# Exploring various entangling gate driving schemes for trapped-ion quantum computers

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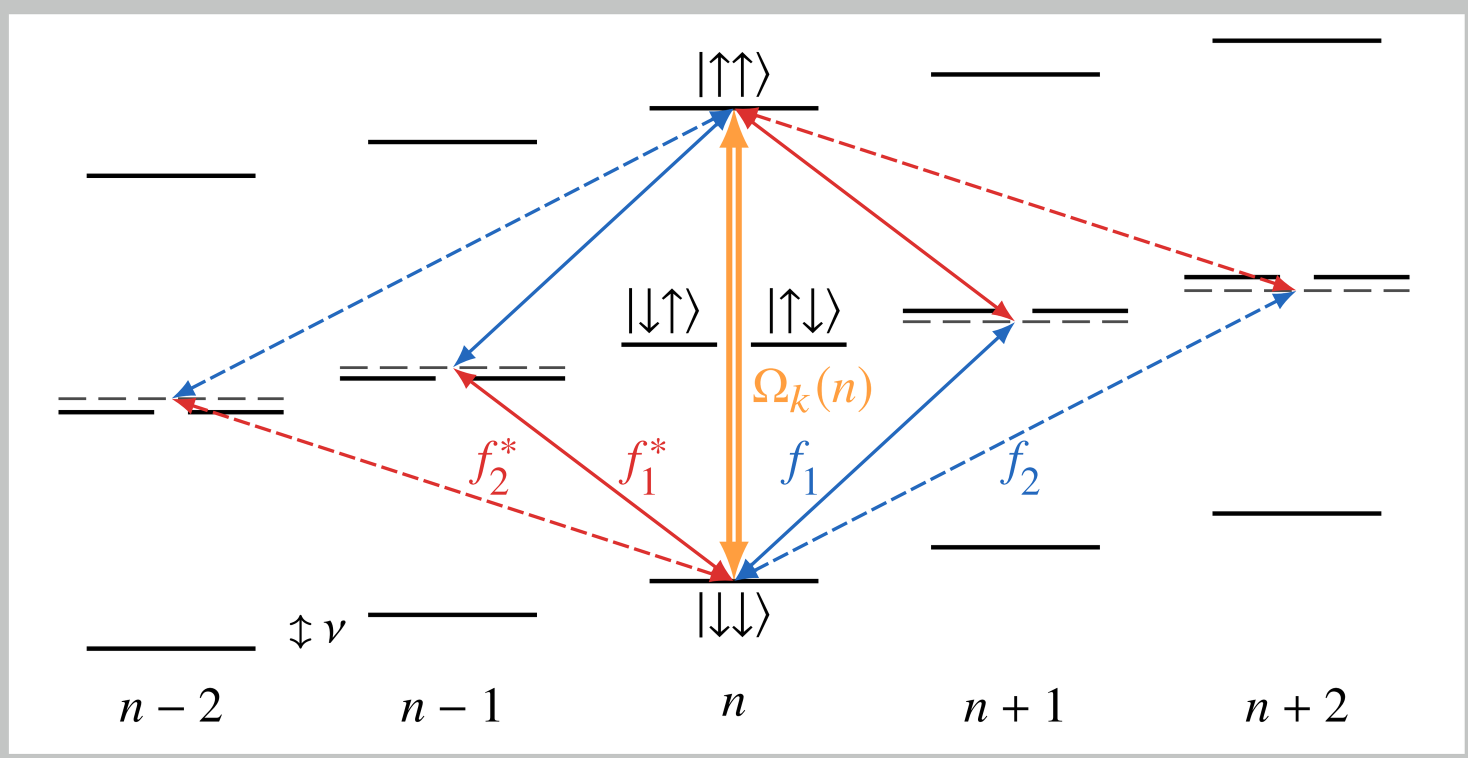
## 1. Introduction

Quantum computers are invaluable tools for certain computational tasks as they can solve these problems faster than any classical computer. Due to this a scalable high fidelity quantum computer is strongly sought after. One promising path towards implementation is via trapped ion systems, but these unfortunately are sensitive to various imperfections in implementation such as errors in laser or trap frequencies and noise from magnetic fields. We explore possible extensions to the so-called Mølmer-Sørensen (MS) gate design, which addresses these problems.

