Qubit Movement-Optimized Program Generation on Zoned Neutral Atom Processors

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Introduction

- Zoned architectures improve gate fidelity ($> 99.9\%$ for 1Q, $> 99.5\%$ for 2Q).
- Standard quantum program structures are inefficient on zoned architectures, requiring excessive zone-to-zone transfers.

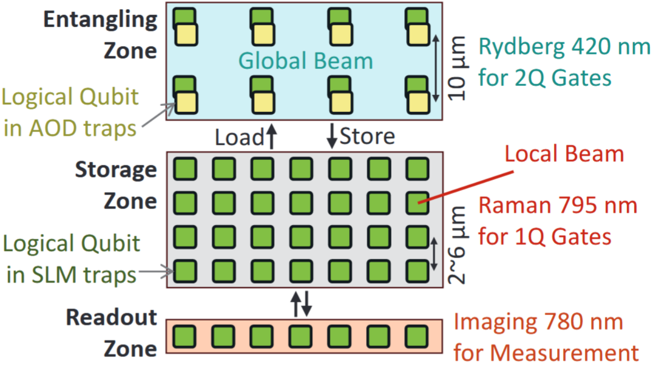


Figure: The entangling zone is dedicated to executing 2-qubit gates, while the storage zone is for single qubit gate.

Motivation

- Naïve program execution causes 78-89% of runtime to be spent on zone-to-zone qubit transfers.
- **Goal:** Optimize program execution by reducing inter-zone qubit movements.

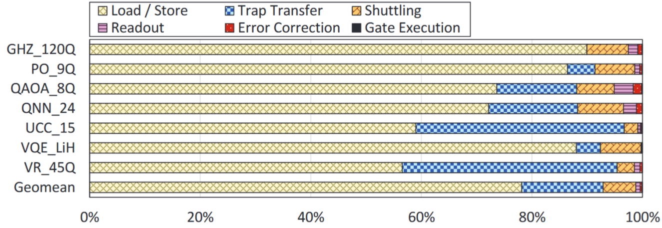


Figure: Execution time breakdown on zoned architectures.

Mantra: Key Techniques

Mantra (Minimizing trAp movemeNts for aTom aRray Architectures) introduces:

- **Fountain-Shaped CZ Chain:** Reduces single-qubit gate overhead and cancels intermediate gates..
- **Preemptive Gate Scheduling:** Executes independent gates earlier to minimize inter-zone transitions.
- **1Q-Gateless ZZ Interaction:** Replaces CZ-based decompositions with direct Rydberg-mediated ZZ rotations

Key Idea: Reduces inter-zone movements and improves overall execution efficiency by **rewriting quantum programs** to mitigate frequent transitions between single-qubit and two-qubit gate execution.

Fountain-Shaped CZ Chain

- Structure CZ chains around a common qubit.

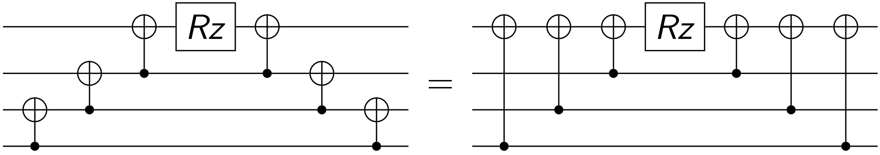


Figure: An example Hamiltonian simulation kernel $e^{-i\theta ZZZZ}$

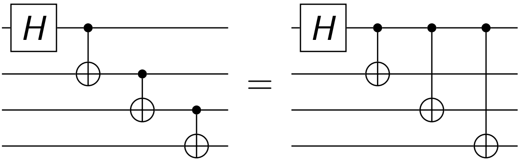


Figure: An example of a 4-qubit GHZ-state circuit.

Preemptive Gate Scheduling

- Identifies independent gates that can be executed earlier in the same zone.
- Reduces zone-to-zone movements while preserving computation dependencies.

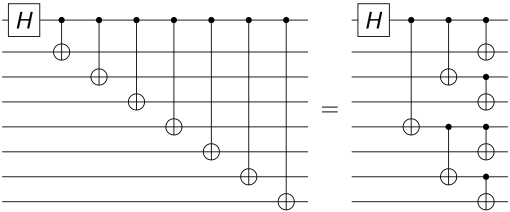
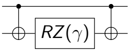


Figure: An example of a 8-qubit GHZ-state circuit.

