Study of Crosstalk Propagation in All-Optical Networks using Perturbation Theory

Yvan Pointurier and Maïté Brandt-Pearce
{yvan, mb-p}@virginia.edu

Charles L. Brown Department of
Electrical and Computer Engineering
University of Virginia, USA

IEEE ICECS'05, December 2005

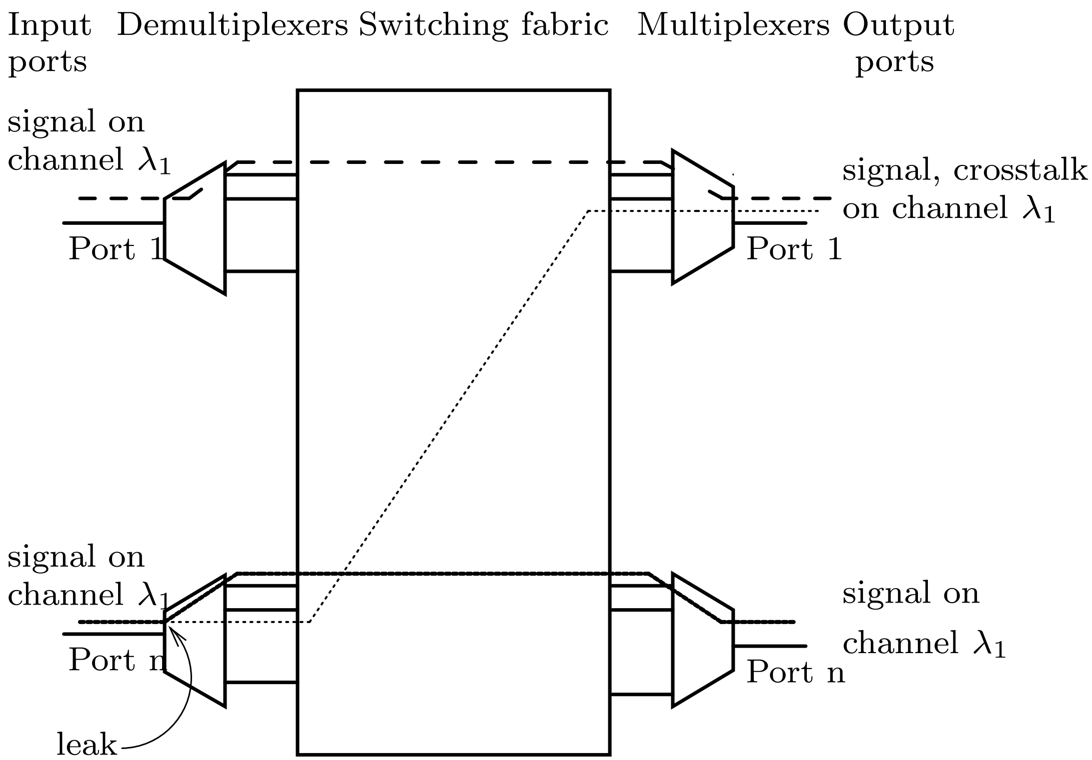
Overview

- ▷ Introduction
  - All-optical networks
  - Crosstalk
  - Modeling and problem statement
- ▷ Analysis
- ▷ Validation by simulation
- ▷ Conclusion

