Protecting Quantum States in Quantum Computing from Noise through Optimized Dynamical Decoupling

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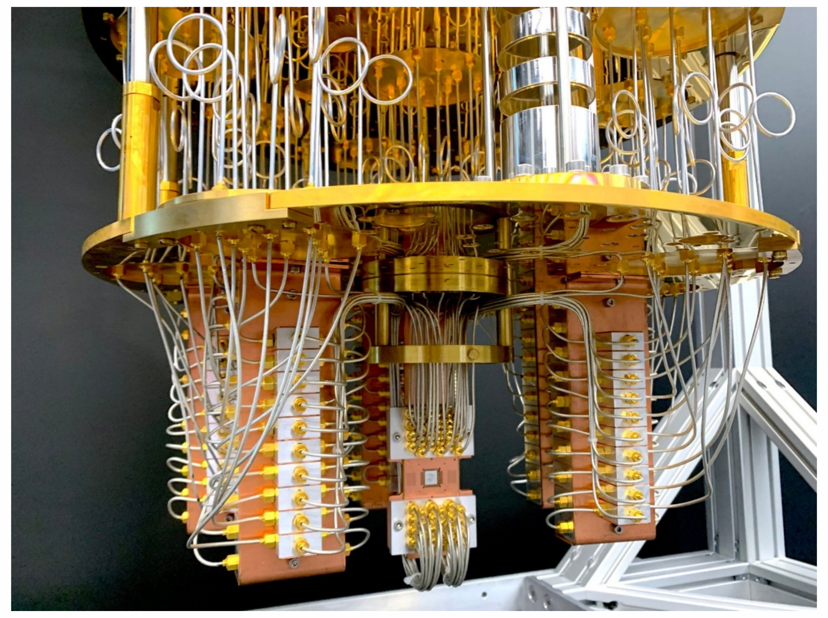
Motivation & Background

Protecting quantum computers from noise is vital to performance.

$$H_0 = \hbar\omega_0 \frac{\sigma_z}{2} + \sum_k \hbar\omega_k b_k^\dagger b_k + \sum_k \hbar\sigma_z (g_k b_k^\dagger + g_k^* b_k)$$

$$\rho_S(t) = Tr_B\{\rho_{tot}(t)\} \qquad \rho_{01}(t) = e^{i\omega_0(t-t_0) - \Gamma_0(t-t_0)}\rho_{01}(t_0)$$

These equations highlight the impact of noise on a quantum state. The state $\rho_{tot}(t)$ is a ½-spin system immersed in a bath described by H_0. The value of $\Gamma_0(t-t_0)$ is purely real and results in the decay of the off diagonals of $\rho_S(t)$, rendering quantum computing impossible.[1]



