Quantum Logic Gates on Time-Bin Encoded Photonic Qubits

I.M. Boras Vazquez

Supervisors: Dr. Nir Rotenberg and Jacob Ewaniuk

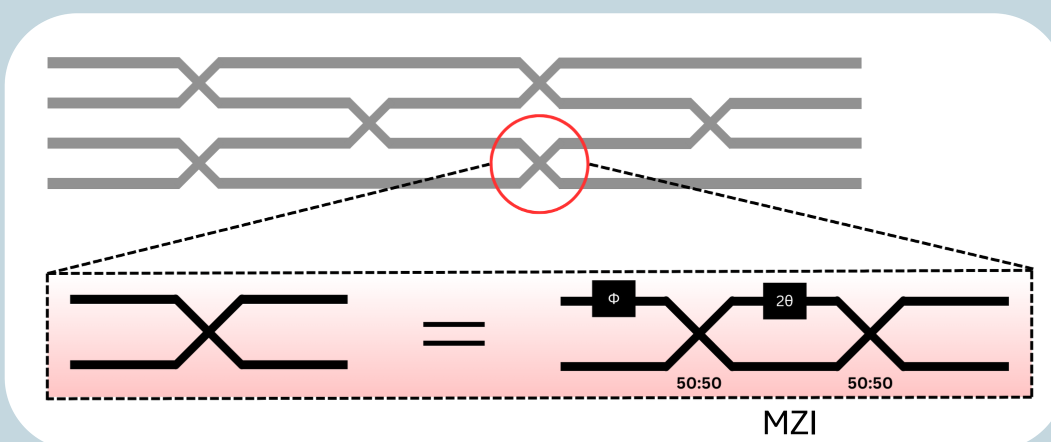
Queen's University

Department of Physics, Engineering Physics and Astronomy

Background and Objectives

Among the various approaches to quantum computing, photonic qubits present themselves as excellent candidates for information processing. Linear unitary transformations are done on photonic qubits by employing an N x N mesh of Mach-Zehnder interferometers (MZIs). These meshes become increasingly large as the number of modes increases. Time-bin encoding allows for these meshes to be simplified and use a singular MZI. Not only does this reduce space but opens the architecture to a range of possibilities.

The Clements spatial mesh is seen below, with an MZI highlighted in red [1]:



The objectives were as follows:

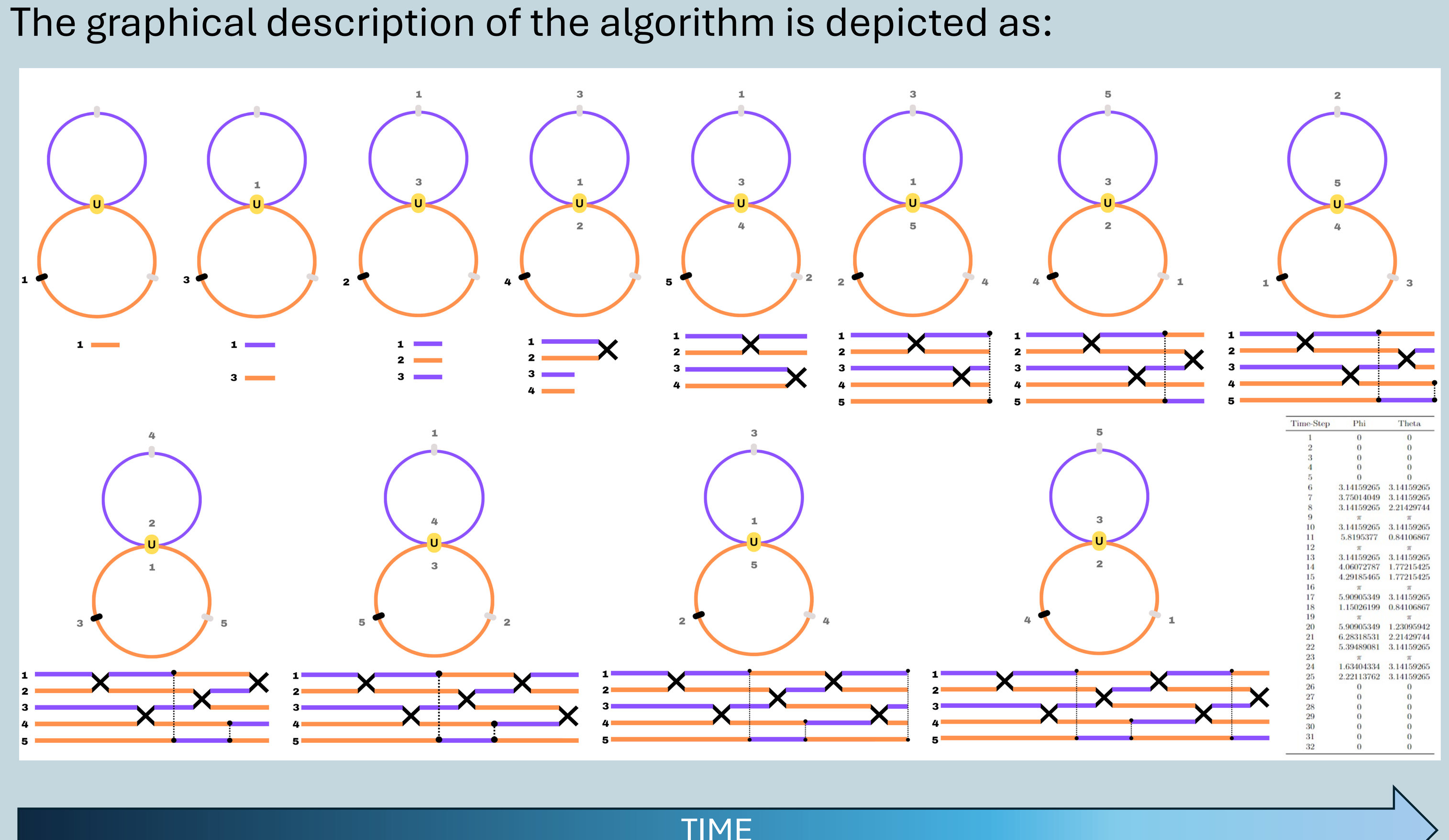
- The model had to employ a time-bin encoded architecture
- The model was to include relevant imperfections to analyze loss in the system
- The algorithm produced had to identify when to apply the necessary phase shifts to apply a CNOT gate
- The algorithm must be able to apply a CNOT gate to the system

