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

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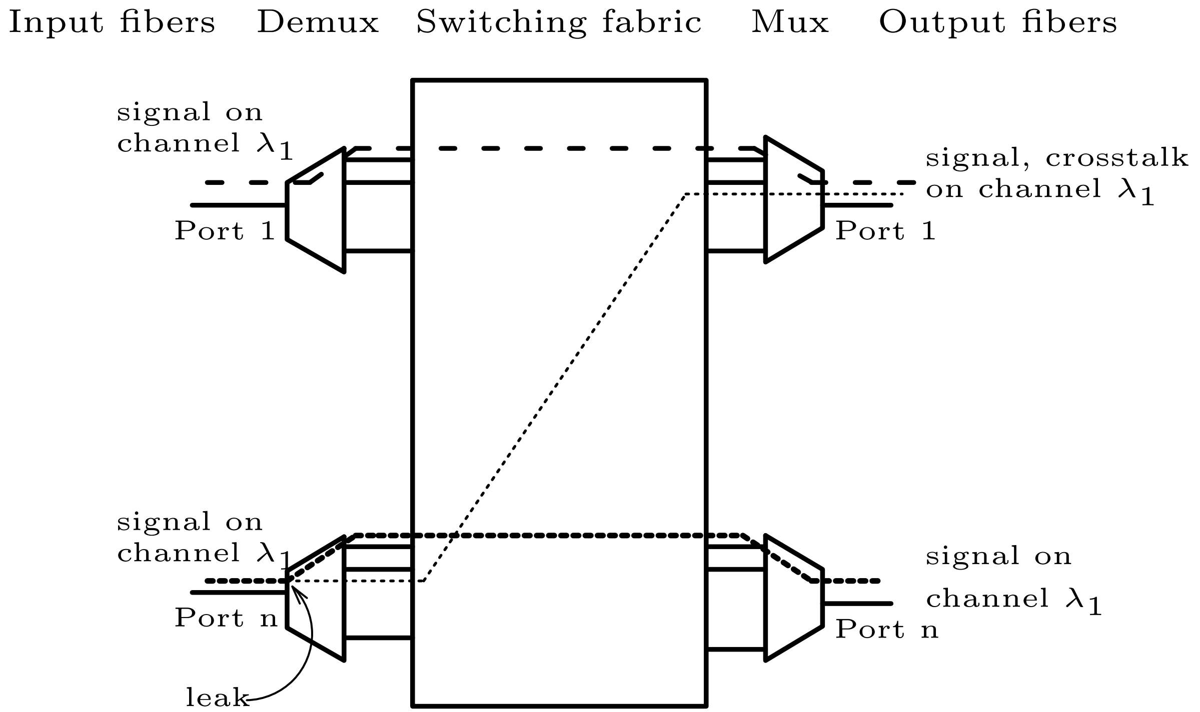
Overview

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

All-optical networks

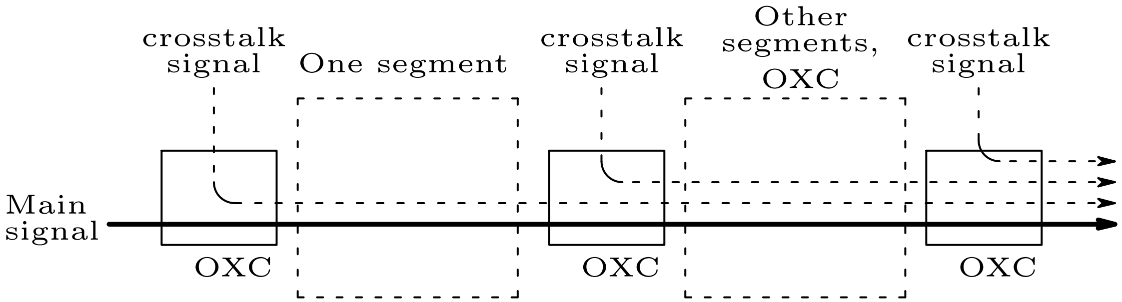
- Current high-speed optical networks
  - Bottleneck due to electrical conversions
- New issues arise with all-optical networks
  - Nodes (OXCs) are subject to crosstalk
  - Crosstalk is transmitted over extremely long paths without electrical signal regeneration

