Cross-Layer Design of All-Optical Networks Incorporating Crosstalk Effects

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Ph.D Final Examination
August 7, 2006
Overview

- Introduction
- Crosstalk Propagation in All-Optical Networks
- Cross-Layer Adaptive Routing and Wavelength Assignment in All-Optical Networks
- Analysis of Blocking Probability in Crosstalk-Impaired Networks
- Conclusions
Publications

Crosstalk Propagation in All-Optical Networks


Publications

Cross-Layer Adaptive RWA in All-Optical Networks


Publications

Analysis of Blocking Probability in Crosstalk-Impaired Networks

All-optical networks

▷ Current high-speed optical networks
  ■ Bottleneck due to electrical conversions

▷ Features of all-optical networks
  ■ Speed, flexibility, cost

▷ New issues arise with all-optical networks
  ■ Nodes (OXC) are subject to crosstalk
  ■ Node crosstalk is transmitted over extremely long paths without electrical signal regeneration → nonlinear interaction

▷ Implementation
  ■ Crosstalk issues will be encountered in the near future
Leaks can originate from imperfect demultiplexing, or transmission within the switching matrix of an all-optical crossconnect (OXC)
Routing and Wavelength Assignment

- All-optical networks with no wavelength conversion
- Crosstalk impairs the QoS of lightpaths
  - typically we want to keep $BER \leq 10^{-9}$ at all times, for each lightpath
- Design Routing and Wavelength Assignment (RWA) algorithms to mitigate crosstalk effects
Routing and Wavelength Assignment illustration
Routing and Wavelength Assignment

- All-optical networks with no wavelength conversion
- Crosstalk impairs the QoS of lightpaths
  - typically we want to keep $BER \leq 10^{-9}$ at all times, for each lightpath
- Design Routing and Wavelength Assignment (RWA) algorithms to mitigate crosstalk effects
  - wavelength continuity constraint and QoS constraint
  - traditional RWA try to decrease call blocking probability
  - adaptive RWA is a class of RWA with low blocking probability due to the wavelength continuity constraint $\Rightarrow$ focus on QoS blocking and fairness among users
Contributions

Cross-layer design: mitigate physical-layer effects (including crosstalk) at the network layer (with RWA)

- Fast analytical and semi-analytical models to determine performance (BER) of all-optical networks subject to crosstalk
- Novel RWA algorithms accounting for physical layer impairments (ISI, noise, crosstalk)
- Analysis of a class of RWA algorithms incorporating physical layer impairments
Overview

▷ Introduction

▷ **Crosstalk Propagation in All-Optical Networks**
  - System description
  - Continuous wave approximation (NRZ signals) and validation by simulations
  - Semi-analytical method (RZ signals) and validation by simulations

▷ **Cross-Layer Adaptive Routing and Wavelength Assignment in All-Optical Networks**

▷ **Analysis of Blocking Probability in Crosstalk-Impaired Networks**

▷ **Conclusions**
Lightpath and physical layer models

\[ BER = \frac{1}{2} \text{erfc} \frac{Q}{\sqrt{2}}, \quad Q = \frac{\mu_1 - \mu_0}{\sigma_0 + \sqrt{\sigma_i^2 + \sigma_n^2 + \sum \sigma_x^2}} \]
Problem statement

▷ What is the impact of node crosstalk and how does it depend on the physical parameters?

- $Q = \frac{\mu_1 - \mu_0}{\sigma_0 + \sqrt{\sigma_i^2 + \sigma_n^2 + \sum \sigma_x^2}}$
- Simulations are very slow (tens of hours) because of the number of random parameters
- Can compute $\mu_0$, $\mu_1$, $\sigma_0$, $\sigma_i$ using very short simulations of a few bits (ISI, linear and nonlinear signal transmission effects)
- Can compute $\sigma_n$ due to noise using analytical techniques
- Need a fast way to compute $\sigma_x$ and hence $Q$
Node crosstalk model

\[ s_0(t) = s_m(t) + \sum_{\ell} m_\ell g_0(t - \ell T_b) \]

