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Multipulse modulation schemes for 100 Gigabit Ethernet

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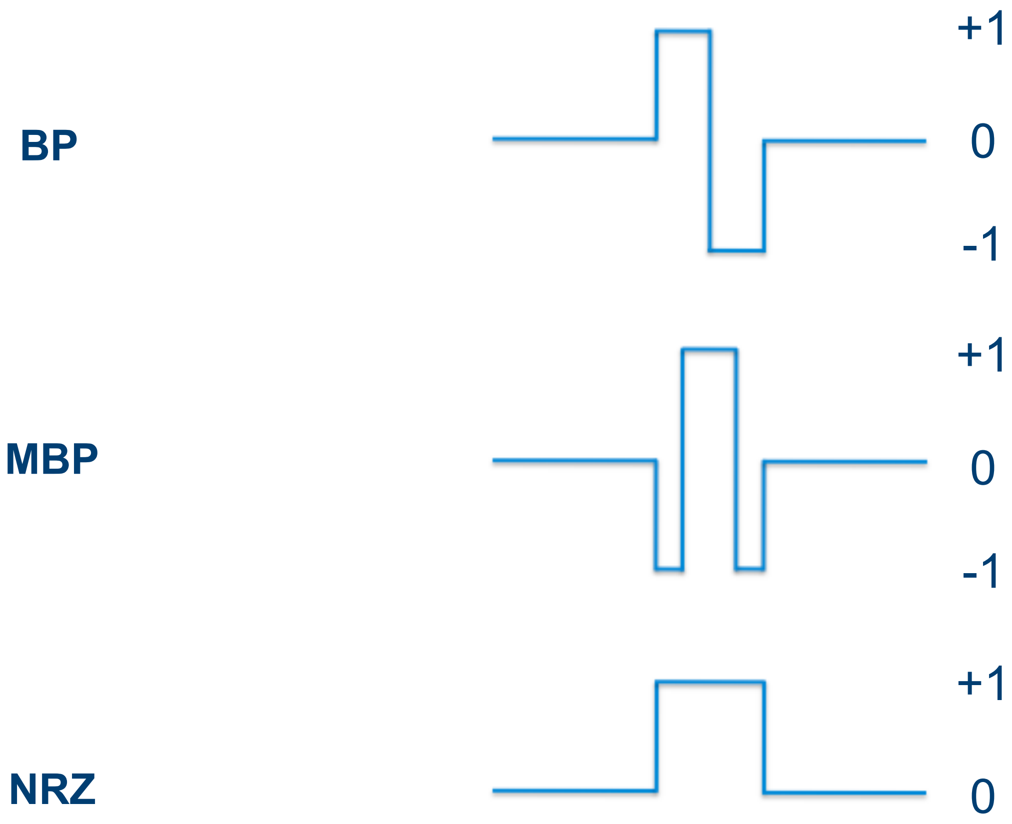
Principle of multipulse modulation

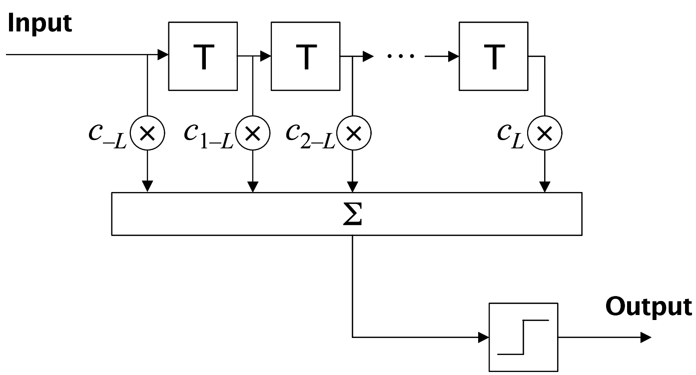
- Consider a simple scheme using three pulses
- Pulse shapes: biphase (BP), modified biphase (MBP) and NRZ:



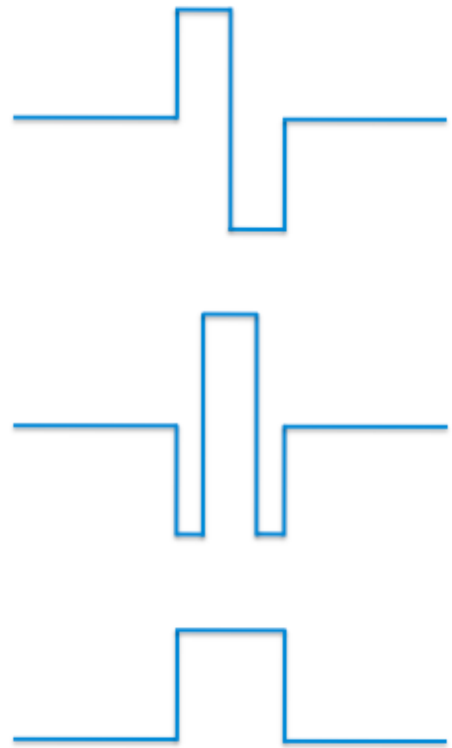
Multiplying any pair of these pulses, it is evident that they are ***orthogonal****, i.e. they have zero cross-correlation*

Generation of pulses using transversal filters

- Simple transversal filters may be used to perform pulse shaping in the transmitter



4-tap transversal filter coefficients



+1 +1 -1 -1

-1 +1 +1 -1

+1 +1 +1 +1

Comments on multipulse modulation

- Advantages include:
  - The use of multiple pulses, rather than multiple levels, avoids the large relative receiver sensitivity penalty seen in links using PAM*n*, where $n > 2$
  - In effect, the multipulse receiver processes multiple *NRZ* signals from the outputs of the matched filters, which may simplify clock recovery and decision circuits relative to PAM
  - The Tx pulse shaping and Rx matched filtering may be performed using simple and potentially low-power transversal filters. The delay lines may be implemented as passive analog structures
  - Incoming independent data channels may be directly shaped to a corresponding pulse, without complicated symbol mapping, gearboxes etc. The number of pulses used may be chosen to be appropriate to the application

- Disadvantages include:
  - The bandwidth requirements are generally larger than a corresponding PAM scheme
  - Bandwidth limitations result in interference between pulses, although this may be cancelled
  - The horizontal eye opening at the outputs of the matched filters may be restricted

Motivation for a 100 Gb/s multipulse scheme

- Motivated by the 4 x 25 Gb/s electrical interface of the next-generation 100 GbE standard

- A *four-pulse scheme* is especially appropriate since each incoming 25 Gb/s data channel may be mapped to a corresponding orthogonal multipulse channel at 25 Gbaud, *without any symbol rate conversion*†

