TWiDDle: Twirling and Dynamical Decoupling, and Crosstalk Noise Modeling

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***Abstract*— Crosstalk remains a major source of correlated error in quantum systems, yet lacks a precise, community-wide definition - hindering systematic analysis and mitigation. This paper introduces a model-driven approach to crosstalk characterisation through three architecture-inspired noise models: (1) simultaneous two-qubit gate execution, (2) shared qubit interference, and (3) proximity-induced noise from shared control or readout hardware. These models act as both diagnostic tools and building blocks for crosstalk-aware quantum programming. We assess their impact across a broad benchmark suite — quantum simulation, Grover's algorithm, and fault-tolerant primitives like surface, Shor, and Steane codes — and evaluate two mitigation techniques: dynamical decoupling and Pauli twirling. While both are discussed in literature, only dynamical decoupling consistently enhances fidelity across noise types. Our work links low-level noise effects to high-level software engineering, underscoring the role of hardware-software co-design in scalable quantum computing. Model-based, hardware-aware design flows and composable noise abstractions improve error mitigation and program portability. Integrating such strategies into the toolchain is essential for building resilient quantum programs under realistic noise conditions.**

***Index Terms*—quantum computing, model-driven engineering, ftqc, nisq, crosstalk, error mitigation, dynamical decoupling, twirling, empirical evaluation**

I. Introduction

As quantum computing advances toward practical applications, mitigating noise — particularly crosstalk — remains a difficult challenge. Crosstalk noise arises from unintended interactions between qubits, often due to residual coupling, shared signal lines, or physical proximity. These correlated errors significantly degrade quantum circuit fidelity and present an obstacle to scalability. Despite its importance, crosstalk lacks a well-defined, standardised and unified model within the quantum hardware and software community. This ambiguity limits our ability to systematically analyse, simulate and mitigate crosstalk within quantum programming toolchains. Previous mitigation efforts — such as crosstalk-adaptive scheduling [1] — have shown promise in suppressing correlated noise, but can introduce negative side effects such as increased thermal relaxation or depolarization errors. These trade-offs highlight the challenge of developing mitigation techniques that are both effective against crosstalk while minimising unwanted side effects. This often requires extensive experimentation. Moreover, many prior studies focus on specific hardware platforms, as crosstalk effects vary significantly across devices, limiting the generalisability of their findings and underscoring the need for model-driven approaches that span diverse quantum workloads. To address these challenges, we adopt a comprehensive, model-based benchmarking strategy that evaluates the effects of crosstalk noise on a broad set of quantum programs. Our benchmark suite includes representative algorithms — such as quantum simulation and Grover's search — and foundational quantum error correction (QEC) codes, including surface, Shor, and Steane codes. Our focus on QEC circuits highlights the dual objective of enhancing NISQ-era applications and preparing for the demands of future quantum architectures. A central contribution of our work is the definition of three phenomenological crosstalk noise models that capture common and plausible sources of correlated noise in hardware. Simultaneous execution of two-qubit gates, shared qubit interactions, and proximity-based noise from shared control or readout infrastructure. These models are designed to be modular, composable, and hardware-informed. In doing so, we provide a foundation for standardised crosstalk benchmarking that can guide future work in modeling, simulating, and mitigating correlated noise across platforms. This serves as a potential common starting point for researchers to develop and compare mitigation strategies under clearly defined and extensible noise scenarios. The results presented offer valuable insights for developing resilient quantum systems. We integrate dynamical decoupling and twirling as noise mitigation strategies. Our results suggest that dynamical decoupling is an effective mitigation technique across different crosstalk noise models, even for small problem sizes. In contrast, Pauli twirling often leads to worse performance than applying no mitigation at all. However, we do not rule out the potential benefits of twirling altogether — it may prove more effective for larger problems, and further investigation is needed before drawing definitive conclusions about its limitations. The paper is augmented by a reproduction package [2], available for download and on Zenodo, which supports extensibility and

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enables the community to build upon our crosstalk models and evaluations toward more universal crosstalk noise models and mitigation.

