Demonstration of a quantum error detection code using a square lattice of four superconducting qubits

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Nature Communications **6**, Article number: 6979 | doi:10.1038/ncomms7979
Received 16 January 2015 | Accepted 18 March 2015 | Published 29 April 2015

The ability to detect and deal with errors when manipulating quantum systems is a fundamental requirement for fault-tolerant quantum computing. Unlike classical bits that are subject to only digital bit-flip errors, quantum bits are susceptible to a much larger spectrum of errors, for which any complete quantum error-correcting code must account. Whilst classical bit-flip detection can be realized via a linear array of qubits, a general fault-tolerant quantum error-correcting code requires extending into a higher-dimensional lattice. Here we present a quantum error detection protocol on a two-by-two planar lattice of superconducting qubits. The protocol detects an arbitrary quantum error on an encoded two-qubit entangled state via quantum non-demolition parity measurements on another pair of error syndrome qubits. This result represents a building block towards larger lattices amenable to fault-tolerant quantum error correction architectures such as the surface code.

Motivation

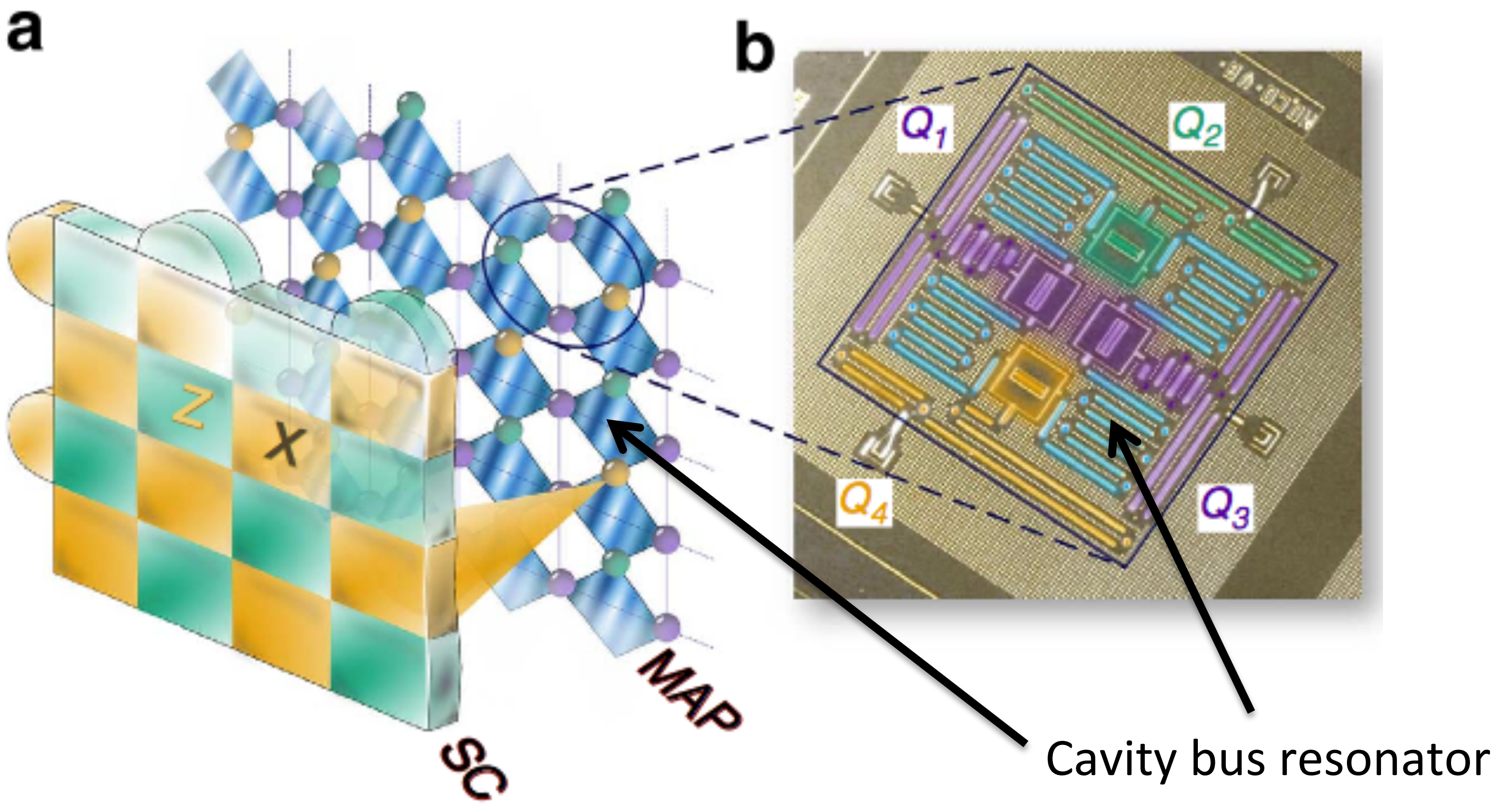
- Reliable quantum computation is more difficult than classical computation:
  - Higher sensitivity to noise effects
  - More error types (bit- and phase-flips)
  - Direct extraction of the information typically destroys the system ➔ need ancillary syndrome systems to perform non-demolition measurements

