Network Optimization of Optical Performance Monitoring

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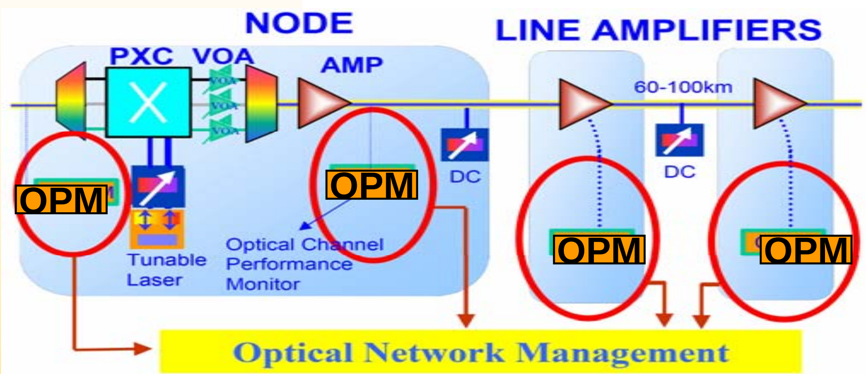
Outline

- Motivations
- Advanced Monitoring Techniques for point-to-point link
  - OSNR Monitoring
  - Chromatic Dispersion Monitoring
  - Multi-impairment Monitoring
- Optimization of performance monitoring networks
  - Optimization of Fault-diagnosis with Minimum Probing
  - Algebraic Monitoring Network
  - Other related works
- Conclusions

Optical Performance Monitoring

- Definition: *Physical layer monitoring of the signal quality, for the purpose of determining the health of the signal in the optical domain*



Applications:	Examples:
Signal quality characterization	■ Relating OSNR with BER ■ Early signal degradation alarm
Fault management	■ Fault detection, localization, and isolation ■ Resilience mechanism activation
Active compensation	■ Dynamic CD + PMD monitoring and compensation
Quality of service (QoS) provisioning	■ SLA fulfillment verification

Ref: A. Vukovic, H. Hua, M. Savoie, “Performance Monitoring of Long-haul Networks,” Lightwave Magazine (2002)

Wish List for the Enhancements of OPM

- higher dynamic range;
- higher sensitivity;
- robustness to various effects;
- multi-impairment monitoring; and
- lower cost.

But how?

$\Rightarrow$ Optimization of Performance Monitoring System

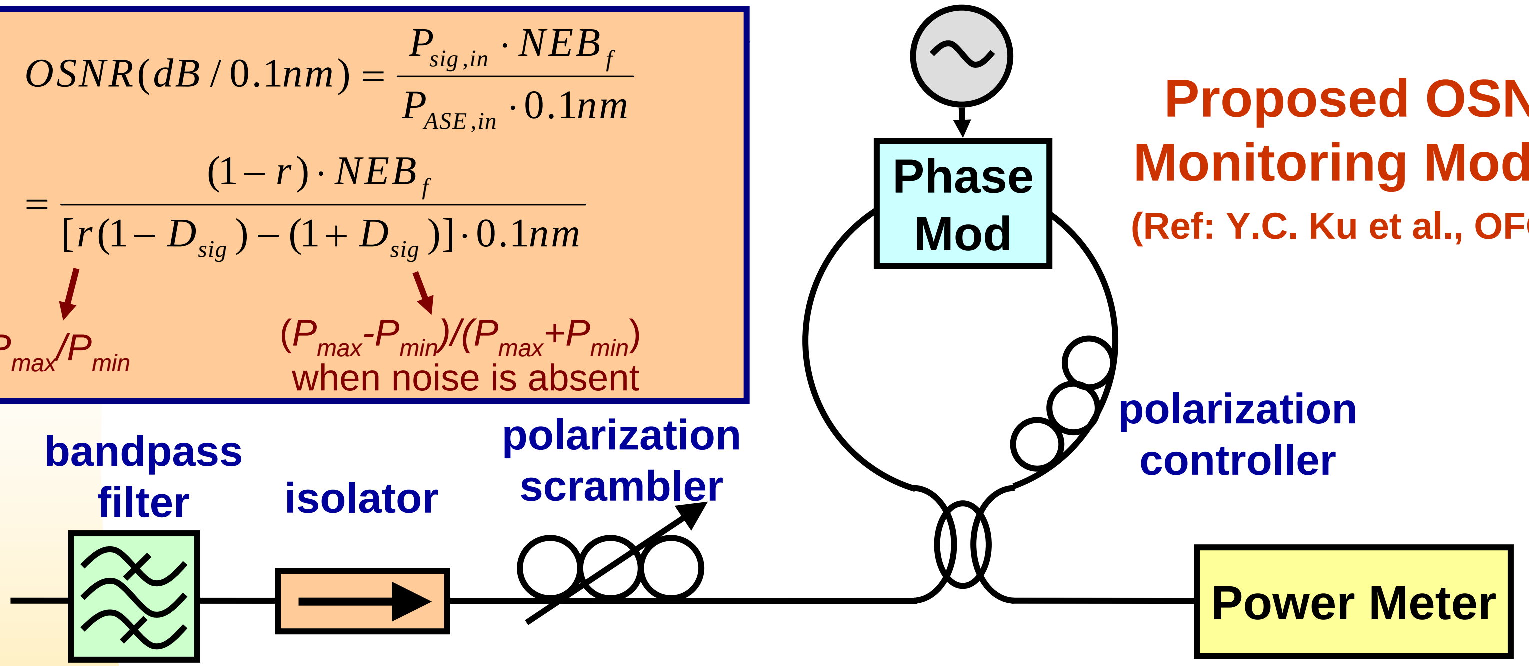
OSNR monitoring module

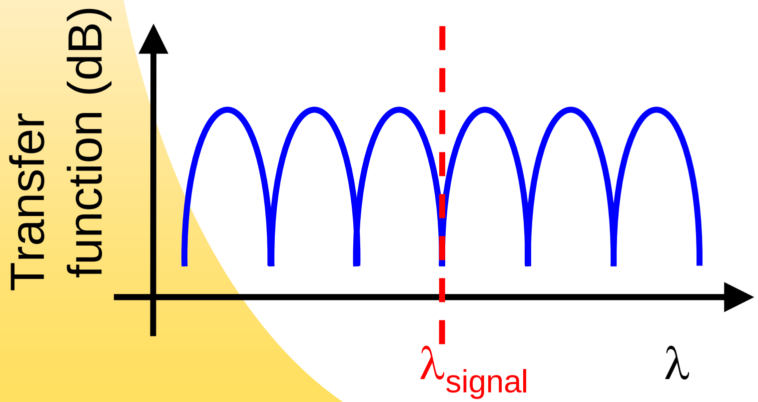
$$OSNR(dB/0.1nm) = \frac{P_{sig,in} \cdot NEB_f}{P_{ASE,in} \cdot 0.1nm}$$

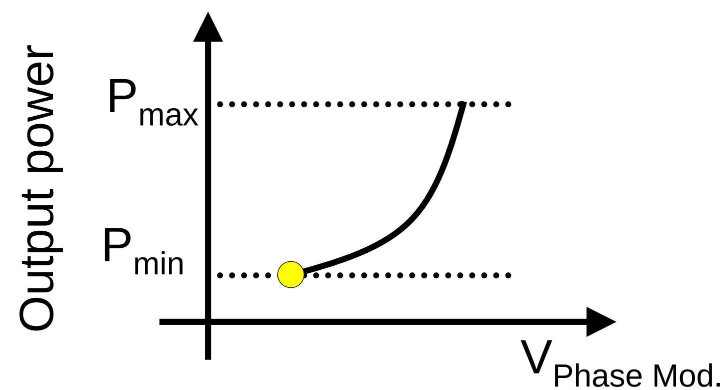
$$= \frac{(1-r) \cdot NEB_f}{[r(1-D_{sig}) - (1+D_{sig})] \cdot 0.1nm}$$

r: P_{max}/P_{min}

D_{sig}: $(P_{max}-P_{min})/(P_{max}+P_{min})$ when noise is absent







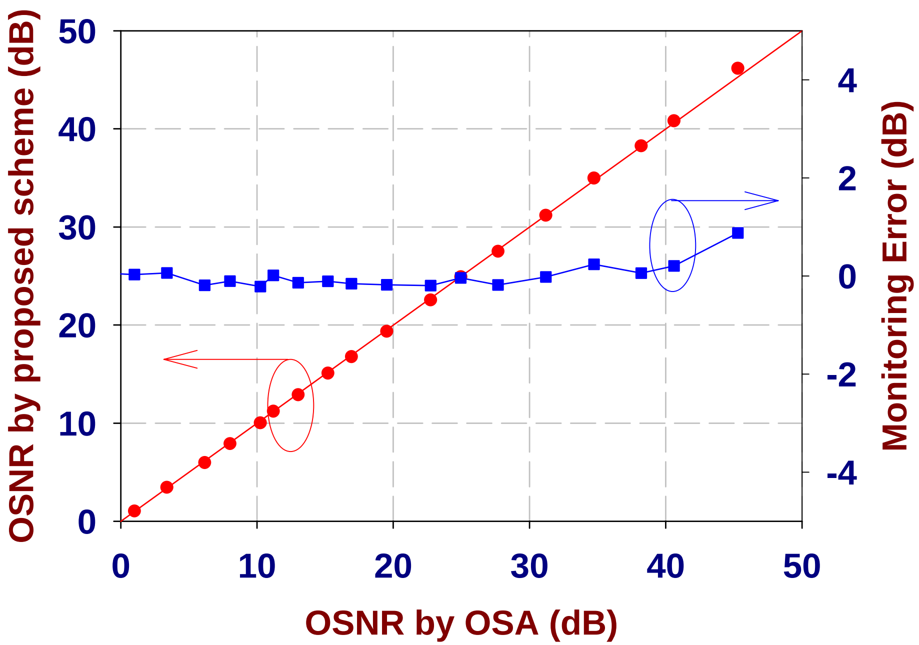
Experimental results: 10Gb/s, back-to-back

