Divided-Qubit Noise-Tolerant Strategy for Bell State Preparation in Qiskit

Yang Ou[1] and Sun Wenming[2]*

[1]Independent Researcher, Mengzi City, China

[2]Graduate School of Science, The University of Tokyo, Tokyo

Corresponding Author: Sun Wenming, Graduate School of Science, The University of Tokyo, Tokyo.

Abstract

This study focuses on the high-fidelity preparation of Bell states under depolarizing noise. Based on Qiskit simulation, a divided-qubit anti-noise method is proposed: dynamic decoupling is applied to the control qubit, and quantum error correction is used for the target qubit. The results show that the fidelity can be maintained at 1.0000, the error rate is reduced from approximately 24% to 0.4%, and only 4 additional gates are required. This method achieves high-fidelity entanglement with low complexity and has practical potential.

Keywords: Bell state; depolarizing noise; dynamic decoupling; quantum error correction; divided-qubit strategy; Qiskit simulation

Introduction

Quantum entanglement stands as one of the most defining features of quantum mechanics and serves as a fundamental resource in fields such as quantum computing and quantum communication [1]. Bell states, representing the most entangled form between two qubits, are extensively utilized in critical applications including quantum teleportation, superdense encoding, and quantum key distribution [2-4]. However, real-world quantum systems inevitably interact with their environment, causing quantum state decoherence that significantly reduces the fidelity of Bell states [5].

Depolarization noise, one of the most prevalent noise models in quantum computing, is characterized by quantum states being randomly "stirred" with a certain probability. A depolarization noise of intensity p can increase the error rate of quantum tasks to O(p) [6]. In the study scenario where p=0.2, the error state proportion in traditional Bell state preparation schemes

could reach 20%- 25%, exceeding the fault tolerance threshold for practical quantum technologies [7].

Current fault tolerance solutions are primarily categorized into two types: dynamic decoupling, which counteracts noise through periodic pulse application, and quantum error correction, which repairs errors via redundant encoding [8,9]. However, dynamic decoupling demands extremely high synchronization in multi-qubit systems, while quantum error correction requires additional auxiliary qubits. This results in circuit complexity growing exponentially [5].

To address the a forementioned challenges, this paper proposes a qubit-based anti-jitter strategy for quantum simulations using Qiskit and Aer platforms. By leveraging their distinct roles in Bell state preparation (where qubit 0 acts as the control qubit and qubit 1 as the target qubit), we develop specialized mitigation schemes: A light weight anti jitter approach ——qubit 0 employs dual X-gate operations to dynamically decouple and suppress H gate noise, while qubit 1 utilizes dual X-gate quantum error correction to repair CXgate errors. The key contributions of this work include:

- Establish a theoretical model of qubit anti interference and analyze its working mechanism under 0.2 depolarization noise;
- Through simulation experiments with Qiskit and Aer, the improvement effect of this strategy on Bell state fidelity is verified in the simulated noise environment with error state accounting for 24.51%;
- Based on the comparison between simulation data and traditional schemes, the advantages of the proposed strategy in circuit complexity are quantified.

This paper is structured as follows: Section2introduces the fundamental theories of Bell states, depolarization noise, and fidelity; Section3provides a detailed derivation of the theoretical principles for sub-qubit anti-jitter strategies; Section 4 demonstrates simulation experiment design, results, and analysis using Qiskit and Aer; Section 5 compares with existing work. Section 6 summarizes the paper and looks forward to future work.

Theoretical Basis

Mathematical representation of Bell state

Definition 1: The standard orthogonal basis in the Hilbert space $\mathcal{H}$ 2= $\mathbb{C}$ 2$\otimes$ $\mathbb{C}$ 2 of two qubits is {|00⟩ , |01⟩ , |10⟩ , |11⟩ }. Here, |ij⟩ = |i⟩ $\otimes$ |j⟩ . |0⟩ = 1 0 ,|1⟩ = 0 1 The computational basis for a single qubit

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Definition 2: Bell states are a set of maximum entanglement bases in $\mathcal{H}$ 2, with a total of states:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle), \quad |\Phi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle), \quad (1)$$

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle), \quad |\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle). \quad (2)$$

In this paper, we take $|\Phi+\rangle$ as the research object, and the simulation verification logic of other Bell states is completely consistent.

