Toward complex arbitrary photon statistics measurement through imperfect integrated single-photon detector arrays

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In the last few decades, quantum photonics has emerged as a captivating and rapidly evolving field at the intersection of quantum mechanics and photonics. The ability to harness the fundamental properties of light at the quantum level holds the key to unlocking revolutionary progresses in advanced computing, secure communication, and high-precision measurements.

In this work, we explore the feasibility of photon statistics measurements with integrated SPAD arrays by employing both analytical modeling and simulations to study realistic devices with their non-idealities.

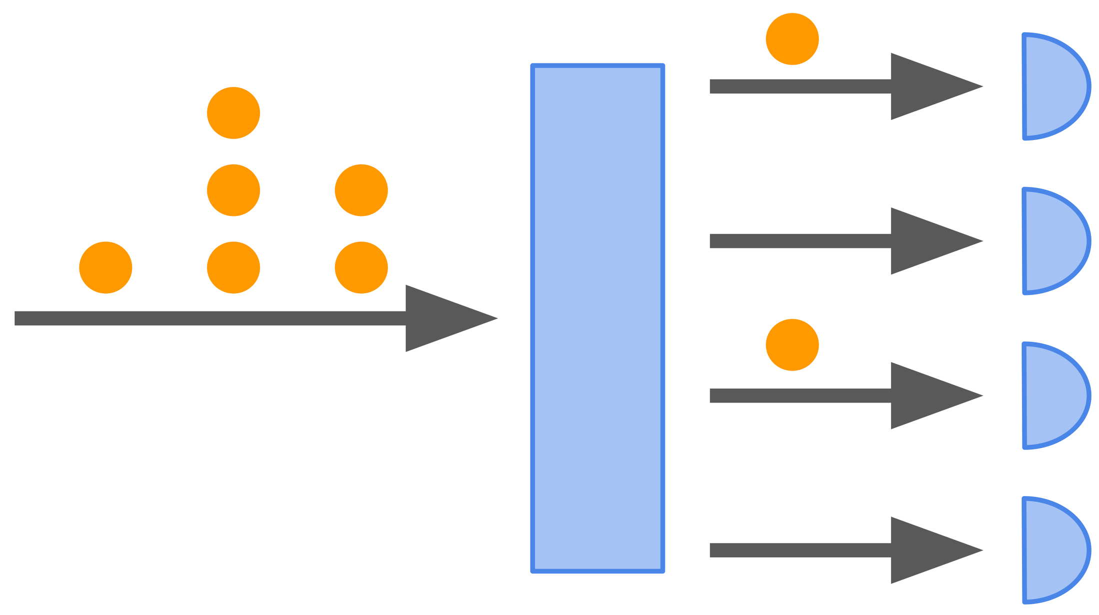
While dark count rate, limited detection effifciency and the finite number of detectors in an array can be accounted for, typical reconstruction methods are shown to struggle with cross-talk at higher photon counts.

Retrieving Photon Statistics

A central problem in quantum photonics is characterizing the statistics of the photon bunches coming from a source.

Typically photon statistics are retrieved using PNR detectors. Alternatively, SNSPD arrays with a spatial demultiplexer setup are used (figure at center).

SNSPDs are employed thanks to their high photon detection efficiency (PDE), which is important to mitigate the distortion due to photon losses.



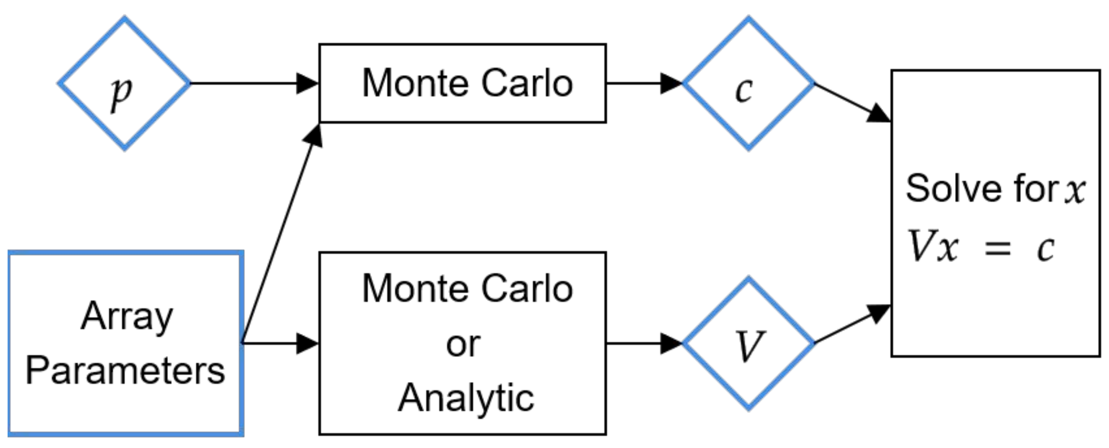
Why integrated SPADs?