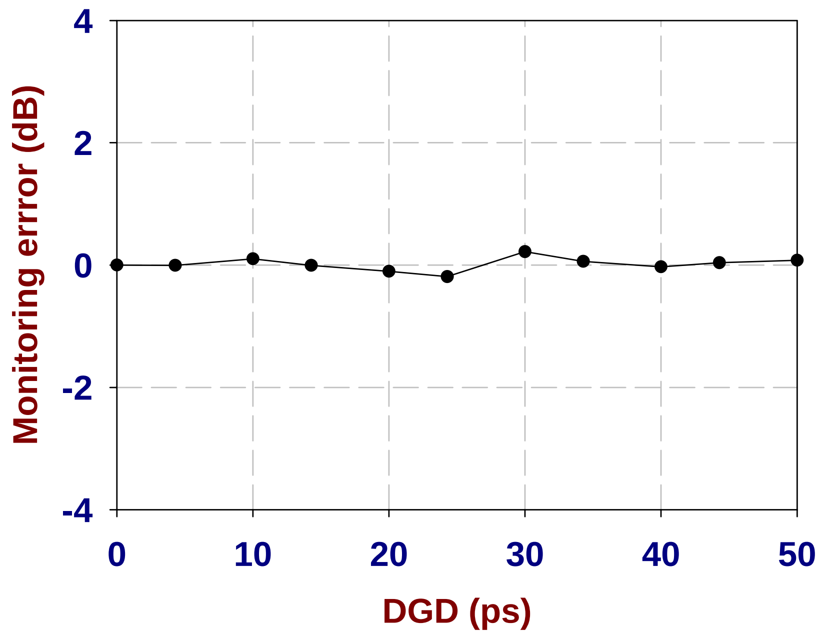
Without PMD:

- Monitoring error < 0.25 dB
- 40-dB monitoring dynamic range

With PMD:

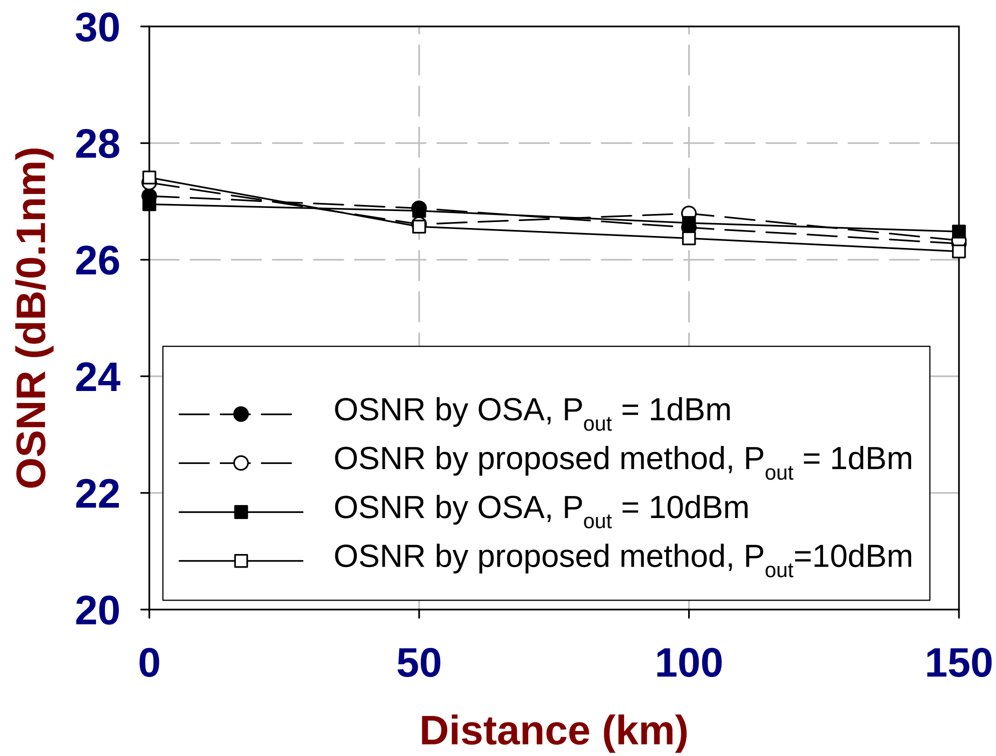
- Influence of DGD
  - reference OSNR 25 dB/0.1nm
  - Monitoring error < 0.25 dB





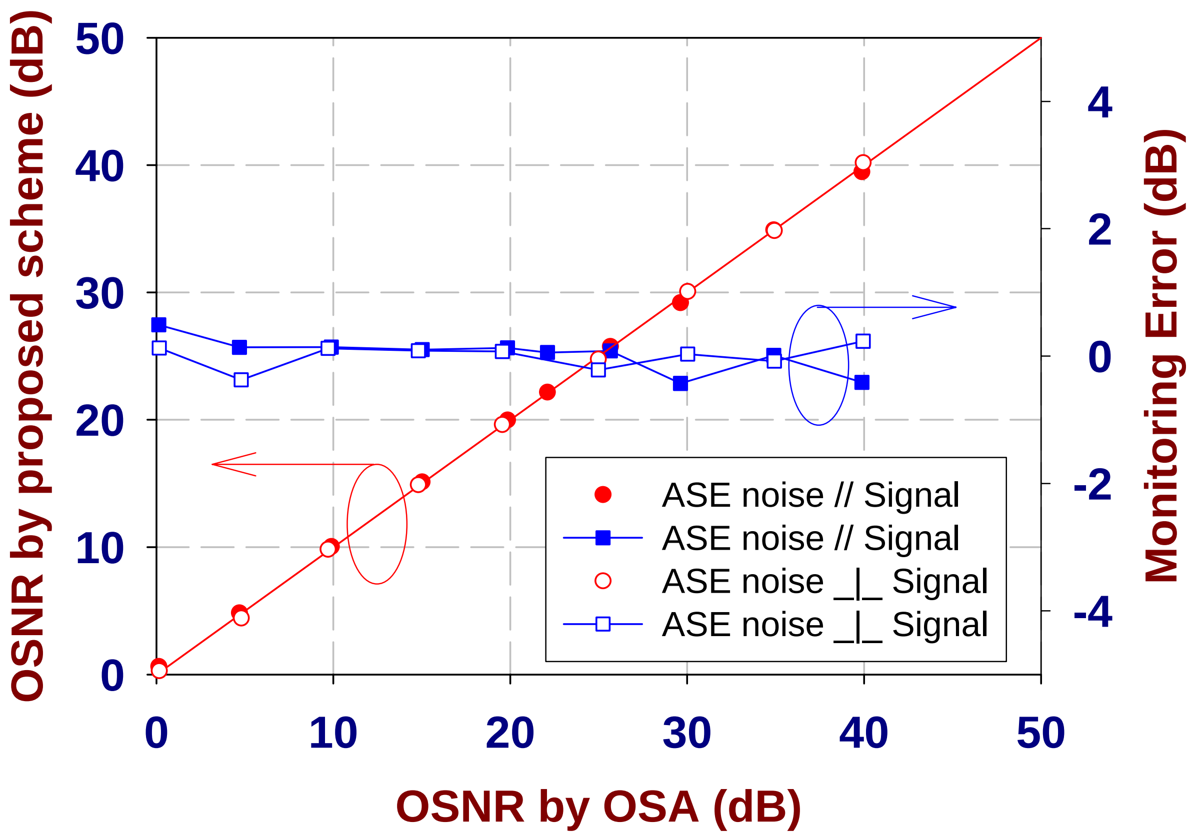
Experimental results: 10Gb/s, 150km, w. ~1.5ps PMD

- Influence of chromatic dispersion and transmitted power
  - An EDFA was added after each 50-km SMF span
  - EDFA output power 1 or 10 dBm



