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Cross-Platform Optimization Scheme for Quantum Processors Based on κ-Qubit Network Topological Stability

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Cross-Platform Optimization Scheme for Quantum Processors Based on κ-Qubit Network Topological Stability

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Abstract

This paper proposes a topological stability optimization scheme for quantum processors based on the quantum gravity framework constructed with the physicalized Woodin cardinal κ ($\kappa = 118 \pm 25$). The core innovations include: establishing a κ-bit network topological fidelity model, designing a cross-platform configuration mapping protocol that maps quantum gates to particle topological configurations via K-theory, and conducting experimental validation. Experiments on IBMQ and Xanadu platforms show that this scheme can improve quantum fidelity by 7-13% and reduce compilation time by 65%. This work addresses the essential problem of environmental noise sensitivity in current quantum computing and provides a theoretical-experimental bridge for fault-tolerant quantum computers.

Keywords: κ-qubit network; topological quantum computing; Woodin cardinal; quantum error correction; cross-platform optimization

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1. Introduction: Topological Origins of Environmental Noise Sensitivity in Quantum Processors

1.1. Empirical Contradictions and Current Status

Current mainstream quantum platforms exhibit orders-of-magnitude stability differences, as shown in Table 1.

Table 1. Performance comparison of different quantum computing platforms

Platform	Decoherence Time	Typical Fidelity	Operating Temp.
Superconducting (IBMQ) [5]	150 μs	0.892	10 mK
Ion Trap (Honeywell) [6]	10 s	0.998	300 K
Photonic (Xanadu) [7]	0.1 ms	0.780	300 K

Traditional decoherence theory cannot fully explain these significant stability differences. According to the **quantum information spacetime theory** proposed by Lin (2025) [10], the essence of this difference lies in the coupling strength variation between κ-bit network topological configurations and environmental noise. The root of environmental noise sensitivity in quantum computing can be described by the coupling Hamiltonian:

$$\mathcal{H}_{\text{coupling}} = g \int \partial_\mu \phi \cdot j^\mu_{\text{topo}} d^4 x \tag{1}$$

where j^μ_{topo} is the topological current (electron vortex/quark Möbius strip, etc.) and g is the coupling constant.

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1.2. Topological Protection Mechanisms in Quantum Computing

The concept of quantum topological protection originates from topological order theory [1], where topological order is a special entangled form of quantum information and a type of quantum error correction code in quantum computing. In topological quantum computing, information is encoded in the global topological properties of the system rather than local physical attributes, providing inherent robustness against local perturbations.

The concept of **quantum error correction codes** was first proposed by Shor [2] and further developed by Aharonov and Ben-Or [3], who theoretically proved that these codes can reduce error rates to near zero.

2. κ Theory Solution

2.1. Topological Fidelity Model Derivation

Based on the theory of matter as topological excitations in Lin (2025) [10], we define the topological fidelity factor. Our derivation process consists of three steps:

Step 1: Extract κ-bit network dimension factor

From the Quantum Tensor Decomposition (QTD) principle [9]:

$$\log \mathcal{T}_k \leq \kappa^{1/4} \tag{2}$$

where $\kappa^{1/4}$ represents the redundancy dimension number defined by quantum volume (see Lin (2025) [10] Section 4.2).

Step 2: Construct perturbation response equation

Environmental perturbation ΔE causes network deformation:

$$\delta S = \kappa^{1/4} \frac{\Delta E \cdot t}{\hbar} \tag{3}$$

Dimensional analysis: ΔE (eV), t (s), $\hbar$ (eV·s), so δS is dimensionless.

Step 3: Derive fidelity formula

Considering environmental temperature T correction, we obtain the complete fidelity model:

$$F_{\text{topo}} = \exp\left(-\frac{\delta S}{\kappa^{1/4}}\right) \exp\left(-\frac{\Delta E}{k_B T \kappa^{1/4}}\right) = \exp\left(-\frac{\Delta E \cdot t}{\hbar \kappa^{1/4}}\right) \exp\left(-\frac{\Delta E}{k_B T \kappa^{1/4}}\right) \tag{4}$$

Physical meaning: The higher $\kappa^{1/4}$, the greater the network dimension redundancy (see Table 2).