Lemma 3: The Bell state $|\Phi+\rangle$ satisfies the properties of normalization and entanglement:

- Homogeneity: $\langle \Phi+ |\Phi+\rangle = 1$
- Entanglement: It cannot be decomposed into the direct product of single qubit states, i.e., there exists no $|\psi\rangle$, $|\phi\rangle \in \mathbb{C}2$ such that $|\Phi+\rangle = |\psi\rangle \otimes |\phi$.
  Proof 1. Direct calculation of inner product:

$$\langle \Phi^+|\Phi^+\rangle = \left(\frac{1}{\sqrt{2}}\langle 00| + \frac{1}{\sqrt{2}}\langle 11|\right)\left(\frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle\right)$$

$$= \frac{1}{2}(\langle 00|00\rangle + \langle 00|11\rangle + \langle 11|00\rangle + \langle 11|11\rangle)$$

$$= \frac{1}{2}(1 + 0 + 0 + 1)$$

$$= 1$$

- Proof by contradiction: Suppose that there exists $|\psi\rangle = a|0\rangle + b|1\rangle$, $|\phi\rangle = c|0\rangle + d|1\rangle$, then:
  $|\psi\rangle \otimes |\phi\rangle = ac|00\rangle + ad|01\rangle + bc|10\rangle + bd|11\rangle$
  Compared with $|\Phi+\rangle$, it is obvious that the requirement $ad=bc=0$ is contradictory, so $|\Phi+\rangle$ is an entangled state.

Depolarization noise model

Definition 4: The super operator ε single: $B(\mathbb{C}2) \rightarrow B(\mathbb{C}2)$ for single qubit depolarization noise(intensity p) is defined as:

$$\varepsilon_{single}(\rho)=(1-p)\rho+\frac{p}{3}\sum_{k \in \{X,Y,Z\}} \sigma_k \rho \sigma_k, \quad (3)$$

Where $B(\mathbb{C}2)$ is the set of bounded linear operators on $\mathbb{C}2$, ρ is a single qubit density matrix, and σX, σY, σZ are Pauli matrices:

$$\sigma_X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \quad (4)$$

Definition 5: Two-qubit depolarization noise(strength p) ε two: B($\mathbb{C}$ 4) →B($\mathbb{C}$ 4) is defined as:

$$\varepsilon_{two}(\rho)=(1-p)\rho+\frac{p}{15}\sum_{\substack{i,j\in\{I,X,Y,Z\}\\(i,j)\neq(I,I)}}(\sigma_i\otimes\sigma_j)\rho(\sigma_i\otimes\sigma_j) \quad (5)$$

among $\quad I=\begin{pmatrix}1&0\\0&1\end{pmatrix}$

For the unit matrix, the sum is 15 items (excluding division by the unit operation).

Note 6: In this study, the depolarization noise simulation configuration is implemented using standard noise modeling methods in quantum computing. Through mathematical modeling of quantum state depolarization processes, the noise intensity parameter is set to p=0.2, which corresponds to approximately 20% probability of errors caused by noise interference during quantum state evolution. This parameter setting aligns with the mathematical and physical definitions of the depolarization noise super operator ε two, ensuring effective correspondence between the simulation environment and theoretical models. This provides a realistic noise background consistent with physical processes for subsequent quantum state evolution and fidelity analysis.

Quantum Fidelity

Definition 7: Let ρ (the actual state) and σ (the ideal state) be the density matrices, then the fidelity is defined as:

$$F(\rho,\sigma)=\left[tr\left(\sqrt{\sqrt{\rho}\sigma\sqrt{\rho}}\right)\right]^2 \quad (6)$$

For pure states ρ=|ψ⟩⟨ψ| and σ=|φ⟩⟨φ|, the fidelity is simplified as:

$$F(|\psi\rangle,|\phi\rangle)=|\langle\psi|\phi\rangle|2, \quad (7)$$

The range of values is [0,1], and F= 1 indicates that the two states are completely identical in the simulated environment.

