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# Transceiver Technologies for Next-Generation PON

Dora van Veen and Vincent Houtsma

OFC 2020

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## Abstract

**Transceiver Technologies for Next-generation PON Networks**
Dora van Veen and Vincent Houtsma

We will review the specific requirements for upgrading passive optical networks and present recent research on high speed optical transmission for Next-Generation TDM-, TWDM- and WDM-PONs based on low cost optical and DSP technologies.

Presentation Number: W1E.2

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- **Introduction**
- Past
- Present
- Future
- Concluding remarks

- Architecture
- Challenges PON
- Burst mode

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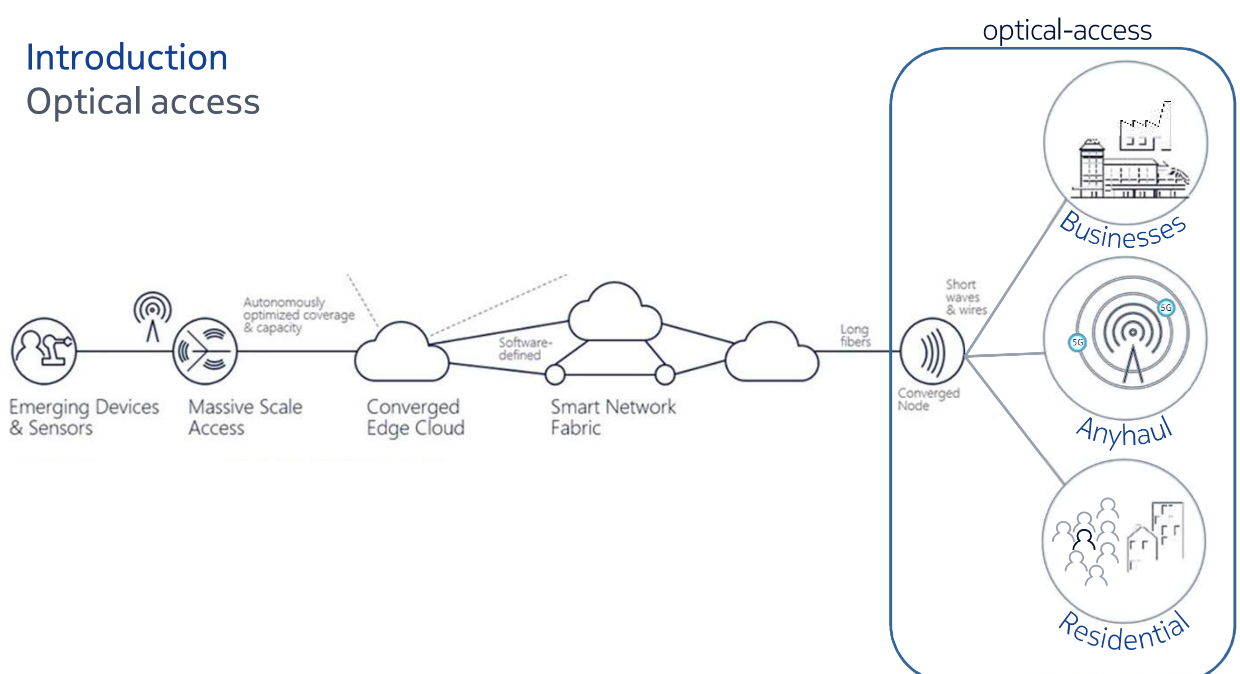
## Introduction
### Optical access

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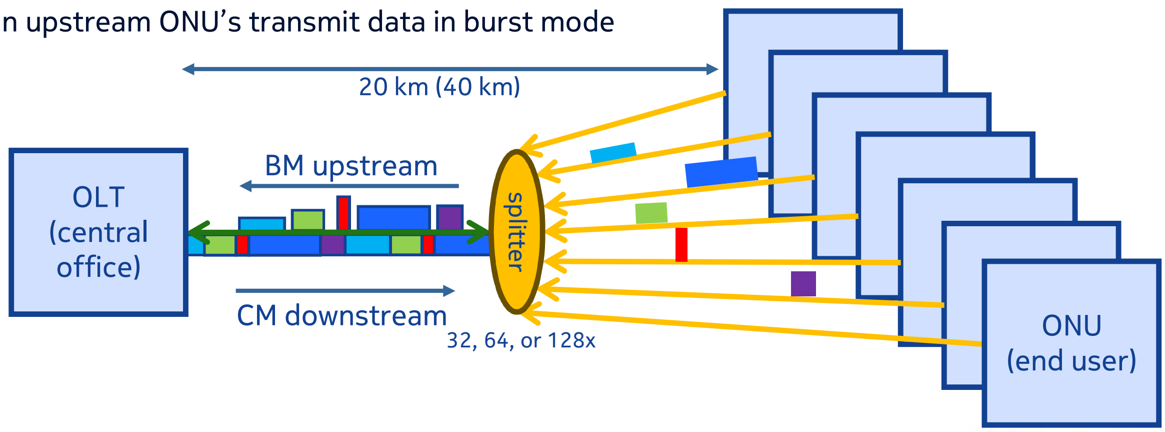
## Introduction
### Architecture TDM-PON

- Single fiber Point to Multipoint network with a passive outside fiber plant (PON) most commonly used architecture
- Time Division Multiplexing/Time Division Multiple Access to share the bandwidth
- In upstream ONU's transmit data in burst mode

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## Introduction
### Challenges PON

- Outside distribution network stays same with every upgrade, conventional optical power budget is ≥29 dB
- PON is the most cost-sensitive network (ONU's are not shared at all)
- Differential loss / dynamic range receivers needs to be large
- Burst mode transmission in upstream
- Operators prefer same hardware at each end-user (colorless ONU)
- Passive optical network, no amplification in field for lowest operational cost

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## Introduction

### Burst mode receiver

- Fast leveling of differential burst amplitudes (up to 20 dB optical power difference possible)
- Fast phase recovery on burst by burst basis


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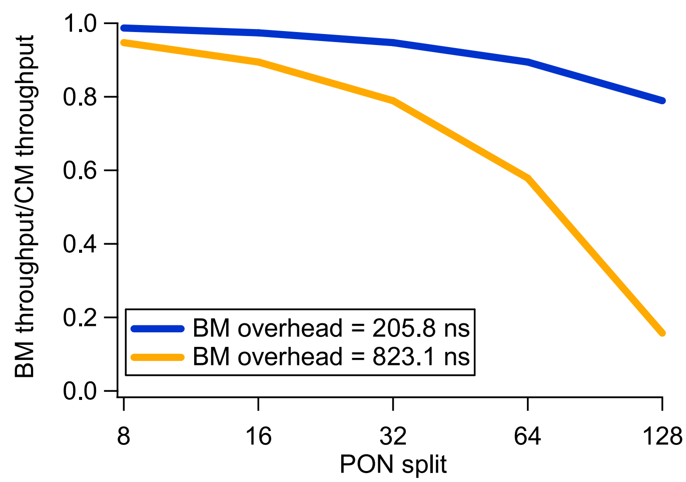
## Introduction

### Burst mode overhead

- PON frame length 125 μs
- Overhead objective is 205.8 ns, and worst case is 823.1 ns for XGS-PON
- Burst length = 125/PON split (μs)
- Upstream FEC fragmentation not modeled

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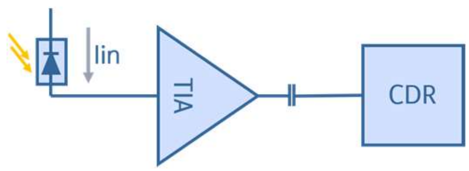
## Introduction
### Challenges burst mode transmission

- A continuous mode receiver is AC-coupled between the analog front-end and the decision circuit (CDR) which works well for DC-balanced signals
- A burst mode receiver needs to be adapted from a conventional AC-coupled receiver to accommodate the DC-unbalanced burst mode signals which will charge and de-charge the capacitor and cause DC-wander




Continuous mode receiver

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## Introduction
### Challenges burst mode transmission

- A burst mode receiver is commonly DC-coupled with adaptive gain to adjust for input signal level for lowest burst mode overhead
- A peak detector is used to measure amplitude and adapt the gain on a burst by burst basis (with reset after each burst)
- DC-coupled receiver requires DC offset compensation on a burst by burst basis
- In IEEE cross layer signaling is not allowed so self-resetting BM receivers have also been developed as well as AC-coupling based burst mode receivers to avoid this

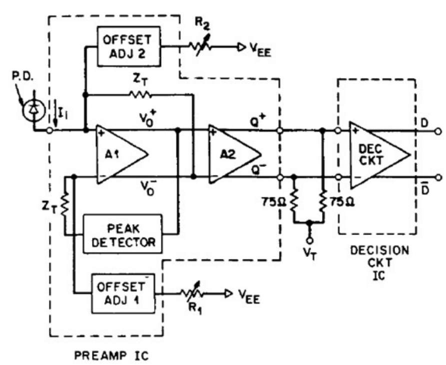


Fig. 2. Schematic of burst-mode compatible dc coupled receiver.


