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Quantum Sensing for the weather

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Project Report

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Abstract

This project explores the use of quantum graph states as a platform for opportunistic weather sensing, extending the capabilities of classical microwave-based methods into the quantum regime. Inspired by techniques that infer rainfall from Commercial Microwave Links (CMLs), we investigate how quantum communication systems, known for their extreme sensitivity to environmental noise, can act as passive weather sensors in free-space channels.

Our objective is to determine how various weather conditions, specifically rain, dust, and turbulence, affect entanglement and other quantum properties of graph states. To achieve this, we developed a detailed Monte Carlo simulation framework in Python that generates graph states with diverse topologies, applies Pauli noise modeled by realistic weather distributions, and analyzes resulting changes in fidelity, Frobenius distance, mutual information, and graph sensitivity.

Through extensive simulations across multiple graph types, 3–8 qubit configurations, and multiple weather intensities, we found:

- Fidelity degradation is primarily governed by weather, not topology.
- Sensitivity (entanglement loss) depends heavily on graph structure.
- Scale-free and branched path topologies exhibit high sensitivity—ideal for sensing.
- Complete and ring topologies demonstrate high resilience—ideal for communication.

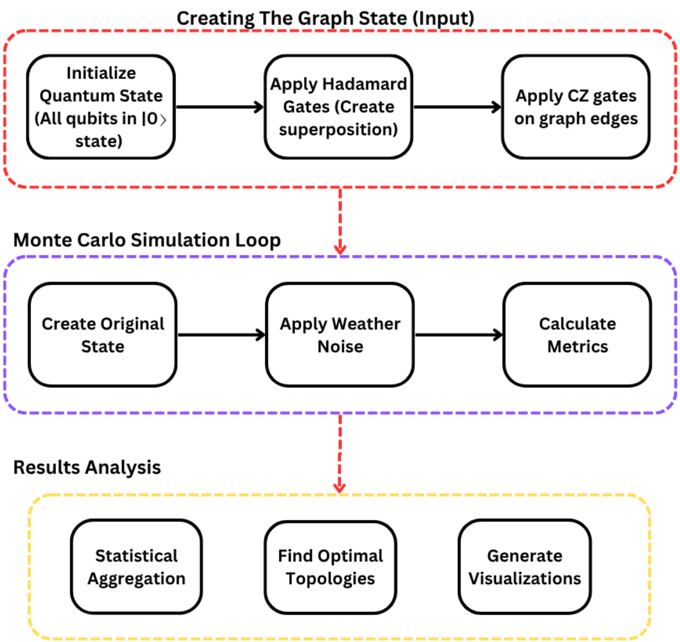

Figure 1 - Simulation Block Diagram

These findings illustrate a fundamental trade-off between sensitivity and stability, providing insight into how quantum networks might adaptively reconfigure based on environmental conditions. While experimental validation remains future work, our simulations offer a strong theoretical foundation for quantum-enhanced environmental sensing.

1 Introduction

Project Goals

The goal of this project is to investigate the feasibility of quantum-based opportunistic weather sensing by leveraging the inherent sensitivity of quantum graph states to environmental disturbances. Specifically, we aim to simulate how different graph state topologies behave under weather-inspired Pauli noise and determine which topologies are most suitable for quantum sensing, like for detecting weather, and which are optimal for quantum communication, the most noise resistant.

Our objectives include:

- Building a simulation framework for applying physically inspired noise models to quantum graph states.
- Measuring fidelity, entanglement degradation, mutual information, and sensitivity.
- Identifying topologies that either maximize sensitivity (for sensing) or resilience (for communication).

Motivation

Classical weather opportunistic sensors, such as Commercial Microwave Links (CMLs) [1], have demonstrated cost-effective and scalable ways to estimate environmental conditions by monitoring signal attenuation across communication infrastructure. However, these methods often lack precision and require additional calibration tools.

Quantum systems offer a natural improvement: their extreme sensitivity to noise makes them ideal for detecting subtle environmental changes, potentially without needing extra calibration.

The motivation behind this project is to extend classical opportunistic sensing methods into the quantum domain, where quantum graph states might act as "weather sensors", their entanglement patterns shifting in predictable ways under different environmental conditions like rain, dust, or turbulence.

Approach

This work adopts a simulation-first approach using Python and the **networkx** and **numpy** libraries to:

1. Generate graph states of various standard and custom topologies.
2. Model environmental noise using Pauli operators governed by realistic probability distributions:
- Poisson × Exponential (rain)
- Weibull (dust)
- Log-normal (turbulence)
3. Apply these noise models in a Monte Carlo framework, evaluating changes across hundreds of trials.
4. Extract and analyze metrics such as:
- Fidelity and Frobenius similarity (state change)
- Sensitivity (relative loss in entanglement)
- Mutual Information and Entanglement Change
5. Compare performance across different graphs and weather types to determine optimal configurations for sensing and communication.

