Active Monitoring of All-Optical Networks [1]

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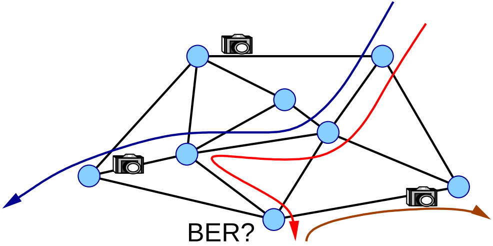
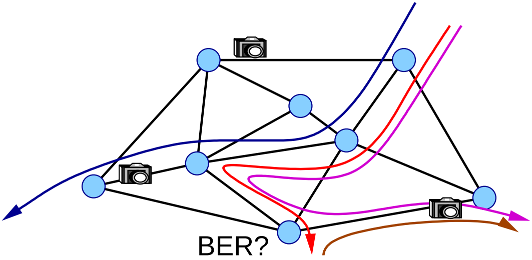
The monitoring problem



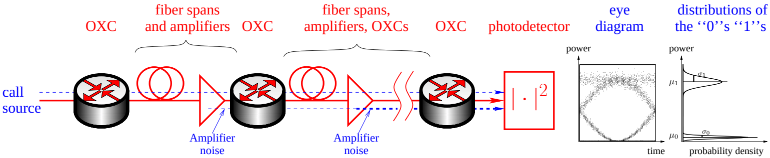
- Impairments accumulate ⇒ Q factor decreases
  ⇒ need monitoring
- Check that network performs as expected or guaranteed
- QoS monitoring: Q factor for all lightpaths?
- Monitoring devices are expensive → limit number
  - Deploy a few monitors, observe limited number of lightpaths
  - Exploit topology-induced correlation between Q factors
  - Estimate Q for non-observed lightpaths

Idea



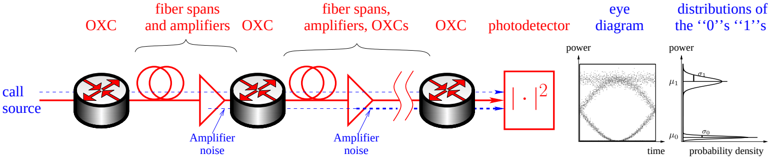
- **Passive monitoring:** inadequate performance
- **Establish** “active lightpaths”
  - Gain more information about non-observed lightpaths
  - No meaningful data on active lightpaths
  - Establish and tear down immediately → little impact on the network performance
  - Use wavelength that are otherwise unused
- **Estimate** Q for non-observed lightpaths

Lightpath and physical layer models



- New issues arise with all-optical networks
  - Intersymbol interference (ISI)
  - ASE (amplifier) noise accumulation
  - Nonlinear crosstalk (XPM, FWM)
  - Node crosstalk

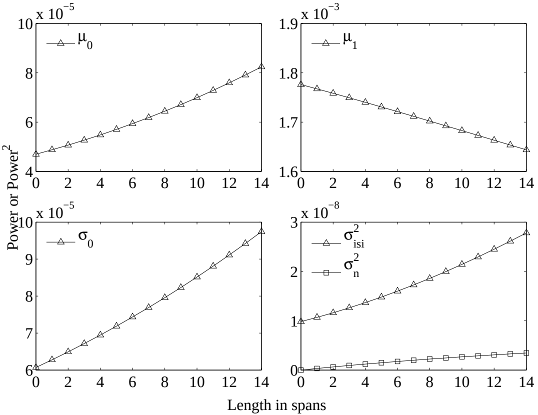
Model



- Monitors are located near photodetection stage
  - Placement problem ?
- Available data: μ_1, μ_0, σ_1, σ_0
- Only for lightpaths that end at monitor-equipped links!
- Noise and ISI only (also nonlinear and node crosstalks)

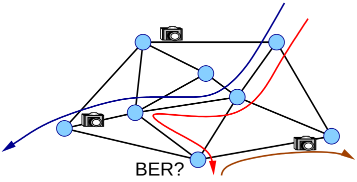
$$Q = \frac{\mu_1 - \mu_0}{\sigma_0 + \sqrt{\sigma_i^2 + \sigma_n^2 + \sigma_{nl}^2 + \sigma_{node}^2}}$$