OXC (all-optical switch) and crosstalk



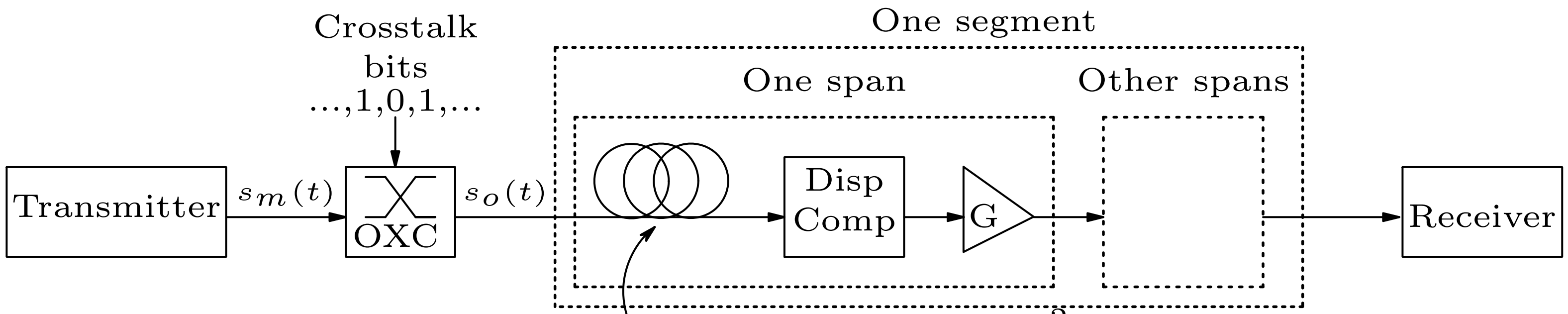
- Leaks can originate from imperfect demultiplexing, or transmission within the switching matrix

Lightpath and physical layer models

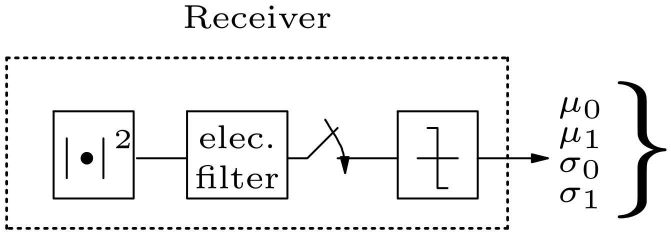


Receiver

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



$$\frac{\partial s_0}{\partial z} = -\frac{\alpha}{2} s_0 + \frac{j}{2}\beta_2 \frac{\partial^2 s_0}{\partial t^2} - j\gamma \left|s_0\right|^2 s_0$$



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

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

Delay-dependent crosstalk pulse shape

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

$$s_{out}(t) = \sqrt{P(t)}\exp\left(j\theta(t)\right) + m g_{\tau,\varphi}(t)$$

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

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

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- Current due to crosstalk:

