Analysing the Robustness of Controllers for Quantum Spin-1/2 Networks

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Background

Quantum technologies have very promising applications in networking, simulation, sensing and computing. However, decoherence, arising from unwanted interactions of a device with environment, and fabrication and control signal uncertainties present a particular challenge for Noisy Intermediate Scale Quantum devices. There are two popular ways to mitigate noise and errors and achieve fault tolerance: Error correction/mitigation algorithms and Robust Quantum Control solutions. **Error Correction algorithms and Quantum Control solutions are two complementary approaches used to tackle the problem of noise in Quantum technologies.**

Quantum Control deals with the study of how the classical world interacts with quantum systems and optimization of these quantum systems to enable useful performance in information processing, sensing and metrology. In this project we work on **analysing robust quantum controllers for information transfer on quantum spin-1/2 networks.**

Aim

The aim of this project is to **investigate the robustness of the controls** schemes achieved from previous gradient-based optimization experiments computationally by calculating the **log-sensitivity** of the controllers w.r.t. structured perturbations: **'delta' S,** with structure **S** and the strength of the perturbation **'delta'.**

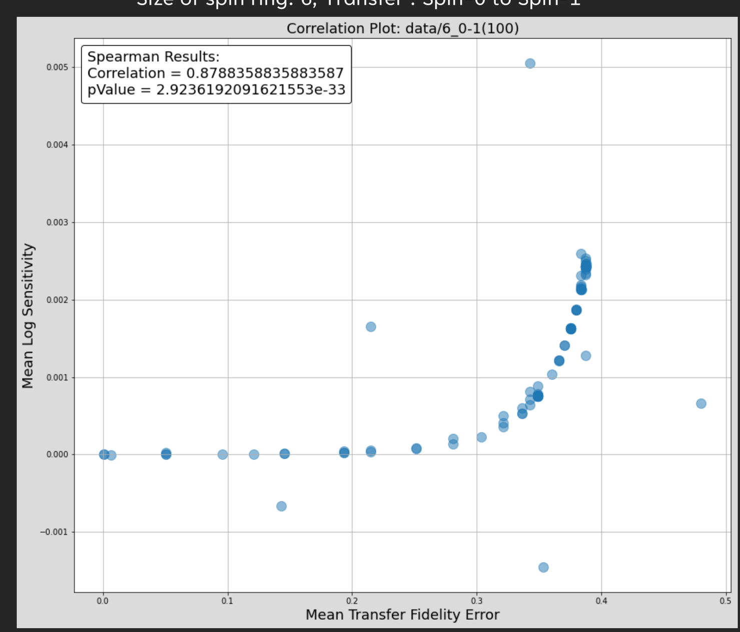
Methodology

- First, we calculated the **transfer fidelity error** (or infidelity) and the log-sensitivity of the top 100 controllers obtained from previous optimization experiments. **A dataset of 1000 controllers found via gradient-based optimal quantum control for information transfer in spin-1/2 XX rings was used [1].**
- To further **analyse the quality and robustness of the controllers**, we took the average fidelity error and average log-sensitivity across 1000 random structured perturbations. And also calculated the **Spearman correlation coefficient** for the average fidelity and the average log-sensitivity to assess their statistical dependence.
- For the next part, we analysed the structure of the spin rings by putting noise (delta:0-10%) on each spin and coupling individually and calculating **the log sensitivity of the delta curve for each spin and coupling.**

