

Quantum Technology for Future Networks

How to benefit from quantum technology before the quantum internet

NIST Workshop on Quantum Networking:
Experiments, Simulation, and Standards for Scalable Infrastructure

Janis Nötzel
Theoretical Quantum Systems Design
TUM

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IEEE QCE
Toronto

Quantum States of Light

- Photons are bosons – they are modelled on the Fock space $\mathcal{F} = \text{span}(\{|n\rangle\}_{n \in \mathbb{N}})$
- Coherent states are elements of the Fock space $|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$
- Displaced thermal states $S_N(\alpha) = \frac{1}{\pi N} \int e^{-|\mu|^2/N} |\alpha + \mu\rangle\langle\alpha + \mu| d\mu(\alpha)$
- The pure loss channel acts as $S_N(\alpha) \longrightarrow S_{\tau N}(\sqrt{\tau} \alpha)$
- The quantum-limited amplifier channel acts as $S_N(\alpha) \longrightarrow S_{GN+G-1}(\sqrt{G} \alpha)$
- The displacement as, $D(\mu)|\alpha\rangle = |\alpha + \mu\rangle$ a phase shifter as

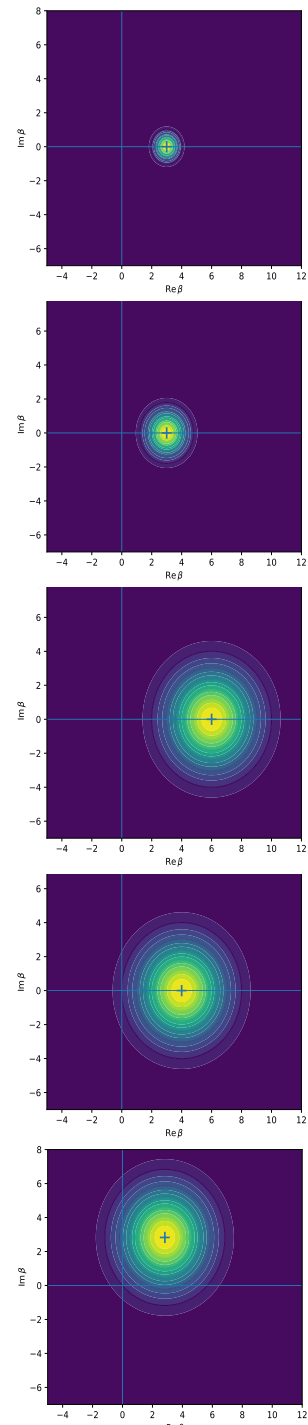
$$V(\phi)|\alpha\rangle = |e^{i\phi}\alpha\rangle$$

A. Serafini, Quantum Continuous Variables: A Primer of Theoretical Methods, 2017

N. M. Rosati, Operating Fiber Networks in the Quantum Limit, JLT, 2023

J. S. Ivan, K. K. Sabapathy, R. Simon, Operator-sum representation for bosonic Gaussian channels, PRA, 2011

A. Holevo, Quantum Systems, Channels, Information, de Gruyter, 2019



Quantum States of Light

Ideal photodetection measures photon number and is insensitive to optical phase

$$\Pi_n = |n\rangle\langle n|, \quad p(n|\alpha) = e^{-|\alpha|^2} \frac{|\alpha|^{2n}}{n!}$$

Homodyne detection interferes the signal $|\alpha\rangle$ with a strong local oscillator and measures one quadrature selected by the local-oscillator phase

$$X_\phi = \frac{1}{\sqrt{2}}(ae^{-i\phi} + a^\dagger e^{i\phi}), \quad p(x|\alpha) = \frac{1}{\sqrt{\pi}} \exp\left[-(x - \text{Re } \alpha)^2\right]$$

Heterodyne detection measures both quadratures simultaneously:

$$M_\beta = \frac{1}{\pi} |\beta\rangle\langle\beta| d^2\beta, \quad p(\beta|\alpha) = \frac{1}{2\pi} \exp\left(-\frac{|\beta-\alpha|^2}{2}\right)$$

A beam-splitter has two in- and two output ports. It transforms coherent states as

$$U(\theta)|\alpha\rangle \otimes |\beta\rangle = |\alpha \cos(\theta) + \beta \sin(\theta)\rangle \otimes |\alpha \sin(\theta) + \beta \cos(\theta)\rangle$$

The Bit from the Quantum Optics Perspective

Let bitvalue 0 be represented by $|\alpha\rangle$ and bitvalue 1 by $|\alpha\rangle$

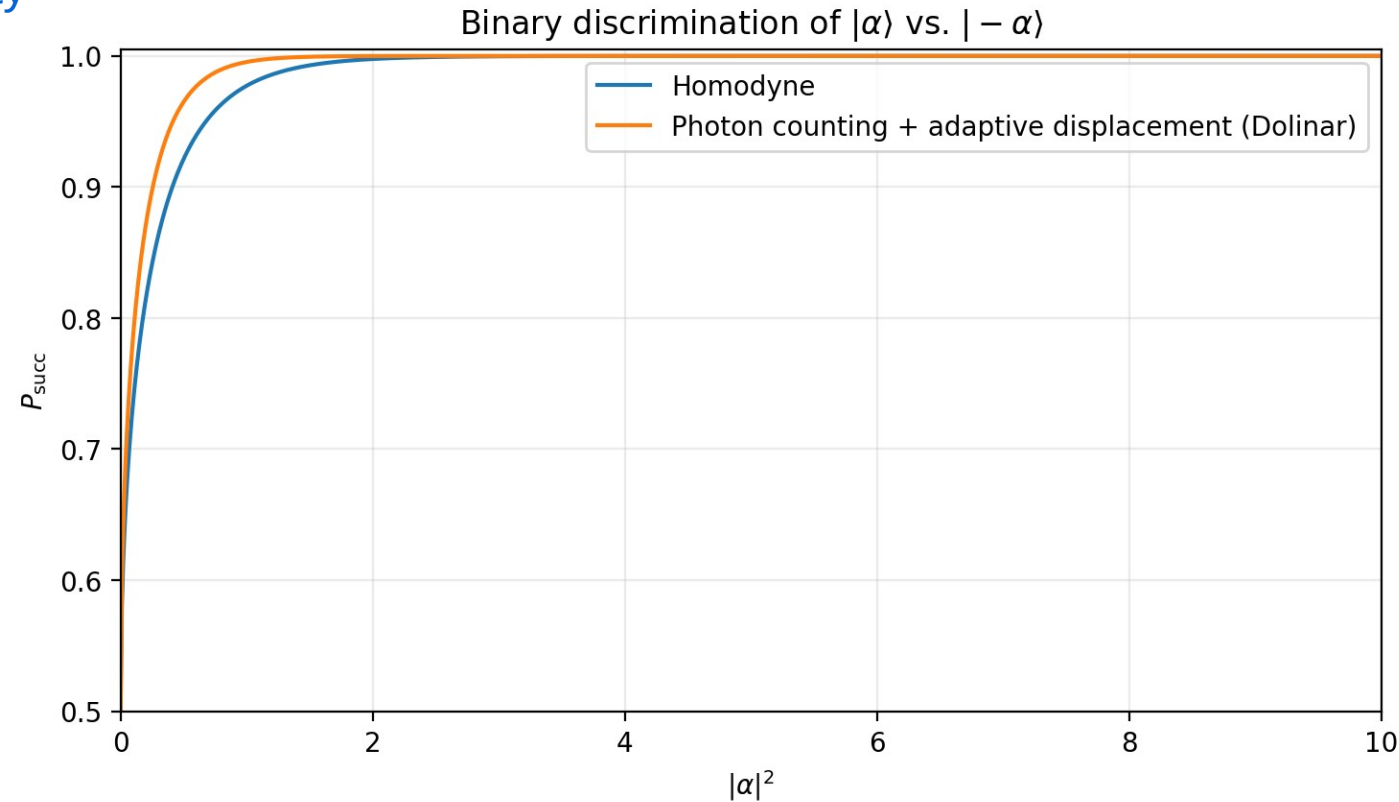
Homodyne measurements give a probability of distinguishing 0 from 1 equal to

$$\frac{1}{2} \left(1 + \operatorname{erf}(\sqrt{2}|\alpha|) \right)$$

Photon counting, displacements, beam-splitters and fast feedback give

$$\frac{1}{2} \left(1 + \sqrt{1 - \exp(-|2\alpha|^2)} \right)$$

(thereby reaching the Helstrom bound)



Takeoka, Sasaki, van Loock, Lütkenhaus,
"Implementation of projective measurements with linear optics and continuous photon counting," PRA, 2005

Data Transmission

Given a specific transmission power, how many bits per second can we send?