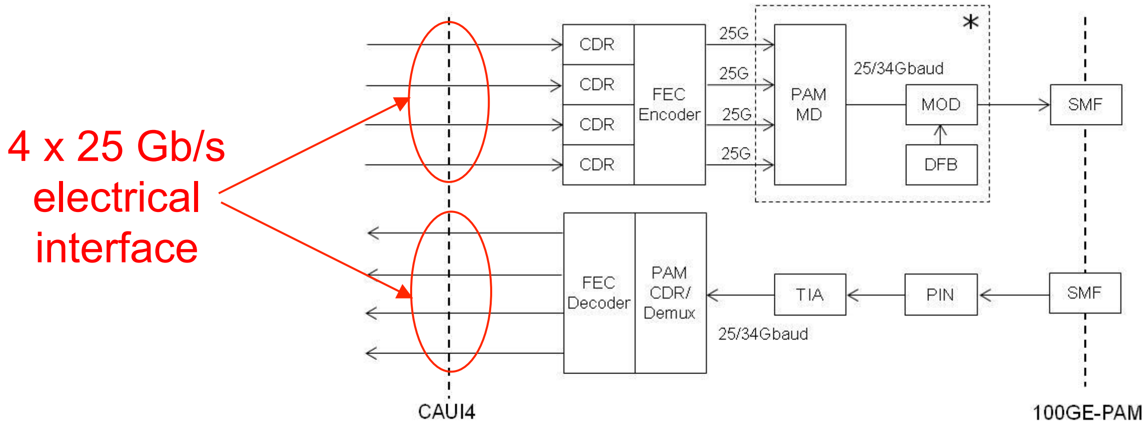


Figure: S. Bhoja   * Multiple Implementations possible

- It is natural to consider the use of orthogonal pulses based upon the fourth-order Hadamard matrix, for which a simple 4-tap transversal filter (10 ps tap spacing) may be used to perform the encoding and decoding operations

$$H_4 = \begin{bmatrix} + & + & + & - \\ - & + & + & + \\ + & - & + & + \\ + & + & - & + \end{bmatrix}$$

† As for multilevel mapping schemes, the lane-to-lane dynamic skew of the interface must be sufficiently small. This is required to ensure synchronization of the pulses

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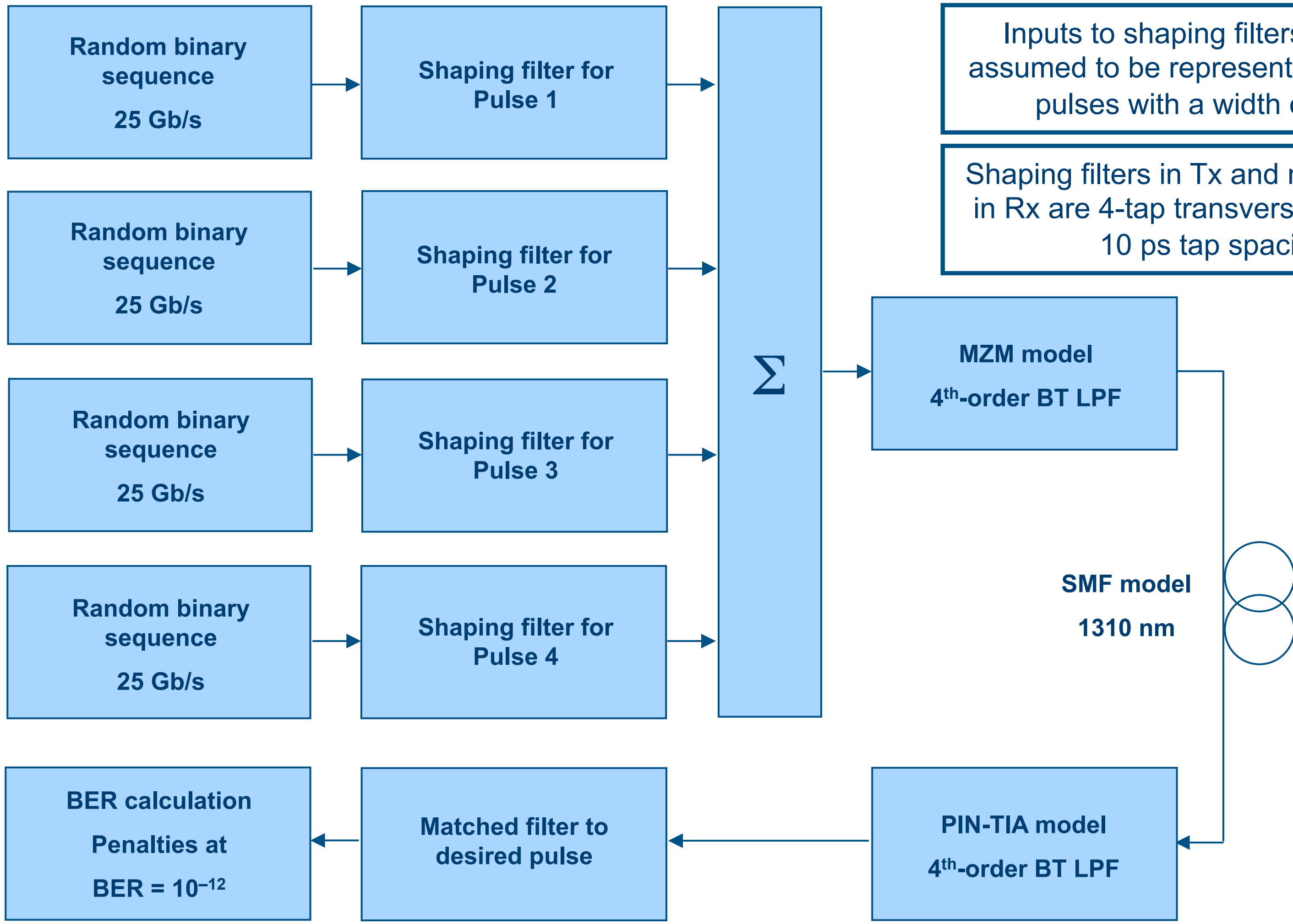
Block diagram



Inputs to shaping filters in Tx are assumed to be represented as bipolar pulses with a width of 10 ps

Shaping filters in Tx and matched filter in Rx are 4-tap transversal filters with 10 ps tap spacing

Simulation parameters

Transmitter

Four independent random binary sequences at 25 Gb/s each shaped to one of four pulse shapes: Pulse 1, Pulse 2, Pulse 3 or Pulse 4. A 4-tap transversal filter with 10 ps tap spacing performs the pulse shaping

MZM model: 4^{th}-order Bessel-Thomson LPF with –3 dBe frequency of 50 GHz

λ = 1310 nm

Fiber

Standard SMF

Receiver

R = 0.9 A W^{-1}; 12 pA/√Hz thermal noise (double-sided PSD)

PIN-TIA model: 4^{th}-order Bessel-Thomson LPF with –3 dBe frequency of 50 GHz

Matched filter (4-tap transversal filter with 10 ps tap spacing) to either Pulse 1, Pulse 2, Pulse 3 or Pulse 4. The tap coefficients of the matched filter are the time-reversed coefficients of the corresponding Tx shaping filter

