Benchmarking the readout of a superconducting qubit for repeated measurements

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Readout of superconducting qubits faces a trade-off between measurement speed and unwanted back-action on the qubit caused by the readout drive, such as T_1 degradation and leakage out of the computational subspace. The readout is typically benchmarked by integrating the readout signal and choosing a binary threshold to extract the 騂readout fidelity騒. We show that such a charac- terization may significantly overlook readout-induced leakage errors. We introduce a method to quantitatively assess this error by repeatedly executing a composite operation 騷a readout preceded by a randomized qubit-flip. We apply this technique to characterize the dispersive readout of an intrinsically Purcell-protected qubit. We report a binary readout fidelity of 99.63% and quantum non-demolition (QND) fidelity exceeding 99.00% which takes into account a leakage error rate of 0.12 ± 0.03%, under a repetition rate of (380ns)$^{-1}$ for the composite operation.

Fast and accurate single-shot qubit readout is crucial for a multitude of quantum computing experiments in- cluding, measurement-based state preparation [1], entan- glement generation [2騳4] and quantum error correction (QEC) [5騳10]. Recent advancements in superconducting qubit readout coupled with near-quantum-limited mea- surement efficiency have made it possible to demonstrate quantum error correction with both surface code [8, 9] and bosonic codes [5騳7]. In these experiments, efficient entropy removal from the quantum system is achieved by repeated application of high fidelity readout and reset of the physical ancilla qubits. A quantum non-demolition (QND) measurement [11] perfectly correlates the post- readout state of the qubit with the readout outcome, alle- viating the need for unconditional reset [12] of the ancilla. A purely dispersive interaction between a qubit and its readout resonator would yield a QND readout scheme. In reality, this interaction is approximately realized in superconducting circuits [13] when an artificial atom is linearly coupled to the readout resonator. The linear hy- bridization of the qubit and the readout resonator leads to Purcell decay of the qubit. This prevents arbitrary increase of the qubit-resonator dispersive interaction χ_{qr} and the external coupling rate of the resonator κ_r, which sets a maximum speed of the readout for a given power. Moreover, at higher readout power, the dispersive ap- proximation breaks down [14], causing readout-induced leakage [15, 16] into the non-computational states of the physical qubit. These limitations prohibit the simultane- ous pursuit of the readout speed, fidelity and QND-ness.

In QEC, entangling operations and ancilla readouts are repeated, as illustrated in Fig.1. The readout-induced leakage errors can leave the ancilla in undesirable highly- excited states for multiple cycles, and can also spread into neighbouring qubits [17]. Thus, even a small leak- age probability poses a greater threat compared to dis- crimination error or Pauli error. Often, the 騂readout fi- delity騒 [1, 18騳23] extracted from the binary-thresholded outcomes is used as the only metric to experimentally optimize the readout parameters. While such a metric is sufficient to quantify the Pauli error (occurring during the readout process) and the discrimination error, it fails to faithfully identify readout-induced leakage, especially if the latter occurs with a low probability compared to other readout errors. The standard measure of QND-ness as the correlation of two successive binary readout out- comes [21騳23] also overlooks leakage when the readout outcomes of the leakage states predominantly fall on one side of the threshold. Therefore, such methods do not reflect the true character of the repeated readout opera- tions. Is there a complete way to benchmark the readout operation with binary outcome?

In this Letter, we demonstrate a novel readout bench- marking technique, 騂pseudo-syndrome detection騒, where we mimic a syndrome detection cycle in QEC by repeat- ing a composite operation騷a readout preceded by a ran- dom qubit flip. This method offers a faithful character- ization of the readout under repeated implementations and provides an accurate estimation of the readout QND- ness. We perform the dispersive readout on a Purcell- protected transmon. We optimize the readout pulses

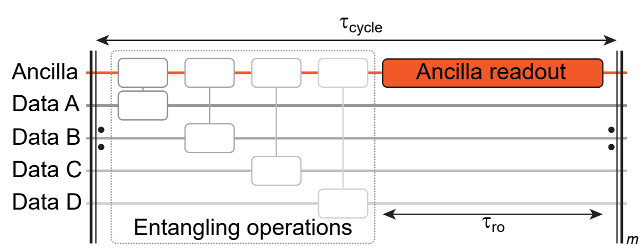

Figure 1. A syndrome detection cycle in QEC. Each cycle consists of an ancilla readout preceded by entangling opera- tions with data qubits, mapping the syndrome onto the an- cilla. We characterize the readout performance by mimicing this experiment on a single ancilla, with the 騂syndrome騒 arti- ficially generated by randomly applying identity and bit-flip operations.