## 2. Mølmer-Sørensen gate

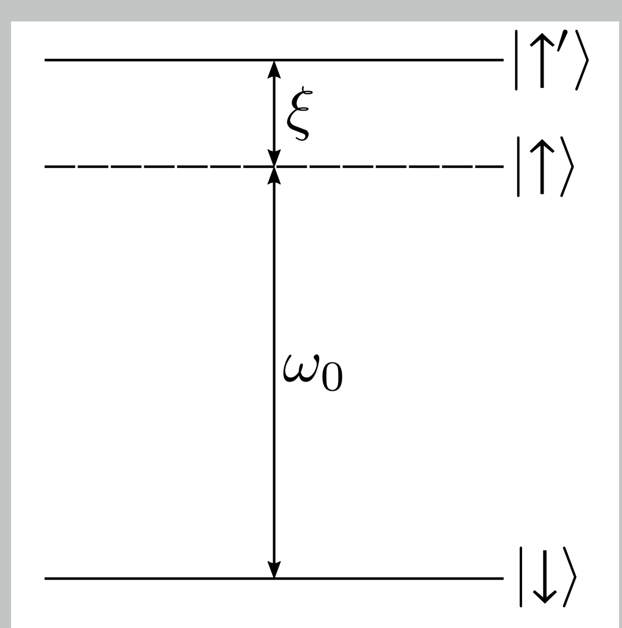



Multi-sideband driving scheme to eliminate temperature dependence. Blue and red arrows indicate blue and red sideband transitions. Figure reproduced from [1].