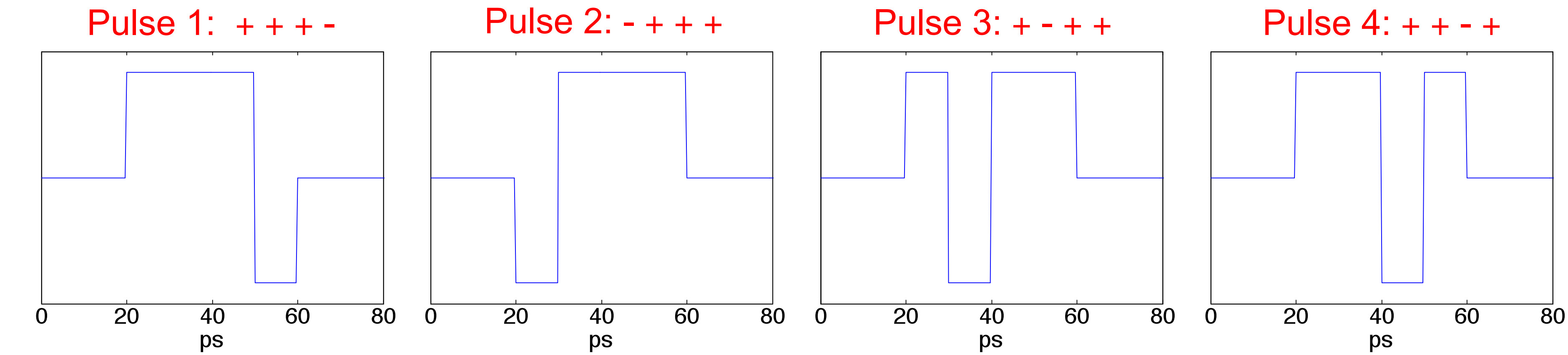
BER calculation performed to determine penalty relative to back-to-back

Penalties calculated at BER = 10^{-12}

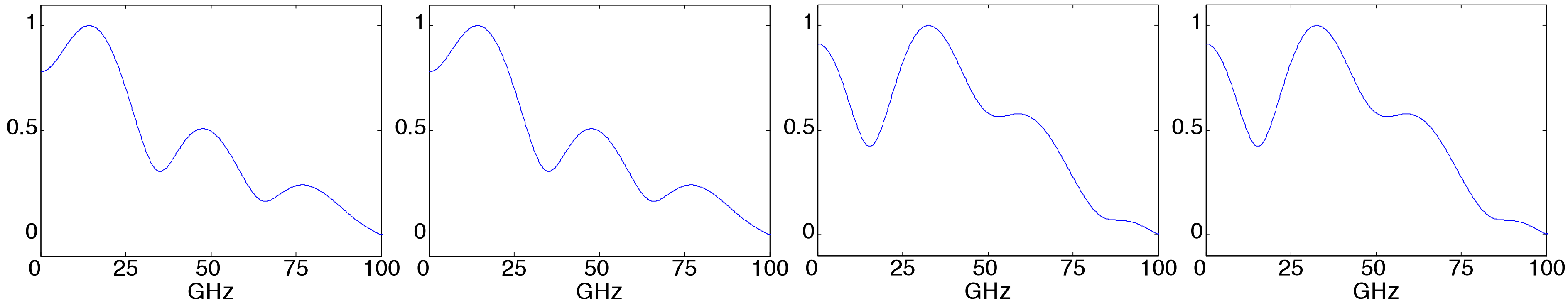
Results presented to provide a relative receiver sensitivity penalty compared to a 32 Gb/s NRZ link

Ideal pulse shapes & RF spectra

- Isolated single-one pulse shapes at output of transmitter *without* MZM bandwidth limitation



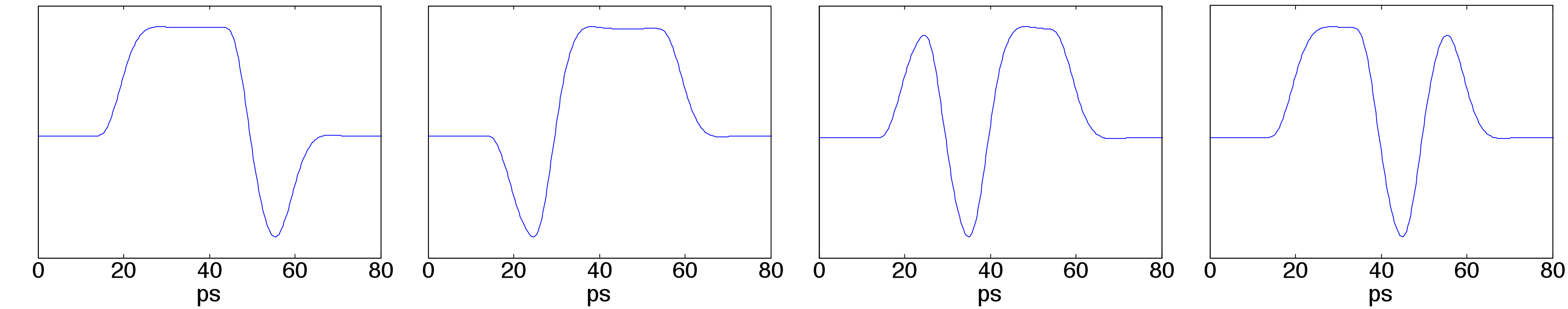
- Corresponding RF spectra (linear vertical scale)



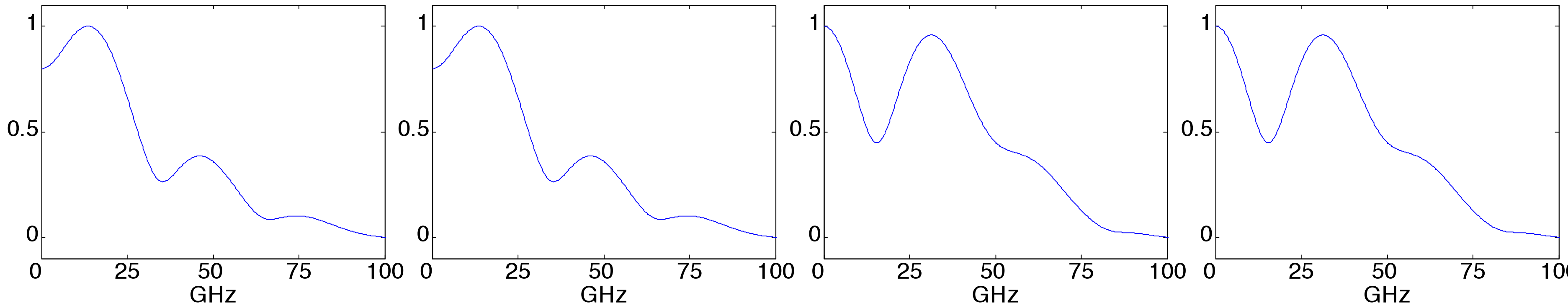
Pulse shapes & RF spectra

- Isolated single-one pulse shapes at output of transmitter *with* MZM bandwidth limitation