Experimental results: 10Gb/s, back-to-back, w/ polarized noise

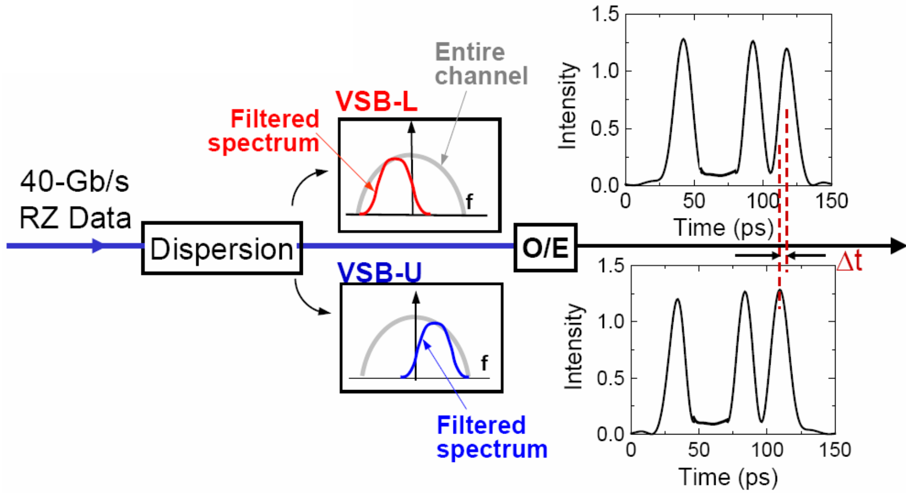
- Influence of partially polarized noise
  - Worst case: DOP=99.69%



Chromatic Dispersion (CD) Monitoring

Previous work on chromatic dispersion monitoring

- Clock phase difference monitoring
  - Pros: No need to modify transmitter, highly sensitive
  - Cons: requires high-speed electronics



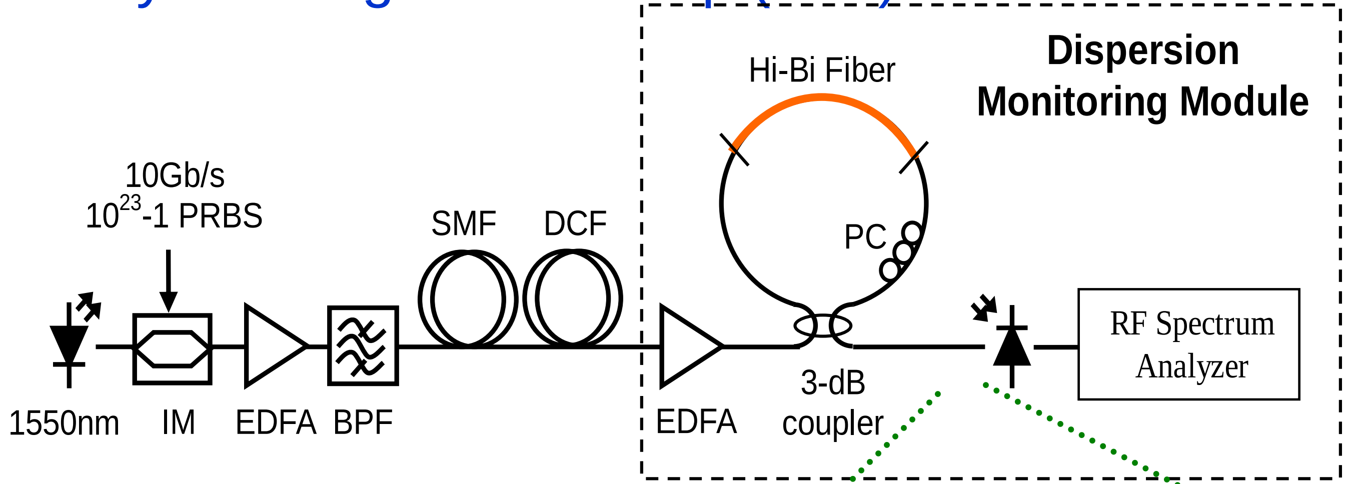
Ref.: Q. Yu, et. al., IEEE JLT, 20, 2267-2271 (2002)

- We propose to use a birefringent fiber loop (BFL) to realize a simple, polarization insensitive CD monitoring scheme without transmitter side modification, and demonstrate in NRZ system

Ref.: Y.C. Ku, et. al., OFC 2006

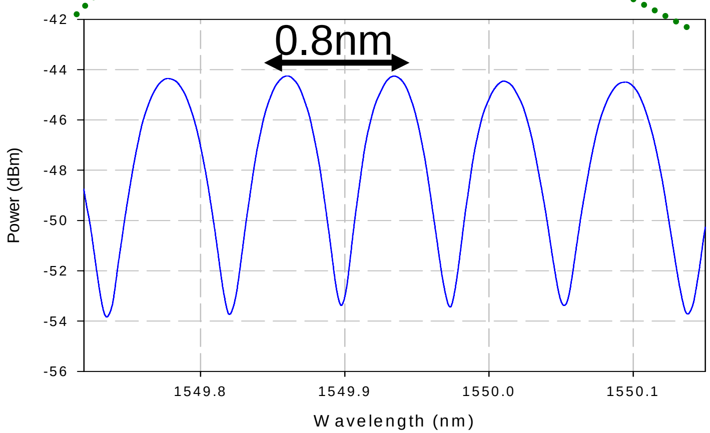
Proposed Dispersion Monitoring Module based on BFL

- Measure RF power at dispersion dependent frequency dip (f_{RF}) produced by birefringent fiber loop (BFL)



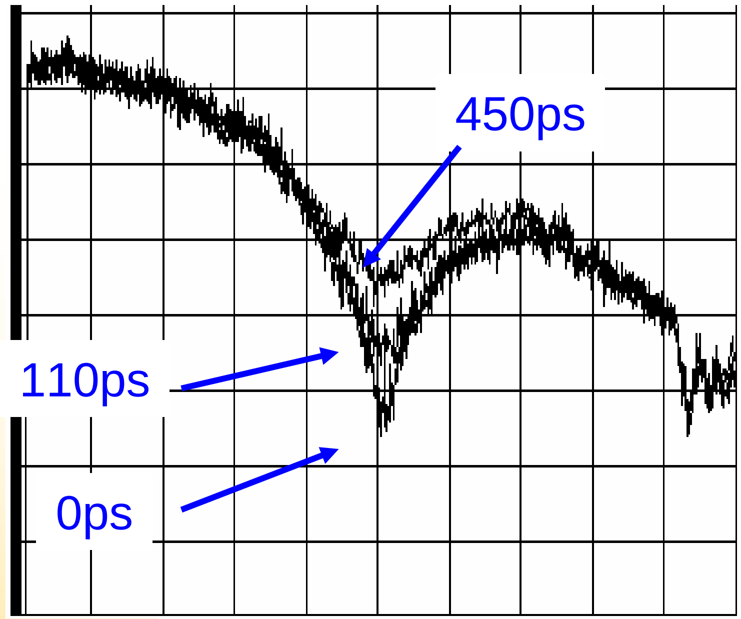
$$P \propto \sin^2\left(\frac{\varphi_\Omega + \varphi_{-\Omega}}{2}\right) = \sin^2\left(\frac{\pi\lambda^2 f_{RF}{}^2}{2} D\right)$$

