ECOC 2023 GLASGOW

TUTORIAL

Towards More and More DSP in Higher Speed PON

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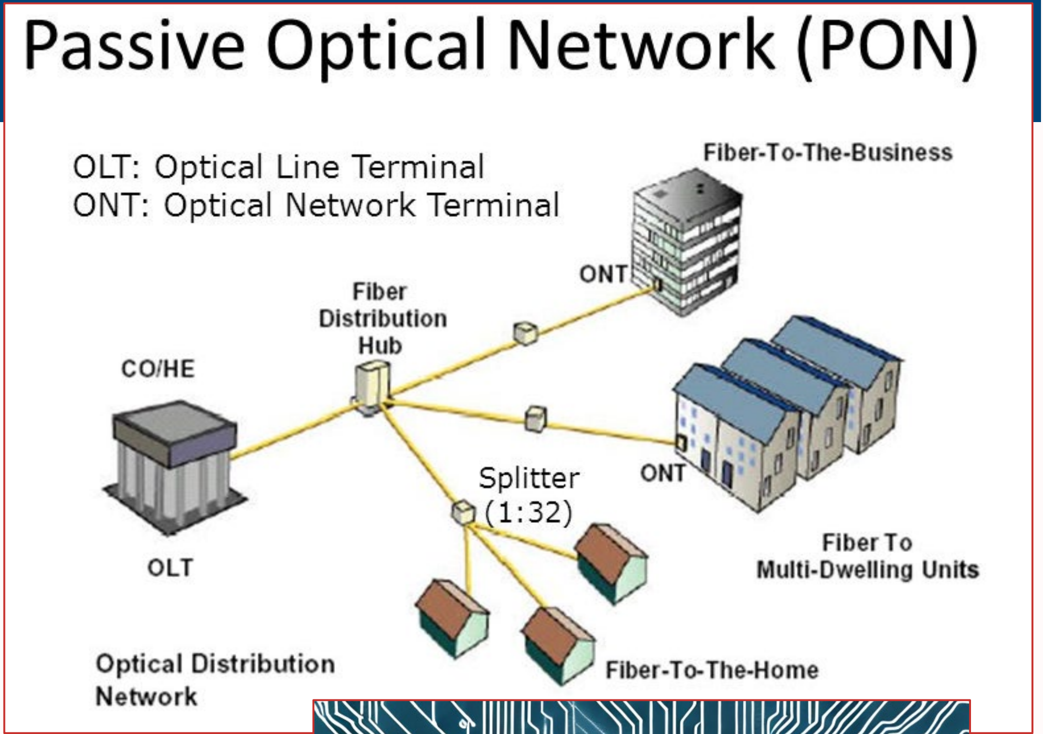
Acknowledgments

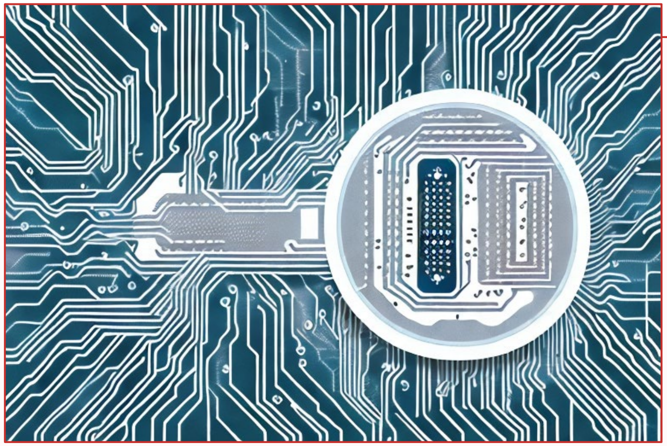
- I like to thank a lot the following people for sharing with me their technical views on the topics of this talk:
  - My PhotoNext Team on optical access at POLITO
    - Giuseppe Rizzelli, Mariacristina Casasco, Valter Ferrero,
      - And my ex collaborator Pablo Torres, now in Infinera
    - www.photonext.polito.it
  - The Telecom Italia (TIM) team on optical access
    - Annachiara Pagano, Maurizio Valvo, Roberto Mercinelli

- In my review, I will often report graphs selected from papers published by groups working on access in Nokia, Orange and Huawei

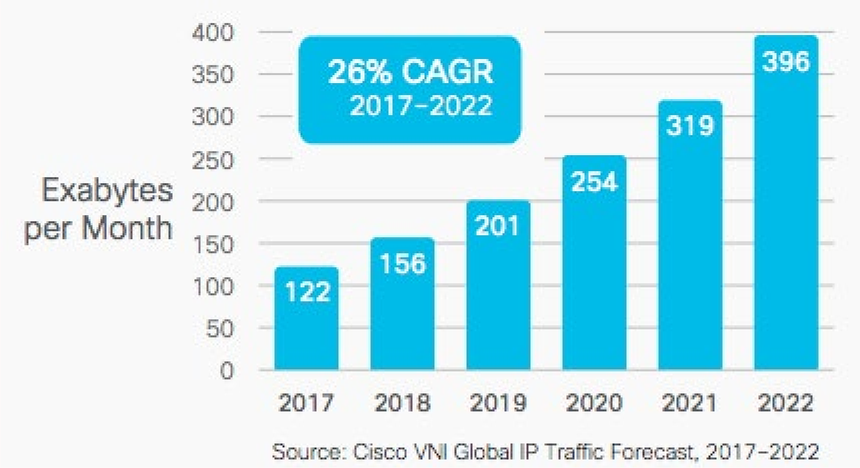
Outline for this Tutorial

- A brief history on Digital Signal Processing (DSP) in PON standards
- Forward Error Correcting Codes (FEC) in PON
- Adaptive equalization in PON
  - The resulting ultimate limitation in power budget, reach, capacity for IM-DD PON
- Research on more advanced DSP techniques
- A look toward the (near?) future: coherent PON





- Let me skip the usual "mantra" about exponential growth of Internet traffic ☺
  - And about access network exponential growth
    - … and get to this tutorial focal points!



Just one number and one fact:

- 1 billion home passed with optical access worldwide today
  - Mostly using PON

- Orange (France) declared that it will decommission copper twisted-pair access by 2030
  - Many other Operators have similar plans

…likely, PON will be the " new copper" for the next 70 years!

Focus of this tutorial and some caveats…

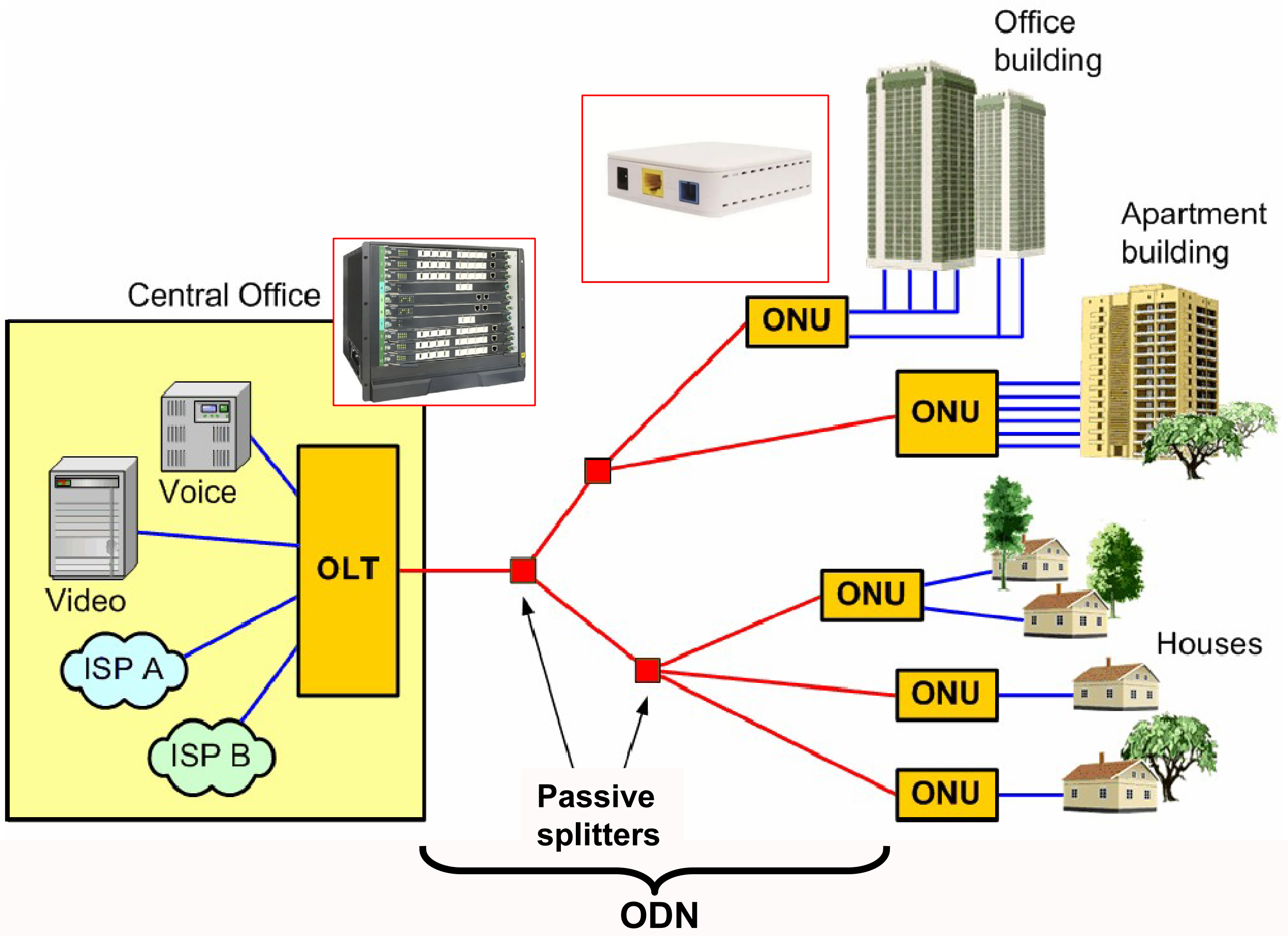
- PON physical layer
  - i.e. mostly the Physical Media Dependent (PMD) Layer
  - I will not discuss on higher layers

- Higher bit rates per lambda (i.e. at least 50 Gbps per lambda… and going higher!)
  - In fact, we will see that DSP in PON basically started from 50G-PON
    - apart from FEC, that started much earlier

- A caveat: when relevant, I will present examples and definitions coming from the ITU-T PON-related Recommendations
    - IEEE standards are similar (… but not identical ☺)

PON Acronyns

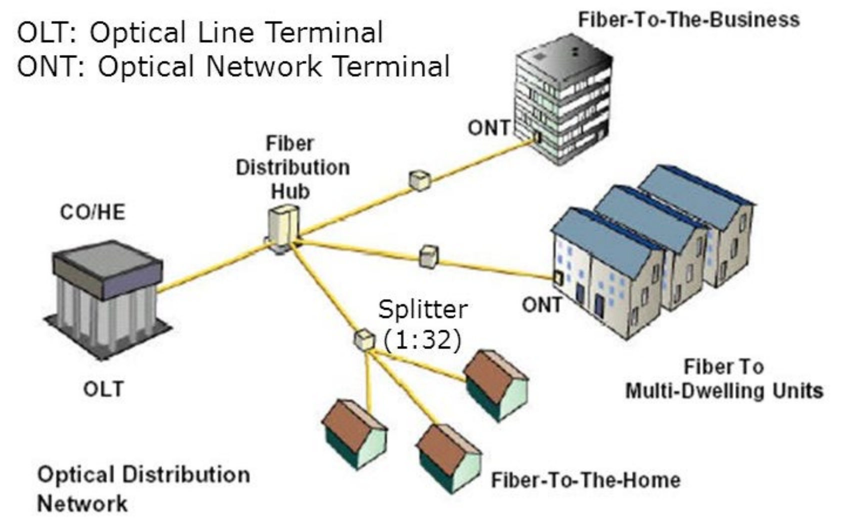
- **OLT**: Optical Line Termination
- **ONU**: Optical Network Unit
  - i.e. the "Optical Modem" in Fiber to the Home (FTTH)
- **ODN**: Optical Distribution Network
  - i.e. fiber + optical 1:N splitter
  - **ODN loss**: overall optical loss introduced by the ODN
    - Or "OPL" Optical Path Loss



What's so "special" about PON at the physical layer?

- **Point-to-multipoint**
  - Typical target split-factor: up to 64 users (at least)
  - Typical target distance: 20 km
- **Shared access using Time Division Multiplexing** (TDM/TDMA, for all standards so far)
  - Burst mode TX and RX in upstream
- **Bidirectional transmission on a single fiber**
  - Using two different wavelengths for downstream and upstream
- **Very ODN high loss** due to the presence of 1xN splitter

Passive Optical Network (PON)

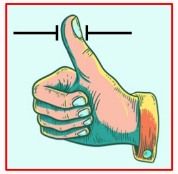


From latest ITU-T standard 50G-PON:

- *Class N1: 29 dB*
- *Class N2: 31 dB*
- *Class E1: 33 dB*
- *Class E2: 35 dB*

"minimum" target loss for practical PON: 29 dB

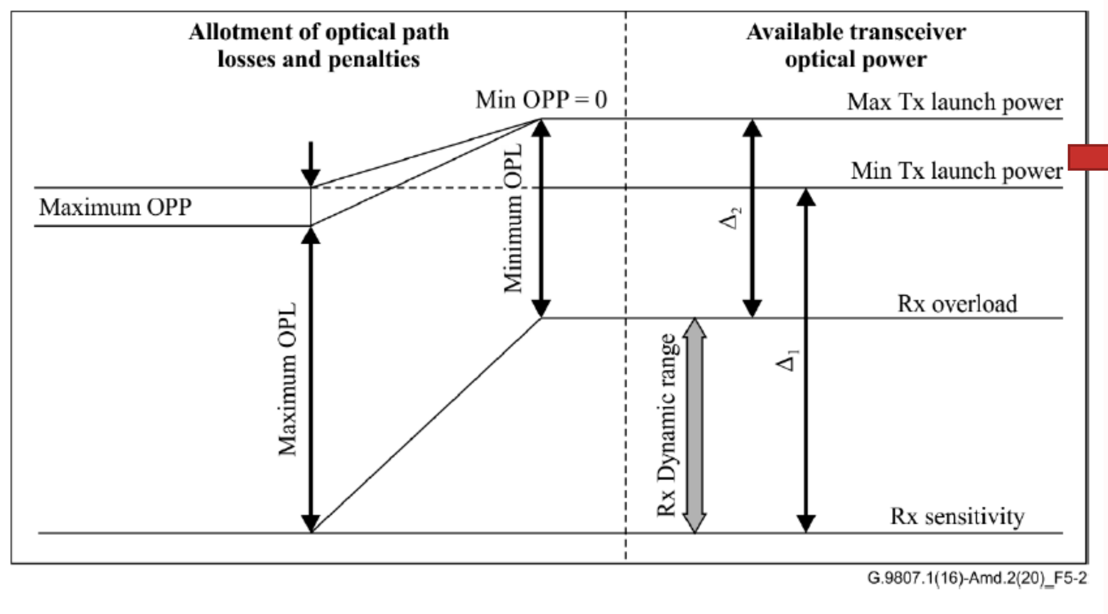
- *20 km in O-band (0.4dB/km) → 8dB*
- *1x64 splitter → 18 dB*
- *Extra loss → 2-3 dB*



Take away message #1

PON is short reach but… it is VERY different from point-to-point short reach (such as all IEEE GBASE-SR)

An example of power budget (XGS-PON ITU-T recommendation)



TX

ODN class		N1	N2	E1	E2
Mean launched power MIN	dBm	+2.0	+4.0	+6.0	+8.0
Mean launched power MAX	dBm	+5.0	+7.0	+9.0	+11.0

Resulting power budgets *(no inline optical amplification)*

30dB 32dB 34dB 36dB

RX

ODN Class		N1	N2	E1	E2
Minimum sensitivity at BER reference level (Note 5)	dBm	–28.0	–28.0	–28.0	–28.0

- Thus PON transceiver CANNOT reuse "as-is" short- and medium- reach transceivers
  - Significantly better sensitivity is required
  - …while bit rate and cost targets are similar

Research in PON is NOT identical to Research in short-reach point-to-point!

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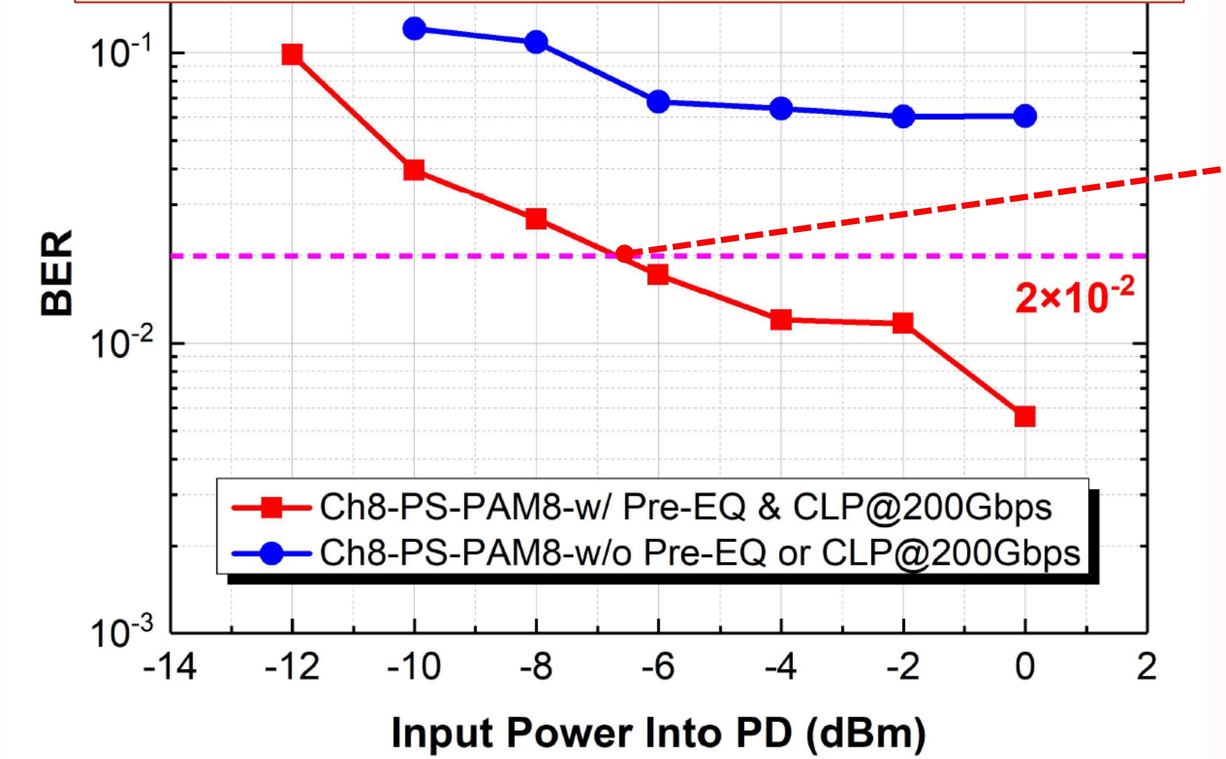
This is just one example on the many recent papers on ultra-high speed IM-DD short-reach



Demonstration of Terabit/s LAN-WDM for the Evolution of B5G/6G Fronthaul Networks

Jiao Zhang, Qingsong Wang, Junhao Zhang, Xiang Liu, Bingchang Hua, Jian Chen, Zhigang Xin, Yuancheng Cai, Mingzheng Lei, Yucong Zou, Liang Tian, Guo Zhao, Meihua Bi, and Min Zhu

DOI 10.1109/JPHOT.2023.3300705

- A result from an excellent paper on short reach point-to-point IM-DD at 200 Gbps for LAN-WDM

$$P_{RX}^{dBm} = -7\,dBm$$

- … but this system would NOT be directly applicable to PON.
  - Even at the "PON minimum" ODN_{loss}=29dB it would require an unrealistic transmitter power:

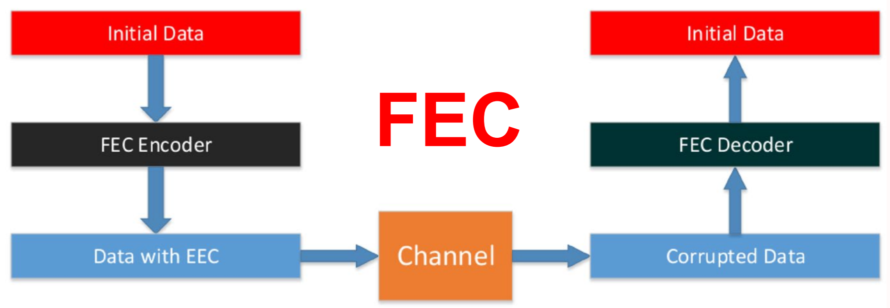
$$P_{TX}^{dBm} \geq +22\,dBm \quad \ldots + \text{margins!}$$

How to obtain higher sensitivity in optoelectronics?

