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Reducing the error rate of a superconducting logical qubit using analog readout information

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***Abstract*—Quantum error correction allows for quantum information to be preserved using logical qubits, which are subject to lower error rates than their constituent physical qubits. The degree of error suppression depends on the choice of error correcting code and distance, the underlying physical error rate, and the accuracy of the decoder. While traditional decoders utilise a binary (hard) syndrome, recent work shows that additional (soft) information captured during qubit readout can be effectively utilised to improve decoding accuracy. In this work, we present experimental results from a distance-three surface code implemented on transmon qubits, where we perform Z-stabiliser measurements to protect the state of the logical qubit against bit-flip errors. We initialise the logical qubit in one of 16 possible computational states representing the logical zero state, and perform repeated stabiliser checks over a variable number of rounds to preserve the state over time. We compare the decoding performance for a hard minimum-weight perfect matching decoder against a soft variant where rich measurement information is incorporated, and demonstrate an improved logical fidelity. Additionally, we employ a recurrent neural network decoder with both soft and hard variants and observe improved performance when soft information is used. The general nature of soft information makes it widely applicable to different physical qubit platforms, where it can be leveraged to shorten measurement times and improve the logical fidelity in quantum error correction experiments. Pre-print available at *arXiv:2403.00706*.**

***Index Terms*—Quantum error correction, soft information, superconducting qubits, decoding.**

I. Introduction

Quantum error correction (QEC) experiments have shown significant progress over recent years, notably the demonstration of logical error suppression by increasing the distance of a surface code [1]. The rate of error suppression achieved in these experiments is a function of the error correcting code and distance chosen, the error rates of the constituent physical qubits and the accuracy of the classical decoder used to process the measurement data. While common error decoding algorithms rely on measurement data in a binary form, additional (soft) measurement information can be captured during qubit read-out and used to improve the accuracy of the decoding process [2], here referred to as soft information decoding. The technique has been showcased in simulations of superconducting circuits [3], and demonstrated experimentally for a spin-qubit system [4] and a superconducting system [5] that was decoded using a uniform error model.

In this work, available as a pre-print in Ref. [6], we utilise soft information to decode experimental data from a bit-flip correcting distance-three code embedded in a 17-qubit device using fixed-coupling flux-tunable transmons. The state of the logical qubit, $|0_\mathrm{L}\rangle$ is encoded in one of 16 initial configurations of the computational state, and stabilized by repeated Z-basis measurements. The measurement information is passed to two types of decoders to obtain a logical fidelity: a minimum-weight perfect matching (MWPM) decoder [7] and a recurrent neural network (NN) decoder [8]. For each decoder, we use two representations of the measurement information: a hard representation where the measurement outcomes are binarized, and a soft variant where we give the decoder a measurement probability instead of a binary outcome. We find the soft variants to outperform their hard counterparts by 6.8% and 5% for the MWPM and the NN decoders respectively.

II. Decoding With Soft Information

The raw measurement signal from the superconducting device is in the form of IQ voltages, which are obtained using a dispersive readout scheme [9]. These values, denoted here as $z = (I, Q)$, form distinct clusters based on the qubit state $|j\rangle, j \in \{0, 1\}$ as seen in fig. 1(a). By repeatedly preparing and measuring each state $|j\rangle$, we fit Gaussian probability density functions (PDFs) to the resulting clusters. To obtain the measurement probabilities required for the decoders, we evaluate the $|0\rangle$-state and the $|1\rangle$-state PDFs for each soft measurement z. For the MWPM decoder, we use these probabilities to modify the edge weights according to the likelihood of a classification error – see fig. 1 (b). For the NN decoder, we use the measurement probabilities to compute defect probabilities and leakage flags, and pass these as input to the decoder.

