Analysis of an Analog Optical Neural Network

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Optical Neural Networks

- Neural networks: powerful machine learning model, but energy consuming [1]
- Potential solution: Optical Neural Networks (ONN) [2]
- Requirements: Reprogrammable, Energy Efficient, Computational Speed

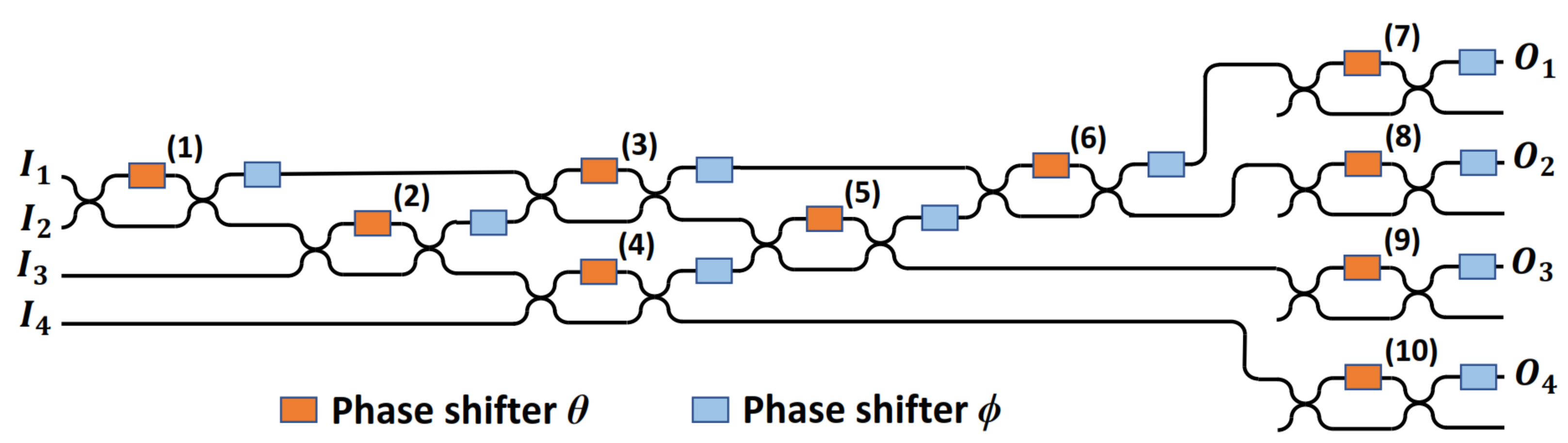

Figure 1. Schematic of the ONN consisting of ten MZIs, each of which configured with two phase shifters.

Benefits

- **Reprogrammable:** Thermal phase shifters allows for full reconfiguration of optical chip (i.e., change weights $[W]_{4\times4}$ in Fig. 2)
- **Energy efficient**: Inherent parallelism present in optics, can efficiently compute matrix multiplication using waveguides and beam splitters [3]
- **Computational Speed:** processes matrix multiplication in linear time as opposed to quadratic time for GPUs [4].