- **High-speed APD-based receivers**
- **SOA pre-amp**

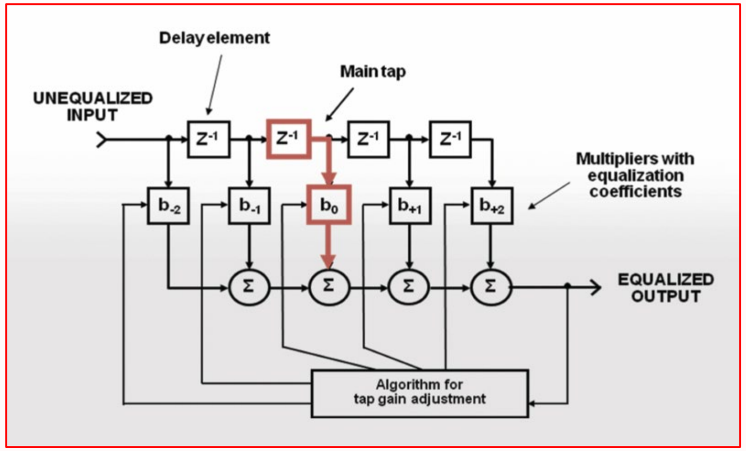
… so what DSP is used for in PON?

- Improve receiver sensitivity (typically using FEC)
  - To combat stringent power budget requirements



- Combat power penalties generated by:
  1. Optoelectronic bandwidth limitations
  2. Chromatic dispersion
     - typical target distance is 20 km, maybe more in the future
  3. … and nonlinear effects
     - Mostly in the optoelectronic devices (TX and RX)
     - Less relevant for the fiber

- Adaptive equalization at receiver
- Pre-compensation at transmitter
- Variable rate transmitters



Can we go for "blue sky" research in PON?

- **Obviously yes**! (particularly in the Academia!)

  BUT

- Remember that the PON Optical Distribution Network installed base is so huge (1billion FTTH home passed worldwide, mostly PON) that telecom operators will NOT change its structure for many years to come
  - For instance:
    - Do you want to propose to change the splitter with a WDM Mux?
    - Do you want to use two separate fibers for upstream and downstream?
      - Ok but… think twice ☺ !

- "Blue sky" research is more reasonable for the PON transceivers (ONU and OLT)
  - BUT ANYWAY… pay attention to costs and complexity!
    - Today (2023) a GPON ONU bill of material is <10€ !
    - … and an XGS-PON <30€

Organization of the presentation

In the rest of the tutorial I will try to clearly discriminate my presentation between:

- The state of the art: current most advanced but standardized PON solutions

- The current open research directions

Graphical labels used in next slides in this presentation

A BRIEF HISTORY ON DSP IN PON STANDARDS

FROM THE ITU-T RECOMMENDATIONS ON PON

The evolution of ITU-T PON standards

STANDARDS

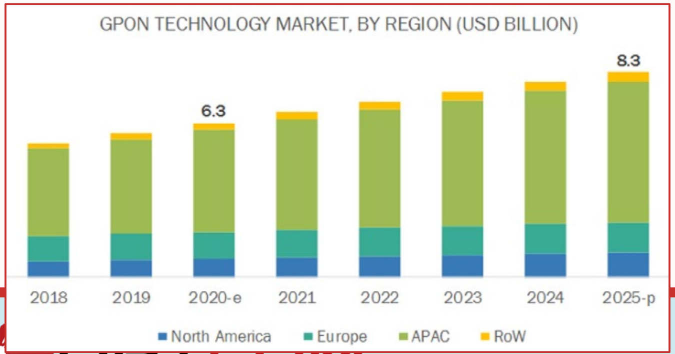
International Telecommunication Union

Year of final ratification by ITU-T

2003

GPON (G.984)

- 2.5Gbps downstream
- Still most commonly deployed today (with E-PON)
- Market volume about 7 Billion USD per year
- IM-DD, NO DSP,
- NO FEC originally
  - … introduced later for highest ODN loss classes



2010-2016

XG-PON and XGS-PON (G.987 and G.9807)

- 10Gbps downstream (2.5G or 10G upstream)
- Start to be commercially deployed now (2023)
- Still NO DSP
- FEC introduced
  - Reed-Solomon FEC for $BER_{preFEC}=10^{-3}$

2013

TWDM-PON (G.989.1)

- In its basic version, four XG-PON in parallel on four DWDM wavelengths (100GHz spacing)
- 4x10Gbps downstream
- Very little commercial deployment so far

2020

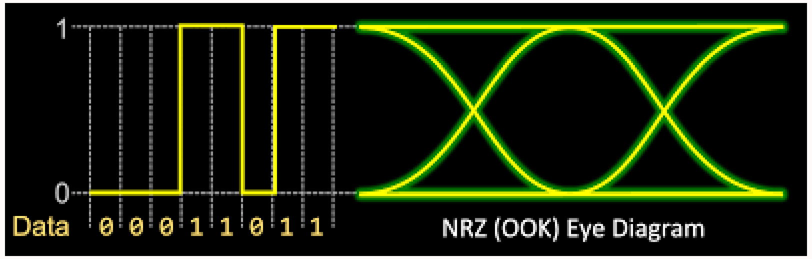
50G-PON (G.9804)

- 50Gbps downstream (25G up)
- Adaptive equalization introduced… the birth of DSP in PON!
- Much stronger FEC
  - LDPC for $BER_{preFEC}=10^{-2}$

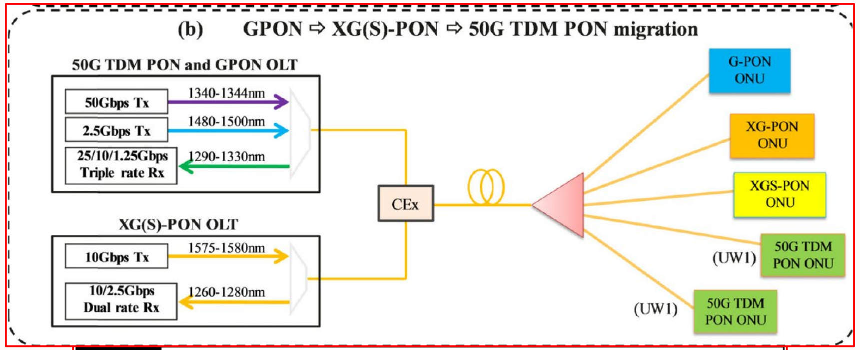
Common features of all approved PON standards (so far)

STANDARDS

- <u>Extremely simple modulation format</u>
  - Intensity modulation and direct detection (IM-DD)
  - Binary NRZ OOK (i.e PAM-2)



- <u>NO optical amplification in the ODN</u>
  - SOA are considered today, but only in the OLT
    - Maybe also in the ONU in the near future



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JOURNAL OF Optical Communications and Networking

Progress of ITU-T higher speed passive optical network (50G-PON) standardization

Dezhi Zhang,[1,*] Dekun Liu,[2] Xuming Wu,[2] and Derek Nesset[3]

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[2]Transmission & Access Research Department, Huawei Technologies Co., Ltd., Wuhan 430079, China
[3]Munich Research Centre, Huawei Technologies Dusseldorf GmbH, Munich, Germany
*Corresponding author: zhangdzh@chinatelecom.cn

- <u>Separate wavelengths for upstream and downstream</u> on a single bidirectional fiber

- <u>TDMA burst mode in upstream</u>

FORWARD ERROR CORRECTING CODES (FEC) IN PON

FEC CODES:
ARE THEY DSP OR NOT?
… WHO CARES ☺ !

A short summary of FEC in PON standards

STANDARDS

- For what concerns already ratified ITU-T standards
  - XG-PON and XGS-PON and highest class GPON: Reed-Solomon RS(248,216)
    - A truncated form of the super-succesfull RS(255,223) code
    - $BER_{ref} = 10^{-3}$
  - 50G-PON: low-density parity check LDPC(17280,14592)
    - A shortened and punctured version of low-density parity check codes
    - The 50G-PON standards specifies the LDPC encoder, while it leaves an open implementation of the decoder
      - LDPC allows for both hard-decision and soft-decision decoding

From the 50G-PON standard: $BER_{ref} = 10^{-2}$
This BER reference level assumes hard-decision FEC decoding with interleaving defined in [ITU-T G.9804.2].

When soft-decision FEC decoding is used, estimate BER_{ref} *is around* $2 \cdot 10^{-2}$

What's next in FEC for PON?

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What's Next?

FLCS-PON—an opportunistic 100 Gbit/s flexible PON prototype with probabilistic shaping and soft-input FEC: operator trial and ODN case studies

Robert Borkowski,[1,*] Yannick Lefevre,[2] Amitkumar Mahadevan,[3] Doutje van Veen,[3] Michael Straub,[1] Ralph Kaptur,[4] Björn Czerwinski,[4] Bruno Cornaglia,[5] Vincent Houtsma,[3] Werner Coomans,[2] René Bonk,[1] and Jochen Maes[2]

[1]Nokia Bell Labs, Magirusstrasse 8, 70469 Stuttgart, Germany

- Flexible FEC usage on a per-ONU base

Table 1. LDPC FEC Code Parameters

Code	N [bit]	K [bit]	M [bit]	S [bit]	P [bit]	R [bit]	Hard decoding hBER [–]	hNGMI [–]	Soft decoding sBER [–]	sNGMI [–]	Net 50G [Gbit/s]	Net 100G [Gbit/s]
50G-PON	17,280	14,592	2688	0	384	0.8444	1×10^{-2}[a]	0.9192	2×10^{-2}[b]	0.9229	42.22	84.44
FLCS-	11,520	8448	3072	6144	0	0.7333	1.85×10^{-2}	0.8671	4.40×10^{-2}	0.8383	36.67	73.33
PON	11,520	8704	2816	5888	256	0.7556	1.73×10^{-2}	0.8740	3.75×10^{-2}	0.8604	37.78	75.56
flexible	11,520	8960	2560	5632	512	0.7778	1.48×10^{-2}	0.8888	2.70×10^{-2}	0.8980	38.89	77.78
rate	11,520	9216	2304	5376	768	0.8000	1.22×10^{-2}	0.9050	2.30×10^{-2}	0.9123	40.00	80.00
code	11,520	9472	2048	5120	1024	0.8222	9.62×10^{-3}	0.9217	1.90×10^{-2}	0.9270	41.11	82.22
family	11,520	9728	1792	4864	1280	0.8444	7.05×10^{-3}	0.9395	1.43×10^{-3}	0.9443	42.22	84.44
	11,520	9984	1536	4608	1536	0.8667	4.34×10^{-3}	0.9597	8.85×10^{-3}	0.9651	43.33	86.67
	11,520	10,240	1280	4352	1792	0.8889	1.85×10^{-3}	0.9805	4.25×10^{-3}	0.9831	44.44	88.89

N, codeword length; K, information length; M, parity length; S, shortening length; P, puncturing length; hBER, BER threshold for a hard-input FEC decoder; hNGMI, NGMI threshold corresponding to hBER; sNGMI, NGMI threshold for a soft-input FEC decoder; sBER, BER threshold in the AWGN channel for a soft-input FEC decoder; net 50G/100G, net (post-FEC) bitrate for 50 Gbit/s NRZ or non-PS 100 Gbit/s PAM-4.

[a]Maximum BER input level as per ITU-T Recommendation G.9804.2.

[b]Approximate maximum BER input level as per ITU-T Recommendation G.9804.2.

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… leading to the general idea of flexible PON physical layer

- All PON standards ratified so far are quite "unflexible"
  - Bit rate, modulation format, FEC are fixed
  - In contrast, the ODN parameters have a wide variability in practical PON installation
    - Fiber length (from 0 to 20 km)
    - Power budget variation: up to 20dB even inside a single PON tree
      - 15dB due to differential optical path loss (DOPL) + 5 dB of transmitted power range

- A large research is active on "adaptive" DSP strategies tailored on the actual parameters of each individual point-to-point link
  - Variable FEC type inside the same TDMA downstream frame
  - But also (… and here we really go into the "DSP realm")
    - Adaptive equalization at receiver
    - Adaptive pre-compensation at transmitter
    - Adaptive modulation formats + probabilistic or geometrical shaping

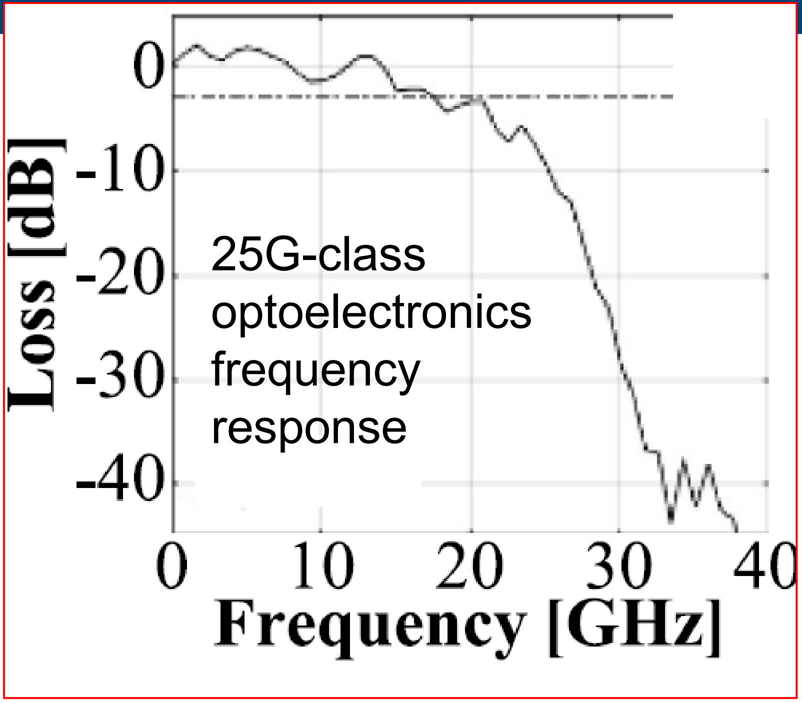
→ *Flexible-PON enabled by DSP new research trend*

A REVIEW ON RECEIVER EQUALIZATION IN PON

(MOSTLY FOR PAM-M)

Why equalization in high-speed PON?

- Starting from 50G-PON, <u>optoeletronic devices introduces severe bandwidth limitations</u>
  - In fact, for cost reasons 50G-PON will try to use 25G-class optoelectronics
  - Even more critical for future 100G-PON



- In IM-DD, also <u>chromatic dispersion</u> generates an equivalent low-pass effect (under reasonable approx. more on this later)

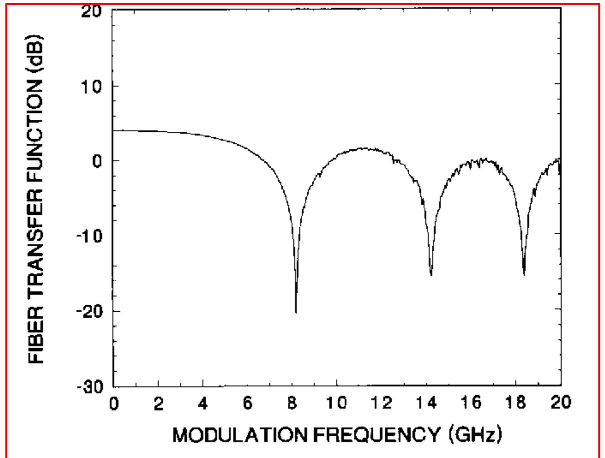
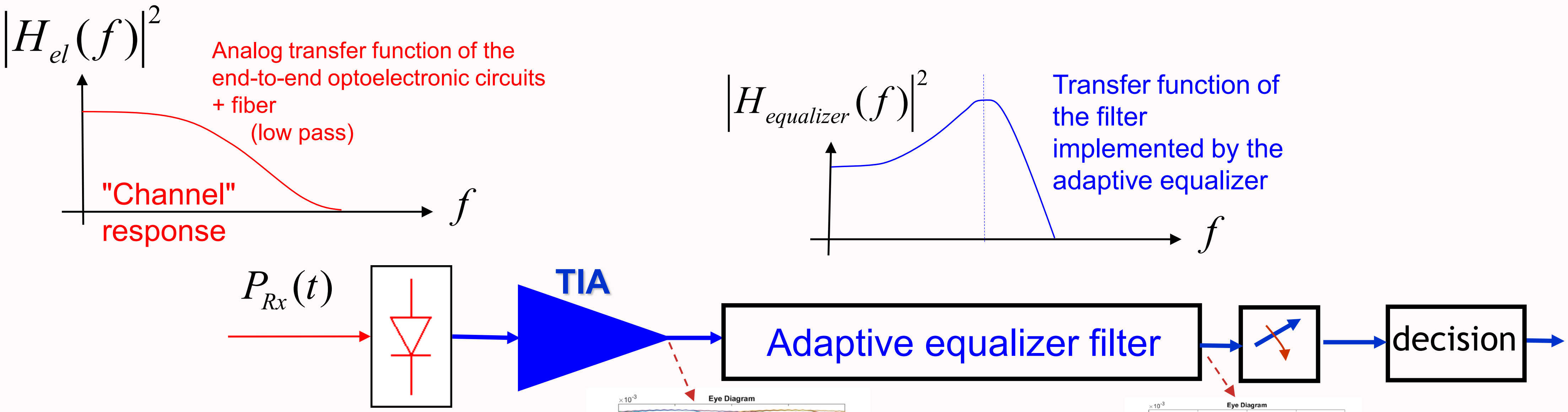


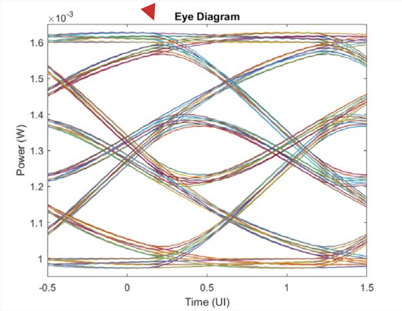
Fig. 1. Measured transfer function of a dispersive optical fiber using an

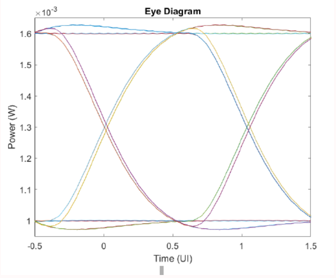
- The most common approach to "DSP-combat" the two effects in IM-DD **<u>is equalization at RX</u>**

Key principles of receiver (adaptive) equalization

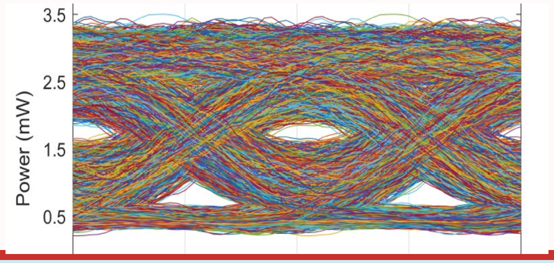


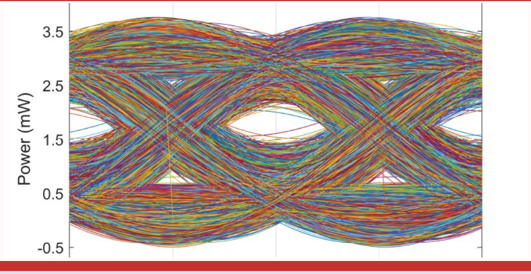
A bandlimited but noiseless example (simulations)



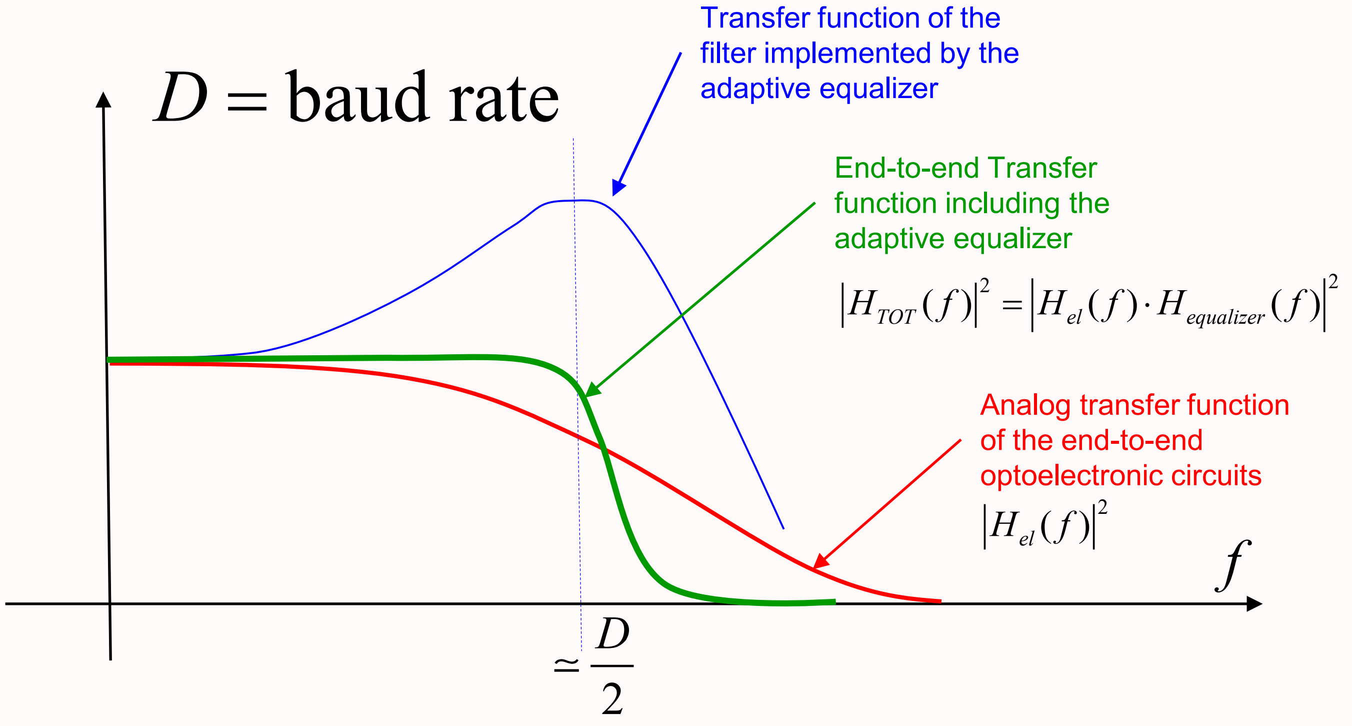


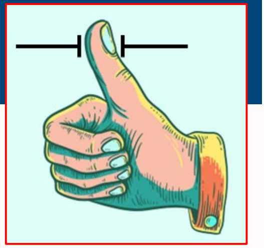
A bandlimited and noisy example (experiments)