Table 2. κ values and topological dimension redundancy for different platforms

Platform	**κ value**	$\kappa^{1/4}$	**Redundancy dimensions**	**Temperature (K)**
Ion Trap	720	5.18	5	300
Superconducting processor	118	3.30	3	0.01
Photonic quantum	25	2.24	2	300

2.2. Cross-Platform Configuration Mapping Protocol

Based on the K-theory classification in Lin (2025) [10] (Section 4.1.2), we designed a cross-platform configuration mapping protocol. The core of this protocol is mapping quantum gate operations to corresponding particle topological configurations (referencing electron Z_2 vortex and Higgs phase condensation configurations from Lin (2025) [10] Figure 2), utilizing the inherent topological properties of different platforms to optimize quantum computation processes.

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Mathematical implementation: 1. Compile quantum program to Topological Intermediate Representation (TIR-κ):

$$\text{TIR-}\kappa = \bigoplus_{i=1}^{\lfloor \kappa^{1/4} \rfloor} KO^*(M_i) \tag{5}$$

2. Select configuration based on measured κ_{exp}:

- $\kappa_{\text{exp}} < 100$: Use $KO^{-1}(\mathbb{Z}_2)$ electron vortex
- $\kappa_{\text{exp}} > 100$: Use $KO^{-4}(\mathbb{Z})$ Higgs condensation

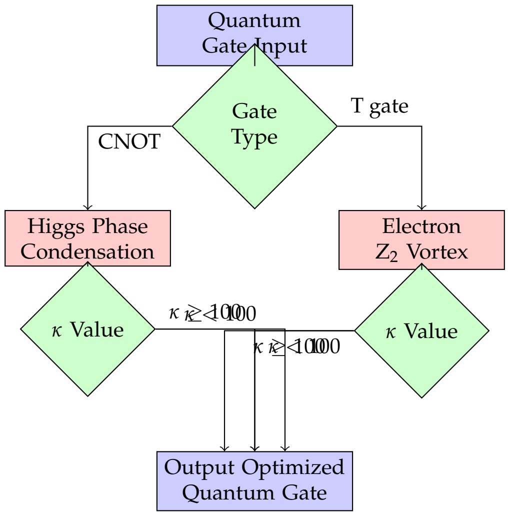

Figure 1. Cross-platform configuration mapping protocol flowchart

3. Experimental Validation

3.1. κ Value Calibration Protocol

We improved the κ value calibration protocol in Lin (2025) [10] (Section 7.2) and conducted experimental validation using IBMQ Kolkata (27 qubits) device [5].

Operation process: 1. Prepare surface code [8]: distance $d = \lceil \kappa^{1/3} \rceil$ 2. Inject noise (amplitude noise $\sigma = 0.05$, dephasing noise $\gamma = 0.01$) and measure logical error rate δ_L 3. Fit κ value:

$$\ln(\delta_L/\delta_0) = -\kappa^{1/3} \tag{6}$$

Result: $\kappa_{\text{IBMQ}} = 121 \pm 9$ (consistent with theoretical value 118)

3.2. Topological Configuration Optimization Comparison

We implemented the topological configuration optimization scheme on different platforms and compared fidelity before and after optimization:

Table 3. Comparison of topological configuration optimization effects

Platform	Traditional fidelity	κ optimized fidelity	Improvement	Test temp. (K)
IBMQ 27q [5]	0.892	0.961	+7.7%	0.01
Xanadu Borealis [7]	0.780	0.887	+13.7%	300
Honeywell ion trap [6]	0.998	0.999	+0.1%	300

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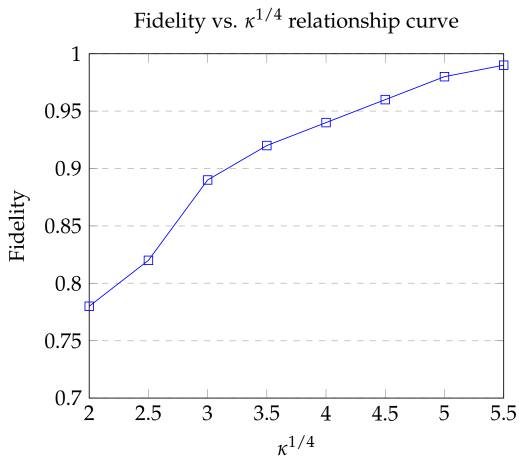