Quantum Advantage in Data Transmission

$$C_S(B, N_S, N_T, \tau) = B \cdot \log \left(1 + \frac{\tau N_S}{B + N_T} \right)$$

Transmittivity

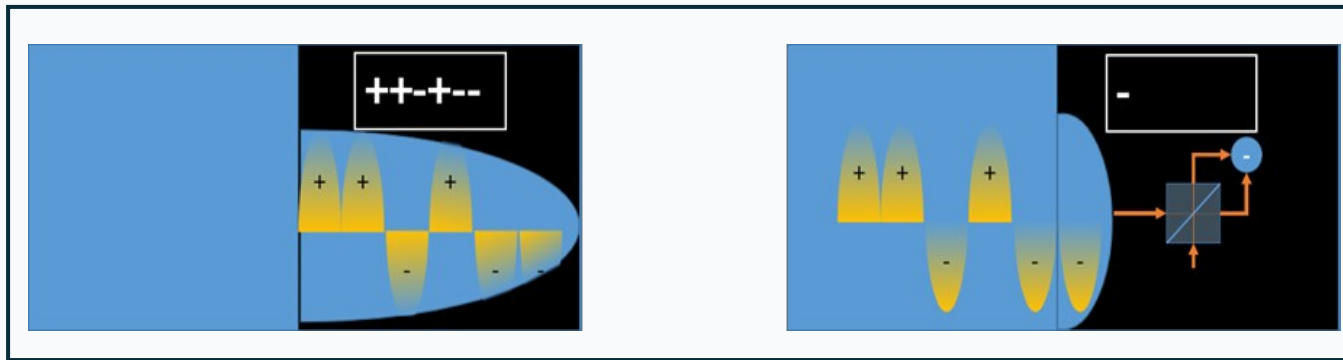
Photons per second

Signal to Noise Ratio (SNR)

Baud rate: signals per second

$$C_H(B, N_S, N_T, \tau) = B \cdot \left[g \left(\frac{\tau N_S + N_T}{B} \right) - g \left(\frac{N_T}{B} \right) \right]$$

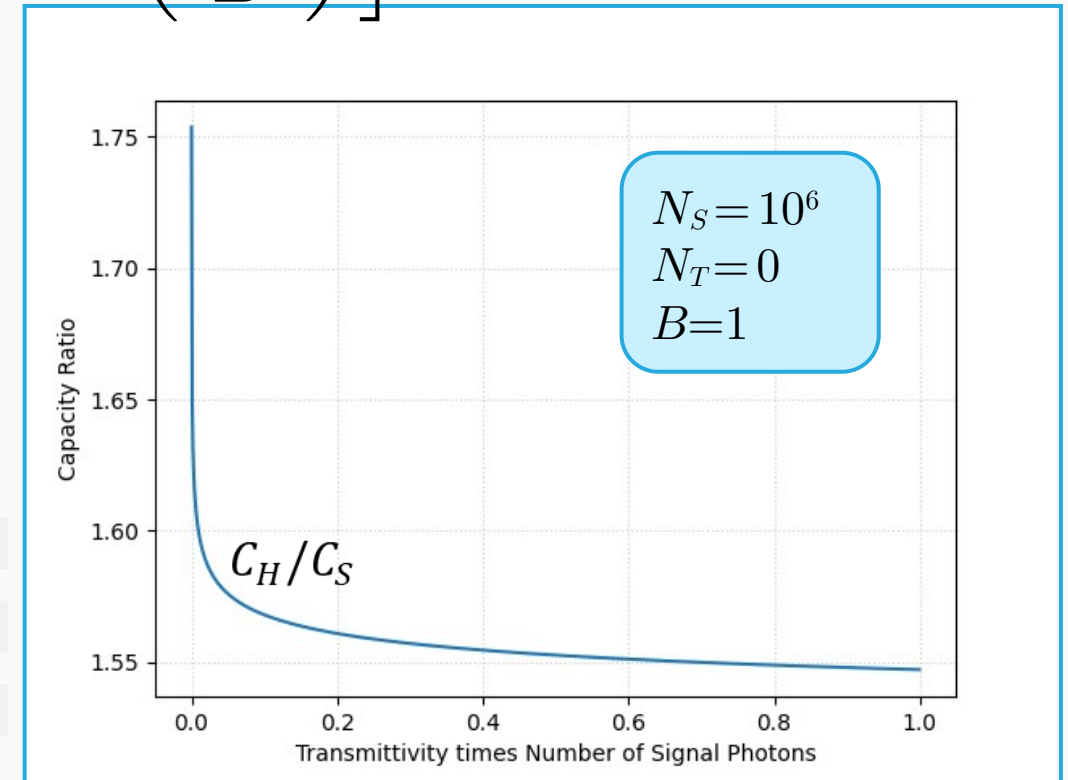
Noise photons per second



A. Holevo, *Bounds for the Quantity of Information Transmitted by a Quantum Communication Channel*, PIT, 1973

Giovannetti et al, *Ultimate classical communication rates of quantum optical channels*, Nat. Phot. 2014

Banaszek et al, *Quantum Limits in Optical Communications*, JLT, 2020



Physical units are ignored for sake of simplicity¹³

Quantum Advantage in Data Transmission

Low Power Sender

Low Noise at Receiver

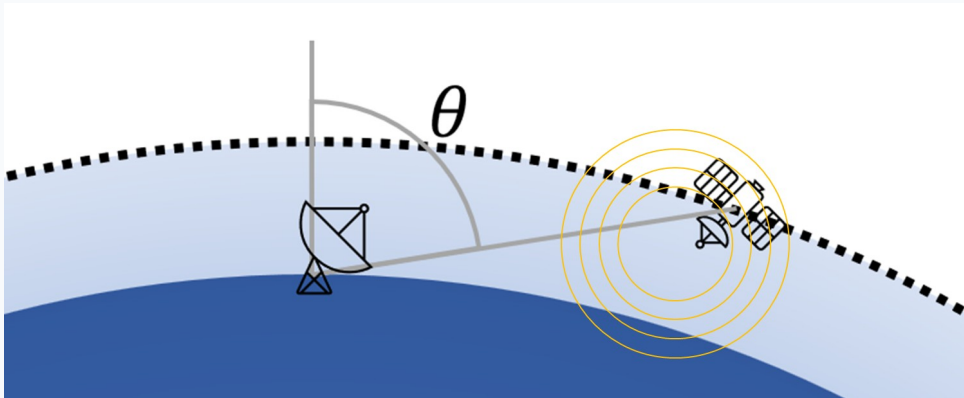
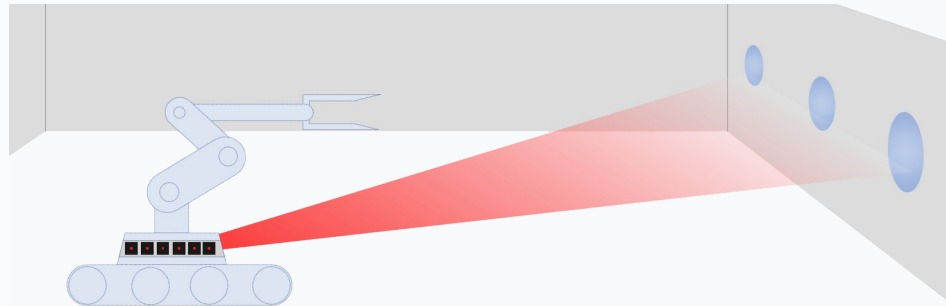
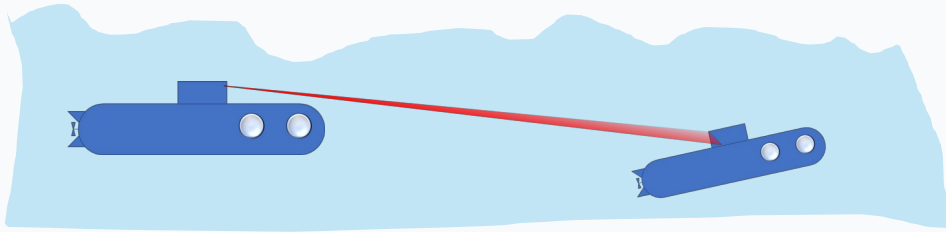
Low Datarate Application

$$N_S = 10^6$$

$$N_T = 0$$

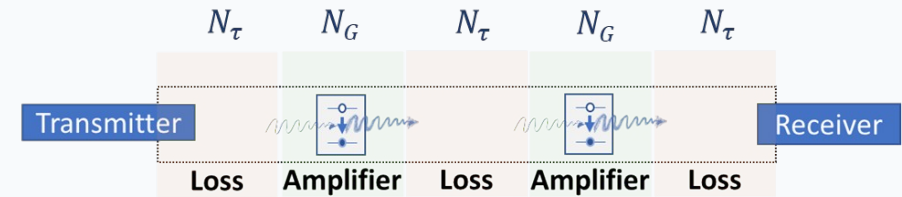
$$B = 1$$

Quantum Advantage in Future Networks



Amiri et al, **N**, *Quantum Advantages for Data Transmission in Future Networks: An Overview*, 2024

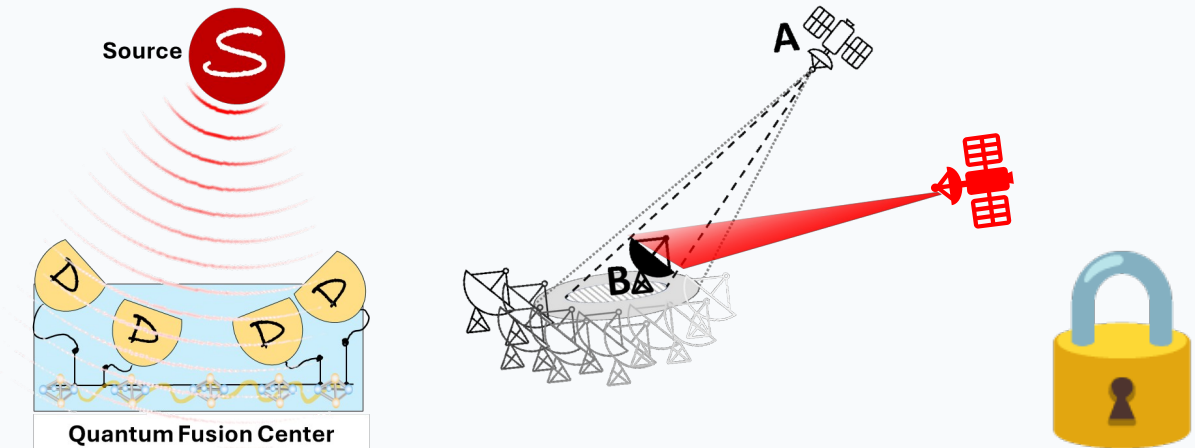
Munar-Vallespir et al, **N**, *Quantum Limits of LEO Satellite Beacon Reading*, 2025



