New design technique for optical links & an application

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Summary

- Bit error ratio, Q-factor and other metrics
- Estimating receiver Q-factor
- Accuracy of the estimation
- Application
  - Electronic “bottleneck” and photonics
  - Optical label switched networks
  - Payload bit error rate monitoring
  - Problem with label monitoring
  - What can be done?
- Conclusions

Optical link design & performance

- Optical link bit error ratio (*BER*) is a key performance measure
- Link design to minimise *BER* often requires expensive, complicated optical simulations
- For amplitude modulated, Non-Return to Zero systems have

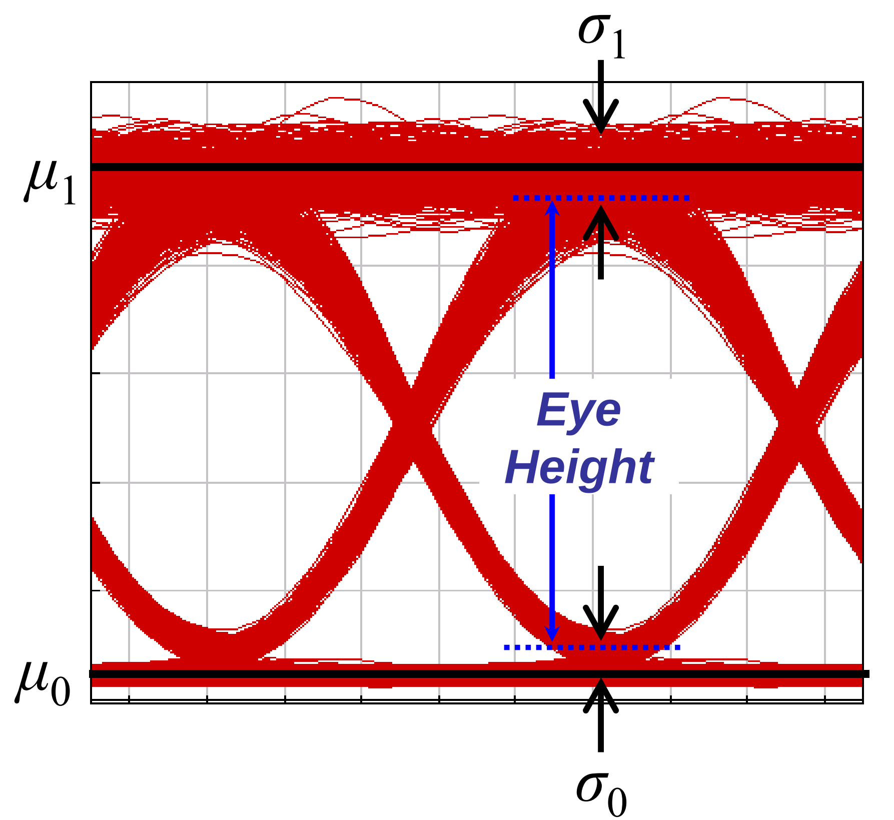
$$BER(Q) = \frac{1}{2}\left[1 - erf\left(\frac{Q}{\sqrt{2}}\right)\right] \approx \frac{1}{\sqrt{2\pi}} \frac{\exp(-Q^2/2)}{Q}$$

Standard signal quality metrics

- Q-factor

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} = \frac{2\mathcal{R}P(r-1)}{\Sigma(r+1)}$$

  - $\mathcal{R}$ = Detector responsivity
  - P = Receive power
  - r = Extinction ratio = μ_1/μ_0
  - $\Sigma = \sigma_1 + \sigma_0$