Pulse 1: + + + - Pulse 2: - + + + Pulse 3: + - + + Pulse 4: + + - +



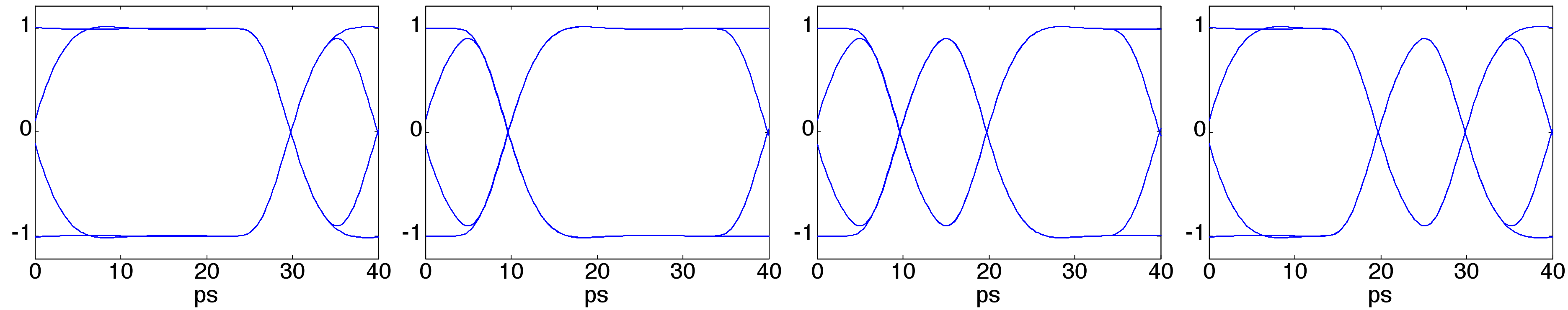
- Corresponding RF spectra (linear vertical scale)



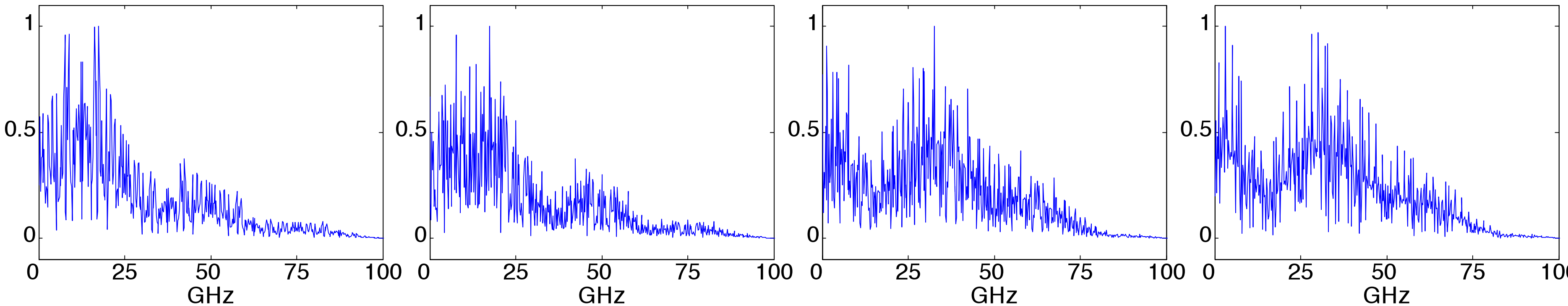
Modulated “eye” diagrams & RF spectra

- Modulated “eye” diagrams at output of transmitter *with* MZM bandwidth limitation

Pulse 1: + + + -　　Pulse 2: - + + +　　Pulse 3: + - + +　　Pulse 4: + + - +



- Corresponding RF spectra (linear vertical scale)

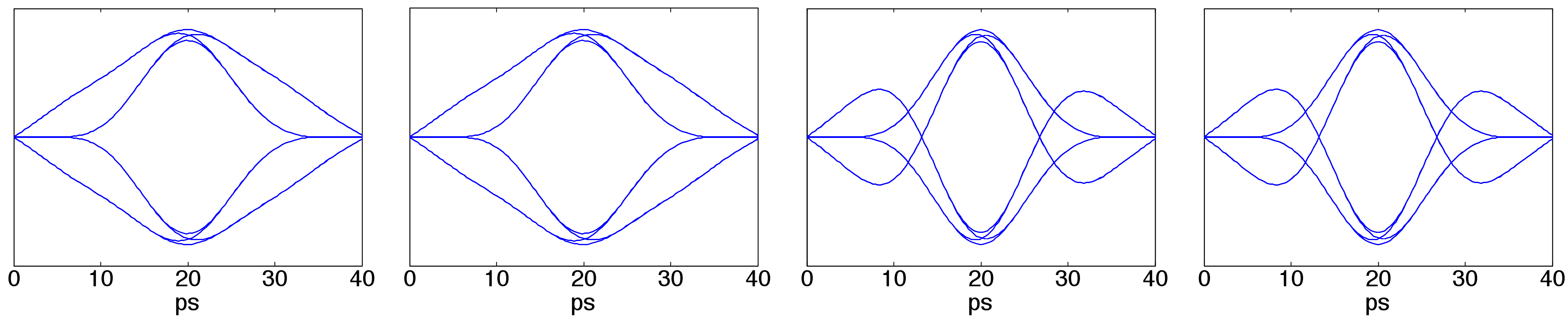


- Spectra indicate that the energy of each channel is mainly concentrated in the 0 – 50 GHz

