Resource-efficient **SIMULATION** of noisy quantum circuits and application to **NETWORK-ENABLED QRAM** optimization

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QRAM

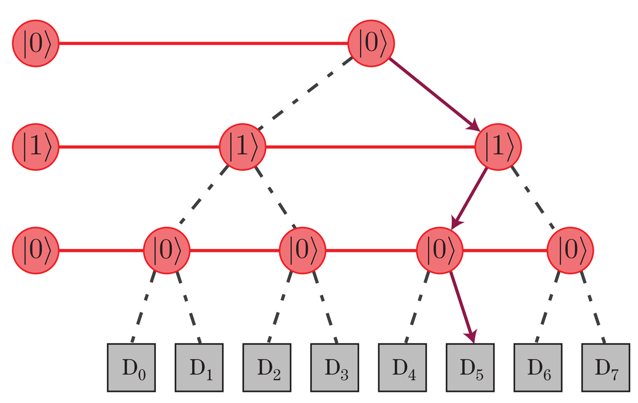
A quantum random access memory (QRAM) [1] is an essential computational primitive for many quantum algorithms. The ability to perform a QRAM query in log(N) time steps, where N is the number of memory cells, implies polynomial speed-ups for applications such as quantum machine learning, matrix inversion , quantum imaging, and quantum searching. However, finding a suitable architecture that can be realized in the near-future remains an active research subject in the theoretical and experimental domains.

[DEF]:

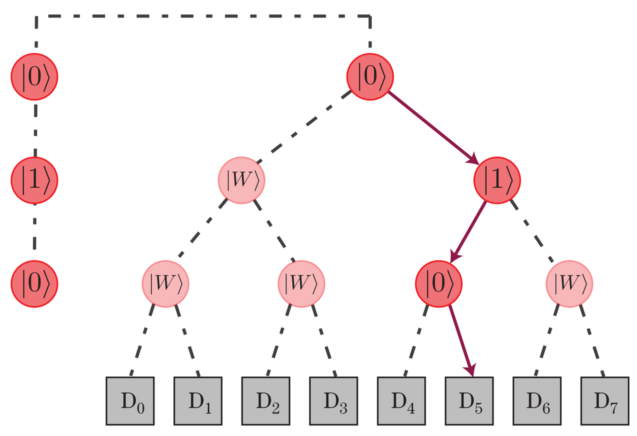
$$|\psi_{\text{in}}\rangle = |\psi'_{\text{in}}\rangle|\emptyset\rangle_b \xrightarrow{\text{QRAM}} |\psi_{\text{out}}\rangle = \sum_{j=1}^{N} \alpha_j |j\rangle_a |D_j\rangle_b$$

There are multiple architectures known in the literature to implement a QRAM, among them:

FANOUT MODEL:



BUCKET-BRIGADE MODEL:



