Accurate Infinite-Order Crosstalk Calculation for Optical Networks-on-Chip

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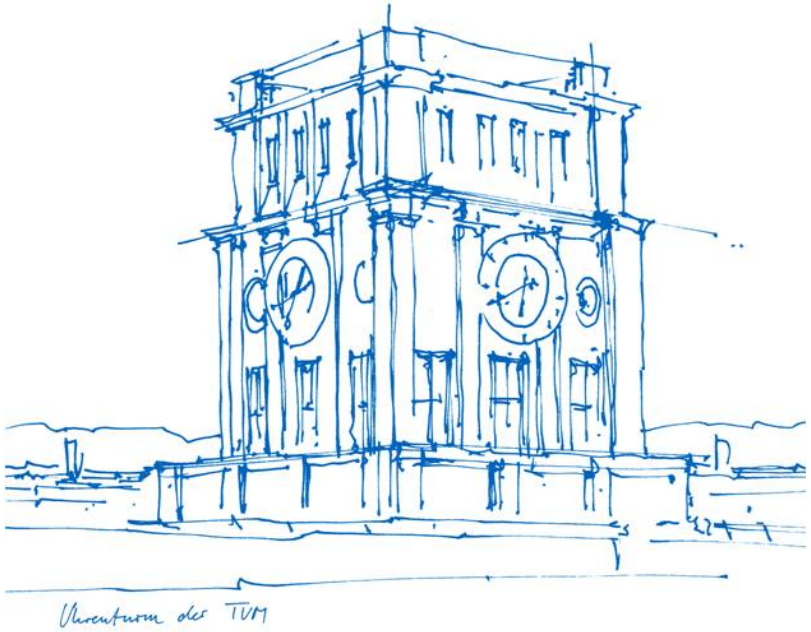

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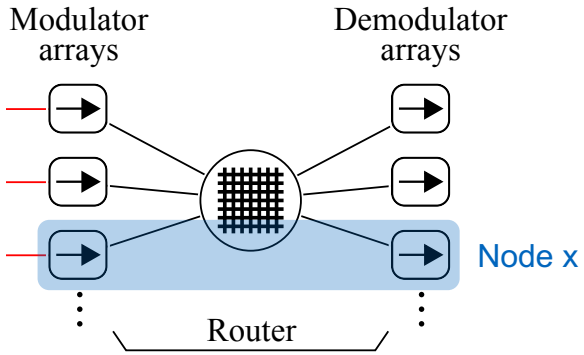
- Intro to ONoCs
- Insertion loss and crosstalk
- Mathematical method
- Example results

- A. Truppel, T.-M. Tseng and U. Schlichtmann, "**Accurate Infinite-Order Crosstalk Calculation for Optical Networks-on-Chip**", in **Journal of Lightwave Technology**, vol. 41, no. 1, pp. 4-16, 1 Jan.1, 2023, doi: 10.1109/JLT.2022.3210159.

(Simplified) Intro to Optical Networks on Chip

ONoCs: introduction

- ONoC – Optical Network-on-Chip
- Transmits information between System-on-Chip components using light
- Each network node (SoC component) can contain 0,1,2+ MAs and DMAs



ONoCs: router optical elements

- **Waveguides**
  - **Guide light** through specific paths (“light tubes”)

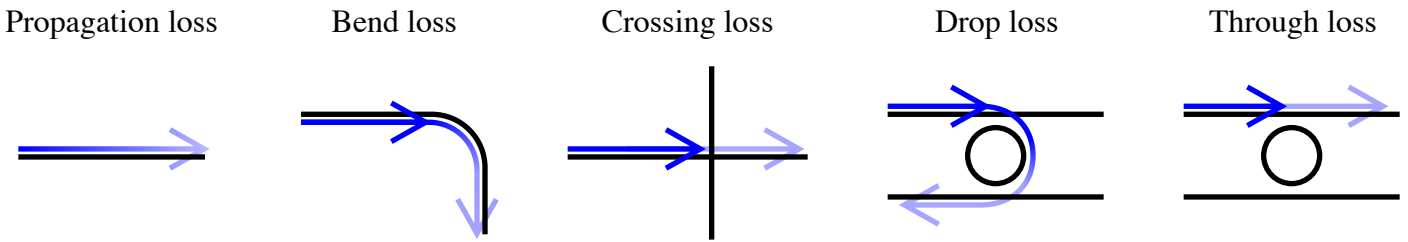
- **Waveguide terminators**
  - Absorb light at the end of waveguides (to avoid reflections)

- **Micro-Ring Resonators** (MRRs)
  - Waveguide rings of specific radii that interact with light based on its wavelength