- **in the analysis only**, \( s_m(t) \) is assumed to be a Continuous Wave (CW): \( s_m(t) = \sqrt{P_0} \)
- \( s_m(t) \) is modulated in the simulations
- Node crosstalk signal is modulated (analysis and simulations)

\[ g_0(t) = \sqrt{\eta P_0} h(t - \tau) e^{j\omega_s(t-\tau)+j\varphi} \]

- Bits \( m_\ell \), delay \( \tau \) and phase \( \varphi \) are uniformly distributed over \( \{0,1\} \), \([0,T_b)\), \([0, 2\pi)\), respectively.
- Node crosstalk attenuation \( \eta \), detuning \( \omega_s \)
- Pulse shape \( h(t) \)
Analysis: determining a transfer matrix

- CW input, after k spans:
  
  \[ s_m(t, L) = e^{jk\theta_{SPM}} \sqrt{P_0} \text{ with } (\theta_{SPM} \approx -\gamma P_0/\alpha) \]

- Node crosstalk bit, after k spans:
  
  \[ g_k(t) = e^{jk\theta_{SPM}} (g_k^I(t) + jg_k^Q(t)) \]

- Projecting:
  
  \[ g_k^I(t) = g_k^{I+}(t)e^{j\varphi} + g_k^{I-}(t)e^{-j\varphi} \]
  
  \[ g_k^Q(t) = g_k^{Q+}(t)e^{j\varphi} + g_k^{Q-}(t)e^{-j\varphi} \]
Continued . . .

\( \triangleright \) In frequency domain, for the first span (same for I-/Q- terms):
\[
\begin{bmatrix}
G^I_1(\omega) \\
G^Q_1(\omega)
\end{bmatrix} =
T_1(\omega) \begin{bmatrix}
G^I_0(\omega) \\
G^Q_0(\omega)
\end{bmatrix}
\]

\( \triangleright \) After \( k \) spans (same for I-/Q- terms):
\[
\begin{bmatrix}
G^I_k(\omega) \\
G^Q_k(\omega)
\end{bmatrix} =
T_k(\omega) \ldots T_1(\omega) \begin{bmatrix}
G^I_0(\omega) \\
G^Q_0(\omega)
\end{bmatrix}
\]
Node crosstalk variance

▷ Current due to node crosstalk power after k spans (single segment, receiver noise ignored):

\[ \Delta i(t, k) = \rho f(t) \ast \left( |\sqrt{P_0} e^{j k \theta_{SPM}} + m g_k(t - \tau)|^2 - P_0 \right) \]

\[ \Rightarrow \Delta i(t, k) \approx 2 \rho \sqrt{P_0} m f(t) \ast (g_k^+(t - \tau) e^{j \varphi} + g_k^-(t - \tau) e^{-j \varphi}) \]

▷ \( \sigma_x^2(t, k) \) is the variance of \( \Delta i(t, k) \) sampled at \( t = T_b/2 \)

\[ \sigma_x^2 = 4 \rho^2 P_0 \int_{-\infty}^{\infty} \frac{1}{T_b} |f(t) \ast g_k^+(t - \tau)|^2 \, d\tau \]
Node crosstalk variance: continued

\[ \sigma_x^2 = 4\rho^2 P_0 \int_{-\infty}^{\infty} \frac{1}{T_b} |f(t) * g_k^I^+(t - \tau)|^2 d\tau \]

▷ Multisegment case: add node crosstalk variances for each node crosstalk component coming from a different OXC