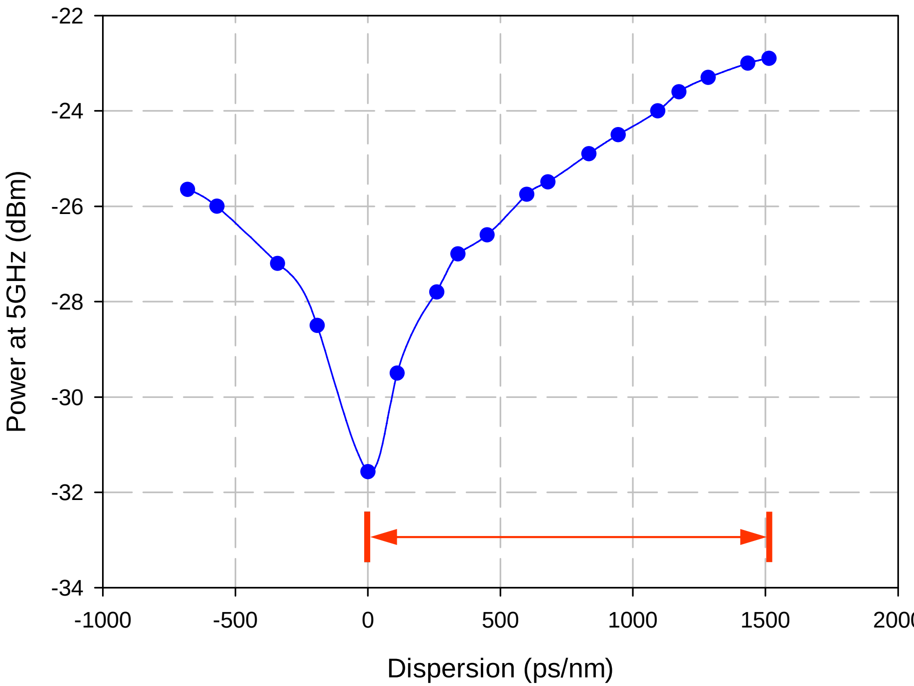
$$f_{RF} = \Omega / 2\pi = 1/2\tau$$



Ref.: Y.C. Ku, et. al., OFC 2006

Experimental Result



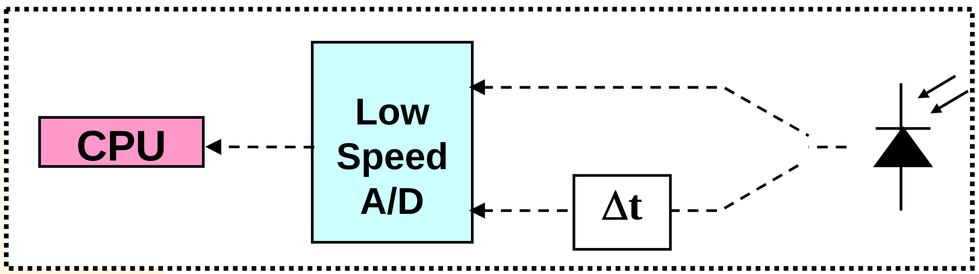


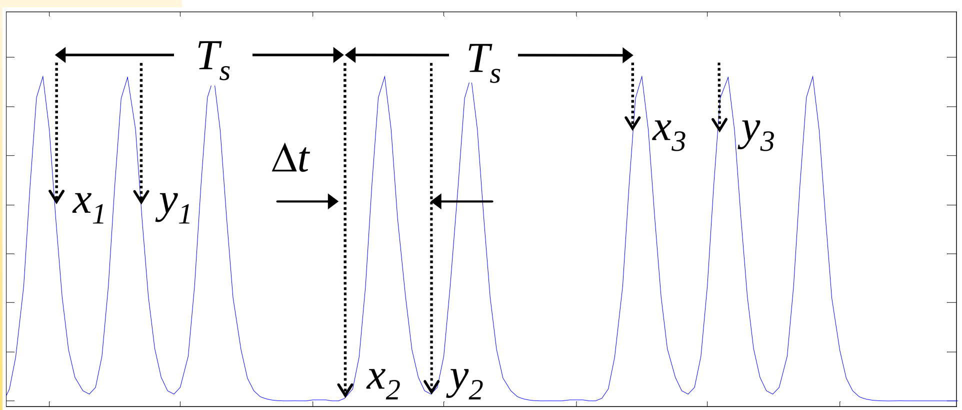
- Measured unambiguous monitoring range: 1500 ps/nm for 10-Gb/s NRZ signal
- In principle, monitoring range can reach $c/2\lambda^2 f_{RF}^2$ = 2497ps/nm

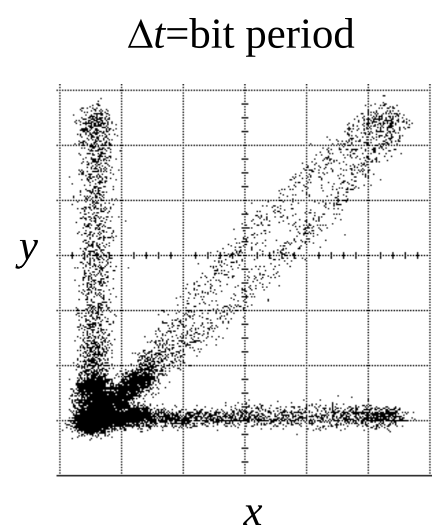
Multi-impairment Monitoring

Multi-impariment monitoring - Delay Tap Asynchronous Waveform Sampling

- Combines asynchronous sampling with two tap delay lines, so that each sample point comprises two measurements (x and y), separated by a fixed time corresponding to the delay length.

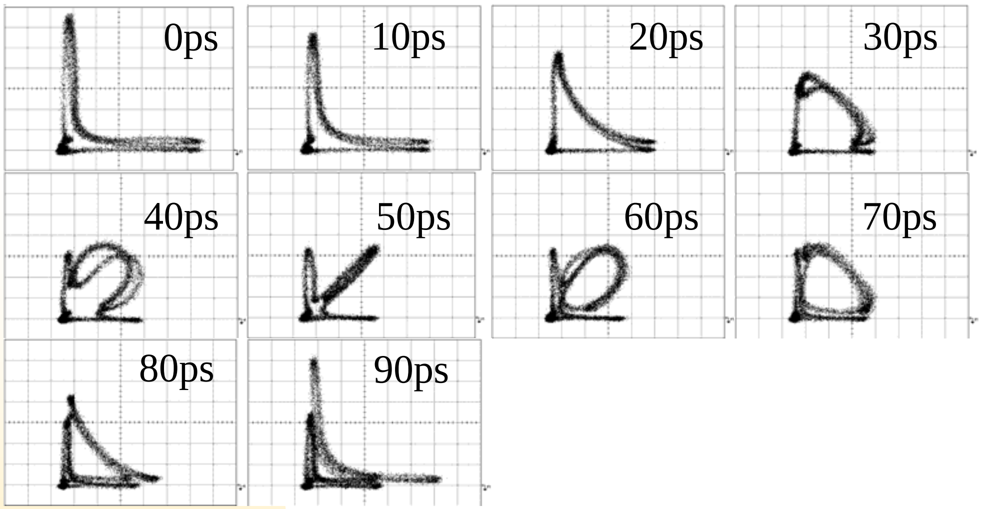


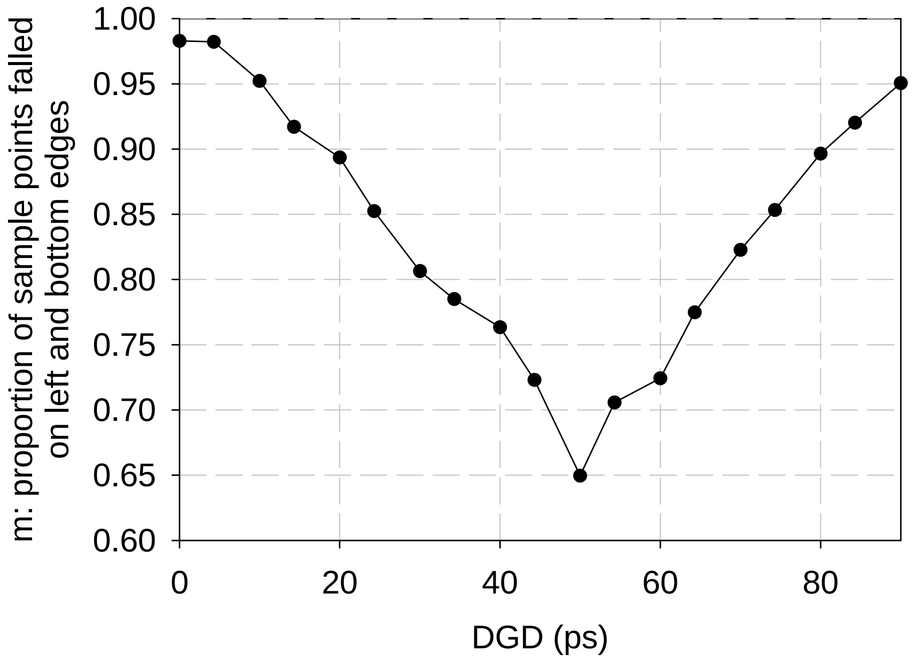




Sarah D. Dods and Trevor B. Anderson, "Optical Performance Monitoring Technique Using Delay Tap Asynchronous Waveform Sampling", OFC OThP5, 2006

Application of asynchronous sampling in PMD monitoring

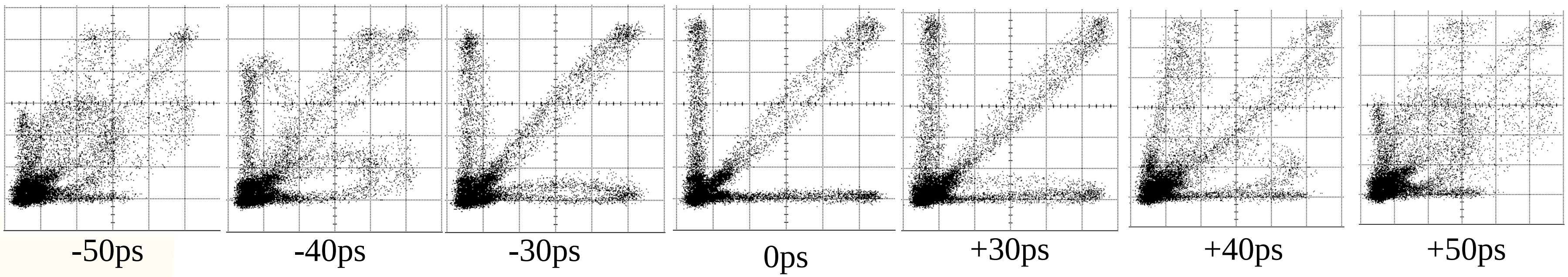




$$m = \frac{\text{number of sample points falling on the left and the bottom edges}}{\text{total number of sample points on the scatter plot}}$$

- The proportion of sample points on the left and bottom edge is used as the effective parameters to evaluate PMD value

Application of asynchronous sampling in misalignment monitoring for RZ-OOK



- The increasing dispersion and rotation of the sample points on the diagonal can serve as effective parameters to evaluate alignment status

$$d = \frac{1}{n}\sum_i \sqrt{x_i^{\,2} + y_i^{\,2}}\,\sin\left(\left|\frac{\pi}{4} - \arctan\frac{y_i}{x_i}\right|\right)$$