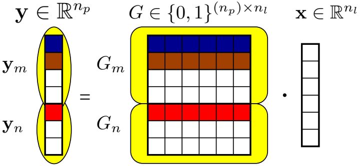
Linearity



- **y** =Q is not linear with # spans
- **y** $\in \{\mu_1, \mu_0, \sigma_1^2, \sigma_0\}$ is **linear** with # spans

Standard estimation problem





- $G = \begin{bmatrix} G_m \\ G_n \end{bmatrix}$=**routing matrix**, $n_p \times n_\ell$
- G_m=**observed/monitored paths** routing matrix, $n_s \times n_\ell$
- G_n=**non-observed** paths routing matrix, $(n_p - n_s) \times n_\ell$
- $\mathbf{y} = \begin{bmatrix} y_m \\ y_n \end{bmatrix}$=**end-to-end** metric, $\mathbf{x}$=**link** metric, $\mathbf{y} = G\mathbf{x}$
- $\mathbf{y}_m$=**observed** metrics, $\mathbf{y}_n$=**non-observed** metrics

Standard estimation problem

- G_m=observed paths routing matrix, $n_s \times n_\ell$
- G_n=non-observed paths routing matrix, $(n_p - n_s) \times n_\ell$
- $\mathbf{y}_m$=observed metrics, $\mathbf{y}_n$=non-observed metrics
- Given observations $\mathbf{y}_p$ and topology G, estimate $\hat{\mathbf{y}}_n$ of $\mathbf{y}_n$ that minimizes relative MSE: $\mathrm{RMSE}\left(\hat{\mathbf{y}_n}\right) = \|\hat{\mathbf{y}_n} - \mathbf{y}_n\|_2 / \|\mathbf{y}_n\|_2$:

$$\hat{\mathbf{y}}_n = G_n G_m^T \left(G_m G_m^T\right)^+ \mathbf{y}_m \text{ [Chua 2005]}$$

- Heuristic used to select G_m given G

Problem statement

- Monitors placement=fixed, cannot select lightpaths at will
- Establish at most n_a new "active" lightpaths
  $\rightarrow$ active lightpaths G_a, new observations $\mathbf{y}_a$
- **Objective:**

$$G_a^* = \arg\min_{G_a} \left(\mathrm{RMSE}\left(\hat{\mathbf{y}}_n\right)\right)$$

$$\hat{\mathbf{y}}_n = G_n G_m'^T \left(G_m' {G_m'}^T \right)^+ \mathbf{y}_m', \ G_m' = \begin{bmatrix} G_m \\ G_a \end{bmatrix}, \ \mathbf{y}_m' = \begin{bmatrix} \mathbf{y}_m \\ \mathbf{y}_a \end{bmatrix}$$

- **Constraint:** physical meaning of G_a
- **Secondary objective:** keep additional lightpaths short
- **Insight:** augment rank of observation matrix G_m'

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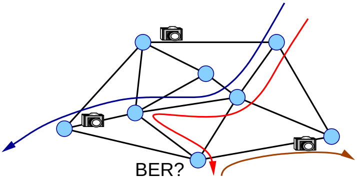