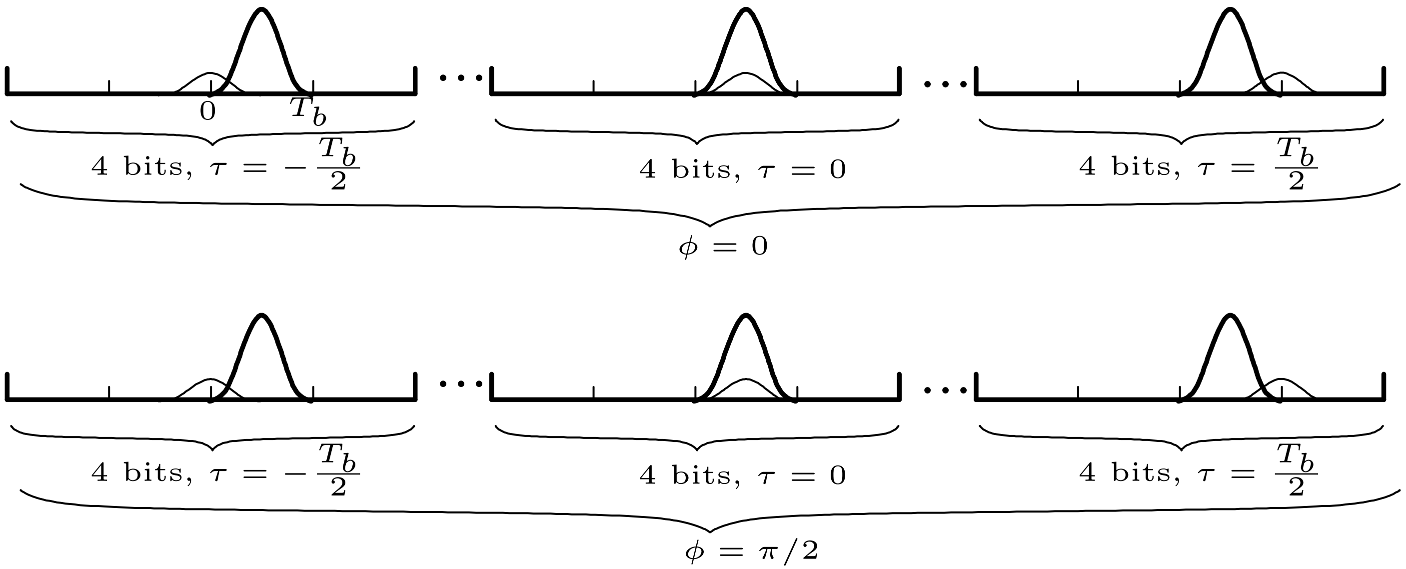
$$\Delta i(t) \approx \rho f(t) * \left(2\sqrt{P(t)} m \left(g_\tau^{I+}(t) \exp\left(j\varphi\right) + g_\tau^{I-}(t) \exp\left(-j\varphi\right)\right) \right)$$

- Variance:

$$\sigma_x^2(t) = 4 \int_{-\frac{T_b}{2}}^{\frac{T_b}{2}} \frac{\rho^2}{T_b} \left| f(t) * \left(\sqrt{P(t)} g_\tau^{I+}(t) \right) \right|^2 \mathrm{d}\tau$$

- We need to determine $g_\tau^{I+}(t)|_{t=T_b/2}$ for all τ

Semi-analytical method



- Use short simulations, use N values for the random delay τ: $\tau_k = k/NT_b$, and 2 phases: $\phi = 0$ and $\phi = \pi/2$

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- Short simulation output:

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

- Estimate of the crosstalk pulse shape for τ_k

$$\begin{aligned} \hat{g}_{\tau_k}^{I+}(t) &= \frac{1}{2}\Re\left\{\exp\left(-j\theta(t)\right)\left(s_{k,0}^{out}(t) - \sqrt{P(t)}\exp j\theta(t)\right)\right\} \\ &\quad - \frac{j}{2}\Re\left\{\exp\left(-j\theta(t)\right)\left(s_{k,\frac{\pi}{2}}^{out}(t) - \sqrt{P(t)}\exp j\theta(t)\right)\right\} \end{aligned}$$

- Estimate for the crosstalk variance:

$$\hat{\sigma}_x^2 = \left(\frac{\rho^2}{N}\sum_{k=0}^{N-1} 4\left|f(t) * \left(\sqrt{P(t)}\hat{g}_{\tau_k}^{I+}(t)\right)\right|^2\right)\Bigg|_{t=T_b/2}$$

Conclusions: modeling of crosstalk effects

- Reduced number of bits transmission simulation by 2 orders of magnitude
  - $2048 \times 32 = 65536$ vs. $\underbrace{32}_{ISI} + \underbrace{4 \times 2 \times 32}_{crosstalk} = 288$ 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