SNSPDs require cryogenic temperatures and aren't scalable, since they can only be operated in a cryostat.

On the other hand, integrated arrays of Red-Enhanced SPADs (RE-SPADs) offer greater scalability at room temperature.

RE-SPADs have lower PDE than SNSPDs, but they feature the ability to scale up the number of detectors and thus possibly increase the photon number range of the array.

In this work we study an 8x8 RE-SPAD array with PDE, dark count rate and cross-talk rate taken from [1].

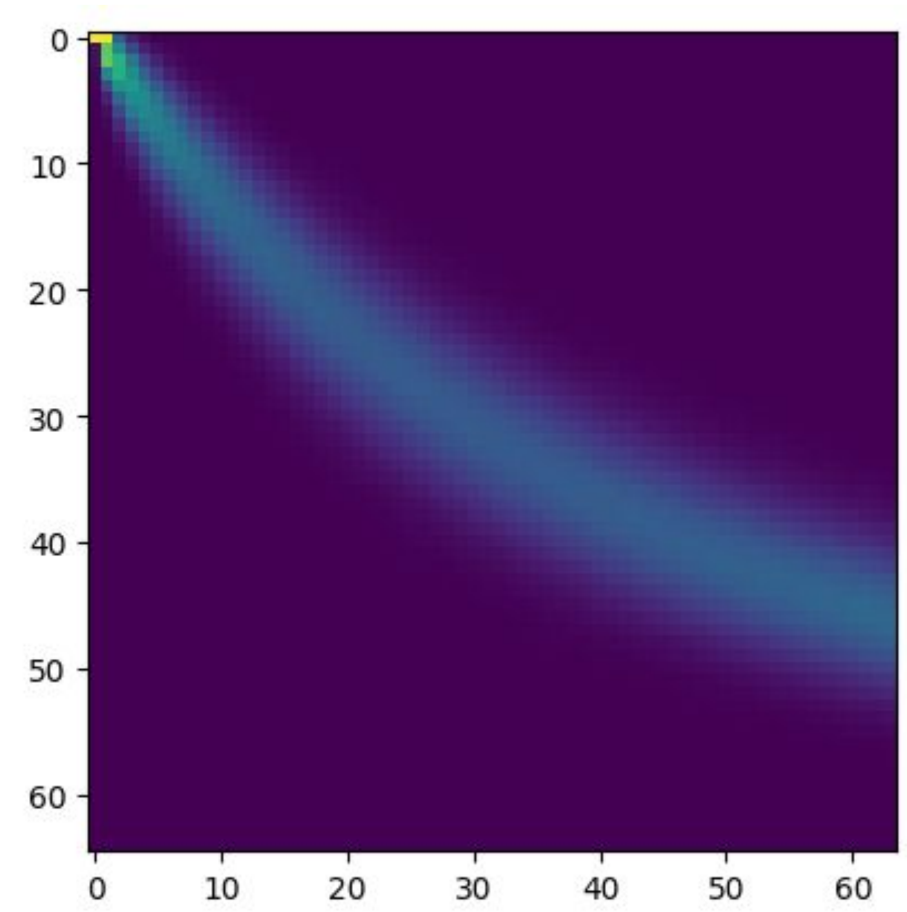