N, M. Rosati, *Operating Fiber Networks in the Quantum Limit*, JLT, 2023



A., **N**, *Fundamental Limits of Eavesdropper Detection ... via Stimulated Brillouin Scattering*, 2025



Seitz, **N**, *Capacity Formulas for the Lossy Bosonic Wiretap Channel*, 2025

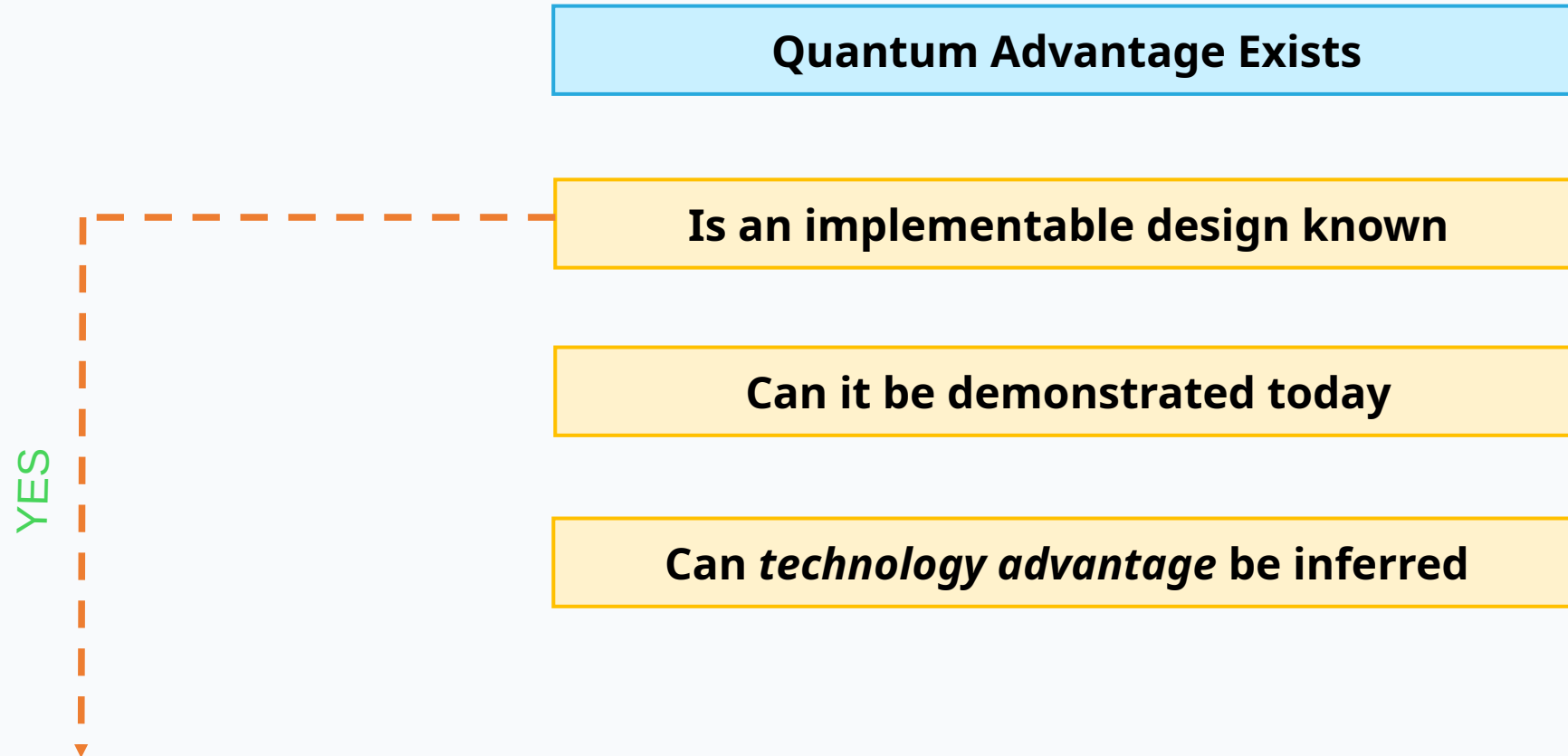
N, Seitz, *Transmitting Correlation for Data Transmission over the Bosonic AVC*, 2026

N, Munar-Vallespir, *Infinite-fold ... Quantum Advantage in ... Sensing*, arXiv: 2503.17235, 2025

N, Adhikari, *Quantum-Limited Blind Source Separation of Classical Light*, 2026

From Concept to Concrete Advantage

Evaluating Candidacy



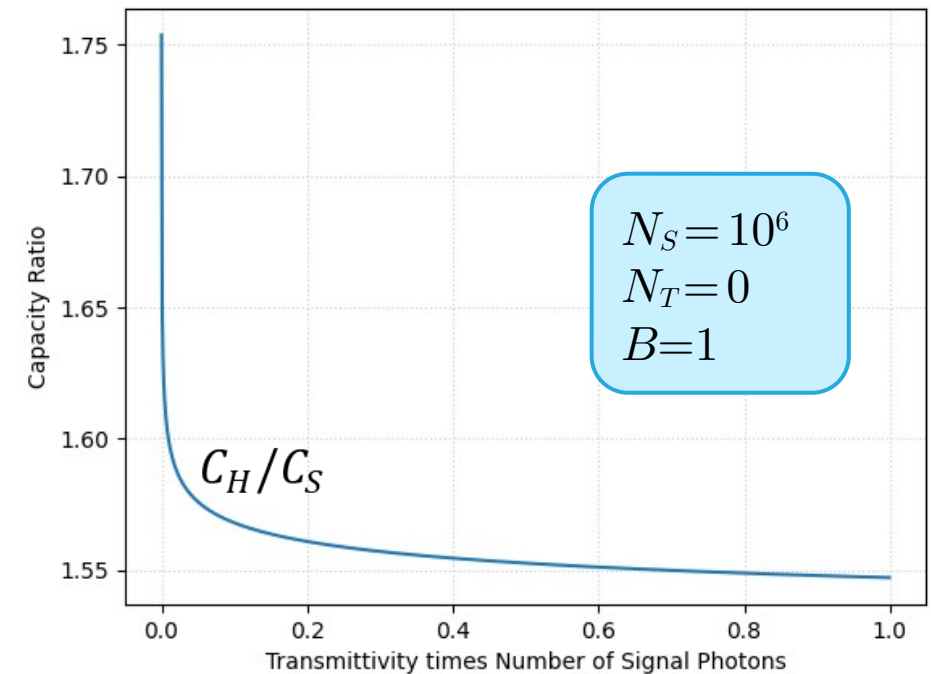
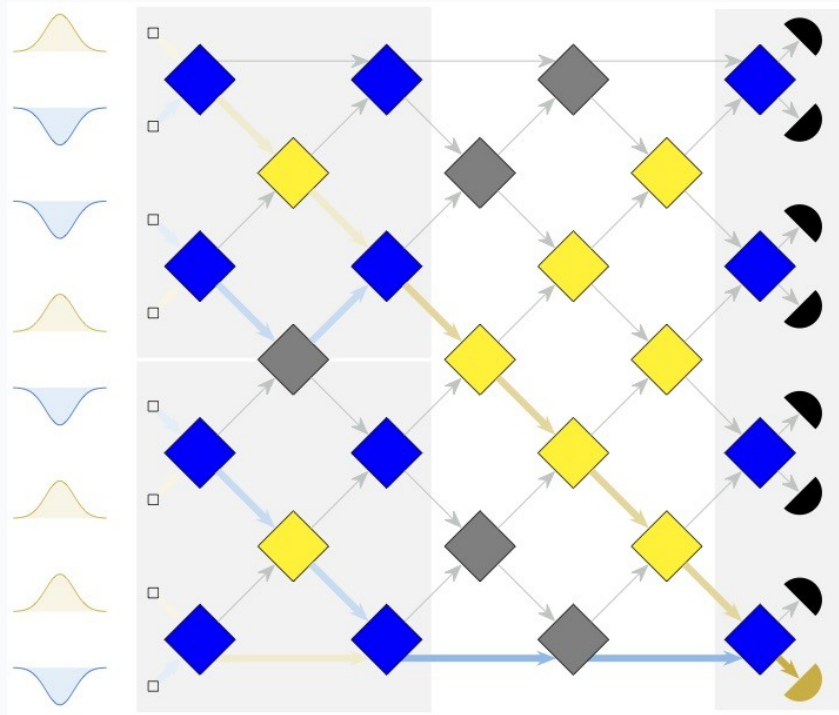
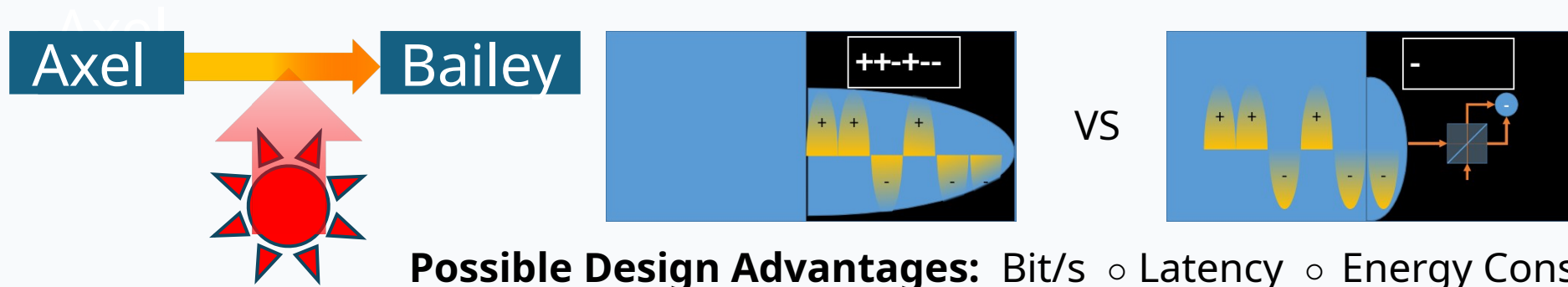
Rengaswamy et al, Belief propagation with quantum messages for quantum-enhanced classical communications, npj, 2021

Guha, Structured Optical Receivers to Attain Superadditive Capacity and the Holevo Limit, PRL, 2011

Giovanetti, Lloyd, Maccone, *Achieving the Holevo bound via sequential measurements*, PRA, 2012

M. Wilde, *Sequential decoding of a general classical-quantum channel*, Proceedings of the Royal Society A, 2013

Joint Detection 1.0: Linear Optics + Photon Counting!