- The surface code is a promising candidate to achieve scalable quantum computing due to its nearest-neighbor qubit layout and high fault-tolerant error thresholds.

Surface code

- 2D grid of qubits
- Local four-qubit Pauli operators (stabilizers) are required to give a +1 eigenvalue
- A -1 eigenvalue tells us that an error has happened
- Half of these detect phase-errors, half detect bit-flip errors

Surface code



Purple sphere: code qubit
Yellow sphere: X-syndrome (phase parity)
Green sphere: Z-syndrome (bit parity)

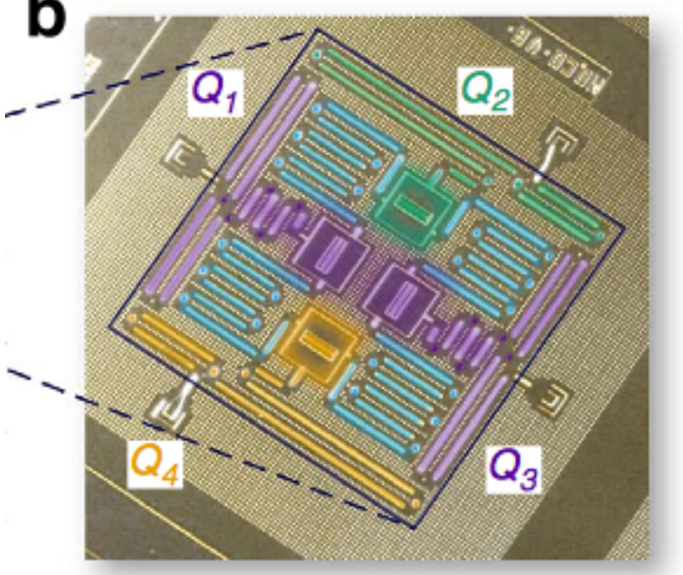
‘Quantum bus’

- Couple two superconducting qubits using microwave photons confined in a transmission line cavity (Schoelkopf group, Nature 2007).
- The interaction is mediated by the the exchange of *virtual* photons, avoiding cavity-induced loss.
- Allows to perform gate operations between arbitrary qubit pairs.
- Surface code vision: Each qubit is coupled with two bus resonators and each bus couples with four qubits.

