Analysis of Blocking Probability in Noise- and Crosstalk-Impaired All-Optical Networks

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All-optical networks

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

- Features of all-optical networks
  - Circuit switched $\rightarrow$ lightpaths; speed, flexibility, cost

- New issues arise with all-optical networks
  - Nodes (OXC$s$) are subject to crosstalk
  - Node crosstalk is transmitted over extremely long paths without electrical signal regeneration

- Implementation
  - Crosstalk issues will be encountered in the near future

- Motivation
  - Obtain order of magnitude of call blocking probability in all-optical networks
  - Cross-layer optical network design
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Node crosstalk model [Deng/Subramaniam-Broadnets2004]

- Imperfect demultiplexing
- “Self-crosstalk”
- All channels are equivalent
  - No distinction between adjacent and non-adjacent channels
Model

**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
Model

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Iterative technique

- Dashed box: wavelength blocking – Dotted box: QoS blocking
- \( X_j \) = number of free wavelengths on link \( j \)
- \( B_R, B_R^w, B_R^q \) are blocking probabilities
  \( B_R = B_R^w + (1 - B_R^w)B_R^q \)
- \( \alpha_j(m) \) = state dependent arrival rate
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 $B^q_R$. 

\[
\begin{align*}
B^w_R | X_j = m & \quad B_R | X_j = m \quad U_R | X_j = m \quad U'_R, R'_R | X_j = m \\
\alpha_j(m) & \quad B^q_R | X_j = m \quad X_T R | X_j = m \\
B^w_R & \quad B_R \quad U_R \quad U'_R, R'_R
\end{align*}
\]
Per-link arrivals

- 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)
Wavelength blocking (overview)

2-link correlation and wavelength equivalence assumptions
- \( \alpha_j(m) \Rightarrow Pr(X_j = m) \Rightarrow \beta_{i,j} \Rightarrow g_R(i) \Rightarrow B_R^w \)
  - \( \beta_{i,j} = Pr(\text{given set of } i \text{ wavelengths free on link } j) \)
  - \( g_R(i) = Pr(\text{given set of } i \text{ wavelengths free on route } R) \)
- Conditionals needed because:
  \[
  \alpha_j(m) = \sum_{R: j \in R} \Lambda_R \left( 1 - B_R^w | X_j = m \right)
  \]
QoS blocking

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

- \( U_R(k) \) = probability that \( k = 0, \ldots, C \) 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:
  \[
  U_R(k) \approx \binom{C}{k} p_R^k (1 - p_R)^{C-k}, \quad k = 0, 1, \ldots, C.
\]
QoS blocking

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

- \( n_{xt}(R, R') = \) number of common nodes between routes \( R \) and \( R' \) where crosstalk can occur
  - Recall: crosstalk from \( R' \) to \( R \) can occur at a node \( N \) when \( R \) and \( R' \) share the link before \( N \) and the link after \( N \)
- \( U'_{R,R'}(k) = \) probability that route \( R' \) injects \( k \) crosstalk components on route \( R \)

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

- \( XT_R(k) = \) probability that route \( R \) is subject to exactly \( k \) 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:**

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

- **Maximum number of crosstalks to keep Q below threshold:**

\[
N_{R_{\text{max}}} = \left\lfloor \sqrt{\frac{\left(\frac{\mu_1 - \mu_0}{Q_{\text{th}}} - \sigma_{0,R}\right)^2 - \sigma_{i,R}^2 - \sigma_{n,R}^2}{\sigma_{x,R}^2}} \right\rfloor
\]

- **QoS blocking:**

\[
B_R^q = \sum_{k>N_{R_{\text{max}}}}^{\infty} XT_R(k).
\]
Computations of the conditionals $U_R|X_j=m$, $U'_R,R'|X_j=m'$, $X_T R|X_j=m$, $B^q_R|X_j=m$ are very similar to the computations of $U_R$, $U'_R,R'$, $X_T R$, $B^q_R$. 
Simulation parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Value</th>
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<tr>
<td>Span length</td>
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<td>Signal peak power</td>
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<td>Bit rate</td>
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<td>Nonlinear parameter</td>
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<td>Min. Q factor</td>
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<td>6</td>
</tr>
</tbody>
</table>

Mesh-8 topology

NSF topology
Blocking probability: mesh of 8 nodes

16 wavelengths, -25 dB and -30 dB crosstalk

**red**: analysis; **black**: simulation
Load in gain for the mesh of 8 nodes

Target average call blocking probability of 0.001 (reference: gain=1 for -25 dB)
Blocking probability: NSF topology

NSF topology, 8 wavelengths, -30 dB crosstalk

red: analysis; black: simulation
Conclusions and future work

- Physical parameters-dependent impact of crosstalk on network performance
- Extended an algorithm that computes wavelength blocking, to include QoS blocking
  - But our work is independent of the wavelength blocking calculations algorithm
- Leads for future work
  - Adjacent vs. non-adjacent channel crosstalk
  - Other impairments (PMD, ...)
- Questions ?