Insertion loss and crosstalk

Insertion loss

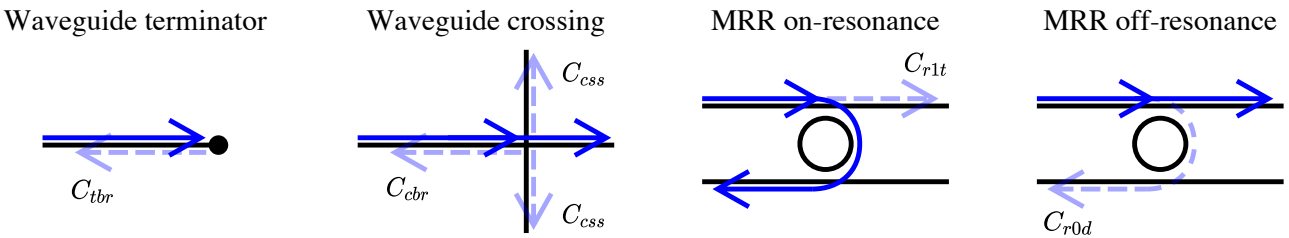
- All ONoC components cause optical power losses:



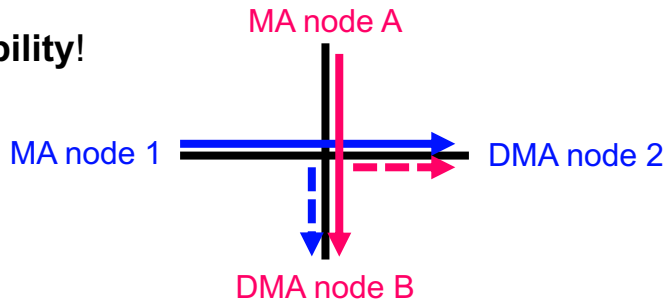
- Insertion loss determines **power consumption**!

Crosstalk: sources of noise

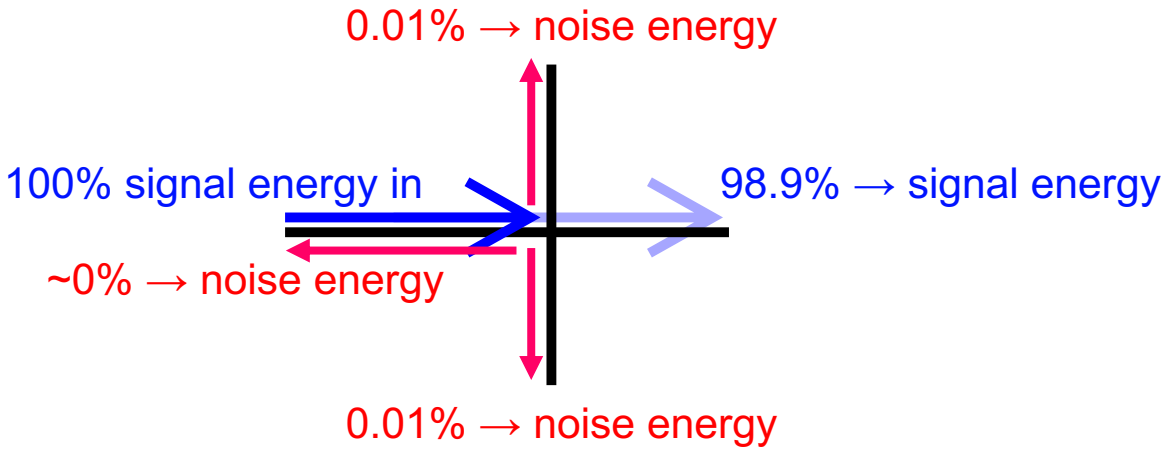
- The ways in which signal energy can stray from its intended path:



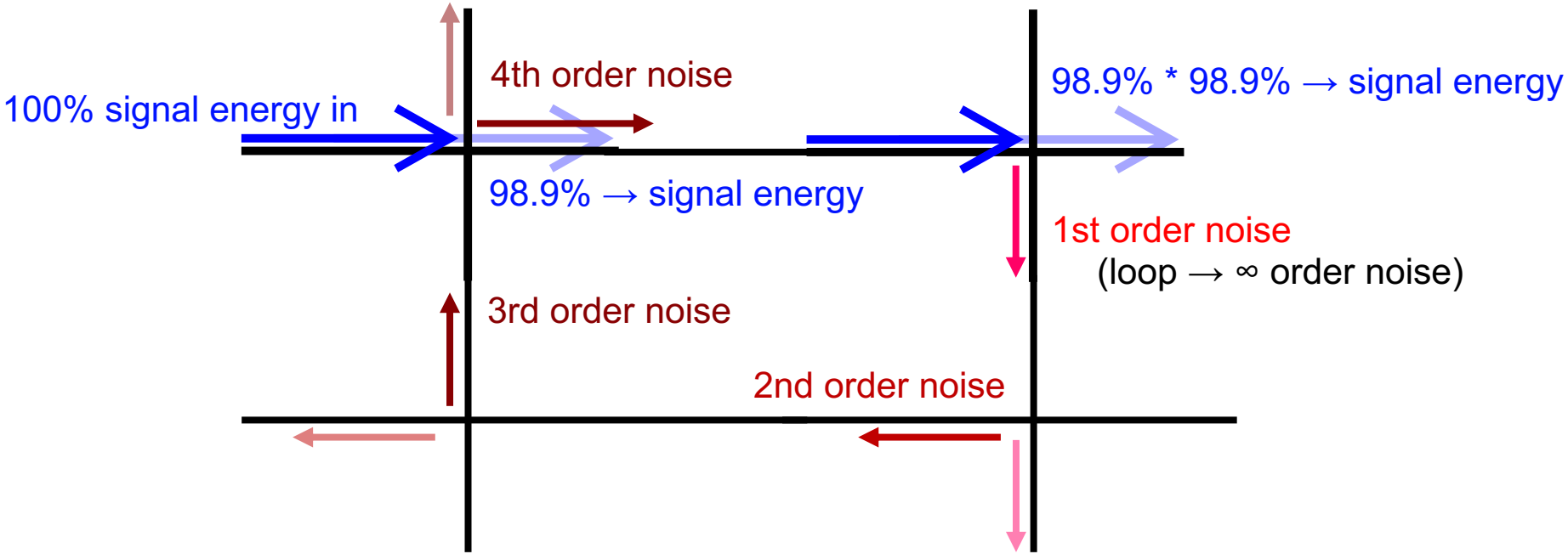
- When signal energy takes unintended paths, it becomes noise
- Noise causes crosstalk, which determines **transmission reliability**!