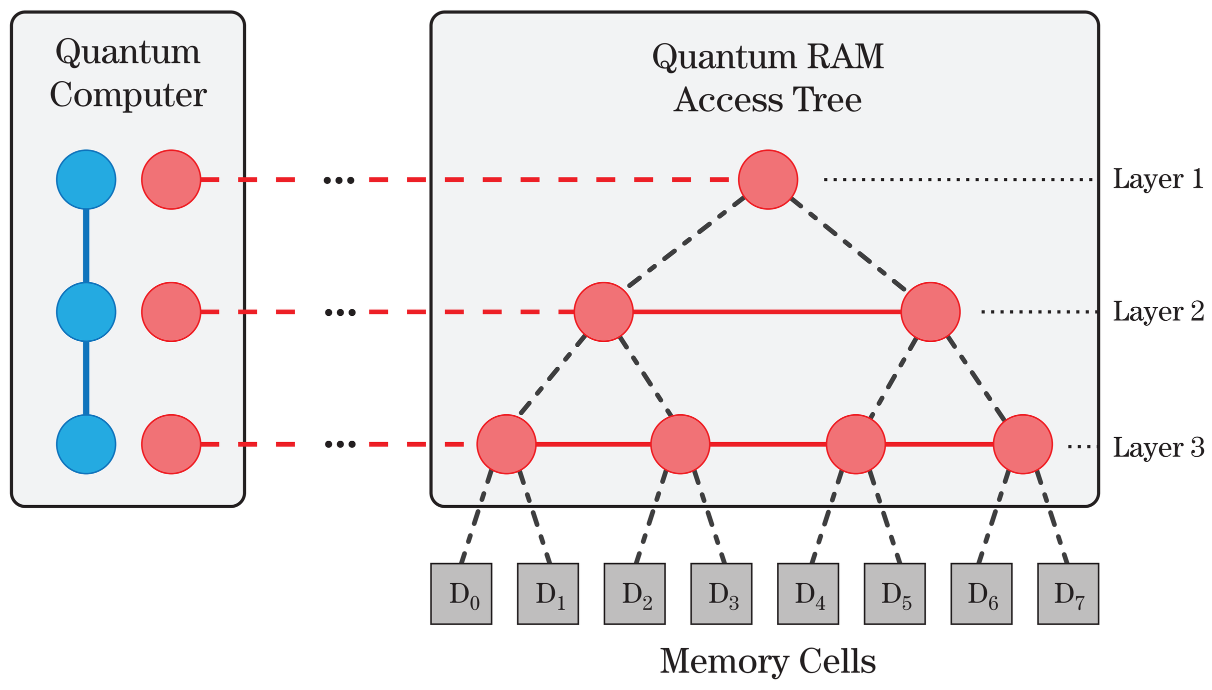


Figure 1. A quantum RAM in the form of a binary tree comprises GHZ states for each routing layer. The left-most node of each layer i is entangled with an ancillary qubit in a remote quantum computer, which hosts the query address qubits (blue). A Bell state measurement in the quantum computer then teleports the address state onto the access tree.

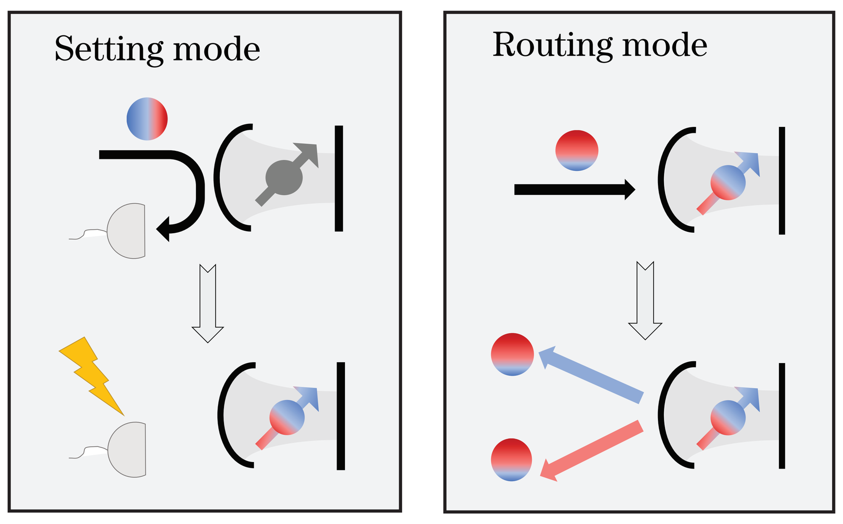
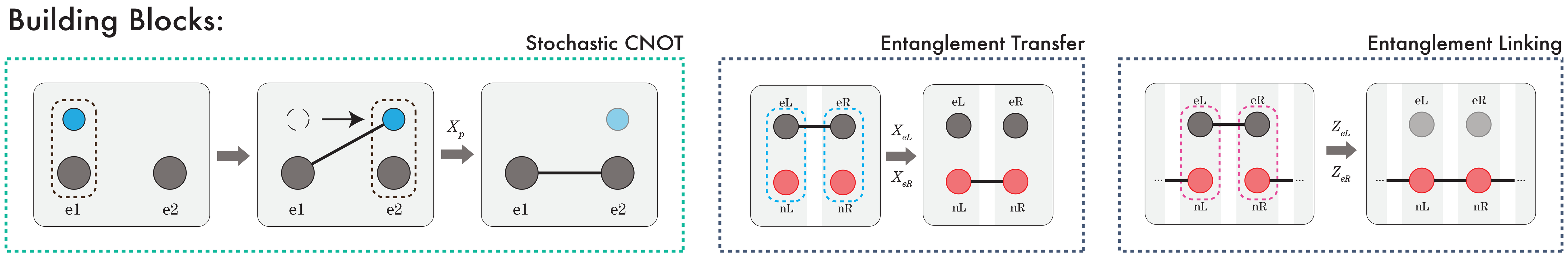