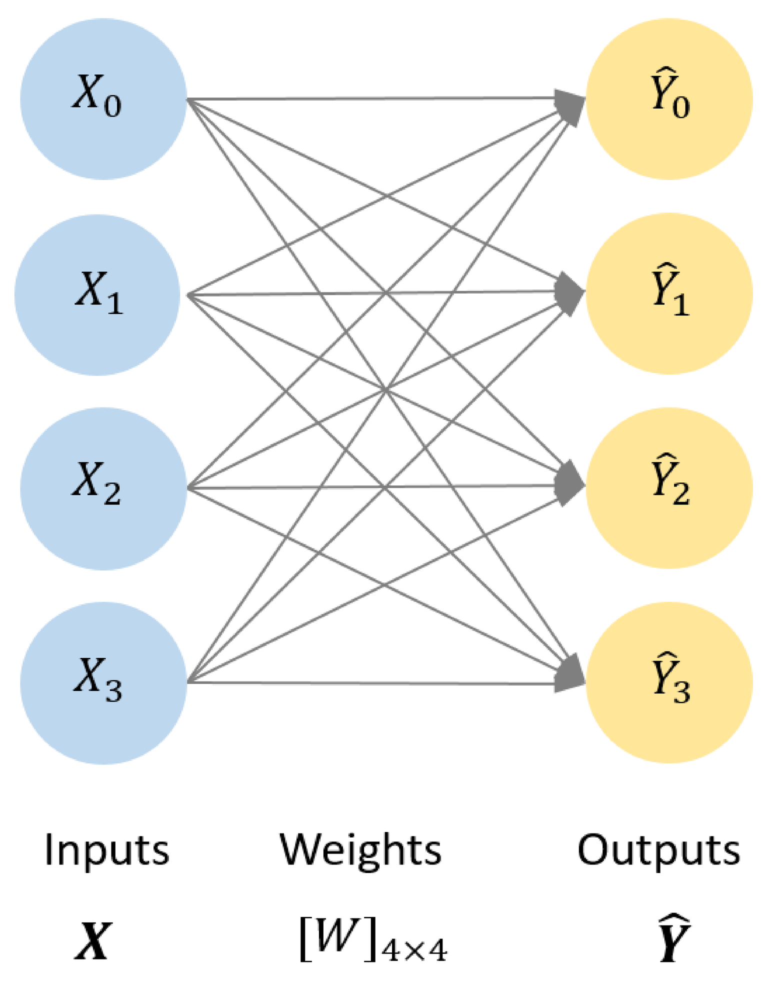

Figure 2. Schematic of a single layer neural network.

Forward Propagation

Inputs: $\boldsymbol{X} \in R^4$

Ground Truth: $\boldsymbol{Y} \in R^4$

Output: $\hat{Y}_j = \Sigma_{i=0}^{3} \mathrm{X_j} * \mathrm{W_{i,j}}$ for $j = 0,1,2,3$

Matrix Notation: $\hat{\boldsymbol{Y}} = \mathbf{X} * [W]_{4\times4}$

Prediction: argmax($\hat{\boldsymbol{Y}}$)

Stochastic Optimization Algorithm

- Start with 20 random phases θ_i and ϕ_i for $i = 1,2,3,\ldots,10$
  Check accuracy
- While accuracy is smaller than required accuracy:
  - Pick one random phase
  - Set it to a random value, recheck accuracy
  - If accuracy increased:
    Keep changed phase
  - Else:
    Revert back to previous phase

Condition for Accuracy

Neural Network correctly classifies a sample if:

$$argmax(\hat{\boldsymbol{Y}}) == argmax(\boldsymbol{Y})$$

Extra Condition for Accuracy

Extra condition, to consider experimental phase error:

$$\hat{Y}_{Max} - \hat{Y}_{Second\ Max} > \zeta$$

Dataset

- Created synthetic dataset to characterize single layer ONN.
- Dataset is linearly separable, i.e., perfectly classifiable.