II. Related work

To address a problem, it first needs to be clearly defined. For crosstalk, realistic noise modeling must account for quantum effects like residual coupling, shared control lines, and entanglement-induced interference — aspects rigorously studied in prior work. Sarovar *et al.* [3] formalise a general framework and detection protocol for crosstalk in multi-qubit processors. Fang *et al.* [4] demonstrate active mitigation of optical spillover crosstalk in trapped-ion systems. To address noise and scalability, strategies like hardware-software co-design, error mitigation, and hardware-efficient methods have been proposed. Hardware-software co-design, as shown by Safi *et al.* [5], highlights the benefits of jointly optimizing hardware and compilation for better scalability. On the other hand, error mitigation improves fidelity but often requires repeated executions, trading sampling overhead for accuracy [6], [7]. Temme *et al.* [8] introduce an error mitigation approach for short-depth quantum circuits, demonstrating how noise can be effectively mitigated without the overhead of full quantum error correction. Maschek *et al.* develop a tunable, calibrated Kraus-based noise model that enables realistic simulations [9]. Our work focuses on integrating dynamical decoupling and circuit twirling techniques, specifically targeting crosstalk noise reduction. Tripathi *et al.* show how dynamical decoupling can suppress ZZ-type crosstalk in superconducting transmon qubits [10]. Crosstalk noise mitigation, a persistent issue in quantum computing, has been the focus in a few research papers. Niu demonstrates the significant effectiveness of dynamical decoupling in reducing unwanted qubit interactions, albeit primarily conducting the experiments on two qubit pairs [11]. Parrado-Rodríguez *et al.* explore active crosstalk suppression at the gate level and analyse how residual crosstalk errors affect fault-tolerant quantum error correction [12]. Seif *et al.* [13] propose a context-aware compiler that adapts to the spatial and temporal structure of quantum operations, using calibration data to suppress coherent, hardware-specific errors like crosstalk. Greiwe present a simulation framework to visualize how imperfections affect algorithm behaviour [14]. Thelen *et al.* compare QAOA variants under realistic noise [15]. Yue *et al.* outline key research challenges in quantum software architecture, emphasizing the need for structured approaches to designing hybrid quantum-classical systems [16]. Our approach abstracts from hardware specifics to define model-driven crosstalk scenarios for platform-independent benchmarking, complementing hardware-calibrated methods within a broader mitigation framework.

III. Foundation

A. Crosstalk

Crosstalk occurs in most quantum computing systems. While the term is widely used, its definition and characterization often lack precision. One contributing factor is the absence of an universally accepted crosstalk model, as the most often arising type of crosstalk can vary across different systems. Generally, crosstalk refers to unwanted interactions between qubits that occur when operations on one qubit affect nearby qubits, leading to errors and reduced fidelity. Various phenomena can be classified as crosstalk.

1) When a control signal intended for one qubit unintentionally affects adjacent qubits. This can happen because of imperfect signal isolation or overlapping control lines particularly in superconducting and trapped-ion qubit systems [4].
2) In frequency-tunable qubit architectures, qubits operating at similar frequencies can unintentionally interact, leading to unwanted couplings [17].
3) Executing multiple instructions in parallel can introduce crosstalk between them and can cause incorrect program execution [18].
4) Measuring the state of one qubit can unintentionally disturb other qubits

In this paper, our models are primarily inspired by research on superconducting qubits, where crosstalk has been shown to have a significant impact on two-qubit gates. Furthermore, one of our models is specifically motivated by the observation that these effects become more prominent when two-qubit gates share a qubit [18] [19].

B. Dynamical Decoupling

Dynamical Decoupling [20] inserts identity-equivalent gate sequences during idle periods to suppress decoherence without altering circuit logic [21]. By randomising idle gate operations, it preserves coherence and reduces correlated errors. Building on prior work [10], [11], we evaluate its effectiveness against crosstalk noise across a broad benchmark and compare it with an alternative mitigation strategy.