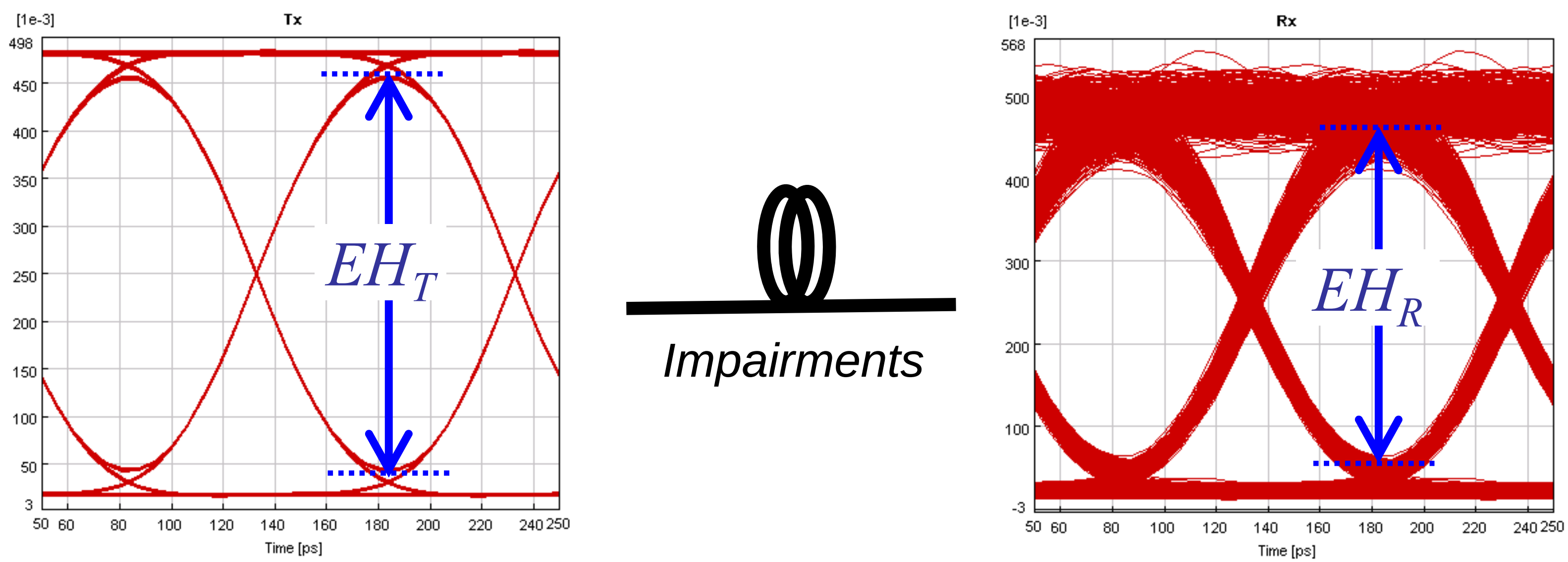


- Eye Height

$$EH = (\mu_1 - \mu_0) - (\sigma_1 + \sigma_0)$$

Eye Closure Penalty

- Measure at source (EH_S) and receiver (EH_R)



$$ECP = \frac{EH_S}{EH_R} = \frac{(\mu_{1,S} - \mu_{0,S}) - (\sigma_{1,S} + \sigma_{0,S})}{(\mu_{1,R} - \mu_{0,R}) - (\sigma_{1,R} + \sigma_{0,R})}$$

ECP to Q-factor relationship

- Have relationship for Q-value at receiver

$$Q_R \approx \frac{\left(P_R/P_S\right)Q_S ECP_{Total}}{1+Q_S\left(\left(P_R/P_S\right)ECP_{Total}-1\right)}$$

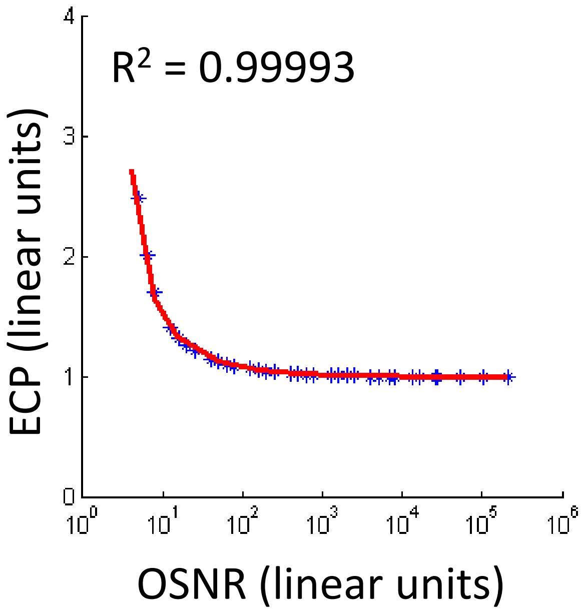
where:

- Q_R = signal Q-factor at the receiver
- Q_S = signal Q-factor at the source
- P_S/P_R = Source power/Receive power
  = net path signal gain from source to receive
- ECP_{Total} = Total ECP of signal between source to receiver