The basic principle behind adaptive equalization





Take away message #2

Rule of Thumb on equalization:

The resulting end-to-end transfer function should be **flat up to at least *f=D/2***

- *Due to the Nyquist criterion for ISI*

Example: a 100Gbit/s PAM-4 system should be flat up to about 25 GHz after equalization

The channel drop in dB around *f=D/2* is thus a key parameter (it sets the equalizer noise enhancement)

- The equalizer filter should be optimized (by proper optimization algorithms) to find an optimum between:
  - Inter-symbol interference (ISI) reduction at equalizer output
  - Noise enhancement due to the high-pass nature of the equalizer filter

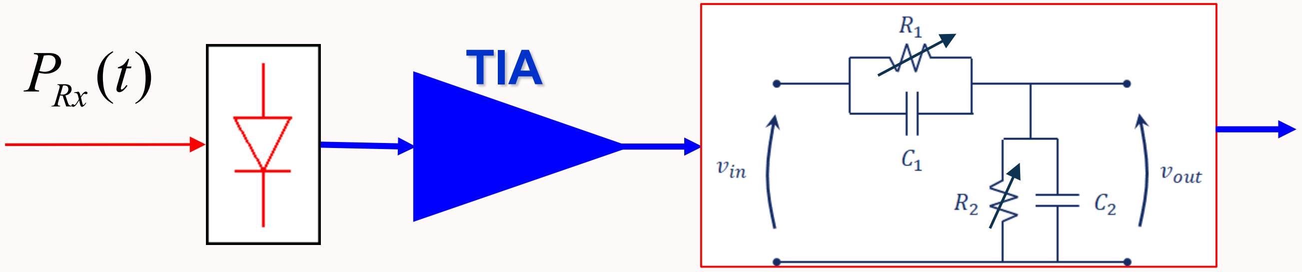
Receiver equalization implementation options

Review of equalization options:

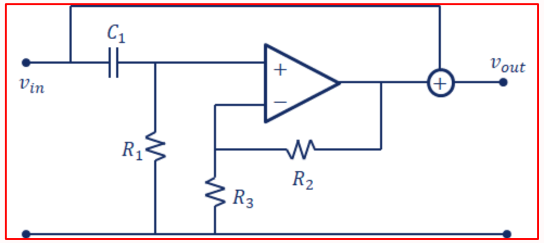
- Mainstream options
  - Analog Continuous Time Linear Equalizer (CTLE)
  - Feed-forward equalizer (FFE) using Finite Impulse Response (FIR) structures
  - Decision-Feedback equalizer (DFE)
- The "information theory" optimal option for a linear channel:
  - Maximum-Likehood Sequence Estimation (MLSE)
    - More advanced (and much more complex!) option
- More esoteric options
  - Neural-network based equalization
  - Volterra series based equalization

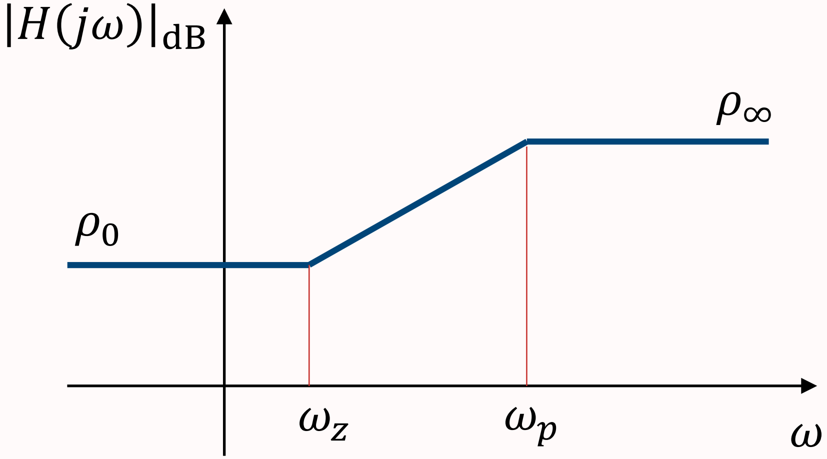
Analog Continuous Time Linear Equalizer (CTLE)

Analog filter with tunable parameters



Active filter implementation

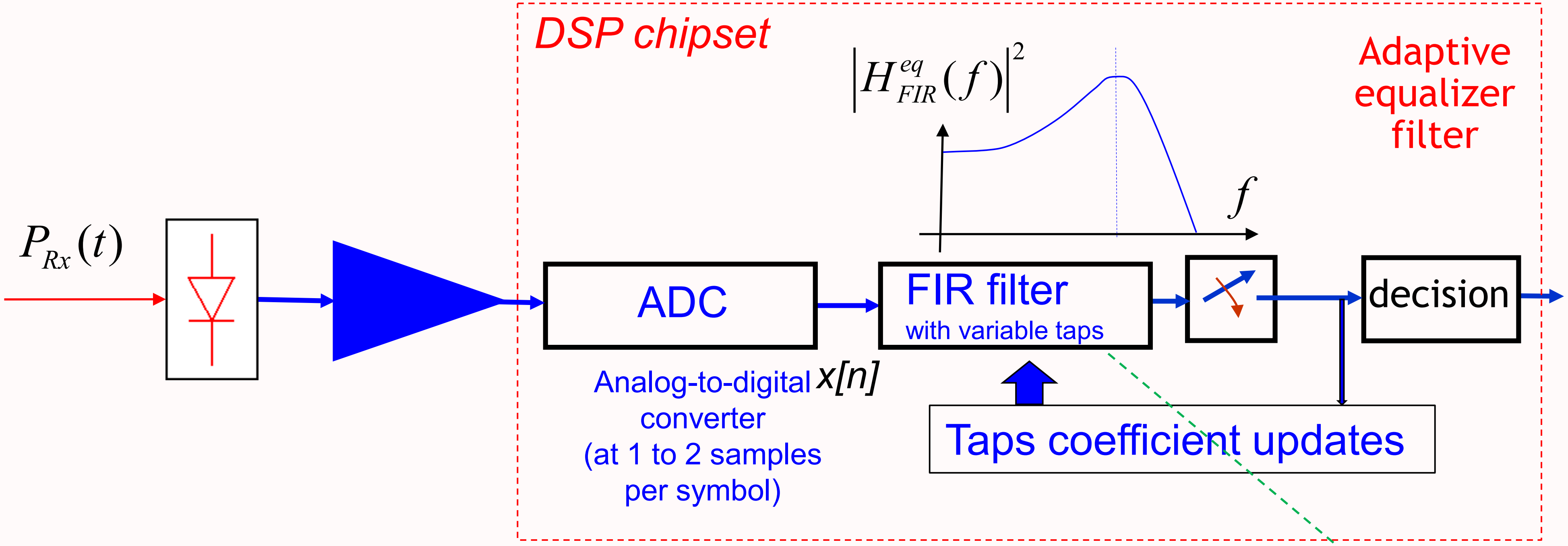




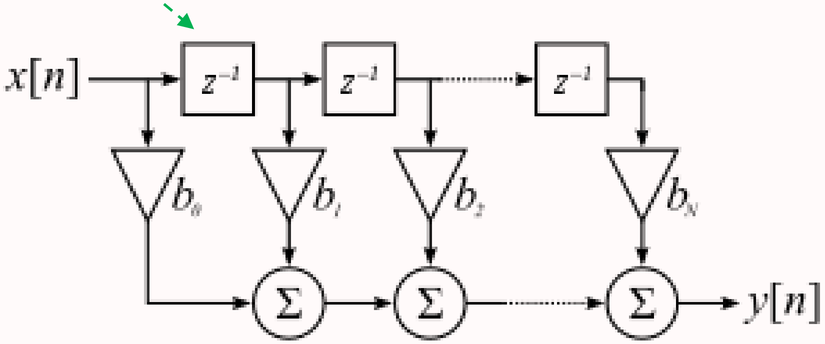
$$H(s) = \frac{R_2}{R_1 + R_2} \cdot \frac{1 + R_1 C_1 s}{1 + \frac{R_1 R_2}{R_1 + R_2}(C_1 + C_2)\, s} = \rho_0 \cdot \frac{1 + \frac{s}{\omega_z}}{1 + \frac{s}{\omega_p}} = \rho_\infty \cdot \frac{s + \omega_z}{s + \omega_p}$$

- **PROs** (compared to the following options)
  - Low complexity
  - Low power consumption
- **CONs**
  - Limited degrees of freedom in transfer function
    - Usually: frequency position of one zero and one pole on the transfer function
      - With constraints given by the use of analog components

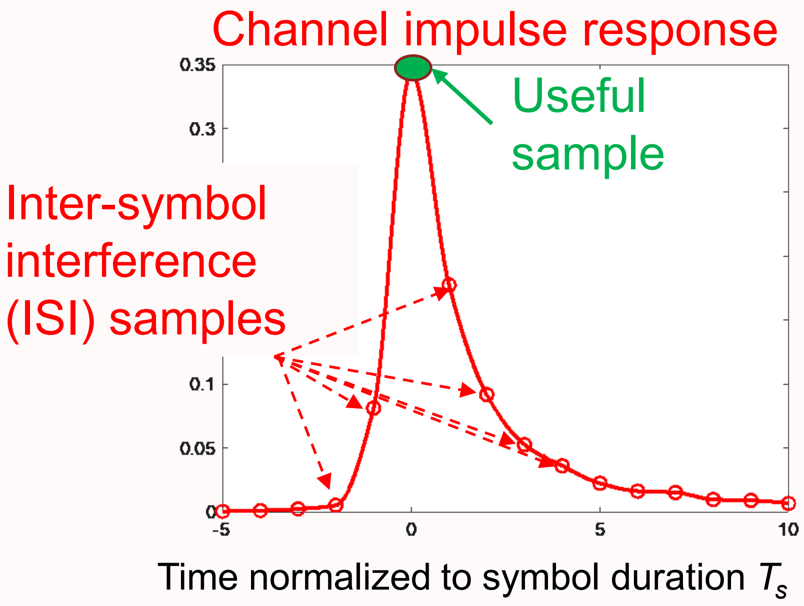
DSP-based Feed-forward Equalizer (FFE)

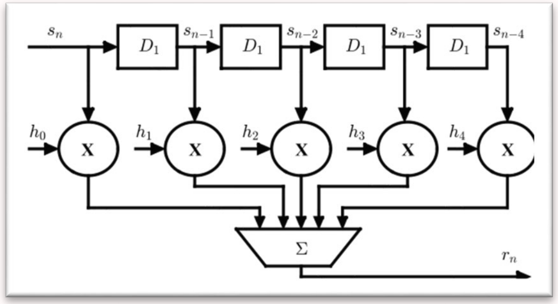


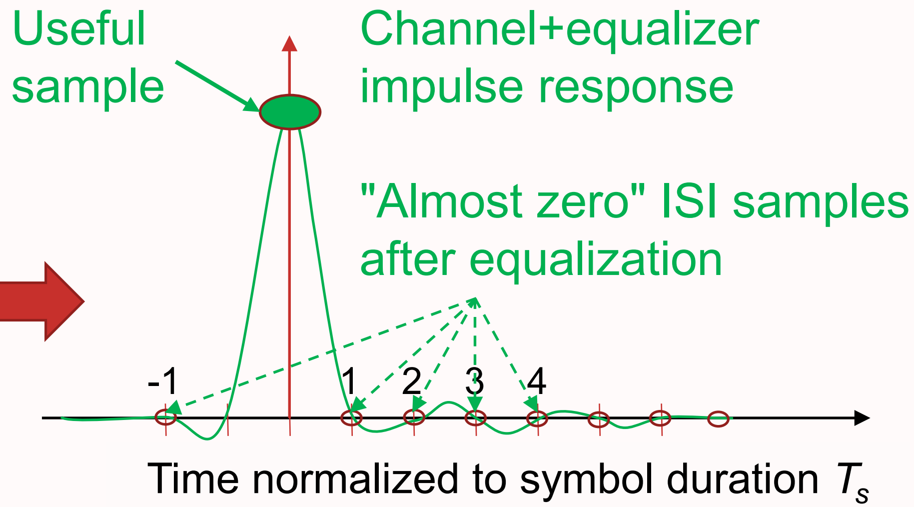
- *Why FIR filter structure?*
  - *Intrinsically stable*
  - *Extensive IP VHDL libraries available for parallel implementation enabling ultra-high speed implementation in ASIC*



Why it works?



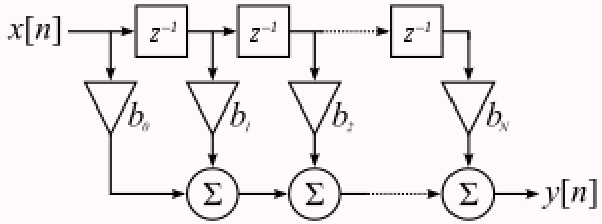




- Many variants available
  - T_s or T_s/2 spaced taps
  - <u>Taps optimization algorithms</u>
    1. Pre-computed (i.e. non adaptive)
    2. Adaptive for zero-forcing ISI
    3. Adaptive for minimum-mean square error (MMSE): minimization of the joint effect of ISI and noise on the useful output sample

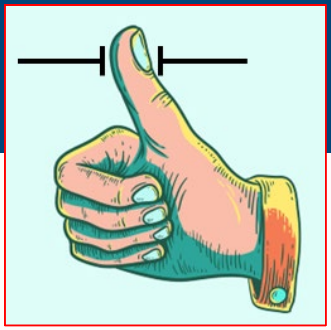
Feed-forward Equalizer (FFE)

- PROS
  - Usually much better performance than CTLE
  - A good compromise in terms of cost-complexity
    - (compare to the following more advanced options)
  - Widespread in all high-speed commercial optical receivers today
    - …including all commercial coherent-receivers



- CONS
  - Compared to CTLE… it requires ultra-fast ADC and DSP digital logic
  - Does not perform well around frequency nulls in the channel transfer function

FFE performances in IM-DD: rule of thumb



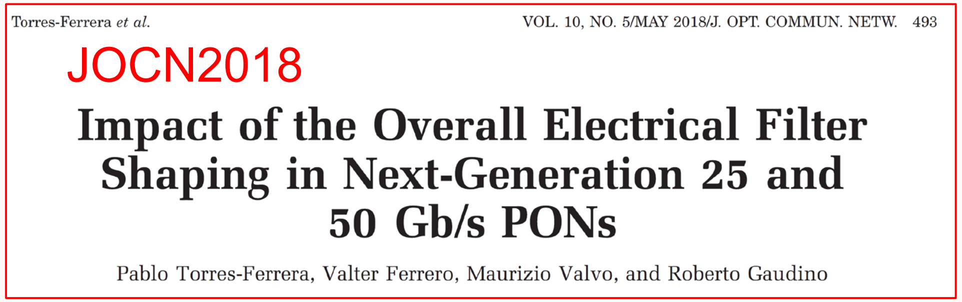
Take away message #3

- Focusing on IM-DD system, and for a given PAM-M modulation at baud rate *D*
  - No equalization is needed until the 3dB overall system bandwidth B_{3dB} is above 0.6·D
  - FFE is greatly effective for B_{3dB} in [0.3·D,0.6D]
  - For B_{3dB} <0.3·D power penalties starts to be huge
    - Due to the noise enhancement effect

Example for 50G-PON using PAM-2
D=bit rate= 50 Gbaud

FFE greatly helps for
→ B_{3dB} =[0.3·D,0.6D] = [15 GHz ,30 GHz]

- A more precise estimation can be done only by knowing
  1. The exact shape of the transfer function
  2. The number of taps of the equalizer
  3. The power penalty one can accept
  4. … and many other aspects (SNR level, BER reference, modulation formats, etc)


Torres-Ferrera *et al.* VOL. 10, NO. 5/MAY 2018/J. OPT. COMMUN. NETW. 493

JOCN2018

Impact of the Overall Electrical Filter Shaping in Next-Generation 25 and 50 Gb/s PONs

Pablo Torres-Ferrera, Valter Ferrero, Maurizio Valvo, and Roberto Gaudino

FFE performances in IM-DD: example

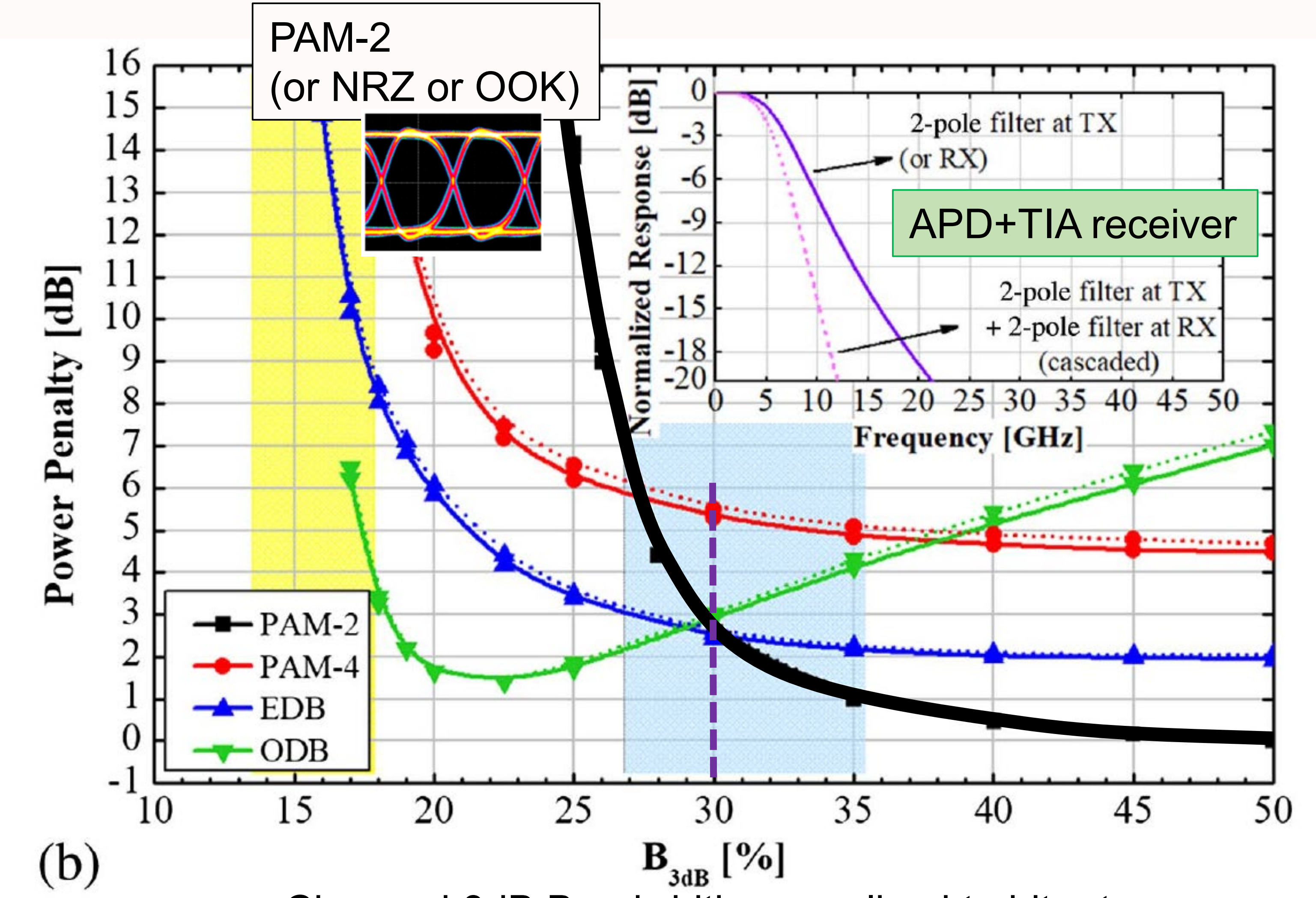
- Example taken from our paper, considering a two-pole transfer function for both TX and RX (with same f_{3dB})
  - Power penalties wrt. "unlimited bandwidth" case
- Let's start focusing on the black curve for PAM-2
  - 2.5dB penalty for B_{3dB}=0.3·D

Torres-Ferrera et al. VOL. 10, NO. 5/MAY 2018/J. OPT. COMMUN. NETW. 493

JOCN2018

Impact of the Overall Electrical Filter Shaping in Next-Generation 25 and 50 Gb/s PONs