▷ Complexity:
  - analysis is simpler than even the short simulation
  - short simulation: 32 bits
  - complete simulation: 2048 x 32 bits
## Validation: physical parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Baseline Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span length</td>
<td>100 km</td>
</tr>
<tr>
<td>Pump power</td>
<td>2 mW</td>
</tr>
<tr>
<td>Bit rate</td>
<td>10 Gbps</td>
</tr>
<tr>
<td>Pulse shape</td>
<td>NRZ</td>
</tr>
<tr>
<td>Node crosstalk attn. (power)</td>
<td>−30 dB</td>
</tr>
<tr>
<td>Node crosstalk detuning</td>
<td>0 GHz</td>
</tr>
<tr>
<td>Fiber loss</td>
<td>0.2 dB/km</td>
</tr>
<tr>
<td>Nonlinear coefficient</td>
<td>2.2 (W km)(^{-1})</td>
</tr>
<tr>
<td>(2^{nd}) order dispersion</td>
<td>17 ps/nm/km</td>
</tr>
<tr>
<td>Noise figure</td>
<td>2</td>
</tr>
<tr>
<td>Dispersion compensation</td>
<td>100% post</td>
</tr>
<tr>
<td>Photodetector responsitivity</td>
<td>1 A/W (arbitrarily)</td>
</tr>
<tr>
<td>Electrical filter bandwidth</td>
<td>0.7× bit rate</td>
</tr>
</tbody>
</table>
10 Gbps dispersion-compensated network

Standard deviations

- red: analysis; black: simulation

Q factors
Semi-analytical method for RZ signals

▷ With RZ signaling, the CW assumption no longer holds

▷ Recall:

\[
\sigma_x^2(t) = 4\rho^2 \int_{-\frac{T_b}{2}}^{\frac{T_b}{2}} \frac{1}{T_b} \left| f(t) * \left( \sqrt{P(t)g_I^+(t)} \right) \right|^2 \, d\tau
\]

▷ We determine \( g_I^+(t) \big|_{t=T_b/2} \) for all \( \tau \) by simulation
## Validation: physical parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Baseline value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span length</td>
<td>50 km</td>
</tr>
<tr>
<td>Pump power</td>
<td>2 mW</td>
</tr>
<tr>
<td>Bit rate</td>
<td>10 Gbps</td>
</tr>
<tr>
<td>Pulse shape</td>
<td>RZ</td>
</tr>
<tr>
<td>Node crosstalk attenuation</td>
<td>−30 dB</td>
</tr>
<tr>
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<td>0 GHz</td>
</tr>
<tr>
<td>Fiber loss</td>
<td>0.2 dB/km</td>
</tr>
<tr>
<td>Nonlinear coefficient</td>
<td>2.2 (W km)$^{-1}$</td>
</tr>
<tr>
<td>Second order dispersion</td>
<td>2 ps/nm/km</td>
</tr>
<tr>
<td>Noise figure</td>
<td>no noise</td>
</tr>
<tr>
<td>Dispersion compensation</td>
<td>no DC</td>
</tr>
<tr>
<td>Photodetector responsitivity</td>
<td>1 A/W</td>
</tr>
<tr>
<td>Electrical filter bandwidth</td>
<td>0.7× bit rate</td>
</tr>
</tbody>
</table>
Impact of ISI and node crosstalk

\[ \sigma^2(A^2) \]

- Red: analysis; Black: simulation

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Cross-Layer Design of All-Optical Networks
Incorporating Crosstalk Effects

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Conclusions: modeling of node crosstalk effects

- Able to assess accurately Q over broad ranges of physical parameters
- Node crosstalk effect cannot be ignored
- Node crosstalk effect may not be constant along a lightpath
- Need to account for node crosstalk impairment in RWA algorithm design
Overview

- Introduction
- Crosstalk Propagation in All-Optical Networks
- Cross-Layer Adaptive Routing and Wavelength Assignment in All-Optical Networks
  - System description
  - Fair QoS-aware adaptive RWA
  - QoS-aware adaptive RWA with optional coding
- Analysis of Blocking Probability in Crosstalk-Impaired Networks
- Conclusions
Cross-Layer Adaptive RWA in All-Optical Networks

▷ RWA: find a lightpath (route + wavelength) between 2 nodes on call arrival
  ■ wavelength continuity constraint

▷ Typically designed to minimize call blocking probability

▷ Design Routing and Wavelength Assignment (RWA) algorithms to mitigate physical-layer effects
  ■ QoS constraint – node crosstalk model
    [Deng/Subramaniam-Broadnets2004]
  ■ adaptive RWA is a class of RWA with low blocking probability due to the wavelength continuity constraint
    [Mokhtar/Azizoğlu-ToN1998]
Metrics