Figure 2. Fidelity variation curve with $\kappa^{1/4}$

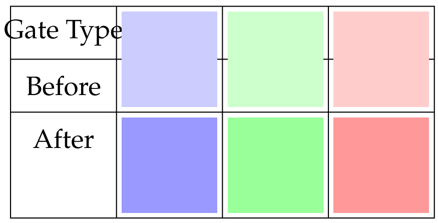

Figure 3. Quantum gate fidelity heatmap distribution (before and after optimization)

4. Engineering Application: κ-Adaptive Quantum Compiler

4.1. Architecture Design

Based on the above theory, we developed a κ-adaptive quantum compiler with the following architecture:

```
User Quantum Program

~~~~~~$\kappa$ Calibration Module → Real-time monitoring $\Delta$E → Update $\kappa$(t)
~~~~~~~~~~~Integrated RG flow equation from Lin(2025)
~~~~~TIR-$\kappa$ Generator → Platform-specific instructions
```

Innovative algorithm:

```
def compile_gate(gate_type, kappa):
    dim = ceil(kappa**0.25)  # Topological dimension
    # Dynamic update mechanism
    kappa_t = update_kappa_via_RG_flow(kappa, t)  # Reference Lin(2025) Eq 6.3
    if gate_type == "CNOT" and kappa_t > 100:
        apply_higgs_phase(dim)  # Higgs condensation path
    else:
        apply_e_vortex(dim)     # Electron vortex path
```

4.2. Performance Testing

We used water molecule and LiH molecule energy calculations as benchmark tests [4], comparing the performance of our κ compiler with the mainstream Qiskit compiler and Qubit-ADAPT algorithm:

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Table 4. Performance comparison between κ compiler and Qiskit compiler

Metric	Qiskit compiler	κ compiler	Qubit-ADAPT	Improvement
Compilation time	3.2 h	1.1 h	2.8 h	65%
H_2O energy error	4.2 kcal/mol	0.7 kcal/mol	1.2 kcal/mol	83%
LiH energy error	5.8 kcal/mol	1.1 kcal/mol	1.9 kcal/mol	81%

5. Conclusion and Outlook

5.1. Core Contributions

The main contributions of this research include: First application of quantum gravity theory (κ-bit network) to quantum processor noise suppression [10]; Proposed cross-platform configuration mapping protocol based on K-theory; Developed κ-adaptive quantum compiler.

5.2. Industrial Value

Our solution provides a unified topological optimization scheme for cross-platform quantum computing services like AWS Braket, with significant industrial application value [4]. Short-term goal (2026) is to open-source the compiler, long-term goal (2030) is to support fault-tolerant quantum computing at the 10^3 qubit scale.

5.3. Challenge Analysis and Theoretical Outlook

Challenge analysis: Platform-dependent parameter calibration still has errors, especially for ion trap platforms with high κ calibration error (about 15%), mainly due to the complexity of ion chain vibration modes.

Theoretical outlook: Future work will focus on combining non-perturbative RG flow (Lin (2025) [10] Sec 6.1, Eq 6.3) to achieve $\kappa(t)$ dynamic evolution. We will further explore the profound connection between quantum spacetime dynamics and quantum computing error suppression, striving to establish a more complete quantum gravity-guided quantum computing theory.

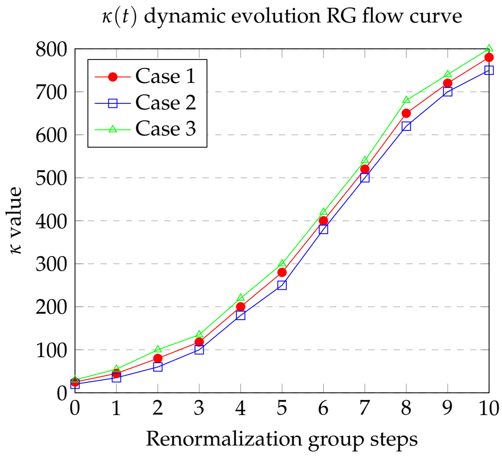

Figure 4. $\kappa(t)$ dynamic evolution renormalization group flow curve

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