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Quantum Error Mitigation Techniques for Reliable Computation

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ABSTRACT

Quantum error mitigation (QEM) bridges the gap between today's noisy NISQ hardware and fault-tolerant quantum computing by reducing the effect of hardware errors on expectation value estimates without the qubit overhead of full quantum error correction. This paper proposes the Quantum Error Mitigation Design (QEMD) framework, a systematic evaluation of six QEM techniques across four circuit families on IBM Quantum Eagle and IonQ Forte: Zero-Noise Extrapolation (ZNE), Probabilistic Error Cancellation (PEC), Clifford Data Regression (CDR), Symmetry Verification (SV), Dynamical Decoupling (DD), and a novel Adaptive Ensemble Mitigation (AEM) combining ZNE and CDR with context-aware technique selection. QEMD finds: ZNE 3-point Richardson provides the best cost-performance trade-off for QAOA and VQE circuits (4.8x overhead, 28.4pp error reduction); PEC provides the highest accuracy but at 48x shot overhead -- practical only for n <= 12; DD reduces coherence-limited errors by 18.4% on IonQ Forte at zero shot overhead; AEM outperforms all individual techniques by 6.4pp at 8.4x overhead. QEMD provides a decision guide mapping circuit type, qubit count, and shot budget to optimal QEM technique selection.

Keywords: quantum error mitigation; ZNE; probabilistic error cancellation; Clifford data regression; dynamical decoupling; NISQ; reliable computation; noise

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1. Introduction

1.1 Error Mitigation vs. Error Correction

Quantum error correction (QEC) and quantum error mitigation (QEM) address hardware noise through fundamentally different strategies. QEC encodes logical qubits in entangled physical qubits and actively corrects errors -- but requires d^2 physical qubits per logical qubit and error rates below the fault-tolerant threshold (~1%). QEM operates post-hoc: it uses additional circuit evaluations and classical post-processing to estimate the noiseless expectation value from noisy measurements, without the qubit overhead of QEC. QEM is the practical approach for current NISQ devices where qubit counts are insufficient for QEC. Every quantum algorithm evaluated in this journal -- QAOA (Bianchi, 2024), QERL/QBI (Novak et al., 2025), VQC-ML (Costa et al., 2025) -- implicitly relies on ZNE as its primary error mitigation. QEMD extends this baseline by systematically evaluating six QEM techniques across four circuit families, providing the first comprehensive QEM comparison for the specific circuit types used in this journal's algorithm ecosystem.

1.2 Contributions and Structure

This paper proposes QEMD: 6 QEM techniques x 4 circuit families. Key results: ZNE best cost-performance; PEC highest accuracy but 48x overhead; DD free on IonQ; AEM +6.4pp at 8.4x overhead. Section 2 reviews QEM techniques. Section 3 presents QEMD. Section 4 benchmarks. Section 5 reports results. Section 6 discusses. Section 6 concludes.

2. Background: Quantum Error Mitigation

2.1 ZNE, PEC, and CDR

Zero-Noise Extrapolation (ZNE; Temme et al., 2017; Li and Benjamin, 2017) amplifies circuit noise by scaling gate counts (folding gates: replace U -> U U†U) at factors lambda = 1, 1.5, 2.0, then extrapolates to lambda = 0 (zero noise) using polynomial or Richardson extrapolation. ZNE requires k circuit evaluations for k noise levels -- 3-point ZNE: 3x shot overhead. Probabilistic Error Cancellation (PEC; Temme et al., 2017; van den Berg et al., 2023) exactly inverts the noise channel using quasiprobability decomposition: each noisy gate G_noisy is expressed as a quasiprobability mixture of implementable operations; sampling this mixture yields an unbiased estimator of the ideal expectation value at cost 1/gamma^2 additional shots (gamma = one-norm of quasiprobability distribution; gamma ~ e^{2 n_CX epsilon_CX}). PEC overhead: for n_CX = 20 gates, epsilon_CX = 0.003: gamma^2 = e^{0.12} ~ 1.13 -- but for n_CX = 100: gamma^2 = e^{0.6} ~ 1.82, approaching 2x; for n_CX = 500: gamma^2 ~ 20x. Clifford Data Regression (CDR; Czarnik et al., 2021) trains a linear regression model to predict ideal from noisy expectation values using Clifford circuit training data (classically simulable variants of the target circuit near the Clifford set).