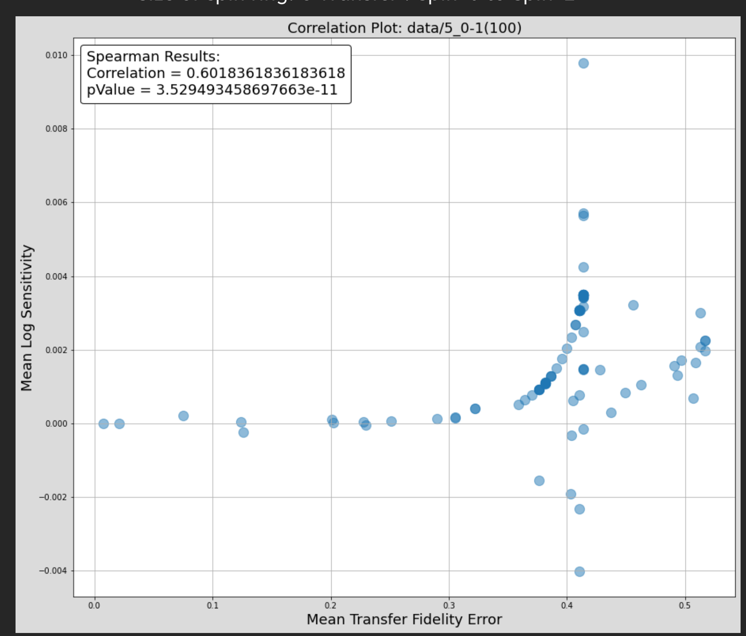
Results

In the project, we looked through spin rings of size 5 and 6, considering the transfer of information from spin 1 to 2,3 (for 5-spins) and spin 1 to 1,2,3 (for 6-spins). Following plots show the statistical dependence of the transfer fidelity and log sensitivity of the controllers using spearman correlation coefficients:

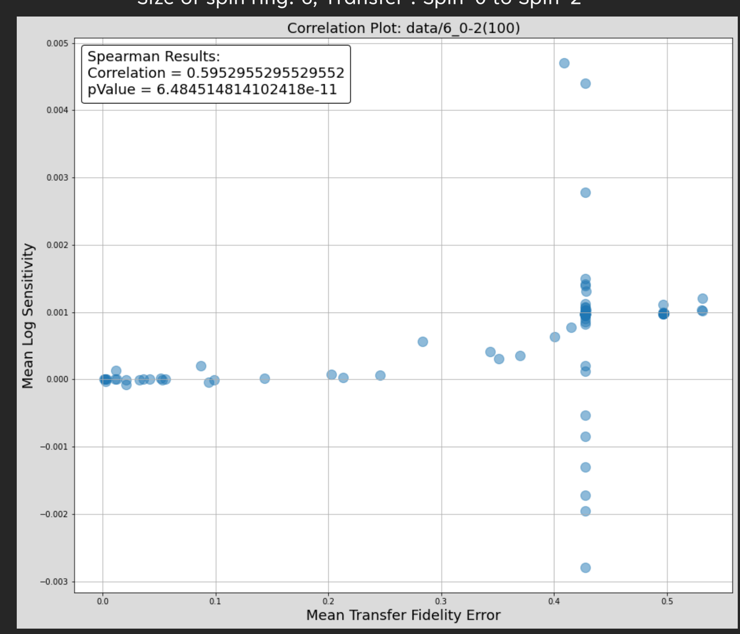
Size of spin ring: 6, Transfer : Spin-0 to Spin-1



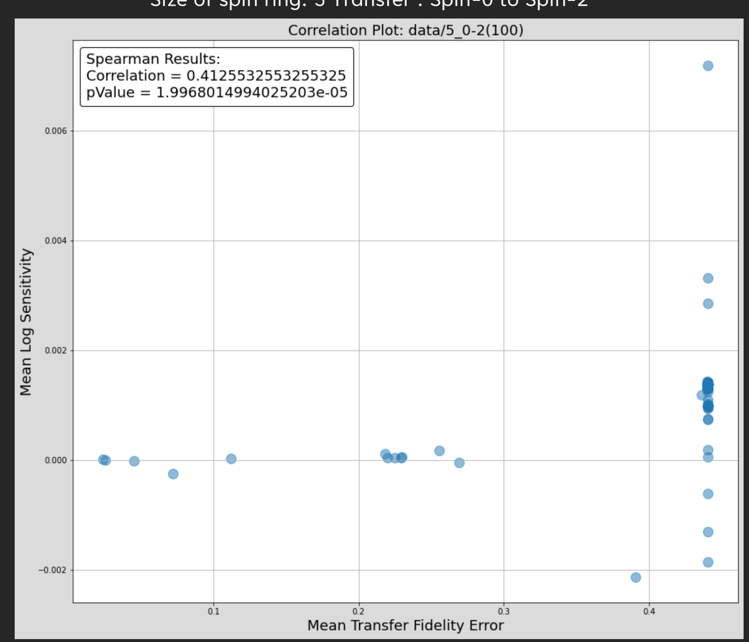
Size of spin ring: 5 Transfer : Spin-0 to Spin-1