- Y. Ota and R. G. Swartz, "Burst mode compatible optical receiver with large dynamic range," J. Lightwave Technol., vol. 8, pp. 1897–1903, Dec. 1990.
- X. Qiu, "[OFC 2013 Tutorial OW3G.4] Burst-mode Receiver Technology for Short Synchronization," *OFC 2013*, Anaheim, CA, 2013, pp. 1-28.
- X. Yin et al., "Experiments on a 10 Gb/s fast-settling high-sensitivity burst-mode receiver with on-chip auto-reset for 10G-GPONs [Invited]," in IEEE/OSA Journal of Optical Communications and Networking, vol. 4, no. 11, pp. B68-B76, Nov. 2012.


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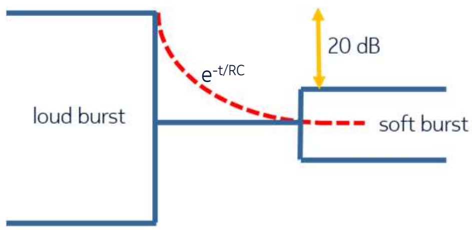
## Introduction
### Challenges burst mode transmission

- For an AC-coupled burst mode receiver the capacitor has to be selected carefully to optimize burst settling time, RC tail leakage from loud to soft burst transition as well as immunity to consecutive identical digits (CID)



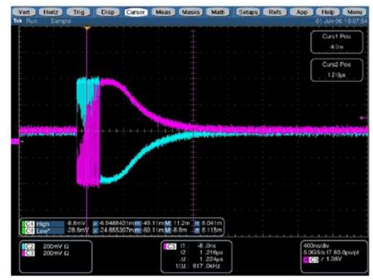



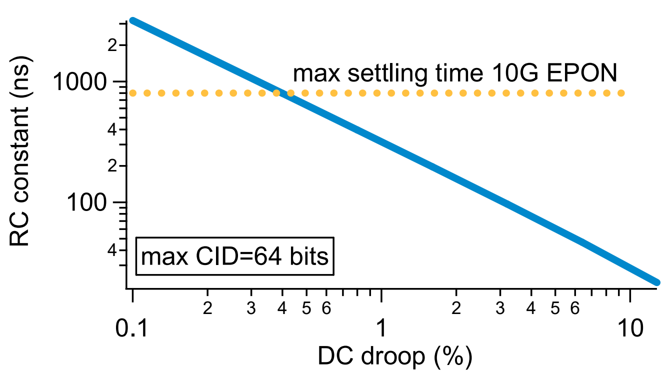
Figure 5 - OLT receive electrical output

- R. Baca and M. Zuhdi, "Technological challenges to G-PON operation," OFC/NFOEC 2008, San Diego, CA, 2008



## Introduction
### Challenges burst mode transmission

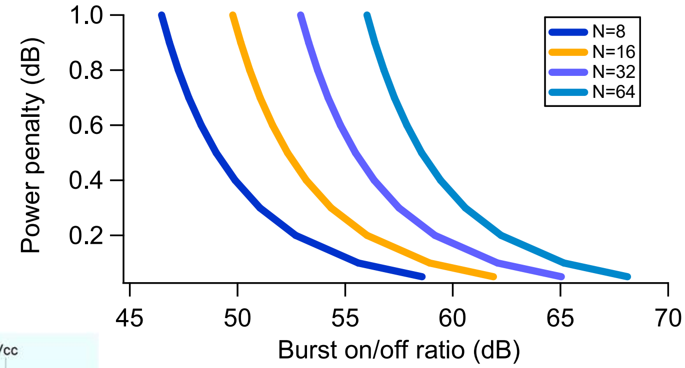
- IEEE 802.3av 10G EPON
- Line code: 64B/66B data encoding
- Sync time: max. 800ns for RX settling plus max. 400ns for CDR lock
- Guard time: max. 512 ns laser on + max. 512 ns laser off

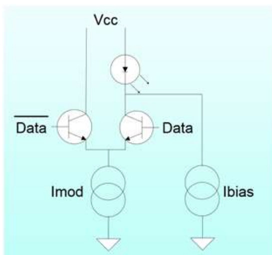



- Haim Ben-Amram, "10GEPON Burst Receiver Simulation", http://www.ieee802.org/3/av/public/2008_01/3av_0801_benamram_2.pdf

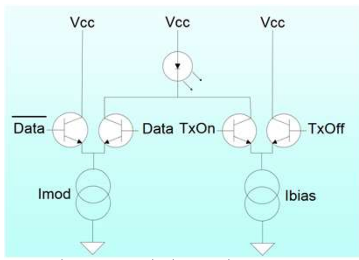
## Introduction
### Burst mode transmitter

- At the ONU side data is transmitted in burst mode
- Non zero off powers cause a power penalty due to interference




conventional laser driver




burst mode laser driver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http://www.ieee802.org/3/efm/public/may02/solina_1_0502.pdf

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## Introduction
### Upstream burst frame

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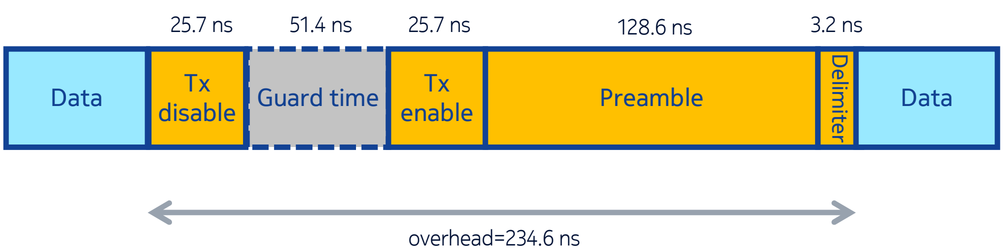
- ITU-T 10G PON objective total overhead = 205.8 ns (worst case 823.1 ns)

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## Introduction
### Upstream burst frame

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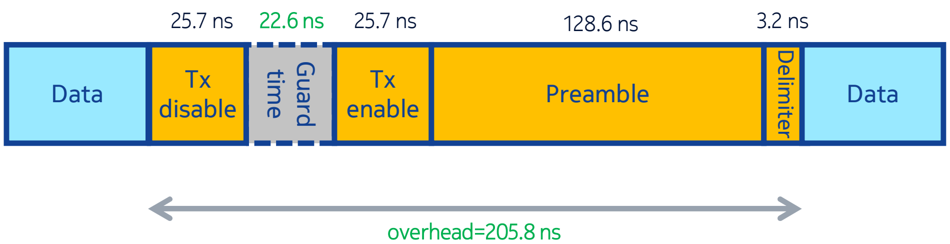



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- Introduction
- **Past**
- Present
- Future
- Concluding remarks

- Beginnings of PON
- PON research in past decades
- RF video overlay


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## Past
### Beginnings of PON

- Not long after introduction of fiber in the DLC (digital loop carrier) feeder did investigation of Fiber to the home (FTTH) start
- First considered architectures were P2P in the form of active double star (active point to point) and single star (point to point) because they are technically the simplest
- British Telecom identified a passive double star (PON) as the most economical and practical way for Telco's to be ready for future broadband services (CATV, BISDN, etc.) in the 80's already
- First burst mode receiver was reported in 1990 by Ota and Swartz
- In 1995 six European telco's and NTT joined to form an industry forum which is now called FSAN (full service access networks) to drive up the volumes.
  - First they defined 155/155 Mb/s ATM-PON

Edward Harstead and Pieter H. van Heyningen. Optical access networks. In Ivan P. Kaminow and Tingye Li, editors, Optical Fiber Telecommunications IVB, pages 438-513. Academic Press, San Diego, 2002.