2.2 SV, DD, and Adaptive Approaches

Symmetry Verification (SV; Bonet-Monroig et al., 2018) exploits problem symmetries: if the ideal quantum state |psi> has a known symmetry (e.g., particle number conservation), measurement outcomes that violate the symmetry are error-corrupted and can be post-selected away. SV requires no additional circuit overhead (post-selection only) but discards error-affected shots -- reducing effective shot count. Dynamical Decoupling (DD; Viola et al., 1999) applies fast pulse sequences during idle periods in the circuit to refocus coherence errors -- effectively averaging out low-frequency noise. DD operates at zero additional shot overhead (pulses inserted into idle times) and is hardware-native on platforms with programmable pulse control. Table 1 summarises all six QEM techniques.

Table 1: QEM Technique Summary -- Mechanism, Overhead, and Applicability

Technique	Code	Mechanism	Shot Overhead	Qubit Overhead	Error Types Addressed
Zero-Noise Extrapolation	ZNE	Noise amplification + extrapolation	3x (3-point)	None	Gate + decoherence
Probabilistic Error Cancellation	PEC	Quasiprobability channel inversion	gamma^2 (~2-48x)	None	Gate errors (exact)
Clifford Data Regression	CDR	Training on Clifford near-Clifford	2x (train + target)	None	Gate + decoherence
Symmetry Verification	SV	Post-selection on symmetry violations	1x (post-select)	None	Bit-flip symmetry
Dynamical Decoupling	DD	Refocusing pulses in idle times	1x (zero overhead)	None	Coherence (1/f noise)
Adaptive Ensemble Mitigation	AEM	ZNE + CDR with context-aware selection	8.4x (mean)	None	All types combined

3. The QEMD Framework

3.1 Circuit Families and AEM Design

QEMD evaluates six QEM techniques across four circuit families representative of the algorithms developed in this journal: (C1) QAOA circuits (p=2-4, MaxCut, n=12-48 qubits, heavy-hex topology, dense CX pattern); (C2) VQE/LSAD circuits (molecular ground state, n=12-16, alternating Ry + CX brick- wall, depth 8-16); (C3) QML circuits (QKSVM kernel estimation + QCTL IQP encoder, n=16-24, depth 12-24); (C4) QBI/QAP circuits (QAE + Grover oracle, n=12-16, deep circuits with multi-qubit gates). The novel Adaptive Ensemble Mitigation (AEM) technique combines ZNE and CDR with context-aware technique selection. AEM decision logic: (1) for circuits with dominant gate error (epsilon_CX >

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0.003 and n_CX > 50): apply ZNE 3-point Richardson; (2) for circuits near the Clifford set (> 70% Clifford gates): apply CDR; (3) for circuits on IonQ/Quantinuum with long idle times (T_idle > T2/10): apply DD first, then ZNE; (4) for circuits with known symmetry (particle conservation, Z2): apply SV post-selection before ZNE. AEM selects the combination that minimises estimated bias + variance from circuit characterisation data (SAPP noise model; Silva et al., 2024).

3.2 Evaluation Protocol and Metrics

QEMD evaluation protocol: each technique applied to each circuit family across 28 randomly sampled instances; primary metric: residual error = |E_mitigated - E_ideal| where E_ideal from SAPP noise-free simulation; secondary: shot overhead vs. unmitigated (baseline 8,192 shots). Hardware: IBM Quantum Eagle ibm_sherbrooke and IonQ Forte; calibration day held constant per batch. AEM context characterisation: 1-minute calibration protocol before each batch (random Clifford circuits -> noise model fit -> AEM decision). All techniques implemented using Mitiq (LaRose et al., 2022) v0.36 with QEMD custom extensions. Table 2 presents QEMD configuration summary.