All-optical networks

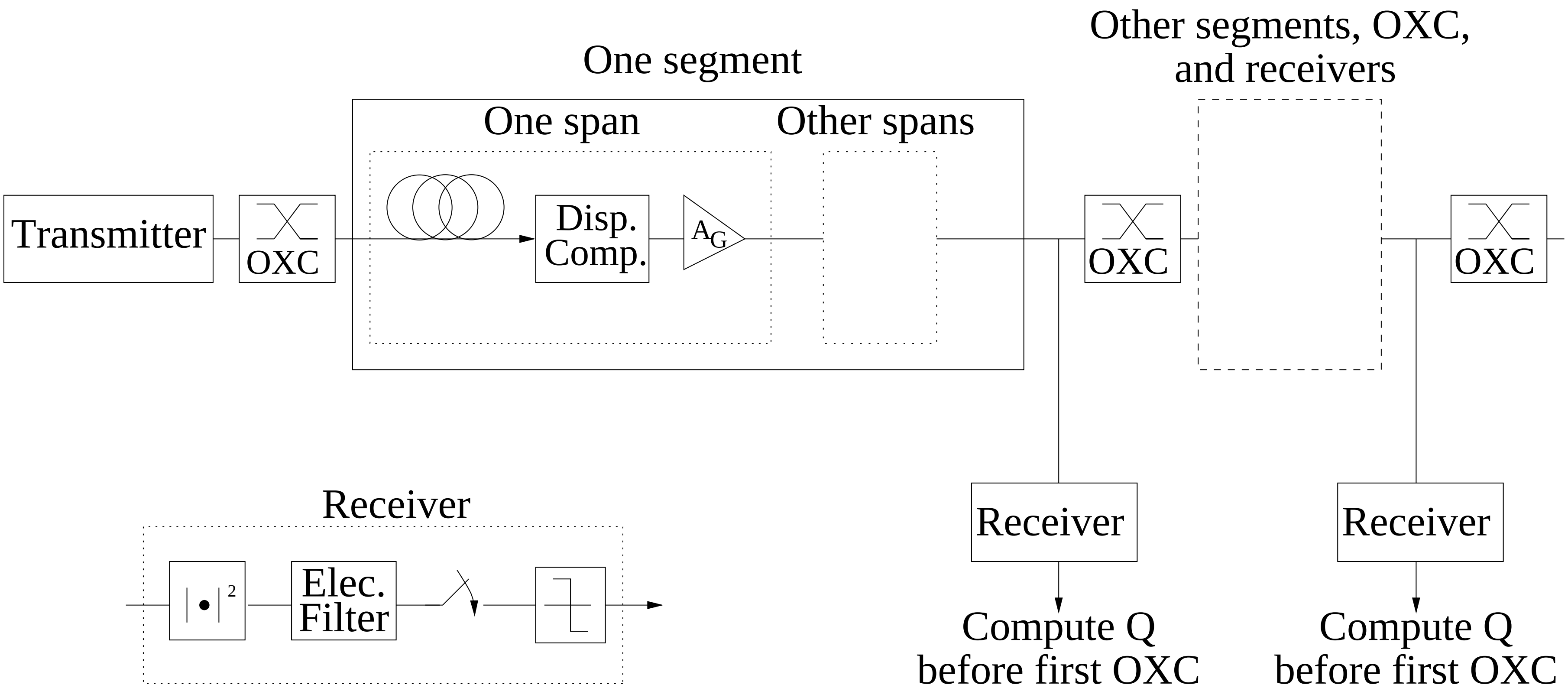
- Current high-speed optical networks
  - Bottleneck due to electrical conversions
- Features of all-optical networks
  - Speed, flexibility, cost
- New issues arise with all-optical networks
  - Nodes (OXCs) are subject to crosstalk
  - Crosstalk is transmitted over extremely long paths without electrical signal regeneration → nonlinear interaction
- Implementation
  - Crosstalk issues not all encountered yet

OXC (all-optical switch) and crosstalk



- ▷ Leaks can originate from imperfect demultiplexing, or transmission within the switching matrix

Lightpath and physical layer models



$$BER = \frac{1}{2}\mathrm{erfc}\frac{Q}{\sqrt{2}}, \quad Q = \frac{\mu_1 - \mu_0}{\sigma_0 + \sqrt{\sigma_i^2 + \sigma_n^2 + \sum \sigma_x^2}}$$

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
  - 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_ℓ, delay τ and phase φ are uniformly distributed over $\{0,1\}$, $[0,T_b)$, $[0,\ 2\pi)$, respectively.
  - Crosstalk attenuation η, detuning ω_s
  - Pulse shape $h(t)$

Problem statement

- **What is the impact of 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 μ_0, μ_1, σ_0, σ_i using very short simulations of a few bits (ISI, linear and nonlinear signal transmission effects)
  - Can compute σ_n due to noise using analytical techniques
  - Need a fast way to compute σ_x and hence Q

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Determining a transfer matrix

- CW input, after k spans:

$$s_m(t,L) = e^{jk\theta_{SPM}}\sqrt{P_0} \text{ with } (\theta_{SPM} \approx -\gamma P_0/\alpha)$$

- 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 ...