Figure 1 illustrates how we modify the standard bosonic circuit by using dynamical decoupling (DD) to mitigate decoherence effects. The bosonic code, which is also part of our benchmark, is an error-correcting encoding scheme that employs a set of Hadamard (H) and controlled-NOT ($CNOT$) operations to encode logical information across multiple physical qubits.

C. Twirling

Pauli twirling transforms arbitrary noise into a more tractable form by surrounding selected gates — often two-qubit gates — with random Pauli operations [21], [22]. This process reduces coherent error accumulation and makes the noise more predictable. It is frequently used alongside other mitigation techniques that perform better under Pauli noise. Twirling is especially relevant for crosstalk, where simultaneous operations on neighboring qubits induce correlated errors. Prior work [23] shows that twirling can convert complex noise into stochastic Pauli channels, simplifying error correction. Figure 2 shows an example with Pauli X twirling applied to bosonic code.

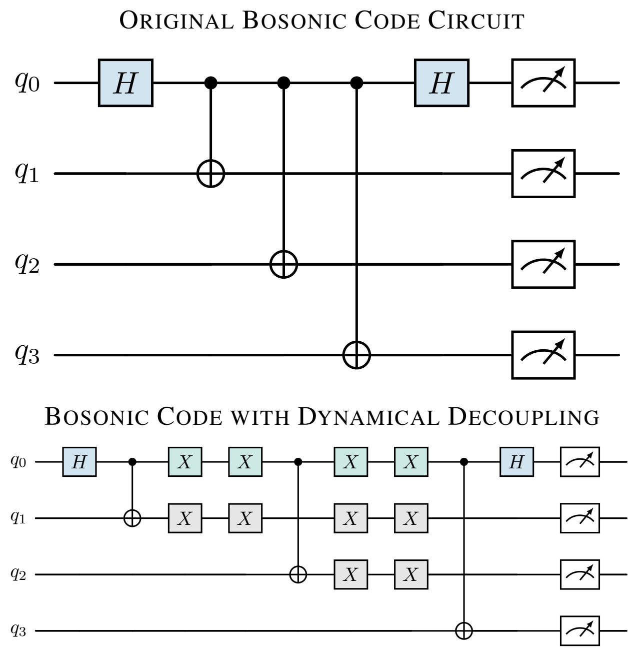

Fig. 1. Illustrative result of bosonic code enhancement with Dynamical Decoupling

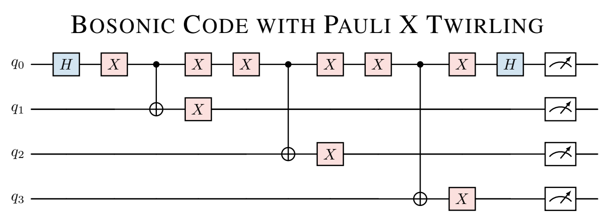

Fig. 2. Illustrative result of bosonic code enhancement with Pauli X twirling

IV. Methodology

A. Setup

We use Qiskit [24] to design and transpile quantum circuits, simulating various crosstalk noise models within an otherwise noiseless environment via *AerSimulator()*. This setup isolates the impact of crosstalk on algorithm performance. Our main goal is to evaluate how different crosstalk variations affect fidelity and to assess mitigation strategies - specifically dynamical decoupling and Pauli twirling. Simulations are based on a 127-qubit backend with IBM's heavy-hex geometry [25], which has a connectivity density

$$c = \frac{N_C}{N_{C,\max}}, \tag{1}$$

where N_C is the number of qubit connections and $N_{C,\max} = N(N-1)/2$ is the all-to-all maximum. For heavy-hex, $c \approx 1.8\%$, meaning each qubit connects to approximately 2.27 neighbours. We increase c by randomly adding edges, enabling us to study how higher interaction density amplifies crosstalk effects. The native gate set matches IBM-Q devices: *RZ*, *SX*, *X*, *CX*, and *CZ*.