## Past
### Beginnings of PON: BT telephony over passive Optical Network (TPON)

- "Flexibility to avoid forecasting problems of both copper and dedicated fiber"
- Pay as you grow
- No street cabling activity neede to enable higher POTS capacity requirements from customer
- Lower cost and maintenance compared to copper and p2p fiber
- Compatibility with broadcast services
- Upgradable to WDM-PON

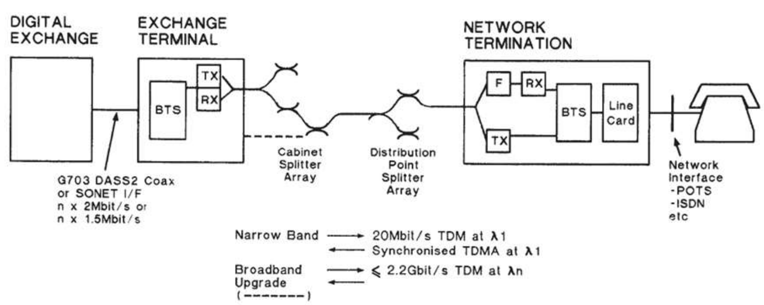



FIG.1 TPON

K. A. Oakley, "An economic way to see in the broadband dawn (passive optical network)," *IEEE Global Telecommunications Conference and Exhibition. Communications for the Information Age*, Hollywood, FL, USA, 1988, pp. 1574-1578 vol.3.

# Past
## PON research in 1990s

- WDM-PON schemes focusing on low cost WDM implementation

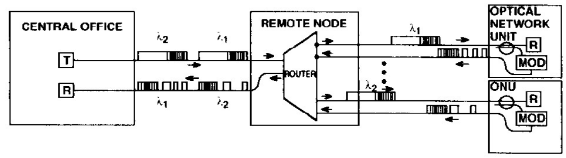



Fig. 1. RITE-Net architecture. Tunable laser source sends downstream packets, which are routed by wavelength to ONUs. A portion of the packet receives upstream modulation and is routed back to the CO.

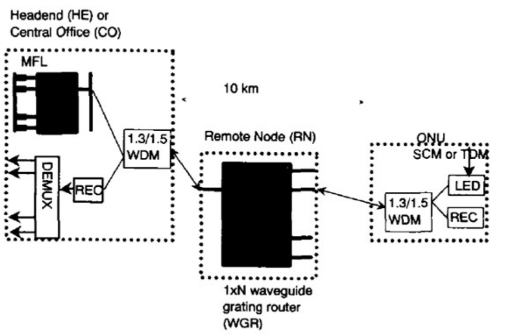
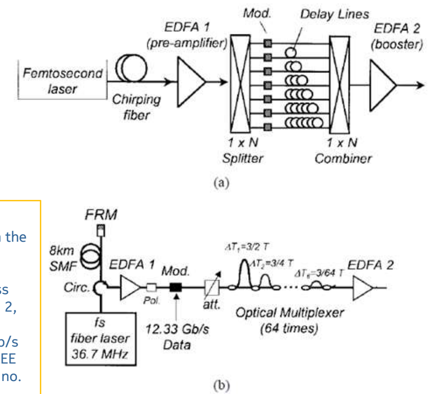



Fig. 1. Layout for the local access router network (LARNet) with N wavelength channels.




- N. J. Frigo *et al.*, "RITE-Net: A Passive Optical Network Architecture Based on the Remote Interrogation of Terminal Equipment," in OFC 1994, paper PD8
- M. Zirngibl *et al.*, "LARnet, a local access router network," in *IEEE PTL*, vol. 7, no. 2, pp. 215-217, Feb. 1995
- L. Boivin *et al.*, "110 channels x 2.35 Gb/s from a single femtosecond laser," in IEEE Photonics Technology Letters, vol. 11, no. 4, pp. 466-468, April 1999.



# Past
## PON research in 20x0s

- Pure WDM-PON based on reflective SOA and coherent detection

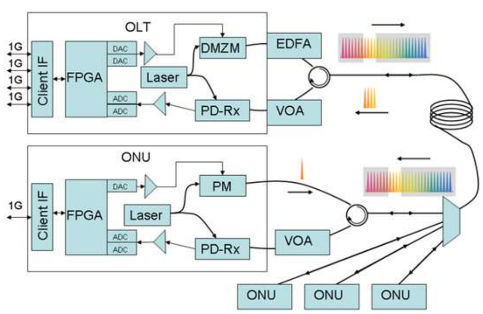
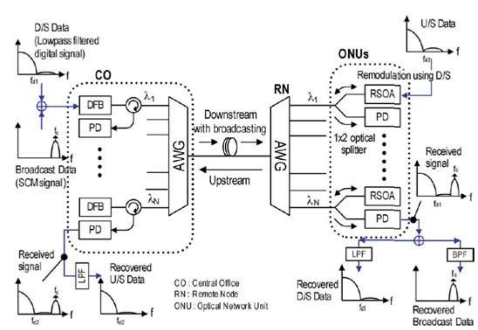



Figure 1: Laboratory setup for transmission experiments with real-time processing. IF – interface, FPGA – field programmable gate array, DAC- digital to analog converter, ADC – analog to digital converter, DMZM – dual Mach-Zehnder modulator, PD-Rx – polarization diversity receiver, EDFA – erbium doped fiber amplifier, VOA – variable optical attenuator, PM – phase modulator




- T. Kim and S. Han, "Reflective SOA-Based Bidirectional WDM-PON Sharing Optical Source for Up/Downlink Data and Broadcasting Transmission," in *IEEE Photonics Technology Letters*, vol. 18, no. 22, pp. 2350-2352, Nov.15, 2006.
- S. Smolorz *et al.*, "Demonstration of a coherent UDWDM-PON with real-time processing," in OFC 2011, Los Angeles, CA

## Past
### RF video overlay – first standardized WDM-PON

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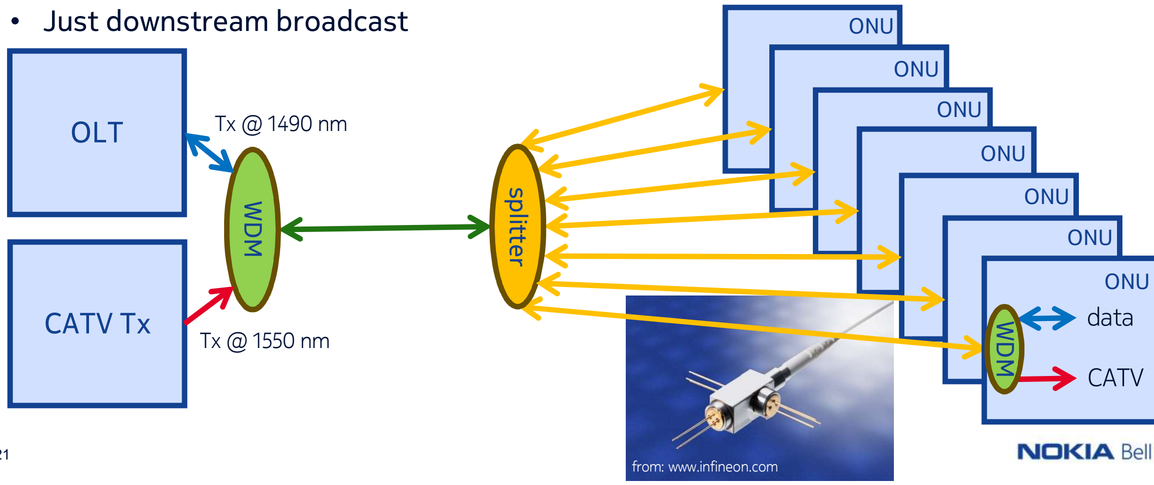
- Before IP video was mature (standardized ITU-T G.983.3 Amd 1, 2002)
- 134 carriers (54-870 MHz) equivalent to ~6.4 Gb/s data
- Just downstream broadcast



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Introduction

Past

## Present

Future

Concluding remarks

- Overview current 10G PON transceiver technology
- Wavelength stable burst mode transmitter
- 25 Gb/s line-rate PON