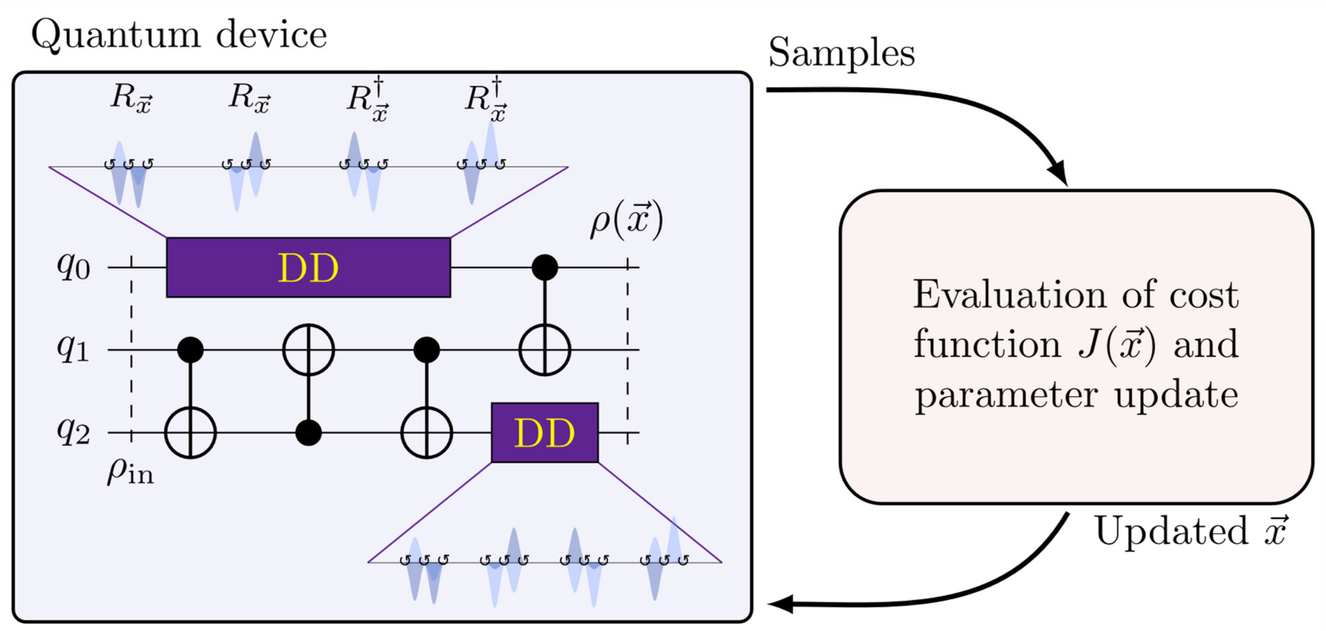
Method

Quantum states can be protected using dynamical decoupling (DD). The challenge is knowing what pulse sequence to use to effectively suppress noise.

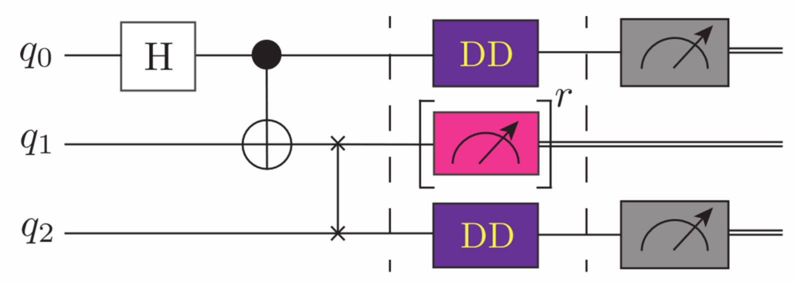
$$H(t) = H_0 + H_{rf}(\omega_0, t) \qquad \tilde{\rho}_{01}(t_N) = e^{-i\omega_0(t_N-t_0) - \Gamma_P(N,\Delta t)}\tilde{\rho}_{01}(t_0)$$

In an idealized model, introducing monochromatic alternating magnetic field applied at resonance, the off diagonals can be protected. Γ_P approaches 0 as Δt decreases which protects the quantum state.[1]

Fig 1. To find the best DD sequence, a classical optimizer can be employed. This technique is called learning dynamical decoupling (LDD).[2]



Method Cont.