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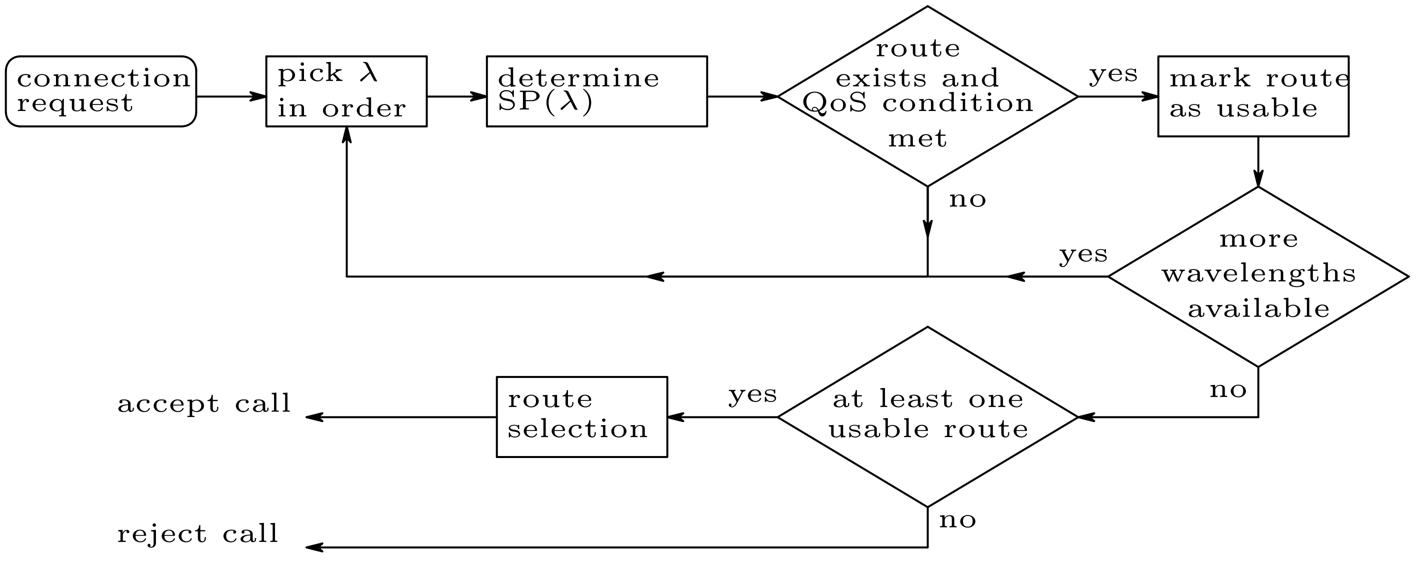
RWA problem