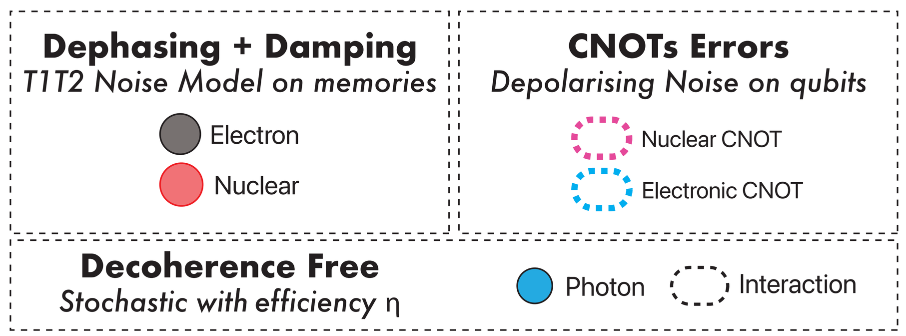
Figure 2. (a) detecting a cavity-reflected photon to herald successful mapping of a photonic address register qubit onto a stationary spin qubit (b) reflecting a subsequent photon to perform spin state-dependent quantum routing in a quantum switch.

Teleportation-based Protocols

Building Blocks:



Noise Sources:



Deterministic Protocol (TD-QRAM) [2]

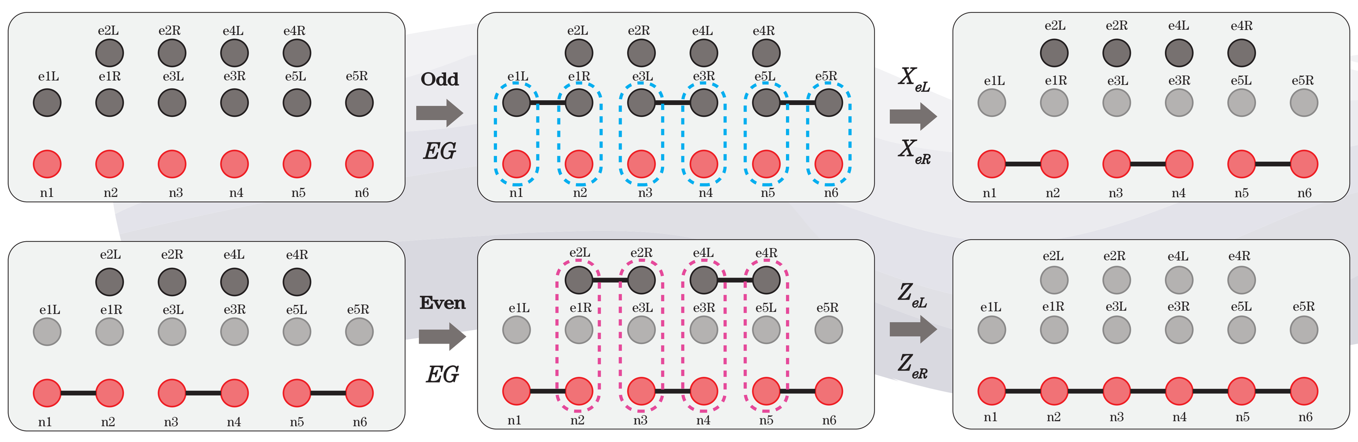
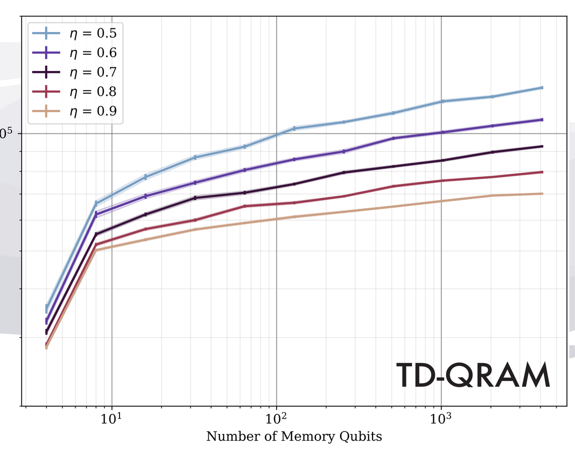
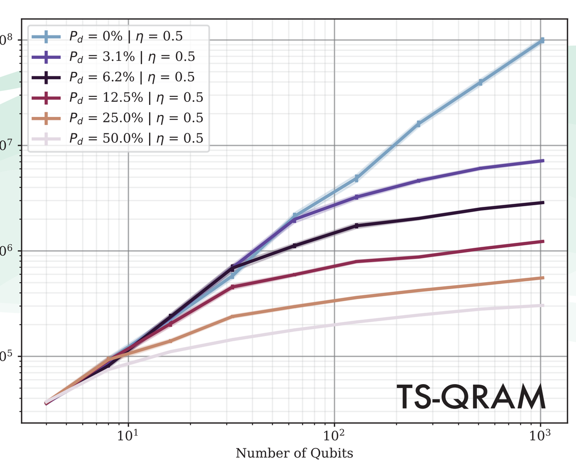


