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

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May 7, 2007 – INFOCOM – Mini-symposium 3, Session 3

All-optical networks

- Current high-speed optical networks
  - Bottleneck due to electrical conversions
- Features of all-optical networks
  - Circuit switched $\longrightarrow$ lightpaths; speed, flexibility, cost
- New issues arise with all-optical networks
  - Nodes (OXCs) 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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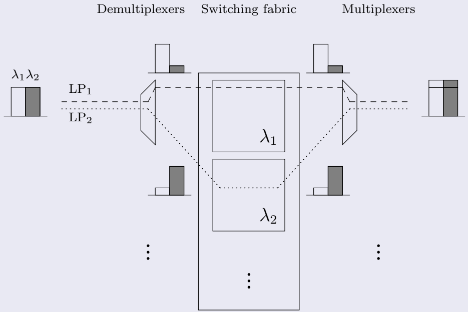
Node crosstalk model [Deng/Subramaniam-Broadnets2004]



- 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

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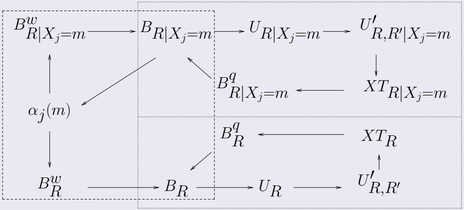
Iterative technique



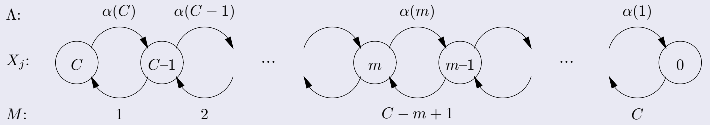
- Dashed box: wavelength blocking – Dotted box: QoS blocking
- X_j = number of free wavelengths on link j
- B_R, B^w_R, B^q_R are blocking probabilities ($B_R = B^w_R + (1 - B^w_R)B^q_R$)
- $\alpha_j(m)$ = state dependent arrival rate

Iterative technique

$$\begin{tikzcd}
B^w_{R|X_j=m} \arrow[r] & B_{R|X_j=m} \arrow[r] \arrow[ddl] & U_{R|X_j=m} \arrow[r] & U'_{R,R'|X_j=m} \arrow[d] \\
 & & B^q_{R|X_j=m} \arrow[ul] & XT_{R|X_j=m} \arrow[l] \\
\alpha_j(m) \arrow[uu] \arrow[dd] & & & \\
 & & B^q_R \arrow[dl] & XT_R \arrow[l] \\
B^w_R \arrow[r] & B_R \arrow[r] & U_R \arrow[r] & U'_{R,R'} \arrow[u]
\end{tikzcd}$$

- B_R^w and B_R^q are interdependent
- The respective algorithms to compute B_R^w and B_R^q, though, are largely independent
- There are techniques in the literature to compute B_R^w
    - We reuse one of them to determine B_R^q

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
- Λ = arrival rate (parameter of a Poisson distribution)
- M = service rate (parameter of an exponential distribution)

Wavelength blocking (overview)

$$\begin{tikzcd}
B^w_{R|X_j=m} \arrow[r] & B_{R|X_j=m} \arrow[rr] \arrow[ddl] & & U_{R|X_j=m} \arrow[r] & U'_{R,R'|X_j=m} \arrow[d] \\
& & B^q_{R|X_j=m} \arrow[ul] & & XT_{R|X_j=m} \arrow[ll] \\
\alpha_j(m) \arrow[uu] \arrow[dd] & & & & \\
& & B^q_R \arrow[dl] & & XT_R \arrow[ll] \\
B^w_R \arrow[r] & B_R \arrow[rr] & & U_R \arrow[r] & U'_{R,R'} \arrow[u]
\end{tikzcd}$$