- ▷ 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

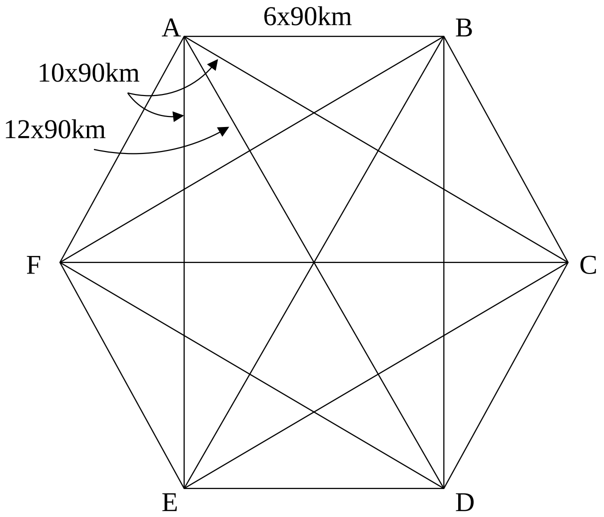
QoS aware algorithms

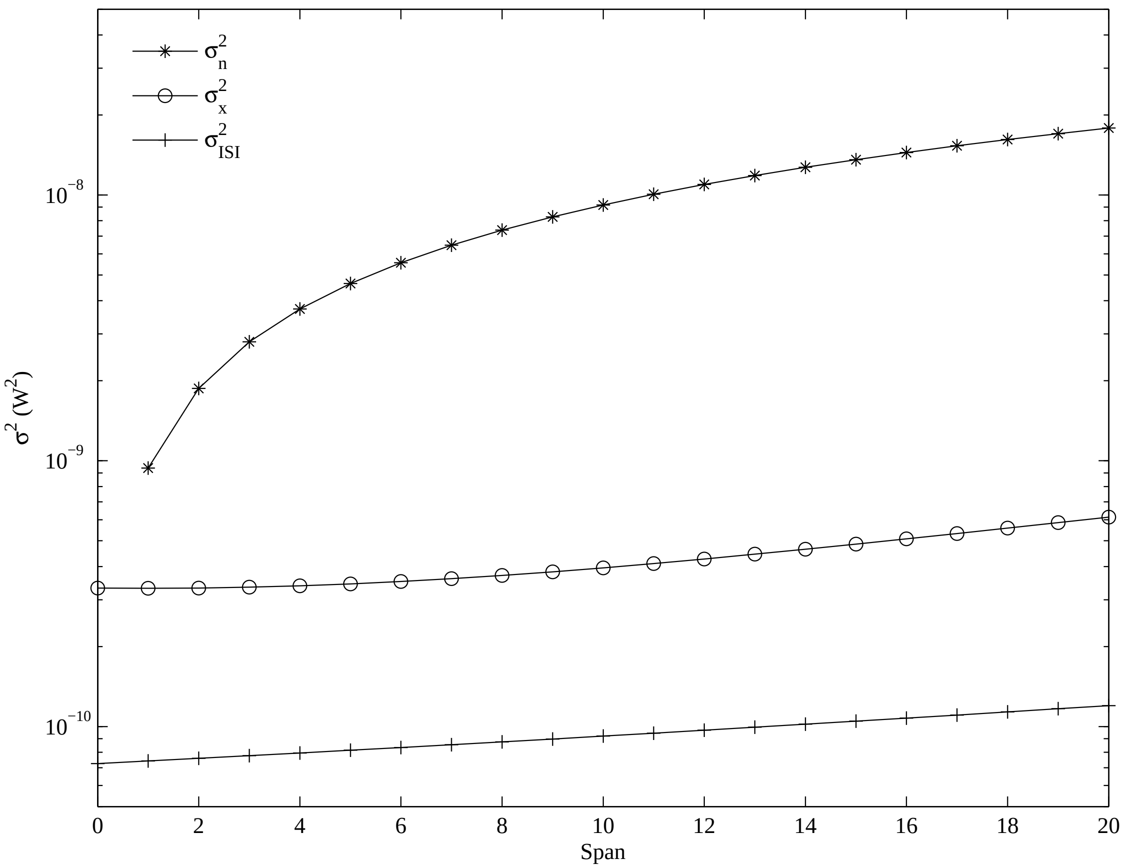


Parameters

	Description	Value
L	Span length	90 km
P_0	Signal peak power	2 mW
R_b	Bit rate	10 Gbps
	Pulse shape	RZ, gaussian
η	Crosstalk attenuation (power)	-30 dB
α	Fiber loss	0.22 dB/km
γ	Nonlinear coefficient	2.2 $(\text{W km})^{-1}$
D	2^{nd} order dispersion	2 ps/nm/km (NZ-DSF)
NF	Noise figure	2
	Dispersion compensation	100% post-DC
ρ	Photodetector reponsitivity	1 (arbitrarily)
B_e	Electrical filter bandwidth	7 GHz