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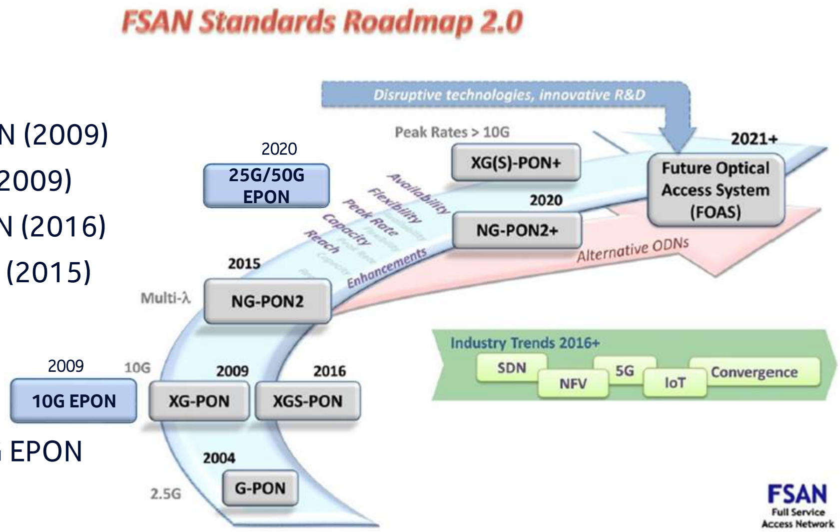
## Present
### Overview current 10G PON transceiver technology

Current standards in use

- IEEE 802.3av: 10G EPON (2009)
- ITU-T G.987: XG-PON (2009)
- ITU-T G.9807: XGS-PON (2016)
- ITU-T G.989: NG-PON2 (2015)
  (Tunable TWDM-PON)

Coming soon:

- IEEE 802.3ca: 25G/50G EPON
  (Fixed TWDM-PON)

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## Present
### Overview current 10G PON transceiver technology

- Downstream wavelength in C-band: EML based Tx
- Upstream wavelength in O-band (except NG-PON2): DML based Tx
- Forward error correction: 8-bit Reed Solomon code
- NRZ modulation
- No signal processing
- Direct detection with APD based receivers


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# Present
## TWDM-PON (NG-PON2)

- Transmitters and receivers are l-tunable (<10 μs – 1 s)
- Minimum 4 wavelengths in up- and downstream (on 50, 100, or 200 GHz grid)
- ODN same as for conventional TDM-PON
- First lab demonstrations around 2012/2013
- Currently commercial systems are available

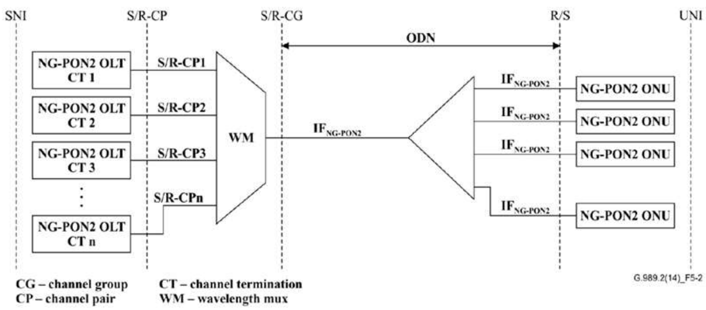


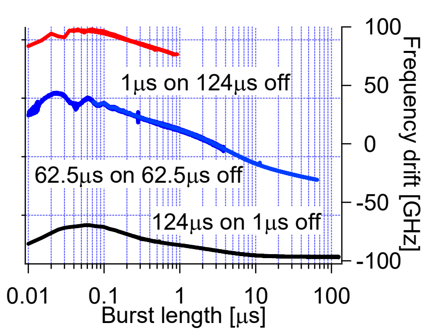

**Figure 5-2 – NG-PON2 reference logical architecture**

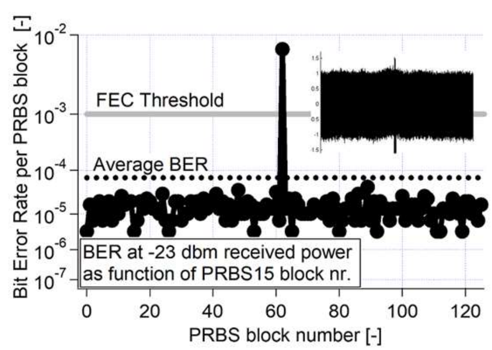
- ITU-T G.989.2, "40-Gigabit-capable passive optical networks 2 (NG-PON2): Physical media dependent (PMD) layer specification", (2014)
- Y. Ma *et al.*, "Demonstration of a 40Gb/s time and Wavelength Division Multiplexed passive optical network prototype system," *OFC/NFOEC*, Los Angeles, CA, 2012
- D. van Veen *et al.*, "System demonstration of a time and wavelength-set division multiplexing PON," *ECOC 2013*, London, 2013



# Present
## Wavelength stable burst mode transmitter

- Up to 100 GHz wavelength grid enables thermal tunable transmitters and receivers but makes the allowable l-excursion stringent (maximum spectral excursion (MSE) ±20 GHz for 100 GHz grid)

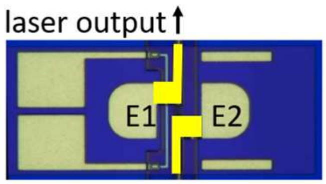



D. van Veen *et al.*, "Wavelength-stable burst-mode laser for next-generation PONs," in *IEEE/OSA Journal of Optical Communications and Networking*, vol. 11, no. 2, pp. A155-A165, Feb. 2019.

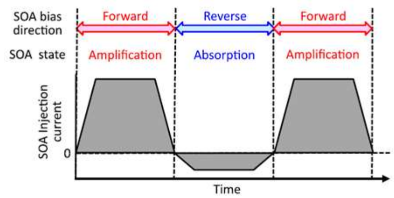
## Present
### Wavelength stable burst mode transmitter schemes

- For TWDM-PON, but also coherent PON in future

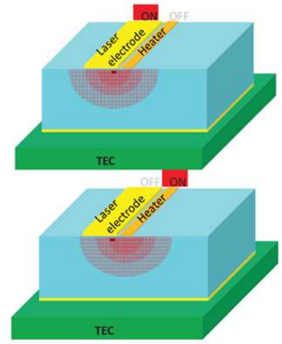



multi-electrode BM Tx

Manipulating laser cavity to turn laser on/off very fast




BM Tx with **reverse biased SOA** as shutter with large on/off ratio




counter heated BM Tx

keeps temperature as constant as possible, initial fast λ-drift hard to compensate


- K. Taguchi *et al.*, "Reverse bias voltage controlled burst-mode booster SOA in λ-tunable ONU transmitter for high-split-number TWDM-PON," in *IEEE/OSA JOCN*, vol. 10, no. 4, pp. 431-439, April 2018.
- X. Wu *et al.*, "Suppression of burst-mode operation induced laser wavelength drift for upstream transmission in TWDM-PON by using an integrated heater for thermal control," *OFC*, Los Angeles, CA, 2017
- H. Debrégeas *et al.*, "Quasi frequency drift suppression for burst mode operation in low-cost thermally-tuned TWDM-PON," *OFC*, Los Angeles, CA, 2017
- D. van Veen *et al.*, "Wavelength-stable burst-mode laser for next-generation PONs," in *IEEE/OSA JOCN*, vol. 11, no. 2, pp. A155-A165, Feb. 2019.