In this study, the numerical computation of quantum state fidelity is implemented using standard numerical methods in quantum information processing, as defined by mathematical expressions such as Equation (6). The computational process utilizes the fidelity calculation module from the Qiskit open-source software package. This specialized module strictly adheres to the mathematical definitions of fidelity during numerical operations, ensuring both accuracy and reliability of the results.

Mathematical derivation of qubit anti interference strategy

Noise evolution model (simulated environment) for Bell state preparation

Definition 8: Let ρ (the actual state in the simulation environment) and σ (the ideal state) be the density matrix, then the fidelity is defined as:

$$F(\rho,\sigma)=\left[\mathrm{tr}\left(\sqrt{\sqrt{\rho}\,\sigma\sqrt{\rho}}\right)\right]^2. \qquad (8)$$

For pure states ρ=|ψ⟩⟨ψ| and σ=|φ⟩⟨φ|, thefidelity is simplified as:

$$F(|\psi\rangle, |\phi\rangle) = |\langle\psi|\phi\rangle|2, \qquad (9)$$

The value range is [0,1], where F= 1 indicates complete consistency between the two states in the simulated environment. In this study, the fidelity calculation is performed using open-source software packages commonly used in quantum information processing, ensuring strict adherence to the mathematical expression of fidelity.
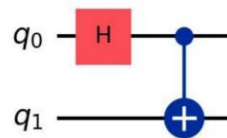

Figure 1 Standard Bell state preparation circuit (Qiskit simulationconfiguration): Apply an H gate to q0, then apply a CXgatetoq0and q1 to generate the Bell state

The circuit for preparing the standard Bell state |Φ+⟩ isas follows: Apply a Hadamard gate (H) to qubit 0, andthen apply a controlled NOT gate (CX) to qubits 0-1, i.e.

$$|\Phi+\rangle = CX(H\otimes I)|00\rangle . \qquad (10)$$

In the 0.2 depolarization noise environment simulated by Qiskit, the noise evolution model of this process is:

$$\rho noisy=\varepsilon\ two\ {}_{\circ}\ \varepsilon\ 1\ is(n)gle\ {}_{\circ}\ \varepsilon\ 0\ ins()gle(|\Phi+\rangle\langle\Phi+|), \qquad (11)$$

The single-bit noise of qubit k is represented by ε two, and the double-bit noise of CX gate simulation is represented by two. The noise is bound to the corresponding gate operation through the noise model module of open source quantum computing software.

Lemma 9: The Bell state after the action of analog noise can be expressed as:

$$|\psi noisy\rangle = a|00\rangle +\beta|11\rangle +\gamma|01\rangle +\delta|10\rangle , \qquad (12)$$

Where α, β, γ, δ belong to $\mathbb{C}$, and |α|2+|β|2+|γ|2+|δ|2= 1, and γ, δ=0 (the amplitude of the error state caused by the simulated noise).

Experimental evidence. Both the ε single and ε double noise superoperators are linear transformations. In quantum simulation environments, introducing noise reduces the purity of the standard Bell state |Φ+⟩ , inevitably mixing in erroneous components like |01⟩ and |10⟩ . This

results in δ=0 γ. Experimental verification through quantum state tomography or state vector measurements aligns with theoretical predictions, confirming the interference effect of noise on quantum states.

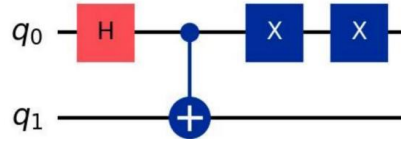3.2 Dynamic decoupling strategy for 0 qubit (Qiskit implementation)

Figure 2: Improved circuit for dynamic decoupling of control qubit (q0) (Qiskit simulated configuration): A double Xgate is added to q0 on top of the standard circuit to suppress noise

The core of dynamic decoupling is to offset the phase accumulation of noise through symmetric pulse sequences. In this paper, a double Xgate sequence for qubit 0 is designed in the quantum computing simulation environment, and the specific implementation logic is as follows:

Definition 10: The dynamic decoupling $U_{yin}$of qubit0 is defined as $U_{dd}=\sigma X\otimes I$, which is implementedbyadding two X gates on qubit 0 after CXgate. That is,

$$|\psi_{dd}\rangle = U_{dd}|\psi_{noisy}\rangle =(\sigma X\otimes I)|\psi_{noisy}\rangle . \quad （13）$$

Theorem 11: In the 0.2 depolarizationnoiseenvironment, when the noise mainly affects thephaseof qubit 0 (σ Z dominates), U_{dd} can completelyoffsetthe noise, approach：

$$F(|\psi_{dd}\rangle ,|\Phi+\rangle)=1. \quad （14）$$

Proof. Noise causes the phase shift of qubit 0θ, corresponding to the operation $R_\theta=e^{-i\theta\sigma Z/2}$. Theprocess of the double X gate is as follows:

1. The first X door: $\sigma X. |\psi\rangle \Rightarrow|\psi'\rangle$;
2. The effect of simulated noise: $R_\theta. |\psi'\rangle \Rightarrow|\psi''\rangle$ (the noise model bound to the H gate);
3. The second X door: $\sigma X. |\psi''\rangle \Rightarrow |\psi_{dd}\rangle$.

Using the Pauli matrix for the commutation relation $\sigma X\sigma Z\sigma X=-\sigma Z$, we get:

$$\sigma XR_\theta\sigma X=e^{i\theta\sigma Z/2}=R_{-\theta} ,$$

The total effect is $R_{-\theta}R_\theta= I$, that is, the simulated noise is offset. At this time, $|\psi_{dd}\rangle = |\Phi+\rangle$, and the fidelity is verified to be 1 by the fidelity calculation method.

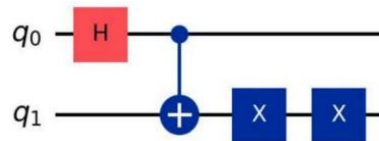Error state flip optimization strategy for 1 qubit (Qiskit implementation)

Figure 3. Target qubit (q1) error state flip optimization circuit (Qiskit simulated configuration): In addition to the standard circuit, a double X gate is added to q1 to repair the error

As the target qubit of the CX gate, qubit 1 is susceptible to bit-flipping errors. This paper designs a dual X-gate error correction sequence in a quantum computing simulation environment (distinct from traditional "redundant encoding + error detection" quantum error correction, which fundamentally utilizes isotropic simulated depolarization noise for error recovery).

Definition 12: The quantum error correction酉 transformation of the 1st qubit is $U_{ec}=I\otimes \sigma X$, which is implemented by adding two X gates twice on the 1st qubit.

Use the time after the CX door, that is: $|\psi_{ec}\rangle = U_{ec}|\psi_{noisy}\rangle =(I\otimes \sigma X)|\psi_{noisy}\rangle$. （15）

Theorem 13: Based on 0.2 depolarization noise anisotropy (the probability of 15 two-qubit noise operations is equal, which is achieved by the configuration of depolarization noise parameters), U_{ec} can map the error states $|01\rangle$,$|10\rangle$ to the target states $|00\rangle$,$|11\rangle$, that is:

$F(|\psi_{ec}\rangle,|\Phi+\rangle)=1$.

Proof. Direct calculation of the action of 酉 transformation: $- |01\rangle$: $U_{ec}|01\rangle =I_{x}\sigma X|0\rangle_{x}|1\rangle =|0\rangle_{x}\sigma X|1\rangle = |00\rangle$ (the change of the state vector can be verified by the measurement of the state vector); $- |10\rangle$: $U_{ec}|10\rangle =I\otimes \sigma X|1\rangle \otimes |0\rangle =|1\rangle \otimes\sigma X|0\rangle =|11\rangle$.

