Logical Performance of 9 Qubit Compass Codes in Ion Traps with Crosstalk

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Abstract

We simulate four quantum error correcting codes under error models inspired by realistic noise sources in near-term ion trap quantum computers: T2 dephasing, gate overrotation, and crosstalk. We use this data to find preferred codes for given error parameters along with logical error biases and a pseudothreshold which compares the physical and logical gate failure rates for a CNOT gate. Using these results we conclude that Bacon-Shor-13 is the most promising near term candidate as long as the impact of crosstalk can be mitigated through other means.

Codes Considered

Bacon-Shor-13	Shor-6Z2X	Shor-6X2Z	Surface-17
Stabilizers			
$Z_0Z_3Z_1Z_4Z_2Z_5$	$X_0X_1X_3X_4X_6X_7$	$Z_0Z_3Z_1Z_4Z_2Z_5$	$Z_1Z_2Z_4Z_5$
$Z_3Z_6Z_4Z_7Z_5Z_8$	$X_1X_2X_4X_5X_7X_8$	$Z_3Z_6Z_4Z_7Z_5Z_8$	Z_0Z_3
$X_0X_1X_3X_4X_6X_7$	Z_0Z_3	X_0X_1	$Z_3Z_4Z_6Z_7$
$X_1X_2X_4X_5X_7X_8$	Z_1Z_4	X_1X_2	Z_5Z_8
	Z_2Z_5	X_3X_4	$X_0X_1X_3X_4$
	Z_3Z_6	X_4X_5	X_6X_7
	Z_4Z_7	X_6X_7	$X_4X_5X_7X_8$
	Z_5Z_8	X_7X_8	X_1X_2
Logical Operators			
$Z_0Z_1Z_2$	$Z_0Z_1Z_2$	$Z_0Z_1Z_2$	$Z_0Z_4Z_8$
$X_0X_3X_6$	$X_0X_3X_6$	$X_0X_3X_6$	$X_2X_4X_6$

Testbed Circuit

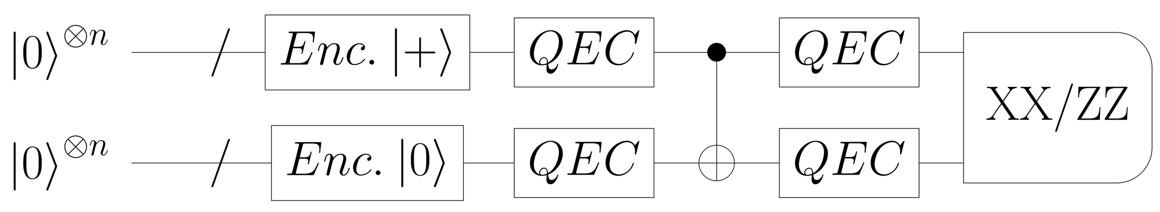

Figure: The circuit that we simulate for each code. From the $XX(ZZ)$ measurements we can gauge the code's performance in generating our desired state of $\Phi_L^+ = \frac{1}{2}(|00\rangle_L + |11\rangle_L)$.

Overrotation Errors

For overrotation errors we model our errors as a stochastic channel

$$\varepsilon_G^s(\rho) = (1-p)I\rho I + pG\rho G$$

where our single qubit error rate, is set as a tenth of our Mølmer-Sørensen error rate:

$$p_{1q} = \frac{1}{10} p_{XX}$$

T2 Dephasing

We only consider idling error in the form of T_2 dephasing due to the long T_1 times in trapped ion systems. Our idling errors are modeled through a stochastic channel

$$E_{idle} = \{\sqrt{1-p_i}I, \sqrt{p_i}Z\},$$

where

$$p_i = \frac{1}{2}\left(1 - \exp\left[-\frac{1}{2}\frac{T_{idle}}{T_2}\right]\right),$$

and T_{idle} is the idling time of the particular qubit.