B. Benchmark

For our experiments, we selected a diverse set of quantum circuits spanning key algorithmic classes and computational paradigms. The benchmark includes Grover's search [26], the Deutsch-Josza algorithm [27], a quantum simulation circuit [28], random circuits, and several quantum error-correcting codes [29], including bosonic [30], repetition [31], Shor [32], Steane [33], and surface codes [34]. This selection supports a comprehensive evaluation of gate-based performance across applications in optimization, factoring, and simulation. The circuits vary in depth, gate complexity, and entanglement structure, enabling a robust analysis of noise effects and mitigation strategies. Due to computational constraints, all simulations are limited to circuits with 4 to 10 qubits.

C. Crosstalk Noise Models

There is currently no standardised model for crosstalk effects across all hardware platforms. To address this, we developed several plausible crosstalk models, drawing inspiration from existing research on superconducting qubits, where it was observed that effects for two-qubit gates are most significant, if they share a neighbor pair and the specific crosstalk challenges observed in IBM hardware [18]. We evaluate three distinct crosstalk noise models to analyse their impact on quantum circuit execution. The simultaneous execution, the shared qubit, and the proximity-based model. Each model captures different physical characteristics of crosstalk behavior in quantum hardware, allowing us to compare their effects on fidelity and noise resilience. The decrease in fidelity for two-qubit gates due to crosstalk was quantified by computing the average gate fidelities across Google Willow, IBM Heron, and Rigetti Aspen-M3. Specifically, we calculated the average fidelity for both two-qubit and affected single-qubit gates, resulting in an observed two-qubit gate fidelity of 0.98847 and corresponding single qubit fidelity of 0.99661. In cases where crosstalk was detected we modeled the resulting noise using Qiskit's *QuantumError*. To quantify the similarity between the ideal and noisy output distributions we use the Hellinger fidelity [35].

1) Simultaneous execution: In the first model crosstalk noise surfaces when at least two CX gates are executed in the same layer of the transpiled circuit. A weaker noise is applied to neighboring single-qubit gates [36].

Model:

- Decomposing the circuit into layers using a Directed Acyclic Graph (DAG) representation.
- Identify layers containing more than one CX gate.
- Apply crosstalk noise to all CX gates in the layer.
- Apply noise to neighboring single-qubit gates.

2) Shared qubit: This model introduces crosstalk noise whenever two *CX* gates share a common qubit. Similar to the simultaneous model, noise is applied to neighboring single-qubit gates [37].

Model:

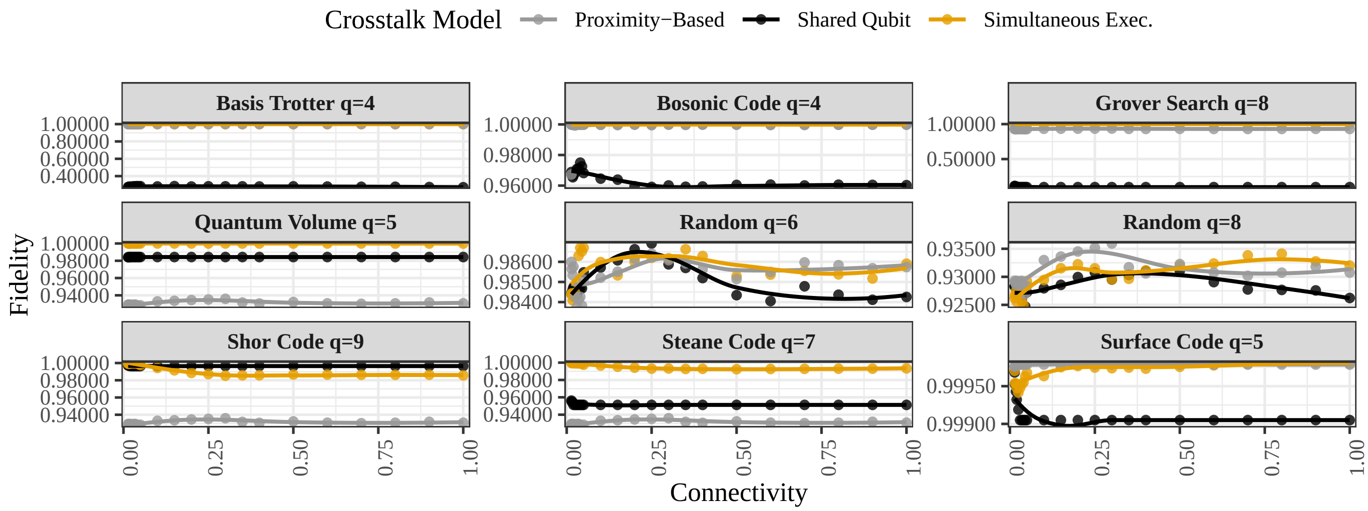

Fig. 3. **Fidelity vs. connectivity** for various quantum circuits under three crosstalk models: Shared Qubit (black), Simultaneous Execution (yellow), and Proximity-Based (gray). Each subplot shows how fidelity degrades per circuit type across connectivity levels.

- Construct a qubit interaction graph based on the transpiled circuit.
- Identify pairs of CX gates that share a common qubit.
- Apply crosstalk noise to these CX gates.
- Apply noise to neighboring single-qubit gates.

3) Proximity-based: This model considers physical qubit proximity to determine whether crosstalk happens. When two CX gates are in close physical proximity on the hardware topology crosstalk noise occurs. Model:

- Extract physical qubit coordinates from the backend properties.
- Calculate the Euclidean distance between qubits involved in CX operations.
- Introducing crosstalk noise if the distance between any two CX gates is below a threshold of 2.
- Apply noise to neighboring qubits, if the distance is below a threshold of 1.

In order to retrieve qubit coordinates we use Qiskit's *Fake127QPulseV1* backend.

V. Experiments

One goal of this study is to identify which crosstalk errors most significantly impact fidelity, to inform both architecture design and error mitigation strategies. We focus in particular on error correction codes, which are central to fault-tolerant quantum computing (FTQC), and examine how they are affected by crosstalk. Understanding these interactions is essential for developing scalable and practical quantum systems. To this end, we compare several crosstalk models and evaluate their effect on circuit fidelity. We then assess the mitigation potential of two techniques — twirling and dynamical decoupling — highlighting which noise models benefit most. While these methods were not developed specifically for crosstalk, they show promising results, as also noted in Chapter II. Finally, we vary backend size and qubit connectivity to explore hardware dependencies; backend size had no noticeable effect, likely due to the small problem sizes, and is thus not discussed further.

VI. Results/Discussion

This section presents the findings from our experiments, starting with the evaluation of the different crosstalk noise models.

A. Evaluation of Crosstalk Variants

The results in Figure 3 show that the shared qubit (black) model consistently leads to the greatest fidelity loss across most benchmarks. The proximity-based model (grey) causes moderate degradation, particularly in densely connected circuits, while the simultaneous execution (yellow) model [28] has minimal impact, including in error correction codes such as Shor, Steane, and surface codes. This indicates that parallel gate execution may remain viable in fault-tolerant settings. While fidelity differences across models are generally small — aside from cases like Grover's algorithm and Basis Trotter — this study considers only small circuits; the impact is expected to increase with larger, more complex systems.

B. Crosstalk Mitigation Techniques

Following our previous analysis, we now compare the impact of two error mitigation techniques in figures 4 5 6. Each plot visualises a different crosstalk model.