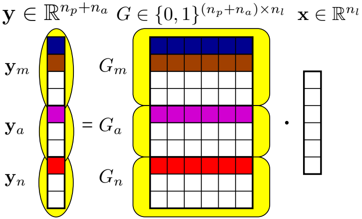

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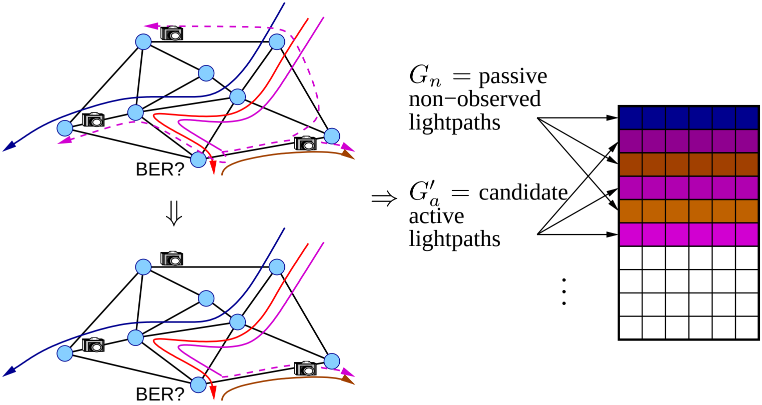
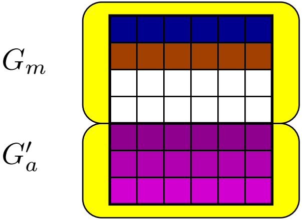
- **Constraint:** physical meaning of G_a
- **Secondary objective:** keep additional lightpaths short
- **Insight:** augment rank of observation matrix G_m'
- G_a is binary $\Rightarrow$ need heuristic

Heuristic



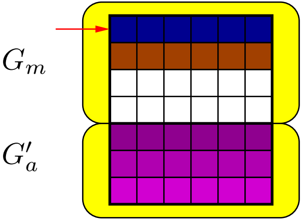
- For each non-observed lightpaths, find path from last node of lightpath to closest monitor $\rightarrow G'_a$
- **Insight:** force observations of (formerly) unobserved links!
- Meet wavelength continuity constraint, but not QoS

Heuristic



- Possibly many ($= n_p - n_s$) candidates, need at most n_a
- Select an increasing number n of rows of $\begin{bmatrix} G_m \\ G'_a \end{bmatrix}$ until n_a rows of G'_a are selected: **rank-revealing technique**
  - rows that best approximate space spanned by first n eigenvectors of $\begin{bmatrix} G_m \\ G'_a \end{bmatrix}$ [Golub-Van Loan]

Heuristic



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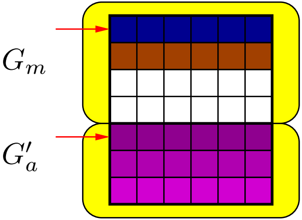

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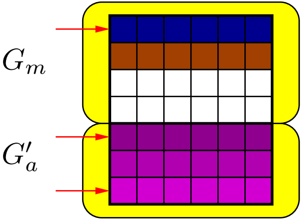

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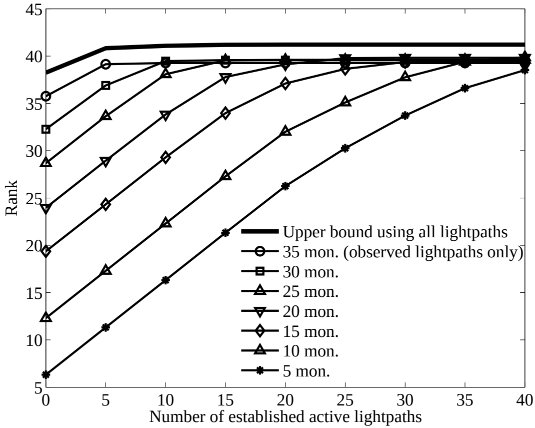
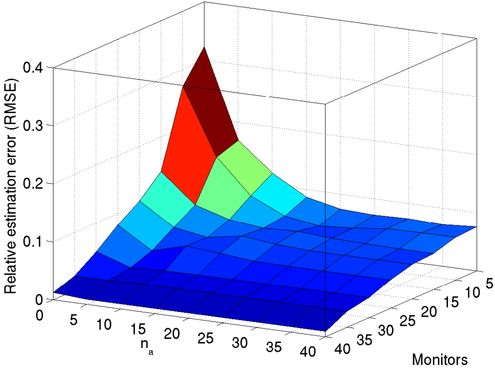
Rank of observation routing matrix G'_m



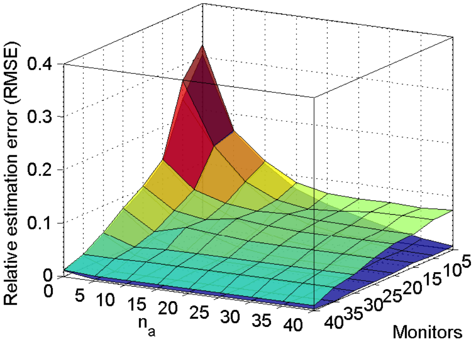
- NSFNET topology, 42 links, ≈ 50 lightpaths
- **Rank increases with slope 1** as the number of active lightpaths n_a increases