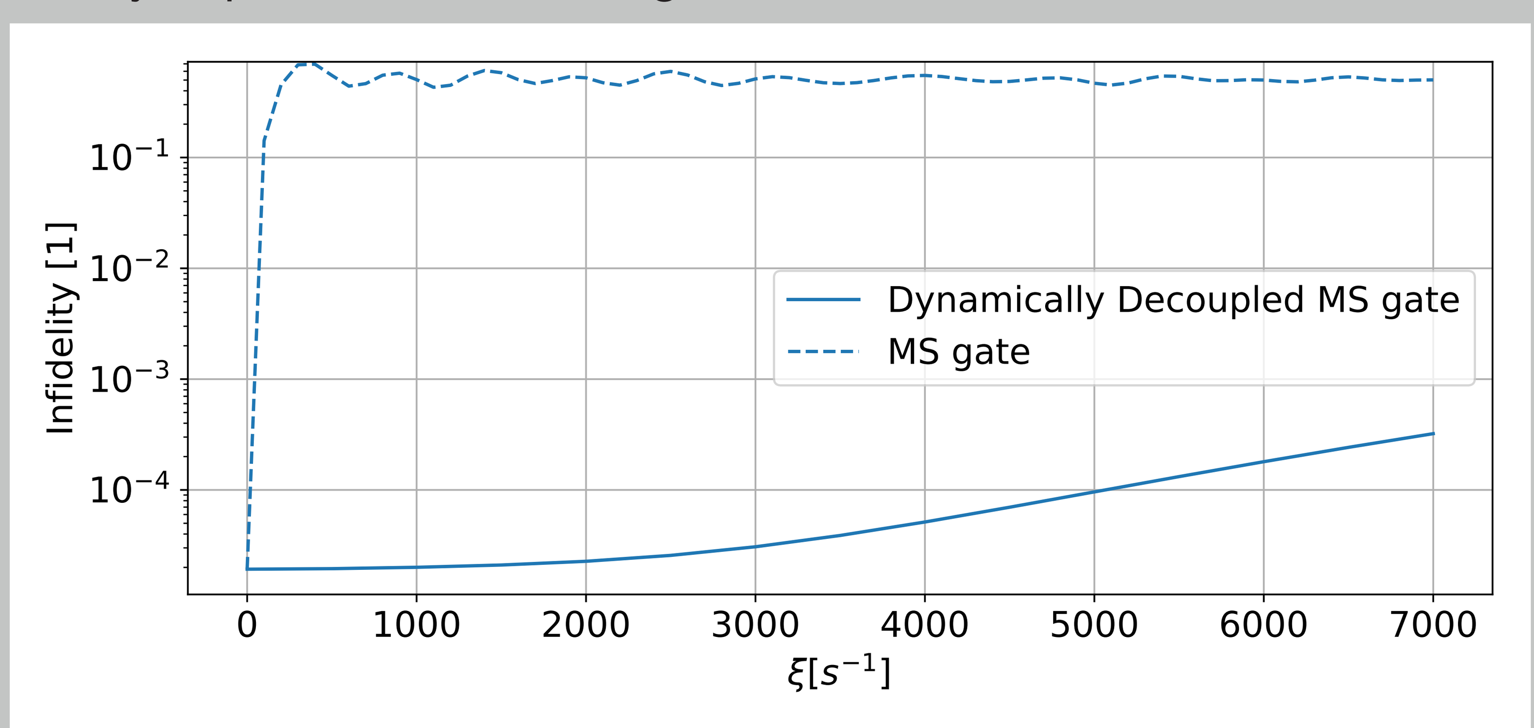
The MS gate is designed to be decoupled from the motional state of the ions. It achieves this by driving the motional sidebands of the two ions simultaneously. These paths interfere resulting in a gate operation independent on the motional state of the ions when they are strongly confined, which corresponds to a small Lamb-Dicke parameter, $\eta$. Due to this, even if heating occurs the gate is unaffected.
Several other gates have been proposed to address various issues in regards to experimental limitations of ion-traps and our goal is to evaluate, which gates would be better suited for experimental implementation, as well as considering whether multiple gates can be combined.

## 3. Qubit frequency errors

Errors in experimental realisation can lead to shifts in the energy level of the qubit. One example of this is magnetic fields perturbing the ion. One scheme designed to address this issue is called dynamic decoupling [2]. By strongly driving to the carrier this error reduces to fast oscillating terms assuming $\left[\hat{H}_G, \hat{S}_y\right] = 0$. These can be ignored if the error is not resonant and is relatively small compared to the correction driving. This is easily implemented on most gates.