Eye Closure Penalty

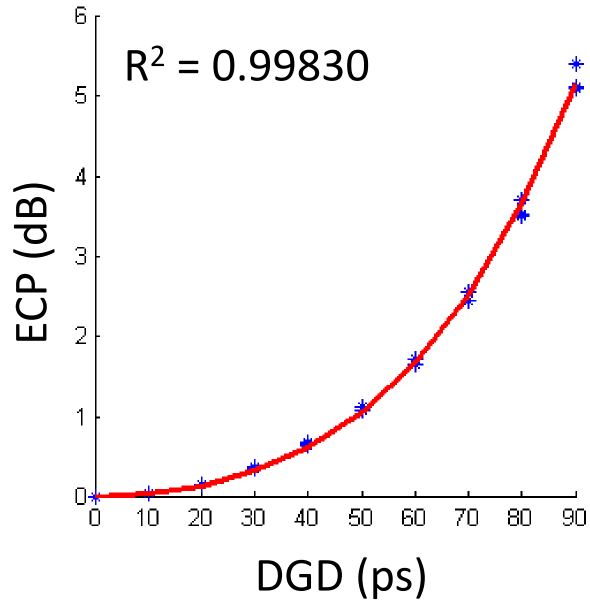
- ECP has known relationships to link parameters

Amplified Spontaneous Emission



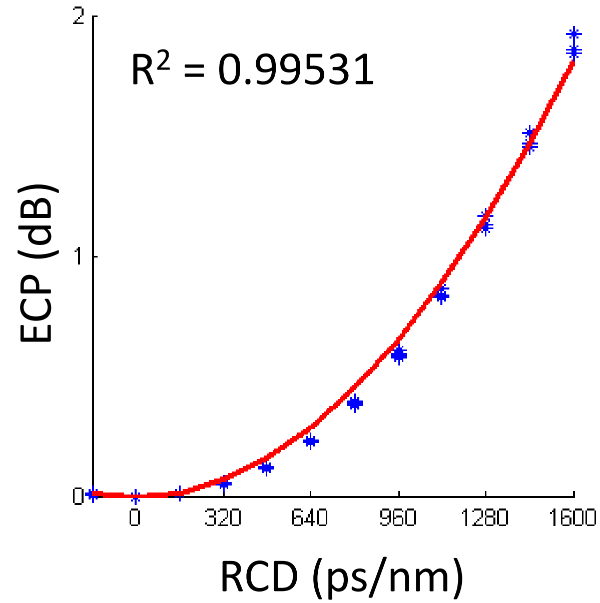
$$ECP_{ASE} = 1 + A_{OSNR} OSNR^{-1/2}$$

1st order PMD



$$ECP_{PMD}(dB) = A_{PMD} DGD^2$$

Residual Chromatic Dispersion



$$ECP_{RCD}(dB) = A_{RCD} \Delta t^2$$

Estimating ECP parameters

- Need to determine parameters:
  - A_{OSNR}, A_{PMD}, A_{RCD}, etc
- We calibrate the receiver for each degradation mechanism
  - For set $Q_S >> 1$, P_S and P_R vary the amount of degradation and measure Q_R
  - Calculate ECP using

$$ECP = \frac{P_S Q_R \left(Q_S - 1\right)}{P_R Q_S \left(Q_R - 1\right)}$$

  - Do curve fit to find A parameter values

Combining ECPs & testing

- Adopt simple sum rule to combine individual ECP values to give ECP_{Total} for multiple impairments acting together :

$$ECP_{Total}(dB) = ECP_{ASE}(dB) + ECP_{PMD}(dB) + ECP_{RCD}(dB)$$

↑ ASE only ECP ↑ PMD only ECP ↑ RCD only ECP

- Tested technique with link simulations (using VPI):
  - 4800 configurations of 10G NRZ modulated link
  - OSNR: **2** to **52** dB
  - 1st order PMD: **0** to **90** ps (45° launch angle)
  - RCD: **-320** to **1600** ps/nm

