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Fidelity-Aware Entanglement Routing and Failure-Resilience Analysis in Multi-Hop Quantum Repeater Networks using an Interactive Software Simulation Laboratory

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Abstract: Quantum repeater networks are a potential foundation for long-distance quantum communication, but entanglement routing is complicated by probabilistic link generation, imperfect entanglement swapping, fidelity degradation, limited resources, and component failures. This paper presents an interactive software simulation laboratory for investigating fidelity-aware routing and failure resilience in multi-hop quantum repeater networks. The framework represents repeaters and communication links as a graph and supports eight topology families: ring, star, linear chain, grid, mesh, random, small-world, and scale-free. A configurable weighted-score heuristic evaluates feasible routes using modelled end-to-end fidelity, estimated request success probability, residual capacity, path latency, and link utilisation. The laboratory also incorporates abstract entanglement-generation and swapping operations, configurable link and repeater failures, network visualisation, performance monitoring, and CSV-based data export. Its graph-based visualisation is intended to support structural interpretation and does not represent a trained graph neural network or learned routing policy. The mathematical model and documented simulation configuration establish a basis for reproducible experiments; however, quantitative comparisons are required to determine the effectiveness of the routing heuristic under different network conditions. Accordingly, this work focuses on the design and capabilities of an exploratory simulation environment rather than claiming demonstrated superiority over existing routing algorithms or quantum-network simulators.

Keywords: Quantum networks, quantum repeaters, entanglement routing, fidelity-aware routing, entanglement swapping, network resilience, topology analysis, simulation laboratory, resource-aware routing.

I. INTRODUCTION

The development of a quantum internet aims to connect geographically distributed quantum processors, sensors, and communication systems through networks capable of distributing quantum information and entanglement. Such networks could support applications including quantum key distribution, quantum teleportation, and distributed quantum computing [1]–[4]. Unlike conventional data networks, however, quantum networks operate under physical constraints that fundamentally influence communication and routing. Quantum states cannot be copied arbitrarily, optical signals experience distance-dependent attenuation, and the quality of shared entanglement is affected by probabilistic generation and imperfect quantum operations. Consequently, the design of effective routing strategies requires consideration of both network connectivity and the physical quality of the quantum resources being distributed. Quantum repeaters provide a means of extending entanglement distribution beyond the practical limitations of direct transmission. A long communication channel can be divided into shorter elementary links, over which entanglement is generated independently. Entanglement swapping subsequently combines neighbouring entangled pairs to establish entanglement between more distant nodes [6], [7]. Although this approach can extend communication distance, its performance depends on several interacting factors, including elementary-link generation probability, swapping success probability, state fidelity, memory limitations, and the availability of network resources. A route containing more hops introduces additional operations and potential failure points, whereas a shorter route may contain low-quality links or heavily utilised repeaters. Thus, minimising hop count or physical distance alone does not necessarily identify the most suitable route for a quantum communication request. This challenge becomes more pronounced as repeater networks grow in size and structural diversity. Different network topologies provide different levels of connectivity, path diversity, resource concentration, and tolerance to component failures. For example, a linear chain provides a restricted set of possible routes, while a mesh or random network may offer multiple alternatives between source and destination nodes. Hub-oriented structures can facilitate connectivity through highly connected nodes but may become vulnerable when those nodes fail. Small-world and scale-free structures introduce additional connectivity patterns