Comparison with Existing Work

This project is inspired by classical opportunistic sensing (e.g., Ostrometzky and Messer, 2015), which estimates rain rates using only CML attenuation data, avoiding radars or additional sensors. While those works apply statistical models like Extreme Value Theory to classical signal degradation, this project builds an analogous quantum approach by studying how quantum states themselves degrade under realistic weather-like noise.

In the quantum realm, prior studies such as [2] showed that single entangled pairs are surprisingly robust. Our work goes further by studying graph states—more complex, structured quantum systems—and applying noise-inspired probabilistic models grounded in physical distributions rather than simplistic error rates.

Unlike existing simulations that often use idealized or symmetric noise models, our framework captures weather-specific asymmetries and physical effects, allowing for deeper insights into real-world performance.

While previous studies on quantum error models have focused primarily on symmetric or channel-agnostic noise (e.g., depolarizing or amplitude damping), these models do not reflect the structured, asymmetric nature of real-world environments. Existing work on graph states (e.g., Hein et al. [3])

largely focuses on their theoretical properties or use in quantum computation, without embedding them in realistic noise contexts. To our knowledge, no prior work systematically explores how graph topology interacts with physically inspired, weather-based noise models to affect entanglement, fidelity, and sensing performance.

2 Theoretical background

This project investigates a novel approach to quantum environmental sensing by simulating the behavior of quantum graph states under realistically distributed Pauli noise inspired by atmospheric conditions. While previous studies have explored the effects of noise on entangled states or simple quantum channels, this work is among the first to combine structured entangled systems (graph states) with weather-driven stochastic noise models rooted in physical probability distributions.

To enable this study, a dedicated simulation framework was developed that supports:

- The generation of complex quantum graph states;
- The application of environmental noise sampled from physically motivated distributions;
- The computation of a variety of entanglement-sensitive metrics;
- And the aggregation of results across hundreds of Monte Carlo trials.

This section presents the key theoretical foundations that support this simulation: the structure and utility of graph states, the modeling of noise using Pauli operators linked to physical weather distributions, and the quantum information metrics used to evaluate system performance under disturbance.

Graph States in Quantum Information

Graph states are highly entangled quantum states associated with a mathematical graph: [3]

- Each vertex corresponds to a qubit
- Each edge corresponds to an entangling operation (Controlled-Z gate).

To construct a graph state: [3]

1. Initialize all qubits in the $|0\rangle$ state.
2. Apply Hadamard gates to place them in superposition.
3. Apply CZ gates to entangle qubits according to the graph's edge list.

Graph states are fundamental in measurement-based quantum computation (MBQC), quantum error correction, and quantum communication networks. [3]

Their structural flexibility makes them ideal for testing how entanglement responds to localized noise, a critical feature for quantum sensing.

Weather-Inspired Pauli Noise Models

Standard simulations often apply idealized noise models (like uniform depolarizing noise), but this project introduces a novel approach: Pauli noise inspired by real-world weather conditions, modeled using physical probability distributions:

- **Rain:** Poisson-distributed droplet arrival + exponential attenuation.
- **Dust:** Weibull distribution.
- **Turbulence:** Log-normal distribution.
- **Clear:** Low, fixed-probability noise baseline across all operators.

Each trial samples the noise stochastically, applying different operators to random qubits based on these PDFs and intensity levels.

Quantum Metrics

Several metrics were implemented to measure how noise affects quantum states:

- **Fidelity:** Measures the overlap between original and noisy states. [4]

$$F = \frac{|\langle\psi|\phi\rangle|^2}{\langle\psi|\psi\rangle \cdot \langle\phi|\phi\rangle} \qquad (1)$$

- **Frobenius Distance:** Matrix norm of the difference between the original and noisy density matrices.
- **Mutual Information:** Quantifies shared information between qubit pairs.
- **Concurrence & Entanglement Change:** Measure bipartite entanglement degradation.
- **Graph Sensitivity:** Measures relative loss of entanglement per edge due to noise:

$$Sensitivity = \frac{\left|\langle C_{original}\rangle - \langle C_{noisy}\rangle\right|}{\langle C_{original}\rangle} \qquad (2)$$

These metrics provide complementary insights into state degradation, stability, and sensing potential.

Monte Carlo Simulation Framework

To capture the probabilistic nature of noise and environmental variation, the simulator employs Monte Carlo techniques:

- Each graph–weather–intensity configuration is simulated multiple times.
- Results are aggregated into distributions to analyze statistical trends in fidelity, entanglement, and sensitivity.
- This allows detection of both average behavior and extreme outliers.

Simulation Design and Contribution

This project introduces a novel simulation framework specifically designed to model quantum graph states under realistically distributed, weather-inspired Pauli noise, a scenario that, to our knowledge, has not been addressed in prior simulation work.

This work incorporates:

- Weather-specific probability distributions (Poisson, Weibull, Log-normal) derived from atmospheric physics.
- Graph state preparation across a broad set of standard and custom topologies.
- Pauli noise sampled stochastically per qubit and per trial, driven by those physical PDFs.
- Monte Carlo analyses to extract statistical insights from fidelity, entanglement, and sensitivity metrics.