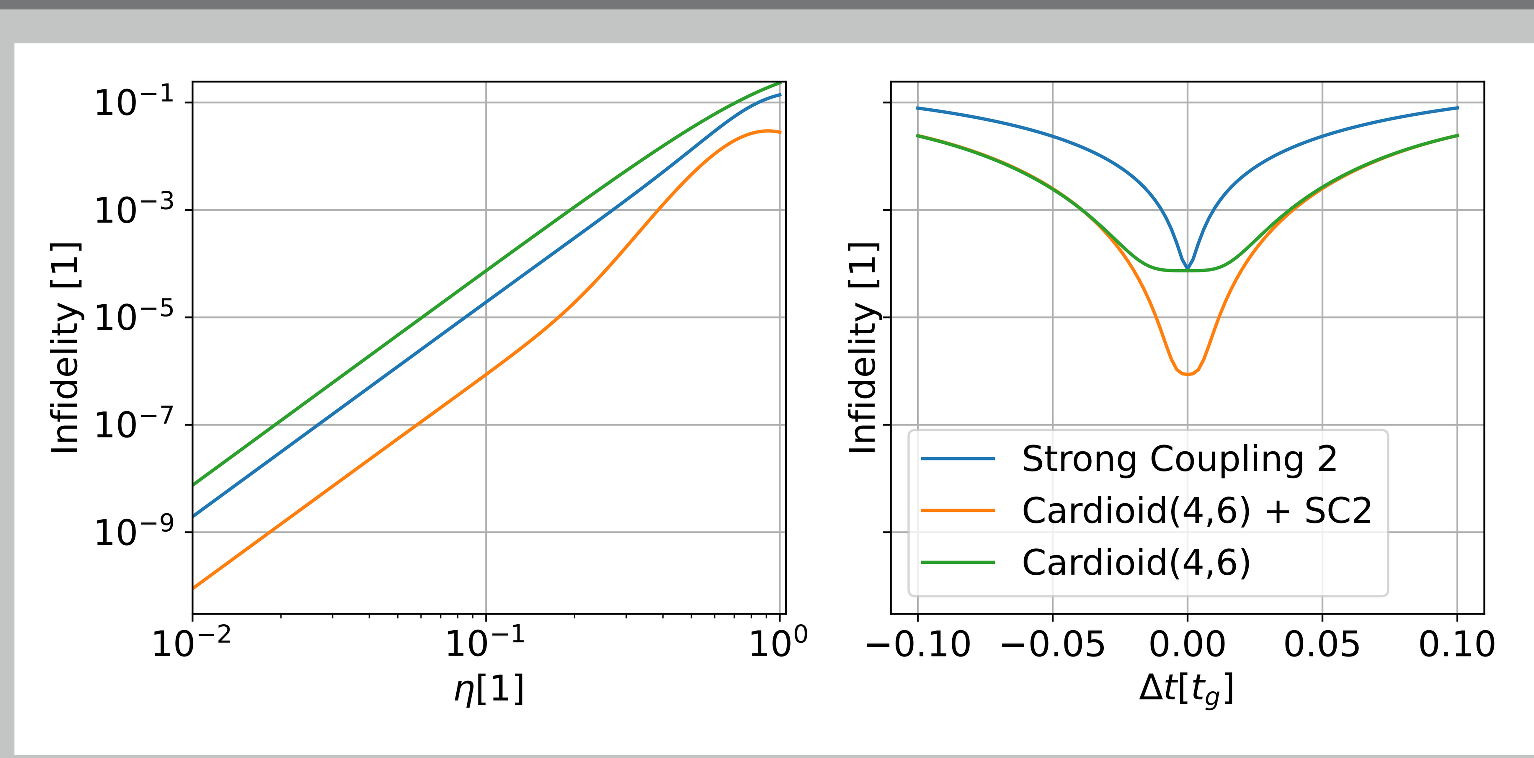



Perturbed energy structure of the qubit



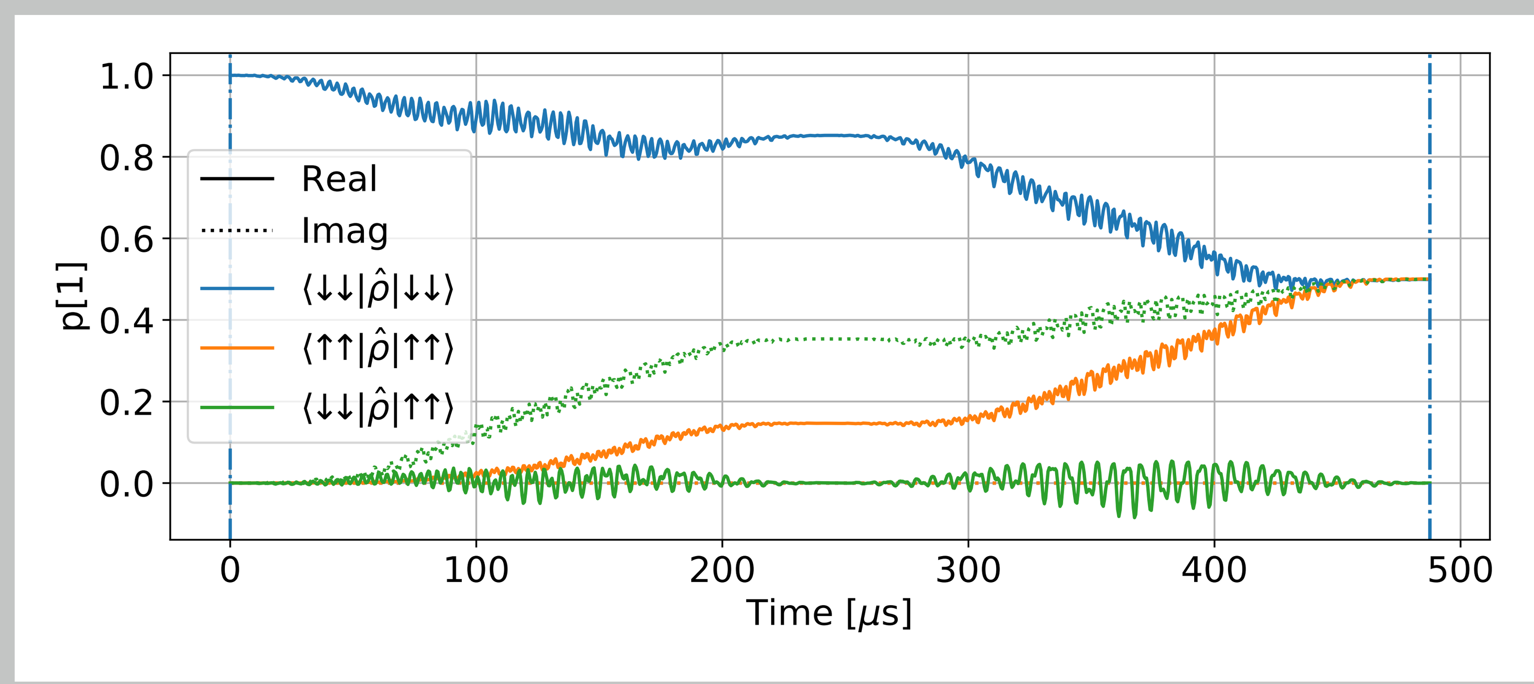

An example of the strong improvement the dynamic decoupling scheme has, demonstrated on the standard MS gate.