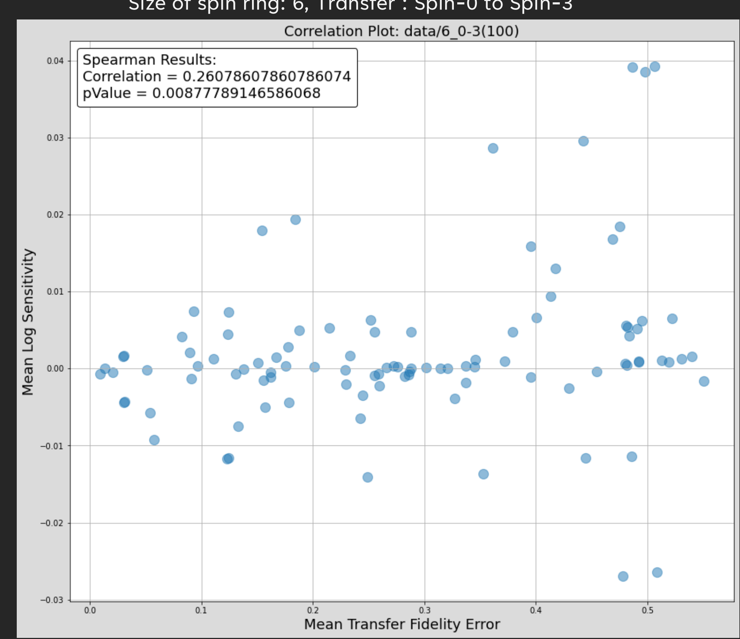
Size of spin ring: 6, Transfer : Spin-0 to Spin-2