This required building a simulation environment from scratch using:

- **NumPy** for quantum state vector manipulation.
- **NetworkX** for graph topology construction and analysis.
- Custom noise modules for weather modeling and stochastic Pauli operator application.
- **Matplotlib** / **Seaborn** for data visualization and result interpretation.

While tools like Qiskit and QuTiP provide general-purpose quantum simulation capabilities, they are not designed to model the intersection of graph structure, physically-inspired noise, and sensing behavior at the level of flexibility and resolution explored in this work.

Therefore, this simulator represents both a research tool and a contribution in itself, enabling new types of analysis and helping bridge classical environmental modeling with quantum information science.

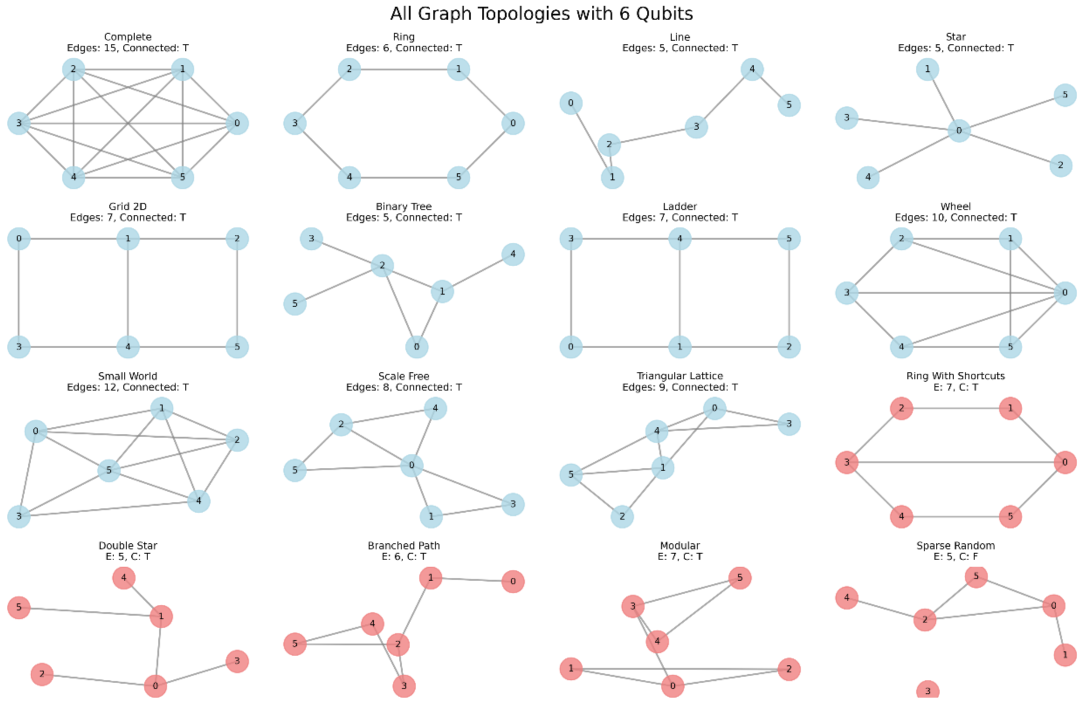

Figure 2 - Different 6 qubit topologies

3 Simulation

This chapter describes the simulation environment developed for the project, including its structure, components, and methodology. It also presents key results and insights derived from the simulations.

Simulation Environment

A custom Python-based simulation framework was developed to model the behavior of quantum graph states under stochastic Pauli noise inspired by physical weather conditions. The simulation is organized into modular components:

- **Graph State Builder:** Uses networkx to generate a wide variety of graph topologies (e.g., complete, ring, line, star…). Each graph state is prepared by initializing all qubits in $|0\rangle$, applying Hadamard gates, and entangling connected qubits via Controlled-Z (CZ) gates.
- **Weather Noise Engine:** Implements probabilistic noise models inspired by atmospheric phenomena, as detailed in Section 2 These control the number, type, and intensity of Pauli errors applied to the graph states.
- **Noise Injection:** Weather-dependent Pauli operators (X, Y, Z) are randomly selected and applied to a subset of qubits. The number and type of errors are determined by sampling from the weather model's PDF at a specified intensity.
- **Monte Carlo Engine:** For each configuration (graph type, number of qubits, weather model, noise intensity), the simulation runs multiple trials (typically 10–100). This ensures statistical robustness.
- **Metric Computation:** For each trial, the simulator computes: Fidelity, Frobenius distance, Mutual information, concurrence-based entanglement, Entanglement change, Graph sensitivity (relative entanglement loss), Mutual information and Resilience (fraction of trials with fidelity ≥ 0.9).
- **Result Logging & Visualization**: All metrics are saved in structured DataFrames and visualized using heatmaps, boxplots, and line charts.