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whose routing and resilience characteristics depend on their construction and operating conditions. These differences motivate systematic investigation of how network structure, route quality, resource availability, and component failures jointly influence entanglement distribution. Research on quantum repeater networks has addressed several aspects of this problem. Foundational work established the principles of repeater-assisted communication and entanglement swapping [6], [7], while subsequent studies examined repeater architectures, routing metrics, entanglement-generation rates, multi-path routing, concurrent requests, and distributed routing protocols [10]–[18]. These contributions demonstrate that routing decisions must account for characteristics beyond conventional shortest-path distance. In parallel, quantum-network simulation platforms, including NetSquid and SeQUeNCe, provide environments for modelling network components and evaluating quantum communication protocols [8], [9]. Such platforms are important for detailed protocol and system studies, although their modelling flexibility may require additional implementation effort when the immediate objective is interactive exploration of topology, routing decisions, and failure scenarios. Despite these advances, there remains practical value in a transparent experimental environment that brings together topology generation, configurable route-quality assessment, resource constraints, controlled failure injection, and visual performance monitoring. In particular, researchers and students benefit from being able to vary network conditions, observe the resulting route selection, examine the consequences of component failures, and export experiment configurations and observations for further analysis. These capabilities complement detailed simulators by supporting early-stage investigation and comparative exploration; they do not replace hardware-calibrated modelling or establish physical-network performance by themselves. To address this need, this paper presents a fidelity-aware entanglement routing and failure-resilience analysis framework implemented as an interactive software simulation laboratory. The network is represented as a weighted graph in which vertices represent quantum repeaters and edges represent communication links. The framework supports eight topology families: ring, star, linear chain, grid, mesh, random, small-world, and scale-free. For a given source–destination request, candidate routes are assessed using a configurable composite utility function that incorporates estimated end-to-end fidelity, success probability, residual capacity, path latency, and link utilisation. Feasibility constraints are applied before route selection so that route quality is considered alongside operational resource availability. The framework also integrates an entanglement-generation and swapping workflow with controlled failure scenarios. Link degradation or loss, depleted channel capacity, and repeater failures can be introduced to examine how network conditions affect route availability and request outcomes. A browser-based dashboard presents routing decisions and performance indicators, including entanglement distribution rate, average fidelity, request success rate, latency, and network health. A graph-message-passing-inspired visual layer is included to make connectivity and route structure easier to inspect; it is an interpretable visualisation component, not a claim that a trained graph neural network has been developed. Experiment configurations and recorded observations can be exported as comma-separated values (CSV) to support subsequent analysis. The objective of this work is not to claim a universally optimal routing algorithm or to demonstrate superiority over existing methods without comparative evidence. Instead, the study establishes an integrated and configurable environment in which routing policies, network topologies, resource constraints, and failure scenarios can be examined systematically. Its usefulness as a research tool depends on transparent model assumptions, consistent experimental conditions, and quantitative validation against appropriate baseline strategies.

The principal contributions of this paper are summarised as follows:

1. Integrated simulation framework: A unified software environment combines network-topology generation, repeater and link representation, route selection, entanglement-generation and swapping abstractions, failure injection, performance monitoring, and CSV export.
2. Multi-factor route-quality formulation: A configurable composite utility model considers end-to-end fidelity, estimated request success probability, residual capacity, path latency, and link utilisation, providing a transparent alternative to route selection based exclusively on hop count.
3. Comparative topology and resilience exploration: Eight topology families are supported, enabling systematic investigation of connectivity patterns and controlled component-failure scenarios under consistent configuration settings.
4. Interactive and interpretable monitoring: A browser-based dashboard exposes route decisions, network status, and performance indicators, while the graph visualisation helps users inspect structural changes and routing outcomes.
5. Reproducible experimental workflow: Configuration and observation exports support repeatable experiments, quantitative comparison, and subsequent validation using statistical analysis and more detailed quantum-network simulators.

The remainder of this paper is organised as follows. Section II reviews the relevant literature, and Section III groups prior work by technical category. Section IV compares the proposed framework with existing approaches, while Sections V and VI discuss the problem formulation and research gaps. Section VII presents the framework architecture, and Section VIII defines the mathematical model. Section IX describes the implementation, and Section X specifies the experimental setup. Section XI discusses the available observations and planned comparisons, Section XII presents limitations, and Section XIII provides practical recommendations. Section XIV concludes the paper and identifies directions for future work.

II. LITERATURE REVIEW

Research on quantum networks has progressed from the theoretical foundations of repeater-assisted communication to

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routing protocols, resource-allocation strategies, and software environments for evaluating network performance. A central challenge across these areas is the reliable distribution of entanglement between distant nodes under probabilistic link generation, imperfect operations, finite quantum-memory lifetimes, and limited network capacity. This section reviews the principal developments relevant to the present study and identifies the specific methodological gap addressed by the proposed simulation laboratory.

A. Foundations of Quantum Repeaters and Entanglement Distribution

The quantum internet envisions interconnected quantum devices capable of supporting secure communication, distributed computation, and other applications that depend on shared quantum states [1], [2]. Early work on quantum cryptography and quantum teleportation established important applications of entanglement in communication and quantum information processing [3], [4]. However, the direct transmission of quantum states over long optical-fibre channels is constrained by photon loss, which increases substantially with transmission distance [5].