Algorithm and Output

The algorithm developed is based on the Clements time-bin configuration. Odd modes are coupled into the system first, starting with mode 1 then 3, then 5, etc. Once all odd modes have been coupled, the even modes are are coupled, beginning with mode 2, then 4, then 6, etc. An extra ancillary (empty) mode is added to the end of the pulse train, allowing for the modes to interfere in the familiar Clements mesh pattern.

The model determines at what time step the necessary phase shifts need to be applied to achieve the desired transformations. The output showing the procedure to apply the CNOT gate can be seen at the end of the graphical depiction of the algorithm.

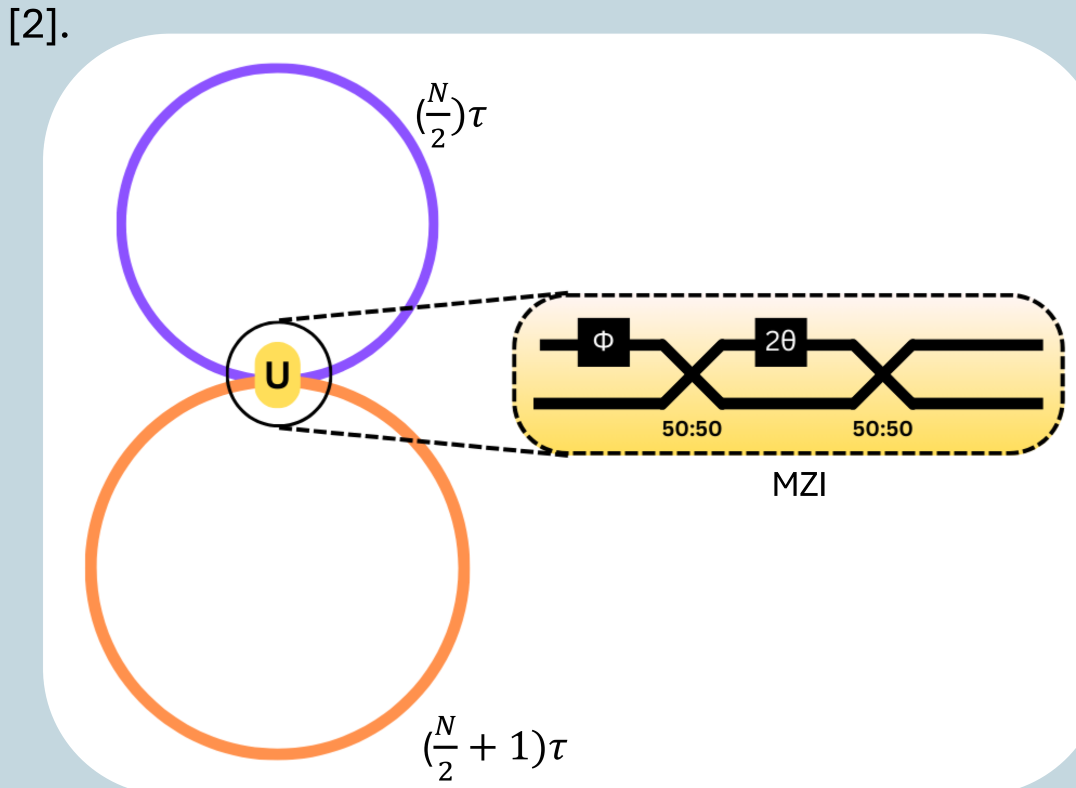
The graphical description of the algorithm is depicted as:



Time-Bin Architecture

The time-bin architecture consists of two fiber-optic cable loops with a Mach-Zehnder interferometer connecting them. The interferometer consists of two phase shifters, each followed by a 50:50 directional coupler. The interferometer is denoted by the yellow notch labelled U.

The modes are first coupled to the bottom loop, and the interferometer is used to apply necessary transformations and couple modes to different loops. The system is described in terms of time-bins, τ. The top loop has a fiber-optic cable length of $(\frac{N}{2})\tau$ and the bottom has a length of $(\frac{N}{2}+1)\tau$. The difference in length allows for the Clements spatial mesh to be reproduced [2].



Conclusions

A realistic time-bin encoded architecture was produced. The algorithm is capable of reproducing any even N x N Clements spatial mesh. The model identifies at what time-step the necessary phase shifts must take place in order for the desired unitary transformation to be performed.

All relevant losses in the system were considered when applying the CNOT gate. A photon width of 1 ns was assumed. It was determined that to reproduce a CNOT gate, 1.47 meters of fiber-optic cable are necessary. An unconditional fidelity of 0.01 was observed in each of the correct input-output state pairs. The conditional fidelities for the system were also calculated, these yielded the expected value of 1.

The model created reproduces a realistic time-bin architecture and can perform the necessary transformations to apply unitary transformations on photonic qubits.

Limitations and Future Work

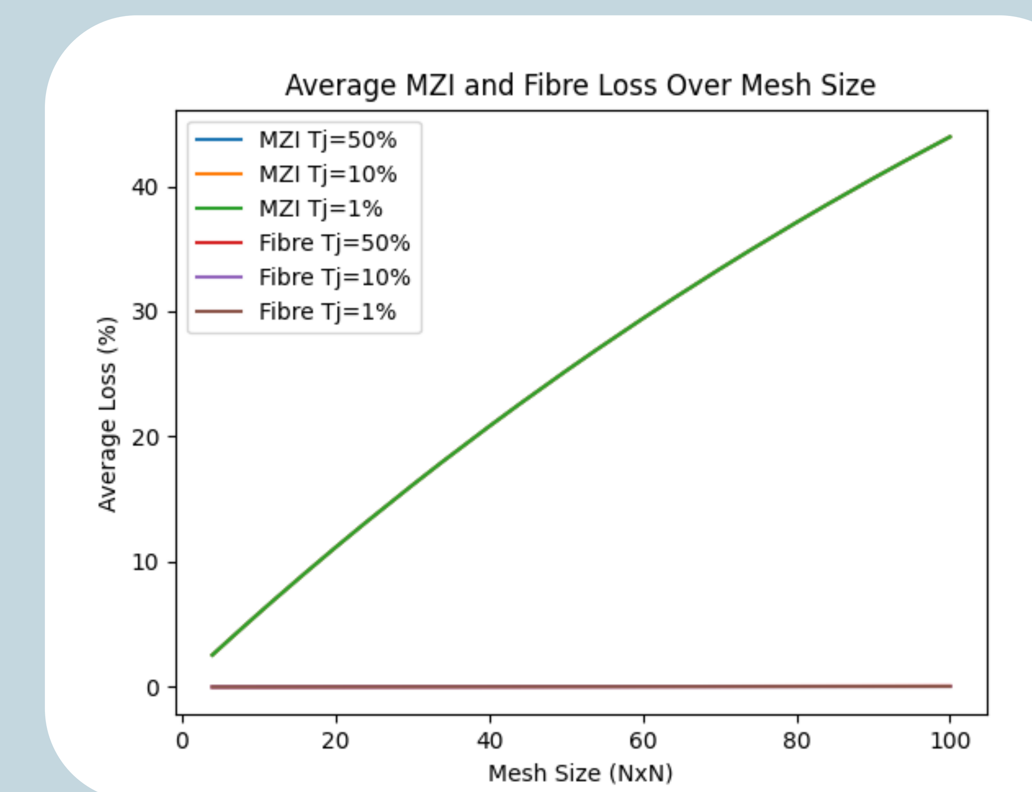
- **Extension to odd modes:** The design is currently limited to even modes, thus can only produce N x N size meshes. Extending the algorithm to odd modes would allow for the creation of any odd N x M mesh
- **Application of other quantum logic gates:** The algorithm can be tested with other quantum logic gates to observe the output and how losses in the system affect the gate's fidelities
- **Code integration:** The algorithm can be combined with existing scripts used to decode phases from unitary matrices to avoid the for users to manually input the desired phase shifts
- **File save system:** The necessary procedure as well as the circuit details, such as fibre lengths, can be saved into a file for better data collection