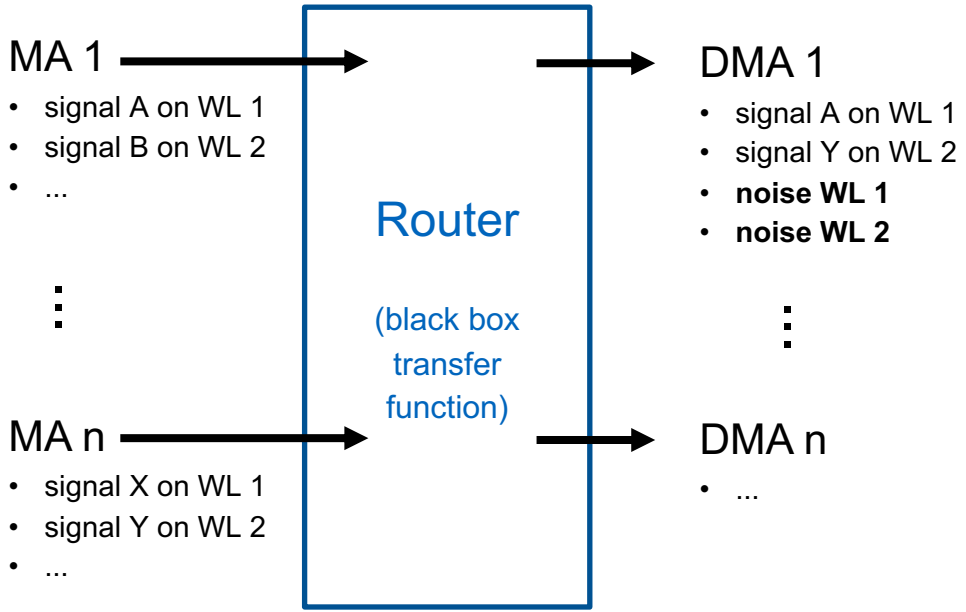
Insertion loss + crosstalk together



Insertion loss + crosstalk: 1st, 2nd, ∞ order noise

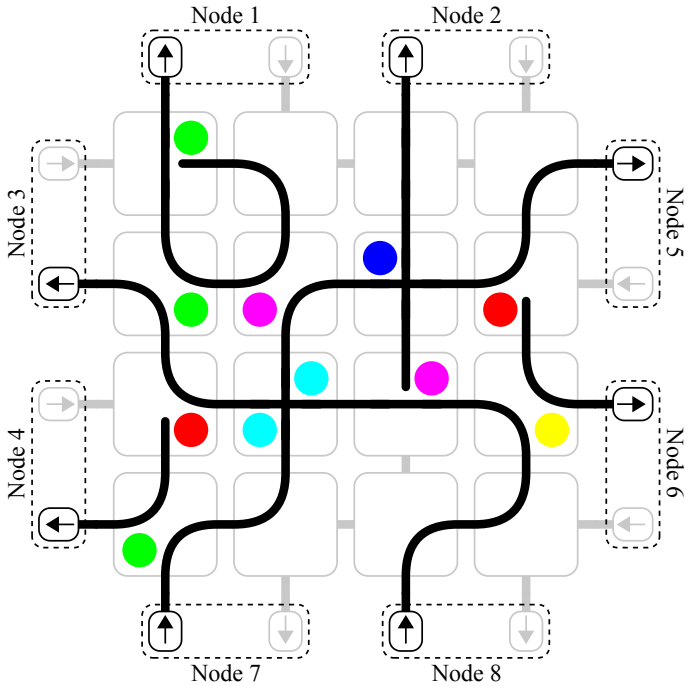


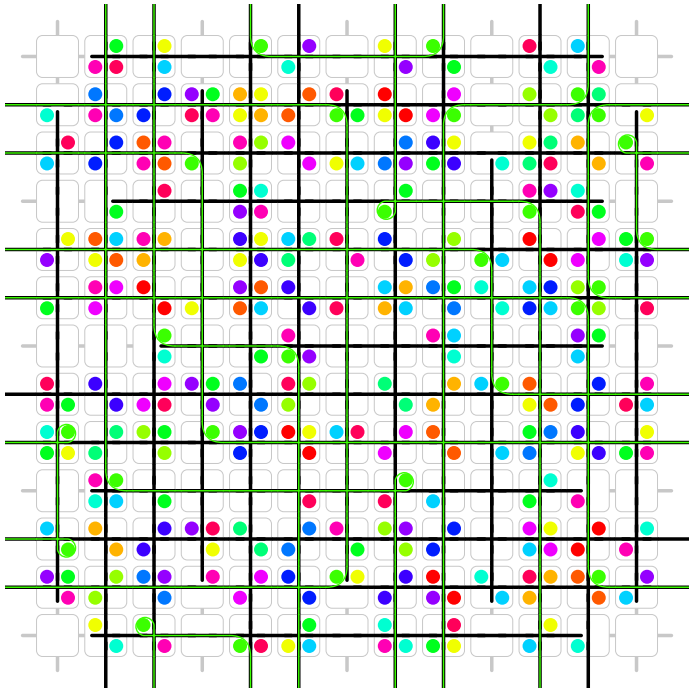
Problem abstraction



Router:
transfer function
from **input** energy
to **output** energy
per wavelength

Router: any ONoC design





Flow graph and transfer matrix

Flow graph, transfer matrix and energy propagation

- Transfer matrix T
  - Square: one row/column per vertex
  - Values: weights of the edges (if no edge, w = 0)

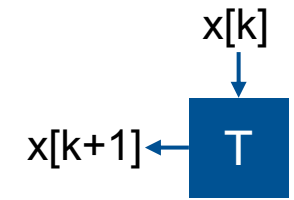
$$[T]_{ij} = w(j,i)$$

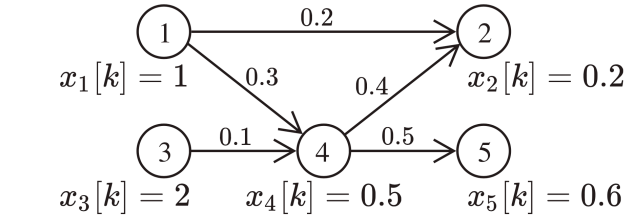
- Energy propagation

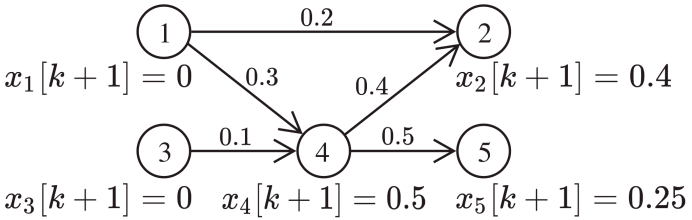
$$x_v[k+1] = \sum_{i \in V} w(i,v)\, x_i[k]$$

equivalent formulation with T:

$$x[k+1] = Tx[k]$$







Steady-state evaluation

- Assume **x[k < 0] = 0**
- Sources are **turned on at k = 0**, each producing a constant amount of energy continuously (i.e. on each time step) forever, as defined by vector b
- Calculate **x[∞]**, i.e. **steady-state** of graph

$$x[0] = b$$

$$x[1] = Tx[0] + b = Tb + b = (T + I)b$$

$$x[2] = Tx[1] + b = (T^2 + T + I)b$$

$$\vdots$$

$$x[\infty] = \left(\sum_{i=0}^{\infty} T^i \right) b$$

Infinite sum of powers?