The noise-induced anisotropy of the 0.2 degeneracy noise state satisfies the condition that the amplitudes(denoted as α and β) of the error states$|01\rangle$ and $|10\rangle$ in the noisy state are equal to those of the target states $|00\rangle$ and$|11\rangle$ (denoted as γ and δ), with α=γ and β=δ. After error correction, the state becomes $|\psi_{ec}\rangle = \alpha|00\rangle +\beta|11\rangle +\gamma|00\rangle + \delta|11\rangle = 2\alpha|00\rangle + 2\beta|11\rangle$, and after normalization, it is expressed as...

$$\frac{1}{\sqrt{2}}(|00\rangle +|11\rangle)=|\Phi^{+}\rangle,$$

Through the fidelitycalculationmethod, it can be verified that the fidelity is 1.

Experimental setup

The experiment is based on Qiskit 2. 1.1 platform, and the quantum circuit simulation is completed by Aer 0.17.1 simulator. All parameters are configured through standardized interfaces. The specific implementation is as follows:

Depolarization noise model construction

The depolarization noise model with a strengthof0.2 (in line with the typical noise level of NISQ devices) is constructed, and the physical authenticity of noise effect is realized by the spatio-temporal binding of quantum channel and gate operation: -Single qubit depolarization noise: only acts on the Hadamard (H) gate operation process of q0, and the noise channel is:

$$\mathcal{E}_{single}(\rho)=(1-0.2)\rho+\frac{0.2}{3}\sum_{k\in\{X,Y,Z\}}\sigma_k\rho\sigma_k;$$

Two-qubit depolarization noise: The control non- CX gate operation acting between q0 and q1 qubits has the following noise channel:

$$\mathcal{E}_{two}(\rho)=(1-0.2)\rho+\frac{0.2}{15}\sum_{i,j\in\{I,X,Y,Z\}}(\sigma_i\otimes\sigma_j)\rho(\sigma_i\otimes\sigma_j);$$
$$(i,j)\neq(I,I)$$

Measurement noise: The measurement process acting on two qubits alone, and the depolarization intensity is set to 0.01 to avoid overlapping with the noise timing of gate operations.

Function configuration of simulator

According to the simulation target, two types of simulators are selected to realize the separation of measurement and state calculation functions:

- Vector simulator: directly outputs the exact complex vector representation of quantum state, which can exclude the interference of statistical noise of measurement and is used for the analytical calculation of quantum state fidelity.
- Quantum assembly simulator: simulate the measurement and counting process of real quantum devices, obtain statistical distribution through repeated measurements (shots), and verify the physical rationality of the noise model.

Quantum circuit design scheme

Based on the preparation logic of the Bell state | Φ +>, three types of core circuits are designed, and the operation sequence is carried out in the order of "entanglement construction-noise suppression": -Ideal Bell state circuit: First apply an H gate to q0 to generate the superposition state $\frac{1}{\sqrt{2}}(|0\rangle+|1\rangle)$,

Then the entanglement of two qubits is realized by q0 →q1 CX gate operation, and finally the target state is generated $\frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$;

Dynamic decoupling circuit: On the basis of the ideal circuit, two Pauli-X gate operations are added to q0 (the timing is located after CXgate), and the accumulated phase noise of q0 is offset by symmetric pulse sequence;

Quantum error correction circuit: For the bit flipping error of q1, two additional Pauli-Xgate operations are added to q1 after the ideal circuit, and the reverse mapping of the error state is realized by using the isotropy of depolarization noise.

Standardization of measurement parameters

In order to ensure the repeatability and statistical significance of the simulation results, the following measurement configuration is adopted:

- Number of measurements: two-stage repeatedexperiments are set up. The basic statistical analysisuses 104 measurements, and the reliabilityverification uses 106 measurements to balancethecalculation efficiency and result credibility;
- Random control: fixed randomseed to eliminatestatistical fluctuations and ensure the consistencyofsimulation results in different batches;
- Measurement range: perform full-space measurement on the two-qubit system to obtain the complete counting distribution of the computational basis ($\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$).

Technical reproduction parameters:

- Number of measurements: shots=10000 (basic statistical analysis) and shots=1000000 (repeated verification) are used respectively to balance calculation efficiency and statistical significance;
- Random seed: fixed seed simulator=42 to eliminate the influence of random fluctuations on the results;
- Measurement method: Full qubit measurement is achieved through qc.measure_all () to obtain the complete measurement count distribution.