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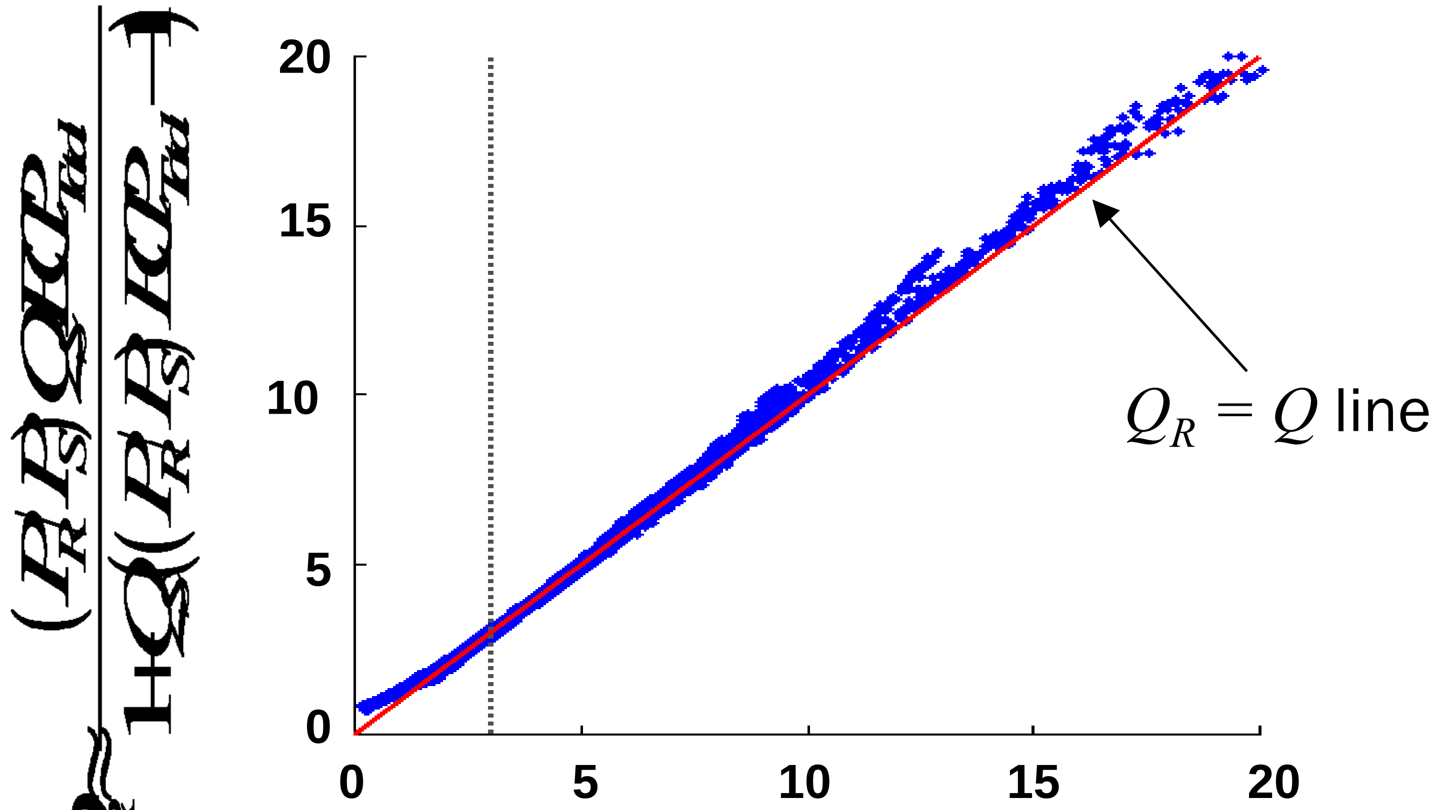
Results