- A very useful formula

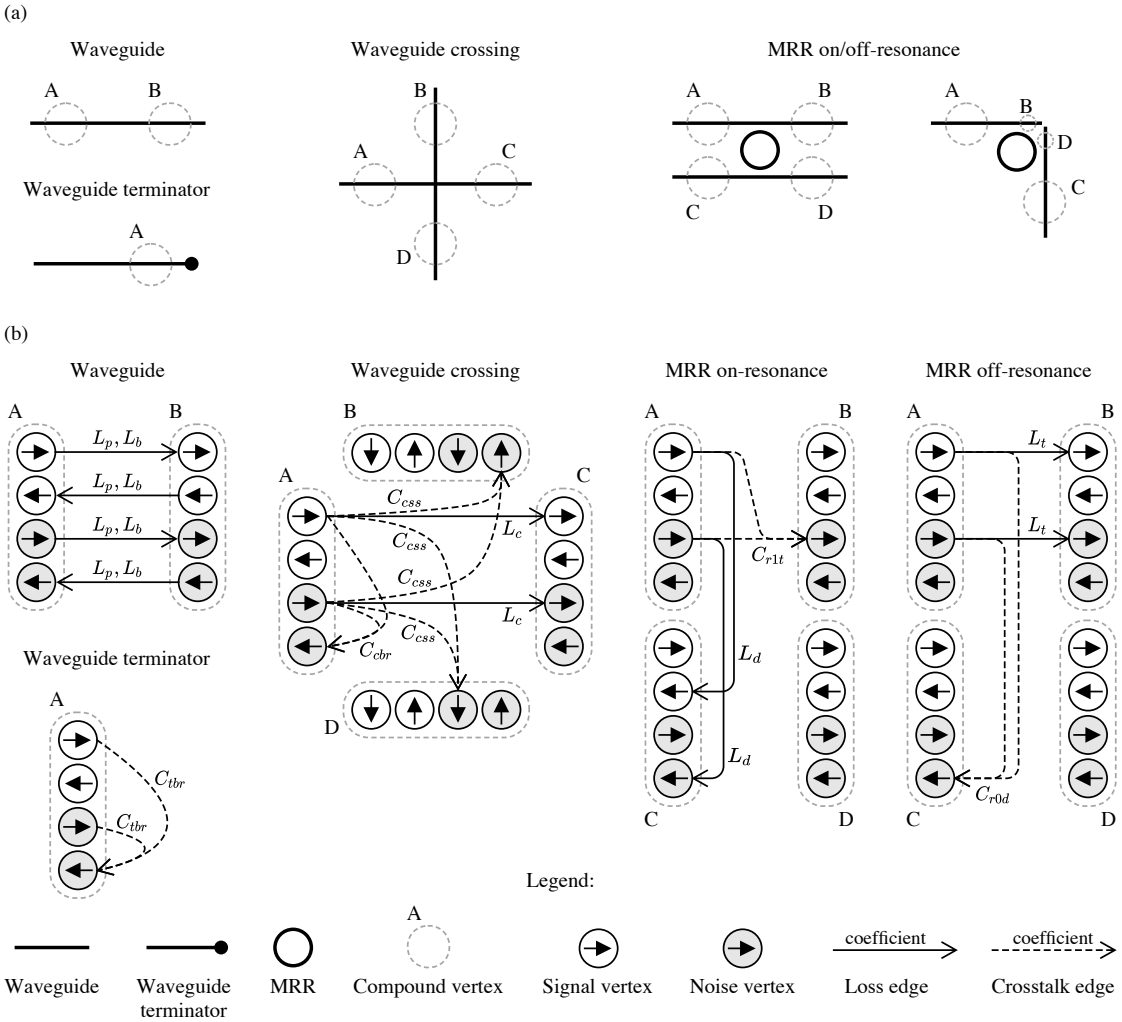
$$\sum_{i=0}^{\infty} M^i = (I - M)^{-1} \quad \forall M \in \mathbb{R}^{n \times n} : \rho(M) < 1$$

- Conclusion: only need to **solve linear system of equations**

$$x[\infty] = \left(\sum_{i=0}^{\infty} T^i \right) b \;\Leftrightarrow\; x[\infty] = (I - T)^{-1} b \;\Leftrightarrow\; \hat{T} x[\infty] = b$$

- Can handle infinite loops and infinite order noise!

ONoC design → flow graph → transfer matrix → results



- Compound vertex = 4 vertices
  - Signal →
  - Signal ←
  - Noise →
  - Noise ←

Calculating insertion loss & noise values

- ONoC → graph → transfer matrix T
- Modulator arrays are source vertices

$$b = \sum_{v \in V} g(v)\delta_v$$

- Calculate steady-state: $\hat{T}x[\infty] = b$
- Read results from steady-state **x[∞]**
  - Signal and noise energy values per wavelength at the DMAs