- In frequency domain, for the first span (same for I-/Q- terms):

$$\begin{bmatrix} G_1^{I+}(\omega) \\ G_1^{Q+}(\omega) \end{bmatrix} = T_1(\omega) \begin{bmatrix} G_0^{I+}(\omega) \\ G_0^{Q+}(\omega) \end{bmatrix}$$

- After k spans (same for I-/Q- terms):

$$\begin{bmatrix} G_k^{I+}(\omega) \\ G_k^{Q+}(\omega) \end{bmatrix} = T_k(\omega) \ldots T_1(\omega) \begin{bmatrix} G_0^{I+}(\omega) \\ G_0^{Q+}(\omega) \end{bmatrix}$$

Contents of the transfer matrix

$$T_k(\omega) = \underbrace{\begin{bmatrix} \frac{1}{2}e^{-j\theta_{SPM}} & \frac{1}{2}e^{j\theta_{SPM}} \\ \frac{1}{2j}e^{-j\theta_{SPM}} & -\frac{1}{2j}e^{j\theta_{SPM}} \end{bmatrix}}_{\text{SPM}} \underbrace{\mathcal{D}(\omega)}_{\text{disp. comp.}} \underbrace{\mathcal{M}_k(\omega) \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix}}_{\text{disp. and NL}}$$

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

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

$$\mathcal{M}_{1,2}(\omega) = e^{-\frac{\alpha}{2}L}Ge^{-\frac{j}{2}(\beta_2 L)\omega^2}\left(-j\frac{\gamma P_0}{\alpha - j\beta 2\omega^2} - \frac{2\gamma^2 P_0^2}{\alpha(2\alpha - j\beta_2\omega^2)}\right)$$

Crosstalk variance

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

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

$$\Rightarrow \Delta i(t,k) \approx 2\rho\sqrt{P_0} m f(t) * \left(g_k^{I+}(t-\tau) e^{j\varphi} + g_k^{I-}(t-\tau) e^{-j\varphi} \right)$$

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

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

Crosstalk variance: continued

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

- Accounting for modulation: in the variance above, replace P_0 by μ_1 from the short simulation
- Multisegment case: add crosstalk variances for each 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