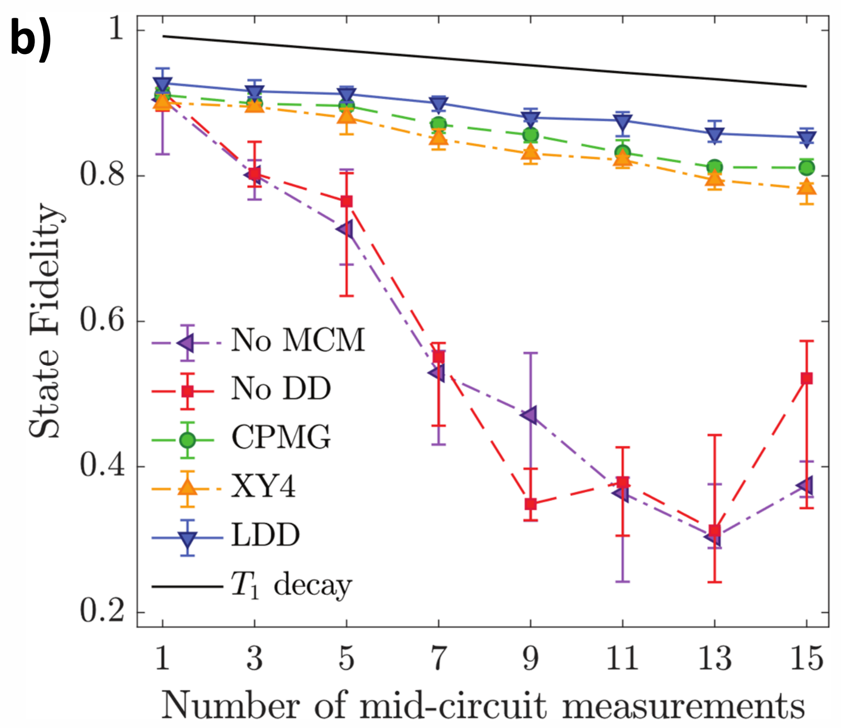
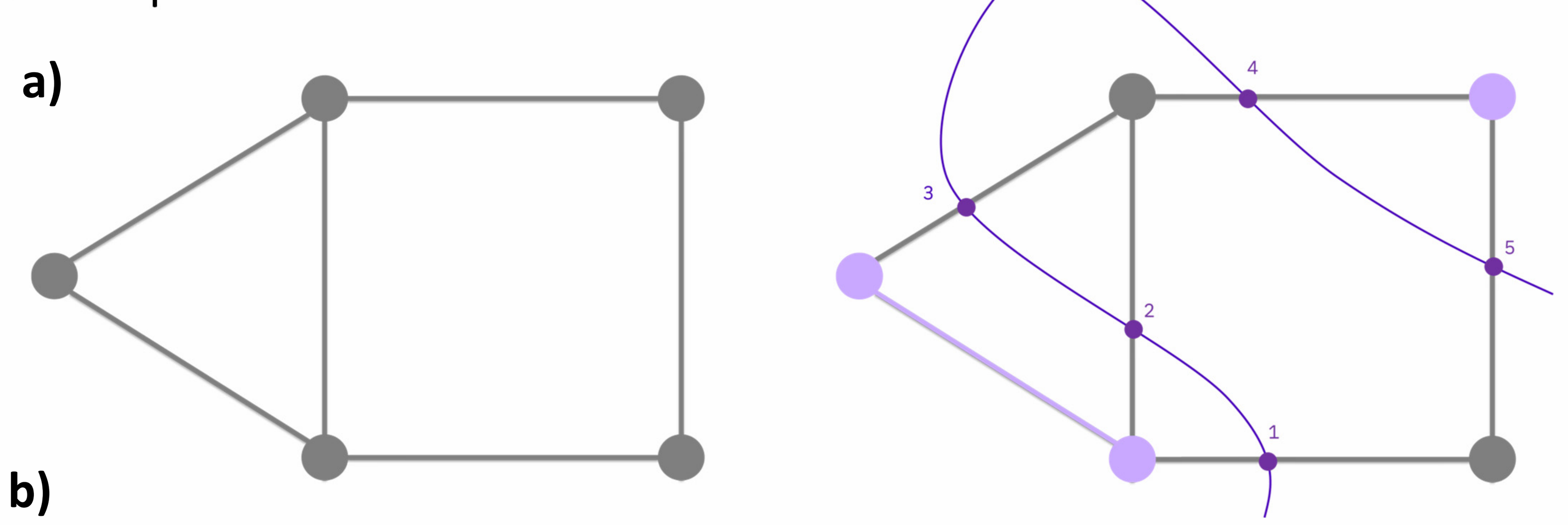
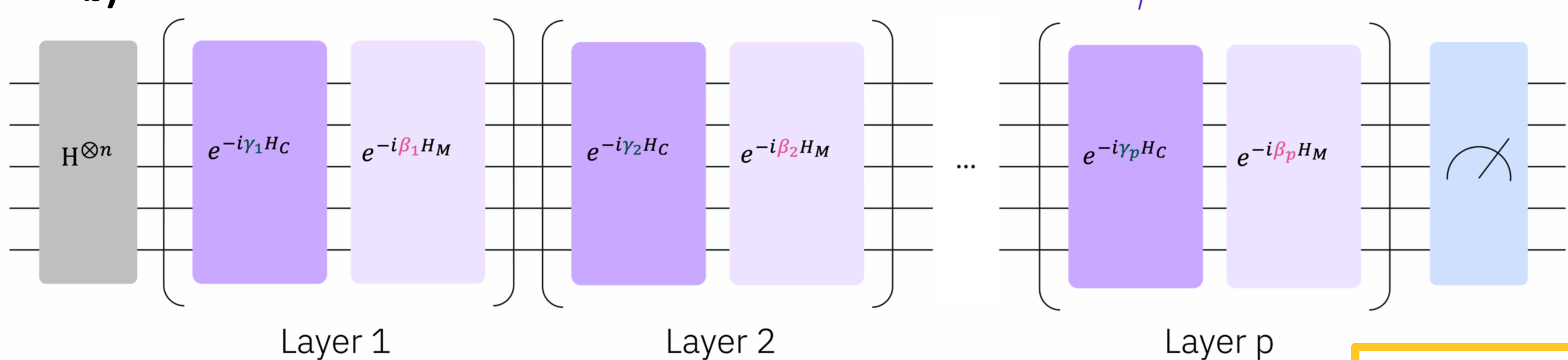