Quantum repeaters address this limitation by dividing long communication channels into shorter elementary links. Entanglement is generated over these links and subsequently extended through entanglement swapping, allowing distant nodes to share entanglement without relying exclusively on direct transmission [6], [7]. Briegel and co-authors demonstrated the importance of repeater-assisted schemes for long-distance quantum communication, while later research investigated different repeater architectures and the trade-offs between achievable communication distance, generation rates, and resource requirements [7], [10].

These foundational studies establish the physical motivation for repeater networks but do not, by themselves, resolve the route-selection problem in an arbitrary network graph. In a multi-hop network, a routing decision determines which elementary links and intermediate repeaters participate in a request. The resulting performance depends not only on the number of hops but also on link quality, swapping operations, resource availability, and the probability that the required operations succeed. These dependencies motivate routing formulations that evaluate end-to-end performance rather than relying exclusively on conventional distance metrics.

B. Entanglement Routing and Path-Selection Strategies

Quantum-network routing extends classical path-selection concepts by incorporating the properties of entanglement generation and quantum operations. Van Meter and co-authors investigated how path-cost definitions influence routing decisions in repeater networks, demonstrating the importance of selecting metrics appropriate to quantum communication [11]. Caleffi subsequently developed a routing approach based on entanglement-generation rate and formulated an optimal algorithm for the considered single-request setting [12]. These studies provide a foundation for evaluating paths according to their ability to support successful entanglement distribution rather than simply minimising the number of intermediate nodes.

Multi-path routing further illustrates the importance of network structure. Pant and co-authors studied protocols that exploit multiple paths to distribute entanglement and showed that path diversity can improve achievable entanglement rates under the assumptions of their model [13]. Shi and Qian investigated routing for concurrent source–destination requests, incorporating redundancy and recovery mechanisms to address the demands of multiple communication pairs [14]. Li and co-authors examined the role of link- and swapping-success probabilities in remote entanglement generation, highlighting the need to account for probabilistic operations when selecting routes [15].

Collectively, these studies show that routing quality depends on the optimisation objective, network state, and operational assumptions. Rate-oriented routing, multi-path strategies, and concurrent-request allocation address related but distinct problems. Their findings also caution against treating any single routing metric as universally sufficient. A path that is attractive in terms of distance or generation rate may be unsuitable when end-to-end fidelity is inadequate, while a high-quality path may be impractical if its resources are heavily utilised.

The present study builds on this established direction by using a configurable composite utility to expose trade-offs among fidelity, estimated success probability, residual capacity, latency, and link utilisation. This formulation is intended as a transparent routing mechanism for interactive experimentation. It is not presented as a proof of global optimality or as a replacement for established specialised routing algorithms.

C. Network Capacity, Distributed Routing, and Link-Layer Services

Beyond individual routing algorithms, theoretical and protocol-level research has examined the limits and organisation of quantum-network communication. Pirandola investigated fundamental limits on quantum communication and the use of network-theoretic bounds to characterise achievable performance [5], [16]. Such bounds provide important reference points for understanding what a routing and resource-allocation strategy can achieve, although they do not directly prescribe the route for every operational request.

Distributed routing provides a complementary perspective. Chakraborty and co-authors developed a routing protocol in which nodes make decisions using local link information, demonstrating that routing need not always depend on a complete global view of the network [17]. At the link layer, Dahlberg and colleagues introduced a service-oriented approach for producing entanglement between neighbouring nodes, helping establish a modular foundation for quantum-network protocol design [18].

These contributions address different levels of the network stack. Capacity analyses characterise fundamental constraints, distributed protocols determine how routing decisions can be

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made, and link-layer services support the generation of elementary entanglement. A simulation environment that combines these ideas must nevertheless distinguish its abstraction level from a complete protocol implementation. In particular, graph-based resource constraints and simplified success models should not be interpreted as fully calibrated representations of quantum hardware unless they explicitly model the corresponding physical and protocol mechanisms.

D. Quantum-Network Simulation Platforms

Software simulation is essential because experimental quantum-repeater networks remain difficult to construct and operate at scale. NetSquid provides a discrete-event simulation platform designed to model quantum networks, including time-dependent effects and hardware-level behaviour [8]. SeQUeNCe offers a modular simulation framework for studying quantum-network architectures, protocols, and entanglement-management functions [9]. These platforms support detailed investigation of network behaviour and provide valuable tools for evaluating protocols under controlled conditions.