1Q-Gateless ZZ Interaction

- **Mantra's approach:** Uses a combination of adiabatic and Levine-Pichler gates to achieve direct ZZ rotations.



$$= \boxed{LP(\gamma) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{-i\gamma} & 0 & 0 \\ 1 & 0 & e^{-i\gamma} & 0 \\ 1 & 0 & 0 & e^{2\gamma+\pi} \end{bmatrix}} \boxed{Ad(\phi_1, \phi_2) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & e^{\phi_2 - 2\phi_1} \end{bmatrix}}$$

Figure: The proposed arbitrary ZZ rotation protocol consisting of a single adiabatic (Ad) and a single Levine-Pichler (LP) gate, where $\phi_1 = (\pi + 2\gamma + \phi_2)/2$.

Results: Performance Improvement

Workloads	Logical Qubits	# of LD/STs (X-basis calculation is allowed.)			# of Physical Gates			Total Circuit Fidelity		
		Standard	Mantra	Reduced	Standard	Mantra	Reduced	Standard	Mantra	Improved
GHZ	40Q	78	10 (8)	87.2% (89.7%)	826	826	0.0%	0.75	0.76	1.5%
	80Q	158	2 (0)	98.7% (100.0%)	1,666	1,666	0.0%	0.56	0.57	2.6%
	120Q	238	2 (0)	99.2% (100.0%)	2,506	2,506	0.0%	0.42	0.43	3.1%
PO	3Q	36	6	83.3%	322	259	19.6%	0.89	0.89	0.9%
	6Q	180	6	96.7%	1,596	1,281	19.7%	0.55	0.58	4.6%
	9Q	432	6	98.6%	3,808	3,052	19.8%	0.24	0.27	11.4%
QNN	8Q	46	16	65.2%	959	567	40.9%	0.68	0.71	5.8%
	16Q	94	32	66.0%	3,731	2,051	45.0%	0.21	0.27	28.6%
	24Q	142	48	66.2%	8,295	4,431	46.6%	0.03	0.11	73.7%
UCC	5Q	160	40	75.0%	1,680	707	57.9%	0.57	0.65	14.9%
	10Q	360	40	88.9%	3,780	1,407	62.8%	0.28	0.40	40.0%
	15Q	560	40	92.9%	5,880	2,107	64.2%	0.14	0.24	71.5%
VR	15Q	84	84	0.0%	910	588	35.4%	0.74	0.78	4.7%
	30Q	174	174	0.0%	1,855	1,218	34.3%	0.54	0.59	9.7%
	45Q	264	264	0.0%	2,800	1,848	34.0%	0.39	0.45	14.6%
Geometric Mean		153.6	20.6 (18.5)	86.6% (87.9%)	2,010.1	1,297.8	35.4%	0.37	0.43	17.1%

Figure: Mantra reduces inter-zone movements by 86.6%, also reduces physical gate counts by 35%, improving overall fidelity by 17%

Execution Breakdown According to Compiler

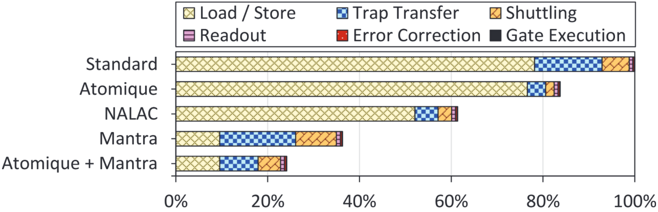


Figure: Execution time breakdown analysis. Combining Atomique and Mantra could further enhance the performance of zoned architectures.

Conclusion

- Zoned neutral atom architectures have high gate fidelities but suffer from slow qubit movement.
- Mantra optimizes qubit movement but depends on CZ-chain flexibility. Fixed-structure circuits cannot benefit from it.
- Results demonstrate significant reductions in execution time and improved fidelity.

Discussion: Co-desgin between Mapping with Synthesis

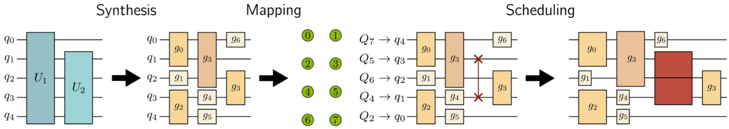


Figure: Illustration of the three steps for platform-dependent compilation.