Pablo Torres-Ferrera, Valter Ferrero, Maurizio Valvo, and Roberto Gaudino



Channed 3dB Bandwidth normalized to bit rate

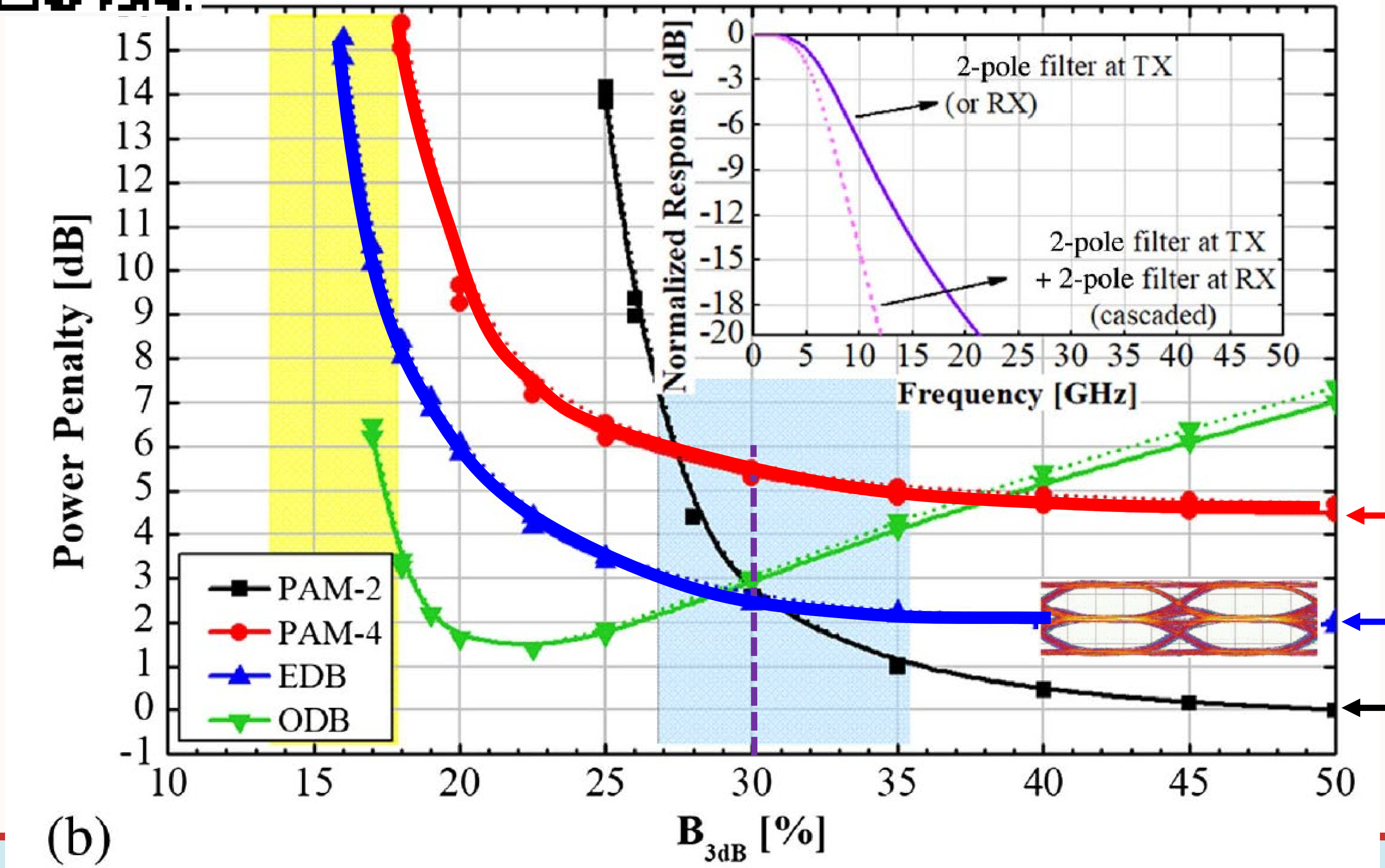
Torres-Ferrera et al. VOL. 10, NO. 5/MAY 2018/J. OPT. COMMUN. NETW. 493

JOCN2018

Impact of the Overall Electrical Filter Shaping in Next-Generation 25 and 50 Gb/s PONs

Pablo Torres-Ferrera, Valter Ferrero, Maurizio Valvo, and Roberto Gaudino

Other (simple) modulation formats

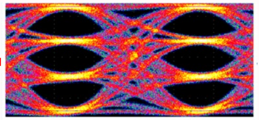


(b)

Bandwidth normalized to bit rate

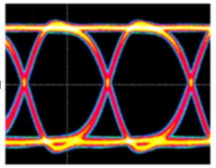
- PAM-4 and Electrical duobinary (EDB) have a strong "starting penalty"
- They "beat" PAM-2 only when:

B_{3dB} <0.3·bit_rate



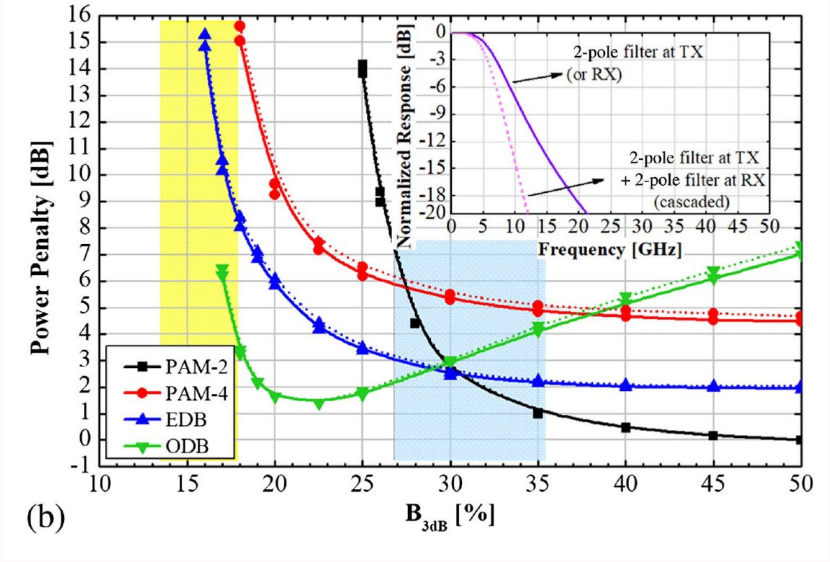
PAM-4

Electrical duobinary

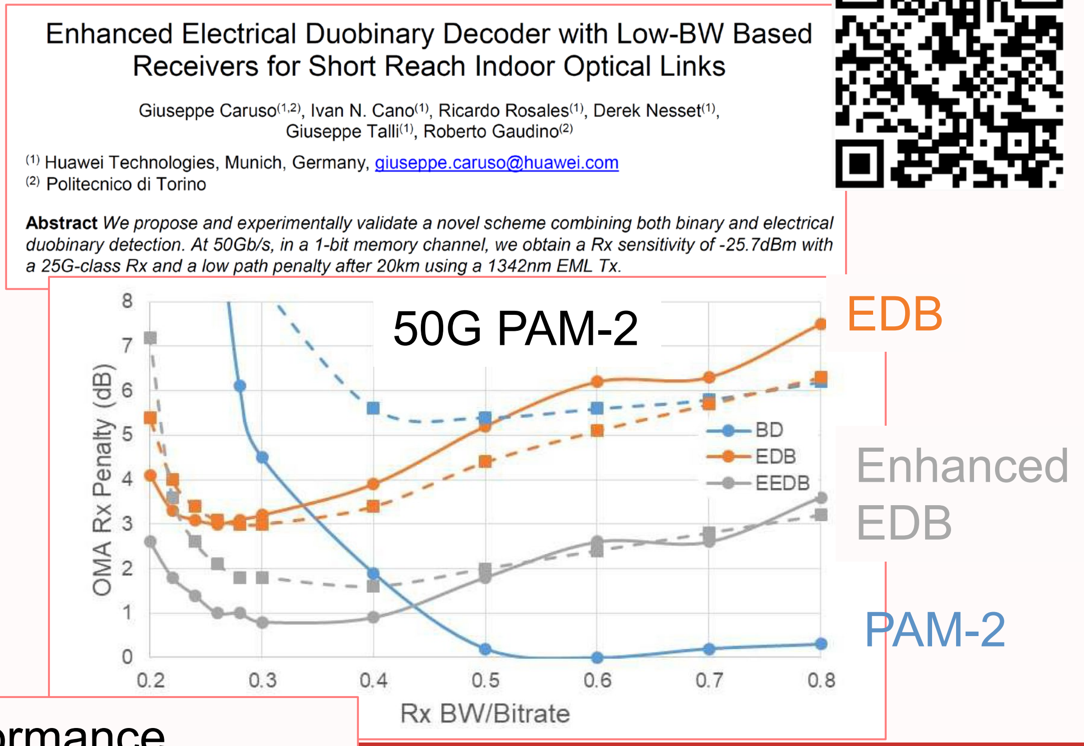


PAM-2 (or NRZ or OOK)

A very important caveat

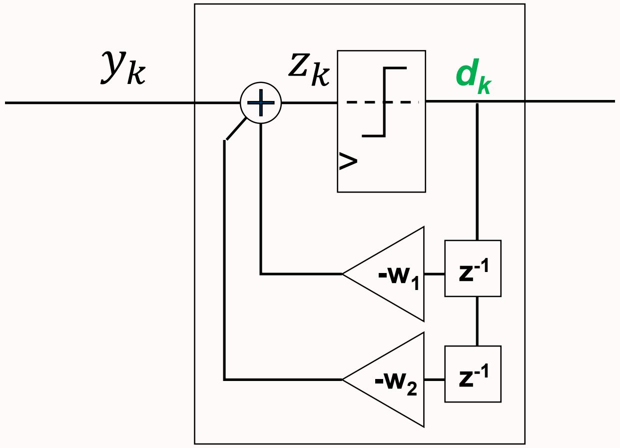


- In this tutorial, I tried to give general trends
- Anyway, "exact" performance results are strongly dependent on system details
  - For instance, sensitivity penalties have different slopes depending on the optical receiver type:
    - PIN+TIA
    - APD+TIA
    - SOA+PIN+TIA
- … and also on receiver implementations
  - Example: EDB was proposed in several possible implementations, each with different performance
    - And its pros and cons



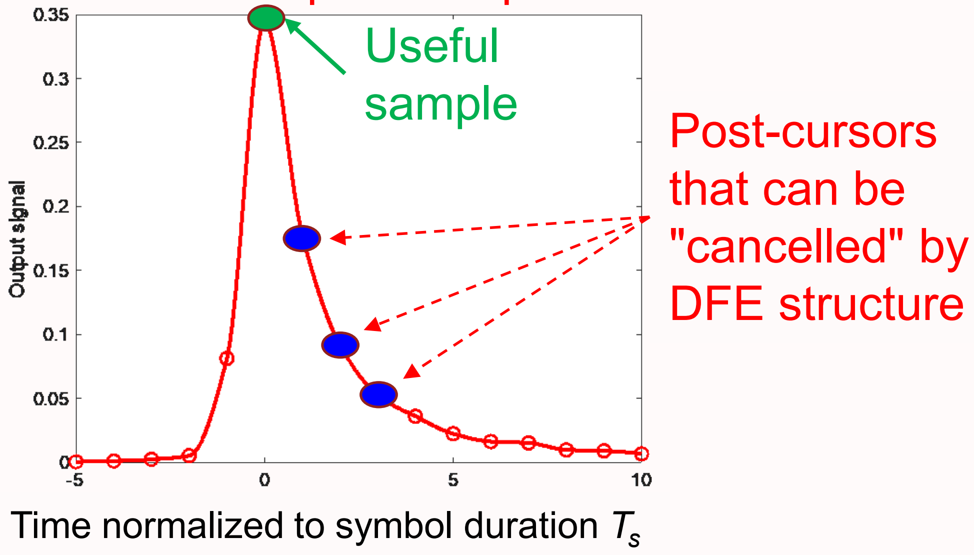
Performance WITHOUT FFE

Decision-feedback equalizers (DFE)



- DFE principle: For cancelling impulse response post-cursors, one can feedback "decided" symbols, again after multiplication by proper weights
  - Intrinsically noiseless samples in the ISI-reduction process (while they are noisy in FFE structures)

Channel impulse response

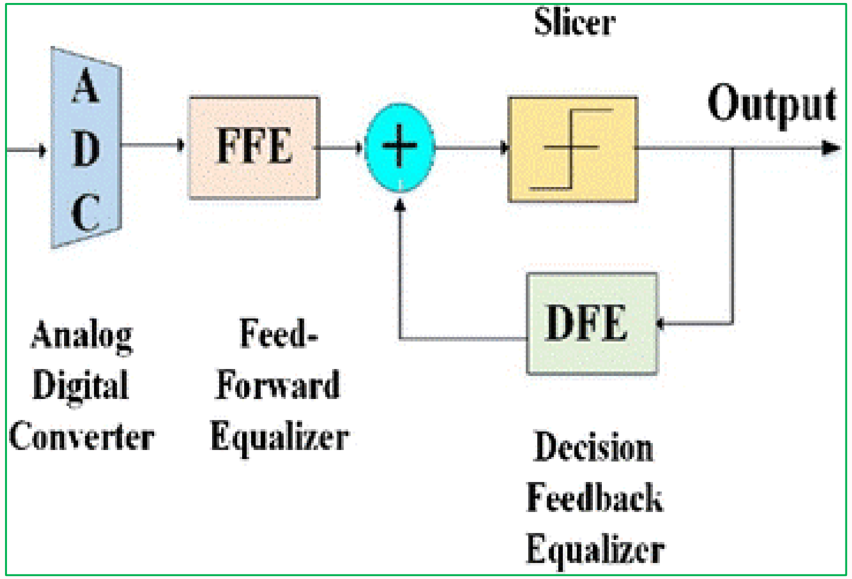


DFE can thus, under proper conditions, achieve better performance than FFE

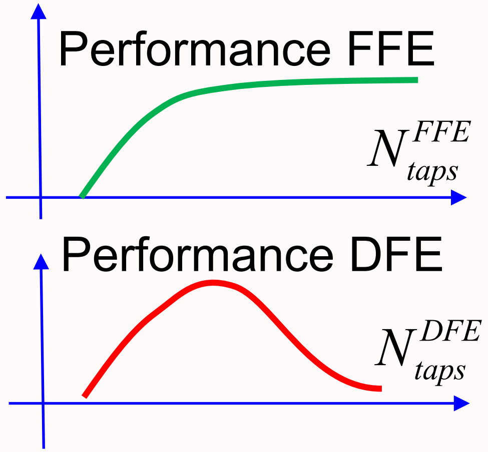
- CONS
  - The symbol "error propagation problem": the number of feedback taps should usually be very small
    - 4-5 taps at most
  - In high speed ASIC design, feedback loops has very tight timing constraints
    - Another reasons why number of taps must be small

Taking the best of both: FFE +DFE structures

- A T_s/2 spaced feed-forward filter with many taps
  - Followed by a DFE with few taps

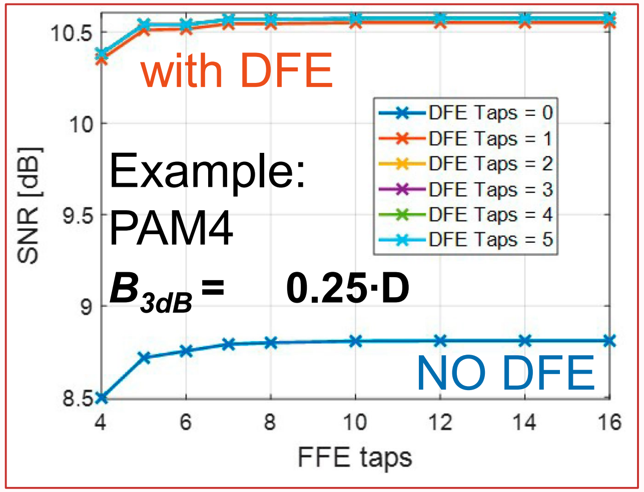


- Optimization of the number of taps
  - Performance usually monotonically increases with number of FFE taps
    - Saturating when number of taps is able to cover the full duration of channel impulse response
  - Due to error-propagation effect, DFE taps should on the contrary be properly optimized on a case by-case study



FFE+DFE Performances vs. number of taps

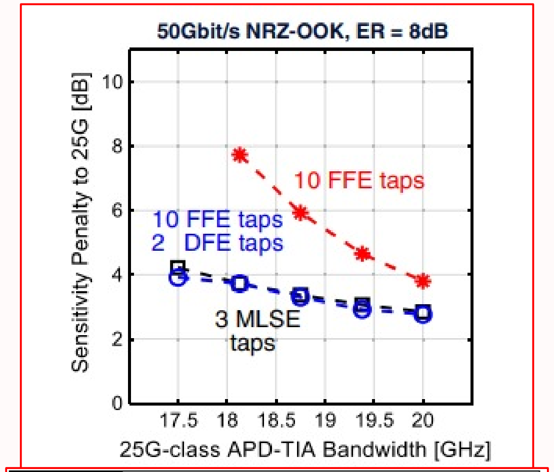
- Optimal number of taps greatly depends on the memory length and time-shape of the channel impulse response to be compensated
  - Here are some papers on equalizer optimization for 50- and 100-G PON



An Analytical Model for Performance Estimation in Modern High-Capacity IMDD Systems

Giuseppe Rizzelli, Pablo Torres-Ferrera, Fabrizio Forghieri, *Fellow, IEEE* and Roberto Gaudino, *Senior Member, IEEE*

https://arxiv.org/abs/2304.10834



Research Article Vol. 12, No. 9 / September 2020 / Journal of Optical Communications and Networking D17
JOURNAL OF Optical Communications and Networking

From 25 Gb/s to 50 Gb/s TDM PON: transceiver architectures, their performance, standardization aspects, and cost modeling

Ed Harstead,[1,*] Rene Bonk,[2] Sheldon Walklin,[3] Dora van Veen,[4] Vincent Houtsma,[4] Noriaki Kaneda,[4] Amitkumar Mahadevan,[4] and Robert Borkowski[2]
[1]Nokia Corporation, Fixed Networks Division, 600 Mountain Avenue, New Providence, New Jersey 07974, USA
[2]Nokia Bell Labs, Lorenzstrasse 10, 70435 Stuttgart, Germany
[3]Nokia, 600 March Road, Kanata, Ottawa K2K 2T6, Canada
[4]Nokia Bell Labs, 600 Mountain Avenue, New Providence, New Jersey 07974, USA
*Corresponding author: ed.harstead@nokia.com

Equalizer Configuration	Country A	Country B	Country C	Overall
	FLCS-PON Mean Net Bitrate [Gbits/s]			
FFE23 + DFE5	67.8–79.5	74.6–85.4	77.8–88.9	75.6–86.7
FFE16 + DFE1	63.6–77.2	71.7–84.7	75.6–88.9	73.0–86.3

C82 Vol. 14, No. 6 / June 2022 / Journal of Optical Communications and Networking Research Article
JOURNAL OF Optical Communications and Networking

FLCS-PON—an opportunistic 100 Gbit/s flexible PON prototype with probabilistic shaping and soft-input FEC: operator trial and ODN case studies

Robert Borkowski,[1,*] Yannick Lefevre,[2] Amitkumar Mahadevan,[3] Doutje van Veen,[3] Michael Straub,[1] Ralph Kaptur,[4] Björn Czerwinski,[4] Bruno Cornaglia,[5] Vincent Houtsma,[3] Werner Coomans,[2] René Bonk,[1] and Jochen Maes[2]
[1]Nokia Bell Labs, Magirusstrasse 8, 70469 Stuttgart, Germany
[2]Nokia Bell Labs, Copernicuslaan 50, 2018 Antwerp, Belgium
[3]Nokia Bell Labs, 600 Mountain Avenue, Murray Hill, New Jersey 07974, USA

PON standards and equalization

STANDARDS

- ITU-T has introduced the provision for equalization in G.9804 50G-PON
  - The actual implementation of receiver equalization structure is anyway completely open in the G.9804.3 Recommendation
  - The only explicit mention to equalization is in the "Transmitter and Dispersion Eye Closure" (**TDEC**, see next slide), that is anyway a TX specification
  - Moreover, no specification yet for upstream burst mode operation

Table 9-3 – FEC codes used for 50G-PON

Direction	Line rate	Type	Notation	BER reference level	FEC code [ITU-T G.9804.2]
Downstream	49.7664 Gbit/s	LDPC	LDPC (17280, 14592)	1E-2	Annex B.1.2
Upstream	49.7664 Gbit/s	FFS	FFS	FFS	FFS
	24.8832 Gbit/s	LDPC	LDPC (17280, 14592)	1E-2	Annex B.1.2
	12.4416 Gbit/s	LDPC	LDPC (17280, 14592)	1E-2	Annex B.1.2

50G upstream not defined yet

25G upstream: equalization is not needed

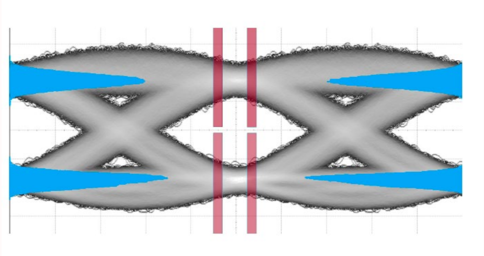
About TDEC (and TDECQ PAM-4)

STANDARDS

(TDEC and TDECQ share the same basic idea)

- TDEC defines the power penalty introduced by a given transmitter compared to an ideal (ISI-free) one when considering:
  - A reference channel
    - G.9804.3 50G-PON: 4th-order Bessel-Thomson, B_{3dB}=18.75 GHz
  - A given adaptive equalizer at the receiver
    - In 50G-PON, the reference is feed-forward equalizer (FFE) using 13 (symbol spaced) taps
  - A given target BER after equalization
    - 10^{-2} in 50G-PON

Launch power in OMA minus TDEC (min) (Note 5)	dBm	+4.75
Maximum transmitter and dispersion eye closure (TDEC) (Note 5)	dB	5



TDEC metric in 50G-PON: analytical and experimental investigation on several implementation aspects

MARIACRISTINA CASASCO[1,5], GIUSEPPE CARUSO[1,2,5], IVAN N. CANO[2], DEREK NESSET[3], MAURIZIO VALVO[4], VALTER FERRERO[1], AND ROBERTO GAUDINO[1]

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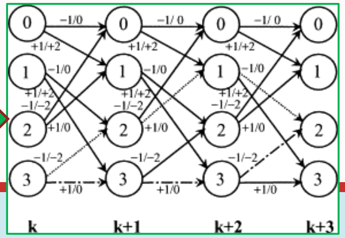
Interoperability and Experimental Evaluation of TDEC(Q) Testing for 50 and 100G PONs

Dora van Veen, Robert Borkowski, Amitkumar Mahadevan & Vincent Houtsma
Nokia, Bell-labs, 600 Mountain Avenue, Murray Hill, NJ 07974 USA
{dora.van_veen,vincent.houtsma}@nokia-bell-labs.com

Maximum Likehood Sequence Estimator (MLSE)

- The FFE+DFE structure is based on amplitude threshold decision on a <u>single sample at the output of the equalizer structure</u>
- Information theory demonstrated that one can do (at least theoretically) even better deciding observing a finite <u>sequence of received symbols</u>. This is the key idea behind <u>Maximum Likehood Sequence Estimator (MLSE) for PAM-*M*</u>
  - Assume that the channel has a memory of *L* symbols
  - Over this time frame, the received (noiseless) sequence has M^L possible realizations
  - The optimal receiver should compare the received noisy signal with these M^L possible sequences
    - and decide for the one at minimum Euclidean distance
- On a linear channel + Gaussian noise, MLSE is the theoretically optimal solution
- MLSE has unfortunately a very high complexity (even using the famous Viterbi algorithm)
  - Mixed solutions are possible: channel shortening FIR + short memory MLSE

FIR for channel shortening



BURST MODE

ADAPTIVE EQUALIZATION FOR UPSTREAM PON

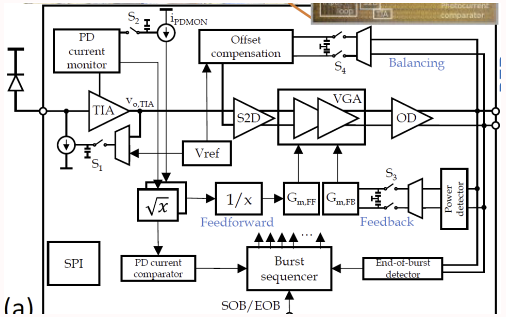
Burst mode equalization for upstream detection

- The 50G G.9804.3 Recommendation has for the moment specified 25G only for the upstream (50G is for further study)
  - Thus, upstream equalization is NOT needed
- Anyway, when and if needed, equalization in the upstream must be TDMA burst mode compliant
  - This requirement opens a very interesting research area, for which there is already a vast literature
  - A first non trivial key requirement is that the burst-mode receiver electronic must be designed to be **linear** over the required huge receiver dynamic range (about 20 dB!)