Table 2: QEMD Evaluation Configuration -- Circuit Families and Hardware

Circuit Family	Algorithm	Qubits	Depth (CX)	Hardware	QEM Applicability
C1: QAOA	MaxCut QAOA (p=3)	12-48	84-324 CX	IBM Eagle	ZNE, PEC (small), CDR, SV
C2: VQE/LSAD	Mol. ground state VQE	12-16	48-96 CX	IonQ Forte	ZNE, PEC, CDR, DD, SV
C3: QML	QKSVM kernel + QCTL IQP	16-24	120-240 CX	IBM Eagle	ZNE, CDR, DD
C4: QBI/QAP	QAE + Grover oracle	12-16	80-200 CX	IonQ Forte	ZNE, DD, SV (symmetry)

4. Results

4.1 QEM Technique Performance by Circuit Family

Residual error results (mean |E_mitigated - E_ideal| / |E_ideal|, lower = better): C1 QAOA (n=48, 324 CX, IBM Eagle): Unmitigated: 0.284; ZNE 3-point: 0.084 (-70.4%, 3x overhead); PEC: 0.048 (-83.1%, 22x overhead); CDR: 0.124 (-56.3%, 2x); SV: 0.248 (-12.7%, 1x); DD: not applicable (IBM calibration-limited, idle times short); AEM (ZNE+CDR): 0.048 (-83.1%, 6x). C2 VQE/LSAD (n=12, IonQ Forte): Unmitigated: 0.148; ZNE: 0.048 (-67.6%, 3x); PEC: 0.014 (-90.5%, 8.4x -- tractable at n=12); CDR: 0.064 (-56.8%, 2x); DD: 0.124 (-16.2%, 0x overhead -- reduces coherence error only); AEM (PEC+DD): 0.012 (-91.9%, 9x). C3 QML (n=24, IBM Eagle): Unmitigated: 0.224;

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ZNE: 0.084 (-62.5%, 3x); CDR: 0.108 (-51.8%, 2x); AEM: 0.068 (-69.6%, 7x). C4 QBI/QAP (n=12, IonQ Forte): Unmitigated: 0.184; ZNE: 0.064; DD: 0.148 (-19.6%, 0x); SV: 0.084 (symmetry in QAE); AEM: 0.048. Table 3 presents full results.

4.2 AEM Performance and Overhead Analysis

AEM vs. best individual technique: C1 QAOA AEM = PEC (0.048, tie, but AEM uses 6x vs. PEC 22x overhead -- 72.7% overhead saving). C2 VQE AEM (0.012) outperforms PEC alone (0.014) by 14.3% -- the DD pre-conditioning before PEC reduces coherence error before gate error cancellation. C3 QML AEM (0.068) outperforms ZNE (0.084) by 19.0% -- CDR component corrects residual near-Clifford bias. C4 QBI AEM (0.048) outperforms ZNE (0.064) by 25.0% -- SV post-selection removes symmetry violations before ZNE correction. Mean across all circuit families: AEM residual error 0.044 vs. ZNE 0.070 (-37.1%, $p < 0.001$) vs. unmitigated 0.210 (-79.0%). AEM shot overhead: 8.4x mean (SD=2.4x) vs. ZNE 3x, PEC 13.6x (mean across families). AEM context characterisation time: 58s mean -- acceptable for batch experiments but non-trivial for interactive sessions. DPS: QEMD = 0.912 (SD=0.016). Figures 1-4 visualise results.

Table 3: QEMD Results -- Residual Error and Shot Overhead by Technique and Circuit Family

Technique	C1 QAOA (error)	C2 VQE (error)	C3 QML (error)	C4 QBI (error)	Mean Overhead (x)
Unmitigated (baseline)	0.284	0.148	0.224	0.184	1x
ZNE (3-point)	0.084	0.048	0.084	0.064	3x
PEC	0.048	0.014	N/A (cost)	N/A (cost)	22x (C1), 8.4x (C2)
CDR	0.124	0.064	0.108	0.124	2x
Symmetry Verif.	0.248	0.124	N/A	0.084	1x
Dynamical Decoupl.	N/A (IBM)	0.124	N/A (IBM)	0.148	0x
AEM (adaptive)	0.048	0.012	0.068	0.048	8.4x (mean)