Simulation Results

The simulations covered:

- 15 graph topologies (standard + custom)
- 3–8 qubits per graph
- 4 weather models (rain, dust, turbulence, clear)
- 6 intensity levels (from 0.2 to 1.5)
- 100 trials per configuration

Fidelity vs. Weather Intensity: Fidelity consistently decreased with rising noise intensity. Weather conditions had a stronger impact than graph structure, with dust and rain producing the lowest fidelities, and turbulence and clear weather maintaining the highest.

Mutual Information Behavior: Mutual information dropped under all noisy conditions, with the sharpest declines observed in larger graphs and under dust-heavy or rainy scenarios. This reflects weakening correlations between qubit pairs.

Entanglement Change: The degree of entanglement loss varied widely across topologies and weather types. In general, rain and dust caused the most significant entanglement degradation, while clear and turbulent conditions preserved it better.

Resilience Scores: Some topologies, such as complete and star, were consistently resilient, maintaining high fidelity in a majority of trials. Others, like line and ring, showed sharp drops in resilience under adverse weather.

Sensitivity Analysis: Graphs such as scale-free and custom branched path demonstrated high sensitivity, their entanglement was highly responsive to noise. Conversely, complete and ring graphs remained largely unaffected.

Size-Dependent Effects: Several topologies exhibited size-dependent transitions. Notably, sensitivity and entanglement degradation effects emerged around 5–6 qubits, with larger graphs showing stronger responses to environmental noise.
We'll talk more about these results in the Analysis of results section.

4 Software Description

The simulation was implemented in Python 3.10, with a modular architecture that separates graph construction, noise modeling, metric evaluation, and batch simulation management. The design emphasizes flexibility for testing multiple topologies, weather scenarios, and qubit counts.

Tools and Libraries

- **NumPy:** used for linear algebra and quantum state manipulation.
- **NetworkX**: for defining and working with graph topologies.
- **Matplotlib** and **Seaborn**: for visualizing results.
- **Pandas**: for organizing simulation outputs into structured DataFrames.
- **TQDM**: for progress tracking during batch simulations.
- **SciPy**: for sampling from custom probability distributions.

Implementation Highlights

- The simulation is fully object-oriented, with distinct classes for:
  - Graph state generation.
  - Noise application.
  - Quantum metric computation.
  - Monte Carlo coordination.
- All outputs (e.g., fidelity, entanglement, mutual information) are automatically logged to CSV files, organized by timestamp.
- A central configuration file controls key parameters such as qubit range, trial count, and graph types, allowing easy reproducibility.

5 Analysis of results

This section presents the simulation results and interprets the impact of environmental noise on different graph state topologies. The metrics analyzed include fidelity, mutual information, entanglement, sensitivity, and resilience. Where relevant, comparisons between topologies and weather types are discussed to uncover performance trade-offs.

Fidelity Trends

Fidelity captures the closeness between the noisy and original quantum state. Across all simulations, fidelity consistently decreases with increasing weather intensity. The nature of the weather has a much stronger influence than the graph structure.

- Clear and turbulence conditions maintain high fidelity, with clear weather almost unaffected by noise.
- Dust causes the most rapid fidelity degradation, often pushing fidelity below 0.5 for most topologies.
- Rain shows moderate deterioration, depending on the intensity.

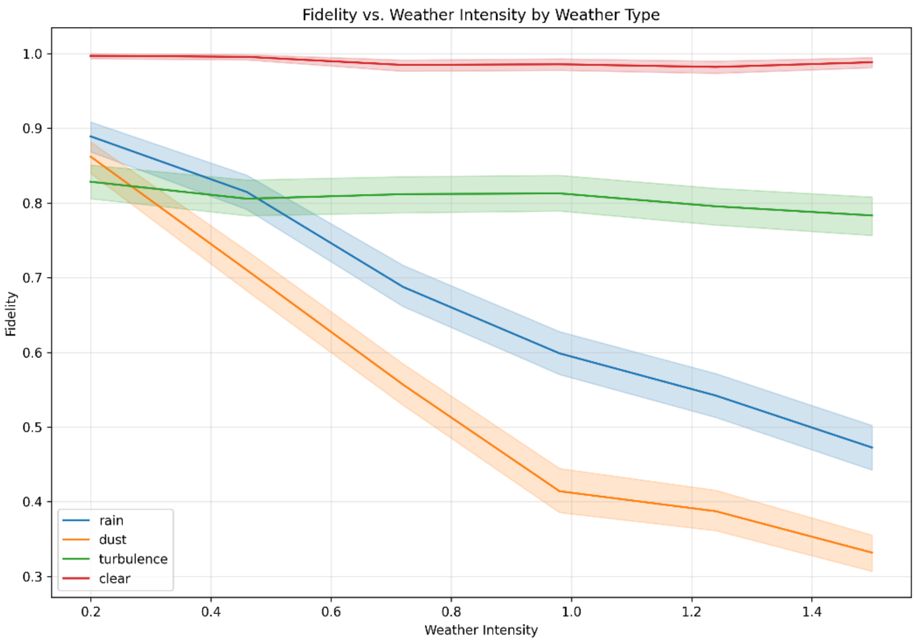

Figure 3 - Fidelity vs. Weather Intensity by Weather Type

Fidelity vs. Topology

To verify the influence of graph structure on fidelity, we plotted fidelity values across all topologies under varying weather intensities. The results show that fidelity is largely topology-independent