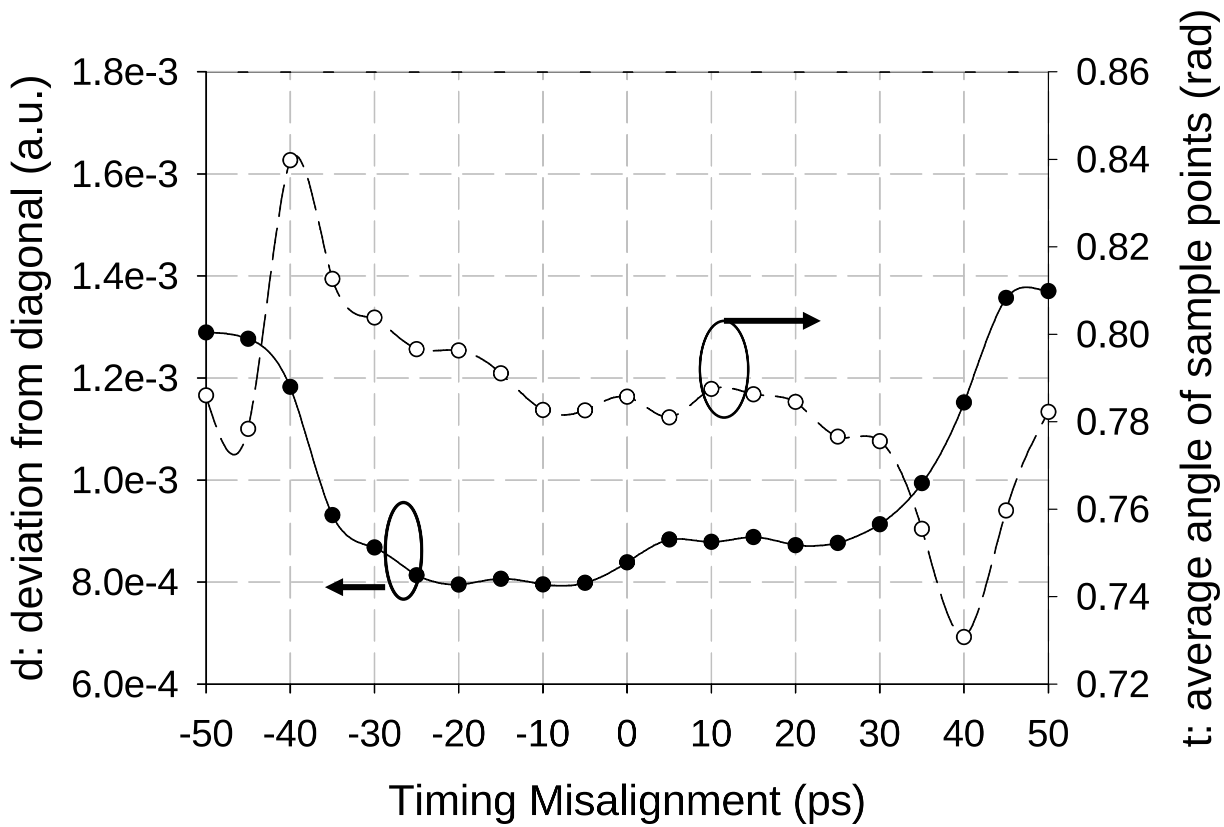
$$t = \frac{1}{n}\sum_i \arctan\frac{y_i}{x_i}$$

d: deviation from diagonal line

t: average angle of sample points

Ref.: Y.C. Ku, et. al., ECOC 2006

Experimental results



- Sign and amount of misalignment can both be estimated

Correlation of Monitored Parameters

- Monitored parameters may be correlated.
- The monitoring schemes need to be able to differentiate different possible impairments

Table 2/G.697 – List of correlation between the underlined impairments and monitoring parameters

Parameters	Total power	Channel power	Channel wavelength	OSNR	Q-factor
Variation of attenuation	X	X		X	X
Frequency (or wavelength) deviation from nominal		X	X	X	X
Optical channel power changes due to gain variations		X		X	X

Ref: ITU-T G.697 Optical monitoring for DWDM systems

- Question:
  - Can we derive one parameter based on the measurement of the other parameters?
  - How about other dimensions of correlations, e.g. *spatial* & *temporal*?

Optimization of Performance Monitoring System

- Consider a performance monitoring system S_{PM} that is formed by all the monitoring devices in a network and the corresponding measurements

- Optimization of S_{PM} :
  1. the minimum number of monitors required
  2. the optimal locations of the monitors – monitor placement problem
  3. the minimum number of measurements needed

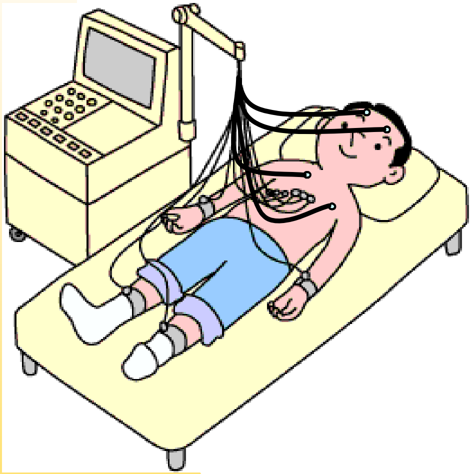
  1–2: CAPEX
  3: OPEX

- Issues:
  - static network vs. dynamic (reconfigurable) network
  - distributed vs. centralized monitoring

Centralized vs. Distributed OPM

- Monitoring
- Diagnosis

distributed monitoring/
centralized diagnosis



centralized monitoring/
centralized diagnosis

single monitoring point for
the whole network

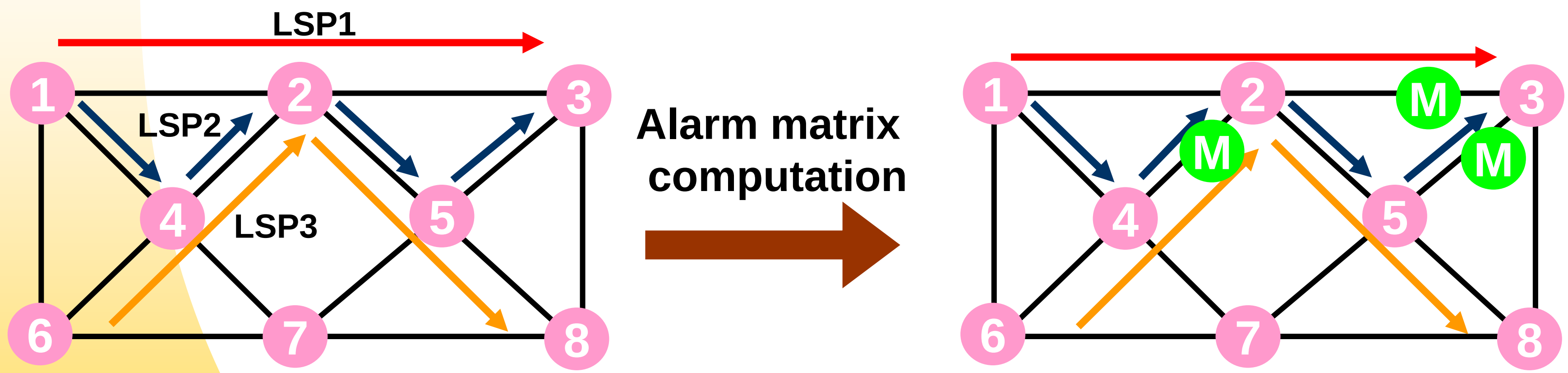
Number and Placement of OPM

Optimization of Placement and Amount of OPM needed

- One-monitor-per-link/component is not optimum if we consider
  - failure probability of link/component
  - scalability with the network size
  - amount of redundant alarm

1. Channel-Based: Design Based on Established Lightpaths

E.g.



Ref: Sava Stanic et al, "Efficient alarm management in optical networks", in Proc. *DARPA Information Survivability Conference and Exposition 2003*, pp. 252-260

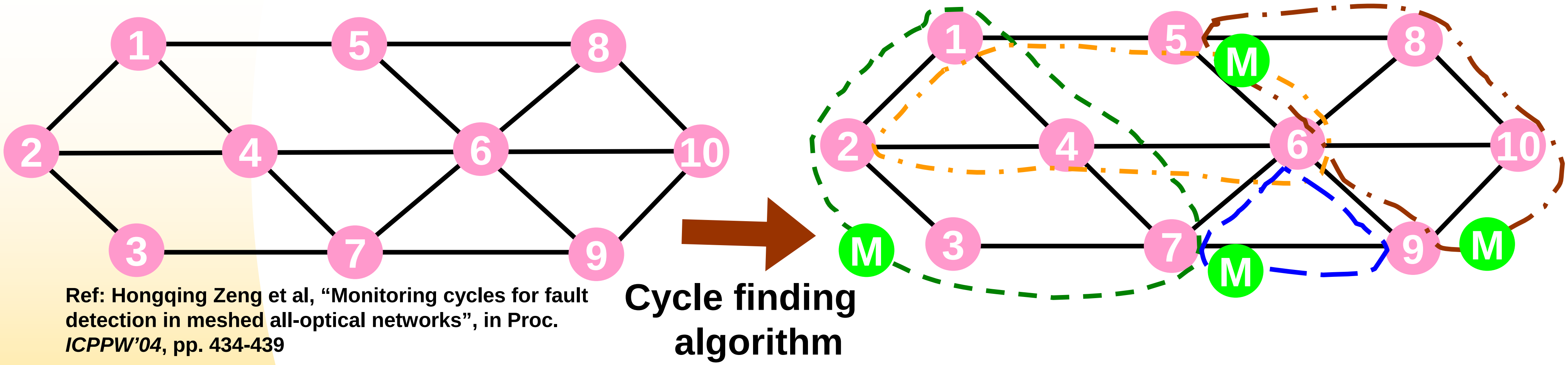
Optimal monitor placement **M: monitor**