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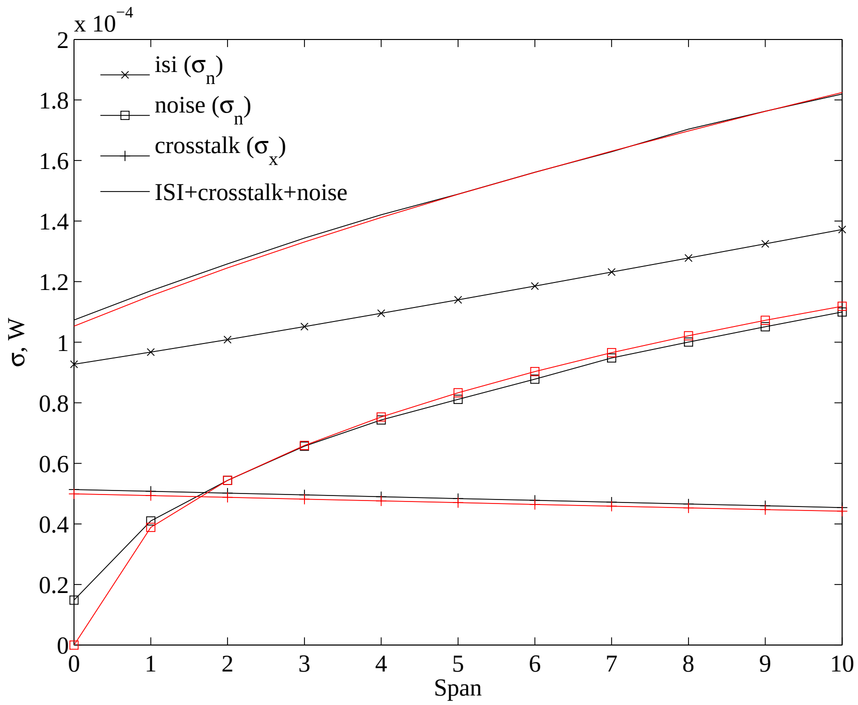
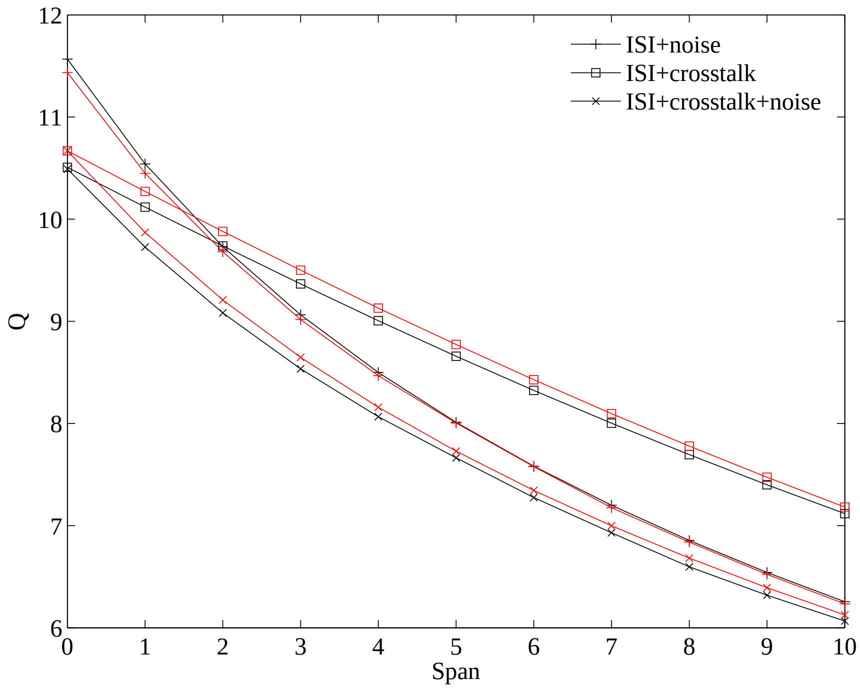
Validation: physical parameters

Description	Baseline Value
Span length	100 km
Pump power	2 mW
Bit rate	10 Gbps
Pulse shape	NRZ
Crosstalk attn. (power)	-30 dB
Crosstalk detuning	0 GHz
Fiber loss	0.2 dB/km
Nonlinear coefficient	2.2 $(\text{W km})^{-1}$
2^{nd} order dispersion	17 ps/nm/km
Noise figure	no noise
Dispersion compensation	100% post
Photodetector reponsitivity	1 A/W (arbitrarily)
Electrical filter bandwidth	0.7 x bit rate