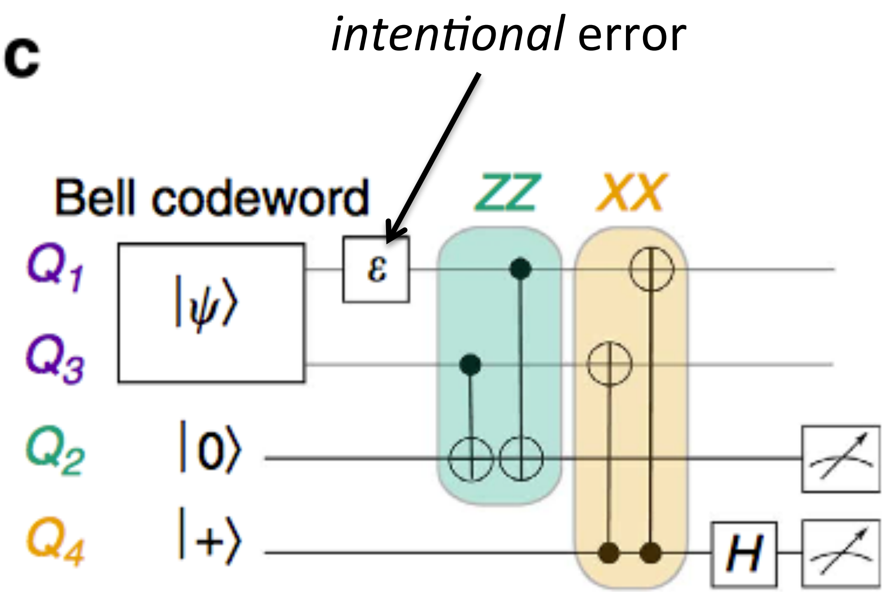
Start small

- The physical device is a 2x2 lattice of superconducting transmons.
- Each is coupled to its two nearest neighbors via two independent superconducting coplanar waveguide (CPW) resonators serving as quantum buses.
- Each qubit is further coupled with an independent CPW resonator for both qubit control and readout.

b



c

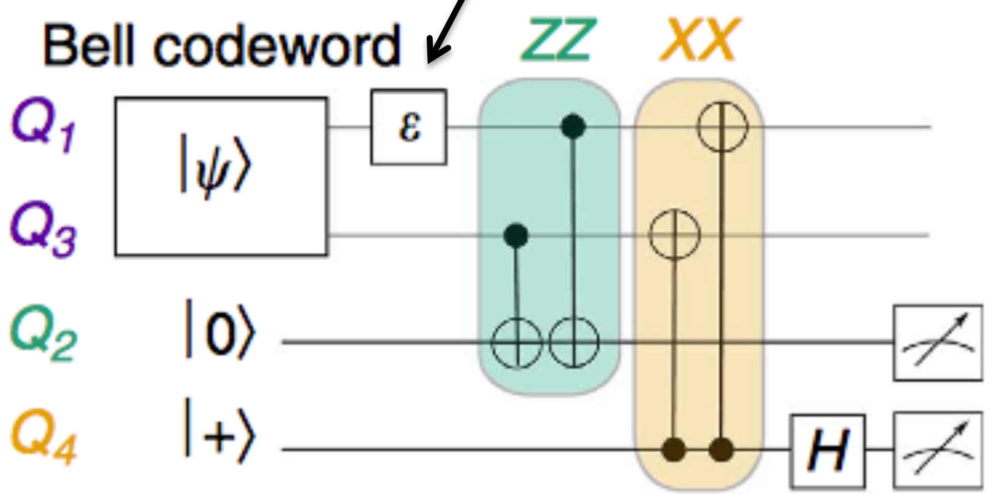


Two-qubit Bell state

- The ‘codeword’ is the unique state $|\Psi>$ such that $XX|\Psi> = ZZ|\Psi> = |\Psi>$
- This is the Bell-state $|\Psi> = (|00> + |11>)/\sqrt{2}$
- We have $|\Psi><\Psi| = (1+XX-YY+ZZ)/4$
- XX and ZZ are the stabilizers of this “code”. It is a [[2,0,2]] code.