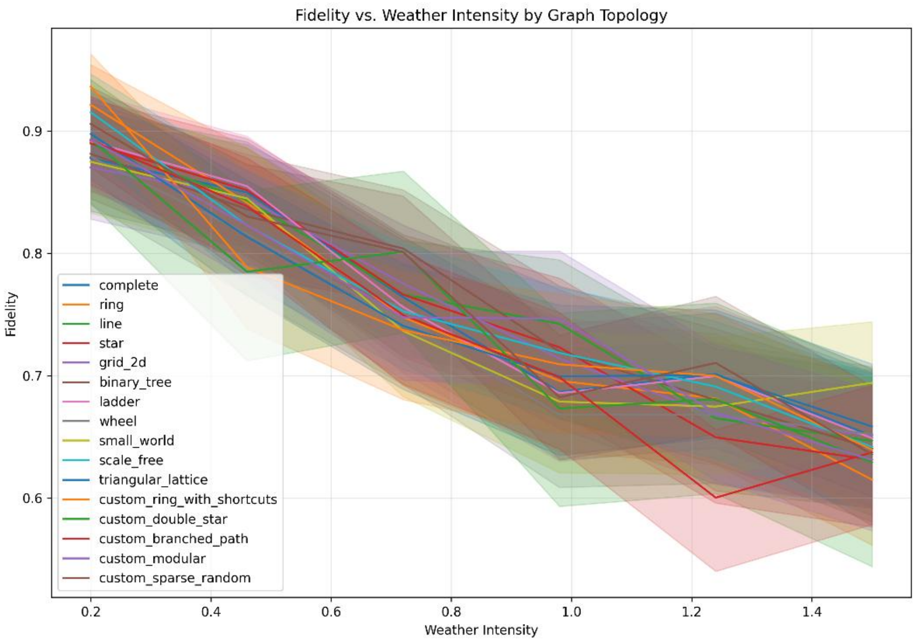

Figure 4 - Fidelity vs. Weather Intensity by Graph Topology

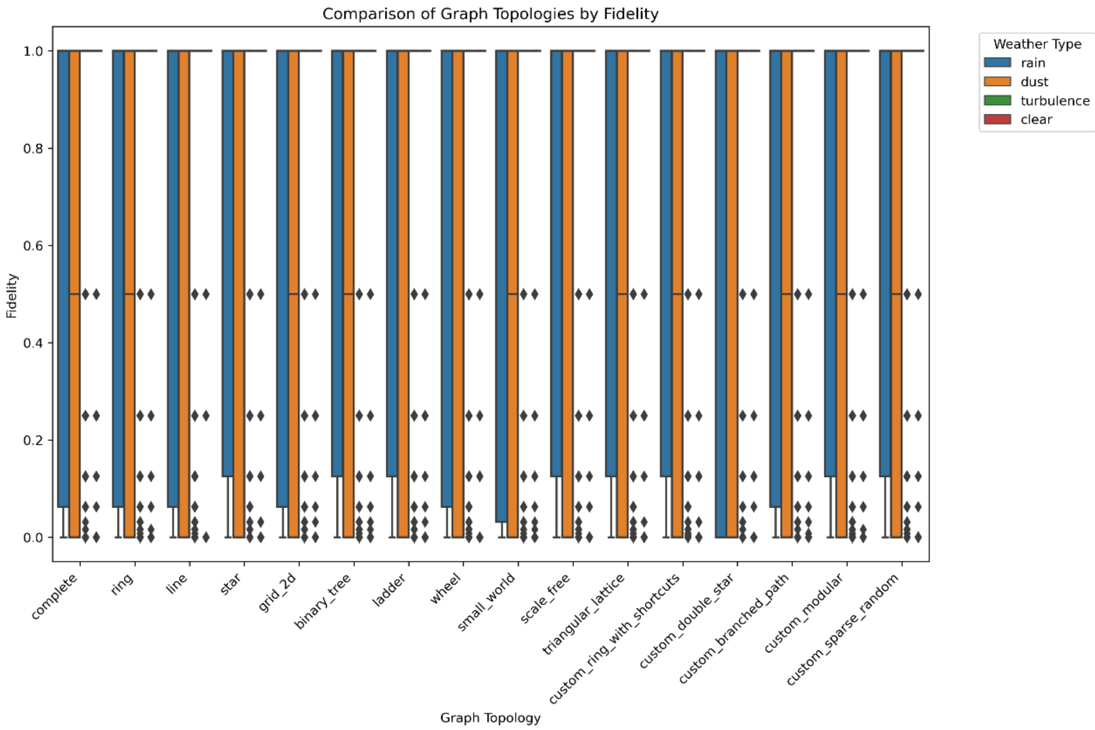

Figure 5 - Comparison of Graph Topologies by Fidelity

These plots confirm that fidelity is largely insensitive to the topology of the graph. Despite the wide variety of structures tested — from complete to scale-free to modular — fidelity drops are nearly identical across all graphs for a given weather type. This means:

- Topology is not a major factor in maintaining quantum coherence.
- Fidelity performance is dominated by the environmental noise model.
- Thus, efforts to improve fidelity should focus on weather-aware design and error correction, not topology optimization.