✓In-service channel performance based ✓Reduce monitor number considerably ×For static network only

Number and Placement of OPM

2. Network-Based: Design Based on Network Topology

E.g. Break down a network into a number of "monitoring cycle" and assign a monitor to each, using an extra supervisory wavelength to probe the health of the cycle



Ref: Hongqing Zeng et al, "Monitoring cycles for fault detection in meshed all-optical networks", in Proc. *ICPPW'04*, pp. 434-439

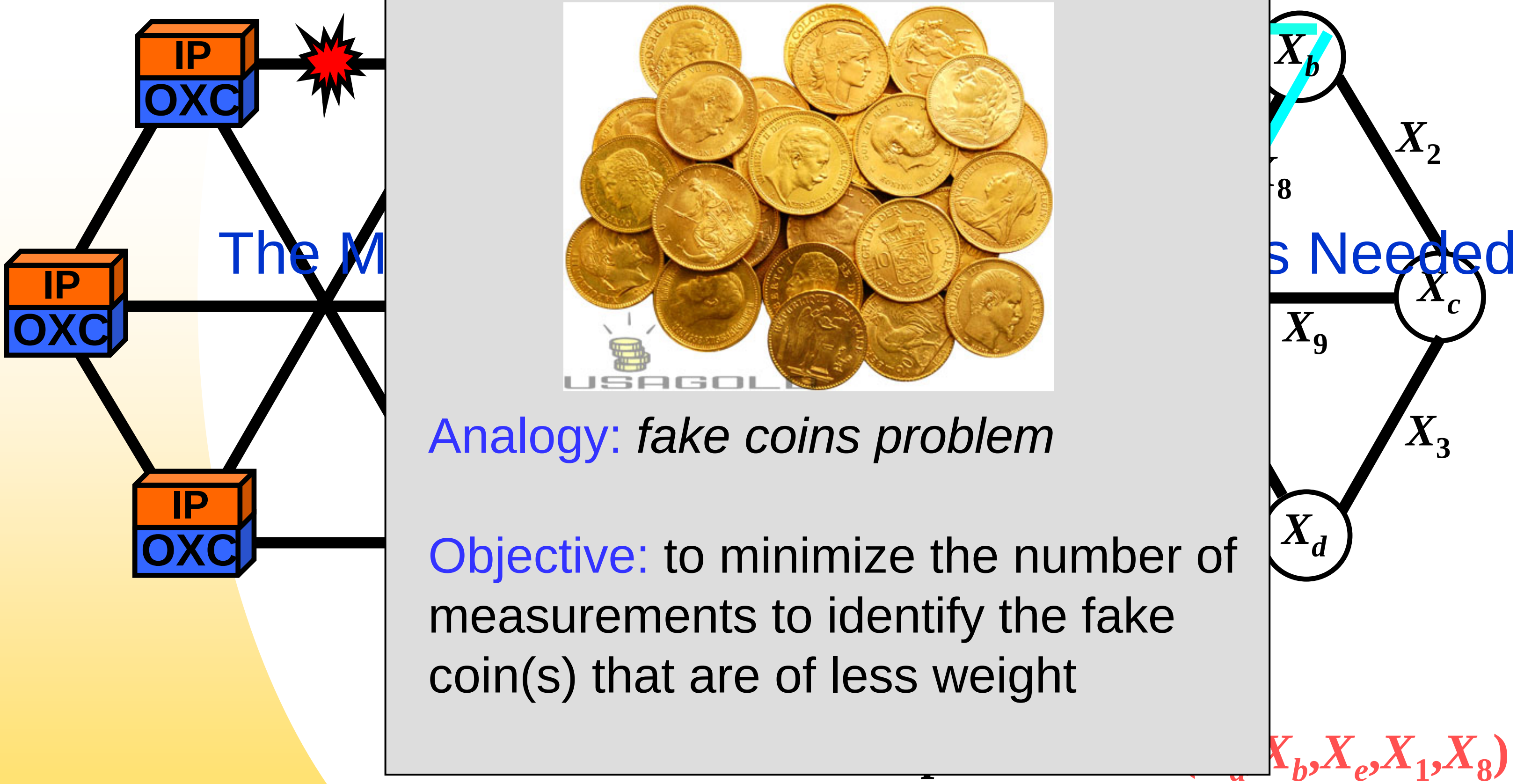
✓Suitable for dynamic networks

×Does not measure in-service channel quality

✓Reduce monitor number considerably

×Extra wavelength needed

Scalable Network Diagnosis for All-Optical Networks via Group Testing Over Graphs

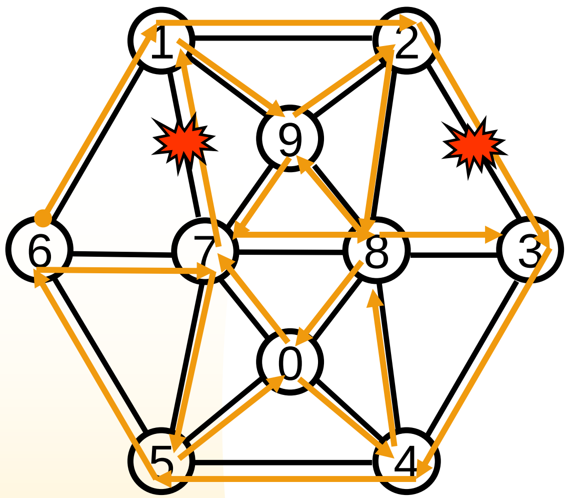


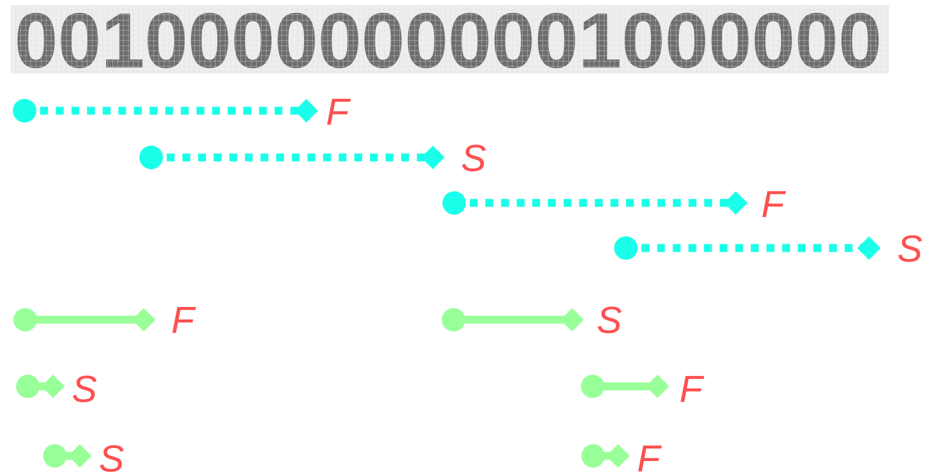
Analogy: *fake coins problem*

Objective: to minimize the number of measurements to identify the fake coin(s) that are of less weight

Y. G. Wen, V.W. S. Chan and L. Z. Zheng, "Efficient Fault Diagnosis Algorithms for All-Optical WDM Networks with Probabilistic Link Failures (Invited Paper)," *Journal of Lightwave. Technology*, vol. 23, no. 10, October 2005, pp.3358-3371.

Asymptotically Optimal Run-Length Probing Schemes via an Information Theoretic Approach



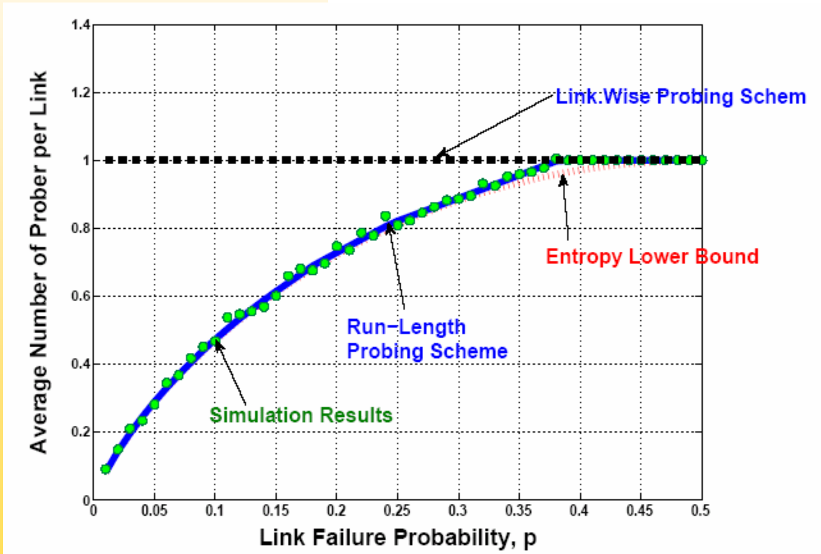


Fault Detection

Fault Localization

Probe Syndrome

FFSSSFSFFS ➩ 1100010110



Guidelines for Fault Diagnosis Algorithms

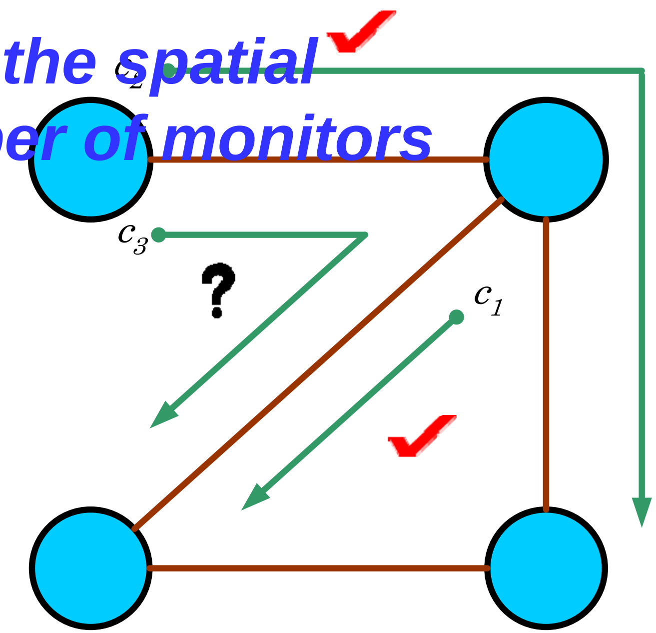
- **The total number of probing is approximately equal to the entropy of the network state**
- **Each probe should provide approximately 1 bit of state information**