Modeling and Reconstruction Method

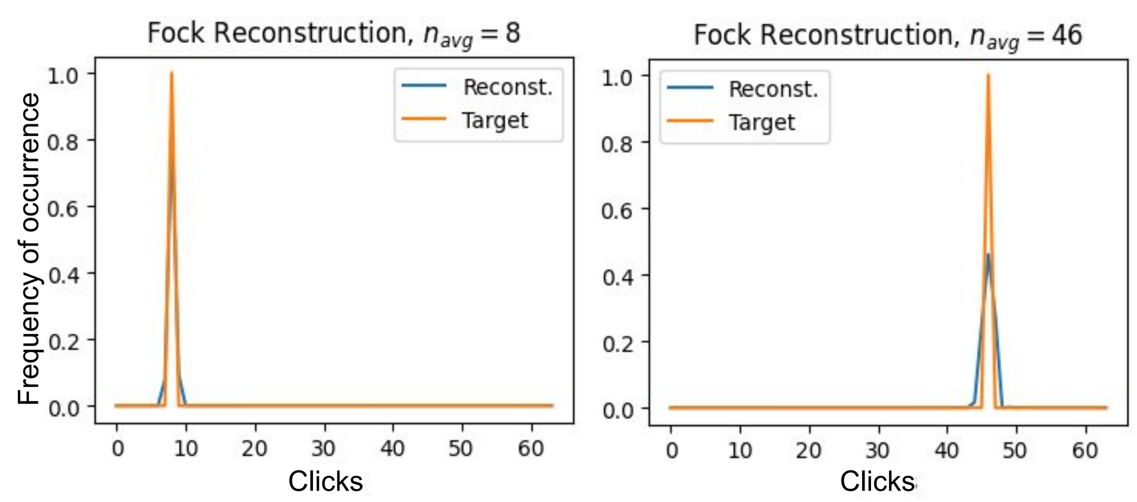
The array is modeled with either an analytic model (up to DCR with no cross-talk) or Monte Carlo simulator (including DCR and cross-talk).

In both cases we obtain a V matrix that relates the probability distribution p of photon bunches and the click distribution c of the SPAD array.

The equation $Vx = c$ is solved through Maximum Likelihood Estimation (MLE) methods.



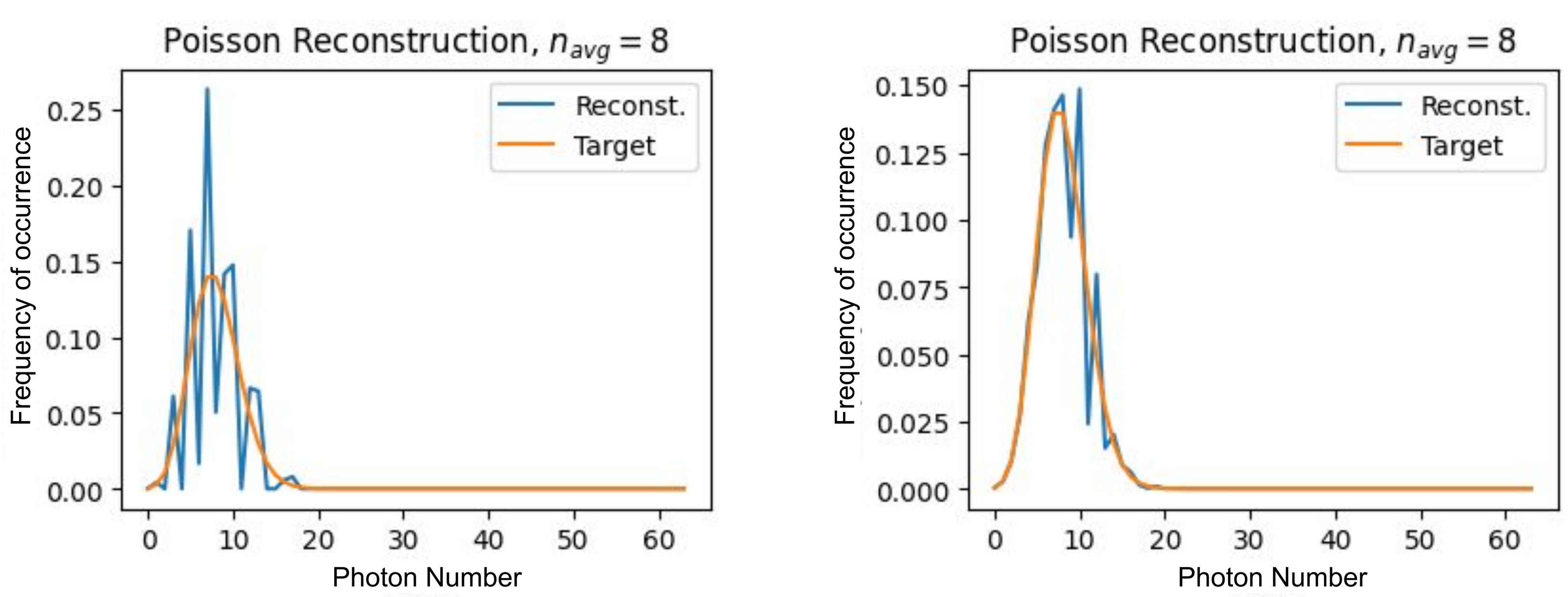
Example of a V matrix obtained through the simulator.