Example setup





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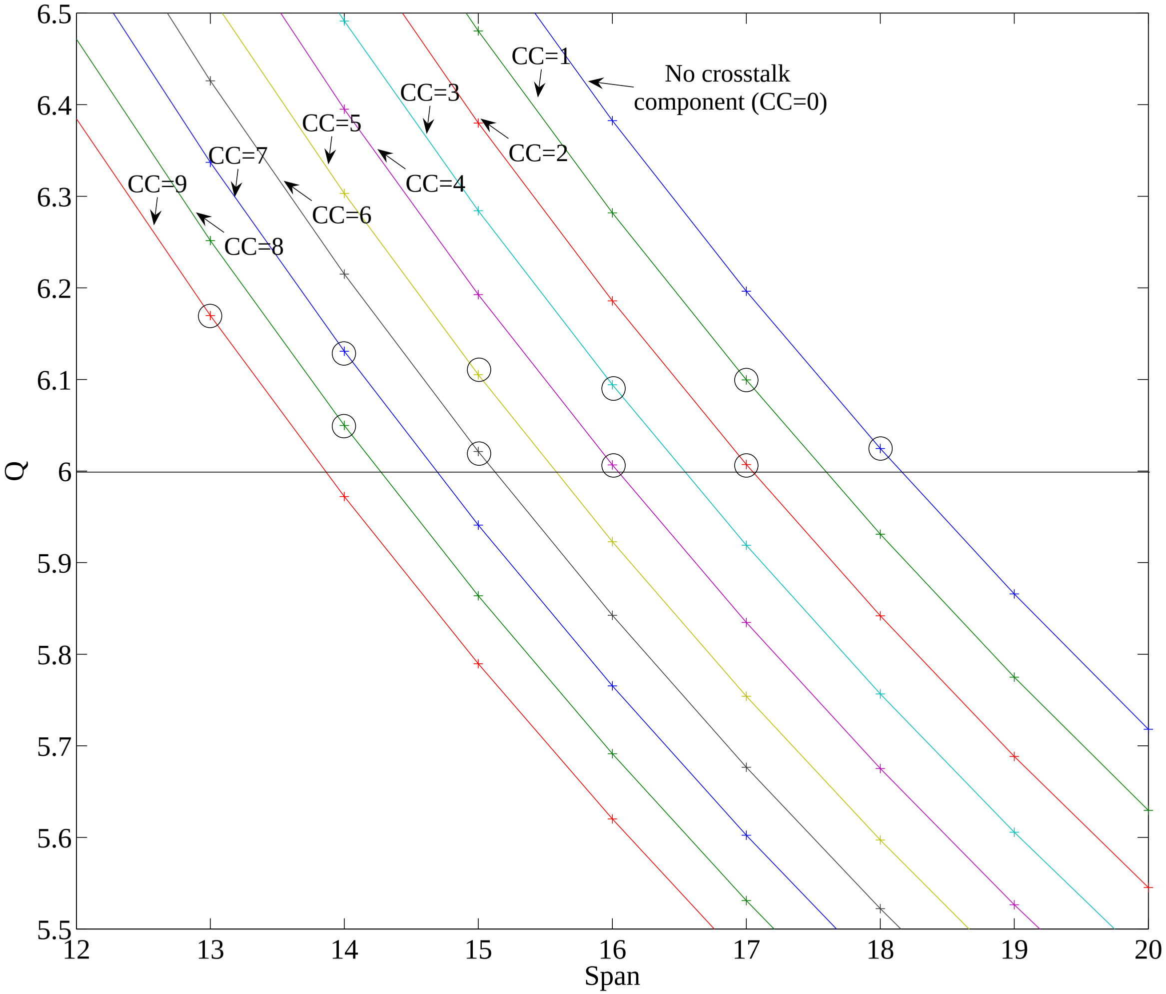
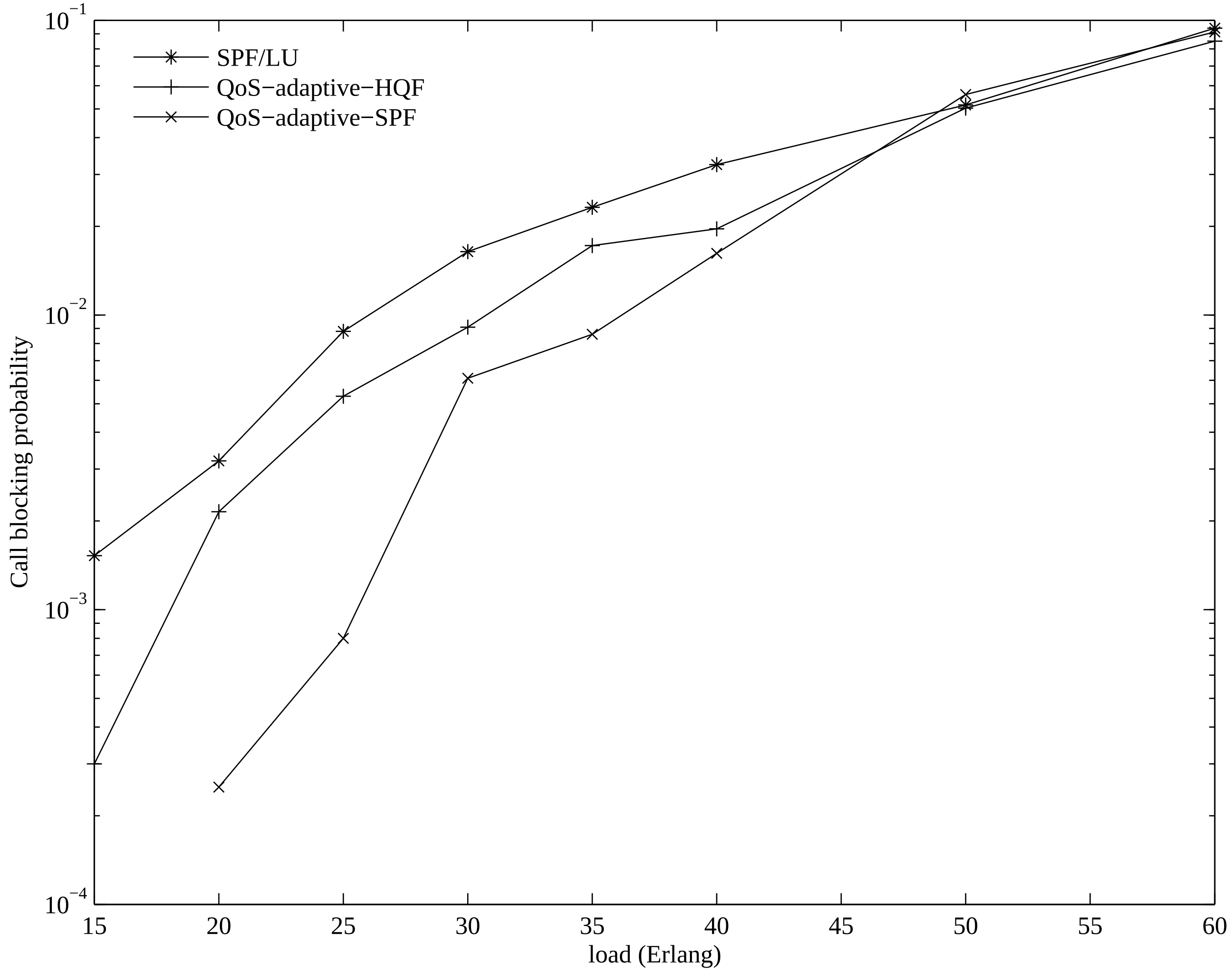


Q
6.5
6.4
6.3
6.2
6.1
6
5.9
5.8
5.7
5.6
5.5
12
13
14
15
16
17
18
19
20
Span
CC=1
No crosstalk component (CC=0)
CC=3
CC=2
CC=5
CC=4
CC=7
CC=6
CC=9
CC=8

Simulation result



Discussion

- The QoS-aware adaptive algorithms perform better that 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