b Add superconducting standard readings to repeated measurements

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The readings of the superconducting terminal face a trade-off between the measured speed and the adverse r eactions of quantum caused by the read driver, such as T_1 degradation and leakage from the computational sub space. Readings are usually extracted by integrating the reading signal and selecting a binary threshold to extra ct the reference standard for "reading fidelity". We show that this characteristic may greatly ignore read-induc ed leak errors. We introduce a method to quantitatively evaluate this error by repeatedly performing composite operations - read out before random quantum wings. We apply this technique to characterize the dispersion rea dings of quantums that are essentially protected by PERCELL. We report a fidelity of 99 . 63% and a fidelity of over 99 . 00%, considering a leak error rate of 0 . 12 ± 0 ± 0 . 03% at (380ns).

Fast and accurate single quantum weight readings are cruci al for a variety of quantum computing experiments, based on measured state preparation [1], entity generation [2-4], and q uantum error correction (QEC) [5-10]. Latest advances in sup erconducting quantum readings and the efficiency of near-qu antum confined efficiency make it possible to demonstrate qu antum error correction [5-7] through surface codes [8, 9] and bone codes [5-7]. In these experiments, effective entropy rem oval from quantum systems is achieved by repeatedly applyin g high-fidelity readings and resetting physical attachment qub its. Quantum non-disassembly (QND) measurement [11] perf ectly correlates the post-read state of the quantum with the re ading results, thus meeting the need for Ancilla's uncondition al reset [12]. The pure dispersed interaction between the quan tum and its readout resonators will produce a QND reading s cheme. In fact, this interaction is achieved approximately in s uperconducting circuits [13] when artificial atoms are linearl y coupled with the read resonator. Linear hybridization and r eadout of quantum resonators lead to the purcell decay of qua ntum. This prevents any increase in the external coupling rate of the Qubit resonator dispersed interaction χ_{qr} and the reson ator κ_r, which sets the maximum reading speed for a given p ower. In addition, at higher readout power, the dispersed appr oaches decomposition [14], resulting in a leak caused by read ings [15, 16] entering the non-computational state of the phys ical quantum. These restrictions prohibit the pursuit of readin g speed, loyalty and QND simultaneously.

As shown in Figure 1, in QEC, the entanglement operation and Ancilla readings are repeated. Leak errors caused by read outs may cause Ancilla to be in an adjacent quantum state at a height of multiple cycles [17]. Therefore, even a smaller pr obability of leakage poses a greater threat than a criminal err or or a Pauli error. Typically, the "reads" [1, 18-23] extracted from binary threshold results are used as the only experiment al indicator

Optimize reading parameters. Although such a measure is su fficient to quantify Pauli errors (occurring during readings) a nd discriminatory errors, it cannot faithfully identify leaks ca used by reads, especially with a lower probability compared to other reading errors. The standard metric of QND degree s erves as the correlation between two consecutive binary read ings, and leakage can also be ignored when the reading resul t of the leakage state falls mainly on one side of the threshol d. Therefore, this method cannot reflect the true characteristi cs of repeated read operations. Is there a complete way to be nchmark the read operation with binary results?

In this letter, we demonstrate a novel reading benchtop m arking technique, namely "pseudo-syndrome detection", in which we mimic the syndrome detection cycle in QEC by r epeating compound operations - read out the reading before the ran-dom Qubit Flip. This method provides a faithful rea d number under repeated implementations and provides an accurate estimate of reading QNDESS. We perform dispers ed readings on protected transmon. We optimized the read pulse

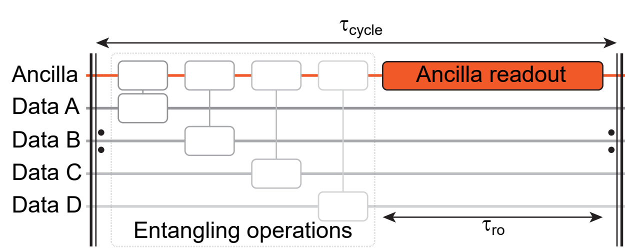

Figure 1. Syndrome detection cycle in QEC. Each loop consists of a n Ancilla read, which was previously an operation that sets the oper ation with the data volume, mapping the syndrome to An-Cilla. We characterize reading performance by mimicking this experiment of a single Ancilla, while "syndrome" forms "syndrome" in art by rand omly applying identity and wing-shaped manipulation.