However, detailed simulation and rapid visual exploration serve different research purposes. Hardware-oriented simulation can represent device behaviour and protocol timing with considerable detail, whereas an interactive laboratory can prioritise rapid configuration, visible route selection, topology comparison, and controlled failure injection. These objectives are complementary rather than mutually exclusive. The proposed framework is positioned in the latter category: it provides an accessible environment for exploring how topology and routing policy interact under configurable abstract network conditions.

This distinction is important when interpreting results. A high-level simulator can help identify hypotheses, compare routing policies within a consistent model, and expose potential failure-sensitive structures. It cannot establish physical feasibility or reproduce hardware-specific performance unless its abstractions are validated against appropriate models or experimental evidence. Accordingly, the framework should be evaluated first for internal consistency, reproducibility, and the usefulness of its comparative experiments.

E. Graph Learning and Emerging Fidelity-Aware Routing

Graph-based learning has attracted attention because network topology and node–edge relationships can be represented naturally using graph neural networks and message-passing operations. Graph convolutional networks provide a general mechanism for learning from graph-structured data [19], while message-passing formulations extend this principle to a variety of graph tasks [20], [21]. Reinforcement-learning-based approaches have also been investigated for routing decisions in repeater networks [22].

These approaches must be distinguished by their actual implementation. A trained graph neural network learns parameters from data or an optimisation process, whereas a graph-message-passing-inspired visualisation can simply display structural relationships without learning a routing policy. The present framework uses the latter interpretation: its graph-oriented visual layer is intended to support inspection and explanation of network structure, not to claim predictive performance from a trained model.

Fidelity-aware routing itself is not an unexplored problem. Earlier research has investigated routing for high-rate entanglement distribution, and more recent work has explicitly addressed end-to-end fidelity guarantees, resource allocation, coherence, and fidelity-aware decision-making [13], [15], [36]. Surveys of quantum entanglement routing also classify a broad range of routing strategies and identify continuing challenges involving fidelity, probabilistic operations, memory lifetimes, and network resources [37]. Consequently, a composite utility that includes fidelity should be understood as a design choice within an established research area, rather than sufficient evidence of algorithmic novelty on its own.

The relevant opportunity for the present study is to integrate configurable route-quality assessment with topology exploration, interactive failure analysis, performance monitoring, and experiment export in a single environment. Such integration enables researchers to investigate how different structural and operational conditions influence the behaviour of a routing policy. Its scientific value depends on the clarity of the underlying mathematical model and on quantitative experiments that compare the policy with suitable alternatives under identical conditions.

F. Research Gap and Positioning of the Present Study

The literature demonstrates substantial progress in repeater theory, entanglement routing, multi-path distribution, resource allocation, distributed protocols, and quantum-network simulation [7]–[18]. Existing routing approaches address different objectives and operating assumptions, while detailed simulators provide capabilities for examining protocol behaviour and hardware-related effects [8], [9]. Graph-learning research offers further possibilities for using network structure in decision-making [19]–[22]. These areas provide the technical foundations for the present work.

The remaining gap addressed here is primarily one of integrated experimentation and comparative analysis, rather than the absence of fidelity-aware routing research. Specifically, the proposed laboratory brings together eight configurable topology families, a multi-factor route-utility formulation, abstract entanglement-generation and swapping processes, controlled link and repeater failures, dashboard-based monitoring, and CSV export. This combination is intended to facilitate systematic investigation of topology-dependent routing behaviour and network resilience within a common experimental workflow.

To make that contribution scientifically meaningful, comparisons must use consistent network sizes, link parameters, resource constraints, traffic conditions, and failure scenarios. The proposed policy should be evaluated against appropriate baselines, such as shortest-path routing and a suitable success- or fidelity-aware strategy. Repeated runs

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should report measured outcomes and variability rather than relying on expected structural behaviour alone. The model's assumptions and limitations must also be stated explicitly so that results from the abstract simulation are not misrepresented as validated hardware performance.

On this basis, the present study contributes an interactive experimental framework for investigating the joint effects of route quality, network topology, resource availability, and component failures. Its intended role is to complement existing quantum-network theory and simulation platforms by providing a transparent, reproducible environment for hypothesis generation and comparative routing analysis.