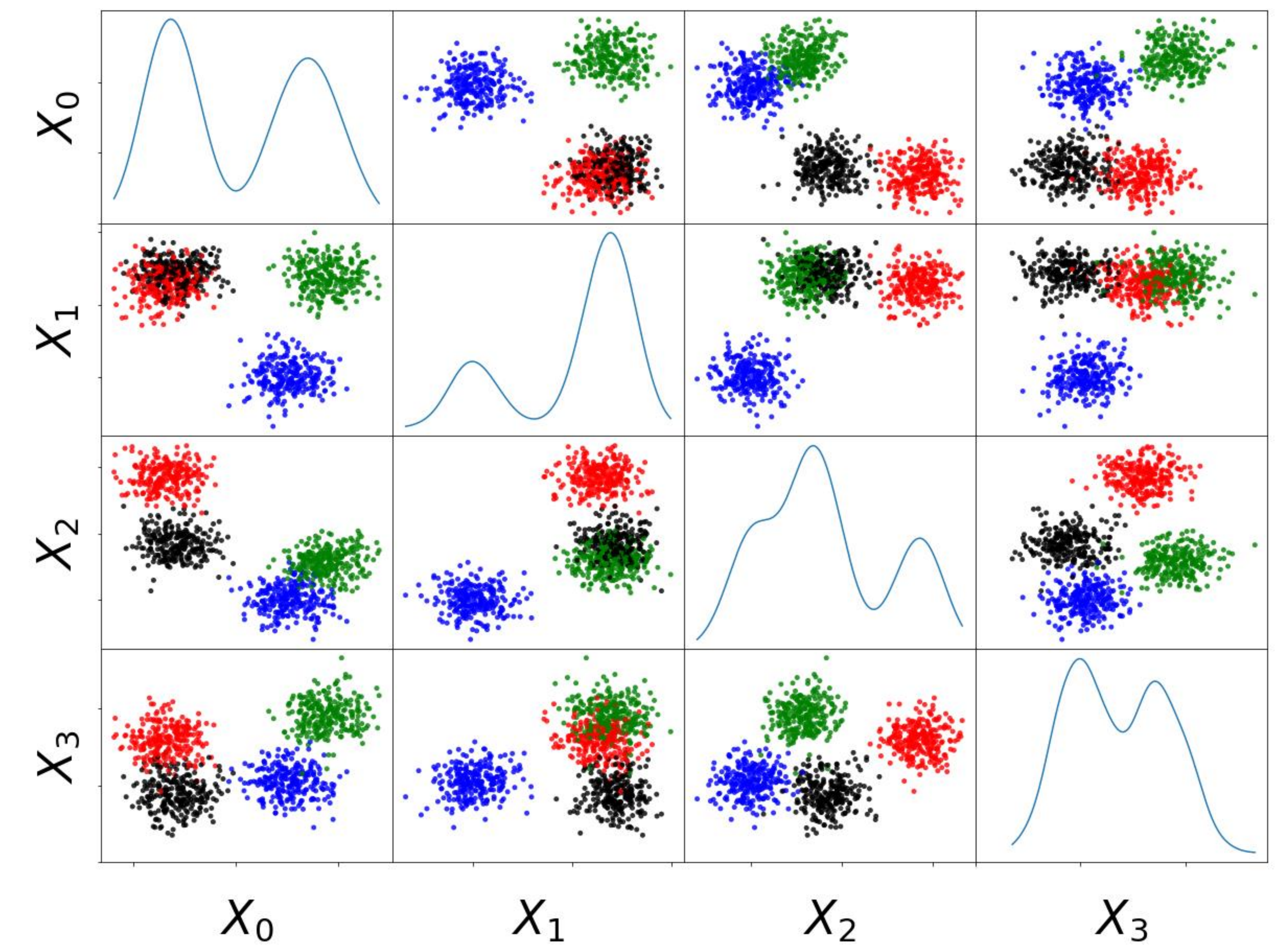

Figure 3. Scatter plot of the dataset . X_j, for $j = 0, 1, 2, 3$ are the features of each class indicated by the different colors.

Sources of Phase Error

- Thermal crosstalk between MZIs
- MZI voltage source inaccuracies
- Silicon photonic fabrication process variations