- 2-link correlation and wavelength equivalence assumptions
- $\alpha_j(m) \Rightarrow \Pr(X_j = m) \Rightarrow \beta_{i,j} \Rightarrow g_R(i) \Rightarrow B^w_R$
  - $\beta_{i,j} = \Pr(\text{given set of } i \text{ wavelengths free on link } j)$
  - $g_R(i) = \Pr(\text{given set of } i \text{ wavelengths free on route } R)$
- Conditionals needed because:

$$\alpha_j(m) = \sum_{R:j\in R} \Lambda_R \left(1 - B^w_{R|X_j=m}\right)$$

QoS blocking

$B_R \to U_R \to U'_{R,R'} \to XT_R \to B_R^q \to B_R$

- $U_R(k) =$ 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:

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

QoS blocking

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

- $n_{xt}(R, R')$ = 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

$$XT_R = U'_{R,R_1} * \ldots * U'_{R,R_p}$$

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:

$$N_R^{\max} = \left\lfloor \frac{\left(\frac{\mu_1 - \mu_0}{Q_{th}} - \sigma_{0,R}\right)^2 - \sigma_{i,R}^2 - \sigma_{n,R}^2}{\sigma_{x,R}^2} \right\rfloor$$

- QoS blocking:

$$B_R^q = \sum_{k > N_R^{\max}} XT_R(k).$$

Iterative technique

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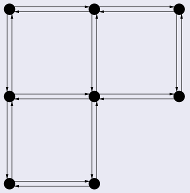
\end{tikzcd}
$$

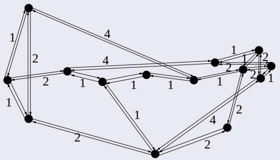
- Computations of the conditionals $U_{R|X_j=m}$, $U'_{R,R'|X_j=m}$, $XT_{R|X_j=m}$, $B^q_{R|X_j=m}$ are very similar to the computations of U_R, $U'_{R,R'}$, XT_R, B^q_R.

Simulation parameters

Mesh-8 topology



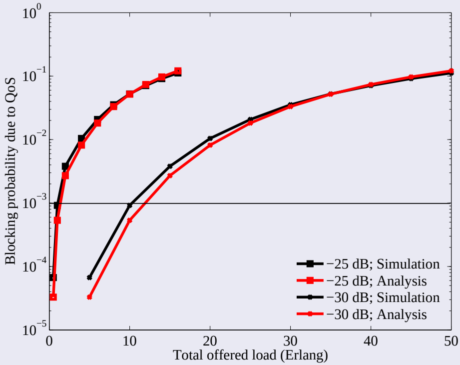
NSF topology



Parameters

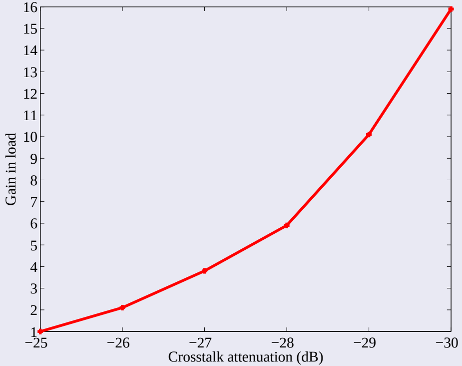
Description	Value
Span length	70 km
Signal peak power	2 mW
Bit rate	10 Gbps
Nonlinear parameter	2.2 $(W.m)^{-1}$
Pulse shape	NRZ
Fiber type	SMF
Dispersion	100% post-DC
Min. Q factor	6

Blocking probability: mesh of 8 nodes



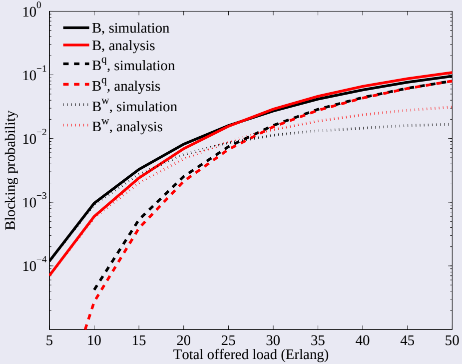
16 wavelengths, -25 dB and -30 dB crosstalk
red: analysis; **black**: simulation

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 ?