- Estimated Q_R gives very accurate measure of actual Q



$$\boldsymbol{Q} = \frac{\mu_{1,R} - \mu_{0,R}}{\sigma_{1,R} + \sigma_{0,R}}$$

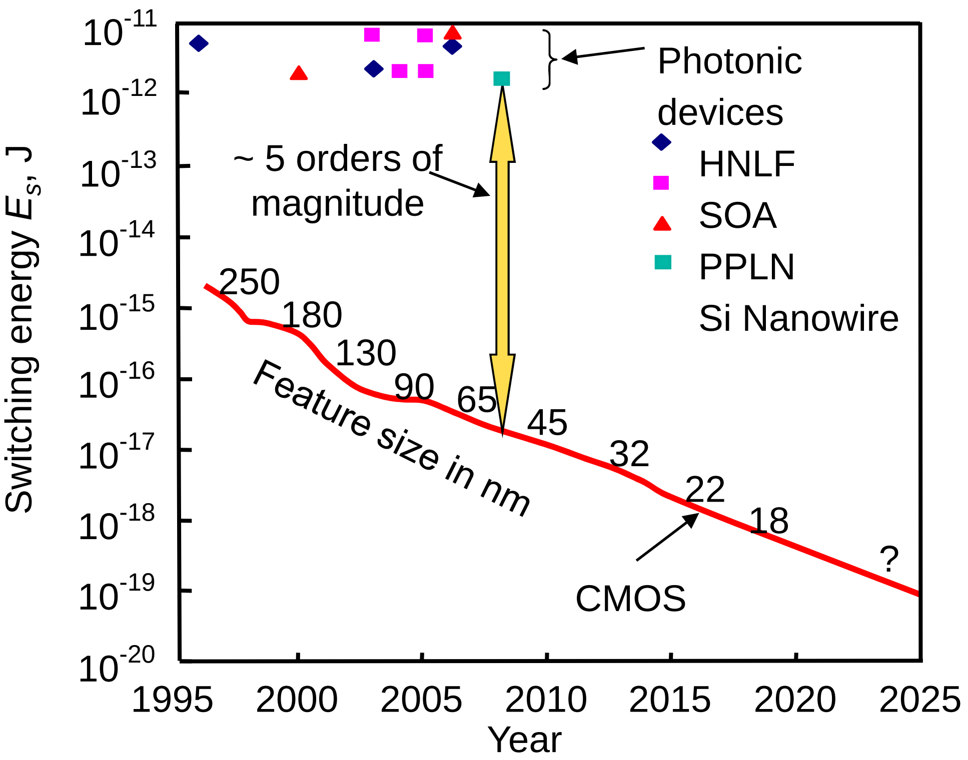
Applications

- Has range of potential uses
  - ASON path selection
    - Need fast estimator of signal quality during path set-up
  - Outage evaluation
    - Probability of BER > set threshold
  - Network control
    - Control of network elements and path compensators
  - Managing all-optical networks
    - Replacing electronics with photonics
      - How far can we go?

Replacing electronics with photonics

- Electronic “bottleneck” is expected for date rates > 100 Gbit/s
- But photonic signal processing is not competitive with CMOS
  - Too energy and space hungry
- All photonic routers are not commercially viable