Size of spin ring: 5 Transfer : Spin-0 to Spin-2

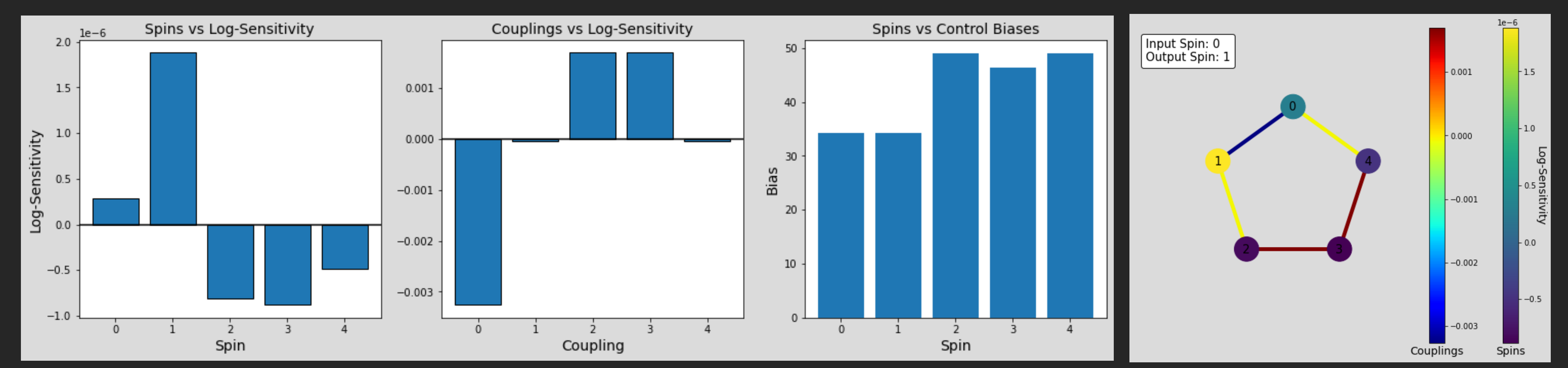


Size of spin ring: 6, Transfer : Spin-0 to Spin-3



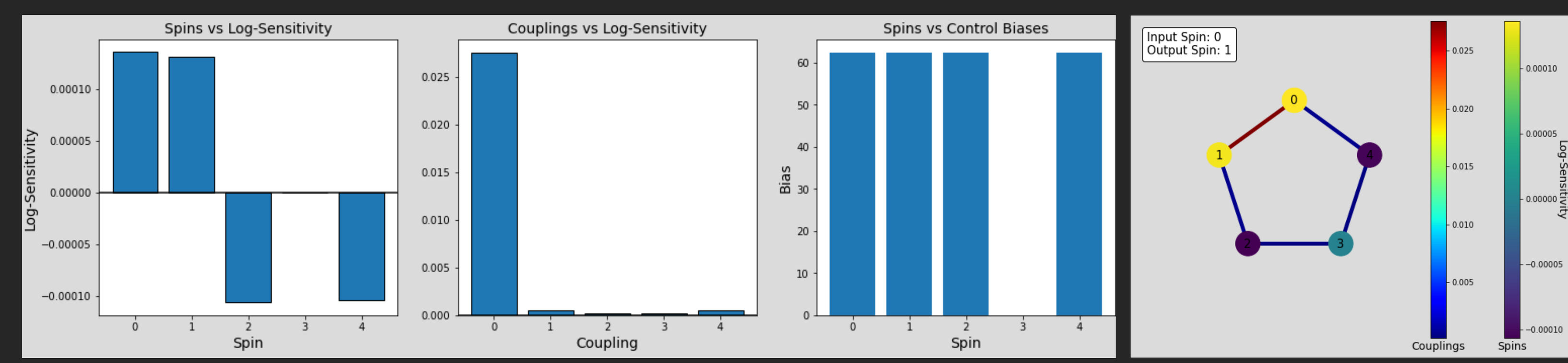
Following are the results of structural analysis of some of the individual controllers:

Size of spin ring: 5, Transfer : Spin-0 to Spin-1, Controller: 51



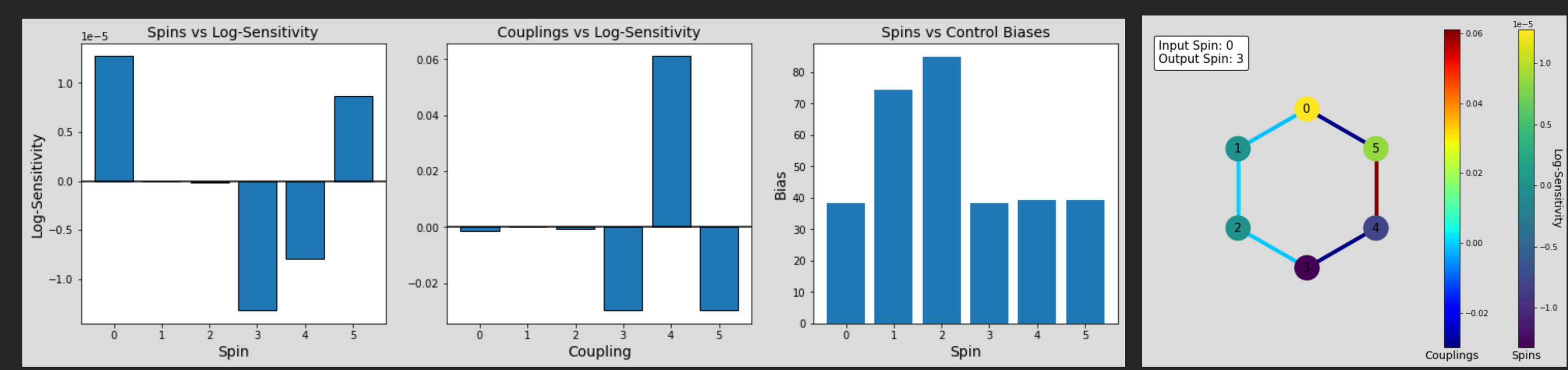
This particular controller is an example of how controllers with slightly lower fidelity tend to be more robust than controllers with high fidelity.