Mutual Information

Mutual information (MI) measures the amount of information preserved between the input and output states. As weather intensity increases, MI decreases across all noise types. Larger graphs with more qubits lose MI faster.

- Dust and rain reduce MI sharply.
- Clear weather maintains near-maximal MI regardless of qubit count.
- The number of qubits correlates with faster MI loss, indicating increased vulnerability in larger systems.

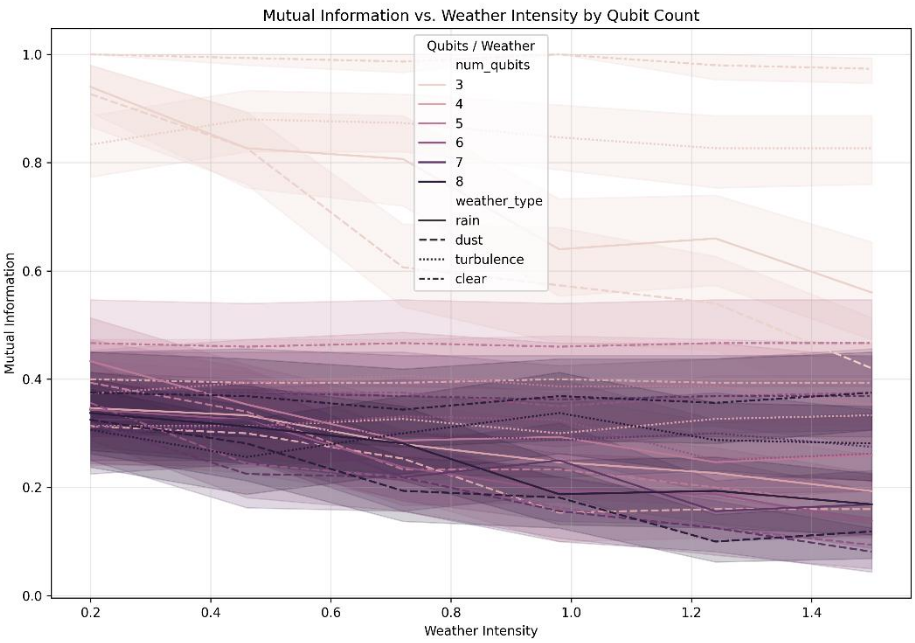

Figure 6 - Mutual Information vs. Weather Intensity by Qubit Count and Weather Type

Entanglement Change

To quantify how entanglement is affected, we calculated the relative change in average concurrence. The results highlight:

- Significant entanglement loss in dust and rain.
- Minor fluctuations in turbulence and clear weather.
- Some topologies (like star, wheel, and small_world) retained partial entanglement, while others (like line and modular) dropped sharply