Linear Burst-Mode Receivers for DSP-Enabled Passive Optical Networks

OFC 2021 © OSA 2021

Xin Yin, Gertjan Coudyzer, Peter Ossieur, Laurens Breyne, Borre Van Lombergen and Johan Bauwelinck
IDLab, Ghent University-imec, 9052 Ghent, Belgium
Author e-mail address: xin.yin@ugent.be



Burst mode equalization research trends

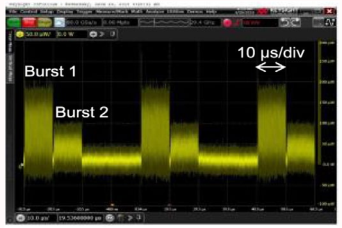
- For burst mode in TDMA upstream PON, (at least) two other key problem pops up:

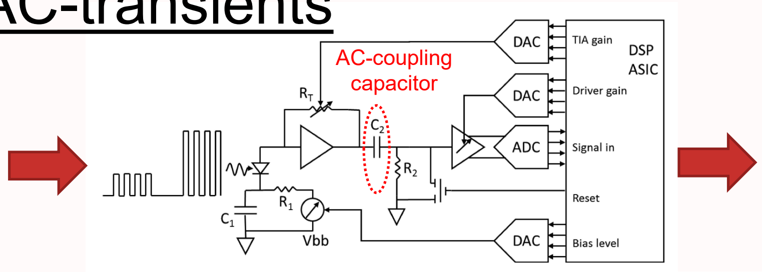
JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 38, NO. 4, FEBRUARY 15, 2020

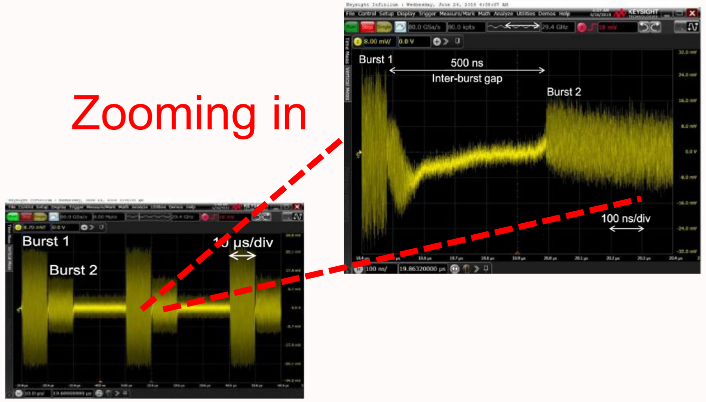
Burst-Mode Error Distribution and Mitigation in DSP-Assisted High-Speed PONs

Frank J. Effenberger, *Fellow, IEEE, Fellow, OSA*, Huaiyu Zeng, *Member, IEEE*, Andy Shen, *Member, IEEE*, and Xiang Liu, *Fellow, IEEE, Fellow, OSA*

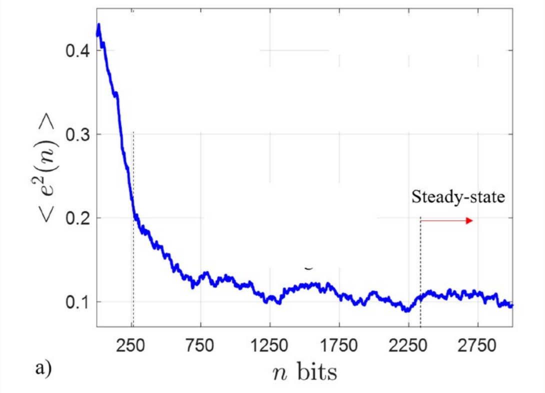
  - A linear high-speed receive is usually AC-coupled, creating a difficult situation for <u>soft-loud packet equalization due to AC-transients</u>







  - The convergence speed of the taps training phase should be as fast as possible (and definitely below 1000 symbols)



Speeding up taps adaptation

Several tricks have been proposed in the literature

- "gear-shifted" LMS: FFE and DFE μ–coefficients are step-wise decreased over time during the "convergence preamble" inside the burst
- Recursive least-square (RLS) FFE-taps adaptation
  - A variant of the taps-adaptation that allows faster convergence (but greater complexity)
- PON specific: use knowledge of the taps from the previous bursts coming from the same ONU

A104 Vol. 12, No. 1 / January 2020 / Journal of Optical Communications and Networking Research Article

JOURNAL OF Optical Communications and Networking

Study of burst-mode adaptive equalization for >25G PON applications [Invited]

Gertjan Coudyzer,[1,*] Peter Ossieur,[1] Laurens Breyne,[1] Antonio La Porta,[2] Stephan Paredes,[2] Johan Bauwelinck,[1] and Xin Yin[1]

[1]Ghent University–imec–IDLab, Department of Information Technology, Ghent, Belgium
[2]IBM Research–Zurich, Rüschlikon, Switzerland

$$w_i[k+1] = w_i[k] + \mu_{\mathrm{FFE}} e[k] r(t_0 + kT - iT/2),$$

$$v_i[k+1] = v_i[k] + \mu_{\mathrm{DFE}} e[k] q[k-i].$$

Assessment of Training Patterns Performances in the context of Burst Mode equalization for 50G-PON

ECOC2023

Gaël Simon[(1)], Fabienne Saliou[(1)], Jérémy Potet[(1)], Dylan Chevalier[(1)], Georges Gaillard[(1)], Philippe Chanclou[(1)]

[(1)] Orange, 2 avenue Pierre Marzin, 22307 LANNION, France, gaelsimon@orange.com

Tab. 1: Summary of convergence duration, Ceq (noise enhancement factor) and TDEC, depending on the preamble.

Preamble:	PRBS31	Bruijn128	Bruijn256	0xBB52	0xAAAA	SSPR
Convergence (bits)	574	538	561	674	37	586
Ceq (dB)	3.0	3.1	3.0	2.1	1.2	2.8
TDEC (dB)	3.46	3.56	3.41	3.30	>7.0	3.56

Burst-mode Equalization Strategies in 25 Gbps US-PON using Duobinary and 10G-class APD for 20-km in C-band

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P. Torres-Ferrera[1], V. Milite[1], V. Ferrero[1], M. Valvo[2], R. Mercinelli[2], R. Gaudino[1]

[1]Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino (TO), Italy, pablo.torres@polito.it
[2]Telecom Italia (TIM), Via Reiss Romoli 274, 10148 Torino (TO

608 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 38, NO. 3, FEBRUARY 1, 2020

Optimization of Band-Limited DSP-Aided 25 and 50 Gb/s PON Using 10G-Class DML and APD

Pablo Torres-Ferrera, Haoyi Wang, Valter Ferrero, *Senior Member, IEEE*, Maurizio Valvo, and Roberto Gaudino, *Senior Member, IEEE*

Speeding up taps adaptation

Burst-mode Equalization Strategies in 25 Gbps US-PON using Duobinary and 10G-class APD for 20-km in C-band

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P. Torres-Ferrera[1], V. Milite[1], V. Ferrero[1], M. Valvo[2], R. Mercinelli[2], R. Gaudino[1]
[1]Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino (TO), Italy, pablo.torres@polito.it
[2]Telecom Italia (TIM), Via Reiss Romoli 274, 10148 Torino (TO

608 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 38, NO. 3, FEBRUARY 1, 2020

Optimization of Band-Limited DSP-Aided 25 and 50 Gb/s PON Using 10G-Class DML and APD

Pablo Torres-Ferrera, Haoyi Wang, Valter Ferrero, *Senior Member, IEEE*, Maurizio Valvo, and Roberto Gaudino, *Senior Member, IEEE*

- We experimentally demonstrated that using previous burst taps as the "initial guess" for taps adaptation in the following burst (from same ONU) is very effective
  - We show convergence in less than 300 bits
- The actual implementation would anyway require significant changes in the current PON physical layer standard
  - The equalizer should "know" from which ONU is currently receiving to retrieve the stored previous taps
  - … which is an information that is available today only by the higher protocol layers

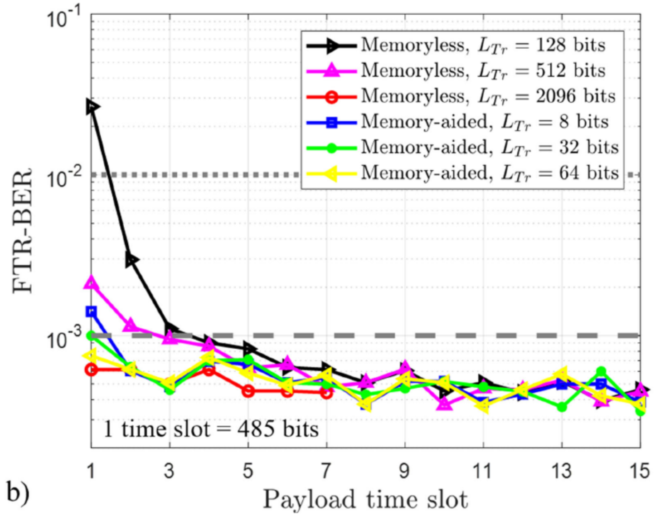


Fig. 10. (a) Error square evolution over time for a given L_{Tr}. (b) FTR-BER over each of the 385-bits time slots for memory-aided and memoryless BM-AE approaches with different training length L_{Tr}. ODN loss = 28.7 dB.

CHROMATIC DISPERSION AND EQUALIZATION

Chromatic Dispersion and PON

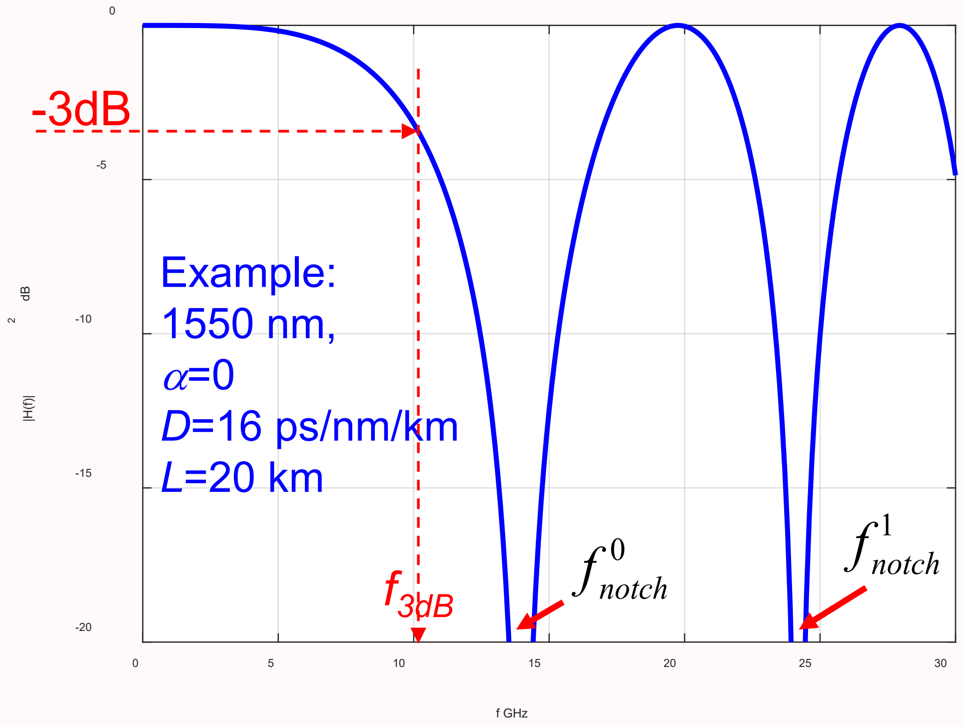
- Given the typical 20km target distance, Chromatic Dispersion (CD) was NOT a problem up to XGS-PON (10Gbps)

- Starting from IEEE 25G-PON and ITU-T 50G-PON, CD became anyway a major issue
  - In fact, these higher speed PON standards had to be specified using both upstream and downstream in O-Band (in specific bands around 1300 nm)
  - For 100G-PON, CD will be critical even at the "borders" of O-Band

- Does adaptive equalization helps?
  - Yes, but to a limited extent

A quick review on CD impact on IM-DD

- Reminder: CD is a linear effect on the optical field
  - So that (rigorously) it is a nonlinear effect in terms of instantaneous power,
    - i.e. on the photo-detected signal



- Anyway, it is well know that a CD "small-signal" linear approximation is possible for IM-DD

Small signal analysis for dispersive optical fiber communication systems
J. Wang; K. Petermann
Journal of Lightwave Technology
Year: 1992 | Volume: 10, Issue: 1 | Journal Article | Publisher: IEEE

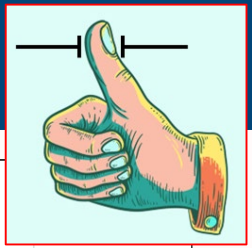
!!!

$$f_{notch}^{i} = \sqrt{\frac{c}{2\left|D \cdot L\right|\lambda^2}\left(1 + 2i - \frac{2}{\pi} sign(D) \cdot \arctan(\alpha)\right)}$$

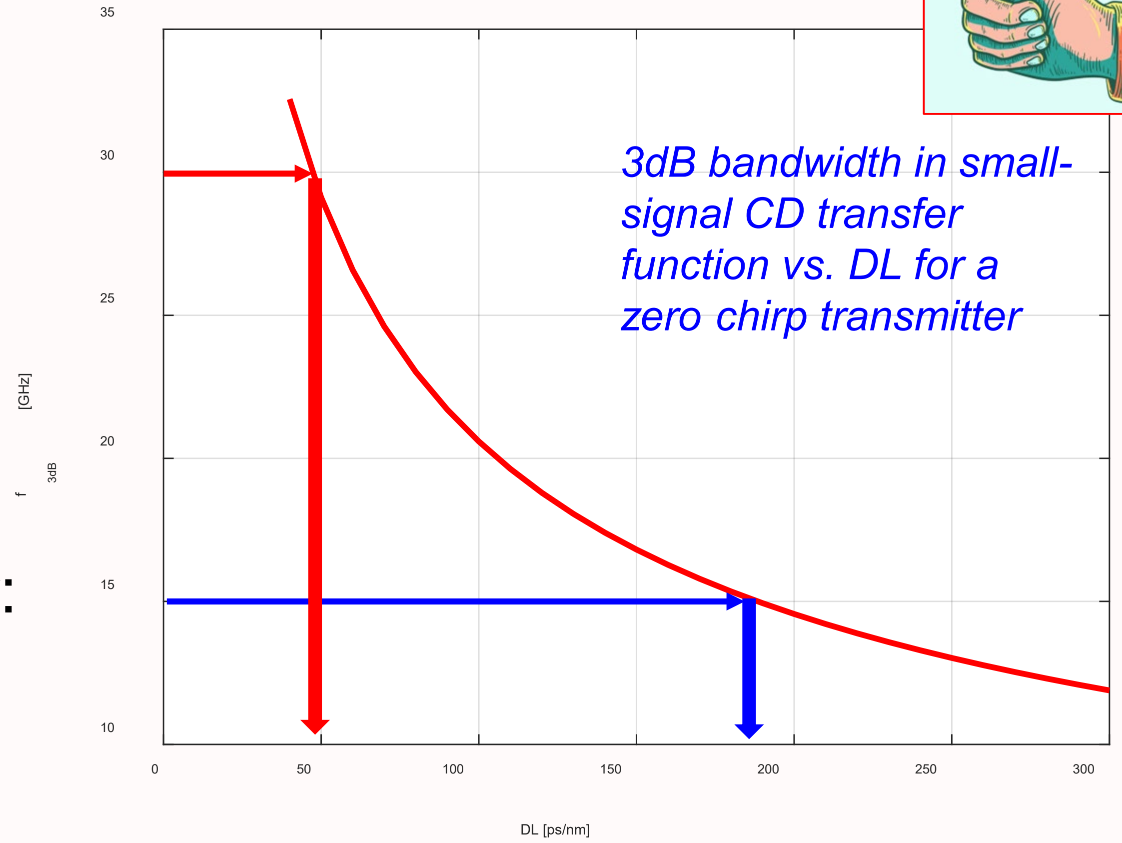
Fiber Dispersion parameter D — Fiber Length L — Modulator chirp α

The "small signal" concept in this approximation practically means a PAM-M outer extinction ratio below a given value (about 5dB in our evaluations)

A rule of thumb on FFE + CD



- Let's assume that the only limiting factor is CD, so that the resulting 3dB bandwidth is given by the figure vs. accumulated dispersion *DL*



We remind the previous "rule of thumb":

using FFE, <u>power penalty starts to be huge</u> for:

$$\boldsymbol{B_{3dB}^{crit}} < 0.3 \cdot \text{baud\_rate}$$

- Thus for 50G-PON PAM-2 $B_{3dB}^{crit} \cong 15GHz$
  - $DL_{max} \approx$ 180 ps/nm
- And for 100G-PON PAM-2 $B_{3dB}^{crit} \cong 30GHz$
  - $DL_{max} \approx$ 50 ps/nm

Situation in which the systems would have a <u>very large penalty due to CD alone</u>.
In fact, ITU-T G.9804.3 50G-PON specifies 77ps/km

… and again, more precise results depends on many system assumptions

518 Vol. 15, No. 8 / August 2023 / Journal of Optical Communications and Networking **Research Article**

JOURNAL OF Optical Communications and Networking

Perspectives on and the road towards 100 Gb/s TDM PON with intensity-modulation and direct-detection

Rene Bonk,[1] Ed Harstead,[2,*] Robert Borkowski,[3] Vincent Houtsma,[3] Yannick Lefevre,[4] Amitkumar Mahadevan,[3] Dora van Veen,[3] Michiel Verplaetse,[4] and Sheldon Walklin[5]

[1]Nokia Bell Labs, Magirusstraße 8, 70469 Stuttgart, Germany
[2]Nokia, Fixed Networks Division, 600 Mountain Ave., Murray Hill, New Jersey 07974, USA
[3]Nokia Bell Labs, 600 Mountain Ave., Murray Hill, New Jersey 07974, USA
[4]Nokia Bell Labs, Copernicuslaan 50, 2018 Antwerp, Belgium
[5]Nokia, Fixed Networks Division, 600 March Rd, Kanata, Ontario K2K 2T6, Canada
*Ed.Harstead@nokia.com

Assumption behind this graph:
- zero dispersion wavelength at 1330 nm
- 100G-PON NRZ

