Comparing Classical Boson Sampling and Stabilised Quantum Circuits for Interferometry

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***Abstract*—Interferometers are devices which use superimposing waves, causing interference to extract information. We propose a method by which quantum information can be obtained and used as a benchmark for quantum circuits, as well as modelling non-linear interferometers. We simulate these with traditional classical methods, then show quantum circuit variants, finally showing how these circuits can be used as benchmarks for qubit coherence, and used to stabilise qubits in quantum circuits.**

I. Introduction

In order to complete these goals, we proceed with the following: first, simulations of interferometers of general interest to familiarise ourselves with the technology, followed by a comparison between unitary sampling and quantum circuit methods, before using the Ramsey interferometry techniques explored with the method outlined in [1] to stabilise the control qubit in our Galton board.

The interferometers of interest are the Mach-Zehnder interferometer (MZI), Michelson interferometer (MI) and the Ramsey Interferometer (RI). We select these interferometers, as conveniently they formulate very similarly, with the main differences being the type of beam splitter used and the position of detectors. These difference correspond to minimal differences in programming, which reduces circuit complexity, and allows for an understanding to be built using simpler mechanisms initially.

II. Mach-Zehnder Interferometer

The Mach-Zehnder interferometer determines a relative phase shift variation between two collimated beams of light. It also has the property that each light path is only traversed once. It consists of two beam splitters, and a mirror.

In our classically computed photonic model, an MZI is a 2-mode interferometer. We use a matrix representation of the beam splitter:

$$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} \tag{1}$$

To encode this as a quantum circuit [2], we use Hadamard gates to represent the 50/50 beam splitters, a single qubit as the initial single photon input, and a unitary operation U(phi) to represent some phase shift.

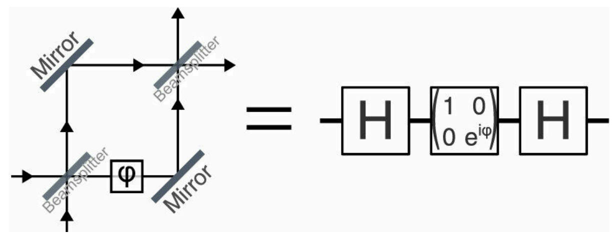

Fig. 1: A quantum circuit equivalent to an MZI. [3]

III. Michelson Interferometer

The Michelson interferometer differs from the Mach-Zehnder by incorporating a single beam splitter and two mirrors that reflect the beams back to the splitter. This creates a configuration where the beams traverse the same path twice, enhancing sensitivity to certain phase shifts. The corresponding quantum circuit can be modeled using similar Hadamard gates for the beam splitter and controlled phase gates to represent reflections and phase accumulations.

In classical simulations, the Michelson interferometer's double pass can be captured by squaring the unitary evolution of a single pass. In the quantum circuit framework, this translates to applying the equivalent gates twice with appropriate phase shifts. This design also allows for modeling decoherence effects over multiple traversals, providing a natural testing ground for qubit coherence under repeated operations.

IV. Ramsey Interferometer and Benchmarking

The Ramsey interferometer is particularly valuable for assessing qubit coherence and dephasing times. By preparing a qubit in a superposition state using a Hadamard gate, allowing it to evolve under a controlled phase shift, and then applying a second Hadamard, the resulting interference pattern provides a direct measure of accumulated phase. Decoherence reduces the visibility of this pattern, enabling quantification of noise effects.

Benchmarking using Ramsey interferometry involves measuring the decay of coherence over time or after application of various noise channels, thus providing a figure of merit for quantum device performance. This benchmarking can be integrated within quantum circuits to dynamically adjust control parameters and optimize gate fidelities.

V. Beating Ramsey limits with deterministic qubit control

From [1], we obtain a method for continuous drive qubit stabilisation.

$$H(t) = \frac{\Delta}{2}\sigma_z + h_y(t)\frac{\sigma_y}{2} \tag{2}$$

In order to demonstrate this in our limited quantum circuits, we use Trotterization to apply this operator as a combination of unitary steps. First order Trotterization will suffice to give a sufficiently accurate unitary operator. For any $H = A + B$, we have that the time evolution operator:

$$e^{-iHt} \approx e^{-iAt}e^{-iBt} \tag{3}$$

Simulations incorporating realistic noise models will help us to confirm that such stabilizing protocols remain robust, highlighting their potential for information processing applications.

We carry this stabilisation out and analyse the results in the Jupyter Notebook extension.ipynb.

VI. Application of stabilising operators to Galton Board

The correction pulse will be:

$$R_y(\delta\theta) \text{ where } \delta\theta \propto \arctan\left(\frac{v_x}{v_y}\right) \tag{4}$$

In order to mimic the time-slicing of the Hamiltonian evolution, we will apply the correction pulse in chunks of $R_y\left(\frac{\delta\theta}{N}\right)$.

Implementation Steps:

Start with the standard Galton circuit:

Initialize ball qubit in center peg.

Use CSWAP-CNOT-CSWAP structure controlled by the control qubit.

Insert stabilization between layers:

After each layer, extract or estimate Bloch components of the control qubit (or infer from expected evolution).

Compute

$$h_y(t) \propto \gamma_2 \cdot \frac{v_x}{v_z} \tag{5}$$

Apply Trotterized slices as

$$U_{\text{stab}} = \prod_{k=0} \exp\left(\boxed{f()} -i\delta t\left(\Delta\frac{\sigma_z}{2} + h_y(t_k)\frac{\sigma_y}{2}\right)\right) \tag{6}$$

This unitary can be approximated by the small rotations:

$$R_z(\Delta\delta t) + R_y\left(h_y\delta t\right) \tag{7}$$

Repeat for each layer:

Execute Galton binning structure

Apply Trotterized stabilization pulses

Move to the next layer.

The above protocol effectively reduces the decoherence of the control qubit by counteracting phase noise through a series of carefully timed pulses. This approach harnesses the quantum Zeno effect by continuously steering the qubit state back to its intended trajectory and "resetting" its evolution, thereby extending the coherence time and improving the overall fidelity of the Galton board simulation.

Demonstrations with fewer shots should indicate that lower sampling rates are sufficient to obtain meaningful stabilization, which is crucial for near-term quantum devices with limited measurement budgets.

VII. Conclusion

We have presented a framework building on classical simulation and quantum circuit implementation of interferometers to benchmark and stabilize qubit coherence. By leveraging interferometric designs such as the Mach-Zehnder, Michelson, and Ramsey interferometers, we bridge traditional optics and quantum information processing techniques in order to improve our Galton Board design.

Our work demonstrates that quantum circuits implementing stabilized interferometric protocols can serve as powerful benchmarks for quantum devices, particularly in the presence of noise and decoherence. The stabilization techniques applied to the quantum Galton board highlight the potential for enhanced control and error mitigation, paving the way for more robust quantum simulations.

Future work includes extending these methods to multi-qubit interferometric configurations and exploring feedback-based real-time stabilization protocols integrated with quantum error correction.

References

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