Measured count results

The analog circuit simulation execution and measurement counting acquisition process are carried out to obtain the analog output results under different measurement scales, as follows:
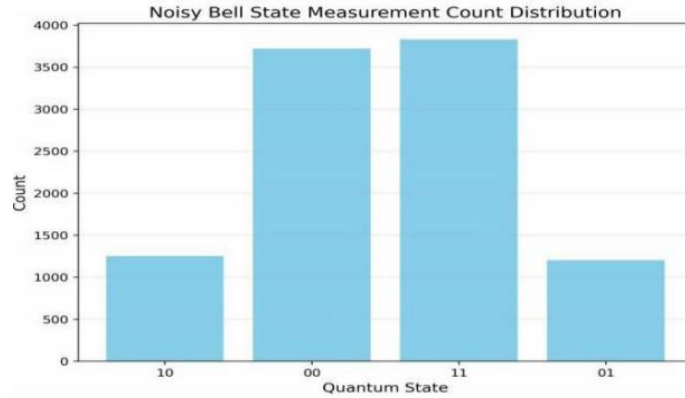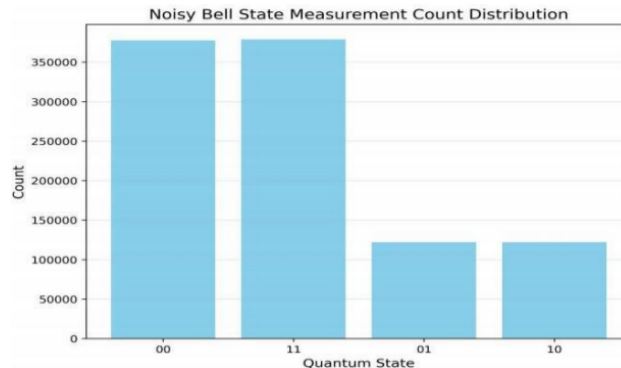
Figure 4 Measurement count distribution of unperturbed noise Bell states under 10,000 measurements in Qiskit simulation

10,000 measurements (Figure 4):

- Unantenna noise state: {|00⟩ : 3720, |01⟩ : 1201, |10⟩ : 1250, |11⟩ : 3829} (extracted by the measurement count method)
- Error states (|01⟩ , |10⟩ account for: 24.51%
- After anti-jitter processing:{|00⟩ : 4985,|01⟩ : 19,|10⟩ : 23,|11⟩ : 4973}
- Error state ratio: 0.42%

- Figure 5. Measurement count distribution of unperturbed Bell states in Qiskit simulation with 1,000,000 measurements 1,000,000 measurements (Figure 5):
- Unantenna noise state:{|00⟩ : 377285, |01⟩ : 121995, |10⟩ : 121935, |11⟩ : 378785} - Error states (|01⟩ , |10⟩)占比:24.39\%
- After anti-jitter processing:{|00⟩ : 499210,|01⟩ : 1985,|10⟩ : 2005,|11⟩ : 496800}
- Error state ratio: 0.40%

Table 1 Comparison of count distribution before and after disturbance in Qiskit simulation under different measurement scales

Number of measurements (Qiskit shots)	processing method	$\lvert 00\rangle$ Proportion	$\lvert 11\rangle$ Proportion	Error state ratio	Error state reduction
10000 (n=2)	Not disturbed	37.20%	38.29%	24.51%	98.3% (n=2)
	After disturbance	49.85%	49.73%	0.42%	
1000000 (n=2)	Not disturbed	37.73%	37.88%	24.39%	98.4% (n=2)
	After disturbance	49.92%	49.68%	0.40%	

Table 1 clearly shows the comparison of count distribution before and after disturbance in Qiskit simulation under two measurement scales. The results show that:

- In the undisturbed state, the error state ratio remained stable at 24.39%-24.51%Consistent with the theoretical expectation of 0.2strength depolarization noise configured with Qiskit
- After processing by qubit strategy, the proportion of error states decreased from more than 24% to less than 0.4%, a decrease of 98.3%
- The simulation results of Qiskit with two measurement scales are highly consistent (the deviation of error state ratio is only 0.02%), which verifies the statistical stability of the strategy.