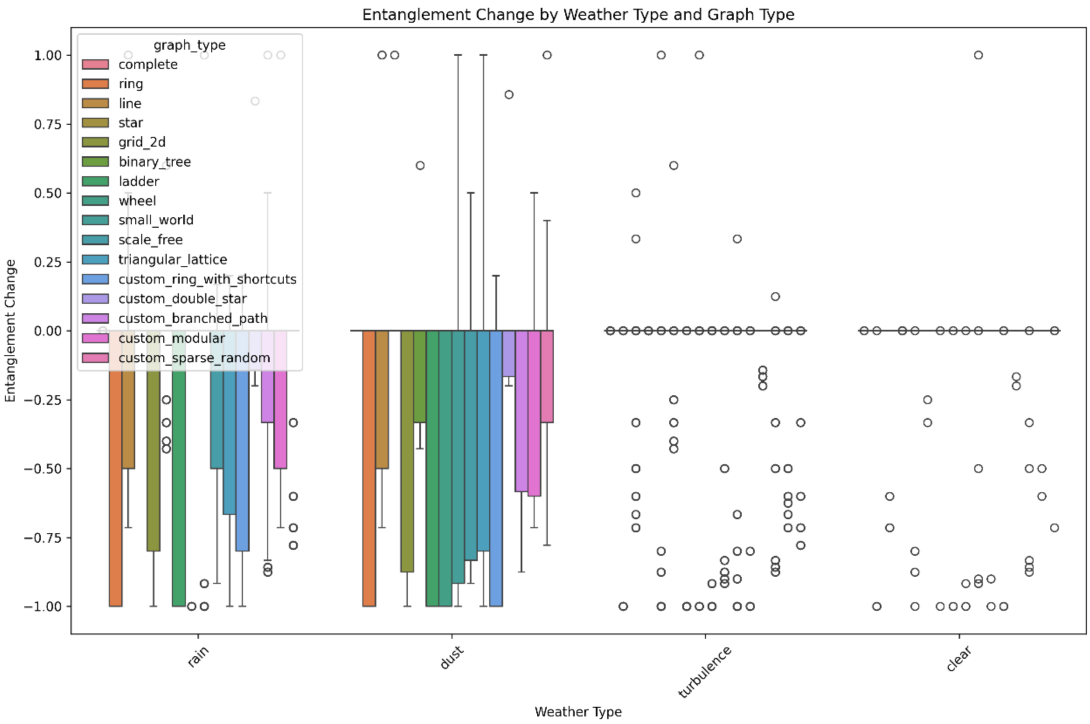

Figure 7 - Entanglement Change by Weather Type and Graph Type

Sensitivity

Sensitivity quantifies how much entanglement is disrupted by environmental noise, making it a critical metric for evaluating quantum graph states in sensing applications. It is defined as the relative change in entanglement before and after noise is applied.