▷ Red: analysis - Black: simulation

10 Gbps dispersion-compensated network

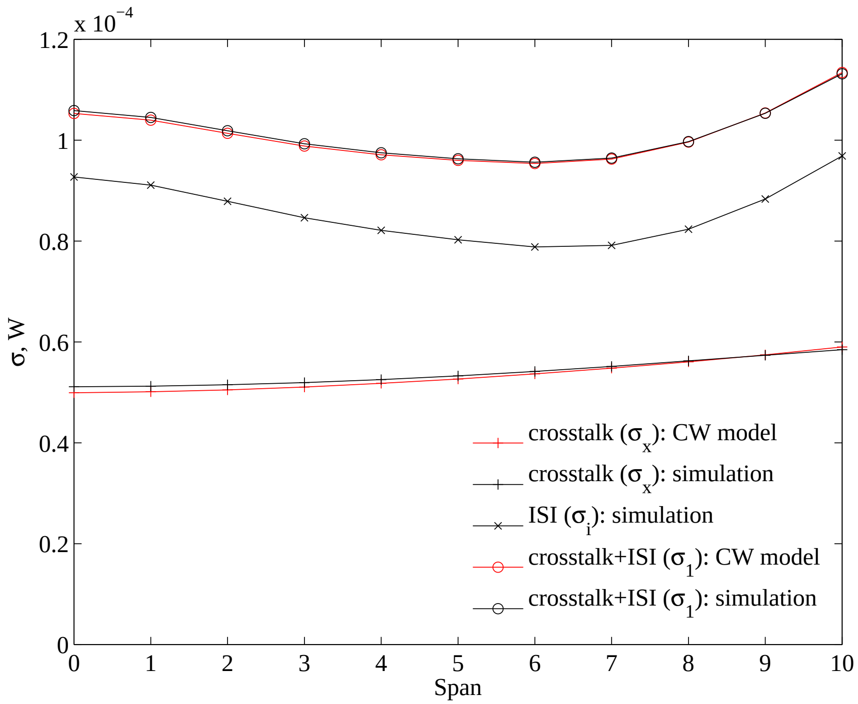




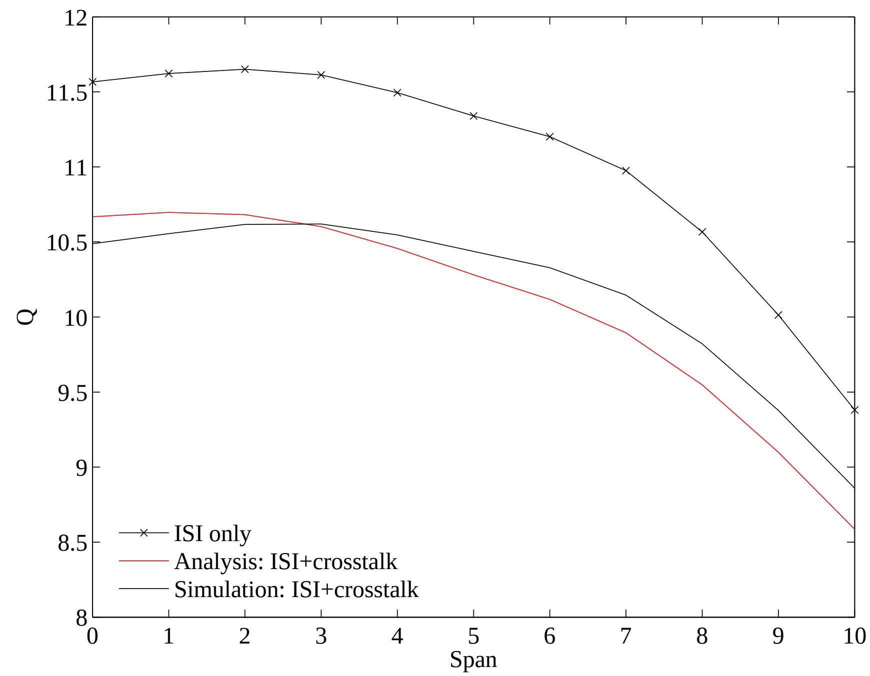
Standard deviations

Q factors

2.5 Gbps non dispersion-compensated network