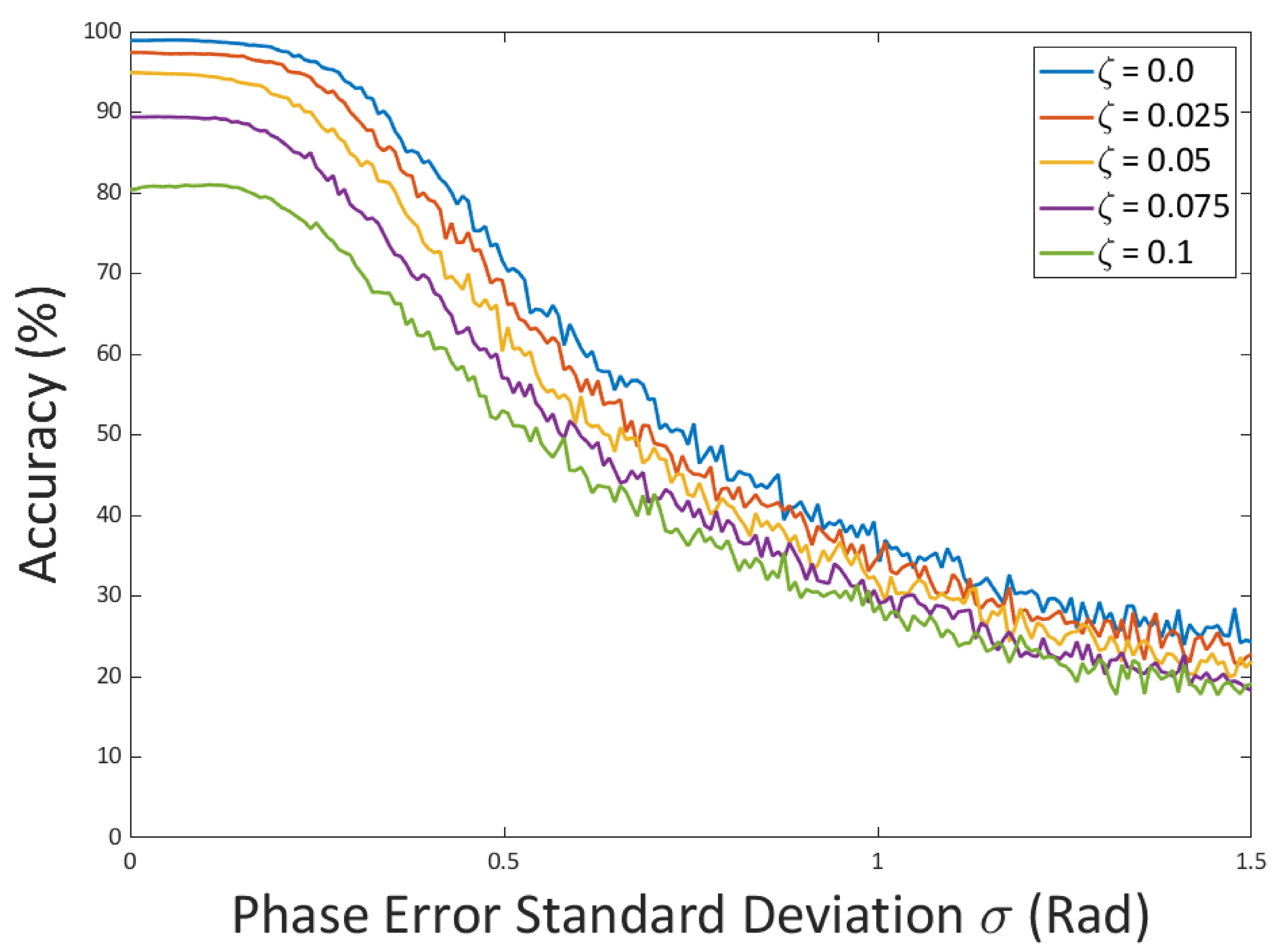

Figure 4. Simulation results of effect of phase noise on accuracy. Increasing the threshold zeta decreases the accuracy of the neural network.

Conclusion

- A single layer ONN was theoretically investigated.
- Using a stochastic optimization algorithm, the optimal phases for the ONN were determined.
- An arbitrary four feature four target dataset was classified.
- The effect of phase errors on the classification accuracy of the ONN was analyzed.
- **Future work**: more complex ONNs with higher energy efficiency and lower phase errors.

Contact

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References

1. "GPU-Based Deep Learning Inference: A Performance and Power Analysis." Nvidia Whitepaper (2015)
2. Tyler W. Hughes, Momchil Minkov, Yu Shi, and Shanhui Fan, Optica **5**, pp. 864-871 (2018)
3. M. Reck, A. Zeilinger, H. J. Bernstein, and P. Bertani, Phys. Rev. Lett. **73**, pp. 58–61 (1994)
4. Ian A. D. Williamson, Tyler W. Hughes, Momchil Minkov *et al*, arXiv:1903.04579v1m (2019)
5. Michael Y.-S. Fang, Sasikanth Manipatruni, Casimir Wierzynski *et al*, Opt. Express **10,** pp. 14009-14029 (2019)
6. F. Shokraneh, M. S. Nezami, and O. Liboiron-Ladouceur, in Asia Communications and Photonics Conference, pp. 1-3 (2018)