Reconstruction Performance on Pure Fock States

The performance of the reconstruction becomes worse as the number of photons increases, but decent results can still be obtained up to tens of photons.

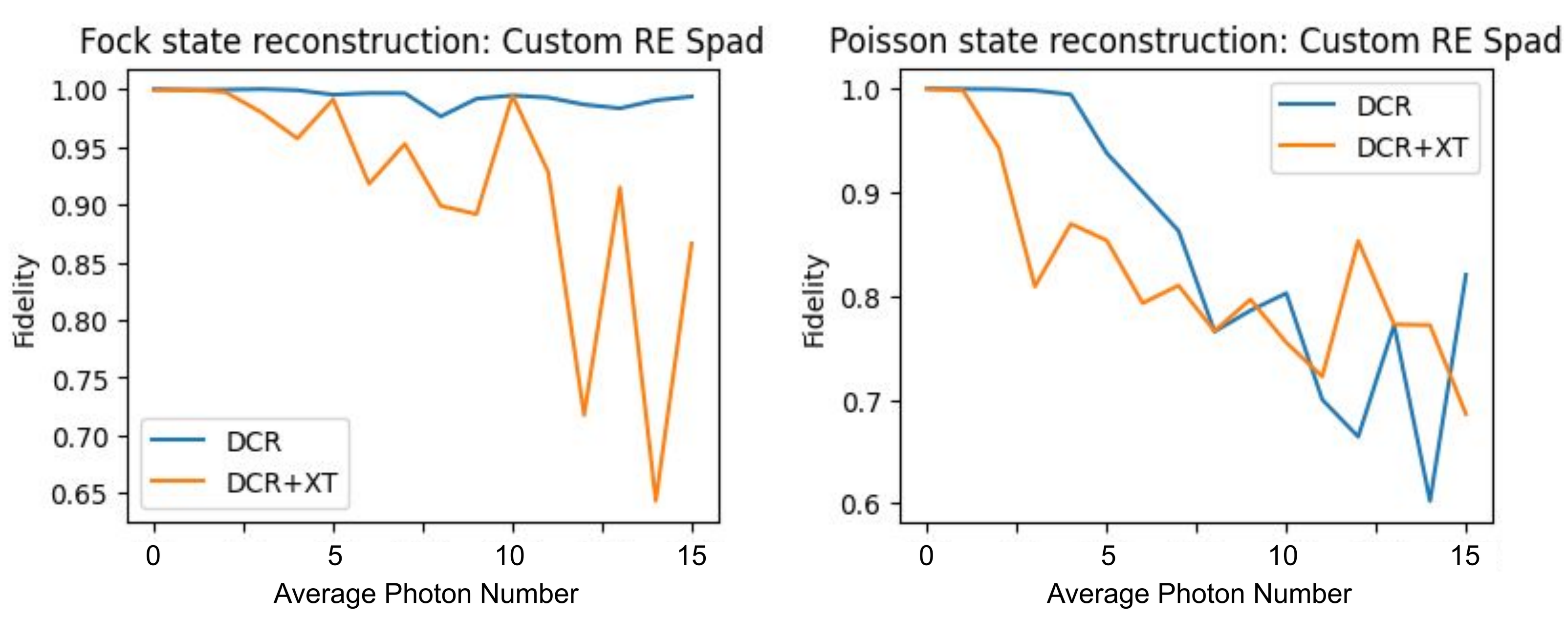
Errors can be ascribed to shot noise on both the V matrix (when not analytic) and the simulated experiment.



Numerical instability in Reconstruction

Broad distributions (Poisson, thermal…) tend to have a numerically unstable reconstruction. This is also due to shot noise primarily: increasing the iterations in the simulator (i.e. performing more measurements) can mitigate this instability.

Pictured: reconstruction with 10^5 iterations versus 10^7 iterations for the same experiment.



Effects of Cross-talk in Reconstruction

Cross-talk is a major contributor in reducing the fidelity of reconstruction. Experimental techniques to reduce cross-talk should be employed.

Fidelity is defined as $\mathcal{F} = \sqrt{p \cdot p_{rec}}$.

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[1] F. Ceccarelli et al., "Red-Enhanced Photon Detection Module Featuring a 32×1 Single-Photon Avalanche Diode Array," in IEEE Photonics Technology Letters, vol. 30, no. 6, pp. 557-560, 15 March15, 2018

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