Guha, Structured Optical Receivers to Attain Superadditive Capacity and the Holevo Limit, PRL, 2011

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M. Wilde, *Sequential decoding of a general classical-quantum channel*, Proceedings of the Royal Society A, 2013

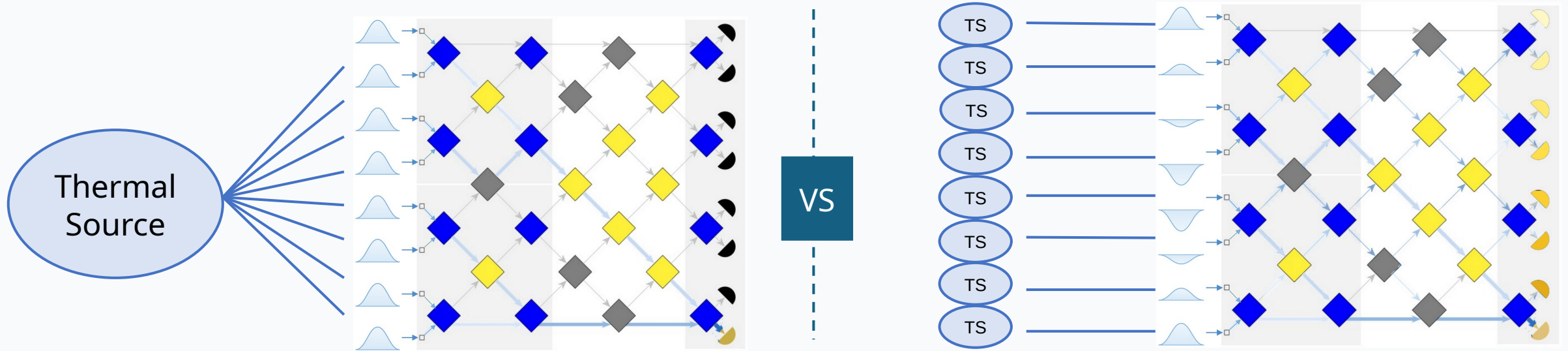
From Concept to Concrete Advantage

Evaluating Candidacy

Is an implementable design known

Where else does it have provable advantage

Optimal Optical Hypothesis Testing



$$\rho_E^{(K)} = \frac{1}{\pi \cdot E} \int e^{-|\alpha|^2/E} |\alpha\rangle \langle \alpha| \otimes^K d\alpha$$

$$K \cdot \ln(K) \cdot E + \mathcal{O}(E^2) \\ \frac{(K-1) \cdot K}{\ln(4)} \cdot E^2 + \mathcal{O}(E^3)$$

$$\rho_E^{\otimes K} = \left(\frac{1}{\pi E} \int e^{-\frac{|\alpha|^2}{E}} |\alpha\rangle \langle \alpha| d\alpha \right)^{\otimes K}$$

Error exponents in asymmetric optical hypothesis testing. For $E \ll 1$, photon counting achieves the optimal $1/E$ scaling

From Concept to Concrete Advantage

Evaluating Candidacy

Is an implementable design known

How can we extend its functionality

Computing on Light

Problem statement: Given the quantum state ρ , find optical network parameters $\theta_{i,j}$ and $\phi_{i,j}$ such that ρ becomes diagonal in the photon number basis

Assumption: ρ is Passive Unitary Normalizable (PUN)

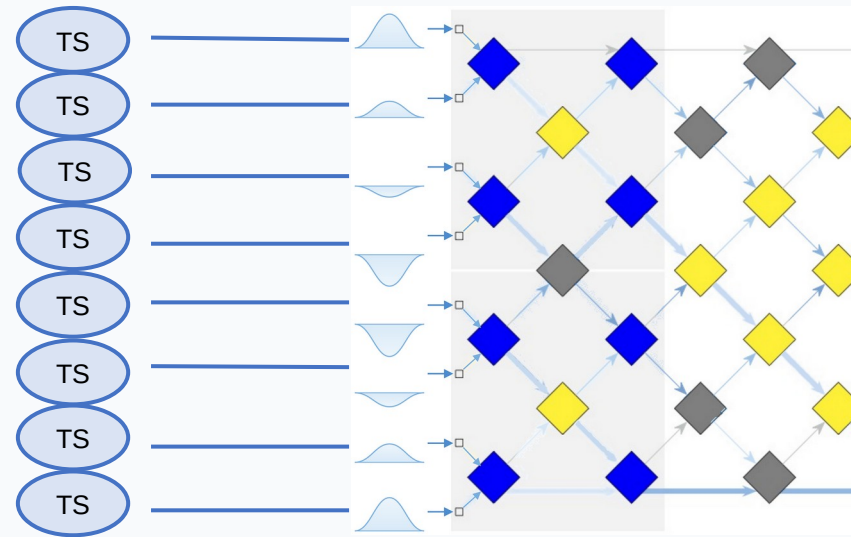
$$\rho = U(\Theta)[S_{N_1} \otimes \dots \otimes S_{N_K}]U(\Theta)^\dagger$$

$$U(\Theta) = \otimes_{i,j=1}^K V_i(\phi_{i,j})U(\theta_{i,j})$$

$$\mathbf{C} = [(a_i^\dagger a_j \rho)]_{i,j=1}^K$$

$\mathbf{C}$ is the correlation matrix. On the logical level, the problem is identical to diagonalizing $\mathbf{C}$.