Loss and Scaling

The time-bin, τ, is given by $\tau = T_P + T_J + T_S$, where:

- **Photon Width (T_P):** Width of photon, the value used was 1 ns.
- **Time Jitter (T_J):** The expected shift of the photon within its time-bin, for analysis purposes, T_J was assumed to be 1%.
- **Switch time (T_S):** Time for the switch (Mach-Zehnder interferometer) to rise. A rise time of 20 ps was used.

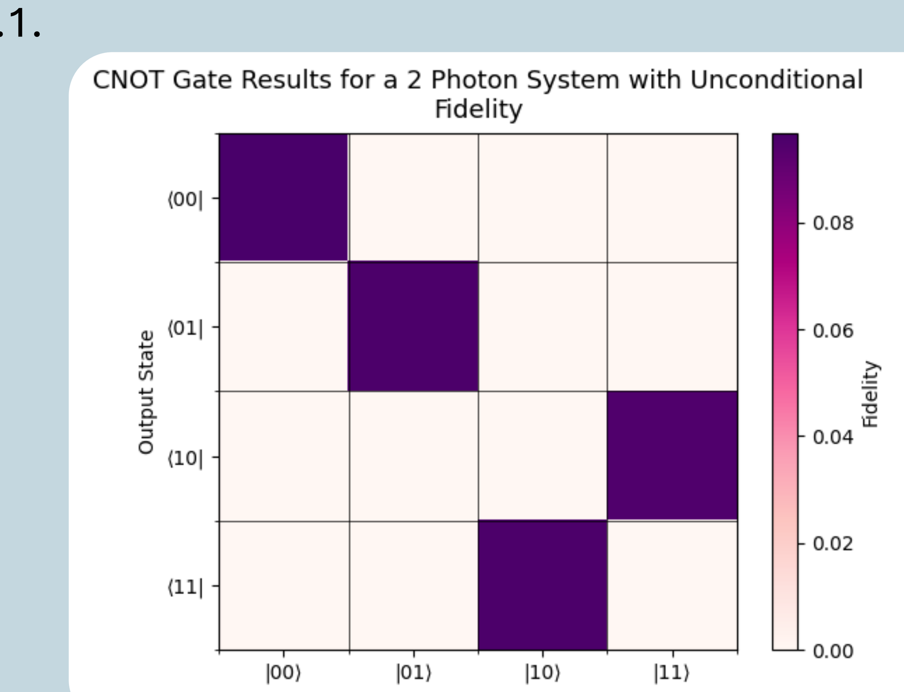
The loss due to the Mach-Zehnder interferometer (MZI) was assumed to be 0.5 dB, while the fiber-optic cable loss was determined as 0.2 dB/km. The effects of each component with different time-jitter values is graphically shown below; the loss due to MZIs dominates and the fiber loss becomes seemingly negligible.



The unconditional fidelity of the applied CNOT gate was calculated and is shown below [3]. The expected outputs are clearly observed and have an unconditional fidelity of 0.1.

The conditional fidelities of the applied CNOT gate were also calculated, yielding the expected value of 1.

The constructed system includes relevant losses, and reproduces expected results.



References

[1] W. R. Clements, P. C. Humphreys, B. J. Metcalf, W. S. Kolthammer, and I. A. Walmsley, "Optimal design for universal multiport interferometers," Optica, vol. 3, pp. 1460–1465, Dec. 2016. Publisher: Optica Publishing Group.

[2] W. R. Clements, Linear Quantum Optics: Components and Applications. Thesis, University of Oxford, United Kingdom, 2018

[3] J. Ewaniuk, J. Carolan, B. J. Shastri, and N. Rotenberg, "Imperfect Quantum Photonic Neural Networks," Advanced Quantum Technologies, vol. 6, no. 3, p. 2200125, 2023. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/qute.202200125.