Network Diagnosis – an algebraic approach

- Objective: *To find an efficient way to determine the quality of different paths, so that it can be used as a metric for path computation in the network layer for channel setup*

- For example:
  - Two existing monitoring channels c_1 and c_2
  - New request to setup c_3
  - NO estimation

Network diagnosis that explores the spatial correlation to minimize the number of monitors



S.T. Ho, L.K. Chen, C.K. Chan, "**On Requirements of Number and Placement of Optical Monitoring Modules in All-Optical Networks**," OECC, paper 7A2-2 (2005)

Linear expressions of optical impairments

- Noise Figure (NF)

$$NF_{overall} = NF_1 + \frac{NF_2}{G_{c2}} + \frac{NF_3}{G_{c3}} + \cdots + \frac{NF_k}{G_{ck}}$$

NF_i : Noise figure of the i^{th} hop

G_{ci} : cumulative gain up to i^{th} hop

- Chromatic dispersion (CD)

$$CD_{overall} = \Delta\lambda \cdot (L_1 \cdot D_1 + L_2 \cdot D_2 + \cdots + L_k \cdot D_k)$$

$\Delta\lambda$: spectral width

D: dispersion parameter

L_i : total length of i^{th} hop

- Polarization-mode-dispersion (PMD)

$$PMD^2_{overall} = \sum PMD^2_{fiber} + \sum PMD^2_{component}$$

Overall impairment for all paths can be derived from impairments of individual fiber link and component

A sample network

x_1 - x_5 : Impairments on links

x_6 - x_9 : Impairments on nodes

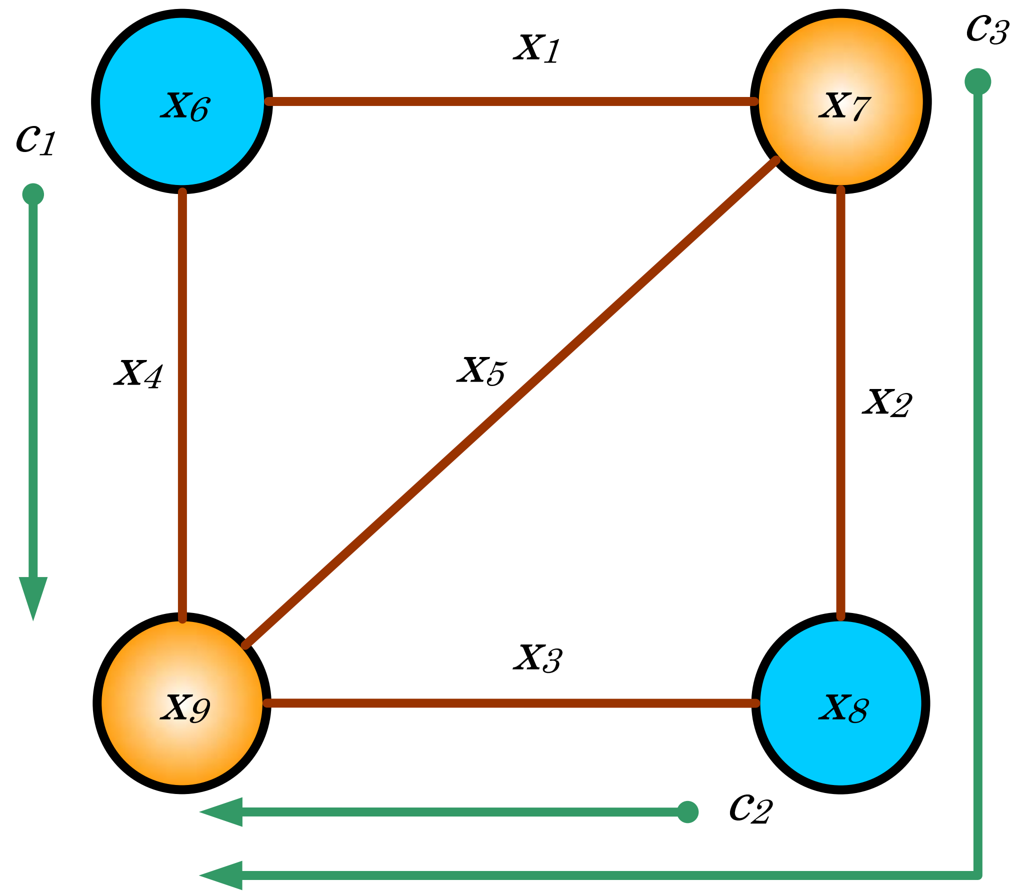
c_1 - c_3 : 3 probing channels

: Node with monitoring module

Accumulated impairment of c_1 :
x_4

Accumulated impairment of c_2 :
x_3

Accumulated impairment of c_3 :
$x_2 + x_8 + x_3$



(The monitoring module contain both monitoring source and monitoring detector.)

Problem formulation

M: Monitoring Matrix

x: individual impairment

y: Accumulated impairment

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} m_{11} & \cdots & \cdots & \cdots & m_{1N} \\ \vdots & \ddots & & & \vdots \\ \vdots & & \ddots & & \vdots \\ \vdots & & & \ddots & \vdots \\ m_{N1} & \cdots & \cdots & \cdots & m_{NN} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_N \end{bmatrix}$$

$$\begin{array}{c|ccccccccc} & x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 \\ \hline c_1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ c_2 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ c_3 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \end{array}$$