## 4. Compound driving schemes



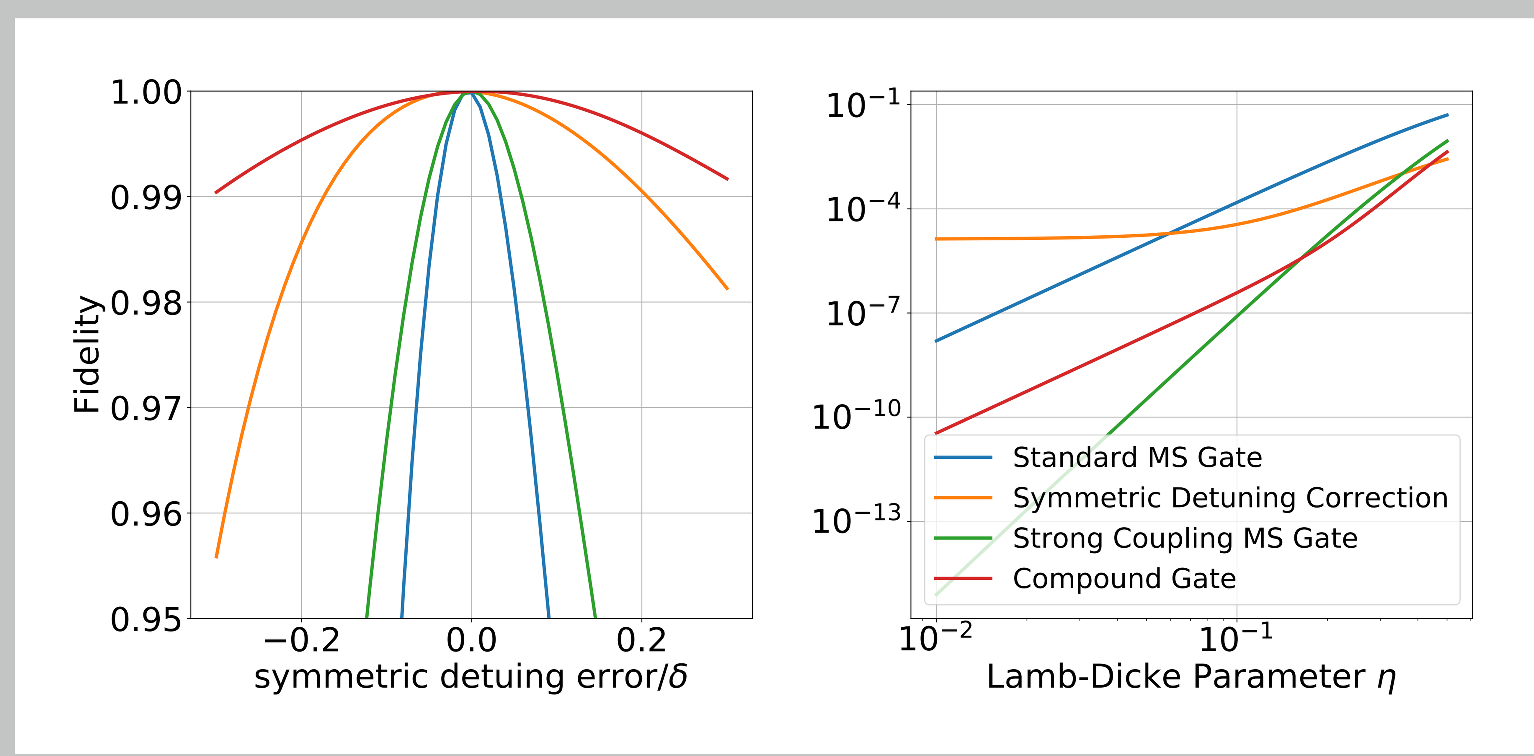

Comparison between fidelities of the two individual and their compound gate.

An exciting idea is to combine driving schemes to create robustness against multiple factors. By combining strong coupling scheme [1] with Cardioid scheme [3], it can operate under high temperatures while being resistant to timing errors, which are properties of each schemes respectively.




Population of states in Cardioid and SC2 compound gate.

Symmetric detuning errors introduced when mis-setting laser frequencies is another common issue to consider. We exploited the ideas for symmetric detuning error correcting scheme [4] and combined it with strong coupling [1] schemes. This again yields a gate that retains the excellent robustness against the symmetric detuning error while improving the robustness at higher temperatures.




Comparison of schemes against symmetric detuning error and Lamb-Dicke Parameter.

## 5. Conclusion

We obtained a scheme solving qubit frequency error which is not widely addressed. We also managed to combine different schemes with strong coupling scheme which have shown to retain the characteristics of their originals, creating robust gates that are feasible to implement in a high-temperature regime.

## References

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[2] T. P. Harty, M. A. Sepiol, D. T. C. Allcock, C. J. Ballance, J. E. Tarlton, and D. M. Lucas, "High-fidelity trapped-ion quantum logic using near-field microwaves," *Physical Review Letters*, vol. 117, Sep 2016.

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[4] A. E. Webb, S. C. Webster, S. Collingbourne, D. Bretaud, A. M. Lawrence, S. Weidt, F. Mintert, and W. K. Hensinger, "Resilient entangling gates for trapped ions," *Phys. Rev. Lett.*, vol. 121, p. 180501, Nov 2018.