## Present
### 25 Gb/s line-rate PON – IEEE 802.3ca

- Relative penalty 10G APD receiver sensitivity versus 25G APD sensitivity ~ 5-5.5 dB
- Dispersion penalty mitigated by also using O-band in downstream
- Standardization by IEEE (2020)

| **10 Gb/s downstream IEEE 802.3av** | **25 Gb/s downstream IEEE 802.3ca** | **D (dB)** |
|---|---|---|
| | Relative b2b penalty ~5-5.5 dB | -5.5 |
| ER=6 dB | ER=8 dB | -4.5 |
| RS(255,239): BERin=1e-3 | LDPC: BERin=1e-2 | -3 |
| Min. ave. launch power +2 dB | Min. ave. launch power + 5dB | 0 |

Introduction

Past

Present

**Future**

Concluding remarks

- Line-rate > 25 Gb/s
- DSP equalization (BM)
- Coherent PON
- Flexible PON
- Optical integration/novel optics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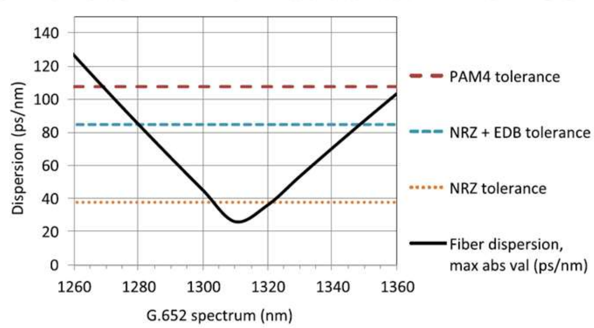
## Future
### Line-rate > 25 Gb/s

- A 25 Gb/s TDM-PON was still possible with NRZ modulation and use of APD/TIA receivers and without digital signal processing (enabled by O-band transmission in both directions and high gain LDPC-based FEC)
- For line-rates beyond 25 Gb/s we need to continue to find new ways to achieve the required PON optical power budget and chromatic dispersion tolerance
- Standardization of 50 Gb/s line-rate TDM-PON has started in ITU-T SG15 Q2

*Fiber dispersion (maximum, 20 km) and dispersion tolerance (EML source, 1 dB penalty) at 50 Gb/s.*




E. Harstead *at al.*, "Technology Roadmap for Time-Division Multiplexed Passive Optical Networks (TDM PONs)," in JLT, vol. 37, no. 2, pp. 657-664, Jan.15, 2019.



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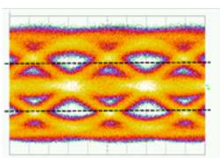
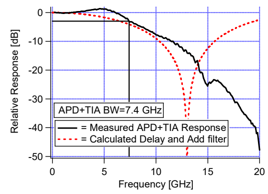
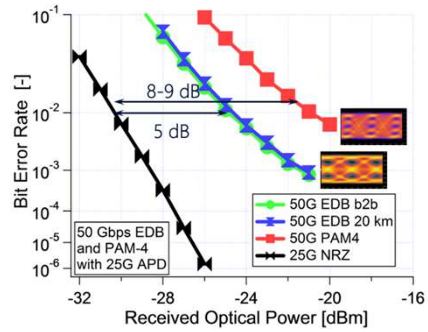
# Future
## Higher order modulation schemes

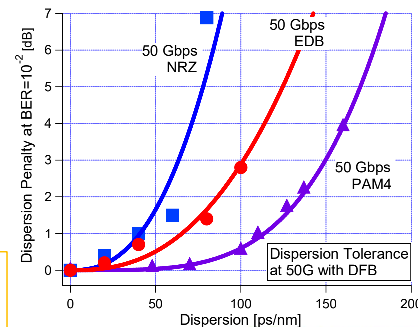
- 50 Gb/s detected with 25G APD/TIA
- Dispersion tolerance increased from NRZ
- EDB: limited bandwidth receiver converts the NRZ signal to electrical duobinary. We showed 25 Gb/s using 10G APD/TIA and 50 Gb/s using 25G APD/TIA






- PAM-4: Spectral width halved from NRZ and improved dispersion tolerance, but reduced b2b sensitivity. Selected modulation scheme for 50 Gb/s line-rates for data centers




- D. van Veen *et al.*, "26-Gbps PON transmission over 40-km using duobinary detection with a low cost 7-GHz APD-based receiver," *in ECOC 2012*
- P. Torres-Ferrera *et al.*, "Field demonstration of 25G-PON and XGS-PON burst-mode upstream coexistence", *in ECOC 2019*

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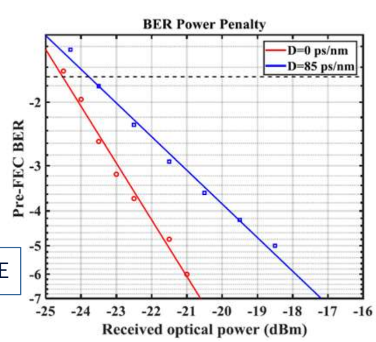
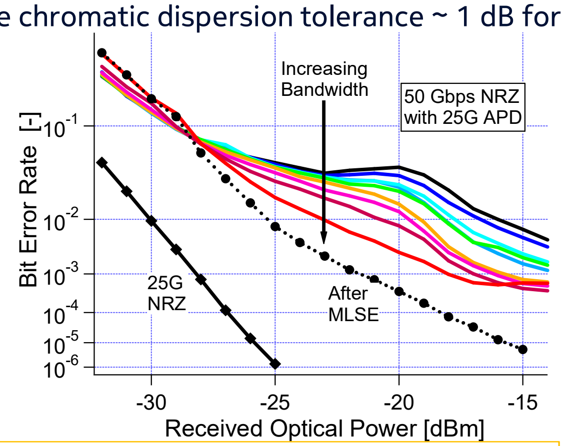
# Future
## Digital signal processing - equalization

- As an alternative to detecting EDB and PAM-4 with 25G optical components, one can equalize 50 Gb/s NRZ signals as well as enable chromatic dispersion tolerance ~ 1 dB for +85 ps/nm (>worst case 20 km @ 1344 nm)

41 tap FFE/MLSE




- M. Tao *et al.*, "Improved Dispersion Tolerance for 50G-PON Downstream Transmission via Receiver-Side Equalization," in OFC 2019, paper M2B.3
- D. van Veen and V. Houtsma, "Strategies for economical next-generation 50G and 100G passive optical networks [Invited]," in JOCN, vol. 12, no. 1, pp. A95-A103, January 2020.

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## Future
### Signal processing - linear burst mode receiver

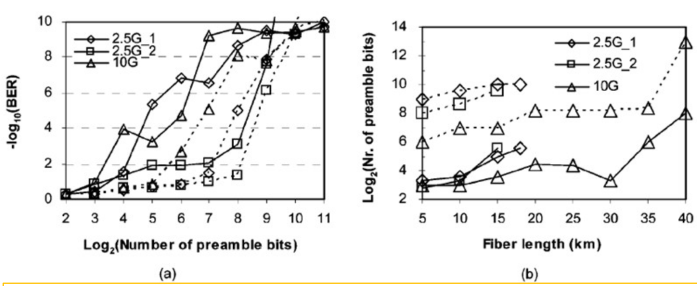
- Current commercial BM-Rx are limiting receivers, suitable for NRZ but not for equalization
- Linear BM-Rx are needed to support signal processing
- Challenges high BW linear BM-Rx:
  - Peak detector less accurate at high line-rates
  - Fast DC offset compensation becomes harder for high BW
  - Linear BM post amplifier needed
- A 50Gbit/s PAM-4 Linear BM TIA is demonstrated with an input dynamic range of at least 17.7 dB for NRZ and 10.9 dB for PAM-4. The settling time is measured to be 48 ns with negligible burst-mode penalty (2019)

- G. Coudyzer *et al.*, "A 50 Gbit/s PAM-4 Linear Burst-Mode Transimpedance Amplifier," in *IEEE PTL*, vol. 31, no. 12, pp. 951-954, June15, 2019.



## Future
### Signal-processing – burst mode

- Burst mode signal processing needs to be very fast, 'average' settings need to be selected or settings need to be loaded per burst
- At 50 Gb/s we can tolerate ~6,430 bits preamble length (up to 2 dB BM penalty)



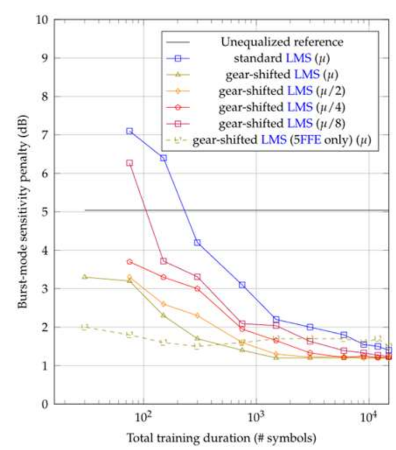
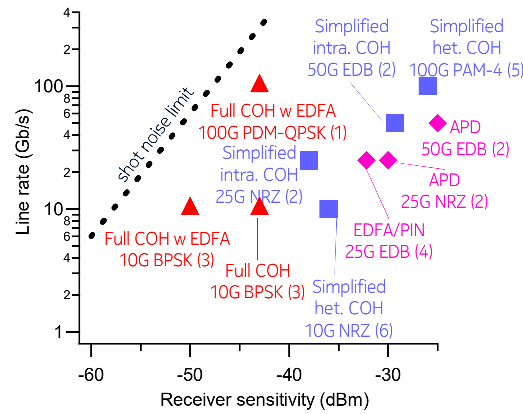




**Fig. 12.** Burst-mode sensitivity penalty as a function of training duration (in # symbols) for LMS and gear-shifted LMS for 5 km of fiber and five-taps FFE/two-taps DFE.