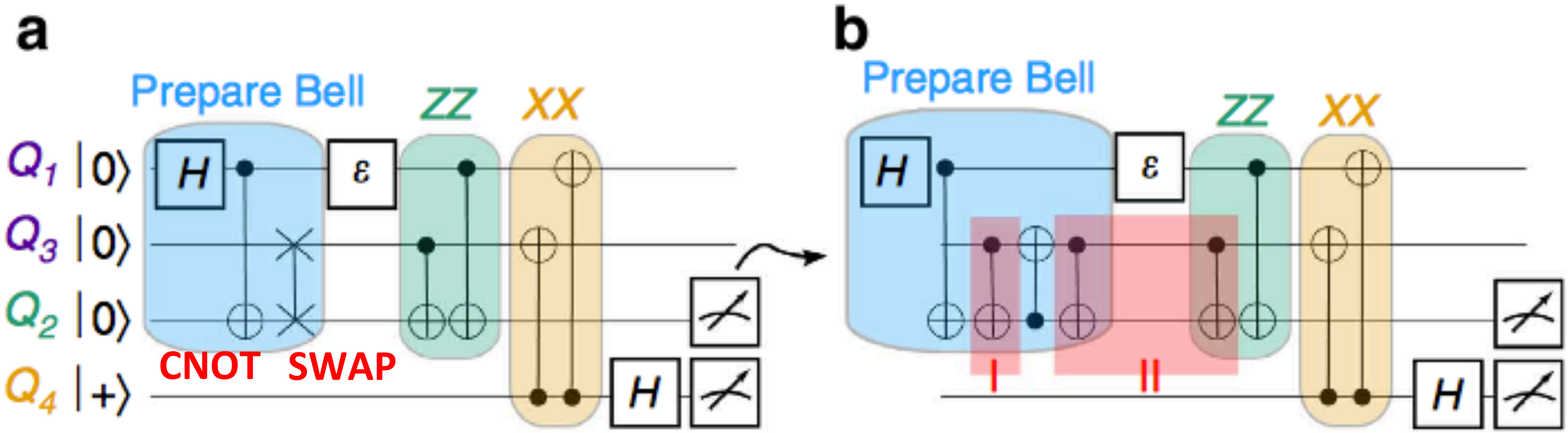
Full protocol

Intentional single-qubit error

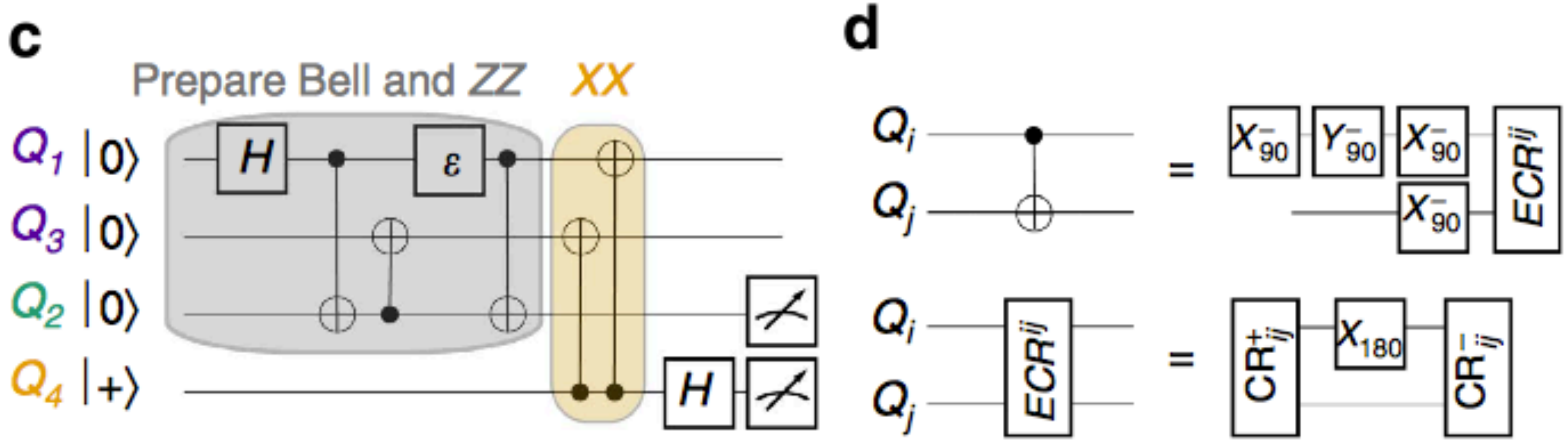


Hadamard gate

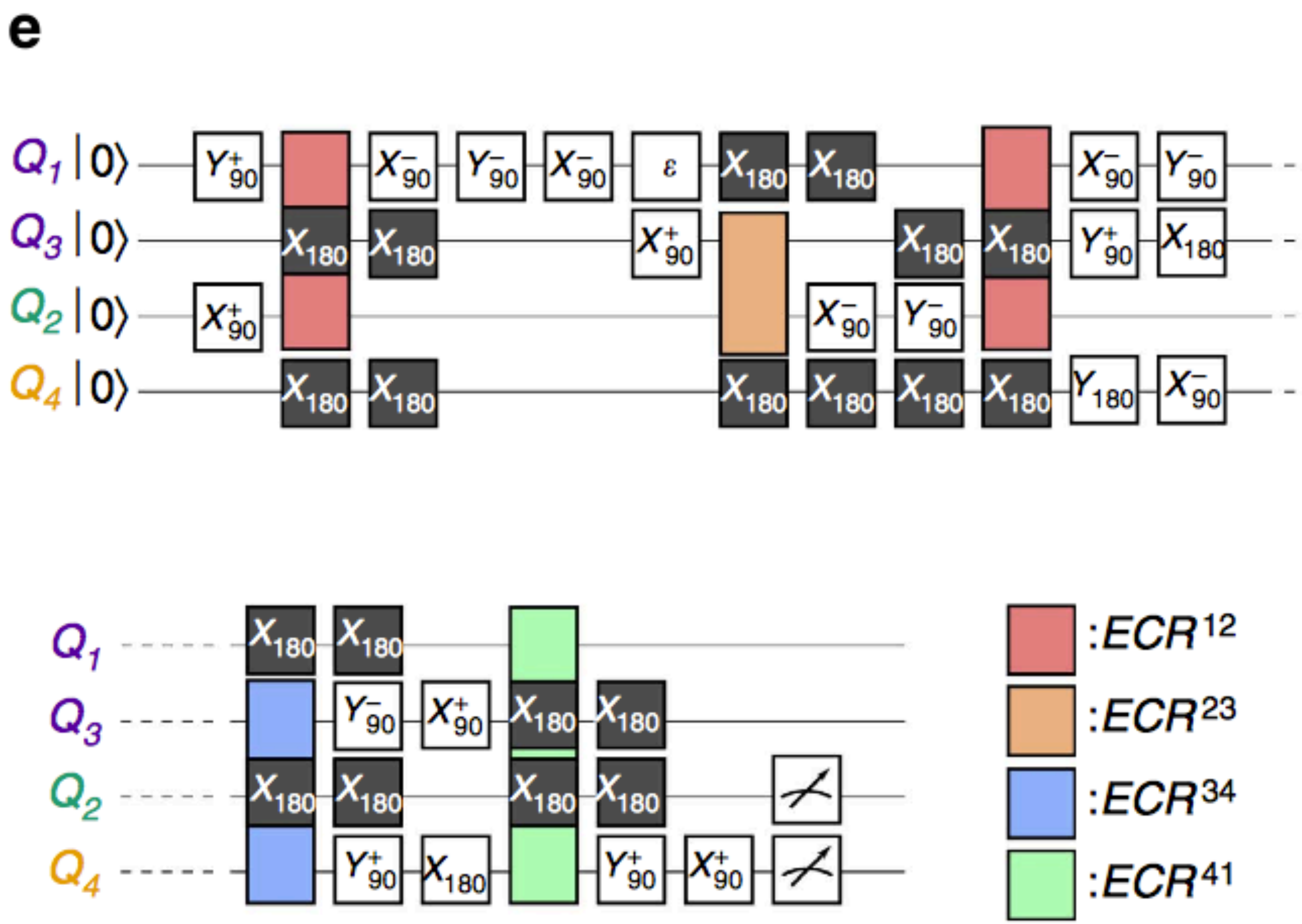