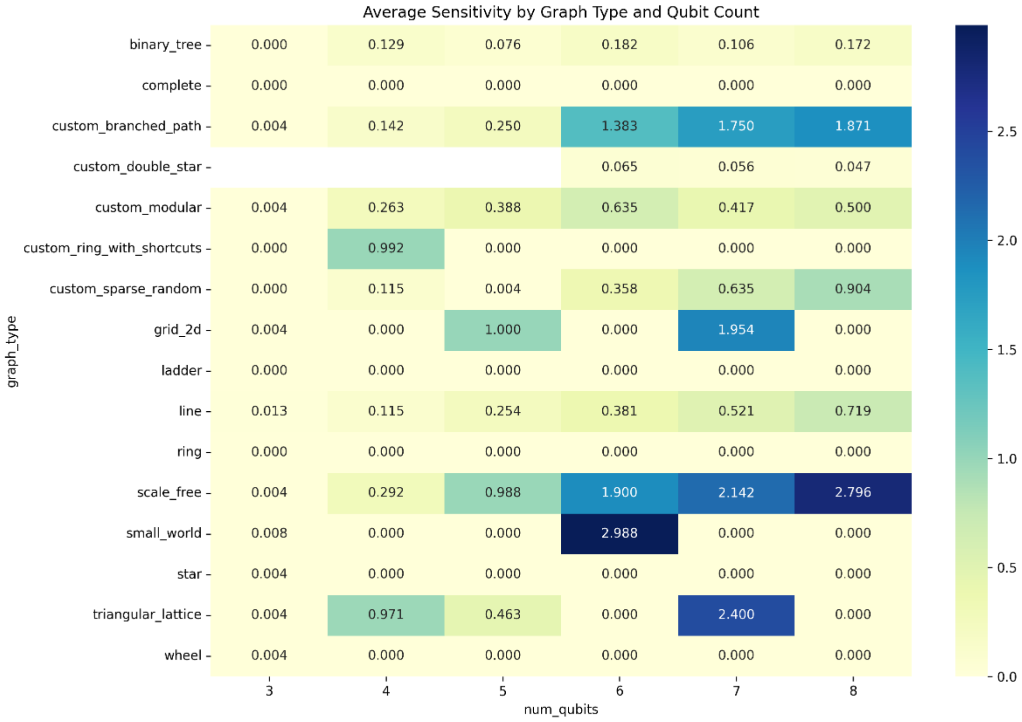

Figure 8 - Average Sensitivity by Graph Type and Qubit Count

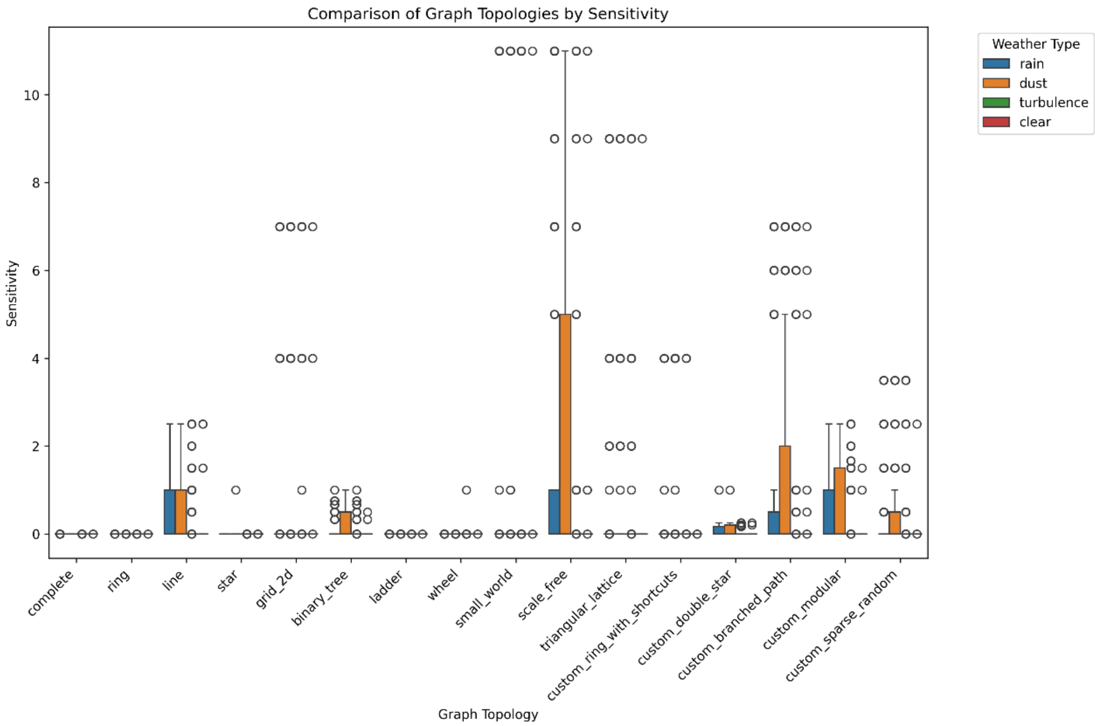

Figure 9 - Comparison of Graph Topologies by Sensitivity and Weather

The sensitivity metric reveals clear differences between graph structures. Both the boxplot and heatmap demonstrate that certain topologies are significantly more responsive to environmental noise, especially as the number of qubits increases. For example, the scale-free graph consistently exhibits the highest sensitivity across all weather conditions, reaching values as high as 2.8 for 8-qubit graphs. The custom branched path topology also shows steadily increasing sensitivity, reaching nearly 1.87 at 8 qubits. The custom modular graph maintains moderate to high sensitivity across all sizes, between 0.26 and 0.63.

In contrast, several topologies show minimal responsiveness. Structures such as complete, ring, star, ladder, and wheel remain near-zero in sensitivity regardless of qubit count or weather. These graphs are highly symmetric and redundant, making them excellent for stable communication but poor candidates for sensing. They do not amplify environmental disturbances, which results in stronger fidelity but low sensitivity.

Some topologies occupy the middle ground. The line, grid_2d, and triangular_lattice graphs display moderate sensitivity that increases with system size. For instance, triangular lattice reaches 2.4 at 7 qubits, and the line graph climbs from ~0.1 to ~0.7 between 4 and 8 qubits.

The impact of weather conditions is also evident in these plots:

- Dust causes the highest sensitivity across all graphs, especially in scale-free and branched structures.
- Rain induces moderate sensitivity, often lower than dust.
- Turbulence and clear conditions have very little impact on sensitivity in any topology.

These results reflect physical intuition. Dust represents a continuous and distributed noise source, amplifying vulnerabilities in topologies with bottlenecks or hubs. Turbulence, on the other hand, is intermittent and localized, often failing to disrupt the global entanglement significantly.

In summary:

- **High-sensitivity graphs** (e.g., scale-free, custom branched path) are ideal for quantum sensing, where responsiveness to noise is beneficial.
- **Low-sensitivity graphs** (e.g., complete, ring) are best suited for reliable quantum communication, due to their noise resistance.

- **Sensitivity increases with qubit count** in many topologies, indicating that graph structure and system size together determine sensing capability.

Ultimately, sensitivity is shaped far more by topology than by noise model, a sharp contrast to fidelity. These findings reveal a key trade-off in system design: the very features that make a graph sensitive to noise also make it less robust, and vice versa.

6 Conclusions and further work

This project set out to explore how realistic environmental noise, modeled after weather conditions, affects the behavior of quantum graph states. By simulating different graph topologies under Pauli noise inspired by rain, dust, turbulence, and clear skies, we analyzed key metrics such as fidelity, resilience, and sensitivity.

Our findings reveal a fundamental trade-off: graphs with high sensitivity (like scale_free and custom_branched_path) are excellent for quantum sensing but suffer from low stability, while low-sensitivity graphs (like complete and ring) preserve quantum states well and are ideal for communication. Weather strongly influences fidelity, but graph topology is the dominant factor in sensitivity.

Improving the System

To enhance the simulation, we propose incorporating Local Clifford transformations and Local Complementation, which could help identify LC-equivalent graphs that behave similarly under noise [5]. This would reduce redundancy in simulations and potentially uncover better-performing structures.

Future Work

A key next step is to design a real-world experiment to test the simulation’s predictions. For example, building photonic graph states and exposing them to tunable noise could validate sensitivity patterns and test the practical impact of Clifford equivalence. Additional research could also explore time-dependent noise and richer sensing metrics like Quantum Fisher Information [6].

This work lays the foundation for designing noise-aware quantum networks, optimized either for stability or for responsiveness, depending on the application.

7 Project Documentation

All project materials are available on GitHub at:

🔗 https://github.com/MarvelousKitty19/Final_Project_Submittion

8 References

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