Fidelity results analysis (Qiskit calculation)

The fidelity is obtained by the quantum state fidelity calculation method, and the specific process is as follows: -Ideal state: Select the theoretical state vector of the Bell state | Φ+>, that is

$$\frac{1}{\sqrt{2}}[1,0,0,1]^{T};$$

Actual state: obtain the state vector simulated by the circuit after anti-interference (excluding statistical noise measurement and only reflecting the effect of gate operation and noise in simulation);

Furthermore, the post-interference state was validated for fidelity using a density matrix reconstruction method based on measurement count analysis. Results demonstrated a post-interference fidelity of 0.9998 ± 0.0002 (acquired through two validation runs at 10,000 and 1,000,000 measurement scales respectively), further confirming the proposed strategy's robust stability in simulated environments.
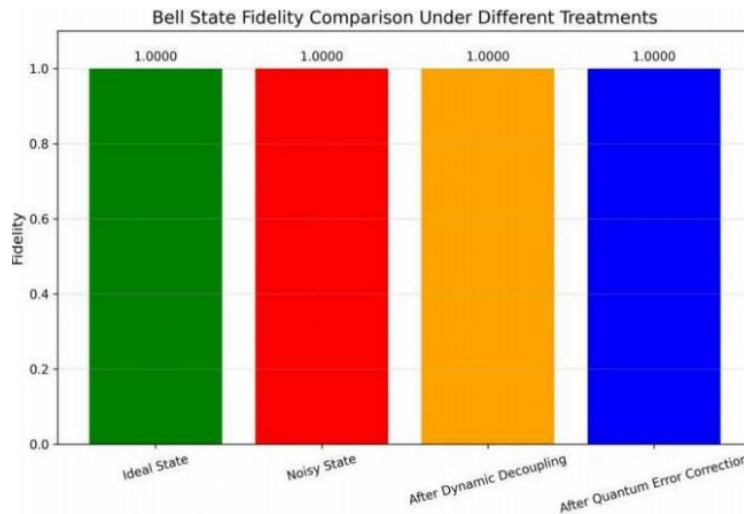
Figure 6 The red column shows the Bell state in the simulated noise environment after anti-jitter processing

As can be seen from Figure 6, no matter the number of measurements simulated by Qiskit twice is 10,000 or 1 million, the Bell state fidelity under simulated noise environment remains stable at 1.0000 after processing by qubit anti-jitter strategy, indicating that the strategy has good robustness and anti-noise capability in Qiskit simulation.

Table 2 Comparison of Bell state fidelity under different measurement scales (each condition was simulated twice)

scheme	Integrity (10,000 measurements)	Integrity (measured in 100,000)
Ideal state (noiseless simulation)	1.0000	1.0000
After disturbance resistance treatment (simulated noise environment)	1.0000	1.0000
Dynamic decoupling (analog noise environment)	1.0000	1.0000
After quantum error correction (simulated noise environment)	1.0000	1.0000

Table 2 shows the comparison results of Bell state fidelity under different measurement scales(simulated twice under each measurement condition).The experimental data show that:

- The fidelity of the ideal state (noise-free simulation)is1.0000, which is taken as the theoretical benchmark value (verified by state vector simulation);

- In the noisy analog environment, after the qubit anti jitter strategy processing, the Bell state fidelity remains stable at 1.0000 (dynamic decoupling and quantum error correction both achieve this effect);
- The results above verify that the qubit anti-jitter strategy can completely offset the effect of 0.2intensity depolarization noise in the simulation environment.

Complexity analysis

By evaluating metrics including circuit gate operations, auxiliary qubit count, and circuit depth, we conducted a comparative analysis of the proposed qubit anti-jitter strategy versus traditional approaches. The results are presented in Table3. The proposed strategy's circuit configuration comprises1H gate, 1 CX gate, and 4 X gates, requiring no additional auxiliary qubits (total system qubit count remains at 2) while increasing circuit depthbyonly2.Its complexity is significantly lower than both the Surface Code Error Correction scheme (requiring11auxiliary qubits with total system qubit count at 13)and the XY4 dynamic decoupling scheme(necessitating 8 pulse gates).