Size of spin ring: 5, Transfer : Spin-0 to Spin-1, Controller: 1



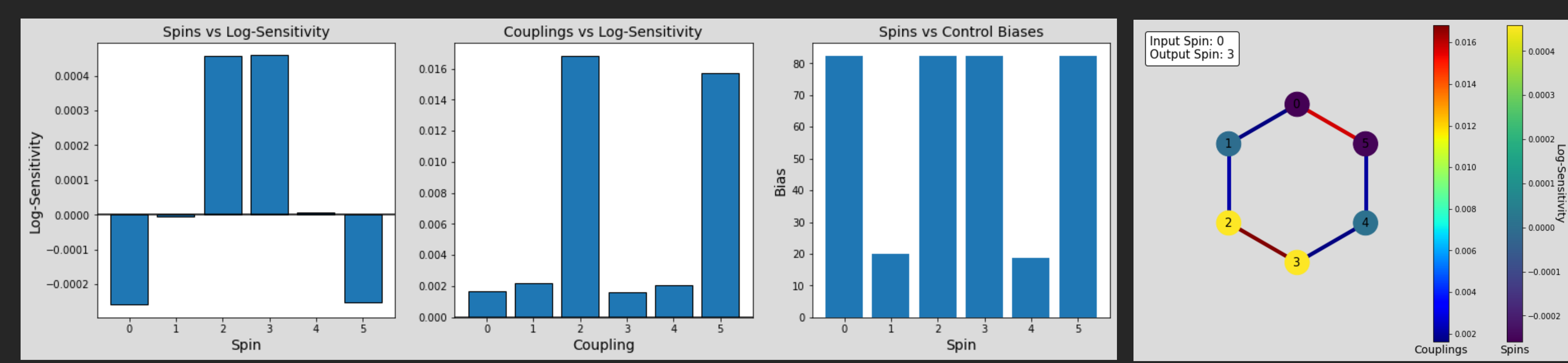
This particular controller is an example of how controllers with very high fidelity tend to be very sensitive to noise.

Size of spin ring: 6, Transfer : Spin-0 to Spin-3, Controller: 3



This controller is an example of how some controllers with high fidelity are also very robust.

Size of spin ring: 6, Transfer : Spin-0 to Spin-3, Controller: 1



In this controller, we can see how there is a symmetry in log-sensitivities of spins and couplings. This maybe be a part of our future work.

Conclusion

- The Spearman Correlation coefficient for our data ranges from **0.26** to **0.87** which **demonstrates that there is some statistical dependence between transfer fidelity and log sensitivity.**
- Results indicated that **very high fidelity controllers are not always robust**, but if the fidelity of the controllers is **a bit lower, they tend to be more robust.**
- The **couplings which are involved in the transfer** of information are **highly sensitive** to noise.
- There are also some cases where **the couplings symmetrically opposite** to the couplings which are involved in transfer have **high sensitivity** to the noise.

References

[1] FC Langbein, SG Schirmer, EA Jonckheere. **Energy Landscape Control Robustness Dataset**. (In preparation).

[2] F. C. Langbein, S. Schirmer and E. Jonckheere, "Time optimal information transfer in spintronics networks," 2015 54th IEEE Conference on Decision and Control (CDC), 2015, pp. 6454-6459, doi: 10.1109/CDC.2015.7403236.

[3] Shermer, Sophie & Jonckheere, Edmond & O'Neil, Sean & Langbein, Frank. (2018). Robustness of energy landscape control for spin networks under decoherence.

[4] Khalid, Irtaza and Weidner, Carrie A. and Jonckheere, Edmond A. and Shermer, Sophie G. and Langbein, Frank C. "Statistically Characterising Robustness and Fidelity of Quantum Controls and Quantum Control Algorithms". https://arxiv.org/abs/2207.07801