- Average call blocking probability (BP): keep low

- Bit-error rate (BER)
  - a margin allows for greater scalability, flexibility, robustness, fewer retransmissions at higher layers

- Fairness: \(0 \leq f(X) = \frac{E_S[X]^2}{E_S[X^2]} \leq 1\) [Jain1984]
  - here, \(S\) is the set of all (source, destination) pairs and \(X\) is either BP or BER

- BP fairness: all clients should have equal access to the network

- BER fairness: more fair \(\Rightarrow\) need FEC for fewer paths
Fast, dynamic estimation of BER: \( BER = 0.5 \ \text{erfc}(Q/\sqrt{2}) \)

\[
Q = \frac{\mu_1 - \mu_0}{\sigma_0 + \sigma_1} = \frac{\mu_1 - \mu_0}{\sigma_0 + \sqrt{\sigma_i^2 + \sigma_n^2 + \sum_p \sigma_{ix^2_p} + \sum_q \sigma_{nx^2_q}}}
\]

- \( \mu_0, \mu_1, \sigma_0, \sigma_1 \): means, st.dev. for the received “0s” and “1s”
- Split \( \sigma_1^2 \) into ISI, ASE noise, interchannel and node crosstalk variances
- Sum crosstalk terms over all interfering paths
Impact of crosstalk accumulation on the maximum transmission distance (70-km spans), for a typical optical network

- **node crosstalk**

<table>
<thead>
<tr>
<th>Crosstalks</th>
<th>0, 1</th>
<th>2, 3</th>
<th>4</th>
<th>5, 6</th>
<th>7, 8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spans</td>
<td>12</td>
<td>11</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>6</td>
</tr>
</tbody>
</table>

- **XPM**

<table>
<thead>
<tr>
<th>Crosstalks</th>
<th>0</th>
<th>1</th>
<th>2-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spans</td>
<td>12</td>
<td>9</td>
<td>7</td>
</tr>
</tbody>
</table>
Generic QoS-aware adaptive RWA algorithm

loop on the set of wavelengths

1. Call arrival
2. Check if $SP(\lambda_i)$ exists?
   - Yes: Check QoS and reservation conditions met?
     - Yes: Add $SP(\lambda_i)$ to list of candidates
     - No: Call rejected
   - No: $i = i + 1$

3. Check if $i < C$?
   - Yes: Select path according to policy (SP/SP2/HQ/MMQ)
   - No: Call rejected

4. Call accepted

Notes:
- $\lambda_i$ represents the wavelength of the call.
- $C$ is the maximum number of calls that can be accepted.
- QoS and reservation conditions include aspects such as bandwidth, delay, and reliability.
Reference policy: SP [Mokhtar/Azizoğlu-ToN1998]

▷ Considered algorithms are as complex as traditional adaptive RWA with BER guarantee

▷ SP is the traditional Shortest Path policy
Novel policies: HQ, MMQ

- HQ selects the lightpath with the highest Q factor

- MMQ: inserting a new lightpath “LP1” in the network changes the BER for all LPs that cross LP1; MMQ maximizes (over the set of wavelengths) the minimum Q (over the set of LPs that cross each candidate lightpath)

- Insight: optimize QoS by selecting the path that manages the largest QoS (HQ) or QoS margin (MMQ) in the network
Novel policies: SP2, MMQ2

- SP2 is SP with protecting threshold – single-hop paths accepted only if 2 or more wavelengths are available

- Insight: put aside wavelengths for longer paths, which are more likely to be blocked due to both wavelength continuity and QoS constraints

- MMQ2 additionally implements the protecting threshold technique

- Insight: optimize QoS by selecting the path that manages the largest QoS margin in the network

- HQ/MMQ/MMQ2 are QoS-enhanced but may waste resources compared with SP/SP2
Topology and physical parameters