Dynamical decoupling (yellow) consistently achieves the highest fidelity and outperforms both twirling (grey) and the unmitigated baseline (black). In some cases, dynamical decoupling provides no clear advantage, but it never degrades performance. in contrast, twirling frequently leads to lower fidelities. This may be attributed to the fact that twirling is often applied in combination with other error mitigation techniques, as noted in II. Furthermore, twirling may be

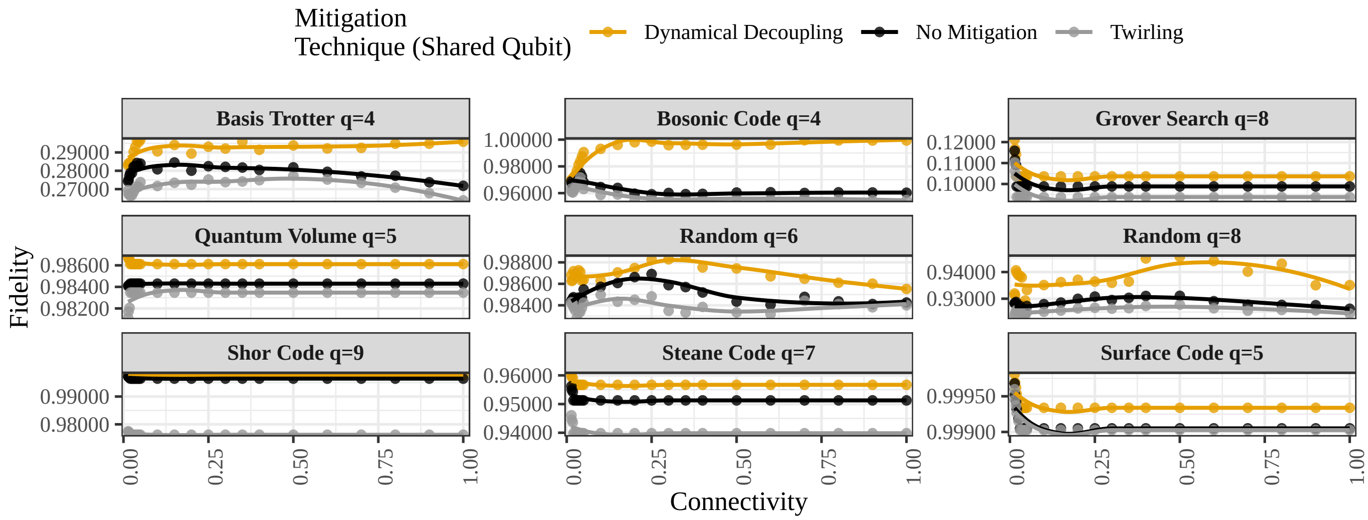

Fig. 4. **Effect of error mitigation on fidelity** under the Shared Qubit crosstalk model. Dynamical decoupling consistently improves fidelity, while twirling shows limited effectiveness.