For zero chirp, max. wavelength is about 1333 nm

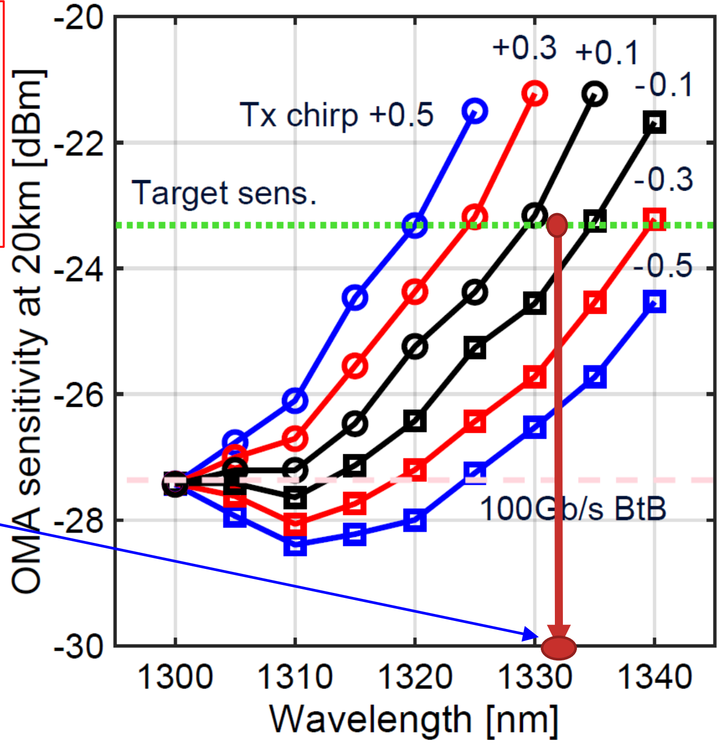
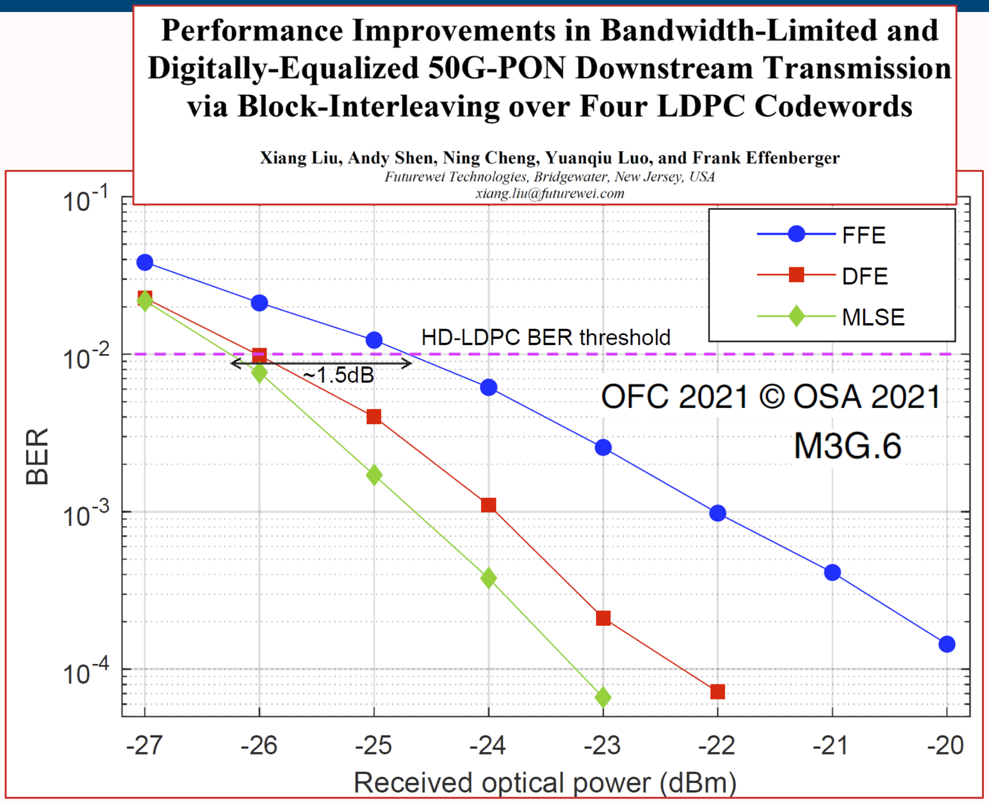


Fig. 6. Impact of OLT transmitter chirp and wavelength on 100 Gb/s PAM2 ONU receiver sensitivity, at 20 km.

Assuming a dispersion slope *S*=0.089 ps/nm^2/km, then at 1333 nm we have *D*=2.9 ps/nm/km and *DL*=58 ps/km
… not so far from the "dispersion rule of thumb" of the previous slide

CD and "standard" equalizers (FFE, DFE, MLSE)

- The first "lobe" of the CD small signal transfer function is a typical low-pass transfer function, with a deep frequency notch
  - FFE affected by strong noise enhancement around frequency notches
  - DFE and MLSE improve performances
- These three equalizers are "natively born" for linear channels



- But… the CD linear transfer function on IMDD is only a small signal approximation!
  - Specifically, it holds true only up to a given extinction ratio (ER)

This observation is the rationale for a huge amount of scientific papers on more complex nonlinear equalizers and modulation formats

NUMERICAL MODELLING
POWER BUDGET, REACH, CAPACITY FOR IM-DD PON USING FFE OR FFE+DFE EQUALIZATION

Theoretical model for IM-DD prediction

- The prediction of IM-DD performance with ISI and noise AND without equalization usually requires numerical time-domain simulations
- Anyway, we recently showed that when FFE or FFE+DFE equalizers are used at the receiver, a completely analytical performance estimation is possible with good accuracy
  - Assuming linear transmitters
  - … and "sufficiently long" equalizers

$$SNR(f) = \frac{5}{36} \cdot \frac{T \cdot (OMA_{TX}^{outer})^2 \cdot |H_T(f)|^2 \cdot |H_{ch}(f)|^2}{PSD_{noise}(f)} \quad (7)$$

$$SNR_{FFE} = \frac{1}{T \cdot \int_{-\frac{1}{2T}}^{\frac{1}{2T}} \frac{1}{\overline{SNR}(f)+1} df} - 1$$

$$SNR_{DFE} = e^{T \cdot \int_{-\frac{1}{2T}}^{\frac{1}{2T}} log[\overline{SNR}(f)+1] df} - 1$$

$$\overline{SNR}(f) = \sum_{\mu} SNR(f - \frac{\mu}{T})$$

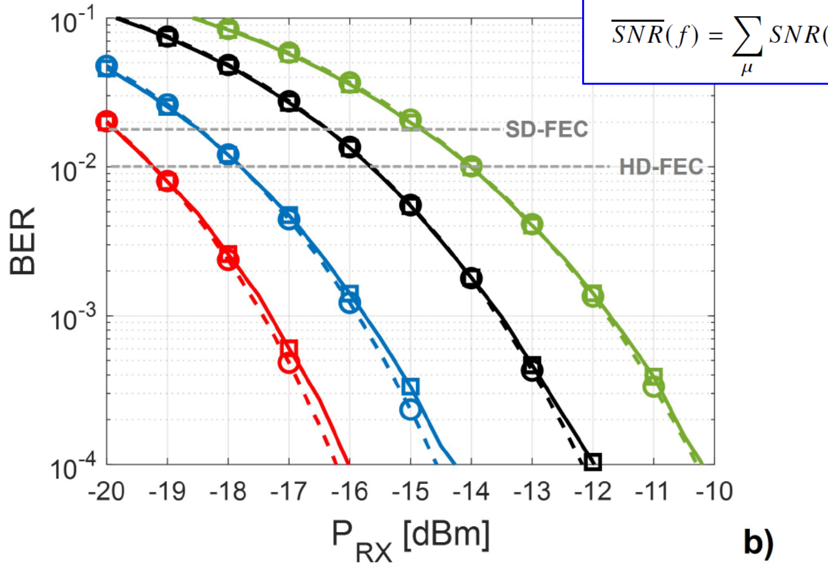


Fig. 8. a) SNR and b) corresponding BER obtained through time domain simulations (solid, squares) and through the proposed analytical model (dashed, circles) as a function of the received optical power using 50 GBaud 4-PAM (i.e. 100 Gbps) with FFE equalization in back-to-back (black, green) and with 25 km SMF in O-band (red, blue). Transmitted power is 11 dBm, ER is 3 dB (black, red) or 6 dB (green, blue). Legend in a) applies to b) as well.

An Analytical Model for Performance Estimation in High-Capacity IMDD Systems

Giuseppe Rizzelli, Pablo Torres-Ferrera, Fabrizio Forghieri, *Fellow, IEEE* and Roberto Gaudino, *Senior Member, IEEE*

https://arxiv.org/abs/2304.10834

Submitted on 21 Apr 2023

NEW TRENDS ON ADAPTIVE TRANSMISSION:

PROBABILISTIC OR GEOMETRICAL SHAPING

Adapting the TX format to the specific ONU

ECOC 2020

50Gb/s TDM PON Digital Signal Processing Challenges: Mining current G-PON Field Data to Assist Higher Speed PON

Gaël SIMON[1], Fabienne SALIOU[1], Philippe CHANCLOU[1], Luiz ANET NETO[1], Hamza HALLAK ELWAN[1]
[1] Orange Labs, 2 avenue Pierre Marzin - 22300 LANNION - France, gael.simon@orange.com

- Available power budget on PON has a large variation even inside the same PON tree
  - See papers on the left, with data coming from deployed fibers
  - Same for chromatic dispersion, since also fiber length is spread from 0 to more than 20km

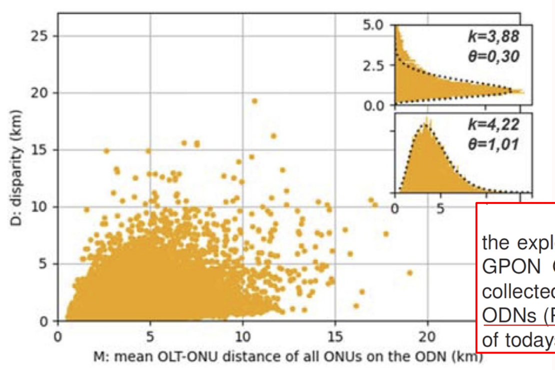


Fig. 5: ODNs characteristics (ONUs per ODN ≥ 48)

In our case, the exploited data are extracted from 3.3 million GPON ONUS from all over France. Data are collected from 3500 OLTs, connecting 123 000 ODNs (PON trees). It represents more than 95% of todays Orange's subscribers in France.

- Flexible-PON idea: optimizing on a "per-ONU" characteristics
  - Adaptive equalization
  - Adaptive FEC
  - but also: probabilistic shaping on PAM-4 to further "tailor" the resulting rate

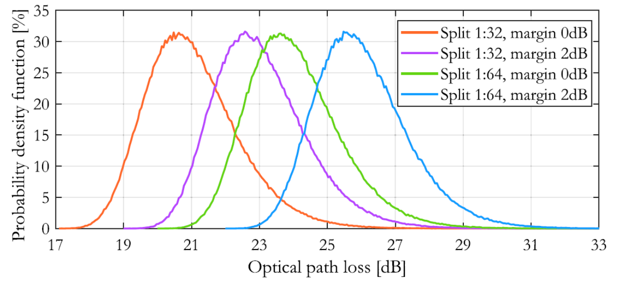


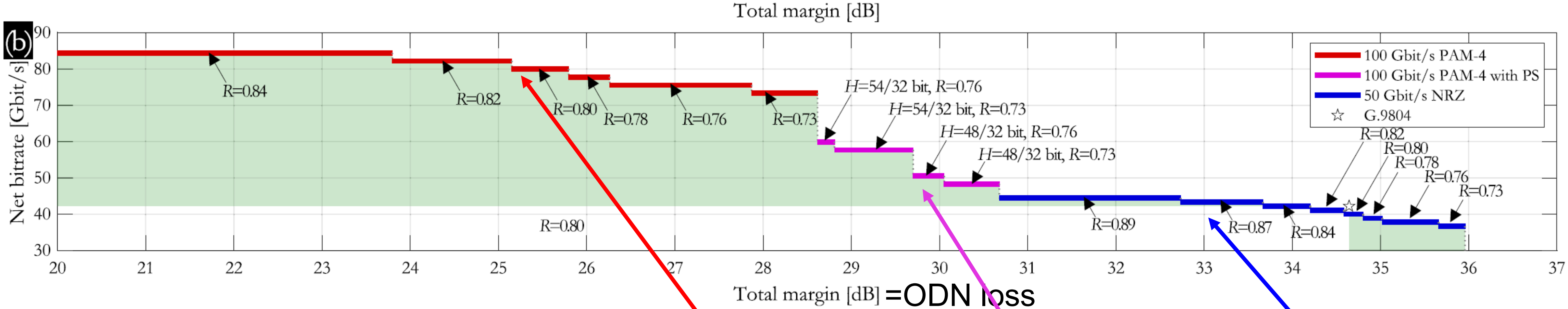
Fig. 9. Case study: synthetic ODNs. ODN distributions generated using the model in [24 … losses.

C82 Vol. 14, No. 6 / June 2022 / Journal of Optical Communications and Networking Research Article
JOURNAL OF Optical Communications and Networking

FLCS-PON—an opportunistic 100 Gbit/s flexible PON prototype with probabilistic shaping and soft-input FEC: operator trial and ODN case studies

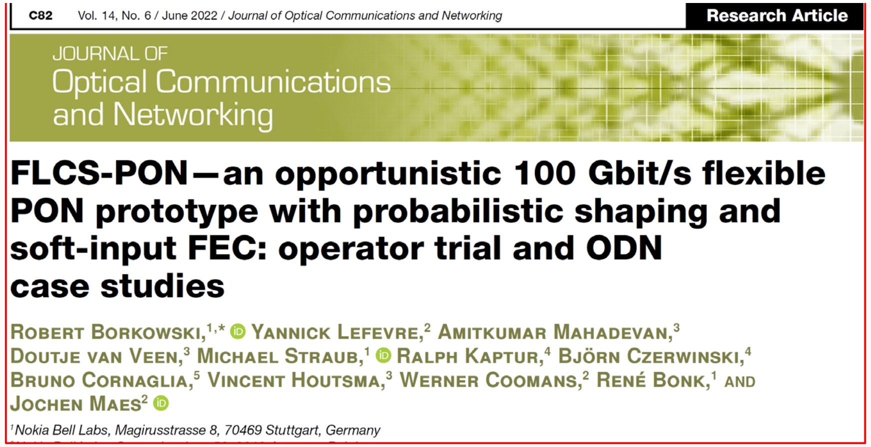
Robert Borkowski,[1,*] Yannick Lefevre,[2] Amitkumar Mahadevan,[3] Doutje van Veen,[3] Michael Straub,[1] Ralph Kaptur,[4] Björn Czerwinski,[4] Bruno Cornaglia,[5] Vincent Houtsma,[3] Werner Coomans,[2] René Bonk,[1] and Jochen Maes[2]
[1] Nokia Bell Labs, Magirusstrasse 8, 70469 Stuttgart, Germany

An example of flexible modulation + variable FEC



=ODN loss

Fig. 6. Experimentally measured FLCS-PON operating envelope for soft-input FEC, including PS variants, showing the highest achievable net bitrate as a function of OPL and MCP. Color coding indicates line rate and presence of PS. Regions that are supported with FLCS-PON but otherwise unsupported with G.9804 are colored green.



C82 Vol. 14, No. 6 / June 2022 / Journal of Optical Communications and Networking Research Article
JOURNAL OF Optical Communications and Networking

FLCS-PON—an opportunistic 100 Gbit/s flexible PON prototype with probabilistic shaping and soft-input FEC: operator trial and ODN case studies

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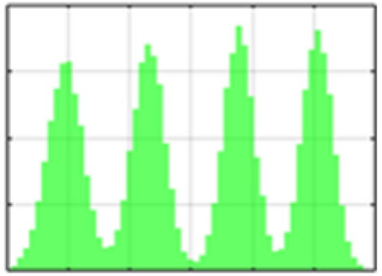
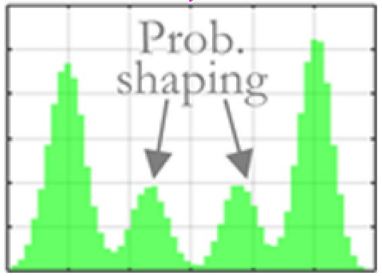
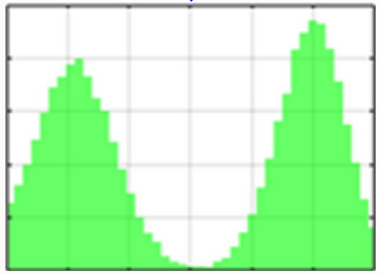


PAM-4



Probabilistic shaped PAM-4



PAM-2

What's Next?

OTHER MODULATION FORMATS

MORE ADVANCED EQUALIZER STRUCTURES

A non-exhaustive taxonomy on advanced solutions … still IM-DD based

What's Next?

Modulation formats

- **Probabilistic-shaped PAM-M (PS-PAM)**
- **Single sideband (SSB) or vestigial sideband (VSB) modulation**
- **OFDM/DMT (in a myriad of variants!)**
- **Carrierless amplitude/ Phase modulations (CAP)**
- **Chirp-assisted modulation**
- **Kramers-Kroning**

Non-linear pre-distortion at TX

Non-linear equalization at RX

- **Neural-network**
- **Simplified Volterra**
- **Volterra-series**
- **Ad-hoc solutions**

… then we have all the coherent solutions (and their coherent-like and coherent-lite variants)

…Houston we have a problem!

- Regarding advanced and nonlinear solutions, there are hundreds of published research papers with tons of different solutions for PON
  - No way to present all of them in a systematic way ☹ !

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 41, NO. 16, AUGUST 15, 2023 5217

Artificial Neural Network Assisted Probabilistic and Geometric Shaping for Flexible Rate High-Speed PONs

Shuang Yao, *Member, IEEE*, Amitkumar Mahadevan, Yannick Lefevre, *Member, IEEE*, Noriaki Kaneda, *Senior Member, IEEE*, Vincent Houtsma, and Doutje van Veen

1972 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 40, NO. 7, APRIL 1, 2022

Fixed-Point Analysis and FPGA Implementation of Deep Neural Network Based Equalizers for High-Speed PON

Noriaki Kaneda, *Senior Member, IEEE*, Chun-Yen Chuang, *Student Member, IEEE*, Ziyi Zhu, *Student Member, IEEE*, Amitkumar Mahadevan, *Member, IEEE*, Bob Farah, Keren Bergman, *Fellow, IEEE*, Doutje Van Veen, and Vincent Houtsma

2018 Asia Communications and Photonics Conference (ACP)

Frequency-Shifted Modulation using a Single DDMZM and Kramers–Kronig Scheme based Direct Detection Receiver in Long-Reach PON

Xiang Gao, Bo Xu*, Yuancheng Cai, Mingyue Zhu, Jing Zhang, and Kun Qiu

Key Laboratory of Optical Fiber Sensing and Communications, Ministry of Education, University of Electronic Science and Technology of China, Chengdu, 611731, China

W1H.3

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The Best Modulation Format for Symmetrical Single-wavelength 50-Gb/s PON at O-band: PAM, CAP or DMT?

Jiao Zhang[1,2,3], Min Zhu[1,2*], Kaihui Wang[3], Qingyi Zhou[1,2], Bingchang Hua[1,2], Yuancheng Cai[1,2], Mingzheng Lei[1,2], Yucong Zou[1,2], Aijie Li[1,2], Weiliang Xu[1,2], Jikuan Wang[1,2], Xiang Liu[1,2], and Jianjun Yu[2,3]

[1] *National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, China*
[2] *Purple Mountain Laboratories, Nanjing, Jiangsu 211111, China*
[3] *Fudan University, Shanghai, 220 Handan Road, 200433, China*
*minzhu@seu.edu.cn

5622 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 41, NO. 17, SEPTEMBER 1, 2023

Experimental Demonstration of a Novel Multi-User Bit and Power Loading Algorithm for OFDM-NOMA PON

Chengju Hu, Geyang Wang, Zhaoquan Fan, and Jian Zhao

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 38, NO. 12, JUNE 15, 2020 3261

Investigation of Modulation Schemes for Flexible Line-Rate High-Speed TDM-PON

Vincent E. Houtsma and Doutje T. van Veen

148 IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 35, NO. 3, 1 FEBRUARY 2023

Real-Time Demonstration of Concurrent Upstream and Inter-ONU Communications in Hybrid OFDM DFMA PONs

Tushar Tyagi, *Member, IEEE*, R. P. Giddings, and J. M. Tang

I thus pick just <u>one advanced example</u> for the next slides

… just by coincidence coming from my group ☺

What's Next?

OUR WORK ON ENABLING 100G DOWNSTREAM TRANSMISSION IN C-BAND

Research Article Vol. 13, No. 2 / February 2021 / Journal of Optical Communications and Networking A111

JOURNAL OF Optical Communications and Networking

100 Gbps/λ PON downstream O- and C-band alternatives using direct-detection and linear-impairment equalization [Invited]

Pablo Torres-Ferrera,* Haoyi Wang, Valter Ferrero, and Roberto Gaudino

Politecnico di Torino, Department of Electronics and Telecommunications, Torino, Italy

**Corresponding author: pablo.torres@polito.it*

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 40, NO. 2, JANUARY 15, 2022 547

Experimental Demonstration of 100 Gbps/λ C-Band Direct-Detection Downstream PON Using Non-Linear and CD Compensation with 29 dB+ OPL Over 0 Km–100 Km

Pablo Torres-Ferrera, Giuseppe Rizzelli, Haoyi Wang, Valter Ferrero, *Senior Member, IEEE*, and Roberto Gaudino, *Senior Member, IEEE*

Rationale for this research

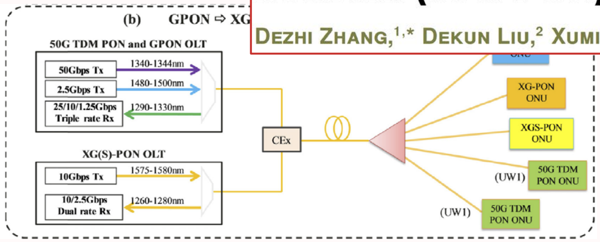
- PON standards up to now have been "backward compatible" in wavelength allocation, in order to allow co-existence on a single PON ODN
- As a result, the wavelength spectrum is almost full
- But high speed PON can work only in O-band
  - due to chromatic dispersion limits
- Can we open up again the C-band for IMDD 100G-PON?