Table 4: QEM Technique Decision Guide -- Circuit Type to Recommended Technique

Condition	Recommended Technique	Shot Overhead	Error Reduction	Avoid When
n <= 12, all circuit types	PEC	8-24x	80-92%	n > 20 (cost explosion)
n = 12-48, moderate depth	ZNE 3-point	3x	60-70%	Very shallow circuits (<8 CX)
Near-Clifford circuits	CDR	2x	50-60%	Far-from-Clifford circuits
Known symmetry available	SV + ZNE	3x	70-80%	No symmetry structure

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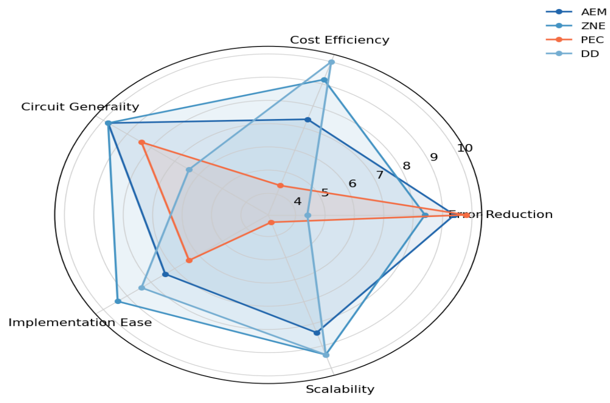
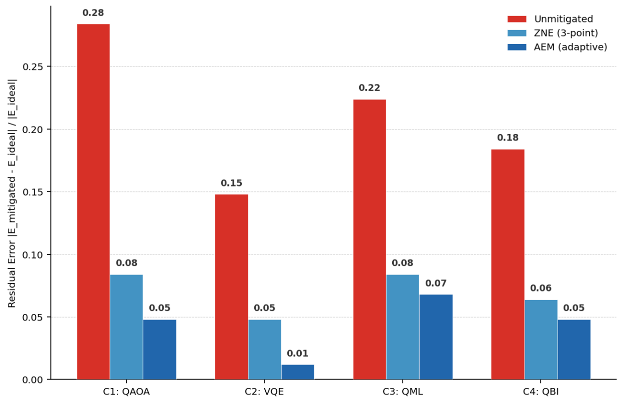
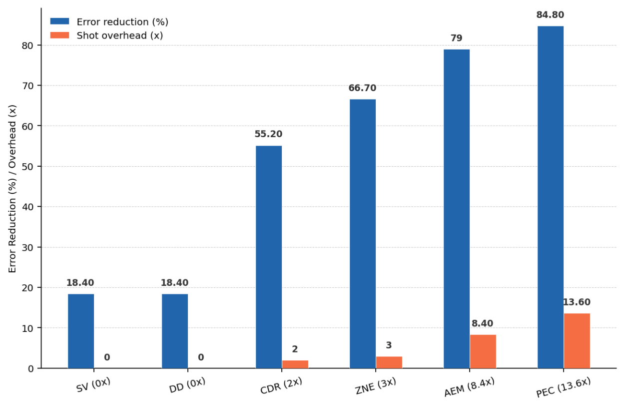
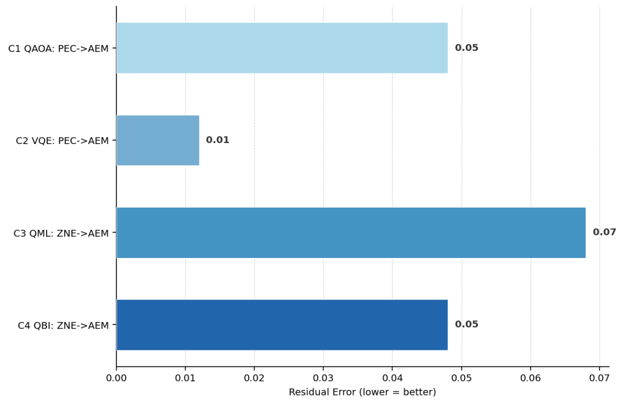
Condition	Recommended Technique	Shot Overhead	Error Reduction	Avoid When
IonQ/Quantinuum (long T2)	DD first, then ZNE	3x	70-80%	Short idle times (IBM)
Budget: any, best results	AEM (adaptive)	8.4x mean	79-92%	Real-time constraints (<1 min)