Full protocol



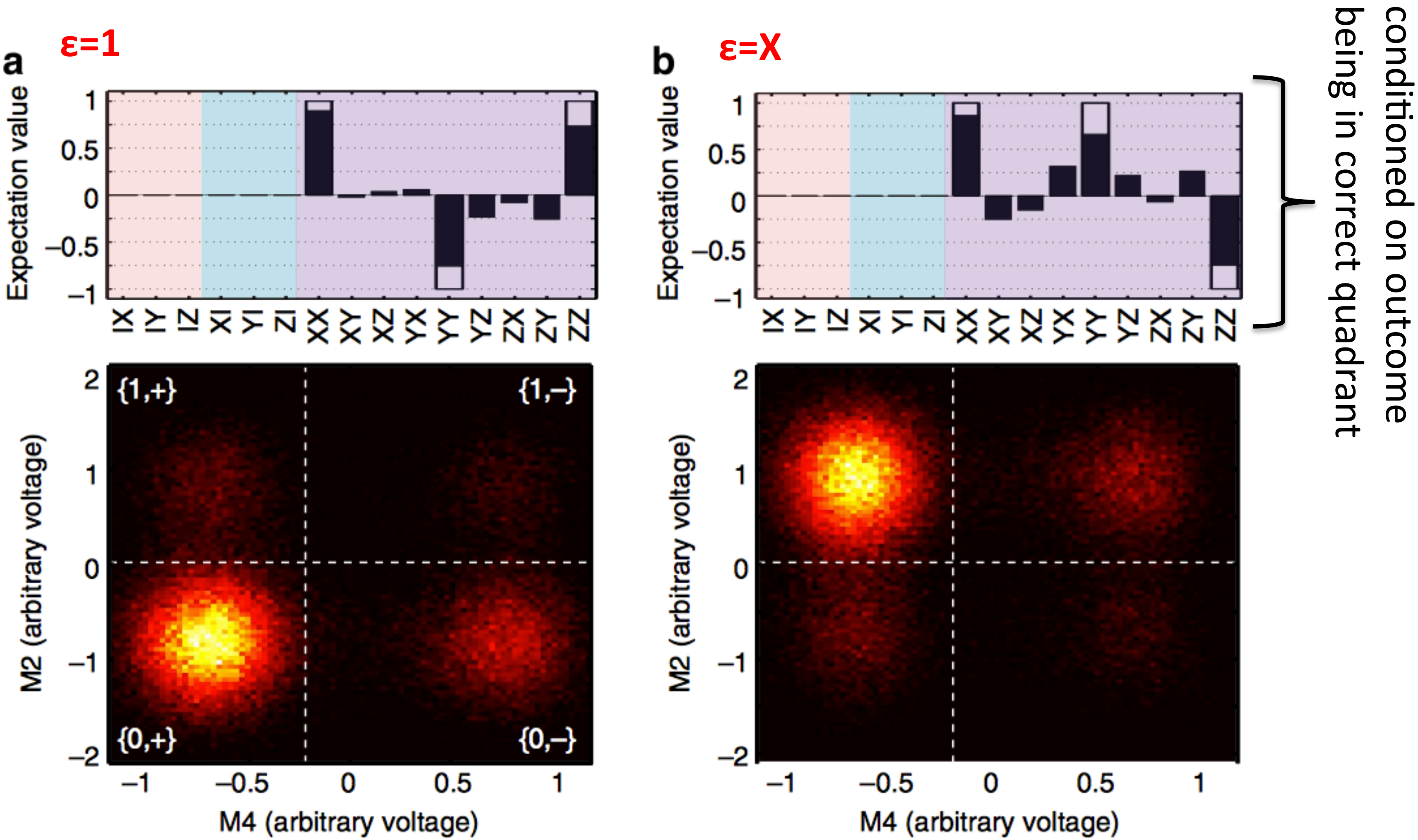
use Q2 as mediator since Q1 and Q3 aren't nearest neighbors



Full protocol



Results



ε=1
a
Expectation value
1
0.5
0
−0.5
−1
IX IY IZ XI YI ZI XX XY XZ YX YY YZ ZX ZY ZZ
{1,+}
{1,−}
{0,+}
{0,−}
M2 (arbitrary voltage)
M4 (arbitrary voltage)
−1
−0.5
0
0.5
1
2
−2
ε=X
b
conditioned on outcome being in correct quadrant

