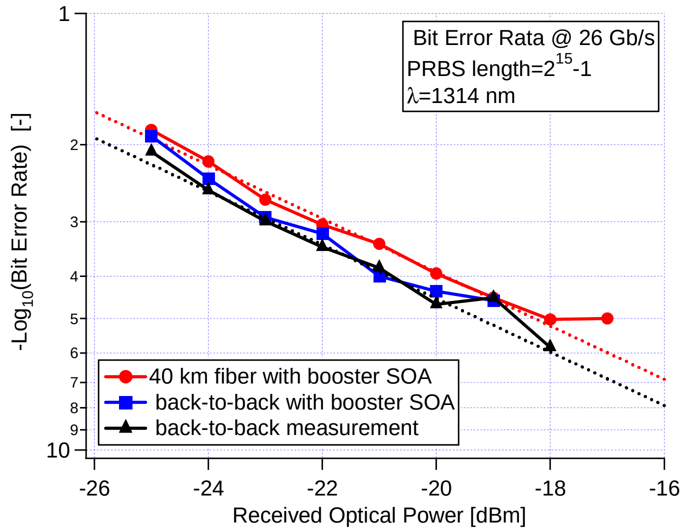


Transmitted NRZ-OOK eye





Received duobinary eye
(with decision threshold levels indicated)



D. van Veen, V. E. Houtsma, P. Winzer, and P. Vetter (Bell Labs), "26-Gbps PON Transmission over 40-km using Duobinary Detection with a Low Cost 7-GHz APD-Based Receiver," ECOC OSA Technical Digest

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40 Gb/s experiment using commercial 25 Gb/s APD
Downstream receiver-encoded duobinary

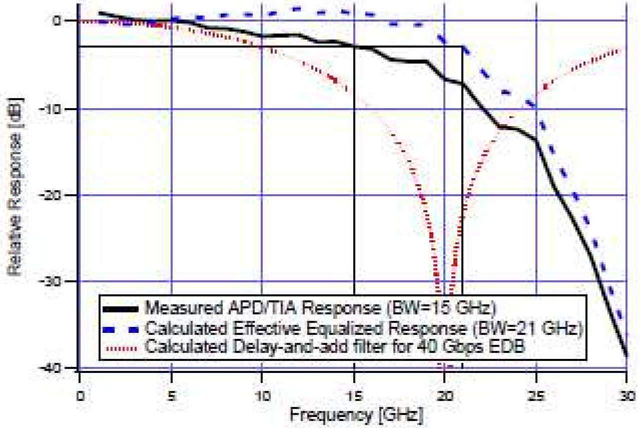


Figure 3 : Measured 25 Gbps APD/TIA Response, Calculated EQ Response and Calculated Delay-and Add filter.

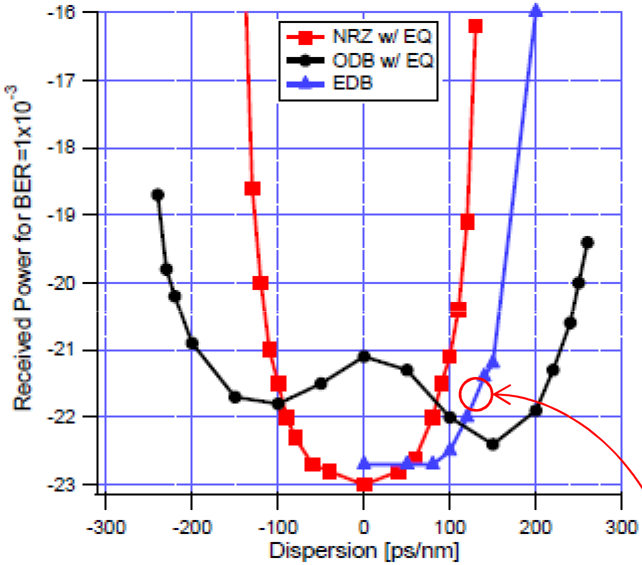


Figure 6 : Dispersion tolerance for EDB detection, equalized ODB and equalized NRZ at 0 dBm optical launched power.