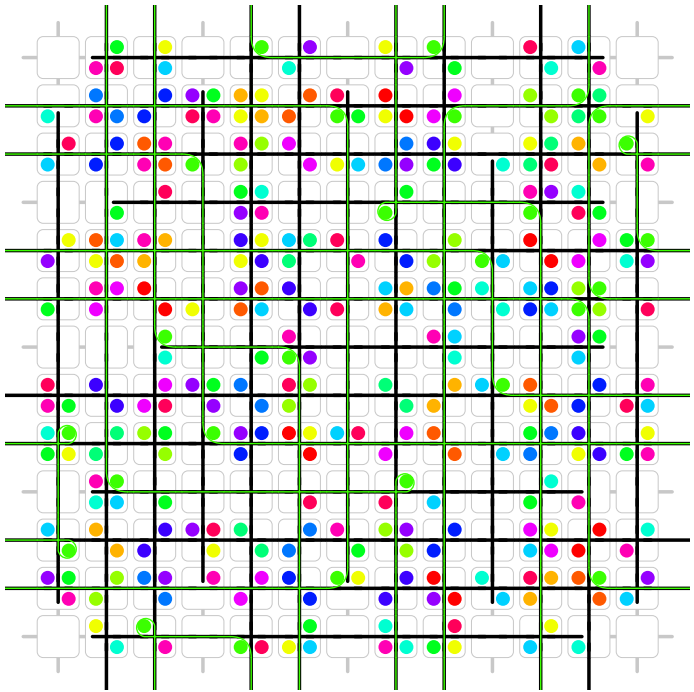
Example results

Example design

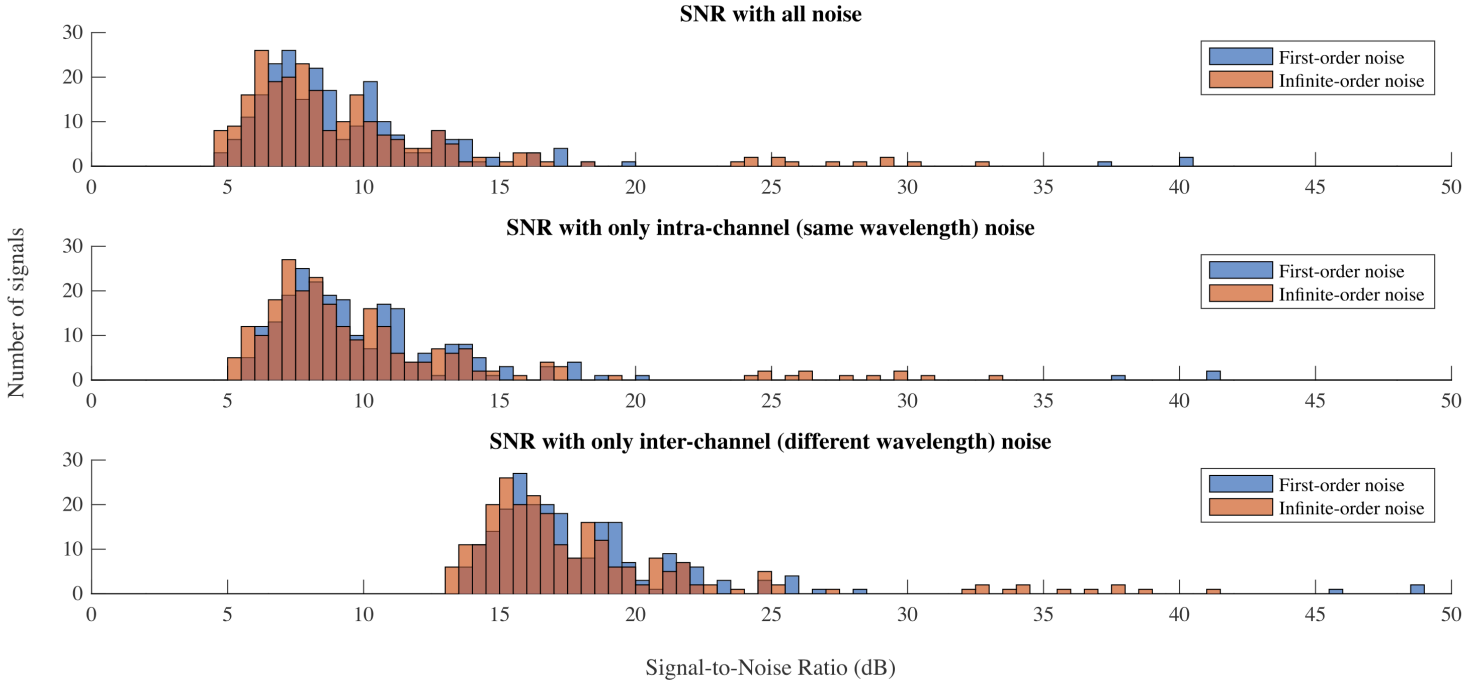
- 16 node network
- 240 signals

- Transfer matrix: 1376 x 1376 (after reduction)

