Multiparameter estimation with single photons

—Linearly-optically generated quantum entanglement beats the shotnoise limit

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1. Introduction

It was previously shown that optical networks using only single photon Fock states, passive linear optics, and single photon detection could achieve post-classical sensitivity for single-parameter estimation when the mode number is small. [1] Furthermore, it was shown that multiparameter estimation could achieve similar results with number-resolving detection. [2] Here, we consider an analogous architecture to the Quantum Fourier Transform Interferometer(QuFTI) proposed in [1] for the estimation of multiple phases simultaneously. Thus, we will see that this yields post-classical sensitivity for multiparameter estimation even for an asymptotically large number of modes. This system is also considered for nondeterministic photon sources and a variety of measurement schemes.

2. Multiparameter Estimation in a Parallel QuFTI

We consider an analogous architecture to the QuFTI proposed in [1], with single photon inputs in each mode, but instead of a single phase, we estimate multiple independent phases simultaneously. The optical unitary investigated is given by $\hat{U} = \hat{V}\hat{\Phi}\hat{V}^{\dagger}$, with $\hat{V}$ being the quantum Fourier transform and $\hat{\Phi}$ being a diagonal array of d phases. The quantum Cramér-Rao bound (QCRB) limits the uncertainty in our measurement and in this case is given by:

$$|\Delta\varphi|^2 \geq d(m-d+1)/(8v(m-d))$$

where $|\Delta\varphi|^2$ is the variance, d the number of phases, m the number of modes, and v the number trials.

3. Measurement Strategies

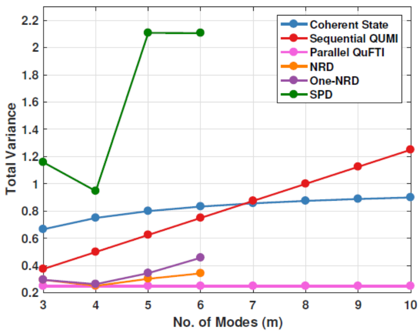

Figure 1: Comparison of variance of Measurement Strategies showing an asymptotic improvement for the Parallel QuFTI over the Coherent State. This is nearly achieved for NRD and One-NRD.

To demonstrate the benefit of our system, we consider additional metrology setups where all are restricted to use the same number of photon resources.(See Fig. 1) The classical case is represented by an uncorrelated coherent state. We also consider a repeated use of a quantum uniform interferometer (Sequential QUMI). We compare also the sensitivity achieved with all single photon detectors (SPD), all number resolving detectors (All NRD), and one number resolving detector with the remaining detectors being single photon detectors (One NRD) against the QCRB for our scheme (Parallel QuFTI).

3. Probabilistic Photon Sources

Although single-photon production has greatly advanced in recent years, many production techniques such as spontaneous parametric down conversion (SPDC) are probabilistic. Thus, we consider a scattershot input similar to [3] where there is a source in each input mode that generates a photon pair. One photon enters the interferometer while the other is detected to herald its twin. We numerically consider a 4 mode, 3 phase Parallel QuFTI which—as seen below—can still outperform a lossless coherent state at around 50% efficiency, or around 65% efficiency for a one-NRD detection scheme.

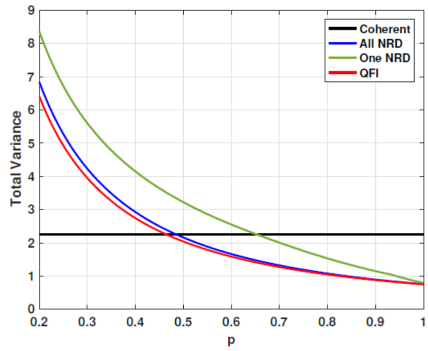

Figure 2: 4-arm, 3-phase example of variance versus photon production probability, assuming all modes have the same probability *p*

4. Conclusion

We have shown a passive, multi-mode interferometer used for multiparameter estimation can demonstrate high sensitivity. Its quantum Cramér-Rao bounds shows an asymptotic constant of 4 times improvement over classical schemes and can achieve this with relatively simple setups and inefficient but heralded single photon sources.

5. References

[1] Motes et al. *Phys. Rev. Lett.* **114** 170802

[2] Pedro M. Duarte et al. *Phys. Rev. Lett.* **114** 070403

[3] Bentivegna et al. *Sci. Ad.*, 1(3)