1 dB penalty at 130 ps/nm

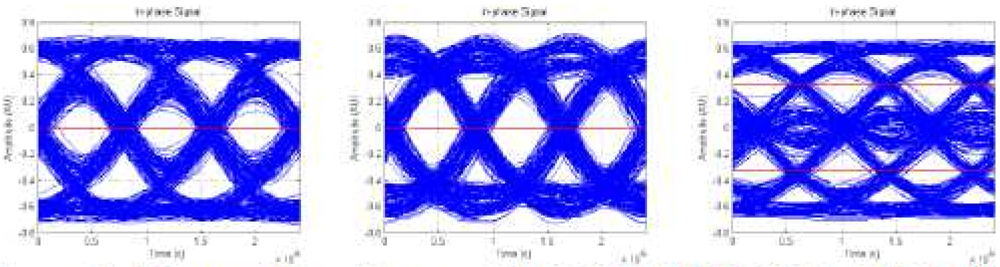
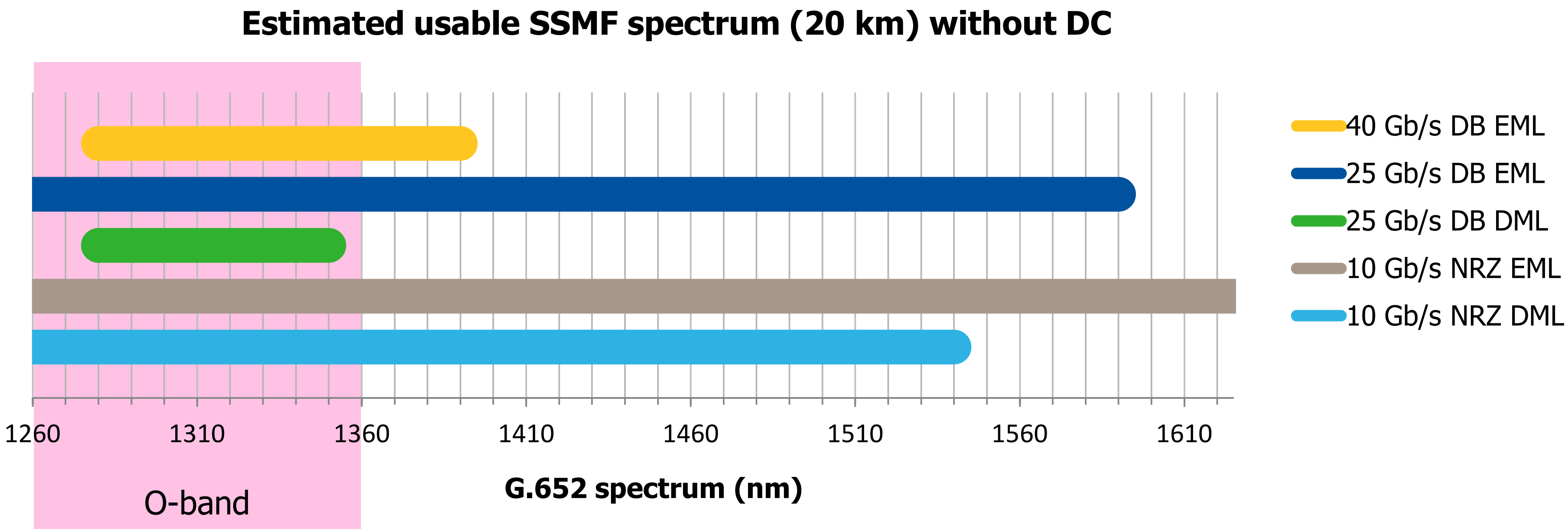


Figure 4 : Measured Eye diagrams b2b a) NRZ b) EQ NRZ c) EDB (filtered).

V. Houtsma, D. van Veen, A. Gnauck and P. Iannone (Bell Labs), "APD-Based DuoBinary Direct Detection Receivers for 40 Gbps TDM-PON", 2014, unpublished