$$S_{N_1} \otimes \dots \otimes S_{N_K}$$



$$U(\Theta) = \otimes_{i,j=1}^K V_i(\phi_{i,j})U(\theta_{i,j})$$

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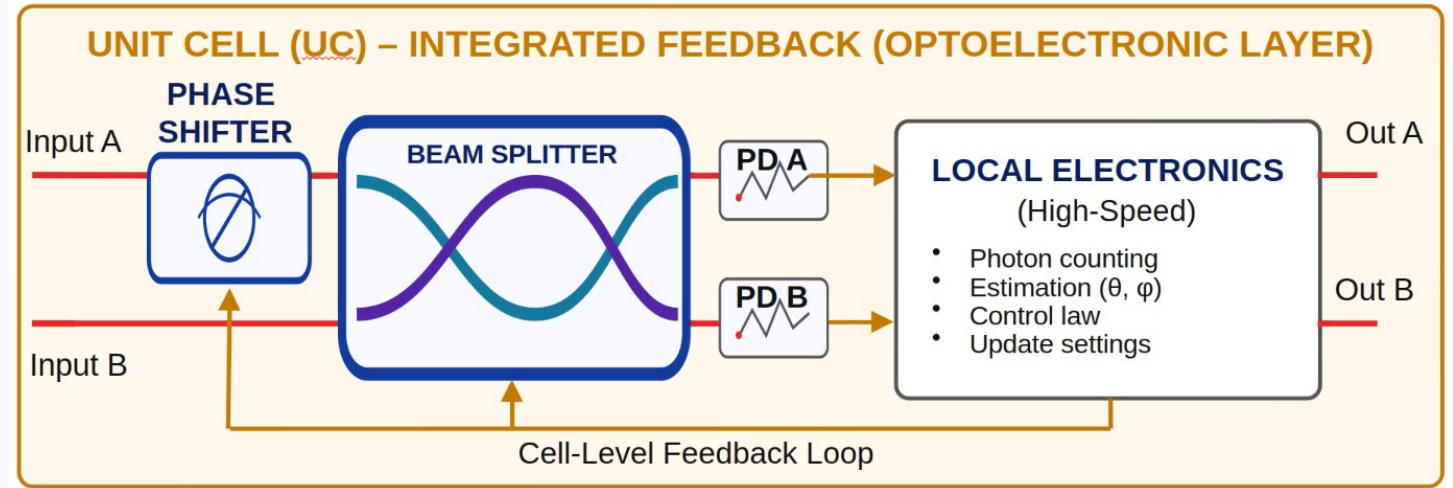
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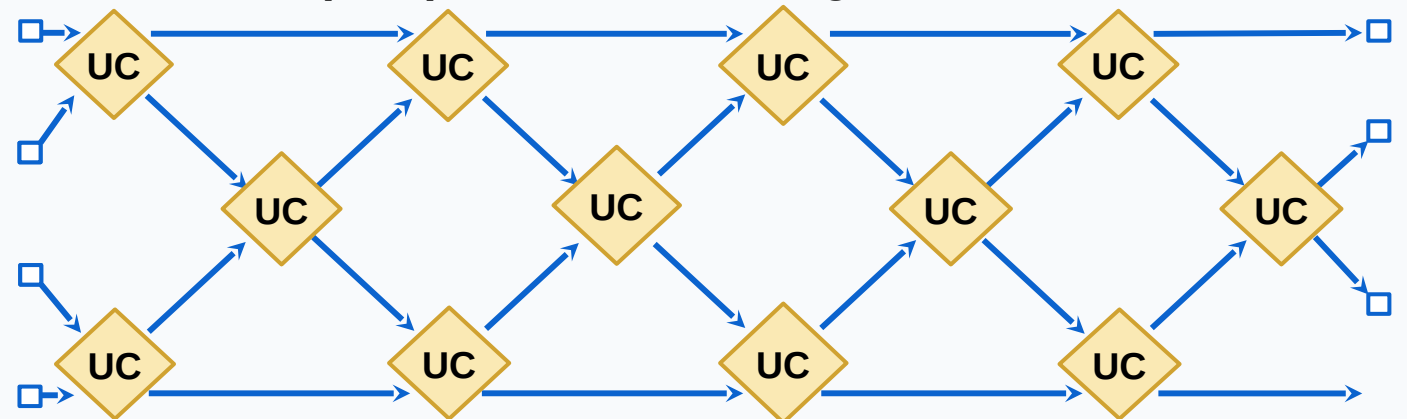
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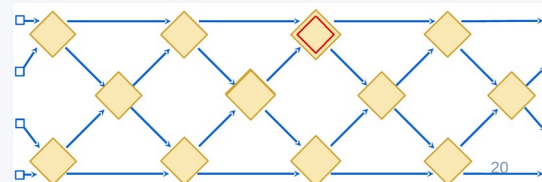
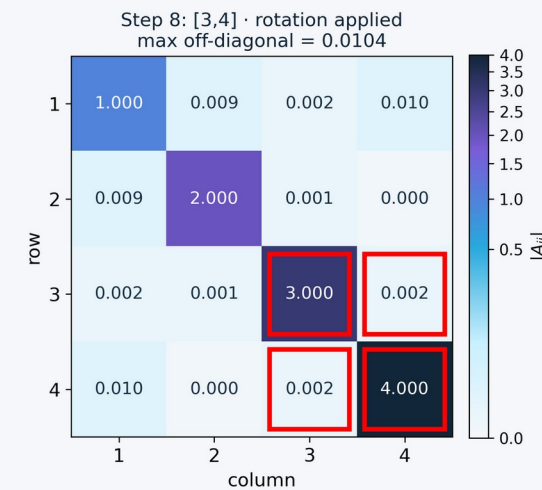
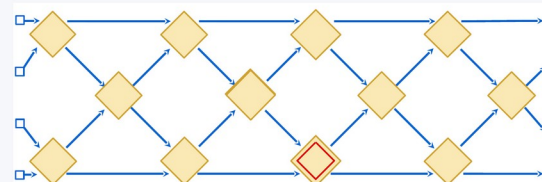
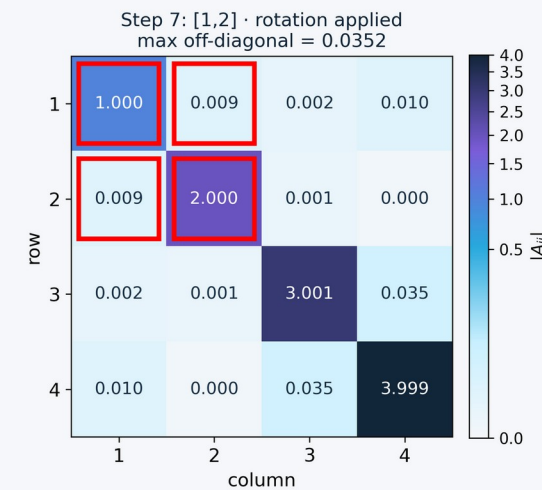
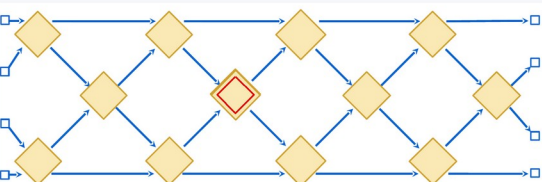
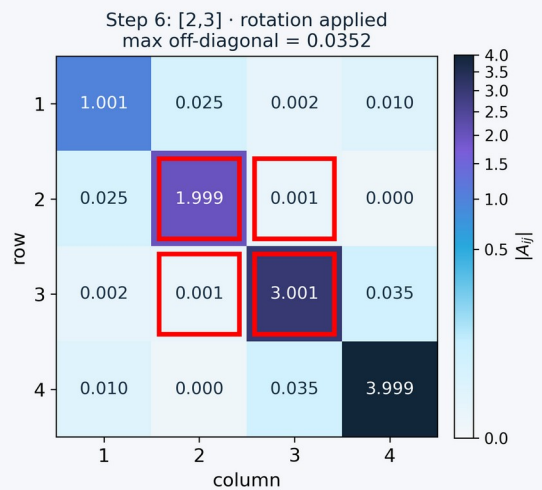
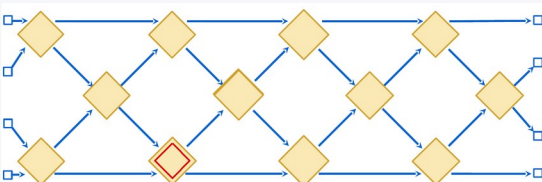
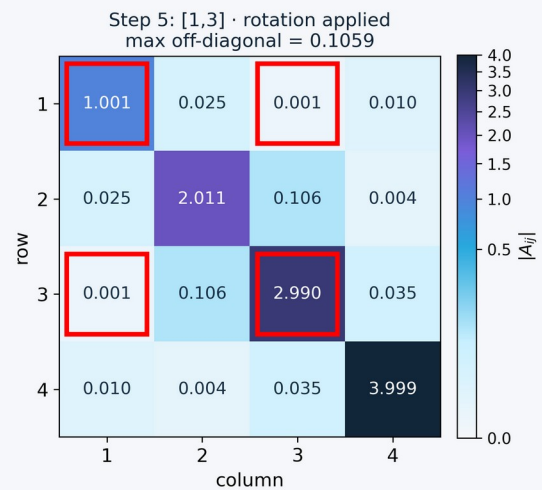
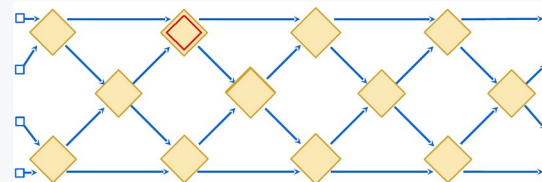
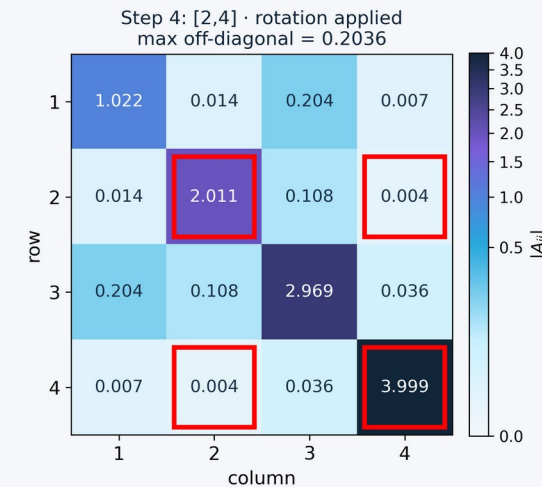
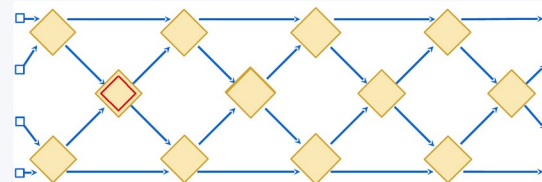
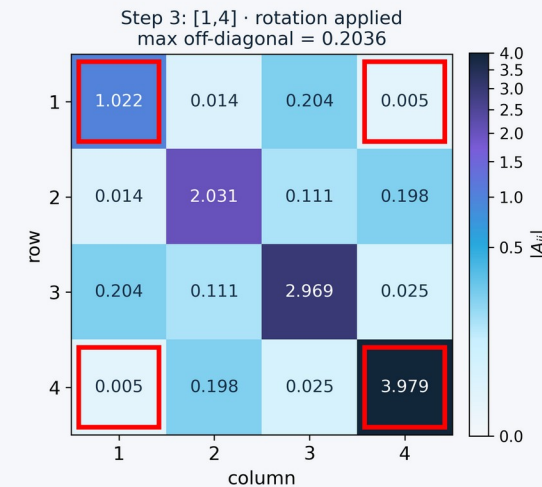
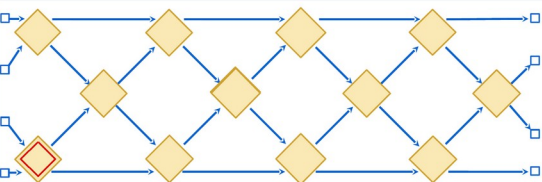
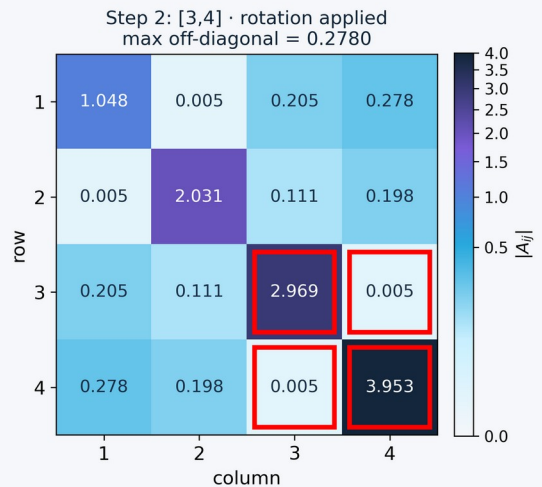
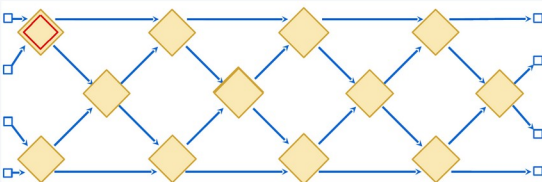
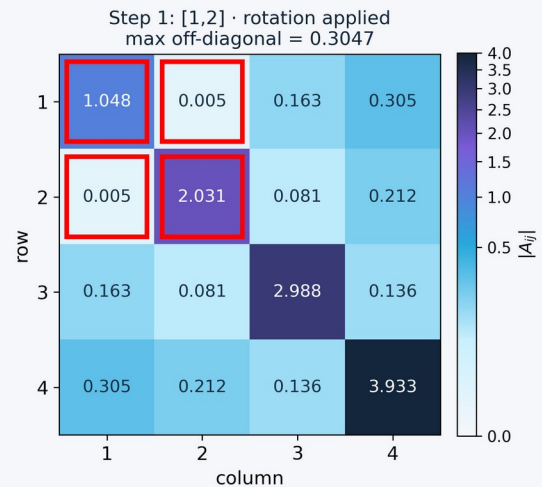
$\mathbf{C}$ is the correlation matrix. On the logical level, the problem is identical to diagonalizing $\mathbf{C}$.