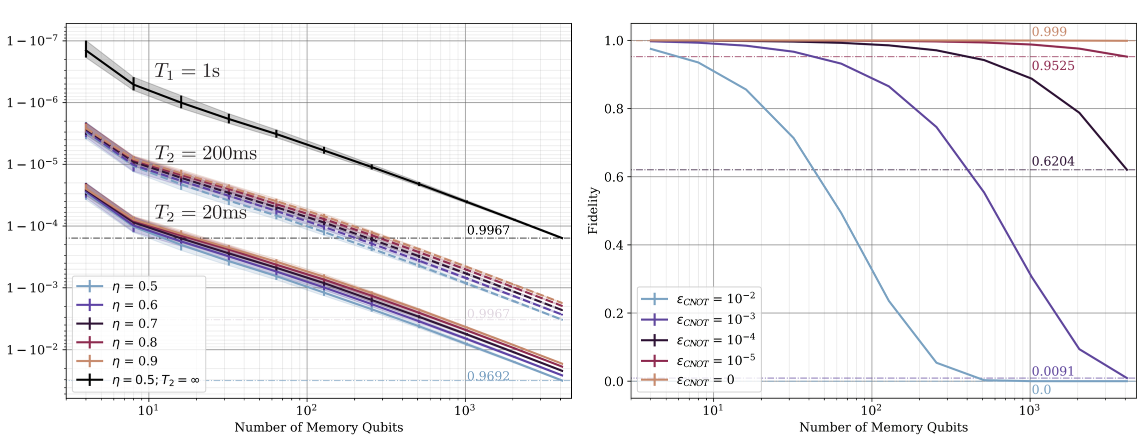
Figure 3. Example of the different steps in creating the GHZ state for a chain of 6-qubits (top) EPR pair creation along the odd-indexed links and transfer; (bottom) Linking of pairs by pre-sharing a EPR along the even-indexed links.

Query Time Scaling:





Fidelity Scaling of TD-QRAM:



Deterministic CNOT errors rapidly render the QRAM access fidelity useless!

Stochastic Protocol (TS-QRAM)