Results

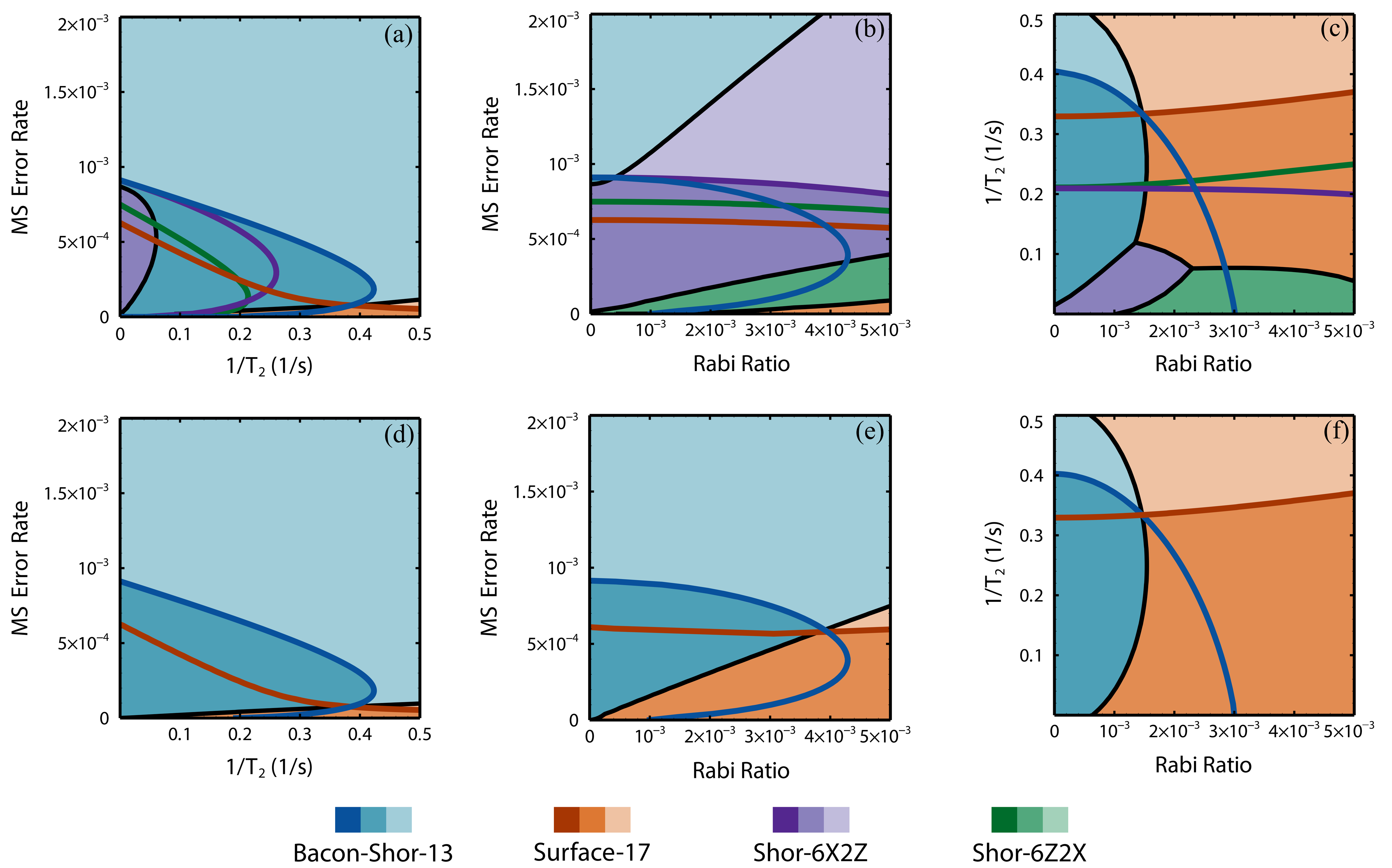

Figure: Figures showing best performing codes and pseudothresholds for different error models and sets of codes. In (c,f) we look at T_2 dephasing and crosstalk with a background overrotation characterized by a Mølmer-Sørensen error rate of 10^{-4}. The darker regions indicate the encoded operation outperforming the unencoded CNOT.

Crosstalk Errors

Crosstalk is an issue that leads to pairwise correlated errors when applying our native entangling gate, the Mølmer-Sørensen gate. When an entangling gate is applied, a global beam is applied to the chain, and individually addressed beams are applied to the involved qubits. These addressed beams can have some degree of overlap with the neighboring qubits. For two-qubit gates, this leads to a possibility for small Mølmer-Sørensen type errors between the involved qubits and any of these nearest neighbors as shown in the below:

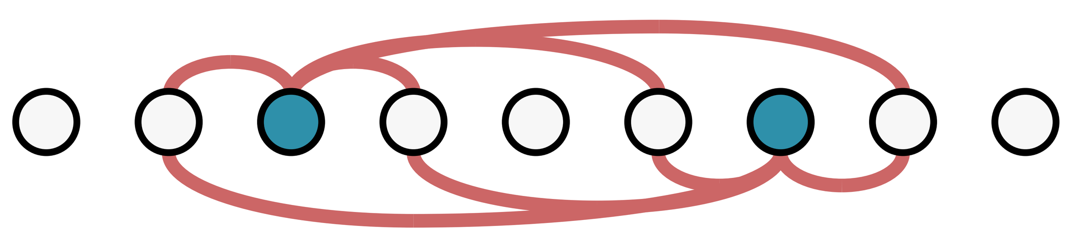

Figure: The first order crosstalk errors, shown in red, which occur during a Mølmer-Sørensen gate on the qubits shaded in blue.

We model this effect through applying the following Kraus channel to all crosstalk pairs:

$$E_{crosstalk} = \{\sqrt{1-p_c}II, \sqrt{p_c}XX\},$$

where

$$p_c = \sin^2\left(\frac{\Omega_c}{\Omega_R} \times \frac{\pi}{4}\right).$$

Ω_c/Ω_R is the two-qubit gate crosstalk Rabi ratio, which gives the ratio of the Rabi frequency experienced by these crosstalk pairs and the Rabi frequency of the intended gate.

Conclusions

Our work shows that the choice of error correcting code is extremely sensitive to the underlying structure of the errors within the physical system, and that there is no code which dominates all cases. This indicates that careful benchmarking will be essential to achieving maximal performance from a quantum computer.

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