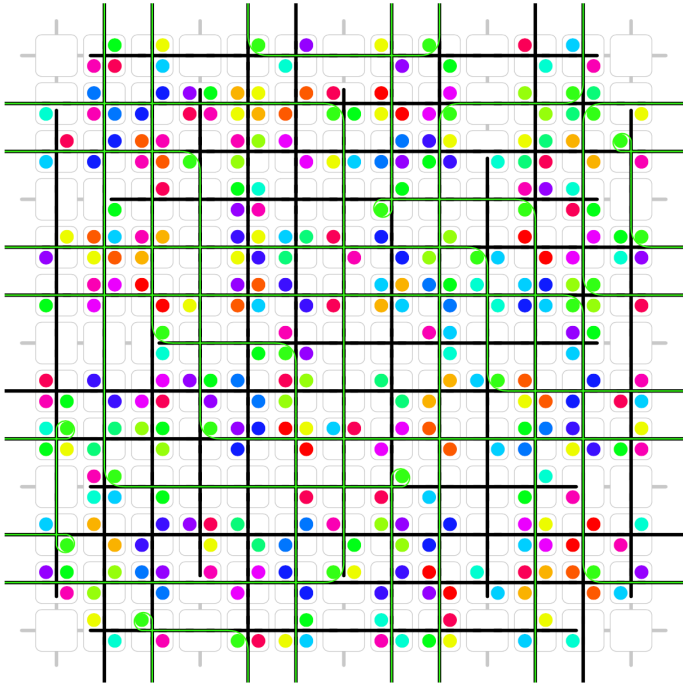
- 17 wavelengths
  - 17 linear systems for i.loss calculation
  - 17 linear systems for noise calculation
    - If 1st order noise: 123µs per system
    - If infinite order noise: 332µs per system