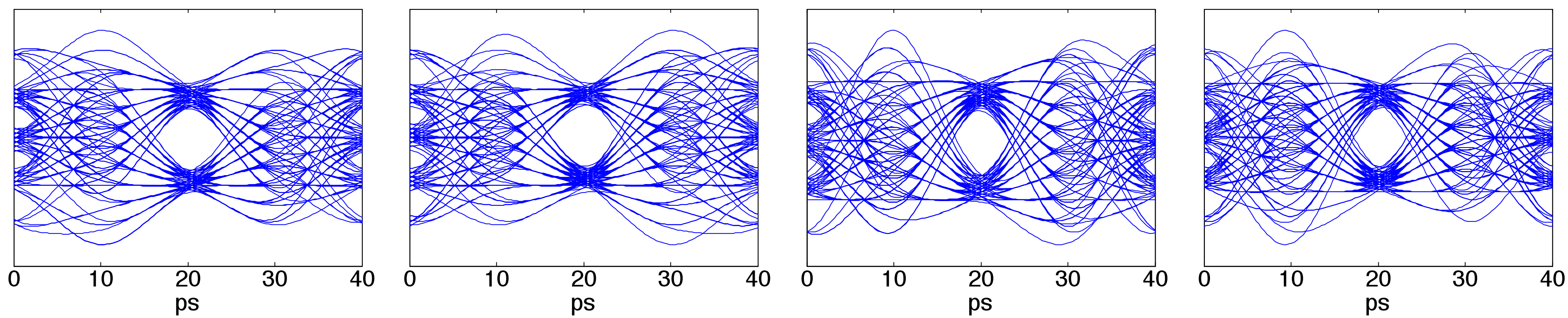
Demodulated eye diagrams

- After matched filter in receiver *with only one channel present*

Pulse 1: + + + -   Pulse 2: - + + +   Pulse 3: + - + +   Pulse 4: + + - +



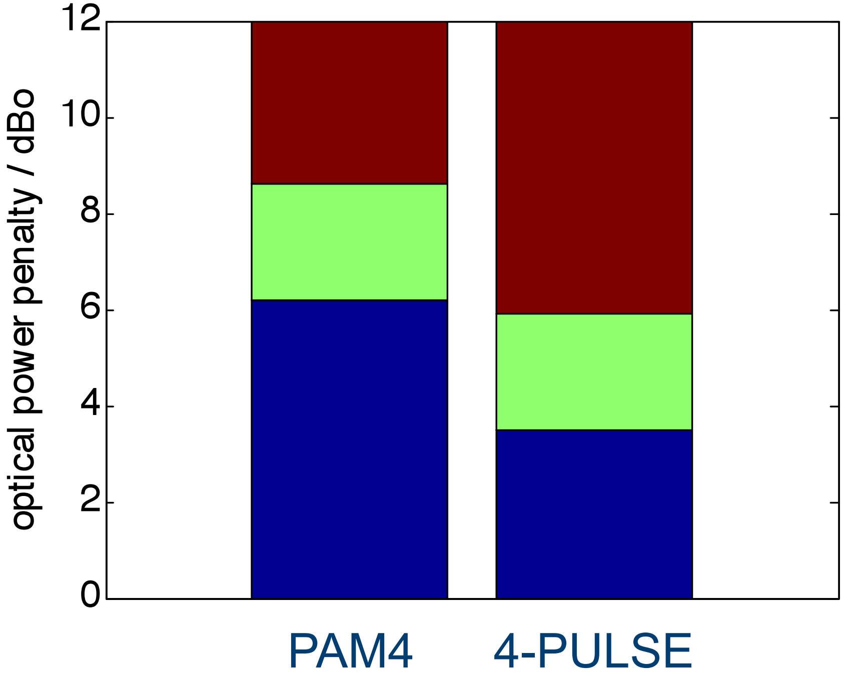
- After matched filter in receiver *with all channels present simultaneously*



- Eye diagrams are open although interference between channels is evident

Power budget comparison with PAM4

• Comparison with PAM4 *since PAM4 found to be the best-performing scheme of all schemes considered in Cambridge University presentation in Minneapolis* [1]



Red: unallocated penalties in a 12 dBo budget

Green: link loss for a 1 km SMF link at 1310 nm

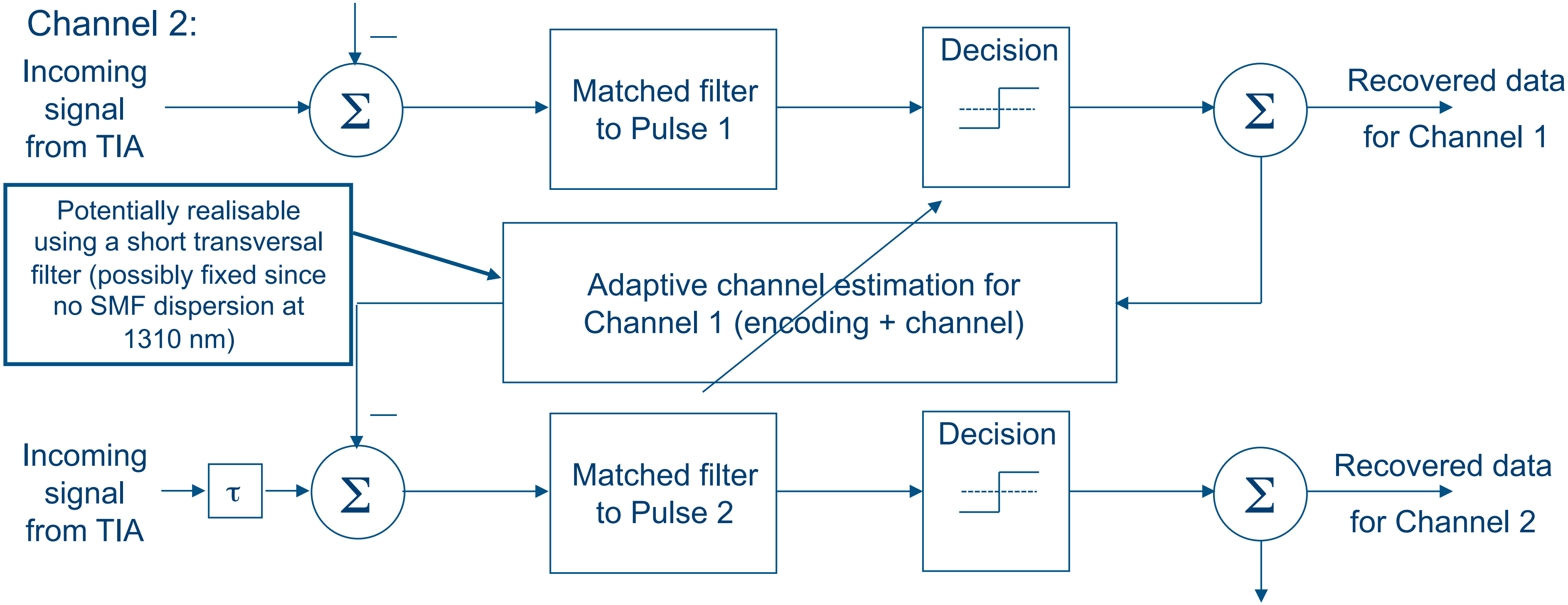
Blue: relative receiver sensitivity penalty (compared to a 32 Gb/s NRZ system)

N.B. Dispersion penalty insignificant at 1310 nm

• The four-pulse scheme exhibits approximately 2 dBo advantage compared to PAM4. The worst-performing channel is shown in the budget

Improving multipulse performance

- Since the multipulse receiver detects all channels, it should be possible to use recovered data on one channel to estimate the interference that channel has caused to others. That estimate of interference can then be subtracted, e.g. this system cancels interference due to Channel 1 from Channel 2:

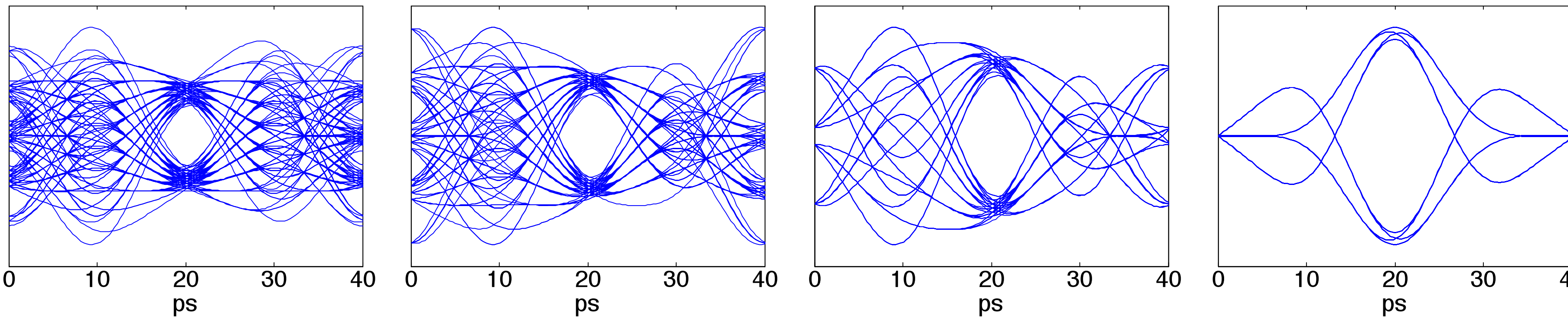


- This is similar to the principle of *multiuser detection*, as used in wireless CDMA systems
- For multiple pulses, iterative approaches may be used. Several types of *joint receivers* exist

Example of interference cancellation

• Considering Pulse 4 as an example:

Without interference cancellation	Cancellation of interference from Pulse 1	Cancellation of interference from Pulses 1 & 2	Cancellation of interference from Pulses 1, 2 & 3



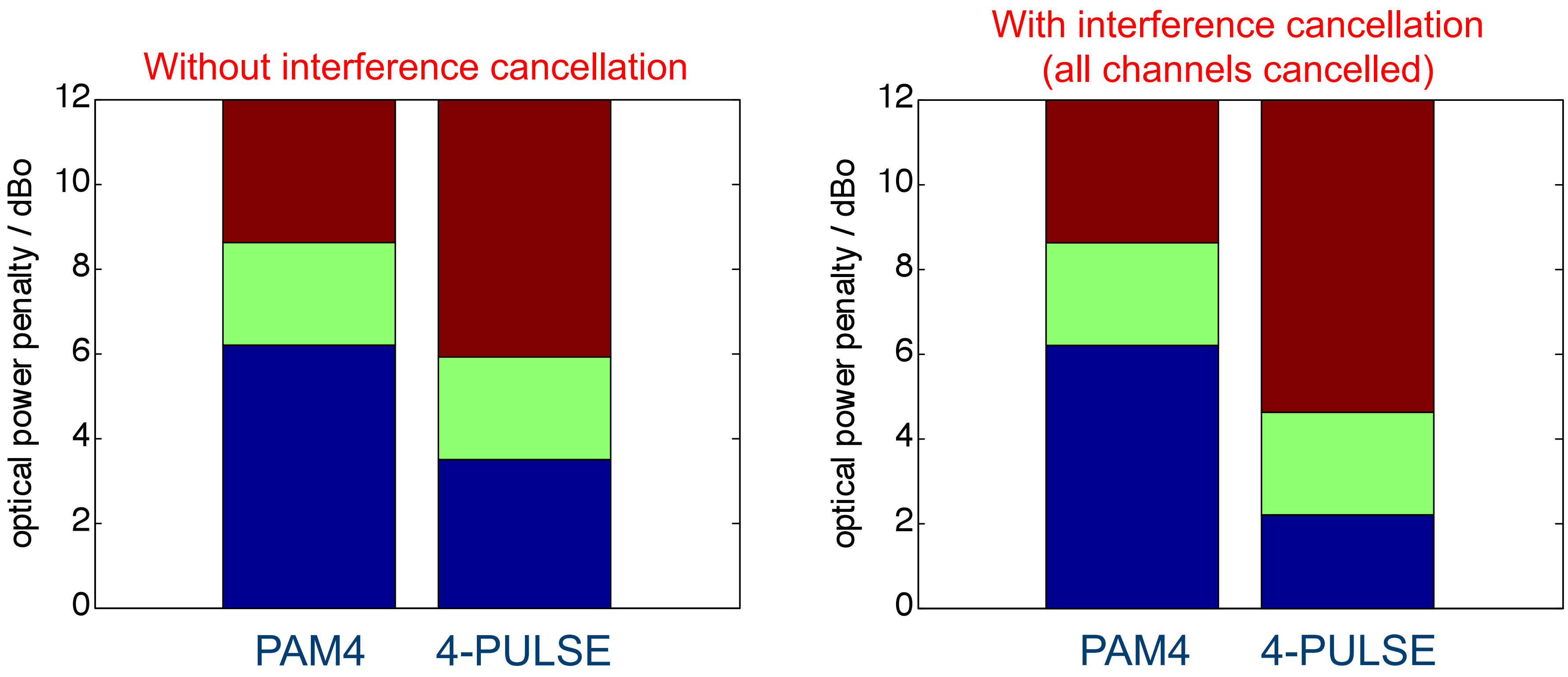
Increasing vertical eye opening

Increasing horizontal eye opening

• After interference cancellation of all channels, resulting eye diagram shows only ISI from the bandwidth limitation of the Tx and Rx. This may be reduced by equalization