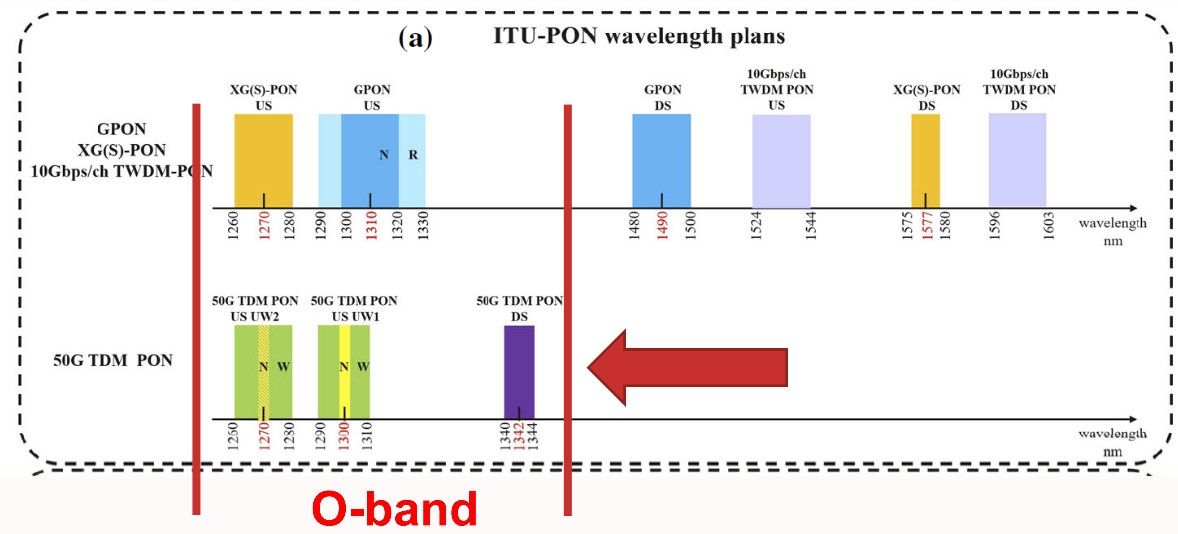

Review Vol. 12, No. 10 / October 2020 / Journal of Optical Communications and Networking D99

JOURNAL OF Optical Communications and Networking

Progress of ITU-T higher speed passive optical network (50G-PON) standardization

DEZHI ZHANG,[1,*] DEKUN LIU,[2] XUMING WU,[2] AND DEREK NESSET[3]

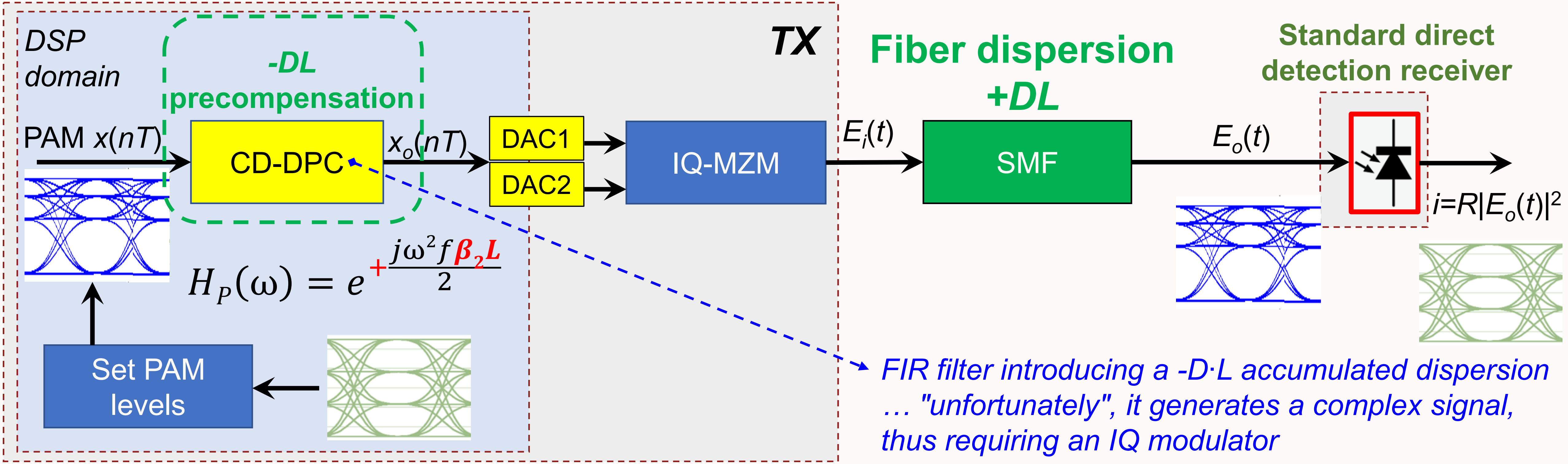




Our proposal: CD Digital Pre-Compensation (CD-DPC)

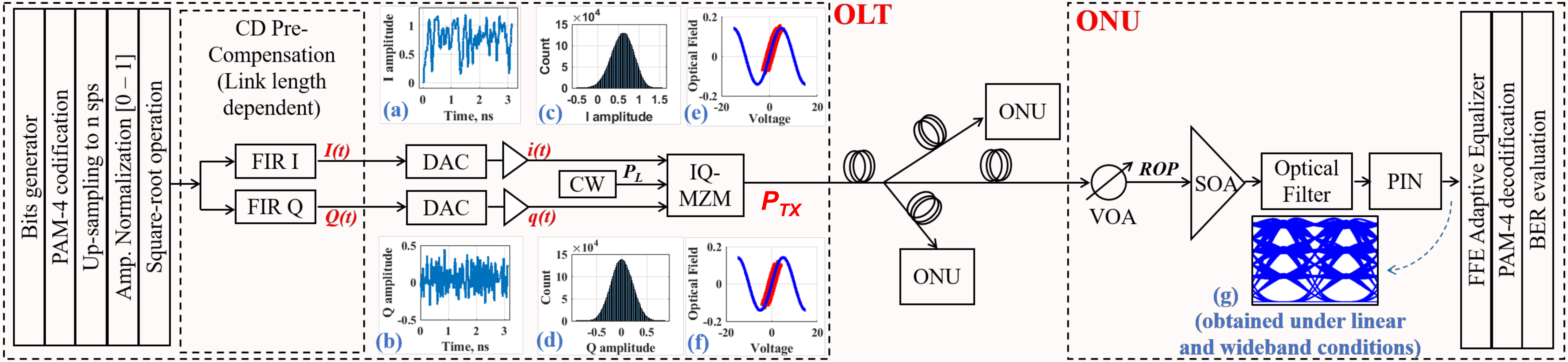
Given a link with (known) accumulated dispersion *D·L* [ps/nm] (or equivalently $\boldsymbol{\beta_2 L}$)

- An electrical PAM-4 signal is sent to a CD-DPC DSP complex filter that implements an accumulated dispersion *-D·L* in the discrete-time DSP domain, generating a complex-valued (*I* and *Q*) signal that is applied to a dual arm IQ-MZM.



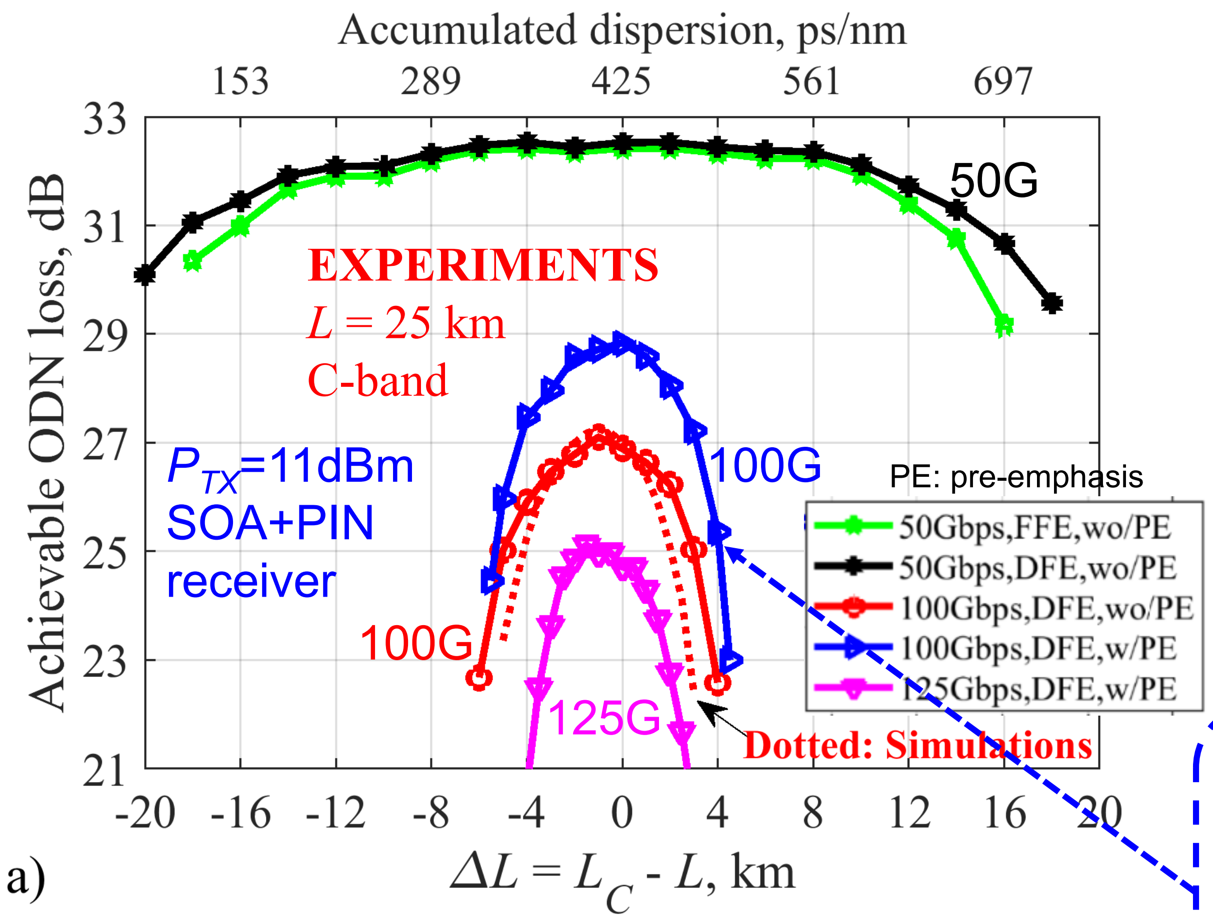
$$H_P(\omega) = e^{+\frac{j\omega^2 f \boldsymbol{\beta_2 L}}{2}}$$

100 Gbps L-band operation



- **Main simulation parameters:**
  - f_{3dB}=20 GHz TX and f_{3dB}=35 GHz RX optoelectronics
  - Transmitter Power (P_{TX}) scanned from 9 to 13 dBm (P_{TX}=11dBm unless something else stated).
  - Gain of SOA (G) of 11 dB, Noise figure F=7dB, Optical filter bandpass BW=75GHz
  - PIN noise parameters (R=0.7 A/W and IRND=22.4 pA/sqrt(Hz))
- **Main experimental parameters:**
  - AWG sampling frequency: 92 GSa/s (i.e 3.6sps - 50Gbps, 1.8sps - 100Gbps, 1.47sps - 125Gbps)
  - 25G-class IQ-MZM with P_{TX}=11dBm and Broad-bandwidth PIN Probe.

Experimental results at 50G and 100G



Here ΔL is the difference between the actual fiber length and the one assumed inside the DSP at TX

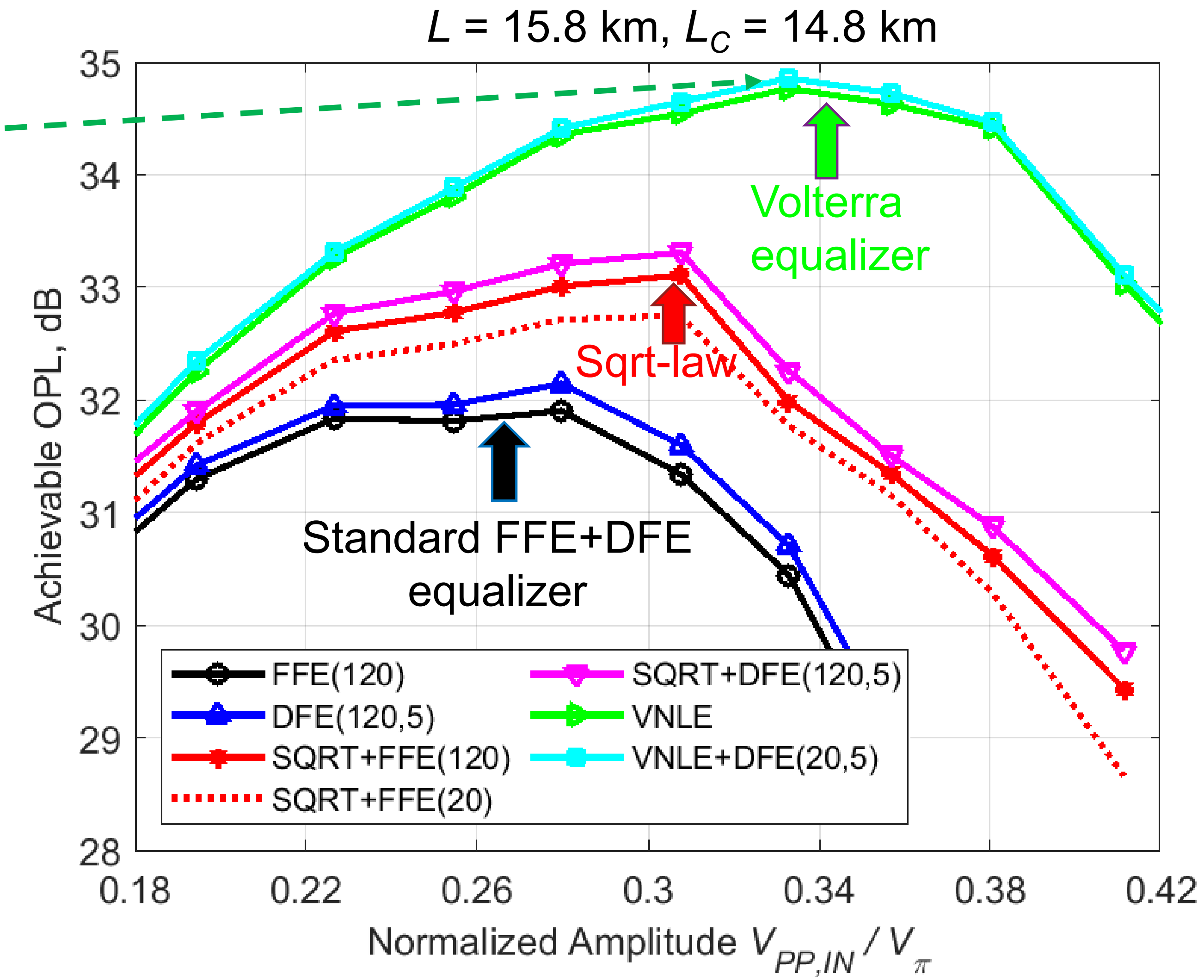
- We recently tested experimentally our proposal
  - On L=25 km but in C-band
  - Accumulated dispersion $D \cdot L \approx 400$ [ps/nm] is about the same as for L=20km in L-Band
- Optimal transmitted power: P_{Tx}=11dBm
- At 50Gbps we experimentally show 32 dB ODN loss over a very broad ΔL range
  - **1dB penalty for ΔL = ±12 km**
- At 100 Gbps we reach 29 dB ODN loss
  - **1dB penalty for ΔL = ±2 km**
  - using pre-emphasis -PE at TX to compensate optoelectronic bandwidth limitations

Adding (even more) complexity…

- Nonlinear equalization based on Volterra series at RX
  - We obtained very similar results with neural network-based equalizer

Example:

- IQ-DD experiment
- 100 Gbps PAM-4, P_{TX}=11dBm
- SOA+PIN receiver
- C-band, 16 km of SMF fiber
  - Up to 34 dB ODN loss



A LOOK TOWARDS THE (NEAR?) FUTURE:

COHERENT PON FOR HIGHER REACH AND CAPACITY?

☹ Another 1 hour tutorial would be needed…

… to give an overview on all what is "boiling" in research today on coherent in PON ☺

From ECOC2023 program: search for "Coherent PON"

M.B.5.1 15:30-16:00

Simplified Coherent Receivers for Passive Optical Networks

Istvan Bence Kovacs, Md. Saifuddin Faruk, Seb J. Savory
University of Cambridge, Cambridge, United Kingdom

M.B.5.2 16:00-16:15

Low-Complexity Balanced Quasi-Coherent Receiver with Integrated 2x2 MMI Balanced Photodiode and TIA for 50G PON

Cheng Wang, Cédric Bruynsteen, Jakob Declercq, Joris Lambrecht, Bart Moeneclaey, Nishant Singh, Xin Yin
Ghent University-imec, Ghent, Belgium

M.B.5.3 16:15-16:30

Local and Remote Laser Frequency Control in Point-to-Multipoint Networks Using Digital Subcarriers

Stenio Ranzini[1], Christopher Fludger[1], Thomas Duthel[1], Bo Liu[1], Antonio Napoli[2], Ales Kumpera[3], Amir Rashidinejad[3], Aditya Kakkar[3], Mark Missey[4], Vince Dominic[4], Parmijit Samra[4], Han Sun[3], Robert Maher[4], Azmina Somani[3], Dave Welch[4]
[1] Infinera, Nuremberg, Germany. [2] Infinera, Munich, Germany. [3] Infinera, Ottawa, Canada. [4] Infinera, Sunnyvale, USA

M.B.5.4 16:30-16:45

Cost Effective 100G Coherent PON Enabled by Remote Tone Delivery and Simplified Carrier Recovery for Burst Processing

Haipeng Zhang, Zhensheng Jia, Luis Alberto Campos, Curtis Knittle
CableLabs, Louisville, USA

M.B.5.5 16:45-17:00

Real-Time Bidirectional Coherent Point-to-Multipoint Passive Optical Network

Tobias Eriksson[1], Telmo Almeida[1], Henrik Åhlfeldt[1], Sezer Erkilinc[1], Xi Chen[1], Johan Hellman[1], Ales Kumpera[2], Amir Rashidinejad[2], Antonio Napoli[3], Chris Fludger[4], Per Lembre[1], Johan Bäck[1], Magnus Olson[1], Dave Welch[5]
[1] Infinera, Stockholm, Sweden. [2] Infinera, Ottawa, Canada. [3] Infinera, Munich, Germany. [4] Infinera, Nuremberg, Germany. [5] Infinera, San Jose, USA

From OFC2023 program: search for "Coherent PON"

Politecnico di Torino 1859

W1I.2 • 08:30 ★ Top-Scored
Rate-Flexible Coherent PON Up to 300 Gb/s Demonstrations With Low Complexity TDM Burst Design, Haipeng Zhang[1], Zhensheng Jia[1], Luis A. Campos[2], Curtis Knittle[1]; [1]*R&D, CableLabs, USA;* [2]*Next-Gen Systems, CableLabs, USA.* Two flexible-rate coherent PON architectures have been demonstrated, featuring a low complexity TDM burst DSP. A peak data rate of up to 300-Gb/s and transmission over 50-km link and 1×32 split ratio has been achieved.

W1I.3 • 08:45 ★ Top-Scored
Pilot-Aided Continuous Digital Signal Processing for Multi-Format Flexible Coherent TDM-PON in Downstream, Guoqiang Li[1], An Yan[1], Sizhe Xing[1], Zhongya Li[1], Wangwei Shen[1], Jiaye Wang[1], Junwen Zhang[1], Nan Chi[1]; [1]*Fudan Univ., China.* To avoid burst-signal processing in downstream transmission during modulation-format switching, we propose and experimentally demonstrate a pilot-aided DSP scheme with continuous SOP tracking, carrier-phase recovery, and channel estimation in the 300G flexible CPON based on 4/16/64-QAMs.

W3F.3 • 14:45
Demonstration of Point-to-Multipoint 100G Coherent PON to Support Broad-band Access and B5G/6G Mobile X-Haul., Yingxin Wei[1], Jiao Zhang[1,2], Weidong Tong[1], Bingchang Hua[2], Qinru Li[1], Junhao Zhang[1], Mingzheng Lei[2], Yuancheng Cai[1,2], Yucong Zou[2], Liang Tian[2], Min Zhu[1,2]; [1]*Southeast Univ., China;* [2]*Purple Mountain Laboratories, China.* We experimentally demonstrate a rate-flexible point-to-multipoint 100G coherent PON with downlink and uplink using digital subcarrier multiplexing to simultaneously support up to 64 nodes for fixed broadband and W-band mmWave wireless access.

08:00–10:00
W1I • Flexible Coherent PON
Presider: Dora van Veen; Nokia Corporation, USA

W1I.6 • 09:30 Invited
High-Performance and Robust Burst Reception in Coherent PON, Junwen Zhang[1]; [1]*Fudan Univ., China.* Abstract not available.