III. EXTENDED RELATED WORK BY TECHNICAL CATEGORY

The preceding literature review outlined the development of quantum-network research and identified the principal approaches relevant to fidelity-aware entanglement routing. This section examines these approaches by technical category, focusing on their modelling assumptions, optimisation objectives, and relevance to topology-dependent routing and resilience analysis. The discussion distinguishes foundational quantum-network theory from routing algorithms, resource-management methods, simulation platforms, and graph-based learning. This distinction is important because these approaches solve different problems and should not be treated as directly interchangeable.

A. Repeater Architectures and Entanglement-Swapping Models

Quantum-repeater architecture determines how entanglement is generated, stored, extended, and consumed across a network. Foundational repeater research established that long-distance entanglement distribution can be supported by dividing a communication channel into shorter segments and combining elementary entangled pairs through swapping operations [7]. Subsequent studies investigated alternative repeater generations and physical implementations, including memory-based and all-photonic approaches [10], [24]–[26].

At the network level, these architectures introduce several quantities that influence route quality: elementary-link generation probability, the fidelity of generated entanglement, swapping success probability, memory lifetime, and the resources available at intermediate repeaters. These quantities interact. A path with more intermediate repeaters may require additional swapping operations and incur further failure opportunities. Conversely, a longer path composed of better-quality links may be preferable to a shorter route containing unreliable links, depending on the application's fidelity and success requirements.

The level of physical detail used to represent these effects varies considerably across studies. Detailed models may account for hardware-specific noise, memory dynamics, operation timing, and protocol behaviour. Abstract models instead represent selected effects through parameters and closed-form expressions, reducing computational complexity and making large network configurations easier to explore. Neither level is universally sufficient: the appropriate choice depends on whether the research objective is physical validation, protocol evaluation, or comparative investigation of routing behaviour.

The proposed laboratory adopts a high-level graph abstraction. Repeaters are represented as vertices with resource and operational attributes, while communication links are represented as edges with configurable quality and generation characteristics. Entanglement generation and swapping are represented through probabilistic and fidelity-related quantities. This abstraction supports systematic topology and routing experiments, but its results must be interpreted within the assumptions of the model. In particular, simplified fidelity equations do not automatically reproduce the behaviour of a specific repeater architecture or quantum-memory implementation.

B. Routing Algorithms and Path-Quality Metrics

Routing algorithms determine how a source–destination request is mapped onto a sequence of links and intermediate repeaters. Classical shortest-path methods provide a useful starting point, but quantum-network routing must consider additional constraints because end-to-end entanglement quality and request success depend on the properties of the selected path [11], [27].

Van Meter and co-authors examined the influence of routing-cost definitions on quantum-network path selection [11]. Caleffi developed a routing formulation based on entanglement-generation rate and derived an optimal algorithm under the assumptions of a single-request setting [12]. These studies illustrate that the routing objective can substantially influence the route selected, even when the network graph remains unchanged.

Multi-path and concurrent-request approaches extend this problem beyond the selection of a single path. Pant and co-authors investigated multi-path routing for entanglement distribution and showed how alternative paths can improve performance under their model assumptions [13]. Shi and Qian considered concurrent communication requests and mechanisms for redundancy and recovery [14]. Li and co-authors incorporated probabilistic link and swapping effects into remote entanglement-generation strategies [15]. Collectively, these contributions highlight the importance of matching the routing strategy to the network's operational conditions and the performance objective being optimised.

A further distinction is needed between a path-cost function and a constrained routing algorithm. A weighted cost can rank candidate paths according to selected characteristics, but a high score does not guarantee that the path satisfies a minimum fidelity requirement, has sufficient resources, or remains available after a failure. Feasibility conditions and quality constraints must therefore be specified independently of the ranking function. Similarly, the weights assigned to different metrics can change the preferred route, making normalisation

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and sensitivity analysis important components of a credible evaluation.

The present laboratory uses a configurable composite utility involving estimated end-to-end fidelity, success probability, residual capacity, path latency, and link utilisation. Its purpose is to make the trade-offs between these quantities visible and experimentally adjustable. This is a multi-criteria design choice, not by itself a new optimality result. To establish the algorithm's value, its decisions must be compared against appropriate baselines under identical conditions, and the effects of different weight settings must be quantified.