Photonic vs CMOS switching energy

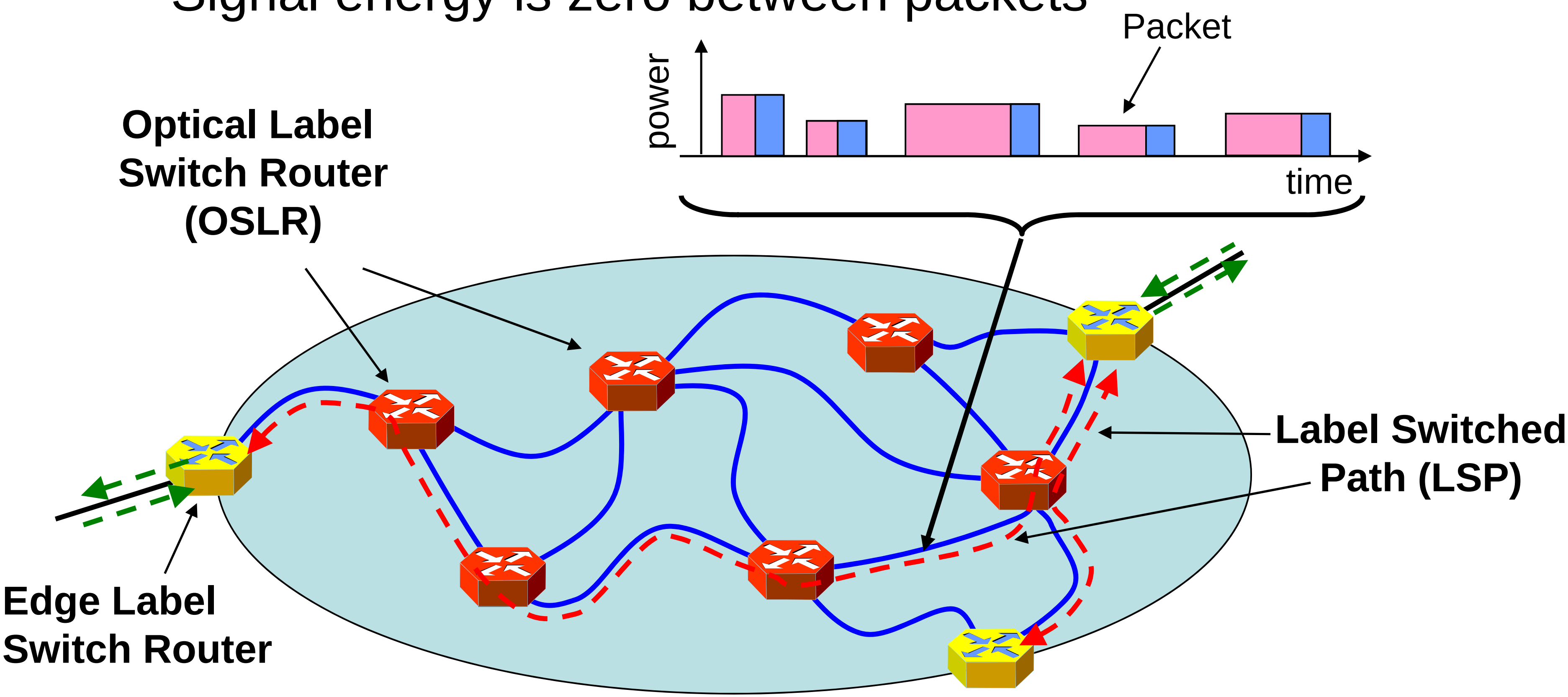


Optical label switching

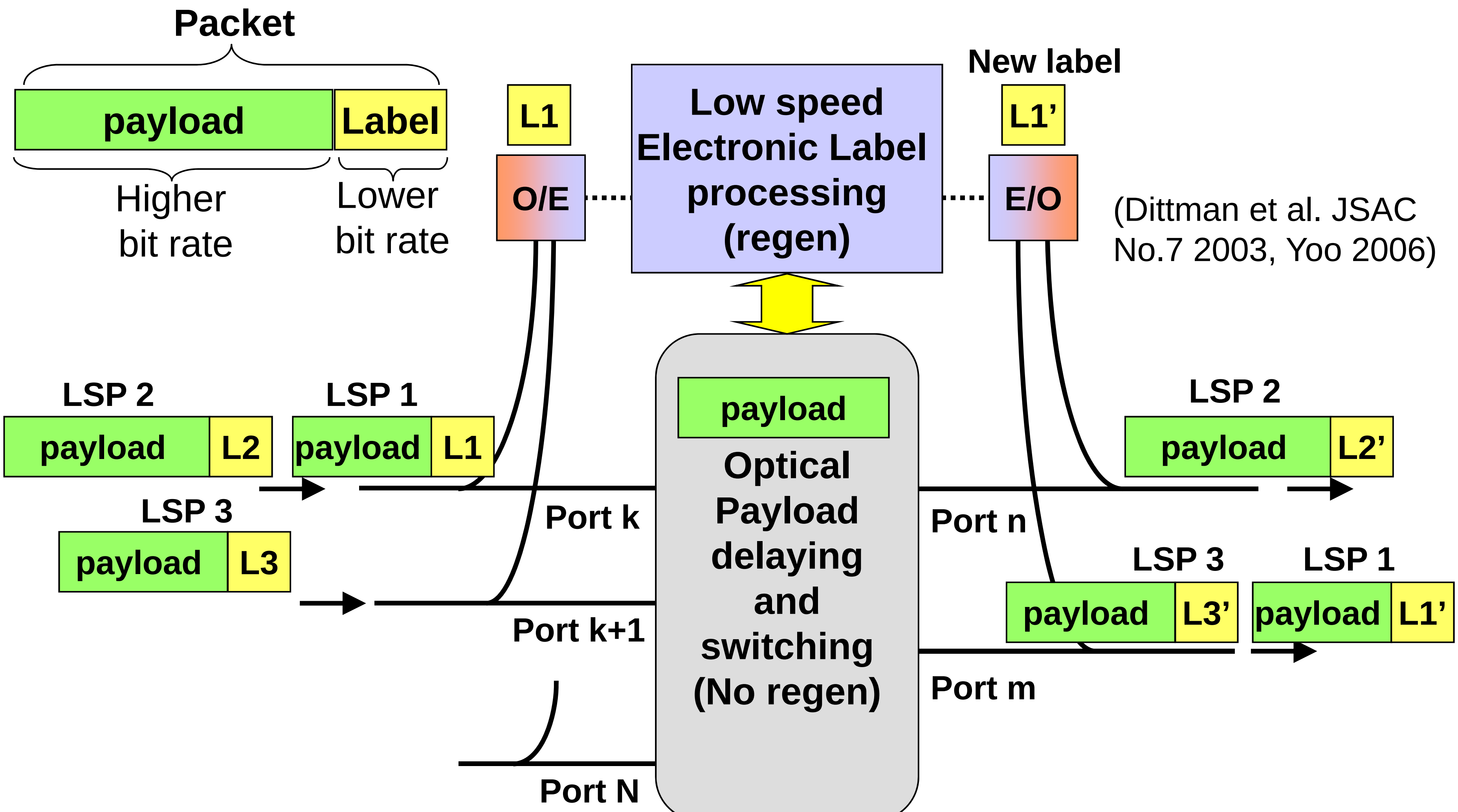
- What about optical label switched routers (OLSRs)?
  - Packet payload stays optical
    - Use high bit rate payload
  - Only the label is processed
    - Use low bit rate label
  - These routers don’t need high speed electronics
    - Reduce cost and power consumption
- Will OLSRs avoid the electronic bottleneck?

