Routing and Wavelength Assignment Incorporating the Effects of Crosstalk Enhancement by Fiber Nonlinearity

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Overview

- Introduction
  - All-optical networks
  - Crosstalk
  - Modeling
- Accounting for crosstalk
- Routing and Wavelength Assignment
- Conclusion
All-optical networks

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

- New issues arise with all-optical networks
  - Nodes (OXC) are subject to crosstalk
  - Crosstalk is transmitted over extremely long paths without electrical signal regeneration
Leaks can originate from imperfect demultiplexing, or transmission within the switching matrix.
Lightpath and physical layer models

\[ \sigma_1^2 = \sigma_{ISI}^2 + \sigma_n^2 + \Sigma \sigma_x^2 \]

\[ Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}, \quad BER \approx \frac{1}{2} \text{erfc} \left( \frac{Q}{\sqrt{2}} \right) \]
Overview

▷ Introduction

▷ **Accounting for crosstalk**

▷ Routing and Wavelength Assignment

▷ Conclusion
Crosstalk model

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

- The main signal \( s_m(t) \) and the crosstalk signal are modulated

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

- Bits \( m_{\ell} \), delay \( \tau \) and phase \( \varphi \) are uniformly distributed over \( \{0,1\}, [0,T_b), [0, 2\pi) \), respectively.
- Crosstalk detuning \( \omega_s \)
- Pulse shape \( h(t) \)
Delay-dependent crosstalk pulse shape

- For a single main bit and crosstalk bit — output:

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

- Splitting in in-phase and quadrature phase components and projecting:

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

▷ Current due to crosstalk:

\[
\Delta i(t) \approx \rho f(t) \ast \left(2 \sqrt{P(t)} m \left(g_{\tau}^{I+}(t) \exp(j\varphi) + g_{\tau}^{I-}(t) \exp(-j\varphi)\right)\right)
\]

▷ Variance:

\[
\sigma_{x}^{2}(t) = 4 \int_{-\frac{T_{b}}{2}}^{\frac{T_{b}}{2}} \frac{\rho^{2}}{T_{b}} \left|f(t) \ast \left(\sqrt{P(t)}g_{\tau}^{I+}(t)\right)\right|^{2} \, d\tau
\]

▷ We need to determine \(g_{\tau}^{I+}(t)|_{t=T_{b}/2}\) for all \(\tau\)
Semi-analytical method

Use short simulations, use $N$ values for the random delay $\tau$:

$$\tau_k = k/NT_b,$$

and 2 phases: $\phi = 0$ and $\phi = \pi/2$
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 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 crosstalk variance:

\[ \hat{\sigma}_x^2 = \left( \rho^2 \left( \frac{N-1}{N} \sum_{k=0}^{N-1} 4 \left| f(t) * \left( \sqrt{P(t)} \hat{g}_{\tau_k}^{I+}(t) \right) \right|^2 \right) \right|_{t=T_b/2} \]
Conclusions: modeling of crosstalk effects

- Reduced number of bits transmission simulation by 2 orders of magnitude
  \[ 2048 \times 32 = 65536 \text{ vs. } 32 + 4 \times 2 \times 32 = 288 \text{ bits} \]

- Still able to assess accurately Q over broad ranges of physical parameters

- Crosstalk effect cannot be ignored

- Crosstalk effect may not be constant along a lightpath
Overview

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▷ **Routing and Wavelength Assignment**
▷ Conclusion
RWA problem

▷ A way to mitigate crosstalk effects

▷ Wavelength continuity condition

▷ Calls can be blocked because no path/wavelength is available or because of a QoS violation
  ■ In this work, QoS $\leftrightarrow$ BER $\leftrightarrow$ Q

▷ Traditionally: do routing (fixed shortest path) and then find a wavelength

▷ Adaptive routing: pick wavelength, find shortest path
QoS aware algorithms

connection request → pick λ in order → determine SP(λ) → route exists and QoS condition met

mark route as usable

more wavelengths available

at least one usable route → yes

accept call

reject call

no

no
## Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span length</td>
<td>90 km</td>
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<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>RZ, gaussian</td>
</tr>
<tr>
<td>Crosstalk attenuation (power)</td>
<td>−30 dB</td>
</tr>
<tr>
<td>Fiber loss</td>
<td>0.22 dB/km</td>
</tr>
<tr>
<td>Nonlinear coefficient</td>
<td>2.2 (W km)$^{-1}$</td>
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<tr>
<td>2nd order dispersion</td>
<td>2 ps/nm/km (NZ-DSF)</td>
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<tr>
<td>Noise figure</td>
<td>2</td>
</tr>
<tr>
<td>Dispersion compensation</td>
<td>100% post-DC</td>
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<tr>
<td>Photodetector reponsitivity</td>
<td>1 (arbitrarily)</td>
</tr>
<tr>
<td>Electrical filter bandwidth</td>
<td>7 GHz</td>
</tr>
</tbody>
</table>
Example setup

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Simulation result

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Discussion

- The QoS-aware adaptive algorithms perform better than traditional algorithms

- The HQF algorithm does not perform as well as the SPF algorithm
  - HQF tends to avoid heavily used wavelengths, hereby “spreading” calls among the wavelengths
  - Work in progress: we will account for this behavior in future versions of the algorithm
Conclusions and future work

- Crosstalk has a lightpath physical parameters-dependent impact on network performance
- Fast, new method to account for crosstalk, based on perturbation theory and small-scale simulations
- Crosstalk impairment mitigation is possible through combined RWA
- Improve HQF RWA to account for wavelength spreading issue
- Design power-RWA to choose signal powers locally or even globally