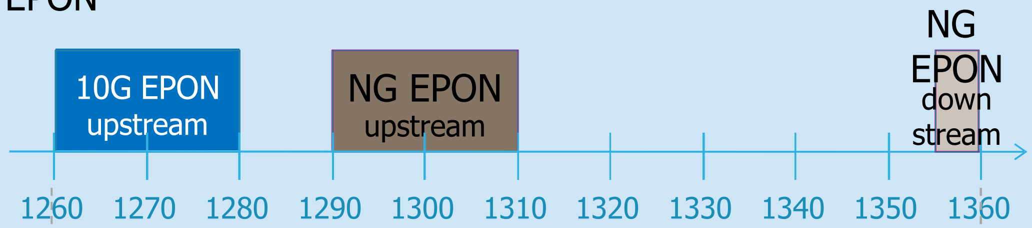
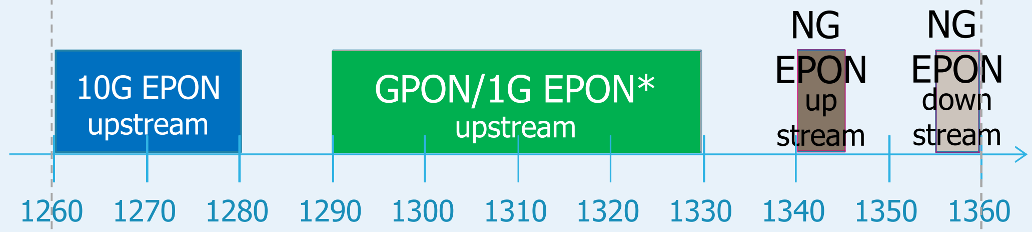
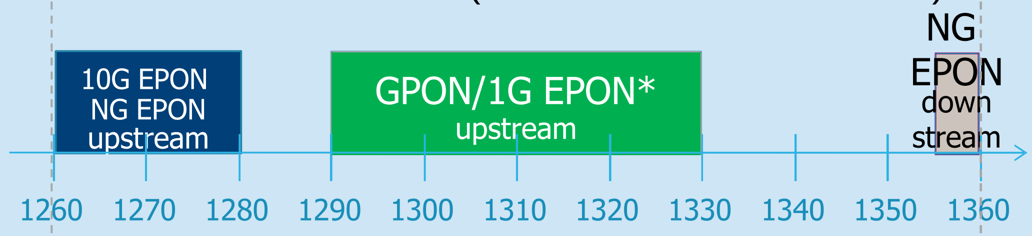
High speed transmission: Chromatic Dispersion

Duobinary improves CD tolerance by ~2x vs. NRZ



- If the O-band is available,
  - no dispersion compensation (DC) is required up to 40 Gb/s (EML).
  - Up to 25 Gb/s can use DML
- If the O-band is not available,
  - 10 Gb/s: can use DML and no DC
  - 25 Gb/s: can use EML and no DC
  - Only 40 Gb/s will require DC
    - DC fiber is low-loss (<3 dB) and low cost, although bulky
    - FBG DCMs are smaller and a potential alternative
    - EDC for duobinary (esp. burst mode) requires more study

Possible O-band co-existence scenarios

ONU Tx	Max Tx range	Co-existence with
10G/25G DML	20 nm	10G EPON 
10G/25G/40G EML	5 nm	10G EPON + GPON/1G EPON* 
10G/25G DML	20 nm	10G EPON + GPON/1G EPON* (shared OLT BMR and MAC) 

*DFB laser typical

O-band

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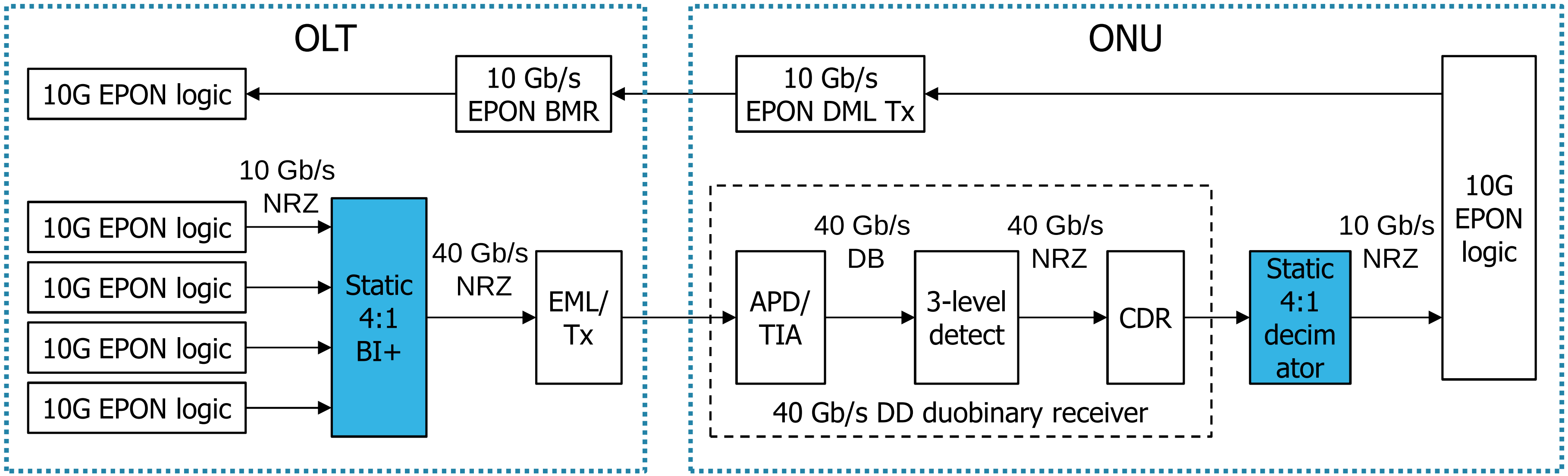
High speed transmission: reducing impact on ONU silicon and power consumption