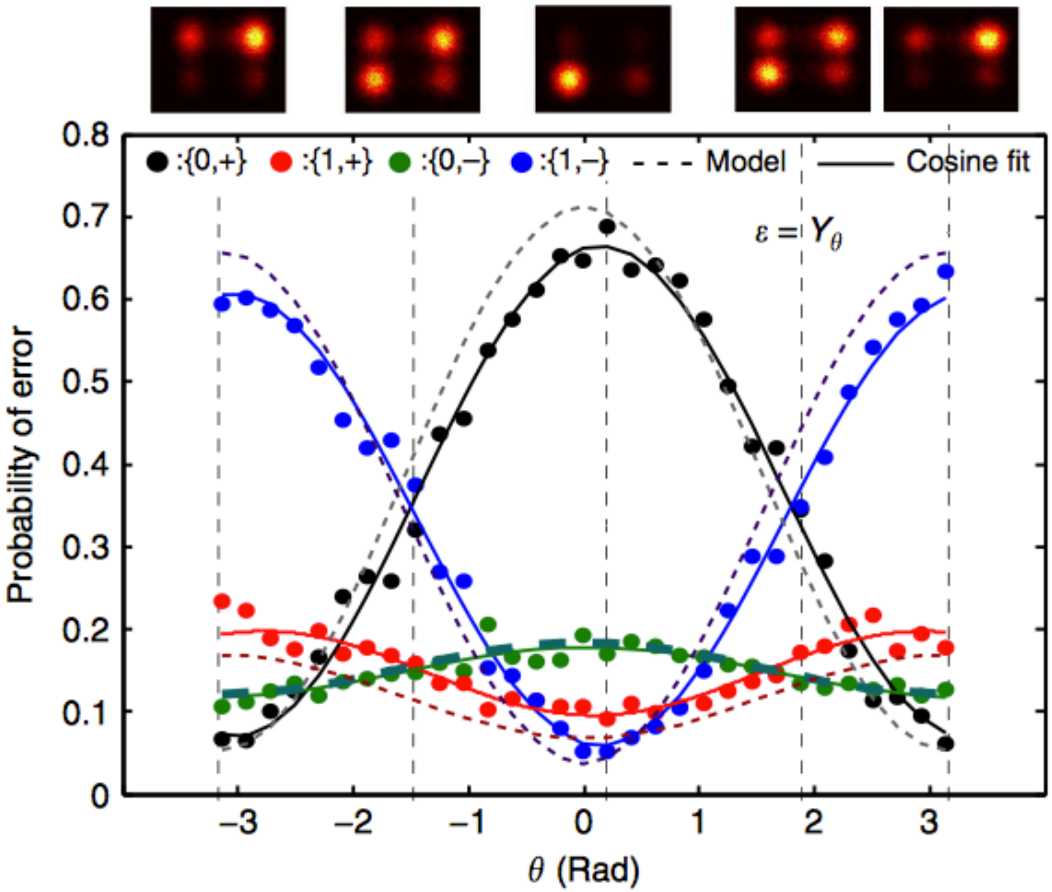
Notes

- Results for Y- and Z-errors are analogous.
- The state fidelity is 0.80–0.84, which is higher than expected from the number of gates and the fidelities of the individual gates.
- "This is because the gates used to prepare the codeword state do not contribute to the accumulated state fidelity loss, but rather reveal themselves as measurement errors."