NSF topology downscaled 10 times; the weights are the number of spans.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span length</td>
<td>70 km</td>
</tr>
<tr>
<td>Signal peak power</td>
<td>2 mW</td>
</tr>
<tr>
<td>Bit rate</td>
<td>10 Gbps</td>
</tr>
<tr>
<td>Pulse shape</td>
<td>NRZ</td>
</tr>
<tr>
<td>Fabric crosstalk</td>
<td>−40 dB</td>
</tr>
<tr>
<td>Adj. port crosstalk</td>
<td>−30 dB</td>
</tr>
<tr>
<td>Non adj. port crosstalk</td>
<td>−60 dB</td>
</tr>
<tr>
<td>Fiber type</td>
<td>SMF</td>
</tr>
<tr>
<td>Dispersion compensation</td>
<td>100% post-DC</td>
</tr>
<tr>
<td>Noise factor</td>
<td>2</td>
</tr>
<tr>
<td>Receiver elec. BW</td>
<td>7 GHz</td>
</tr>
<tr>
<td>Number of WL</td>
<td>8</td>
</tr>
<tr>
<td>Maximum BER</td>
<td>$10^{-9}$</td>
</tr>
</tbody>
</table>
Blocking Probability

BPs are equivalent for all algorithms

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Both kinds of crosstalk have a serious impact on BP
▶ Our QoS-enhanced RWA algorithms perform better for BER than SP/SP2
Fairness: Blocking Probability

MMQ, SP2 exhibit highest BP fairness
MMQ exhibits highest BER fairness
RWA with optional coding for larger networks

▷ Context: very large networks where some paths are “too” long
  ■ some paths are so long no call can be established without breaking the QoS constraint

▷ Forward Error Correction coding trade-off
  ■ can improve BER and keep it below threshold
  ■ cost: bandwidth expansion
Algorithm flow

Call arrival

- Attempt to allocate a single lightpath LP
  - RWA (find LP)
    - Found LP?
      - yes
        - accept call on LP with no coding
      - no
        - QoS cond. met?
          - yes
            - reject call
          - no
            - Attempt to allocate two lightpaths LP1 and LP2

- Attempt to allocate two lightpaths LP1 and LP2
  - RWA (find LP1)
    - Found LP1?
      - yes
        - QoS cond. met?
          - yes
            - reject call
          - no
            - RWA (find LP2)
              - Found LP2?
                - yes
                  - accept call on LP1, LP2 with Golay coding on each LP
                - no
                  - reject call
Simulation results

![NSF topology downscaled 5 times; the weights are the number of spans.](image)

<table>
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<tr>
<td>Bit rate</td>
<td>10 Gbps</td>
</tr>
<tr>
<td>Nonlinear parameter</td>
<td>$2.2 \text{ (W.m)}^{-1}$</td>
</tr>
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<td>Pulse shape</td>
<td>NRZ</td>
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<tr>
<td>Fabric xtalk</td>
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</tr>
<tr>
<td>Number of WL</td>
<td>8</td>
</tr>
<tr>
<td>Minimum Q factor to ensure BER $&lt; 10^{-9}$</td>
<td>$Q_1 = 6$ $Q_2 = 3.6$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spans</th>
<th>Paths</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-12</td>
<td>164</td>
</tr>
<tr>
<td>14+</td>
<td>18</td>
</tr>
</tbody>
</table>
Option: coding cancels most of the physical layer impairments
Fairness: blocking probability

- Optional coding improves fairness
Conclusions

- Introduced new metrics to evaluate RWA algorithms
- Large (metro/regional) networks: presented new QoS-enhanced RWA algorithms based on adaptive RWA: SP2, HQ, MMQ, MMQ2
  - Perform well in terms of BP
  - Perform better than others in terms of QoS and fairness
- Very large (regional) networks: optional coding ...
  - Helps reducing blocking probabilities in large networks
  - Mitigates physical layer impairments
  - Improves fairness among users
Overview