- Downstream bit interleaving (BI) allows low cost ONU silicon to operate at user rates.
- Can be a simple static BI or dynamic BI
  – Example of simple static BI: 40 Gb/s 4:1 BI, analogous to TWDM wavelength stacking, allows the ONU to operate at 10 Gb/s (after the decimator).



Example of a 40/10 NG EPON using static 4:1 bit interleaving

  – Dynamic bit interleaving: where the aggregate TDM PON bandwidth can be 100% flexibly allocated across the ONUs

ONU components summary

PON flavor	Laser		APD
	O-band available	O-band not available	
25/10	10 Gb/s DML		10 Gb/s APD
25/25	10 Gb/s DML	10 Gb/s EML	
40/10	10 Gb/s DML		25 Gb/s APD
40/25	10 Gb/s DML	10 Gb/s EML	
40/40	25 Gb/s EML		

Can be satisfied by:

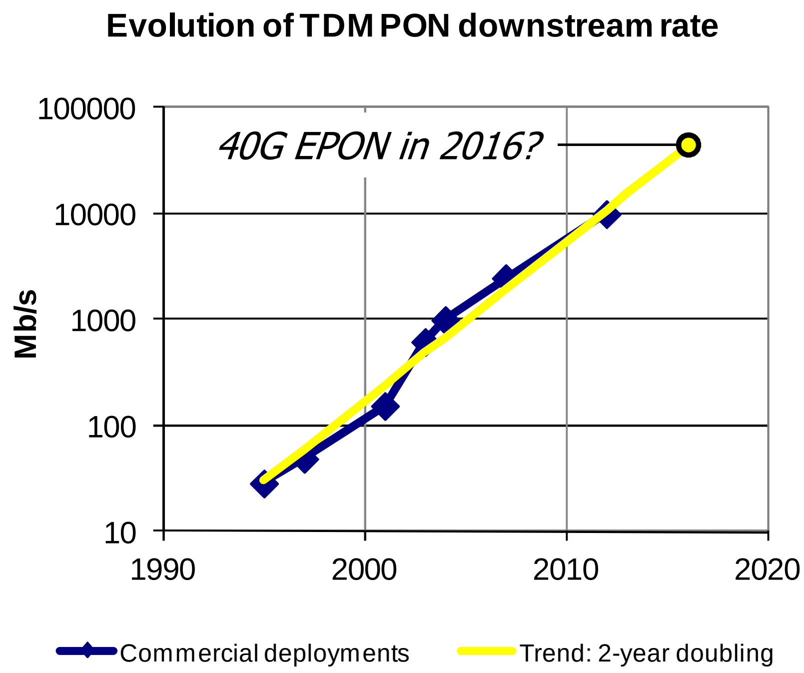
10 Gb/s components

25 Gb/s components

- 100GBASE-ER4 25 Gb/s APDs will use the same materials, manufacturing processes, and packaging technologies as today's low cost 10 Gb/s receivers
- Therefore, the incremental variable cost will be driven by testing at higher speed and lower yield. This premium should become small over time.

TDM PON historical trend

PON type	Commercial Deployment	Year	Line rate (Mb/s)	
			Down	Up
Narrowband	Deutsche Telekom OPAL	1995	29	29
Narrowband	NTT Pi PON	1997	49	49
ATM PON	NTT	2001	155	155
BPON	NTT West	2003	622	155
EPON	NTT East	2004	1000	1000
GPON	Verizon FiOS	2007	2488	1244
10G EPON	China Telecom	2012	10000	1000



At each step, TDM PON has overcome 3 main challenges without the aid of WDM

- Higher speed optics and electronics
- More optical power/receiver sensitivity to sustain SNR
- Narrower linewidth lasers to combat chromatic dispersion

Can this be repeated for 25 Gb/s? or 40 Gb/s?