Coherent PON

W1I.5 • 09:15
Demonstration of Beyond 100G Three-Dimensional Flexible Coherent PON in Downstream With Time, Frequency and Power Resource Allocation Capability, Wangwei Shen[1], Sizhe Xing[1], Guoqiang Li[1], Zhongya Li[1], An Yan[1], Jiaye Wang[1], Junwen Zhang[1], Nan Chi[1]; [1]*Fudan Univ., China.* We propose and demonstrate a novel three-dimensional flexible coherent PON with the resource-allocation capability in time, frequency and power domain. High flexibility is demonstrated with >100G over 20-km fiber for coherent PON in downstream.

W1I.4 • 09:00
Low-Cost 100G Coherent PON Enabled by TFDM Digital Subchannels and Optical Injection Locking, Haipeng Zhang[1], Zhensheng Jia[1], Luis A. Campos[2], Curtis Knittle[1]; [1]*R&D, CableLabs, USA;* [2]*Next-Gen Systems, CableLabs, USA.* We demonstrate a novel 100G TFDM coherent PON architecture featuring low-cost ECL-free ONU enabled by remote optical carrier delivery through injection locking. System performance shows no degradation compared to a regular ECL based system.

Th2A.21
Nonlinear Phase Shift Pre-Compensation for Improved Power Budget in a 200 Gbps Simplified Coherent PON, Pablo Torres-Ferrera[1], Md Saifuddin Faruk[1], Istvan B. Kovacs[1], Seb J. Savory[1]; [1]*Univ. of Cambridge, UK.* We experimentally investigate a simple fiber nonlinearity pre-compensation technique for 200 Gbps PON downstream using a simplified coherent receiver. A power budget improvement of 1.0 dB is achieved for 50 km reach in C-band.

M1E • Coherent Technologies for Data Centers

S1F: Where are the Boundaries Between IM-DD and Coherent?
Room: 8

Organizers: Clint Schow, *Univ. of California, Santa Barbara, USA;* Di Che, *Nokia Bell Labs, USA;* Sam Palermo, *Texas A&M University, USA;* Paola Parolari, *Politecnico di Milano, Italy*

MW2 • MW Panel II: PAM vs. Coherent for Data Center Connectivity
12:15–13:45

In Data Center…

MW6 • MW Panel VI: Satellite Communications - Coherent Optics in Free Space
12:15–13:45

…and even in Satellite Comm!

DSP-based Coherent PON

- **PROs**
  - From a transmission perspective, coherent in PON may enable not only 200G-PON but even 400G-PON on today standard ODN
  - Moreover, coherent can also "break" the traditional 20km "PON barrier", towards extended reach PON
  - And it can even break the 1x64-split barrier, allowing more than 64 ONUs per PON
- **CONs**
  - Cost and complexity: PARAMOUNT relevance for PON!!
    - Many papers are proposing simplified coherent solutions
  - "Traditional" full-coherent long-haul solutions are NOT directly suitable for single-fiber bidirectional transmission and for upstream burst mode operation
    - Many papers are thus proposing
      - Fast-convergence variants of "traditional" coherent DSP
      - Subcarrier-based coherent for point-to-multipoint bidirectional

What about metro+PON convergence?

- Telecom operators often investigates on a convergence between metro and access to "jump" one central office
- There is a ongoing research trend on studying solutions for convergence between metro and access networks
  - i.e. all-optical transparent lightpaths generated in the metro and routed toward a PON to the final termination
    - And vice-versa
- In this possible future scenario, <u>coherent seems again the only viable solutions</u>
  - for 100+G high speed transmission,
    - For 10G, there is already the "Super-PON" standard (IEEE 802.3cs-2022)

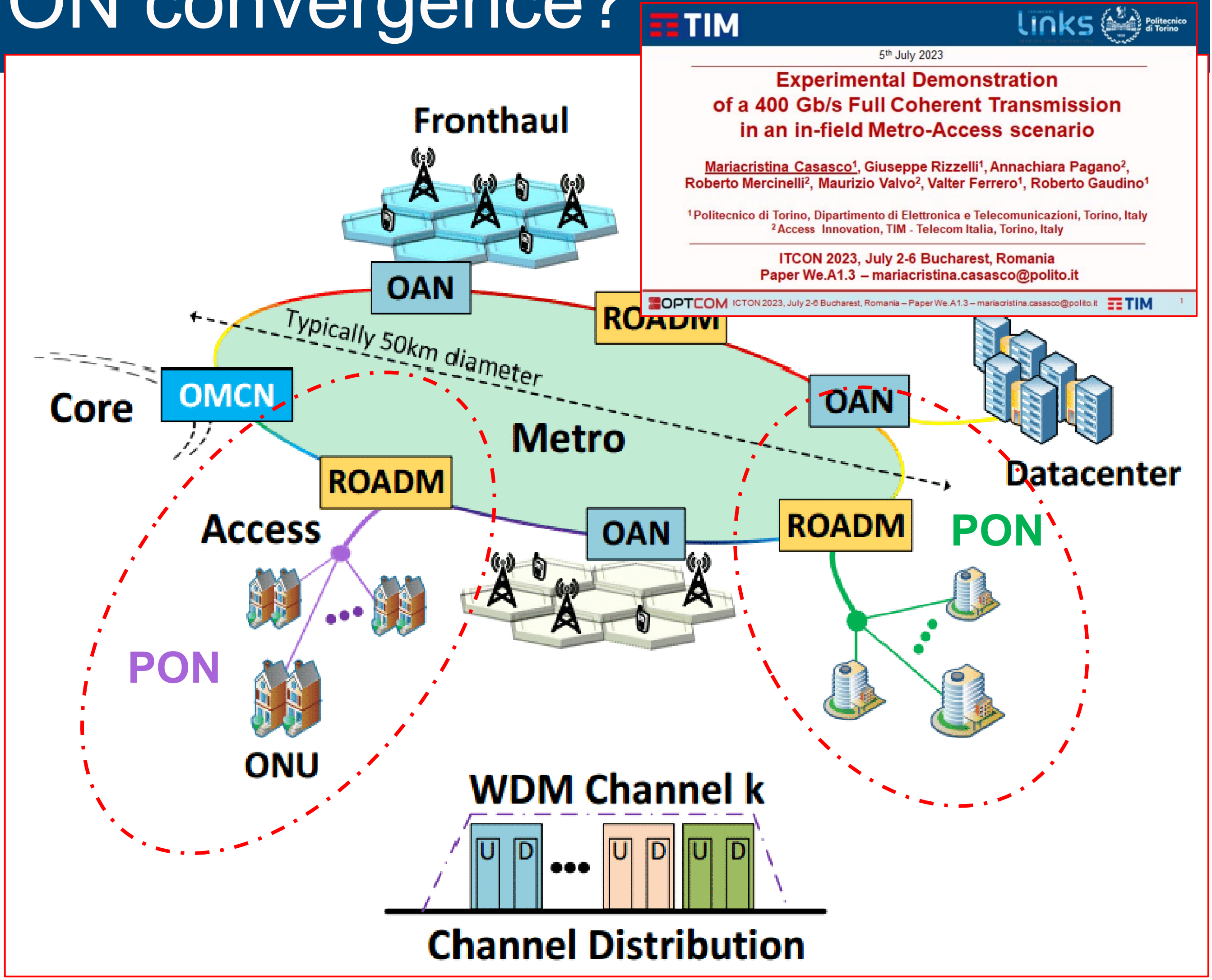
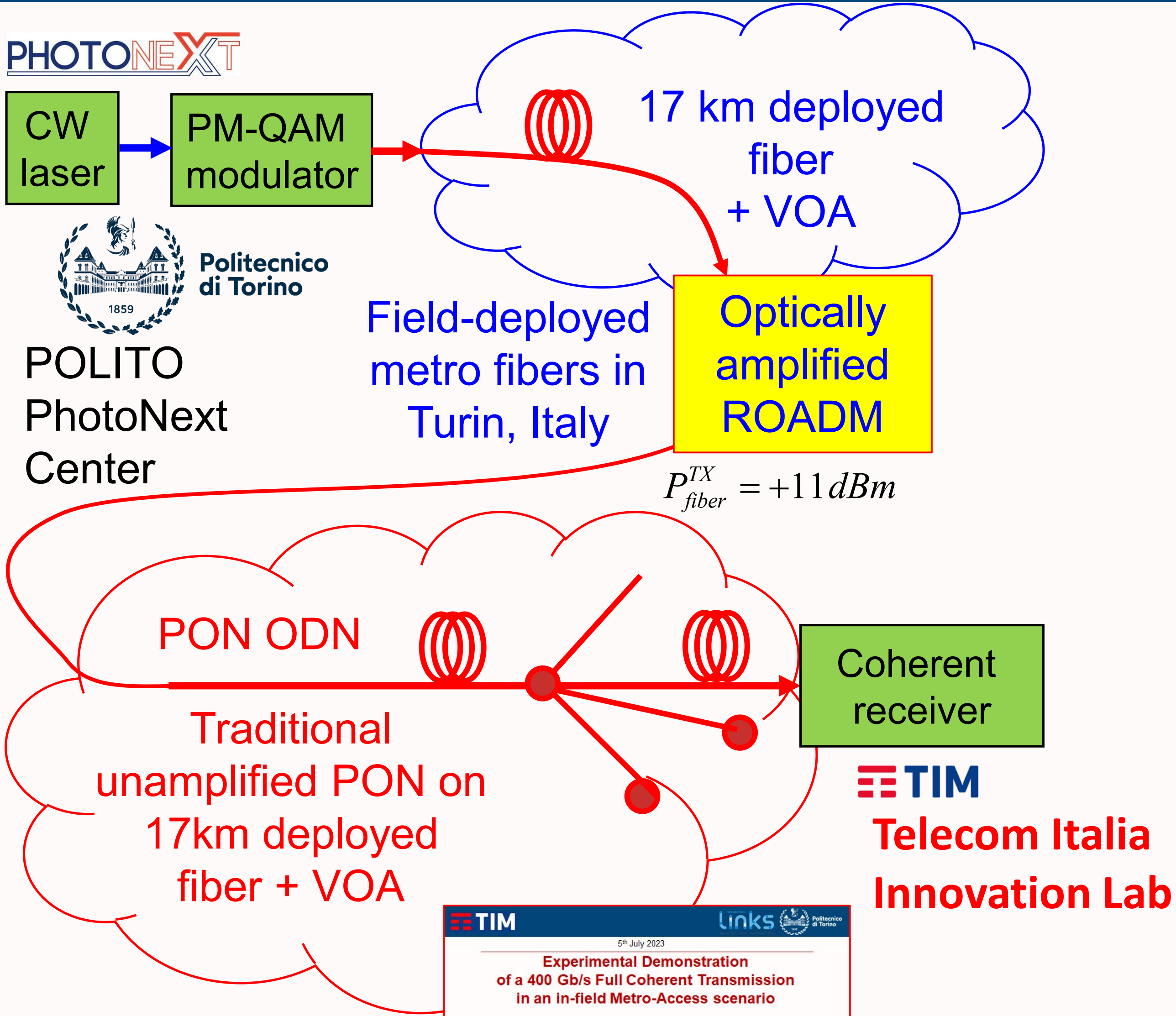
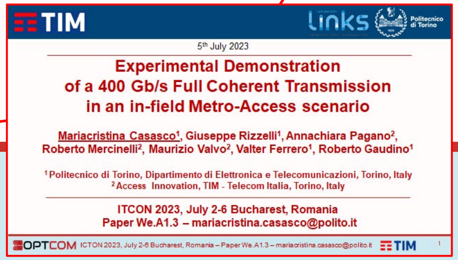


Figure taken from: https://www.researchgate.net/publication/325999589_Cost-effective_ROADM_design_to_maximize_the_Traffic_Load_Capacity_of_u-DWDM_coherent_metro-access_networks

Experimental Scalability curves at 400 Gbit/s




TIM links Politecnico di Torino

5th July 2023

Experimental Demonstration of a 400 Gb/s Full Coherent Transmission in an in-field Metro-Access scenario

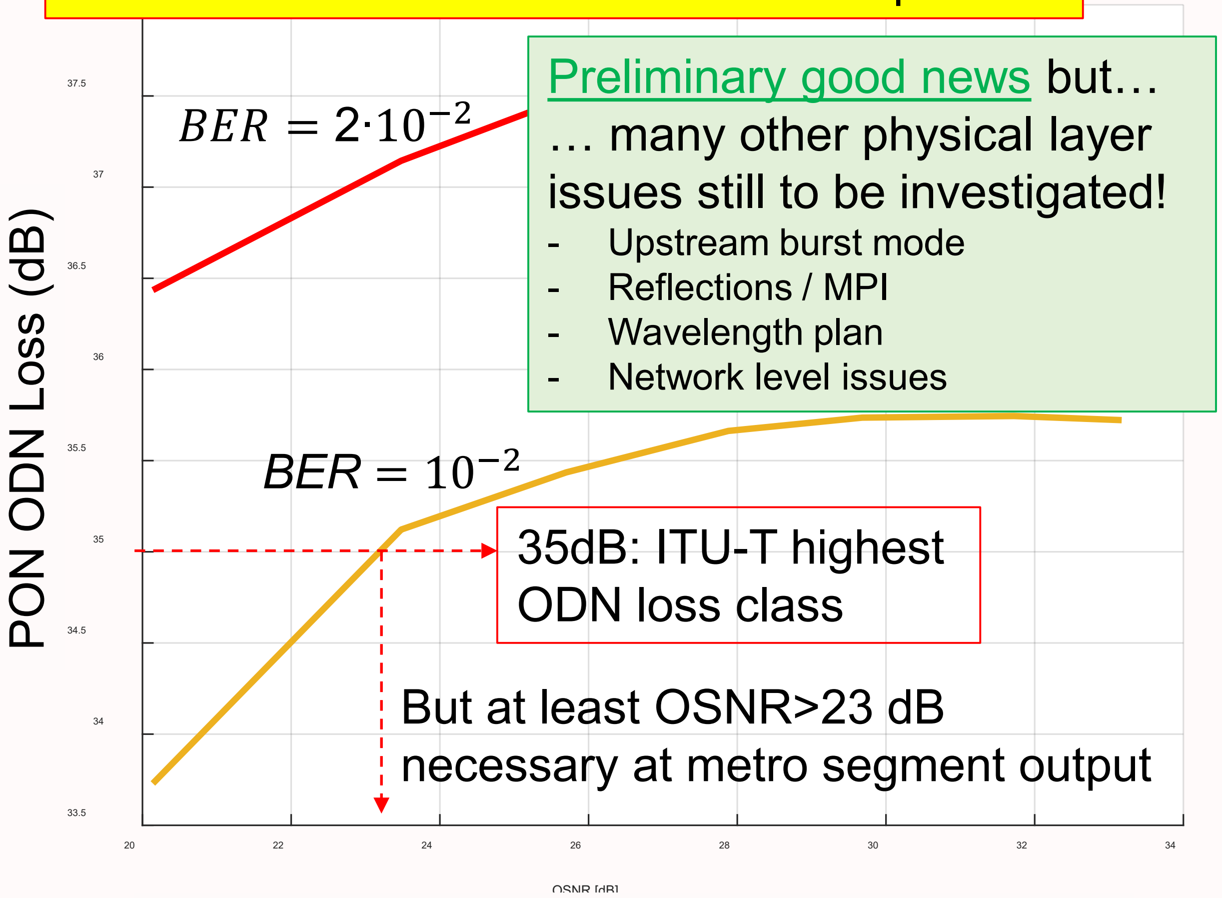
Mariacristina Casasco[1], Giuseppe Rizzelli[1], Annachiara Pagano[2], Roberto Mercinelli[2], Maurizio Valvo[2], Valter Ferrero[1], Roberto Gaudino[1]

[1] Politecnico di Torino, Dipartimento di Elettronica e Telecomunicazioni, Torino, Italy
[2] Access Innovation, TIM - Telecom Italia, Torino, Italy

ICTON 2023, July 2-6 Bucharest, Romania
Paper We.A1.3 – mariacristina.casasco@polito.it

OPTCOM ICTON 2023, July 2-6 Bucharest, Romania – Paper We.A1.3 – mariacristina.casasco@polito.it TIM 1

400Gbit/s (raw bit rate) commercial transceiver PM-16QAM 50Gbaud BER contour plots



Optical OSNR (dB) at metro segment output

Preliminary good news but…
… many other physical layer issues still to be investigated!

- Upstream burst mode
- Reflections / MPI
- Wavelength plan
- Network level issues

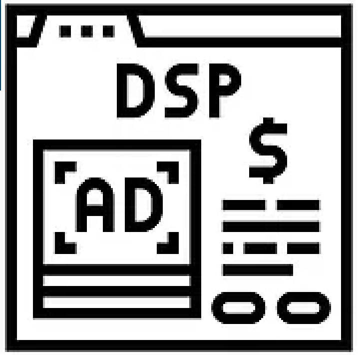
The EU project ALLEGRO and B5G-OPEN

The following very large EU projects are (among several other topics) investigating the idea of metro-access convergence

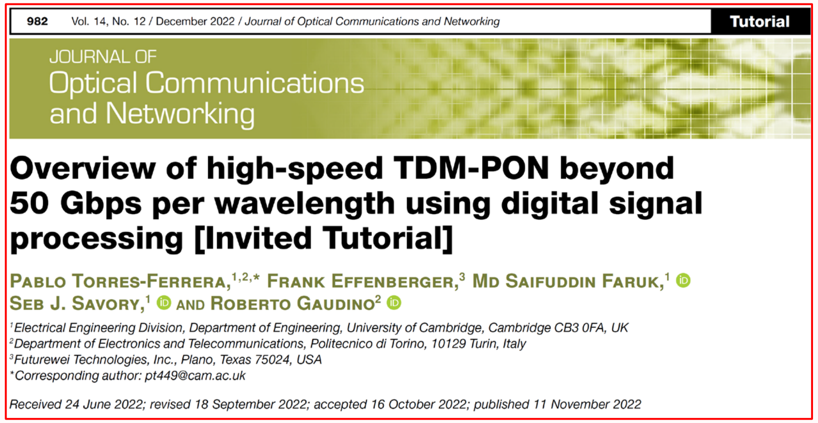
- Horizon Europe RIA "ALLEGRO" (Agile uLtra Low EnerGy secuRe netwOrks, Start date: 01 January 2023)
  - https://www.allegro-he.eu/
- Horizon 2020 RIA "Beyhond 5G Open" (Start Date: 01 Nov 2021)
  - https://www.b5g-open.eu/
- SEASON "SElf-mAnaged Sustainable high-capacity Optical Networks",
  - https://www.season-project.eu/

CONCLUSION

Conclusions… with my personal bets!



- Let's start easy: above 50G-PON, advanced DSP is more and more needed (!!)
  - But the $ (or € or £) is key ☺
- 100G-PON: IM-DD at its "absolute limits"… but still physical layer doable
  - Flexible PAM2 and PAM4 combined with strong equalization
    - +SOA amplification at OLT and ONU
    - And maybe flexible modulation at TX
- 200G-PON (and more): coherent needed IF 200G per wavelength
  - Key issue would be CAPEX and OPEX cost
  - At the physical layer: a very interesting field of research is open!
    - Burst mode coherent AND/OR subcarried multiplexed
    - Simplified coherent (not only DSP, but also optoelectronics)
  - The other possible direction: WDM Nx50G or Nx25G


982 Vol. 14, No. 12 / December 2022 / *Journal of Optical Communications and Networking* **Tutorial**

JOURNAL OF Optical Communications and Networking

Overview of high-speed TDM-PON beyond 50 Gbps per wavelength using digital signal processing [Invited Tutorial]

PABLO TORRES-FERRERA,[1,2,*] FRANK EFFENBERGER,[3] MD SAIFUDDIN FARUK,[1] SEB J. SAVORY,[1] AND ROBERTO GAUDINO[2]

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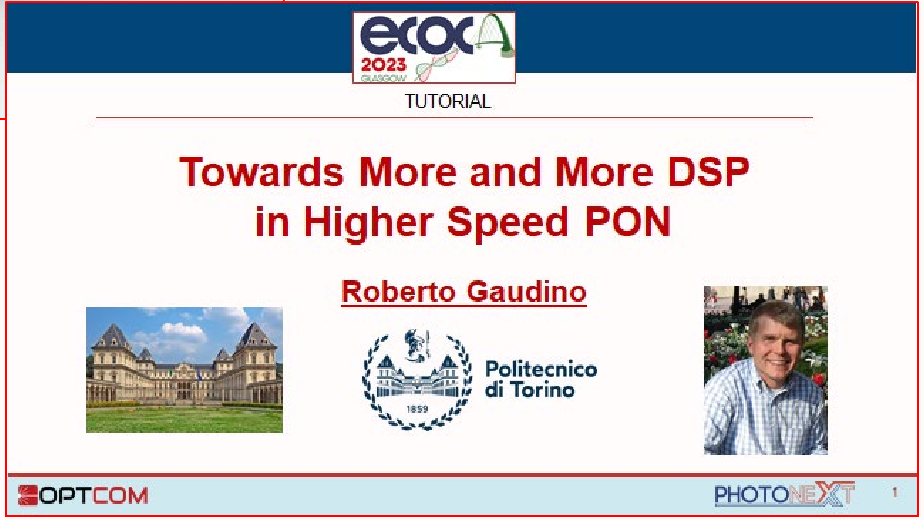
JOCN
November 2022

The Tutorial slides will be made available at this QR-code link

Interested in our papers on PON? Follow this QR-code!



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PHOTONEXT