Power budget comparison with PAM4

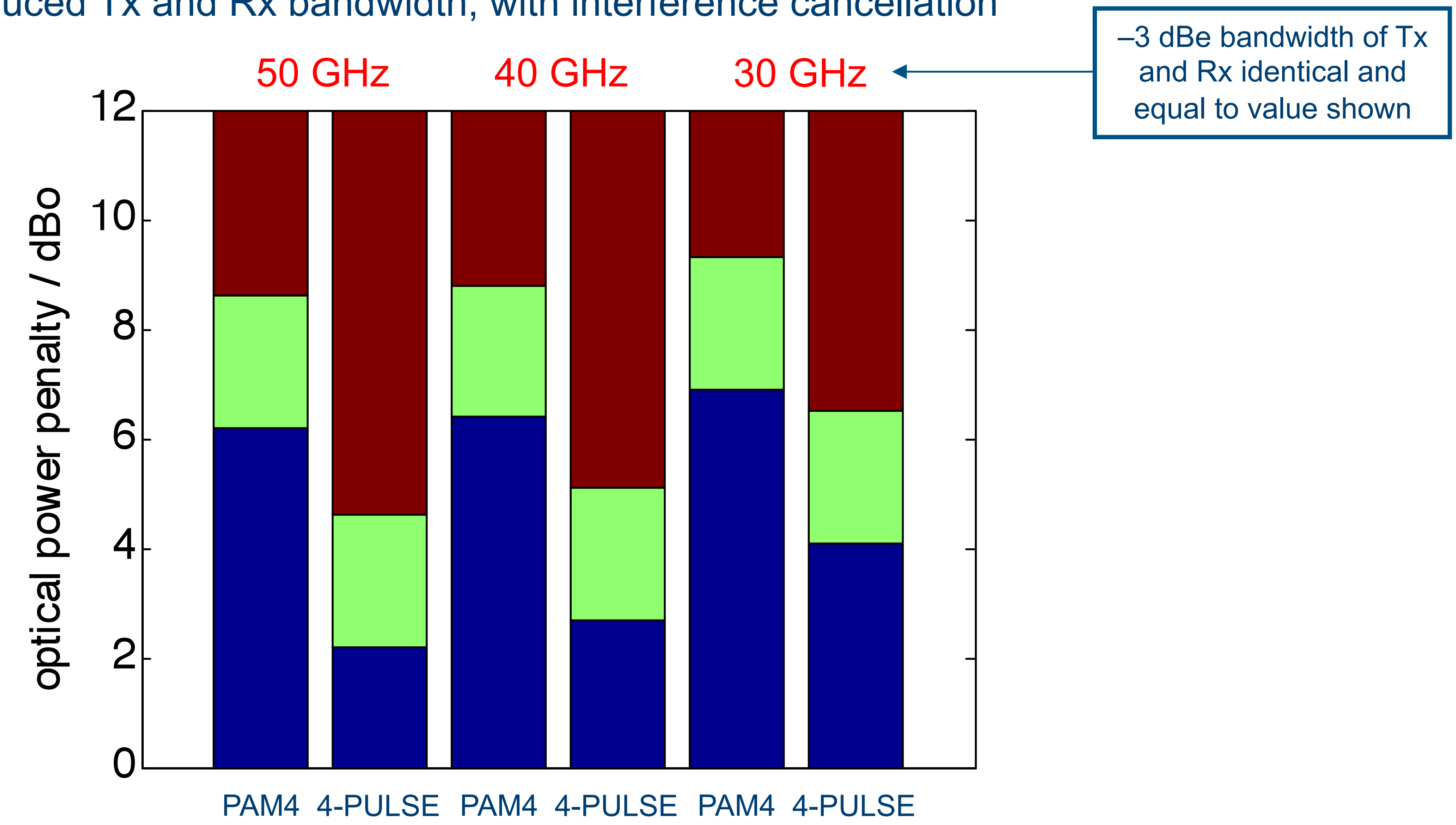
• 100 Gb/s four-pulse scheme compared with PAM4, with and without interference cancellation. The interference cancellation is assumed to be ideal



• With interference cancellation, approximately 4 dBo advantage compared to PAM4. The worst-performing channel is shown in the budget

Power budget comparison with PAM4

- Consider reduced Tx and Rx bandwidth, with interference cancellation



- Advantage with respect to PAM4 remains, even with reduced Tx and Rx bandwidth

Power consumption

- Multipulse scheme
  - Transmitter
    - 4 x 25 Gbaud CDR — 4 x 250 mW[3] — 1000 mW
    - 4 x 4-tap transversal filter (fixed CTLE)† — 4 x 30 mW[3] — 120 mW
    - 1 x MZM driver — 1 x 600 mW[4] — 600 mW
  - Receiver
    - 1 x PIN-TIA — 1 x 200 mW — 200 mW
    - 4 x 4-tap transversal filter (fixed CTLE) — 4 x 30 mW[3] — 1000 mW

Total: 3040 mW

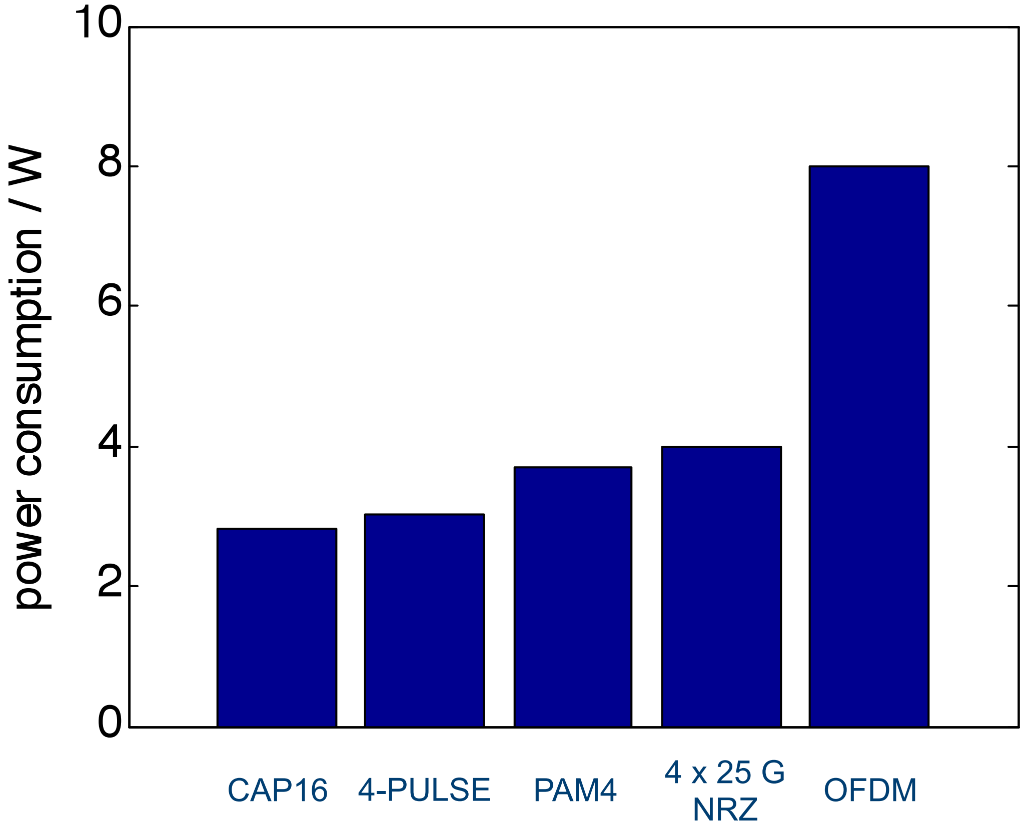
- PAM4
  - Transmitter
    - 4 x 25 Gbaud CDR — 4 x 250 mW[3] — 1000 mW
    - 1 x gearbox (4 x 25 Gbaud → 2 x 50 Gbaud) — 1 x 1000 mW — 1000 mW
    - 1 x 50 Gbaud PAM4 mapper — 1 x 200 mW — 200 mW
    - 1 x MZM driver — 1 x 600 mW[4] — 600 mW
  - Receiver
    - 1 x PIN-TIA — 1 x 200 mW — 200 mW
    - 1 x 50 Gbaud CDR — 1 x 500 mW[3] — 500 mW
    - 1 x 50 Gbaud PAM4 demapper — 1 x 200 mW — 200 mW