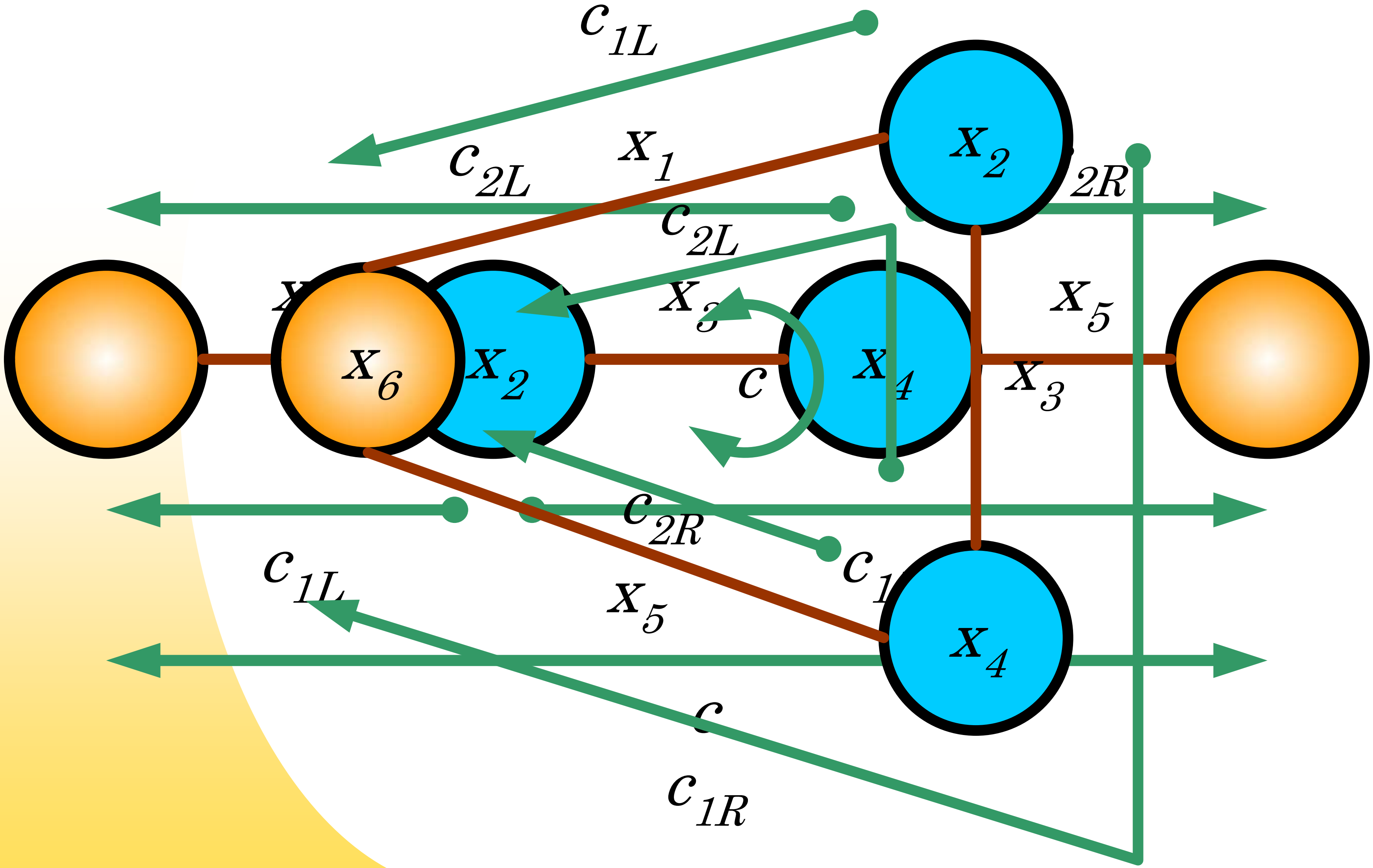
$$y = Mx \rightarrow x = M^{-1}y$$

$c_1 : x_4$ $\quad$ $c_2 : x_3$ $\quad$ $c_3 : x_2 + x_8 + x_3$

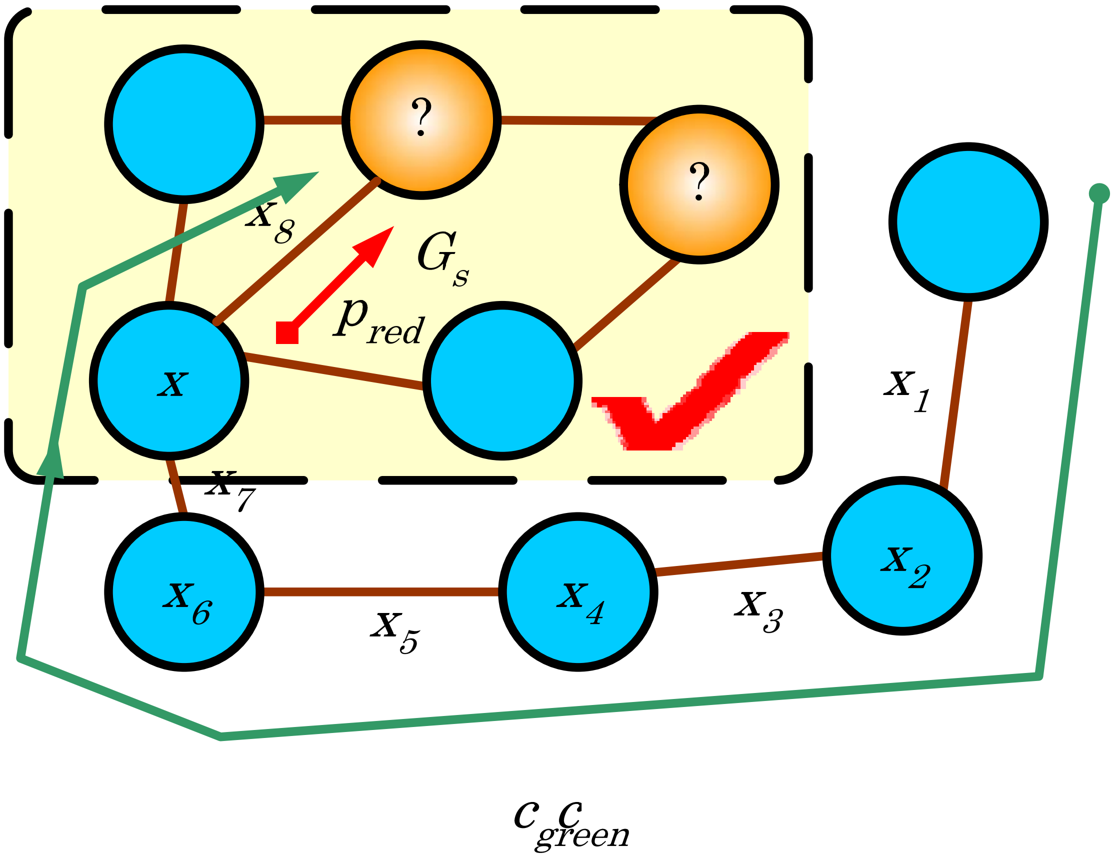
- For the previous example, total **9** impairment variables to be determined and **2** ... g channels from all ports by time division manner or by proper labeling

Q: What is the minimum number of monitoring modules and where should they be placed?

Bus & Ring networks



Two-link-connected network

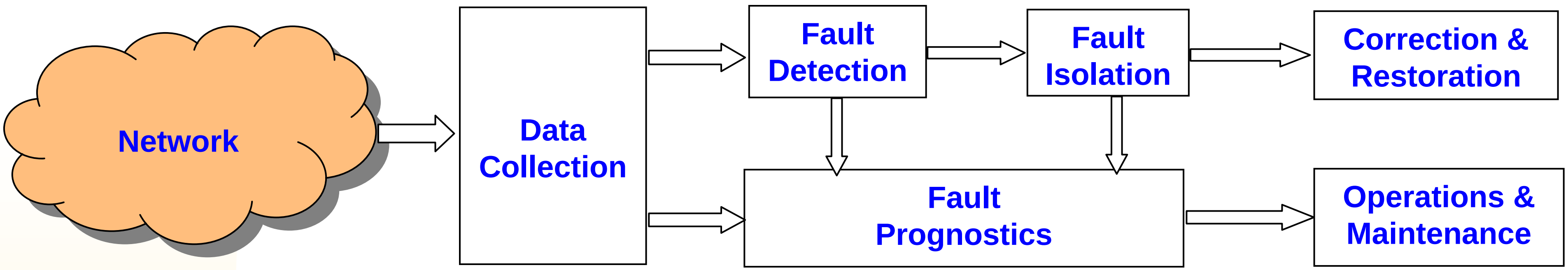


$$Impairment(c) = Impairment(c_{green}) - Impairment(p_{red}) - x$$

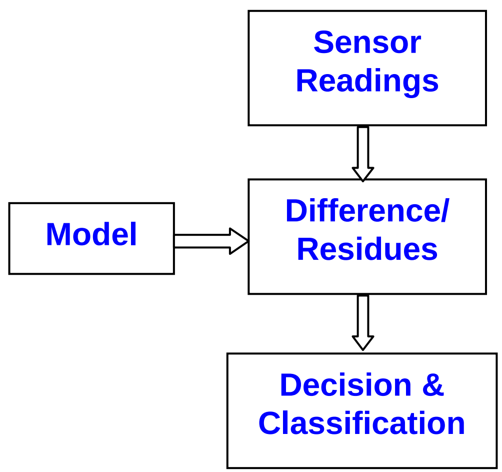
Summary of Algebraic Network Diagnosis

- Proposed a novel algebraic approach of monitoring optical impairments in both un–directional nodes and links
- Proved that two monitoring modules are <u>necessary and sufficient</u> to support our monitoring scheme in two–link–connected network
- For every node that becomes a leaf node after removal of all leave nodes in the original network, installing one monitoring module at it is necessary and sufficient to support the proposed probing scheme
- For general networks with bridges, first transform the network to a tree-like structure and then solve it by "divide-and-conquer" method
- With the probing scheme, any single-fault can be located in the whole network

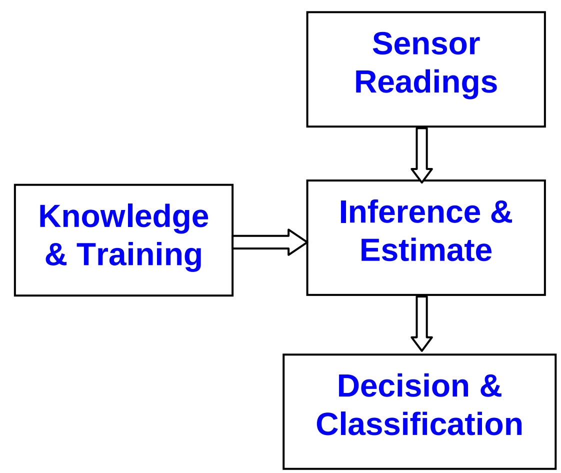
Intelligent Fault Diagnosis for Optical Networks: Detection, Isolation and Prognosis



Two fault-diagnosis formulation approaches:
- model-based
- data-driven



Model-based Approach



Data-driven Approach

YG Wen, MIT

Conclusions

- OPM in next-generation high-speed transparent reconfigurable networks is essential
- Enhancements of OPM, including higher dynamic range, higher sensitivity, robustness to various effects, and multi-impairment monitoring, are desirable to make the OPM system more effective.
- By exploring the correlation of different spatial or time domain information, it is possible to further enhance the efficiency of OPM.
- Some works on the Optimization of OPM network to derive theoretical bounds for the min. number of monitoring module or the number of probing are presented.

- Acknowledgement:
  - Projects supported in part by Hong Kong SAR Government CERG Grant 411006
  - Contributors ***S.T. Ho, Z.C. Xie, Y.C. Ku, C.K Chan, and Y.G. Wen***

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