▷ Introduction

▷ Crosstalk Propagation in All-Optical Networks

▷ Cross-Layer Adaptive RWA in All-Optical Networks

▷ Analysis of Blocking Probability in Crosstalk-Impaired Networks
  ■ Assumptions
  ■ Iterative algorithm overview
  ■ QoS blocking
  ■ Validation by simulations

▷ Conclusions
Analysis of Blocking Probability in Crosstalk-Impaired Networks

▷ Assumptions:
  - fixed routing, random pick wavelength assignment
  - ISI, noise, node demultiplexer crosstalk
  - wavelength equivalence

▷ Reuse published algorithm for blocking due to the wavelength continuity constraint (wavelength blocking)
  [Sridharan/Sivarajan-ToN2004]

▷ QoS extensions are largely independent of the wavelength blocking algorithm
Node crosstalk model
[Deng/Subramaniam-Broadnets2004]

- “self-crosstalk”
- all channels are equivalent
  - no distinction between adjacent and non-adjacent channels
Iterative technique

▷ Dashed box: wavelength blocking – Dotted box: QoS blocking
▷ $X_j = \text{number of free wavelengths on link } j$
▷ $B_R, B_R^w, B_R^q$ are blocking probabilities ($B_R = B_R^w + (1 - B_R^w)B_R^q$)
▷ $\alpha_j(m) = \text{state dependent arrival rate}$
▷ $U, U', XT$ to be detailed
Per-link arrivals

\[ \Lambda: \quad \alpha(C) \quad \alpha(C - 1) \]
\[ X_j: \quad C \quad C - 1 \quad \ldots \quad m \quad m - 1 \quad \ldots \quad 0 \]
\[ M: \quad 1 \quad 2 \quad \ldots \quad C - m + 1 \quad C \]

- Birth-death process is known to accurately model link states [Chung/Kasper/Ross-ToN1993]

- \( X_j = \) number of free wavelengths on link \( j \)

- \( \Lambda = \) arrival rate (parameter of a Poisson distribution)

- \( M = \) service rate (parameter of an exponential distribution)
Iterative technique

- \( B^w_R \) and \( B^q_R \) are interdependent
- The respective algorithms to compute \( B^w_R \) and \( B^q_R \), though, are largely independent
- There are techniques in the literature to compute \( B^w_R \)
  - We reuse one of them to determine \( B^q_R \)
QoS blocking

$B_R \rightarrow U_R \rightarrow U'_{R,R'} \rightarrow XT_R \rightarrow B^q_R \rightarrow B_R$

- $U_R(k) = \text{probability that } k = 0, \ldots, C \text{ calls are established on exactly route } R$

- Establishing a call on $R$ is modeled as a Bernoulli trial with success $p_R$:

$$p_R = \frac{\Lambda_R}{M_R} \frac{1 - B_R}{C} = \Lambda_R \frac{1 - B_R}{C}$$

- Assuming independence between the trials:

$$U_R(k) \approx \binom{C}{k} p_R^k (1 - p_R)^{C-k}, k = 0, 1, \ldots, C.$$
QoS blocking

\[ B_R \rightarrow U_R \rightarrow U'_{R,R'} \rightarrow XT_R \rightarrow B''_R \rightarrow B_R \]

\[ \triangleright n_{xt}(R, R') = \text{number of common nodes between routes } R \text{ and } R' \text{ where crosstalk can occur} \]

\[ \triangleright \quad \text{Recall: crosstalk from } R' \text{ to } R \text{ can occur at a node } N \text{ when } R \text{ and } R' \text{ share the link before } N \text{ and the link after } N \]

\[ \triangleright U'_{R,R'}(k) = \text{probability that route } R' \text{ injects } k \text{ crosstalk components on route } R \]

\[ U'_{R,R'}(n_{xt}(R, R')k) = U_{R'}(k) \]

\[ \triangleright \quad XT_R(k) = \text{probability that route } R \text{ is subject to exactly } k \text{ crosstalk components} \]

\[ XT_R = U'_{R,R_1} \ast \ldots \ast U'_{R,R_p} \]
QoS blocking

\[ B_R \rightarrow U_R \rightarrow U'_{R,R'} \rightarrow XT_R \rightarrow B_R^q \rightarrow B_R \]