Global perspective for K=4, light enters from left



Computing on Light



Computing on Light: Performance

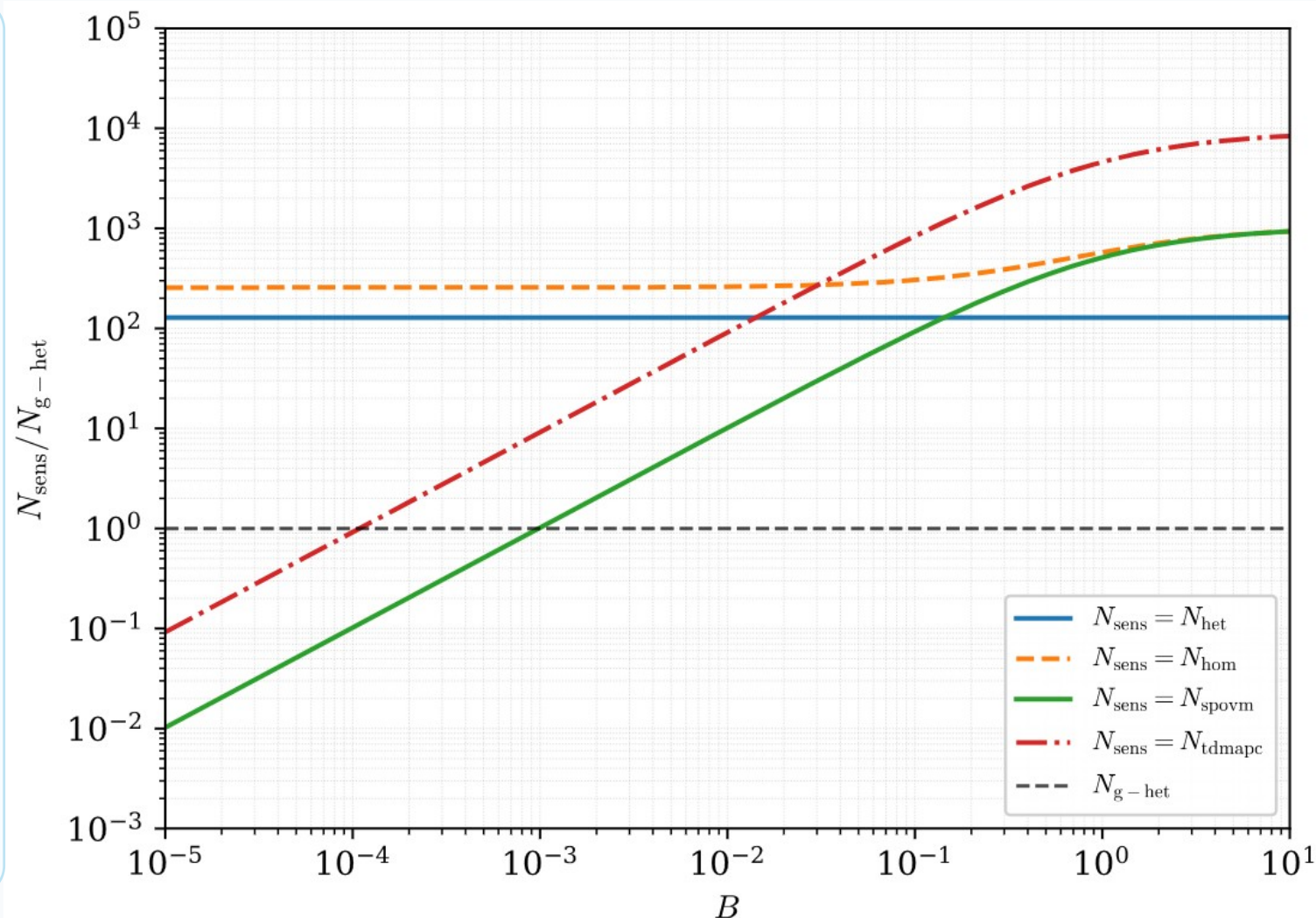
PERFORMANCE

We compared the the number of samples $\mathbf{N}$ that is needed to achieve accuracy ϵ with probability at least $\mathbf{p}$

Candidates for comparison: UC level and global hetero- and homodyne measurements as well as UC level product- and collective quantum strategies.

Assuming $|N_i - N_j| \geq \Delta$ & $\Delta \leq N_i \leq B$, and $B \ll 1$ we observe a $1/B$ runtime improvement when replacing a system using hetero- or homdyne detection with a UC based one using photon counting or collective measurements.

Shot noise is the bottleneck.



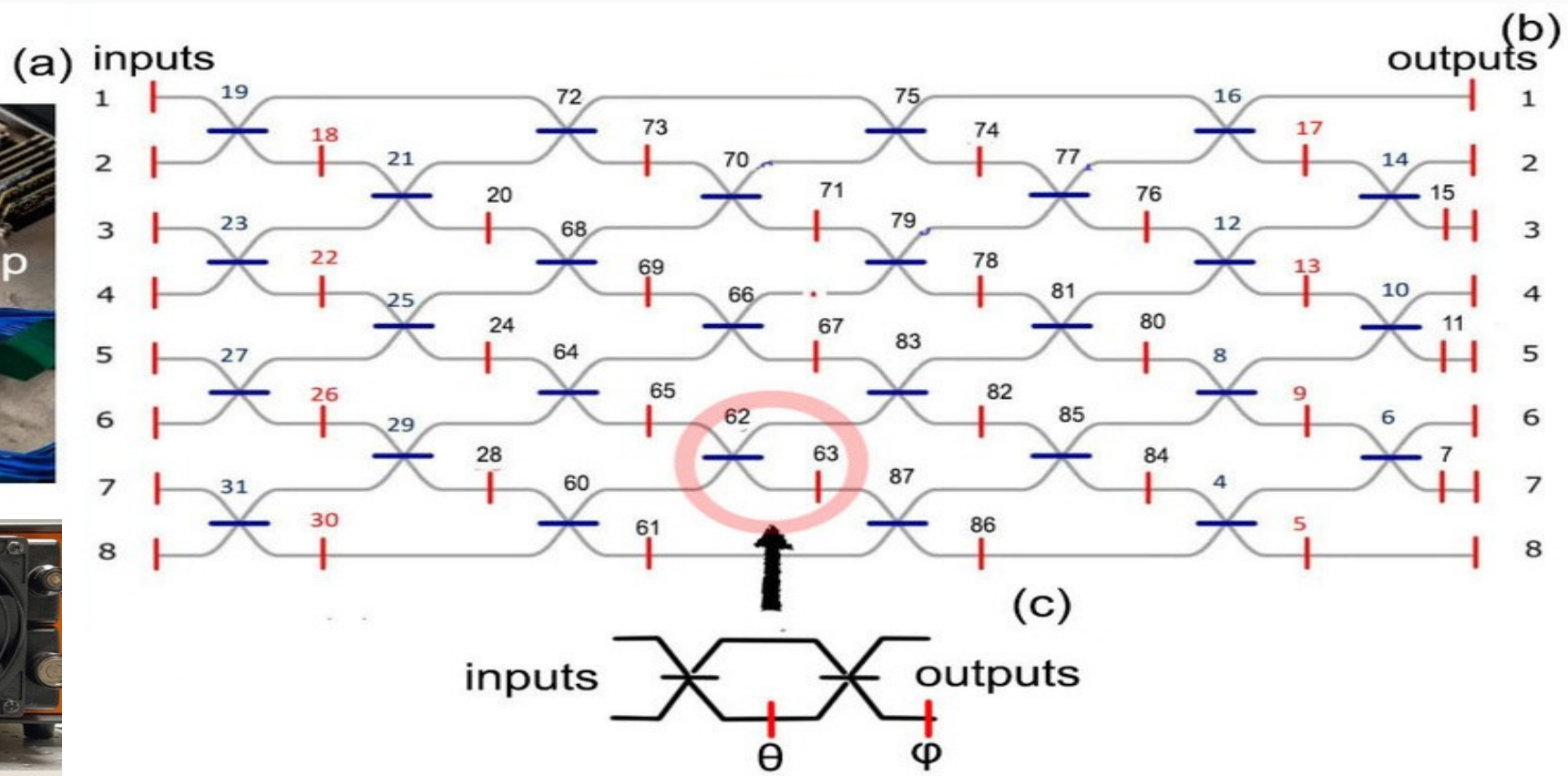
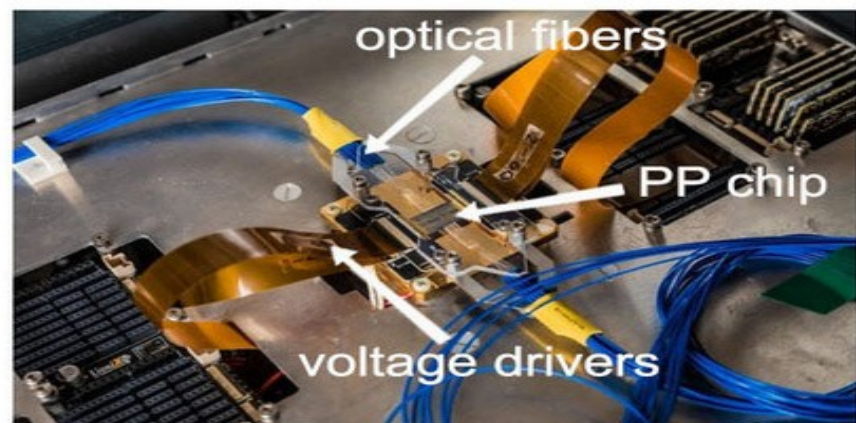
Evaluating Candidacy