- P. Ossieur et al., "Burst-Mode Electronic Equalization for 10-Gb/s Passive Optical Networks," in IEEE Photonics Technology Letters, vol. 20, no. 20, pp. 1706-1708, Oct.15, 2008.
- G. Coudyzer et al., "Study of burst-mode adaptive equalization for >25G PON applications [Invited]," in IEEE/OSA JOCN, vol. 12, no. 1, pp. A104-A112, January 2020.

# Future
## Coherent PON

- ≥ 50 Gb/s
- Increases optical power budget
- Extra modulation dimensions possible (phase, polarization) to achieve > 50 Gbps
- Opens up C-band (full dispersion mitigation)
- Flexibility





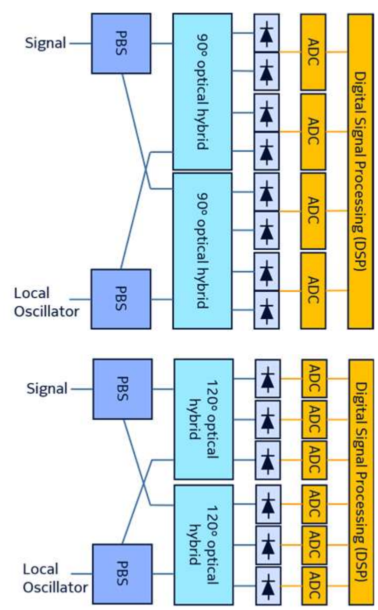
[1] D. Lavery *et al.*, "Realizing high sensitivity at 40 Gbit/s and 100 Gbit/s", OFC 2012
[2] V. Houtsma and D. van Veen, "Bi-Directional 25G/50G TDM-PON With Extended Power Budget Using 25G APD and Coherent Detection," J. Lightwave Technol. 36, 122-127 (2018)
[3] K. Kikuchi and S. Tsukamoto, "Evaluation of sensitivity of the digital coherent receiver," J. Lightw. Technol. 26 (13), 1817–1822 (2008)
[4] V. Houtsma and D. van Veen, "Demonstration of symmetrical 25 Gbps TDM-PON with 31.5 dB optical power budget using only 10 Gbps optical components," *ECOC 2015*
[5] J. Zhang, *et al.*, "Single-Wavelength 100-Gb/s PAM-4 TDM-PON Achieving Over 32-dB Power Budget Using Simplified and Phase Insensitive Coherent Detection," *ECOC 2018*
[6] J. A. Altabas *et al.*, "Real-Time 10 Gbps Polarization Independent Quasicoherent Receiver for NG-PON2 Access Networks," in Journal of Lightwave Technology, vol. 37, no. 2, pp. 651-656, Jan.15, 2019.




# Future
## Coherent PON

- Transport networks uses polarization- and phase-diverse intradyne coherent receiver based on 90º optical hybrids and balanced detection (full COH)

- Alternatively one can build such a receiver based on 120º optical hybrids/3x3 couplers with single-ended detection

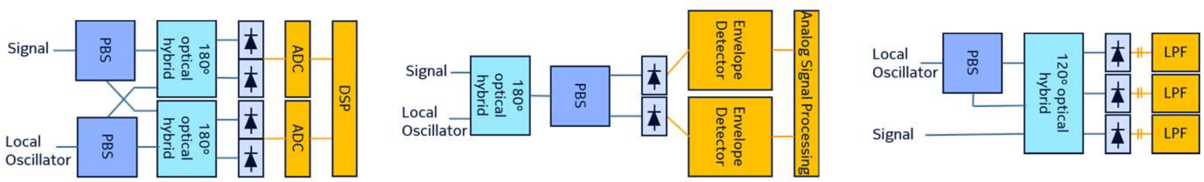



$$I_I = I_2 - 0.5I_1 - 0.5I_3 = |ELO||ES|cos\varphi$$
$$I_Q = \sqrt{3}/2(I_3 - I_1) = |ELO||ES|sin\varphi$$


- D. Lavery *et al.*, "Recent Progress and Outlook for Coherent PON," *OFC 2018*, San Diego, CA, 2018
- C. Xie et al., "Colorless coherent receiver using 3 × 3 coupler hybrids and single-ended detection," Opt. Exp., vol. 20, pp. 1164–1171, 2012.

# Future
## Low complex coherent PON

- Low complexity/cost coherent
- Heterodyne detection based on 2x2 coupler
- Polarization diverse detection based on 3x3 coupler (heterodyne/intradyne)

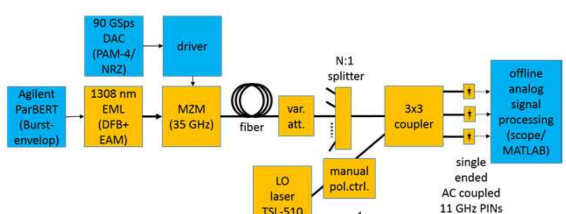


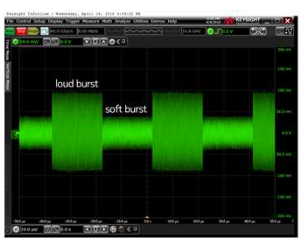

E. Ciaramella, "Polarization-Independent Receivers for Low-Cost Coherent OOK Systems," in *IEEE Photonics Technology Letters*, vol. 26, no. 6, pp. 548-551, March15, 2014



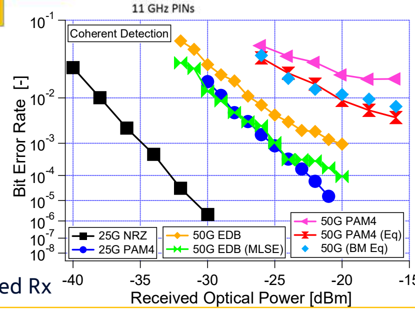


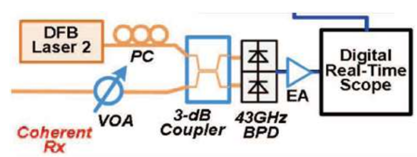
# Future
## Coherent PON

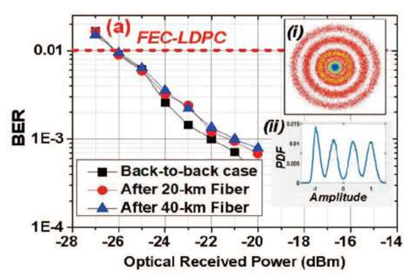



Coherent Detection with AC-coupled Rx



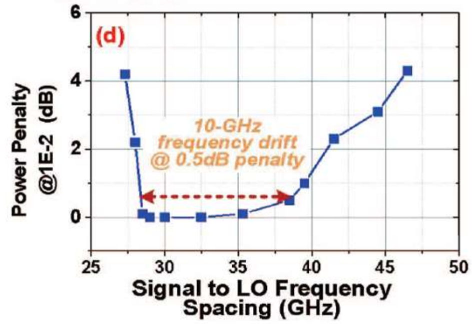



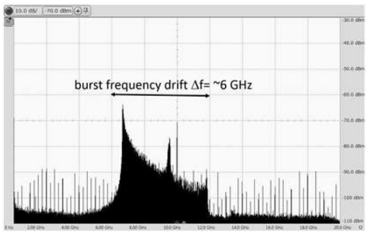



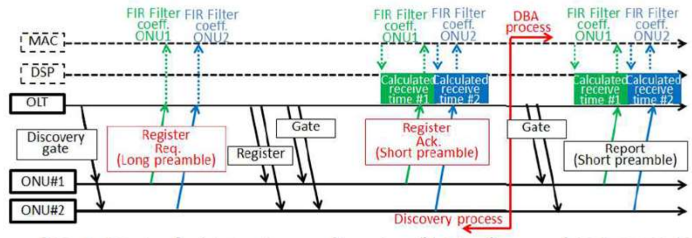

- D. van Veen and V. Houtsma, "Bi-directional 25G/50G TDM-PON with Extended Power Budget using 25G APD and Coherent Amplification," in *OFC 2017*
- J. Zhang *et al.*, "Single-Wavelength 100-Gb/s PAM-4 TDM-PON Achieving Over 32-dB Power Budget Using Simplified and Phase Insensitive Coherent Detection," in ECOC 2018