Interpretation

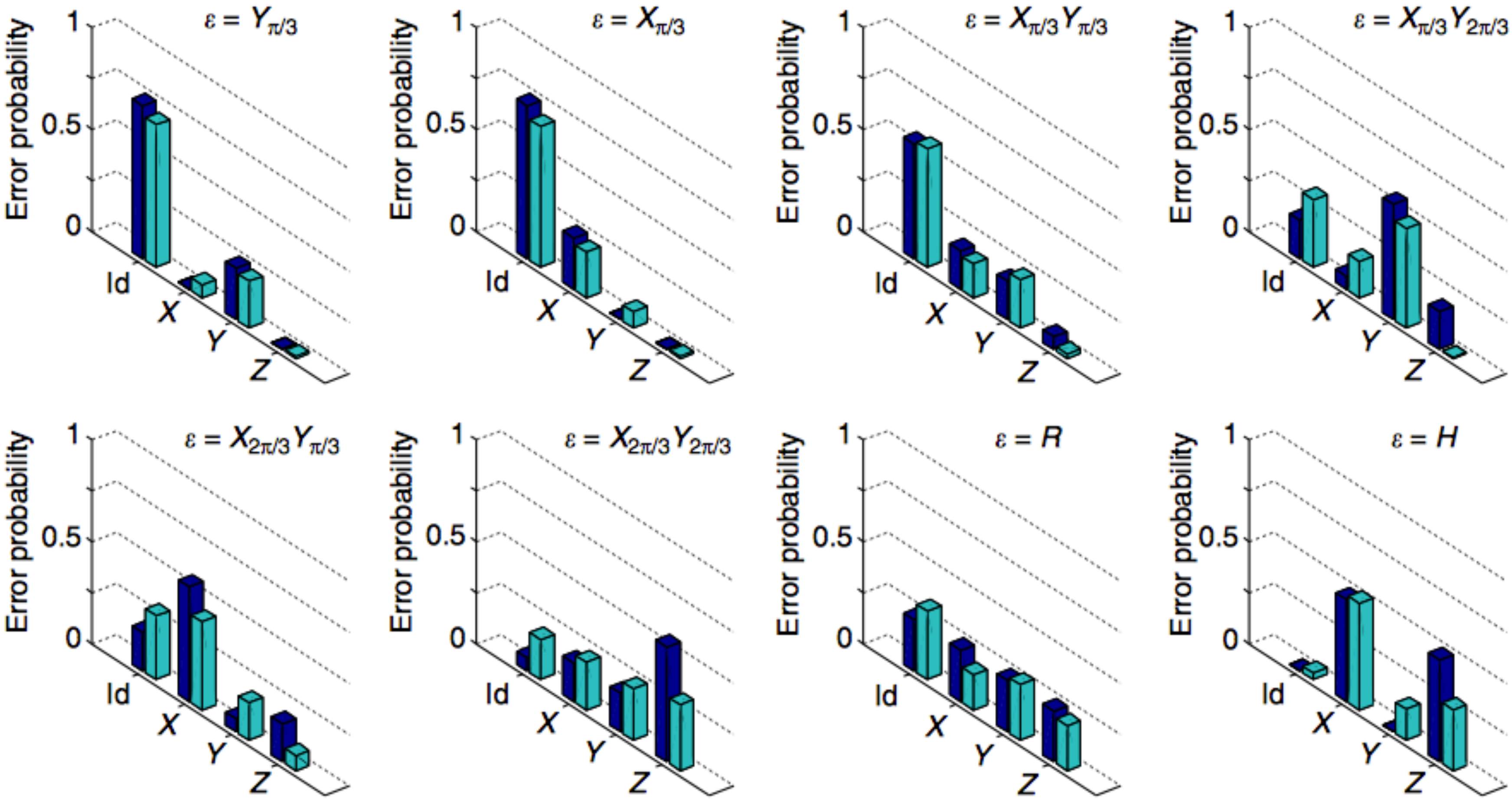
- The resulting density matrix has zero overlap with one-qubit operators.
- These would require conjugating
  $|\Psi\rangle\langle\Psi|=(1+XX-YY+ZZ)/4$
  with a two-qubit operator.
- Such a process is inhibited, since the two code qubits are not connected by a bus.

Rotations around Y-axis



Model: Master-equation simulations that take into account the measured coherence times and assignment fidelities.

Detection of arbitrary errors



R: X -> Y -> Z -> X

H: X <-> Z

Discussion

- They demonstrate the detection of arbitrary single-qubit quantum errors on a square lattice of qubits.
- The experiments combine a variety of key components required for scaling quantum systems up to larger numbers of qubits:
  - High-fidelidy one- and two-qubit gates
  - High single-shot assignment fidelities allowing for non-demolition measurements of code qubits
  - Improved system design to minimize crosstalk effects in non-trivial lattices of nn-coupled qubits.

Discussion (ctd.)

- Improved fidelities will be required to reach fault-tolerance thresholds.
- Demonstrating large-scale experimental quantum error correction will need shorter measurement times and measurement repeatability.