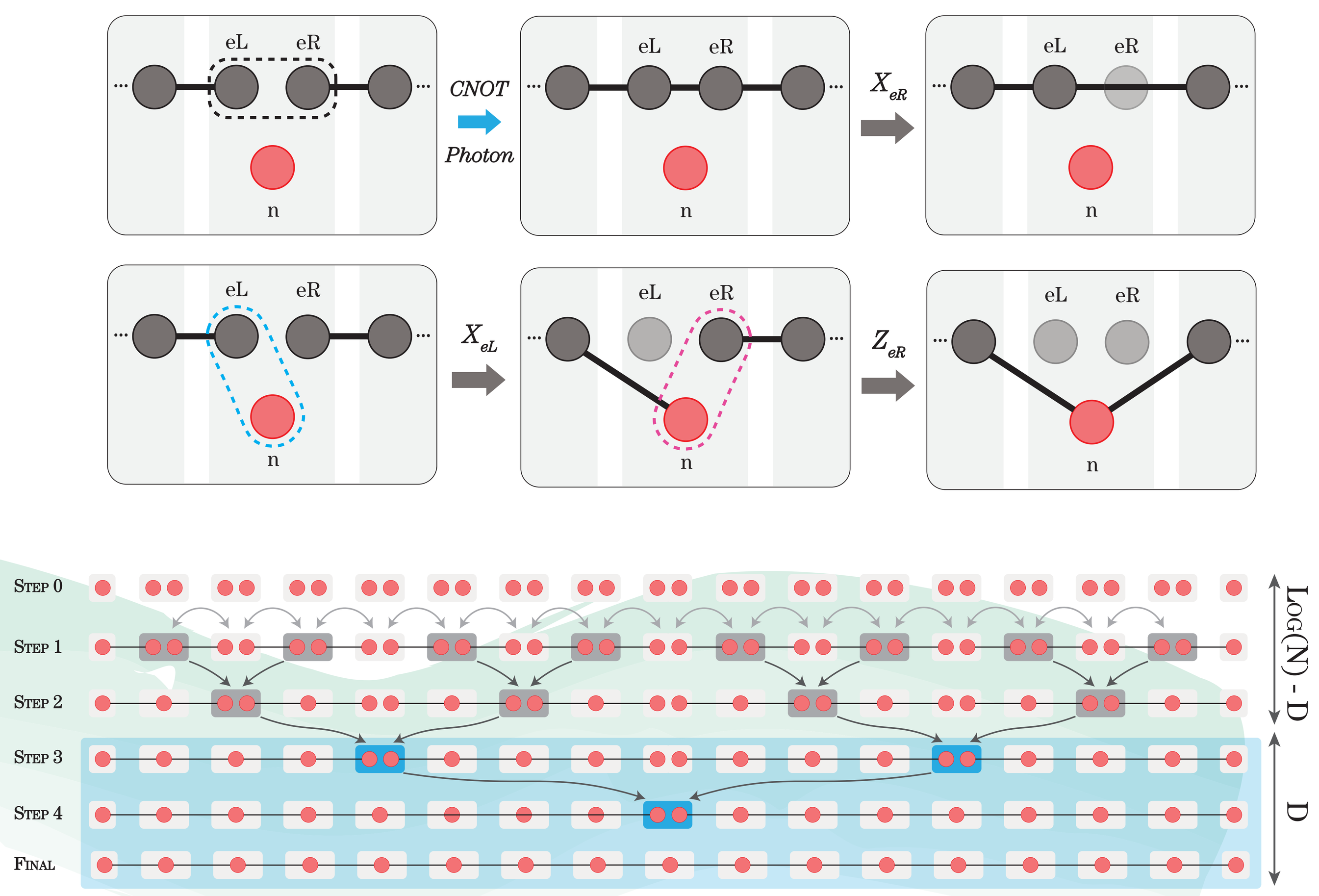
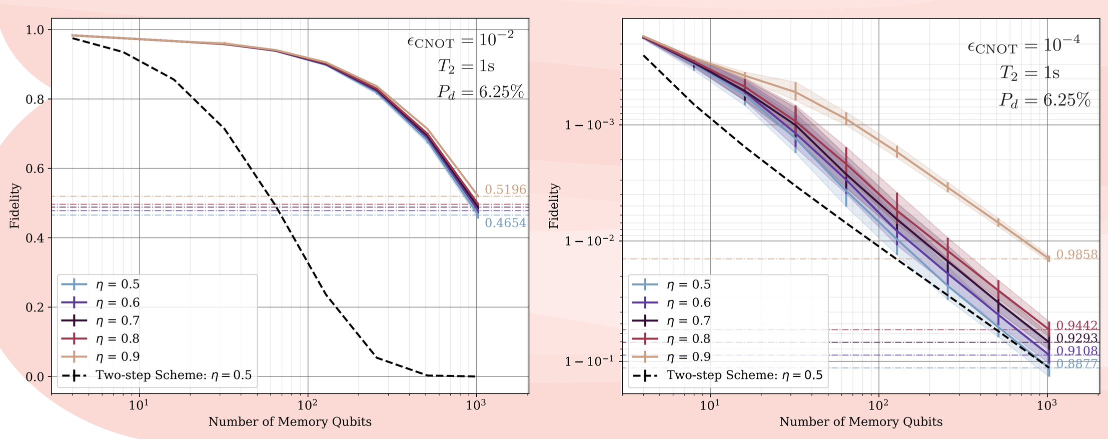


Figure 4. (top) Stochastic link of two different GHZ states; (middle) Deterministic link of two different GHZ states; (bottom) Order for the linking of pairs, where the last layers perform deterministic linking, instead of stochastic, to guarantee the correct query time scaling.

Fidelity Scaling of TS-QRAM:



- Better fidelity (CNOT errors bypassed)
- Query time verifying scaling
- Distributed-ready architecture

Simulation on NetSquid [3]

We have used NetSquid to simulate the protocol in a noiseless discrete-time event simulation, resorting to the stabilizer formalism in polynomial time. While doing so, we also retrieve all the information necessary to reconstitute all the noise from qubits spent decohering in memories, together with the information about the channels of decoherence that would have been applied in real noisy simulations, both for waiting times and gate errors. With this information at hand, we have access to the time-evolved state of the QRAM tree at all steps of the protocol. To reconstruct the density matrix, we find the analytical expressions for each of the building blocks. This is what allows to postpone the noise calculations to the end of the simulation, without losing the effects of the natural stochastic behavior of the protocol.

References:

[1] V. Giovannetti, S. Lloyd, and L. Maccone, Physical Review Letters 100, 160501 (2008)

[2] K. C. Chen, W. Dai, C. Errando-Herranz, S. Lloyd, and D. Englund, PRX Quantum 2, 030319 (2021)

[3] T. Coopmans, *et al.*, Communication Physics 4, 164 (2021)

Our work: arXiv:2210.13494

Acknowledgments:

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