Total: 3700 mW

† Assumed to include differentiating pulse generators at inputs and summing circuit at outputs

Power consumption

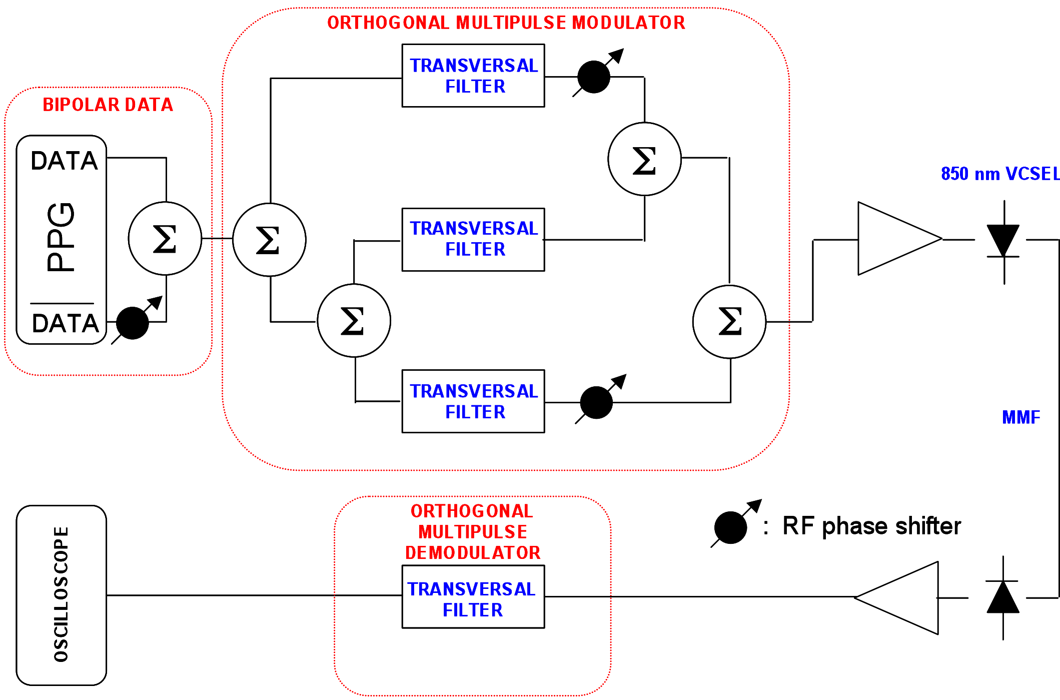
- Estimated total power consumption (Tx + Rx) compared with three other schemes

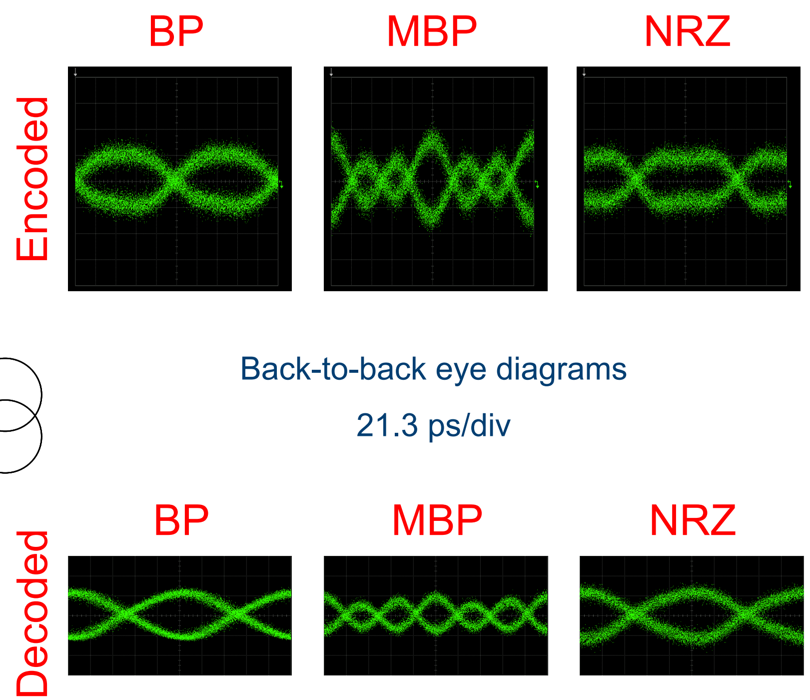


- Multipulse approach exhibits same power consumption as CAP16 (within the accuracy of the estimate) with potential advantage compared to PAM4

Experimental result

• Three-pulse (30 Gb/s aggregate) experiment presented at ECOC 2011 [2]





• VCSEL BW ≈ 18 GHz; PIN-TIA BW ≈ 15 GHz; transversal filter BW ≈ 12 GHz

• 30 Gb/s aggregate suggests that 100 Gb/s aggregate would be feasible if these BW limitations were scaled by ≈ 3

Conclusions

- Multipulse schemes considered for 100 GbE links

- A four-pulse 4 x 25 Gb/s scheme is highly relevant to the 4 x 25 Gb/s electrical interface of 100 GbE, avoiding symbol mapping

- The multilevel penalty associated with PAM*n*, where $n > 2$, is avoided

- Power budgets indicate the potential for superior performance compared with the best performing scheme presented at the last meeting (PAM4)

- A receiver which exploits knowledge of all pulses has the potential to improve the performance further

- Experimental work at 30 Gb/s with low-bandwidth components suggests feasibility of 100 Gb/s

References

[1] J. L. Wei, J. D. Ingham, R. V. Penty, I. H. White, “Performance studies of 100 Gigabit Ethernet enabled by advanced modulation formats,” *IEEE 802.3 Interim Meeting: IEEE 802.3 Next Generation 40 Gb/s and 100 Gb/s Optical Ethernet Study Group*. Minneapolis, MN, USA, May 2012

[2] J. D. Ingham, R. V. Penty, I. H. White, D. G. Cunningham, P. Westbergh, J. Gustavsson, Å. Haglund, A. Larsson, “Orthogonal multipulse modulation for next-generation datacommunication links,” *37th European Conference on Optical Communication*, paper Tu.3.C.2. Geneva, Switzerland, September 2011

[3] J. King, S. Bhoja, “MMF links, EQ and FEC,” *IEEE 802 Plenary Meeting: IEEE 802.3 Next Generation 40 Gb/s and 100 Gb/s Optical Ethernet Study Group*. Atlanta, GA, USA, November 2011

[4] S. Bhoja, “Study of PAM modulation for 100GE over a single laser,” *IEEE 802.3 Interim Meeting: IEEE 802.3 Next Generation 40 Gb/s and 100 Gb/s Optical Ethernet Study Group*. Newport Beach, CA, USA, January 2012