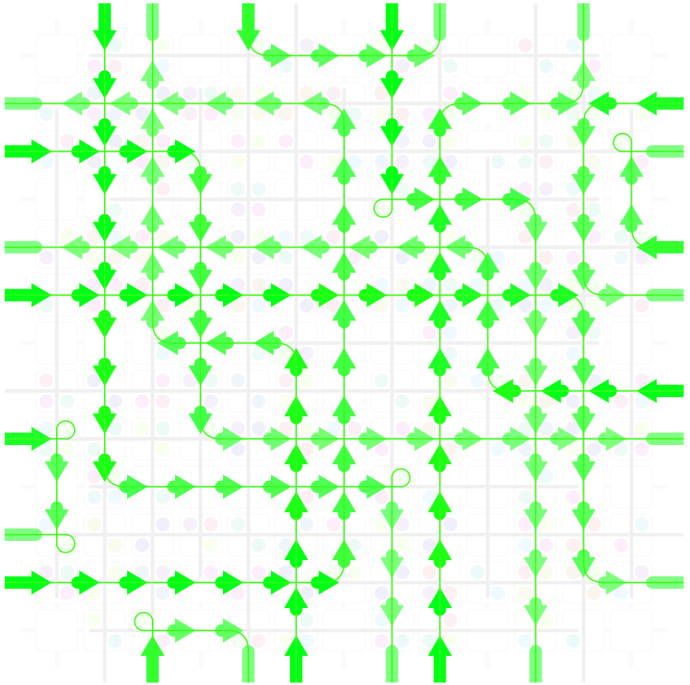


SNR results

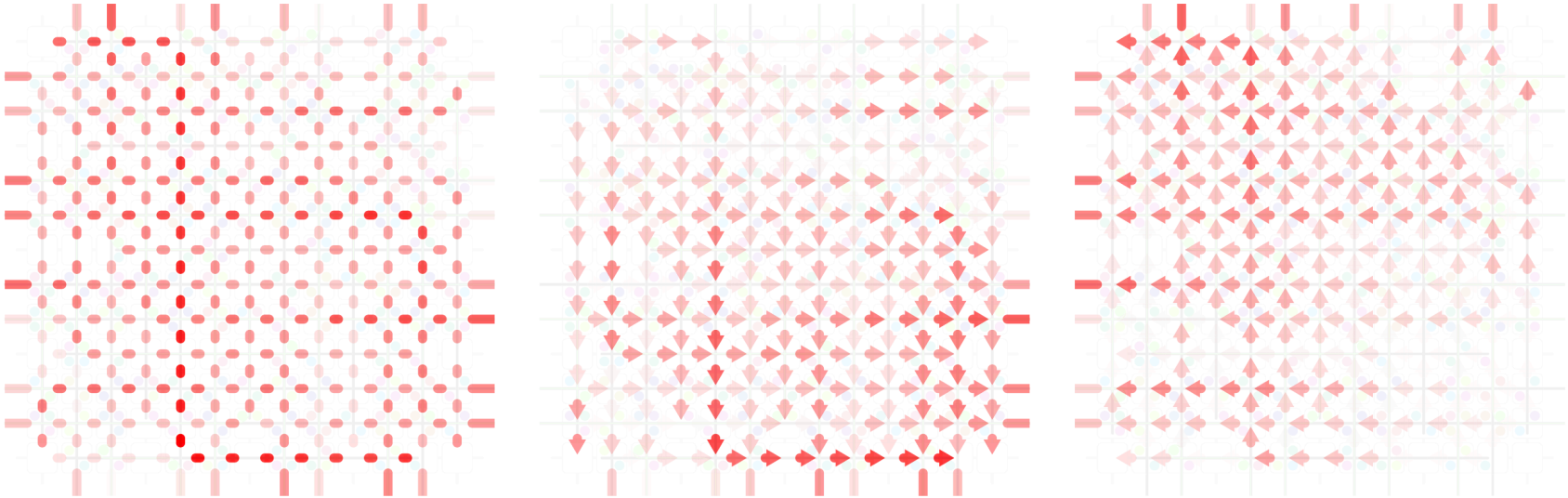

SNR with all noise
First-order noise
Infinite-order noise
SNR with only intra-channel (same wavelength) noise
First-order noise
Infinite-order noise
SNR with only inter-channel (different wavelength) noise
First-order noise
Infinite-order noise
Number of signals
Signal-to-Noise Ratio (dB)

Heatmap





Heatmap



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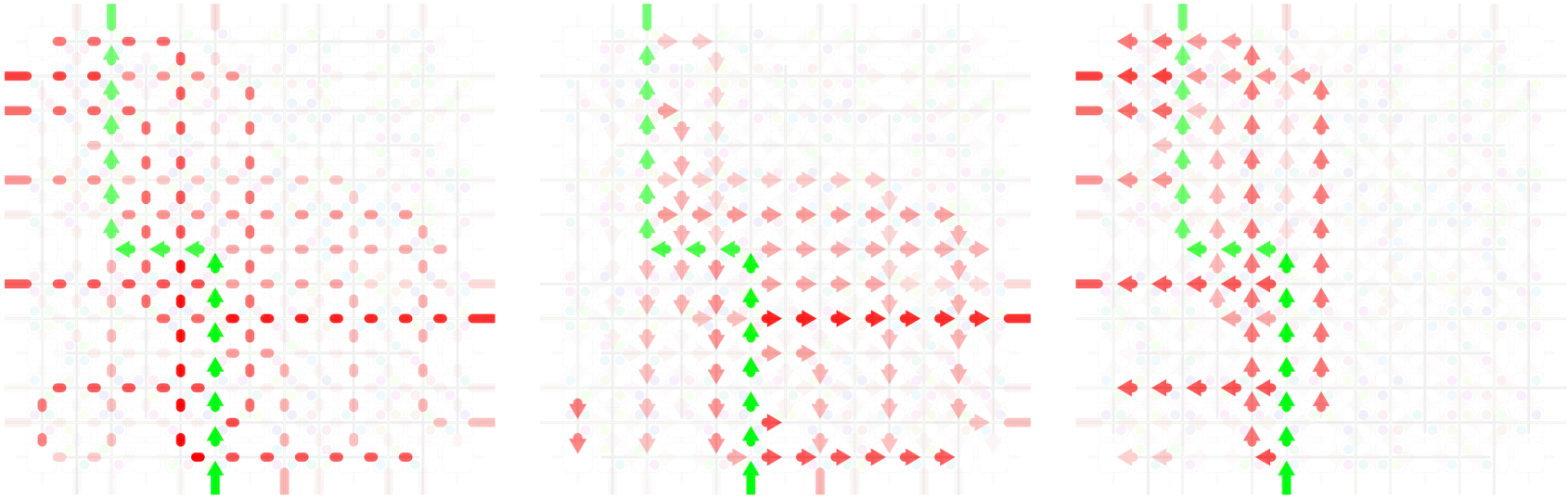
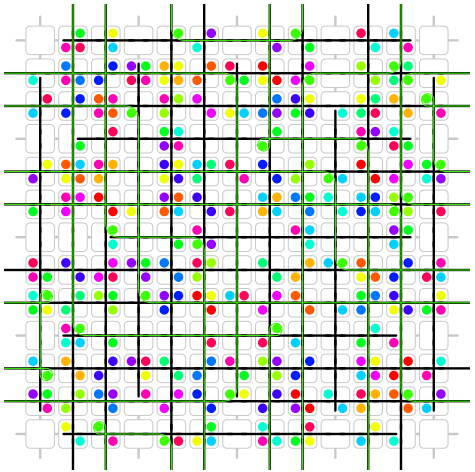
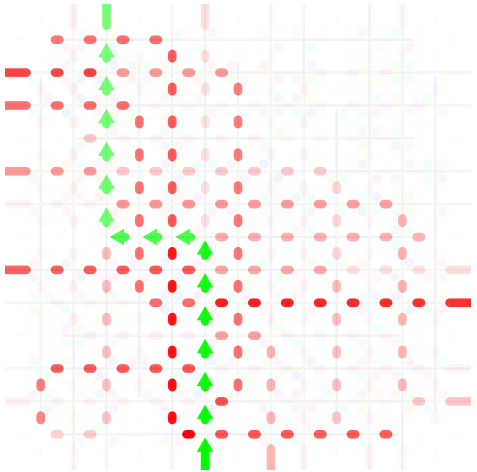


Questions?





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