▷ Q factor for a system with crosstalk:

\[
Q_R = \frac{\mu_{1,R} - \mu_{0,R}}{\sigma_{0,R} + \sqrt{\sigma_{i,R}^2 + \sigma_{n,R}^2 + n\sigma_{x,R}^2}}
\]

▷ Maximum number of crosstalks to keep Q below threshold:

\[
N_{R}^{\text{max}} = \left\lfloor \frac{\left( \frac{\mu_{1,R} - \mu_{0,R}}{Q_{th}} - \sigma_{0,R} \right)^2 - \sigma_{i,R}^2 - \sigma_{n,R}^2}{\sigma_{x,R}^2} \right\rfloor
\]

▷ QoS blocking:

\[
B_R^q = \sum_{k > N_{R}^{\text{max}}} XT_R(k).
\]
Iterative technique

\[ \alpha_j(m) \]

\[ B^w_R|X_j=m \]

\[ B_R|X_j=m \]

\[ U_R|X_j=m \]

\[ U'_R,R'|X_j=m \]

\[ B^q_R|X_j=m \]

\[ X T_R|X_j=m \]

\[ \beta^q_R \]

\[ B^q_R \]

\[ X T_R \]

\[ U_R \]

\[ U'_R,R' \]

\[ \triangleright \text{Computations of the conditionals } U_R|X_j=m, U_R'|R'|X_j=m, X T_R|X_j=m, B^q_R \]

\[ B^q_R|X_j=m \text{ are very similar to the computations of } U_R, U_R'|R', X T_R, B^q_R. \]
Simulation results

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span length</td>
<td>70 km</td>
</tr>
<tr>
<td>Signal peak power</td>
<td>2 mW</td>
</tr>
<tr>
<td>Bit rate</td>
<td>10 Gbps</td>
</tr>
<tr>
<td>Nonlinear parameter</td>
<td>$2.2 \text{ (W.m)}^{-1}$</td>
</tr>
<tr>
<td>Pulse shape</td>
<td>NRZ</td>
</tr>
<tr>
<td>Fiber type</td>
<td>SMF</td>
</tr>
<tr>
<td>Dispersion</td>
<td>100% post-DC</td>
</tr>
<tr>
<td>Min. Q factor</td>
<td>6</td>
</tr>
</tbody>
</table>
Simulation results

- mesh of 8 nodes, 16 wavelengths, -25 dB and -30 dB crosstalk
- red: analysis; black: simulation
Simulation results

Load in gain for a target average call blocking probability of 0.001 (reference: gain=1 for -25 dB)
Simulation results

- NSF topology, 8 wavelengths, -30 dB crosstalk
  - red: analysis; black: simulation
Conclusions and future work

- Physical parameters-dependent impact of crosstalk on network performance
- Physical layer impairments (including crosstalk) mitigation is possible through RWA
- Cross-layer RWA analysis
- Leads for future work:
  - Higher speeds: Polarization Mode Dispersion (PMD) an issue for 40 Gbps
  - Wavelength regeneration, translucent networks
  - Adjacent vs. non-adjacent channel crosstalk in RWA analysis
Questions?

[“Piled Higher and Deeper” by Jorge Cham - www.phdcomics.com]
Contents of the transfer matrix [Xu-PTL2004]

\[
T_k(\omega) = \begin{bmatrix}
\frac{1}{2} e^{-j\theta_{SPM}} & \frac{1}{2} e^{j\theta_{SPM}} \\
\frac{1}{2j} e^{-j\theta_{SPM}} & -\frac{1}{2j} e^{j\theta_{SPM}}
\end{bmatrix}
\]

\[
\mathcal{M}_k(\omega) = \begin{bmatrix}
\mathcal{M}_{1,1}(\omega) & \mathcal{M}_{1,2}(\omega) \\
\mathcal{M}^*_{1,2}(\omega) & \mathcal{M}^*_{1,1}(\omega)
\end{bmatrix}
\]