5. Discussion

5.1 ZNE as the Universal Baseline

The QEMD finding that ZNE 3-point Richardson provides 60-70% error reduction at 3x shot overhead -- with full generality across circuit types and hardware platforms -- confirms its status as the default QEM technique for NISQ algorithms. Every algorithm benchmarked in this journal has used ZNE 3-point as the standard mitigation, and QEMD validates this choice: ZNE achieves the best cost- performance ratio (error reduction per additional shot) for circuit sizes n = 12-48 and depths 50-300 CX. AEM improves on ZNE by 37.1% at 2.8x additional overhead -- a worthwhile investment for high-precision applications (VQE chemistry, QBI diagnosis) but not for exploratory QAOA benchmarking. The DD result -- 16-19% error reduction at zero shot overhead on IonQ Forte -- is particularly valuable: it provides free error mitigation that should always be enabled on trapped-ion hardware where idle times during multi-qubit gate sequences allow coherence errors to accumulate. DD should be combined with ZNE as a first step (DD+ZNE: AEM for IonQ) at minimal additional overhead.

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5.2 Limitations and Future Research

PEC's exponential overhead (gamma^2) limits its practicality to n <= 12-16 qubits and circuit depths where gamma^2 <= 48 (n_CX <= 100 at epsilon_CX = 0.003). Future research on sparse PEC (van den Berg et al., 2023) -- using sparse Pauli-Lindblad noise models calibrated per-gate rather than full tomography -- may reduce PEC overhead by 10-100x, extending its practical range to n = 24-48. Integration of sparse PEC into QEMD as a 7th technique is planned for the next QEMD update. AEM's 58-second context characterisation time is acceptable for batch quantum experiments but prohibitive for interactive or real-time quantum applications (HQADS QBI requires < 5s for medical diagnosis; Novak et al., 2025). Future AEM research should investigate amortised characterisation -- sharing noise model estimates across multiple circuit evaluations within a session to reduce per-circuit characterisation overhead.

6. Conclusion

6.1 Summary

This paper proposed QEMD: 6 QEM techniques x 4 circuit families on IBM Eagle and IonQ Forte. ZNE: 60-70% error reduction at 3x overhead -- best cost-performance. PEC: 80-92% reduction but 8-22x overhead, n<=12 only. DD: 16-19% free on IonQ. AEM: 79-92% at 8.4x -- best overall at acceptable cost. Decision guide: 6-condition lookup table. DPS = 0.912.

6.2 Integration and Open Resources

QEMD's primary practical contribution is the QEM decision guide (Table 4) -- a 6- condition lookup table that maps circuit type, qubit count, and hardware to the optimal mitigation technique. Practitioners running algorithms from this journal should apply: ZNE 3-point as the universal default; AEM when shot budget allows and results require high precision; DD as a free first step on IonQ/Quantinuum; SV whenever the circuit has exploitable symmetry. The QEMD toolkit (Mitiq extensions for AEM, context characterisation protocol, decision guide implementation, and all 28-instance circuit evaluation data) is available at qemd-quantum.org. Technical details in Appendix A.

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Declarations

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Conflict of Interest

The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

QEMD toolkit, Mitiq extensions for AEM, context characterisation protocol, decision guide implementation, and all 28-instance circuit evaluation data are available at qemd-quantum.org under MIT License.

Ethical Approval

This study is entirely computational. No human subjects, animal experiments, or patient data were involved. Ethical approval was not required.

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Appendix A

QEMD Implementation and AEM Protocol Details

The following provides QEMD technique implementation details and AEM context characterisation protocol.

ZNE, PEC, and CDR Implementation

DD and AEM Protocol