Fig 2. Running the circuit above with mid-circuit measurements (MCM) (a) on IBM's quantum computers had significantly improved performance with the use of LDD seen to the right (b).[2]

Furthering investigation on LDD's capability to improve performance, an important problem from classical computing, max cut, was mapped onto the IBM's quantum machines and tested.

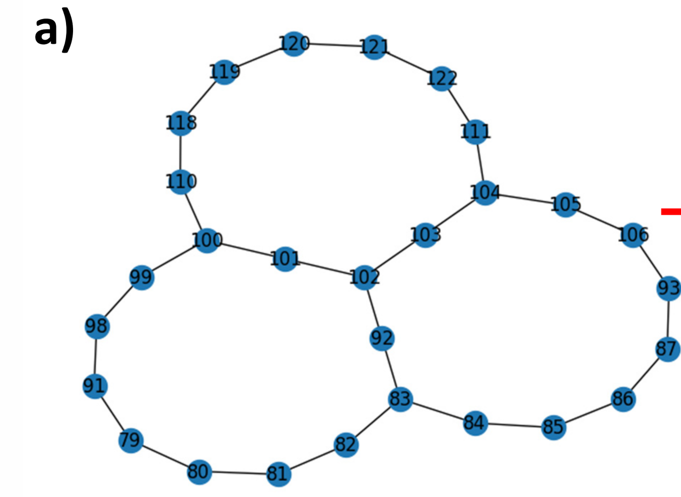




$$H_C = \sum_{ij} Q_{ij} Z_i Z_j + \sum_i b_i Z_i \qquad H_M = \sum_i X_i$$

Fig 3. Max cut is simply trying to find the largest cut that separates the nodes into two groups (a). It can be mapped to a quantum computer with the Hamiltonian H_C and H_M in the circuit above (b). The circuit is repeatedly run while a classical optimizer adjusts the β_i's and γ_i's to minimize the energy. This is known as the quantum approximate optimization algorithm (QAOA).[3]