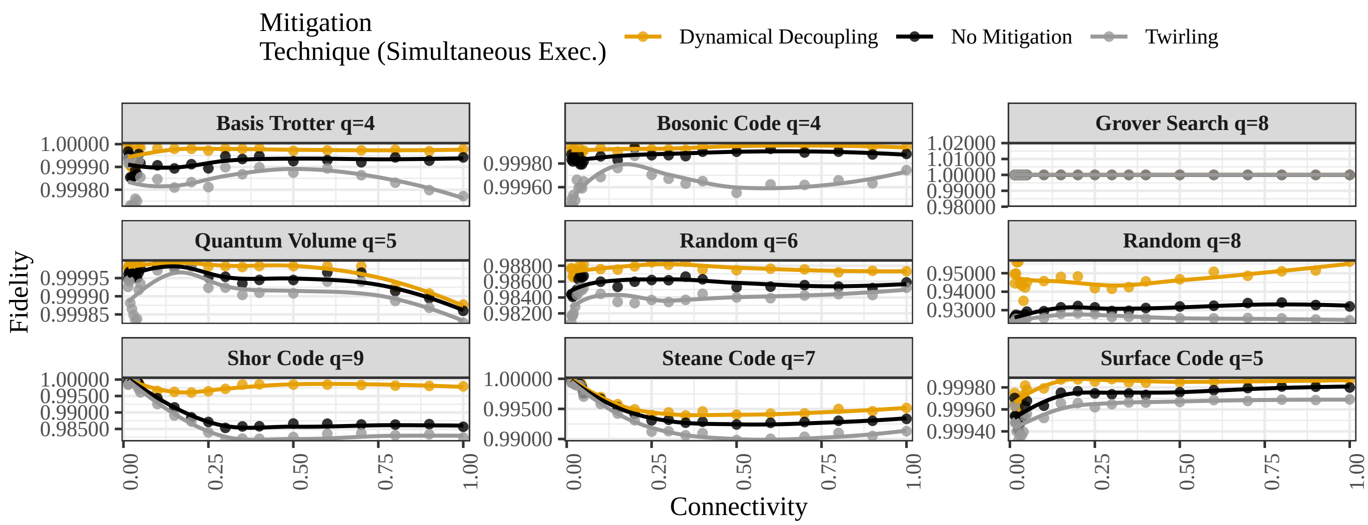

Fig. 5. **Effect of error mitigation on Fidelity** under the Simultaneous Execution crosstalk model. Dynamical decoupling consistently improves fidelity, while twirling shows limited effectiveness

more effective at enhancing circuit fidelity in larger systems by leveraging statistical averaging, as it redistributes errors rather than eliminating them. However, in smaller circuits, the additional noise introduced by randomisation can outweigh its benefits. Therefore, for small-scale uses cases, avoiding twirling for crosstalk error mitigation is preferable.

C. Circuit Depth vs. Connectivity

Our results show that beyond a connectivity of approximately 0.3 (Figure 7), circuit depth no longer improves, regardless of algorithmic structure. This aligns with prior findings from the paper on the ”Influence of HW-SW-Co-Design on Quantum Computing Scalability” [5]. The optimal connectivity for minimising circuit depth does not align with the connectivity levels that yield the most effective crosstalk mitigation. While it is reasonable to assume that shallower circuits would result in reduced error, this relationship does not hold straightforwardly in the presence of crosstalk. In some benchmarks, we observe a noticeable shift in fidelity trends around a connectivity of 0.3, rather than a simple convergence. This suggest that crosstalk effects interact with connectivity in more complex ways, and minimal circuit depth alone is not a sufficient indicator for optimal performance under realistic noise.

VII. Conclusion

Achieving robust error correction requires insight into the various layers of the quantum computing stack. Our analysis