Summary

- Duobinary modulation is a tool in a tool box that can be used to achieve higher bit rates from lower speed components
- Although we have performed simulations and experiments, more study is required, especially for the upstream:
  - Transmitter-encoded duobinary modulation
  - Duobinary modulation and burst mode transmission
  - Burst mode duobinary EDC

PON duobinary references

FSAN, “Forty gigabit time division multiplexed PON (XLG-PON)”, section 6.2 in “Next-generation 2 access network technology” white paper, 2012 (unpublished)

D. van Veen, D. Suvakovic, H. Chow, V. Houtsma, E. Harstead, P. J. Winzer, and P. Vetter, "Options for TDM PON beyond 10G," in *Advanced Photonics Congress*, OSA Technical Digest (online) (Optical Society of America, 2012), paper AW2A.1.

D. Suvakovic, H. Chow, D. van Veen, J. Galaro, B. Farah, N. P. Anthapadmanabhan and P. Vetter, “Low Energy Bit-Interleaving Downstream Protocol for Passive Optical Networks”, 2012 IEEE Online Conference on Green Communications (GreenCom), p.26-p31 (2012).

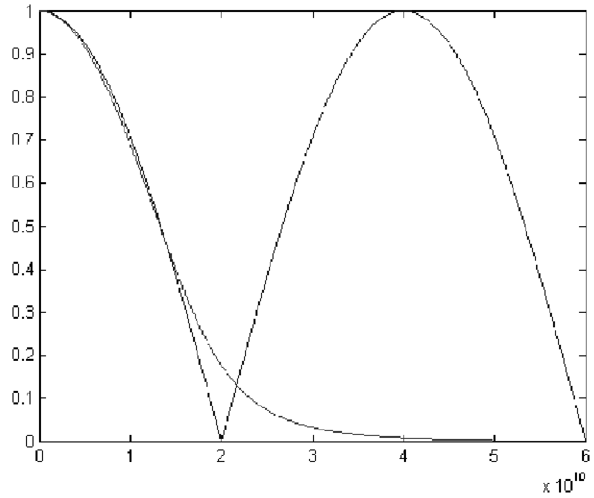
D. van Veen, V. E. Houtsma, P. Winzer and P. Vetter, "26-Gbps PON Transmission over 40-km using Duobinary Detection with a Low Cost 7-GHz APD-Based Receiver," in *European Conference and Exhibition on Optical Communication*, OSA Technical Digest (online) (Optical Society of America, 2012), paper Tu.3.B.1.

D. van Veen, V. Houtsma, A. Gnauck, P. Iannone, “40-Gb/s TDM-PON over 42 km with 64-way Power Split using a Binary Direct Detection Receiver”, in *European Conference and Exhibition on Optical Communication*, 2014