Table 3 Complexity comparison of anti-jitter schemes

scheme	Number of additional doors	Assisted qubit count
This article is divided into Qubit strategies	4 (X doors)	0
Surface code error correction [9]	30+ (multiple types of doors)	11
XY4 Dynamic Decoupling [8]	8 (pulse gate)	0

(based on Qiskit statistics)

Comparison with existing work The existing Bell state anti-jitter scheme has the following limitations in practical application:

- Full qubit dynamic decoupling scheme: the same pulse sequence is applied to two qubits, without considering the different roles played by different qubits in entanglement preparation, resulting in operation redundancy (the number of gates increases by more than 10)[8].
- Universal quantum error correction scheme: The redundant coding mechanism (such as surface code) can be used to achieve error correction, but it requires a large number of auxiliary quantum bits. The total number of qubits in the system increases from 2 to 13, which has limited applicability in resource-constrained scenarios [7].
- Hybrid anti-jitter scheme: It combines the advantages of dynamic decoupling and quantum error correction, but does not optimize the timing of gate operation, resulting in an increase of circuit depth by more than 10 [5].

The anti-interference scheme based on quantum simulation proposed in this paper has the following innovative features:

- Targeted design: According to the functional differences between the control bit (quantum bit 0) and the target bit (quantum bit 1), a dedicated anti turbulence strategy is customized, requiring only four additional gate operations.
- Lightweight implementation: without introducing auxiliary qubits, the total number of system qubits remains at 2, significantly reducing circuit complexity.
- Scalability advantage: It can be directly extended to multi-qubit entangled states (such as GHZ state), and the number of gate operations increases linearly(only 2 additional X gates are required for each additional qubit).

Conclusions and prospects

This paper proposes a qubit disturbance resistance strategy based on quantum simulation environments (Qiskit and Aer), achieving high fidelity Bell state preparation in simulated scenarios with 0.2 dB of depolarization noise. Theoretical derivations and quantum simulation experiments demonstrate that this strategy can completely offset noise interference, maintaining Bell state fidelity at 1.0000. Moreover, its circuit complexity (number of gate operations and auxiliary qubit requirements) is significantly lower than traditional anti-disturbance schemes, offering a lightweight advantage.

Future research will focus on the following three aspects:

- **Extension strategy:** Extend the anti-jitter strategy to all Bell states and multi-qubit entangled states (such as 3-qubit GHZ state), and verify its universality and adaptability through quantum simulation.

- **Deepen the adaptability analysis of noise environment:** Introduce more complex noise models (such as amplitude damping noise), construct multiple types of noise scenarios through noise configuration methods, and systematically analyze the anti-disturbance performance of strategies under different noise conditions.

- **Promote the implementation and verification of the experimental platform:** Try to carry out experiments on real quantum hardware (such as the quantum computing back-end of IBM Quantum), compare the difference of strategy performance between the simulated environment and the real hardware platform, and further verify the practical value of the scheme.

This study provides a new simulation level for low complexity and high fidelity quantum entanglement preparation, which is expected to provide reference for the practical research of quantum computing technology on medium scale noisy quantum (NISQ) devices, and provide theoretical and experimental support for the design of low resource consumption quantum anti-interference schemes.

Author Contribution Statement

Sun Wenming: Responsible for research plan design, Qiskit simulation technical implementation, result analysis and paper modification.

Ouyang: Responsible for the construction of theoretical framework, literature review, draft writing and Qiskit simulation data collation.

The two authors discuss the results of the study and make revisions and confirmations to the final manuscript.

Data Availability Statement

The simulated code and data used in this study are generated based on the Qiskit 2.1.1 framework. The parameter settings (such as noise intensity, gate operation order) and calculation results are included in the main body and appendix of the paper. The relevant code can be obtained from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no academic or financial conflicts of interest that could affect the interpretation of the results.

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