Optical label switched networks

- Packet based transport via Label Switched Paths (LSPs)
- No circuit switched transport layer
  - Signal energy is zero between packets



Optical label switched router (OLSR)



Eliminate high speed electronics from router

Payload bit error rate (BER) monitoring

- Must monitor payload BER
- Transporting damaged payloads wastes resources
  - Damaged payloads reduce service quality
  - System alarms, fault location
- Multiple LSPs are input into each LSR port
  - Port traffic
    - Asynchronous
      - Varying length packets
      - Varying time between packets
    - Varying signal quality
      - Different LSPs follow different optical paths
        - » Subject to different degradations

Payload BER monitoring

- Optical layer monitoring
  - Easily implemented in circuit switched transport layer
    - Tones, digital encoding, low frequency modulation
  - Not available in packet based transport network
  - Must be low cost
- What can be done in OLSR networks?
- Yang et al. (2004) propose monitoring label BER to ascertain payload BER
  - Label electronically regenerated at each OLSR
    - Label & payload signal quality become unrelated

The challenge

- Must monitor payload error rate
  – Errored payloads waste resources
- Payload remains optical
  – Cannot optically measure of payload error rate
- Cannot use circuit switched network methods
  – OLS network is packet transport
    - No circuit switched transport layer
- One proposal is to monitor the label
  – But routing label is regenerated at every node
- What about a two part label?
  – Let us see

Two part label

Short	Short	Long (e.g Ethernet frame)
Label 1	Label 2	Payload
Bit rate, BR_L	Bit rate, BR_L	Bit rate, $BR_L = BR_P / k$

Not regenerated (Label 2 and Payload)

- Label 1 is regenerated at each OLSR
  - Used for routing packet stream only
- Label 2 not regenerated at each OLSR
  - Used for payload monitoring
    - E.g. Check-sum, BIP-8
- $BR_L = BR_P / k$ ($k = 2, 4, ..$)
  - Eliminate high speed electronics from router
  - Reduce cost & power

Label BER & payload BER

- Packet Error Rate (PER) for packet N_P bits long

$$PER = 1 - \left(1 - BER\right)^{N_P} \approx N_P \cdot BER$$

- Need $PER_{Label} \sim PER_{Payload}$
  - Otherwise will not detect errored payloads quickly enough
    - Very many errored payloads before an errored label is detected
  - Hence: $N_P BER_P \sim N_L BER_L$
- Also want $N_L << N_P$
  - Maximise customer paying traffic
- Hence require $BER_L >> BER_P$

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ECP, impairments & BER

- *ECP* exhibits known relationships to impairments
  - Expressed as function of signal bit rate (*BR*)

$$ECP_{ASE}(k \times BR) \approx k^{1/2} ECP_{ASE}(BR)$$ ASE

$$ECP_{RCD}(k \times BR) = \left\{ ECP_{RCD}(BR) \right\}^{k^2}$$ Fibre dispersion

$$ECP_{PMD}(k \times BR) = \left\{ ECP_{PMD}(BR) \right\}^{k^2}$$ PMD

- For non-return to zero intensity modulated signal BER is function of Q-factor

$$BER \approx \tfrac{1}{2} erfc(\sqrt{Q}/2)$$

ECP, impairments & BER

- Using our equation for Q_R,

$$Q_R \approx \frac{G \cdot Q_T \cdot ECP}{1 + Q_T \left(G \cdot ECP - 1 \right)}$$

where:

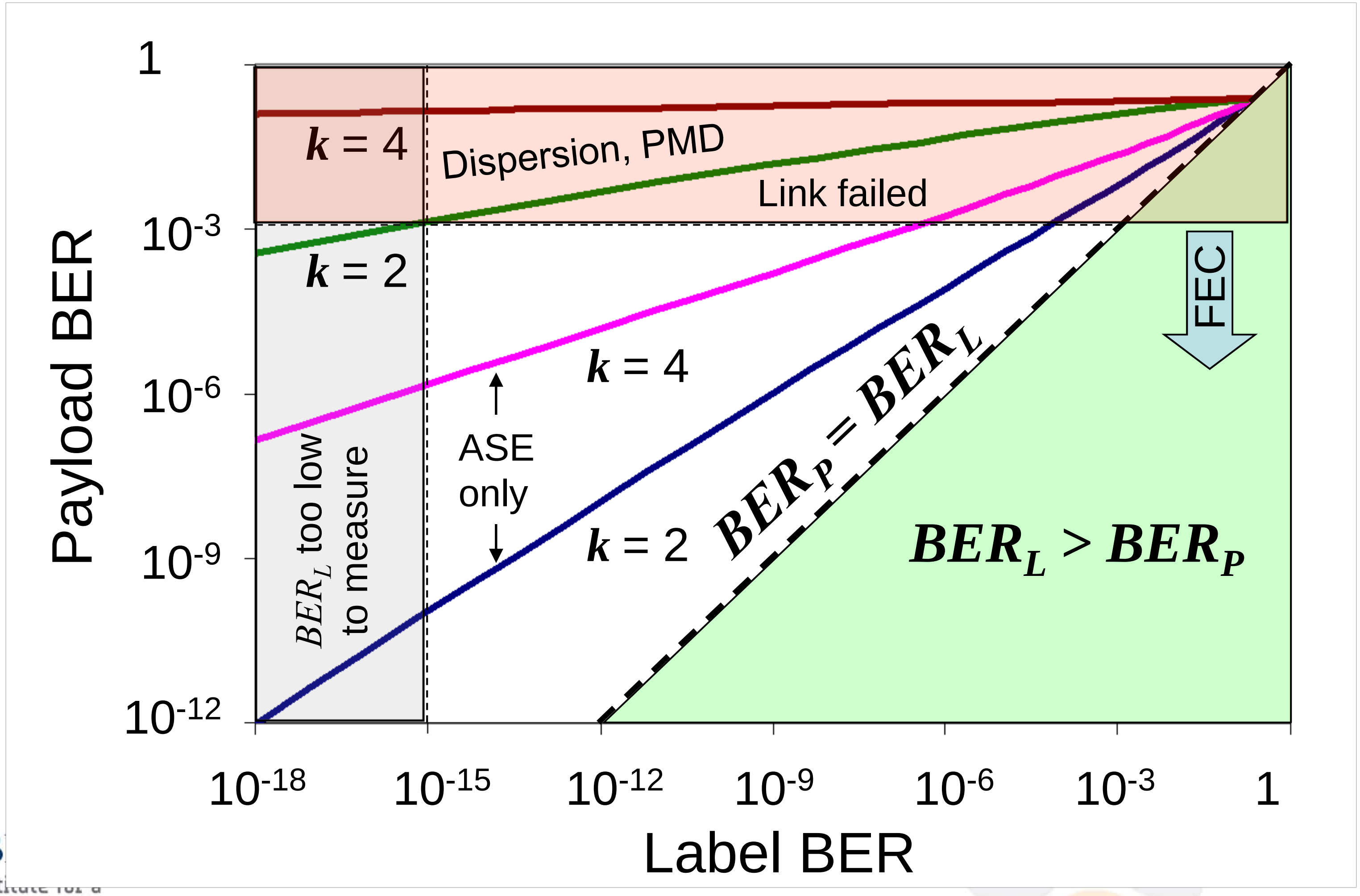
- When $BR_{Payload} = k \times BR_{Label}$ we find

$$Q_{R,Payload} \approx k^{-2} Q_{R,Label} Q_T \left[Q_T - Q_{R,Label} \right]^{-1}$$ (Fibre dispersion, PMD)

$$Q_{R,Payload} \approx \left(\left(Q_{R,Label} - 1 \right) \left(1 + X \right) + k^{1/2} \right) \left[k^{1/2} + \left(Q_{R,Label} - 1 \right) X \right]^{-1}$$ (ASE)

Results

- Label monitoring may work for ASE alone
  - Fails for other degradations



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Results

- Label monitoring requires $k = 1$
  – May as well directly monitor the payload

- What can be done?
  – "Accelerating" very low BER_L measurements will not work
    - Require circuit switched transport layer

  – Different label modulation format will not work
    - Different degradation mechanisms will determine BER_L

  – Asynchronous monitoring of payload is feasible
    - Can accommodate asynchronous nature of LSP traffic
    - Requires detector electronics at payload bit rate
    - Monitor analysis can be a low speed

Technique summary

- Accurate method to estimate receive Q-value for simultaneous multiple optical impairments
- Method requires calibration for separate degradation mechanisms
  - Can then be applied to arbitrary combinations of multiple degradations
- Quick, simple and cheap
- Multiple applications

Application summary

- Payload monitoring in OLSR networks is essential
- Circuit based monitoring techniques not applicable
  - Due to packet nature of LSP traffic
- Monitoring lower bit rate label will not work
  - Can have BER_L ~ 0 and BER_P ~ 1
    - Label is OK but payload ruined
- Direct asynchronous monitoring of payload is feasible
  - Cannot totally eliminate high speed electronics