Results



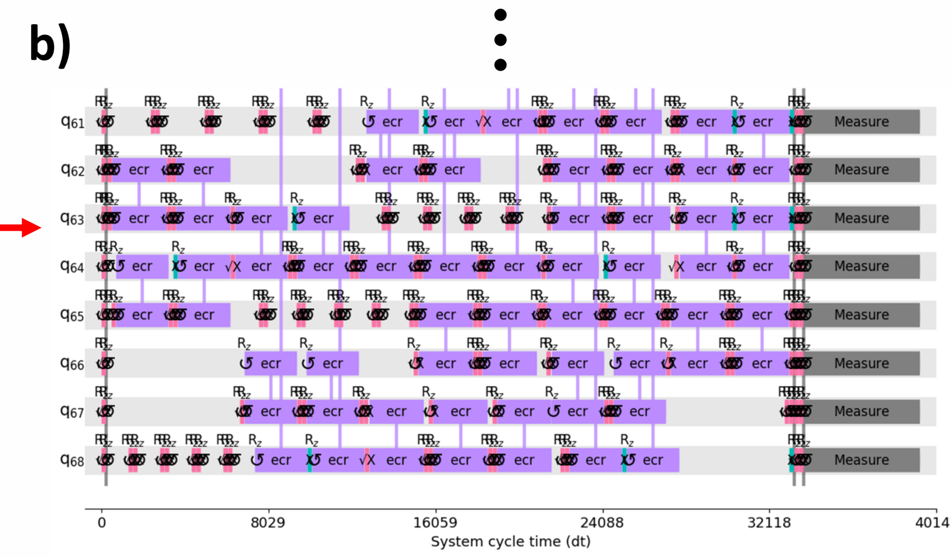
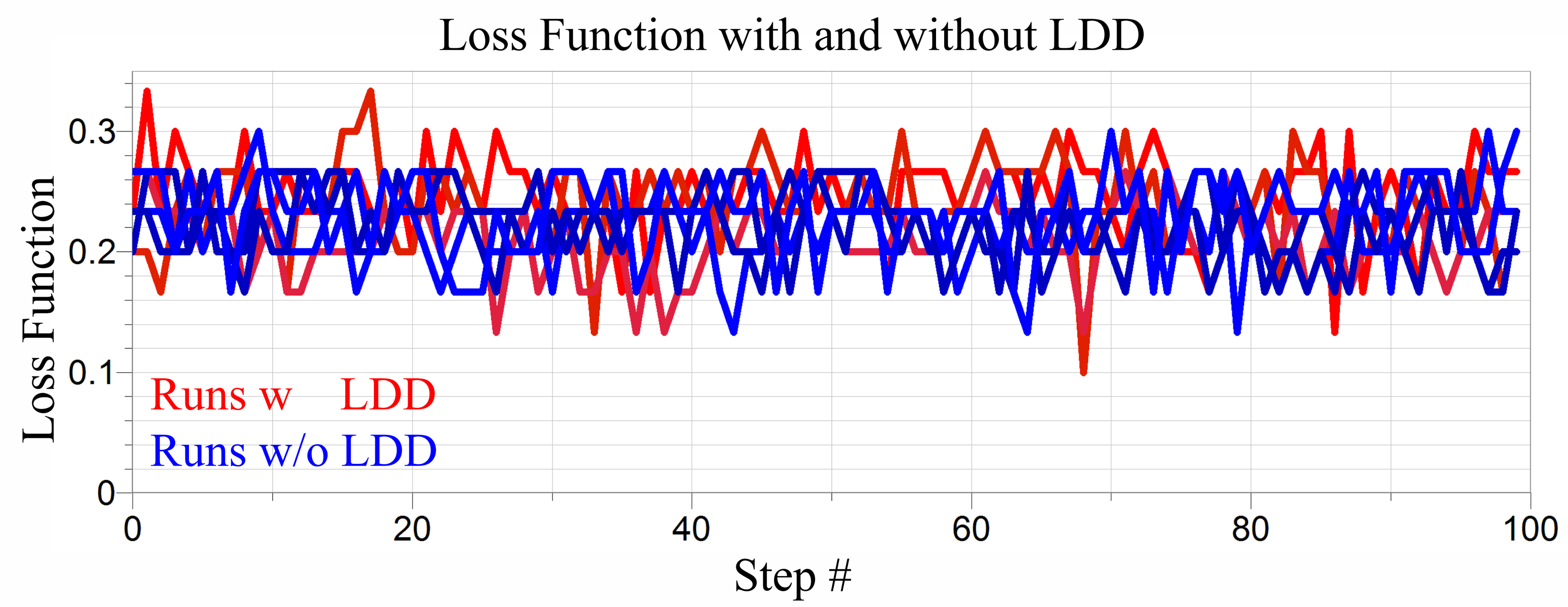


Fig 4. The graph (a) was mapped onto IBM's quantum computers. The circuit resulting can be seen above (b). *Note: it has been clipped due to its size.*



$$Loss\ function = 1 - \frac{QAOA\ cut - min\ cut}{max\ cut - min\ cut}$$

Fig 5. The graph from figure 4 was run both with and without LDD. The optimizer took 100 steps, reset, and then was run again several times. Each line corresponds to a run. The loss function is a calculation of how close the circuit was to the max cut at each step. Ideally, the loss function would go to zero.

Conclusion

Running the quantum approximate optimization algorithm with learning dynamical decoupling reached a minimum loss function of 0.100. Without learning dynamical decoupling, it reached a minimum of 0.133. **Learning dynamical decoupling was demonstrated to improve the performance of quantum computers.**

References

[1] L. Viola, and S. Lloyd, Dynamical suppression of decoherence in two-state quantum systems, Phys Rev A 58, 2733 (1998).

[2] A. Rahman, D. J. Egger, and C. Arenz, Learning How to Dynamically Decouple, Phys. Rev. Applied 22, 054704 (2024).

[3] Utility-Scale QAOA. https://learning.quantum.ibm.com/course/quantum-computing-in-practice/utility-scale-qaoa

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[5] James S. Spontaneous Perturbation Stochastic Approximation SPSA. https://www.jhuapl.edu/SPSA/

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