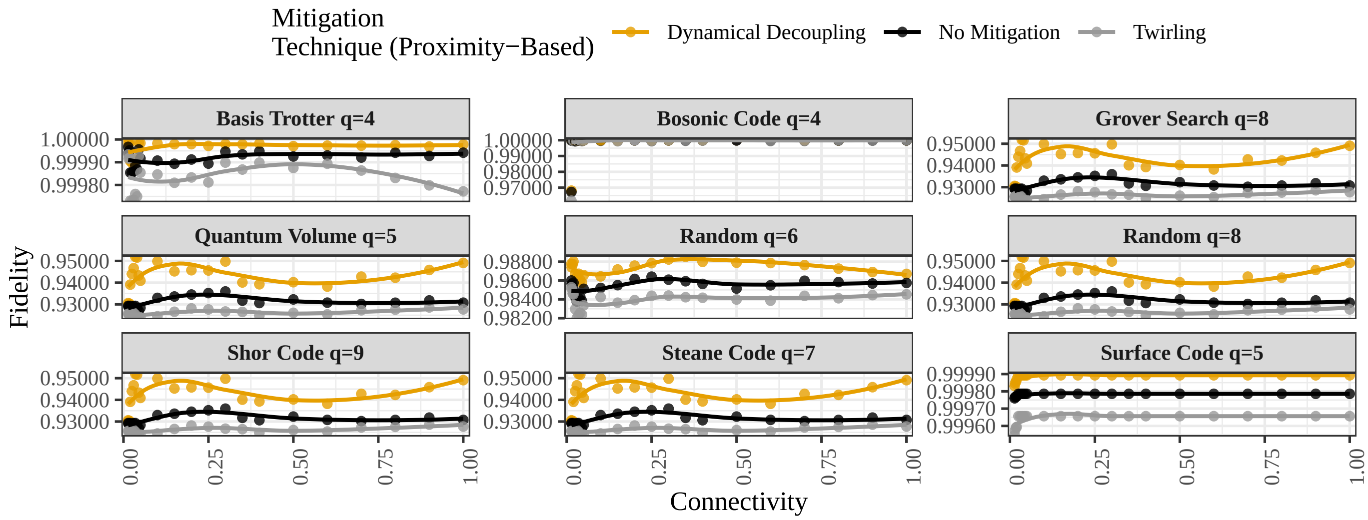

Fig. 6. **Effect of error mitigation on Fidelity** under the Proximity-based crosstalk model. Dynamical decoupling consistently improves fidelity, while twirling shows limited effectiveness.

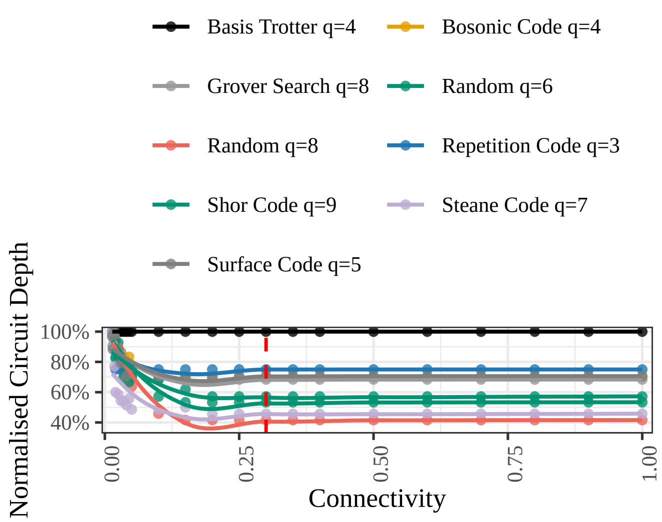

Fig. 7. **Circuit depth** as a function of connectivity density for various quantum circuits. Depth converges at a connectivity of approximately 0.3.

demonstrates that crosstalk errors play a significant role in determining quantum circuit fidelity. Several key takeaways from our study include:

- Quantum systems prone to errors from neighboring qubits executing two-qubit gates should be avoided, as they significantly reduce circuit fidelity.
- Crosstalk impact depends on algorithmic structure, crosstalk model and connectivity, while optimal circuit depth consistently converges at a device connectivity of 0.3, aligning with other studies.
- Dynamical decoupling is a robust mitigation technique, which improves fidelity decreases across different types of circuits, independent of various crosstalk models.
- Twirling has the prospect to have a more beneficial impact on larger qubit problems.
- There is a trade-off between crosstalk mitigation techniques and circuit depth. In a few cases, applying mitigation techniques increase circuit depth, introducing new sources of error. Future work should explore how these trade-offs manifest in combination with other noise models such as thermal relaxation, or depolarization noise.

A. *Outlook*

All our experiments involve circuits with fewer than eleven qubits. As systems scale, crosstalk is expected to worsen due to increased interaction complexity. While simulating large-scale circuits is computationally expensive, simplified mathematical models can help predict performance degradation, offering scalable baselines for evaluation and guiding noise-aware software design. To ensure reproducibility and comparability across platforms, the community must define a standardised, software- and hardware-aware formalism for crosstalk. The current lack of consistency hinders meaningful comparisons of noise models and mitigation strategies. A unified framework, rooted in empirical and theoretical insights, would promote alignment across the stack. Our findings show that even without full fault tolerance, software-level methods like dynamical decoupling are valuable in suppressing correlated noise—though they come with trade-offs in depth and noise redistribution, which must be tailored to specific regimes and algorithms. Ultimately, a model-driven approach to quantum software engineering is essential for navigating noisy landscapes and developing reliable quantum software. Our lightweight yet extensible crosstalk models offer a foundation for developing crosstalk aware circuits.

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