Can we demonstrate the system today

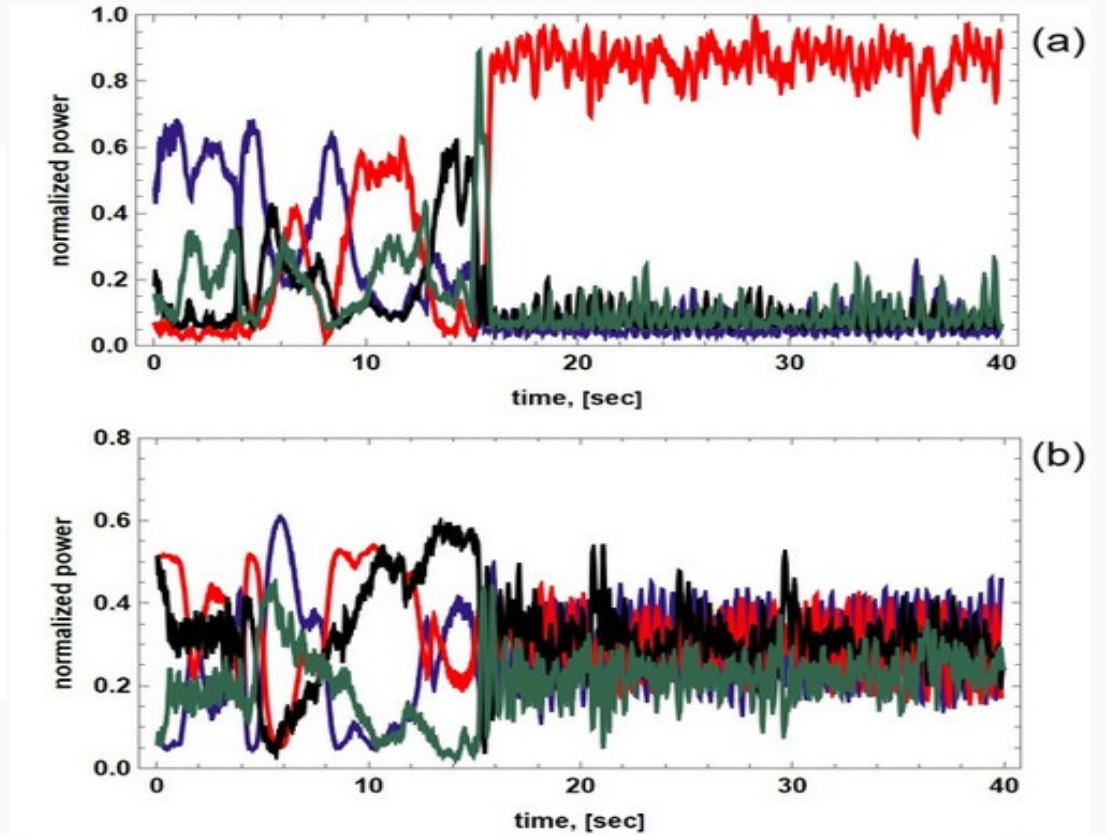
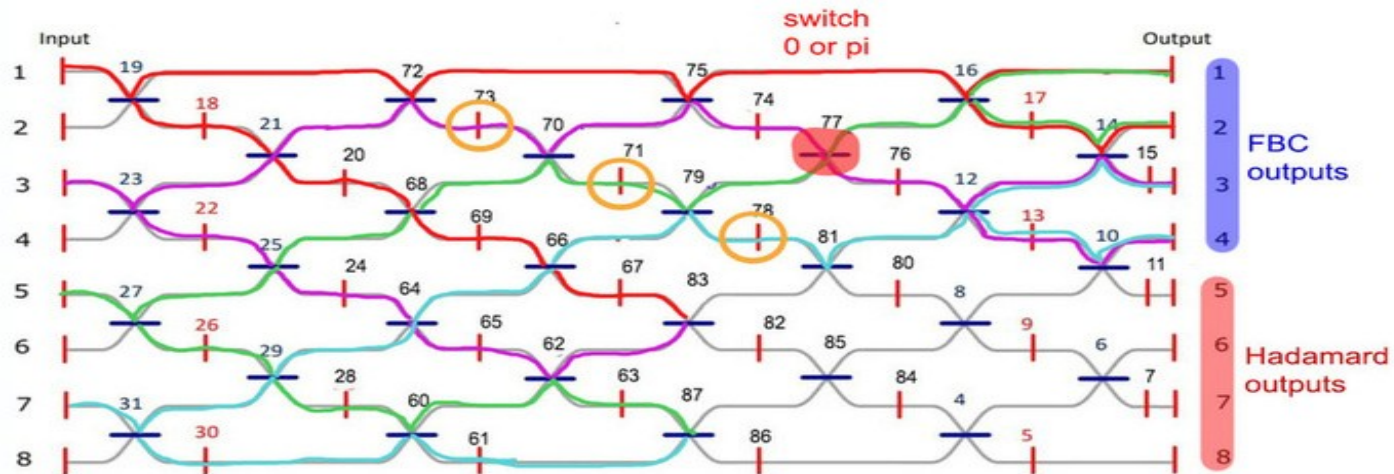
Can *technology advantage* be inferred

The Photonic Processor

Material: silicon nitride



Multi-Input Phase Stabilization



I. A. Litvin, G. Elmas, P. Kohl, N. "Stable Signal Processing With a Photonic Processor," JLT, 2025

Litvin, I. A., Elmas, G., Kohl, P., N. Multi-input signal phase stabilization in photonic processors with on-chip feedback control. Optics Express, 2026

Observation

Optical joint detection exists in laboratories

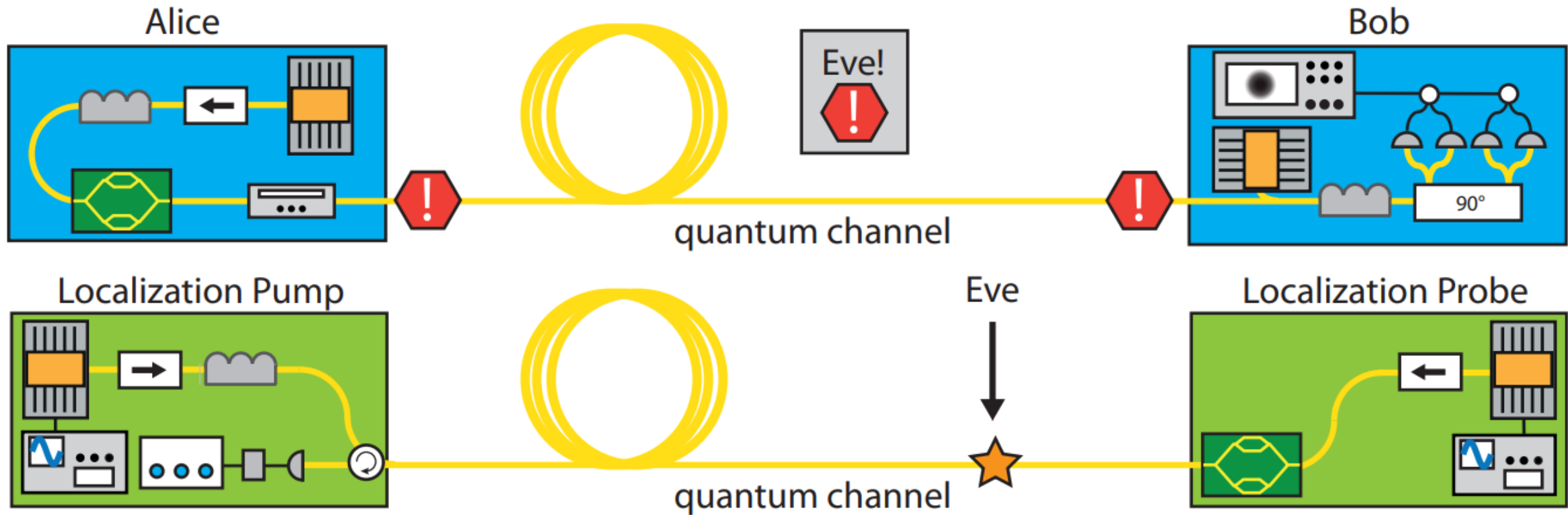
There are many practical and fundamental challenges