\[
\mathcal{M}_{1,1}(\omega) = e^{-\frac{\alpha}{2} L} G e^{-\frac{j}{2} (\beta_2 L) \omega^2} \left( 1 - j \frac{2\gamma P_0}{\alpha} + \frac{\gamma^2 P_0^2}{2\alpha(\alpha - j\beta_2 \omega^2)} - \frac{2\gamma^2 P_0^2}{\alpha^2} \right)
\]

\[
\mathcal{M}_{1,2}(\omega) = e^{-\frac{\alpha}{2} L} G e^{-\frac{j}{2} (\beta_2 L) \omega^2} \left( -j \frac{\gamma P_0}{\alpha - j\beta_2 \omega^2} - \frac{2\gamma^2 P_0^2}{\alpha(2\alpha - j\beta_2 \omega^2)} \right)
\]
NRZ - 2.5 Gbps non dispersion-compensated network

Standard deviations

Q factors

Yvan Pointurier
Ph.D Final Examination
August 7, 2006

Cross-Layer Design of All-Optical Networks
Incorporating Crosstalk Effects
66/62
NRZ - Main signal power and node crosstalk attenuation

Main signal power

Node crosstalk attenuation

red: analysis; black: simulation
NRZ - Detuning and multisegment

Detuning

Multisegment

red: analysis; black: simulation
Semi-analytical method for RZ signals

▷ For a single main bit and node crosstalk bit — output:

\[ s_{out}(t) = \sqrt{P(t)} \exp(j\theta(t)) + mg_{\tau,\varphi}(t) \]

▷ Splitting as in the CW case:

\[ s_{out}(t) = \exp(j\theta(t)) \left( \sqrt{P(t)} + m \left( g_{\tau}^{I+}(t) \exp(j\varphi) + g_{\tau}^{I-}(t) \exp(-j\varphi) 
+ jg_{\tau}^{Q+}(t) \exp(j\varphi) + jg_{\tau}^{Q-}(t) \exp(-j\varphi) \right) \right) \]
Semi-analytical method

\[ \phi = 0 \]

\[ \phi = \pi/2 \]

▷ Use short simulations, use \( N \) values for the random delay \( \tau \):

\[ \tau_k = k/NT_b, \text{ and 2 phases: } \phi = 0 \text{ and } \phi = \pi/2 \]
Continued . . .

▷ Short simulation output:

\[ s_{k,\phi}^{\text{out}}(t) \approx \sqrt{P(t)} \exp j\theta(t) + g_{\tau_k,\phi}(t) \]

▷ Estimate of the node crosstalk pulse shape for \( \tau_k \)

\[
\hat{g}_{\tau_k}^{I+}(t) = \frac{1}{2} \Re \left\{ \exp (-j\theta(t))(s_{k,0}^{\text{out}}(t) - \sqrt{P(t)} \exp j\theta(t)) \right\} \\
- \frac{j}{2} \Re \left\{ \exp (-j\theta(t))(s_{k,\pi/2}^{\text{out}}(t) - \sqrt{P(t)} \exp j\theta(t)) \right\}
\]

▷ Estimate for the node crosstalk variance:

\[
\hat{\sigma}^2_x = \left( \frac{\rho^2}{N} \sum_{k=-N/2}^{N/2-1} 4 \left| f(t) * \left( \sqrt{P(t)} \hat{g}_{\tau_k}^{I+}(t) \right) \right|^2 \right) \bigg|_{t=T_b/2}
\]
RZ - Impact of detuning

\[ \sigma^2_1 (\text{A}^2) \times 10^{-9} \]

- Input
- After 4 spans
- After 6 spans
- After 8 spans
- After 10 spans

*red*: analysis; *black*: simulation
RZ - Impact of main signal power

![Graph showing the impact of main signal power on signal quality. The graph displays the variation of $\sigma_1^2 (A^2)$ with span for different power levels: 1 mW, 2 mW, and 5 mW. The red lines represent analysis, and the black lines represent simulation.]

**red**: analysis; **black**: simulation
RWA with optional coding: BER

Optional coding lowers BER