# Future
## Coherent PON – burst mode

- Wavelength stable BM transmitter required to minimize required detector bandwidths
- Pre-calculated coefficients to compensate for factors that are the same for all bursts from a ONU



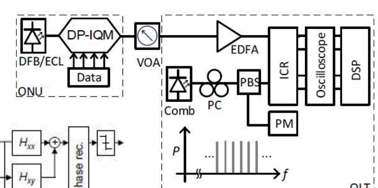

- R. Koma *at al.*, "Wide dynamic range burst-mode digital coherent detection using fast ALC-EDFA and pre-calculation of FIR filter coefficients," in *OFC 2016*
- D. van Veen and V. Houtsma, "Bi-directional 25G/50G TDM-PON with Extended Power Budget using 25G APD and Coherent Amplification," in *OFC 2017*
- J. Zhang *et al.*, "Single-Wavelength 100-Gb/s PAM-4 TDM-PON Achieving Over 32-dB Power Budget Using Simplified and Phase Insensitive Coherent Detection," in ECOC 2018



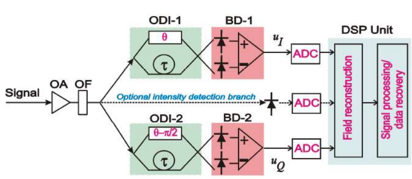


# Future
## Coherent PON – LO alignment for upstream burst mode

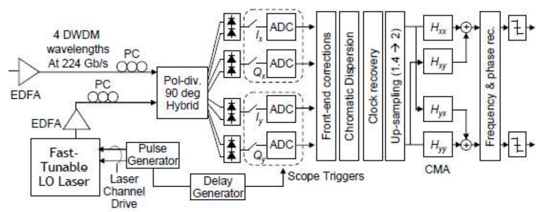
- Δλ signal and local oscillator determine required detector bandwidths, so they need to be aligned (and λ-stable BM transmitter is also needed)



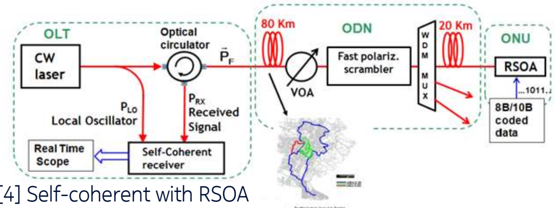

[3] Using comb-laser as LO to enable a usable λ-window for ONU Tx




[1] Transmitting LO from OLT (self-coherent detection)




[2] Fast-tunable LO to align with ONU Tx




[4] Self-coherent with RSOA

[1] Xiang Liu *et al.*, "Digital self-coherent detection," Opt. Express 16, 792-803 (2008)
[2] J. E. Simsarian *et al.*, "Fast-tuning 224-Gb/s intradyne receiver for optical packet networks,", OFC 2010
[3] M. M. H. Adib *et al.*, "Colorless Coherent Passive Optical Network using a Frequency Comb Local Oscillator," OFC 2019
[4] S. Straullu *et al.*, "Optimization of self-coherent reflective PON to achieve a new record 42 dB ODN power budget after 100 km at 1.25 Gbps," Opt. Express 20, 29590-29598 (2012)

# Future
## Coherent PON - polarization

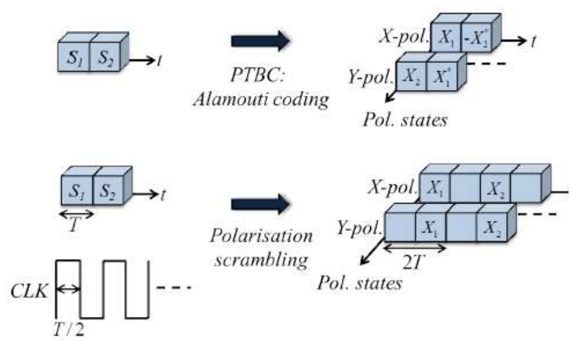



Fig. 4: Schematic of the Alamouti-coding (top) and polarisation scrambling (bottom), yielding polarisation-independent operation.

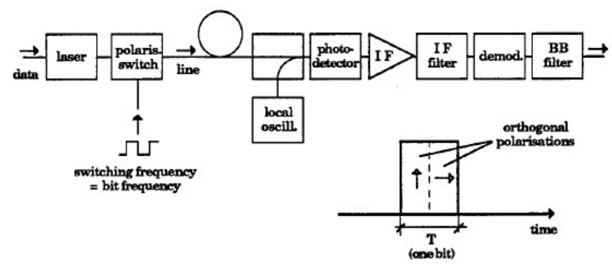



Fig. 1 – Polarisation diversity transmission by sinchronous intra-bit polarisation switching.


- MS Erkılınç *et al.*, "Comparison of Low Complexity Coherent Receivers for UDWDM-PONs (λ-to-the-User)", Journal of Lightwave Technology 36 (16), 3453-3464, 2018
- G. Marone *et al.*, "Polarisation independent detection by synchronous intra-bit polarization switching in optical coherent systems," IEEE International Conference on Communications, Including Supercomm Technical Sessions, Atlanta, GA, USA, 1990, pp. 1658-1662 vol.4.

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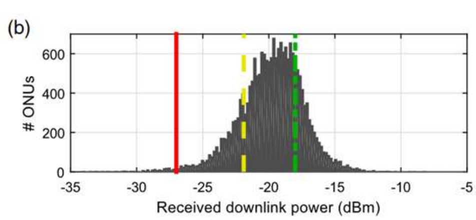
# Future
## Flexible PON – line-rate

- Constant line-rate PON is not optimal for resource usage and power consumption
- Installation margins for operators
- Every receiver is designed for worst case
- Minority of users have the worst case receiver sensitivity and minimum received optical power (variation ONU Tx launch power, variation fiber drop lengths, variation optical dispersion penalty, variation splitter loss per ONU, etc.)





- R. van der Linden *et al.*, "Increasing Flexibility and Capacity in Real PON Deployments by Using 2/4/8-PAM Formats", in Journal of Optical Communications and Networking, 9, (1), pp A1-A8 (2017)
- F. Vacondio *et al.*, "Flexible TDMA access optical networks enabled by burst-mode software defined coherent transponders," in ECOC 2013

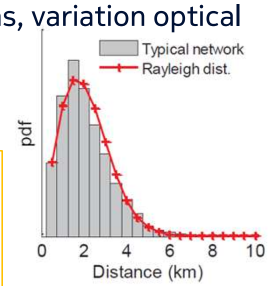
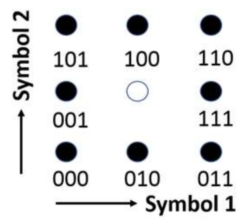




**Fig. 5:** distributions (pdf) of the central office – end user distances in typical network, with a Rayleigh fit.

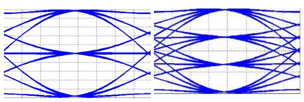
## Future

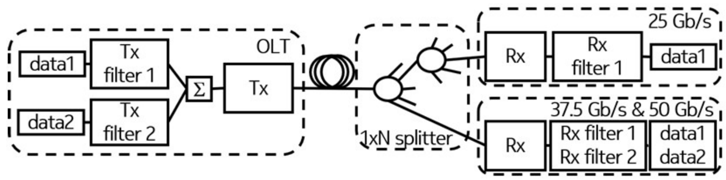
### Flexible PON - line-rate

- Lowest complexity multi-rate can be based on PAM-2/3/4, CAP-4 or NRZ+EDB modulation