Interface design shows up as engineering bottleneck

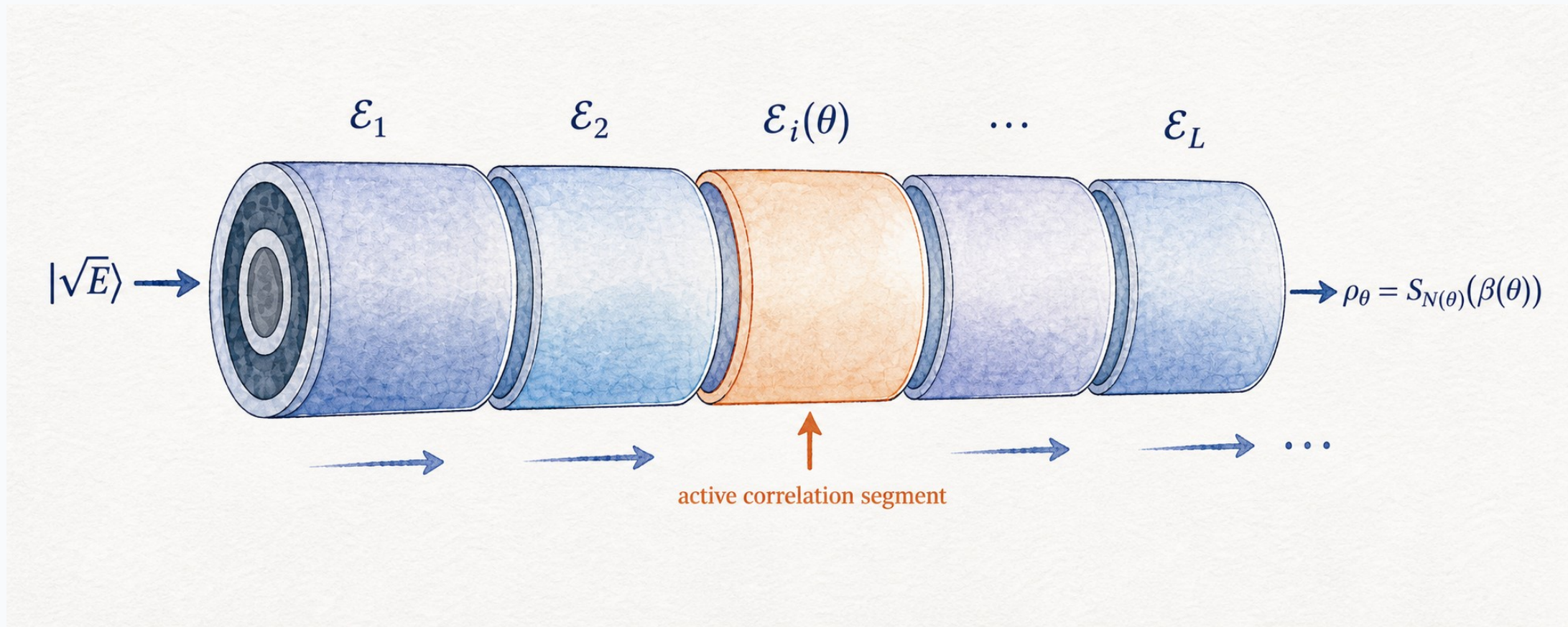
Coupling- and processing losses impact advantage

Can we derive yet simpler, more practical applications?

Simplification to SPDs



Simplification to SPDs



To be presented in detail at 2026 IEEE GLOBECOM

Simplification to SPDs

Fisher information (FI):

→ How much information does random variable $X(\theta)$ contain about parameter θ ?

Quantum Fisher information (QFI):

→ same with $X(\theta)$ replaced by $\rho(\theta)$ and allowing coherent measurements over many copies of $\rho(\theta)$

Heterodyne FI (HFI):

→ Obtained when heterodyning $\rho(\theta)$ and inferring theta from the measured results

Each unbiased estimator of θ has variance lower bounded by the inverse FI, QFI, or HFI

$$\text{QFI}(\theta) = \frac{4|\partial_{\theta}\beta(\theta)|^2}{2N(\theta) + 1} + \frac{[\partial_{\theta}N(\theta)]^2}{N(\theta) [N(\theta) + 1]}$$

HOW TO REACH QFI

Following the QLAN idea:

- (1) coarse-grained estimate using
e.g. heterodyning yields estimate γ
- (2) displace received field by γ
- (3) apply photon counting yields M
- (4) estimate θ from γ and M

$$\text{HFI}(\theta) = \frac{2|\partial_{\theta}\beta(\theta)|^2}{N(\theta) + 1} + \frac{[\partial_{\theta}N(\theta)]^2}{[N(\theta) + 1]^2}.$$

Yamagata, Fujiwara, Gill, "Quantum local asymptotic normality based on a new quantum likelihood ratio," The Annals of Statistics, vol. 41, no. 4, Aug. 2013

Adhikari, N, Fundamental Limits of Eavesdropper Detection and Localization in Optical Fiber via Stimulated Brillouin Scattering, arXiv, 2026

Organizing your Quantum Technology Team

File

Edit

Board

Report



10

backup.json

config.toml

experiment.json

measurement_test.json

new.json

number_state.json

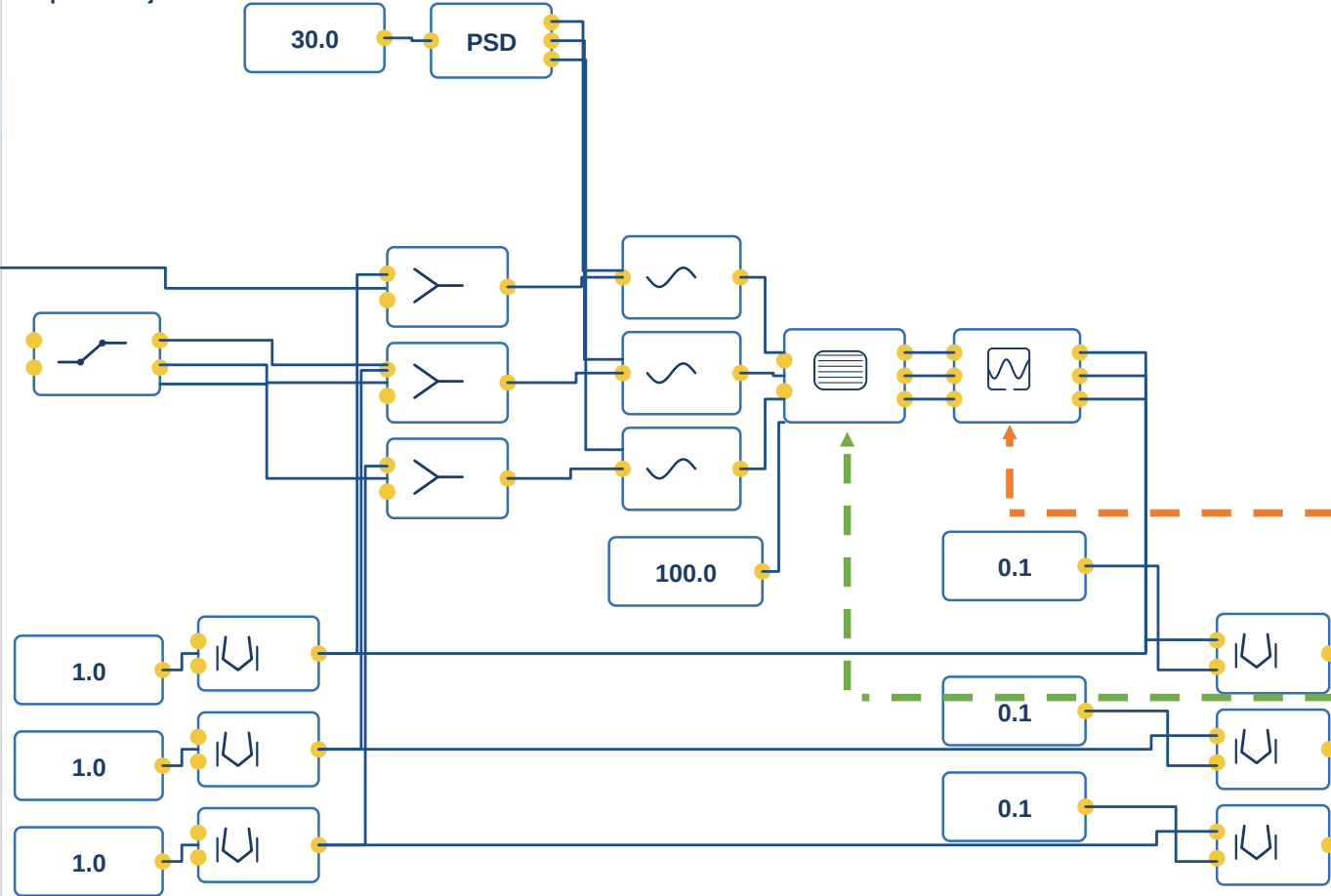
phase_shift_test.json

> custom

> plots

MATH → DESIGN → IMPLEMENTATION

experiment.json



Component Library

Variables

Float Variable

Int Variable

Time Variable

Sources

Ideal Coherent Photon Source

Ideal N Photon Source

Ideal Single Photon Source

Ideal Squeezed Photon Source

Beam Splitters

Ideal Beam Splitter

Control

Clock Trigger

Simple Trigger

Phase Shift

Ideal Phase Shifter

Fiber

Ideal Fiber

Detectors

Ideal Detector

Investigation

Photon Distribution

Extra

Encoder

Excitation

Messages

OpticalMemoryDecoder

Pulse Center

I/O Logic

Strict I/O logic per component allows transition from mathematical to executable.

Experimental feedback ensures match with physical reality.

Fundamental Research

Established Technology



QREED – Quantum Optical Experiment Editor

Thanks