III. Numerical Results

We plot the logical fidelity as a function of the number of rounds R for the MWPM decoder in fig. 2 and for the NN decoder in fig. 3. The lowest error rate achieved is 4.73% for the NN decoder, and 4.94% for the MWPM decoder. A consistent improvement in logical performance is seen

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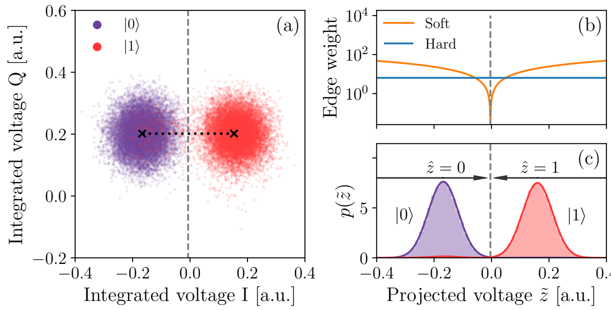

Fig. 1: (a) The measurement response of the $|0\rangle$ and $|1\rangle$ states in IQ space, showing a projection line that connects the means of the two Gaussian peaks (black dotted line). (b) Edge weight as a function of projected voltage $\tilde{z}$ for soft and hard measurements. Measurement errors are most likely in the region $\tilde{z} \approx 0$ where the edge weight is minimized. (c) Histogram and fitted probability density function $P(\tilde{z} \mid j)$ for state preparations $j \in \{0, 1\}$.

for both decoders, present for each of the 16 different state preparations. Computing the logical error rate ϵ_L from an exponential fit to the logical fidelity, we find the soft variants of the MWPM and NN decoders have 6.8% and 5% lower logical error rates than their respective hard counterparts.

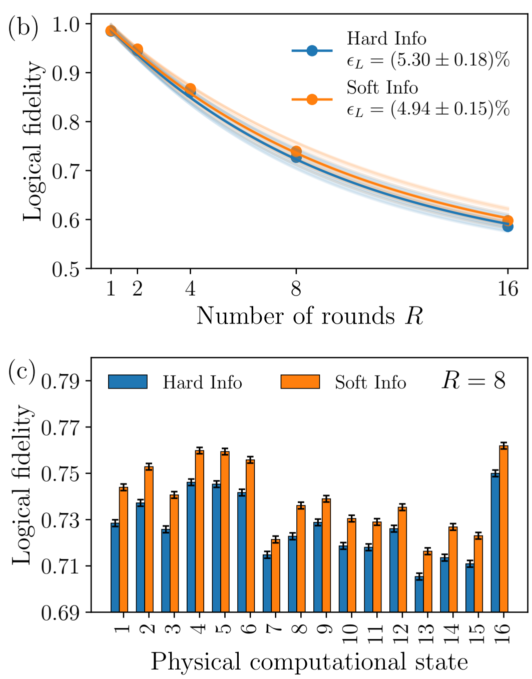

Fig. 2: (a) Logical fidelity of the MWPM decoder as a function of the number of rounds R. (b) Logical fidelity for $R = 8$ for each state preparation that makes up $|0_{\mathrm{L}}\rangle$.

We expect further improvements in logical performance to be achievable with a larger distance code. Additionally, shorter measurement times used with soft information decoding may lead to superior logical performance.

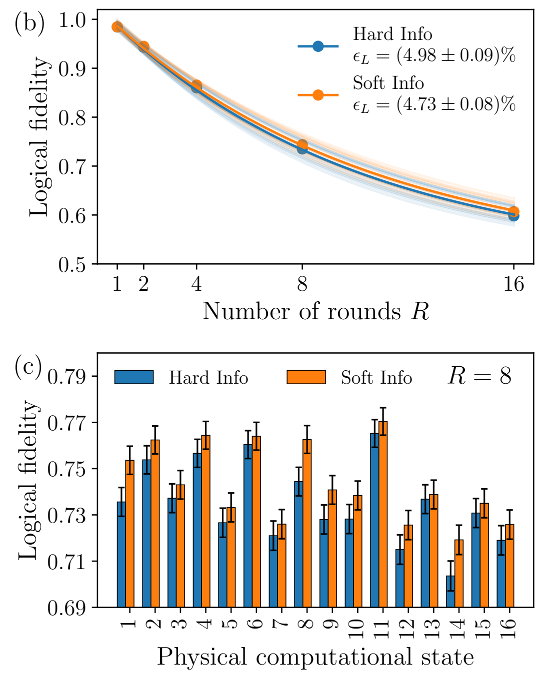

Fig. 3: (a) Logical fidelity of the NN decoder as a function of the number of rounds R. (b) Logical fidelity for $R = 8$ for each state preparation that makes up $|0_{\mathrm{L}}\rangle$.

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