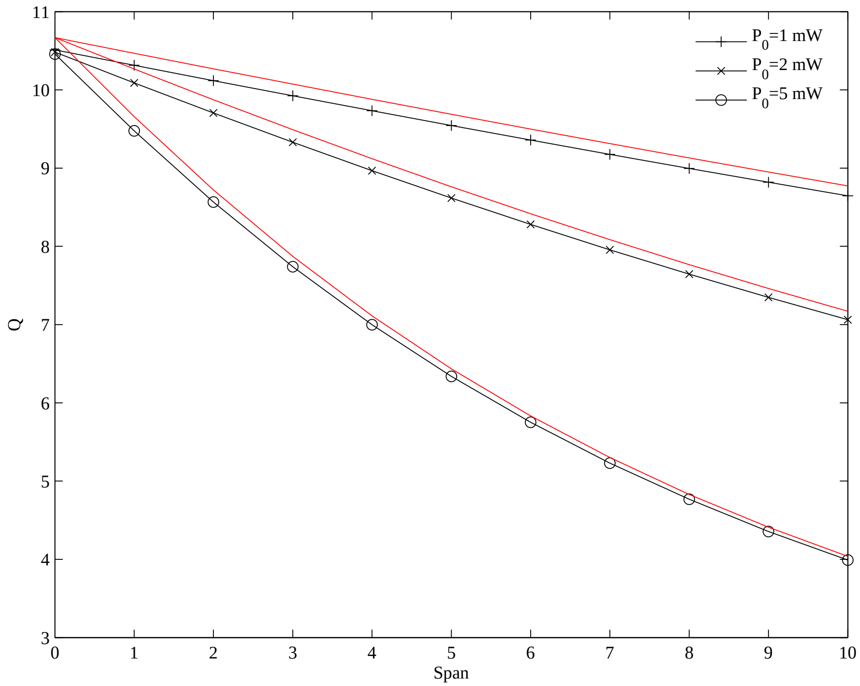


Standard deviations

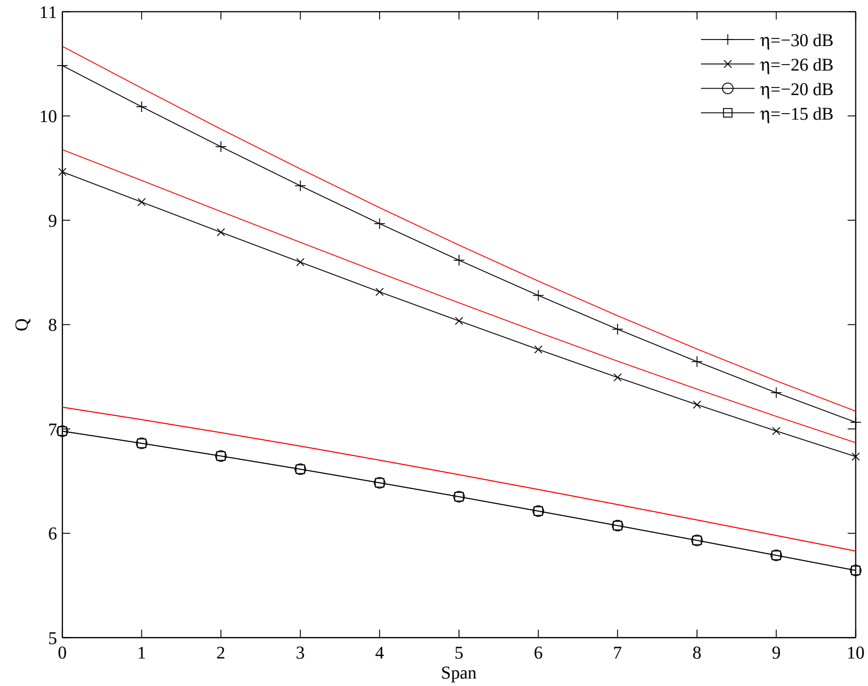


Q factors

Main signal power and crosstalk attenuation

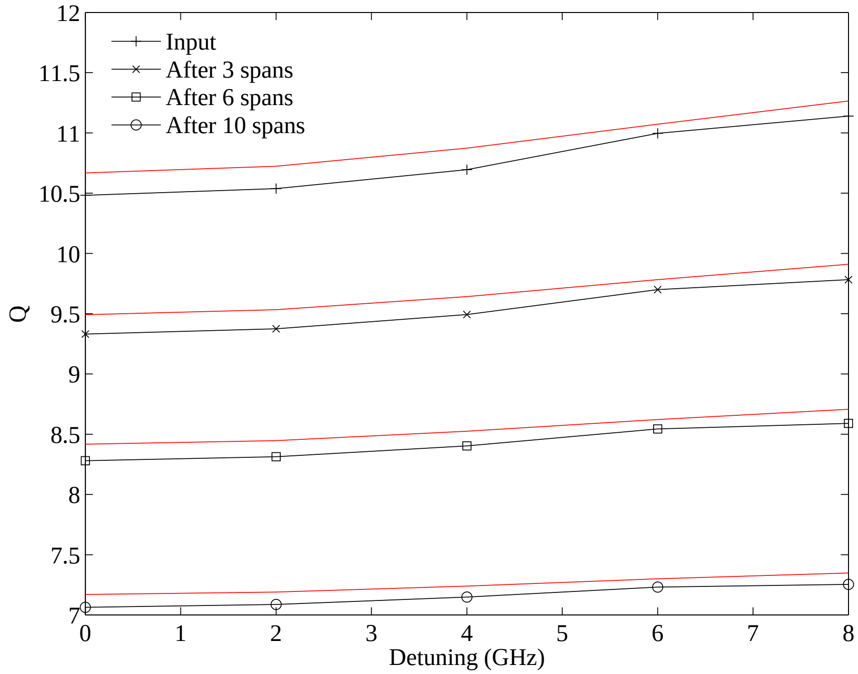


Main signal power

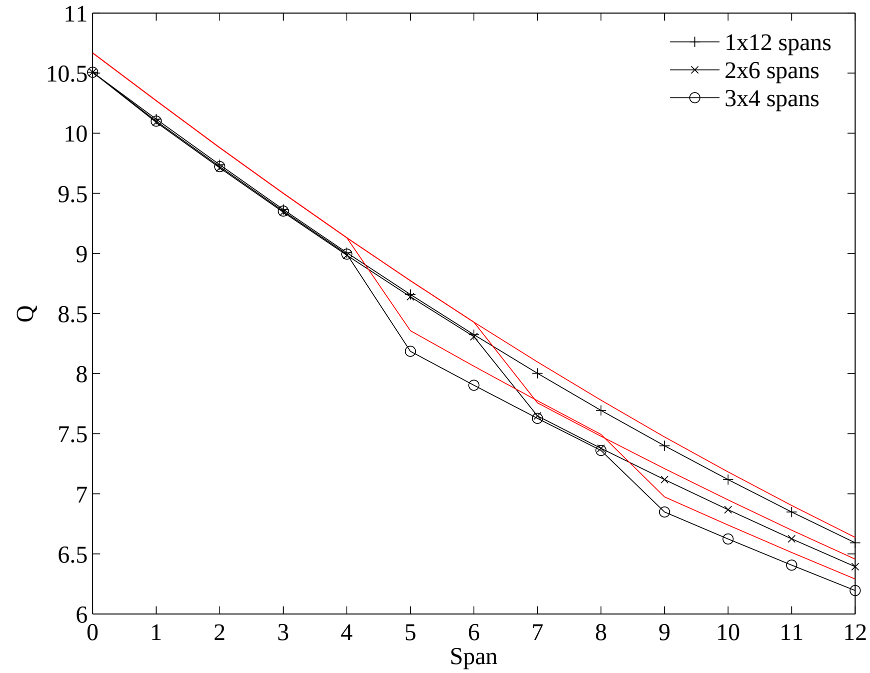


Crosstalk attenuation

Detuning and multisegment



Detuning



Multisegment

Conclusions: modeling of crosstalk effects

- ▷ 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
- ▷ Current work: crosstalk-aware RWA algorithms