Simulation results



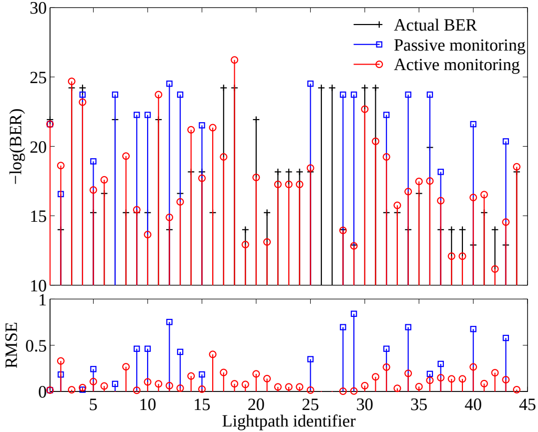
- Relative MSE in terms of $\log(\mathrm{BER})$ $(\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\frac{Q}{\sqrt{2}})$
- **Trade-off:** hardware monitoring vs active lightpaths vs estimation accuracy

Linearization noise floor



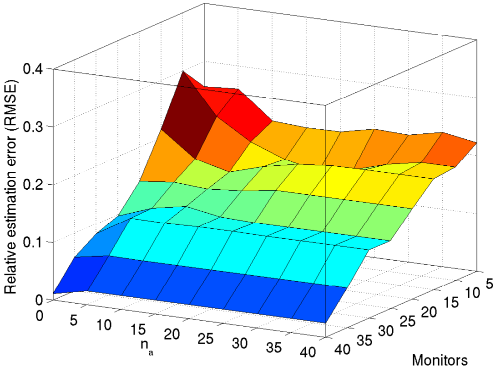
- Relative MSE in terms of $\log(\mathrm{BER})$
- Existence of a **"linearization noise"** floor

Example



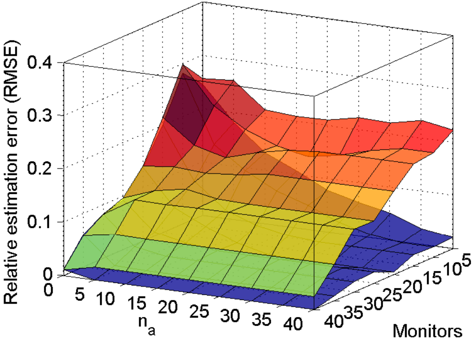
- 5 monitors, $n_a = 15$ active lightpaths
- More lightpaths estimated with active monitoring

With nonlinear and node crosstalk



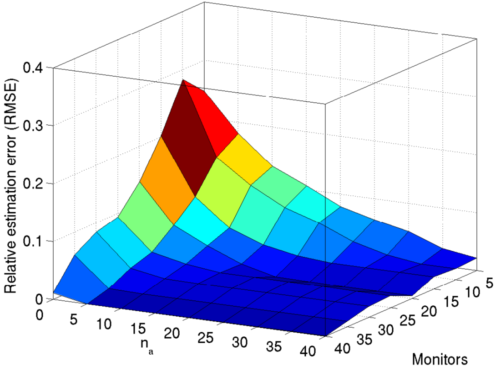
- The trade-off is not so apparent here...

Combining analytical method with real measurements



- Combining **analytical model** and **measurements** can improve monitoring performance

Combining analytical method with real measurements



- Combining **analytical model** and **measurements** can improve monitoring performance
- Need to find a linear transformation and a good model for the ASE noise

Conclusions

- Exploit **trade-off** between

  # hardware monitors (expensive)

  and

  # new "active" lightpaths (inexpensive)

- Place active lightpaths appropriately

  $\Rightarrow$ **reduce** hardware monitors, **same** monitoring performance

- Necessitates **linearization assumption**

  $\Rightarrow$ hybrid (**analytical** + **measurements**) estimation framework?

- **Future work:** soft error detection/localization