Backup

Delay-and-add filter and low-pass filter approximation

Calculated delay-and-add filter and ideal low-pass filter approximation



Calculated delay-and-add filter and measured APD/TIA responses

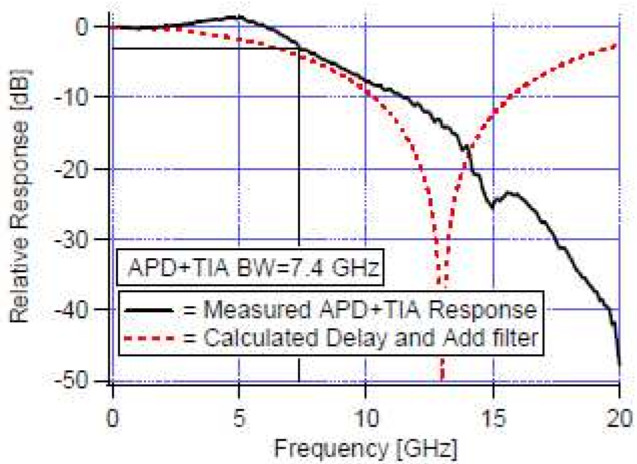
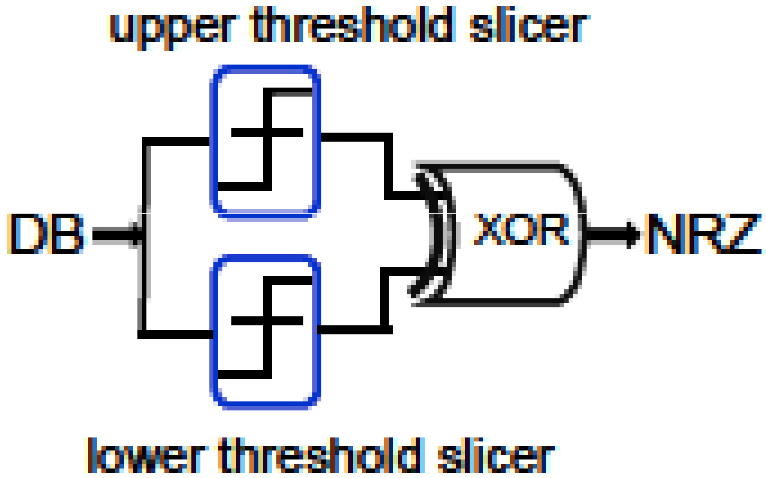


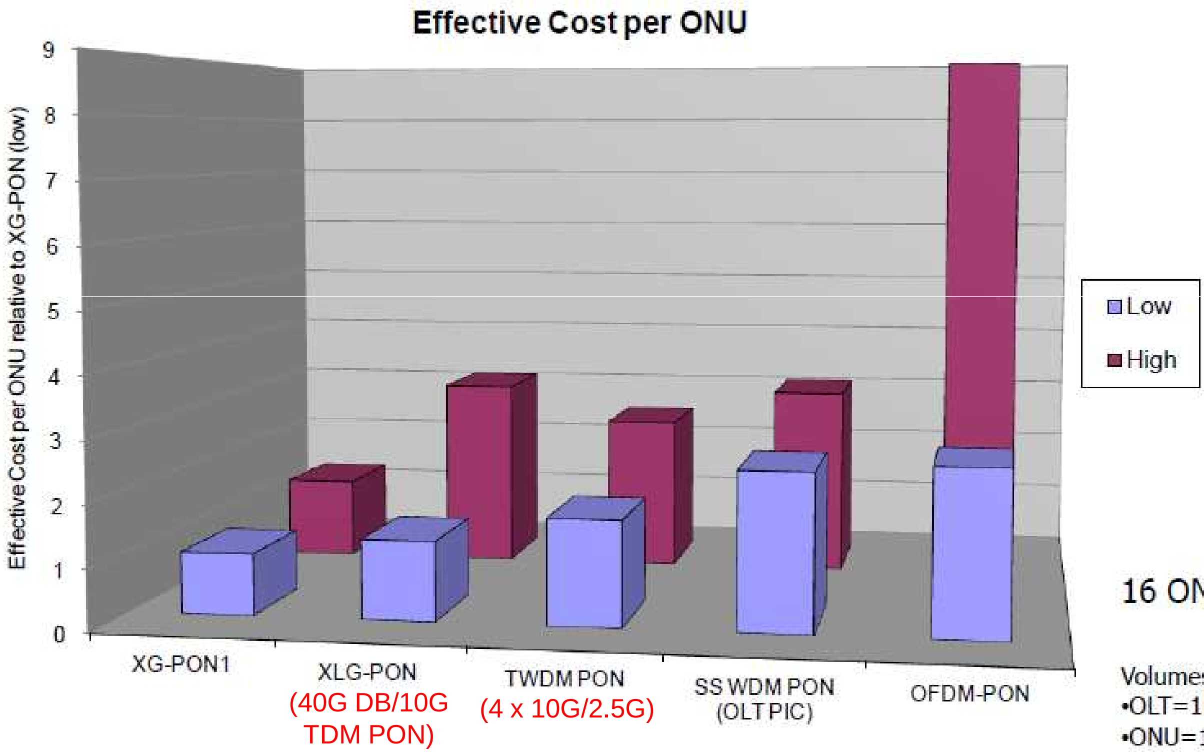
Fig. 2. Measured APD/TIA response and calculated Delay and Add filter for 26-Gbps.

Duobinary demodulator implementation



Historical: presented to FSAN, Jan. 2012

Cost comparison (year 2015).
Cost uncertainties are bounded



16 ONUs/OLT port

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

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