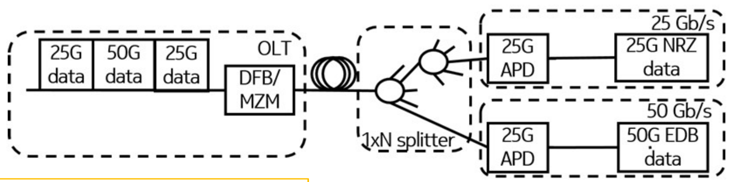



PAM-3 over two symbols






CAP-4 setup




D. van Veen *et al.*, Flexible 50G PON based on multi-rate PAM and CAP-4 with user interleaving, in ECOC 2019

NRZ/EDB setup

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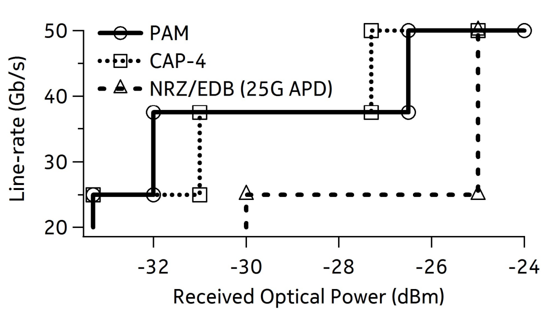
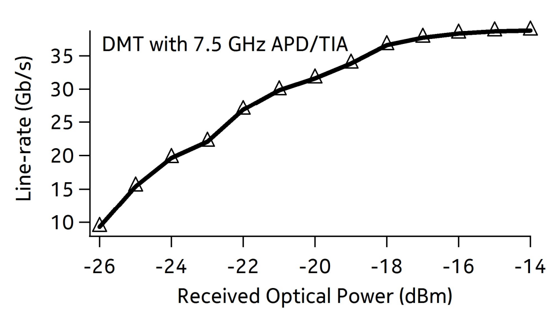
## Future

### Flexible PON - line-rate

- More bandwidth granularity can be achieved with multi-carrier modulation like DMT with bit-loading
- Example: mapping of 25 Gb/s receiver sensitivity to -3σ of normal distributed received power distribution yields ~32 Gb/s for PAM-2/3/4, ~34 Gb/s for NRZ/EDB, and ~35 Gb/s for DMT/OFDM

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# Future
## Optical components: high speed EML (/SOA)

- With an EML it is difficult to increase the output power and reduce chirp simultaneously, you can't design the refractive index change and the absorption coefficient independently The optical loss will be large when the chirp parameter is designed to be small and visa versa.

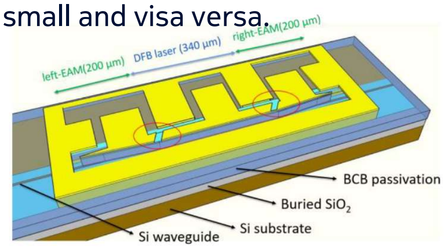



Fig. 1. Schematic of the III-V-on-silicon laser structure. The device consists the central DFB section and two coupling tapers on each side. The tapers ar electrically isolated by etching angled patterns into the p-InP (red circles).

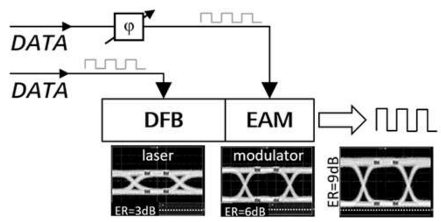
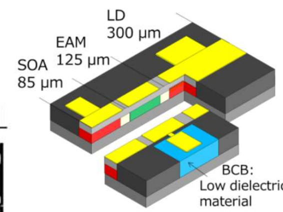


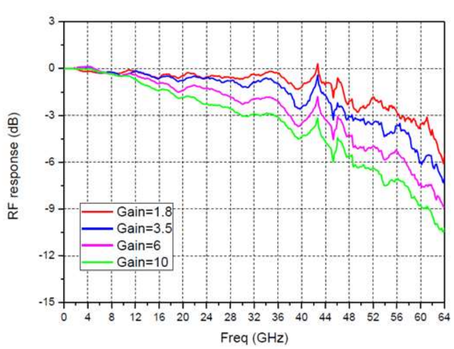

Fig. 1: Principle of operation of the laser modulated EML (LM-EML).




- Abbasi *et al.*, "III–V-on-Silicon C-Band High-Speed Electro-Absorption-Modulated DFB Laser," in *Journal of Lightwave Technology*, vol. 36, no. 2, pp. 252-257, 15 Jan.15, 2018
- I. Cano *et al.*, "Increasing the modulated output power from an EML transmitter through a novel dual-drive scheme", ECOC 2019
- T. Shindo *et al.*, 106 Gbit/s PAM4 60-km fibre-amplifierless transmission using SOA assisted extended reach EML (AXEL) with average output power of over 9 dBm, ECOC 2019



# Future
## Optical components – high bandwidth APD



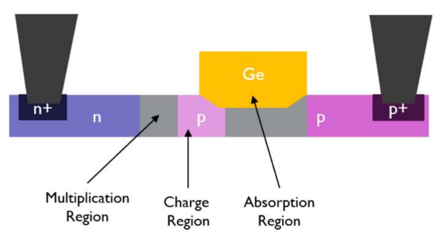
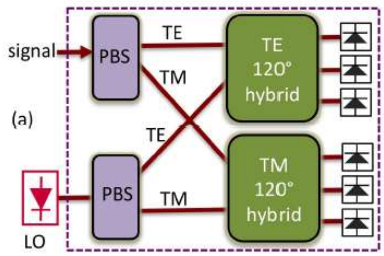




Fig. 1 Schematic diagram of the Si-contacted waveguide integrated Ge/Si based separate absorption charge multiplication avalanche photodiode.

- M. Huang et al., "56GHz Waveguide Ge/Si Avalanche Photodiode," 2018 Optical Fiber Communications Conference and Exposition (OFC), San Diego, CA, 2018
- S. Srinivasan *et al.*, Silicon-contacted waveguide integrated Ge/Si avalanche photodiode with 32 GHz bandwidth and multiplication gain > 8, in ECOC 2019

## Future
Optical integration – Silicon Photonics

- High performance external modulators for low chirp transmitters
- Coherent PON



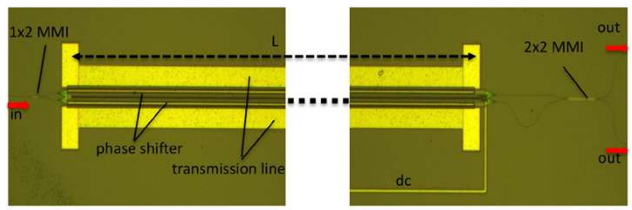




Fig. 1. Photograph of a single-drive push-pull silicon MZM.

- Po Dong *et al.*, "High-speed low-voltage single-drive push-pull silicon Mach-Zehnder modulators," Opt. Express **20**, 6163-6169 (2012)
- Po Dong, Chongjin Xie, and Lawrence L. Buhl, "Monolithic polarization diversity coherent receiver based on 120-degree optical hybrids on silicon," Opt. Express 22, 2119-2125 (2014)



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## Concluding remarks

- TDM-PON versus WDM-PON?
  - WDM-PON has been on the radar since early beginnings of PON
  - Line-rate per l is reaching the limits of PON over the legacy fiber plants
- Signal processing versus higher performance optical components?
  - DSP-enabled equalization
  - Coherent PON still has many challenges, but seems to be a logical next generation system
- Availability higher layer info to optimize PHY layer
  - Settings per ONU
- Flexibility



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## Additional references


- Jun Shan Wey, "The Outlook for PON Standardization: A Tutorial," J. Lightwave Technol. 38, 31-42 (2020)
- J. Prat et al., "Towards ultra-dense wavelength-to-the-user: The approach of the COCONUT project," 2013 15th International Conference on Transparent Optical Networks (ICTON), Cartagena, 2013, pp. 1-4
- T. Duong, N. Genay, P. Chanclou, B. Charbonnier, A. Pizzinat and R. Brenot, "Experimental demonstration of 10 Gbit/s upstream transmission by remote modulation of 1 GHz RSOA using Adaptively Modulated Optical OFDM for WDM-PON single fiber architecture," 2008 34th European Conference on Optical Communication, Brussels, 2008
- Q. Deniel, F. Saliou, L. A. Neto, N. Genay, B. Charbonnier, D. Erasme, and P. Chanclou, "Up to 10 Gbit/s transmission in WDM-PON architecture using External Cavity Laser based on Self-Tuning ONU," in Optical Fiber Communication Conference, OSA Technical Digest (Optical Society of America, 2012), paper JTh2A.55.
- G. Simon et al., "Focus on Time-Dependent Wavelength Drift of DMLs Under Burst-Mode Operation for NG-PON2," in Journal of Lightwave Technology, vol. 34, no. 13, pp. 3148-3154, 1 July1, 2016.
- R. Bonk, "SOA for future PONs," in Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2018), paper Tu2B.4.




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