C. Capacity Constraints, Resource Allocation, and Distributed Operation

Quantum entanglement is a consumable resource, and repeater networks must manage finite link-generation capacity and limited intermediate-node resources. Consequently, the existence of a connected path does not necessarily mean that a request can be served. A link may have insufficient available capacity, a repeater may be unavailable, or an otherwise feasible route may have a low probability of successful entanglement distribution.

Theoretical capacity analysis provides a complementary perspective by identifying limits on achievable quantum communication performance. Pirandola and co-authors investigated fundamental limits on repeaterless quantum communication [5], while subsequent network-capacity analyses considered bounds and resource-allocation questions in more general settings [16]. Such results establish useful reference points, but theoretical limits and practical route-selection rules serve different purposes. A capacity bound characterises what may be achievable under specified assumptions; it does not necessarily determine the best route for a particular request at a particular time.

Distributed routing provides another perspective on resource management. Chakraborty and co-authors investigated a protocol in which nodes make routing decisions using local link information [17]. At the link layer, Dahlberg and colleagues described a service-oriented architecture for generating entanglement between neighbouring nodes [18]. These studies emphasise the importance of separating network-wide routing decisions from the lower-level mechanisms that produce elementary entanglement.

For comparative simulation, resource constraints should be modelled consistently across all routing policies. Otherwise, differences in reported performance may reflect unequal capacity assumptions rather than the effectiveness of the routing strategy. The proposed laboratory therefore treats residual capacity, link utilisation, and component availability as inputs to route assessment and failure analysis. These attributes allow the consequences of resource depletion to be explored within the abstract model; they should not be interpreted as a complete implementation of distributed resource reservation or link-layer scheduling unless those mechanisms are explicitly implemented.

D. Network Topology and Structural Resilience

Network topology determines the possible routes between nodes and influences how failures propagate through a network. Different graph structures offer different combinations of path diversity, connectivity, average path length, and dependence on highly connected nodes. These properties are relevant to quantum networks because a surviving path is useful only if its links and intermediate operations can still support the required entanglement quality and success probability.

A linear chain has a restricted route structure, so the loss of a critical intermediate component can disconnect the source from the destination. A ring can offer an alternative route around a failed link, although the alternative may contain more hops. Grid and mesh structures provide additional path choices, depending on their dimensions and connectivity. Random and small-world graphs can produce different combinations of local connections and long-range links. Scale-free graphs can contain highly connected hubs, creating efficient routes in some circumstances but also introducing vulnerability to targeted hub removal.

The classical complex-network literature has documented the distinction between random failures and targeted removal of highly connected nodes, particularly for networks with heterogeneous degree distributions [30], [31]. These findings motivate topology-aware failure experiments, but their quantitative conclusions cannot be transferred automatically to quantum networks. Quantum routing introduces additional conditions: a graph may remain connected while all available routes violate a fidelity threshold or have insufficient success probability.

Accordingly, resilience should be assessed using both structural and service-level measures. Connectivity and the number of surviving routes indicate whether alternative paths remain available. Request success rate, delivered fidelity, and latency indicate whether the remaining routes are operationally useful under the chosen model. The proposed laboratory supports eight topology families and controlled link or repeater failures to examine these distinctions under consistent configurations. Whether one topology outperforms another remains an empirical question that must be resolved through repeated experiments rather than inferred solely from graph structure.

E. Quantum-Network Simulation Platforms

Quantum-network simulators provide the computational infrastructure needed to evaluate protocols and network configurations that are difficult to investigate experimentally. NetSquid is a discrete-event simulation platform designed for quantum-network research, including time-dependent network processes and hardware-related modelling [8]. SeQUeNCe provides a modular environment for examining quantum-network architectures and protocols [9]. Both support research questions that require more detailed representation of network components and communication processes than a lightweight graph model can provide.

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The proposed laboratory addresses a different, complementary use case. Rather than attempting to reproduce every physical process, it prioritises interactive configuration of topology and routing parameters, visual inspection of selected routes, controlled failure injection, performance monitoring, and export of experiment observations. These functions are intended to reduce the effort required for exploratory comparisons and educational demonstrations.

The distinction should be understood in terms of modelling scope rather than a general claim that one platform is superior to another. Detailed simulators provide capabilities that an abstract dashboard does not replace, while a lightweight interactive environment can make selected routing trade-offs easier to inspect. A sound evaluation should therefore compare capability coverage and intended use, not claim equivalent physical accuracy. Promising findings from the abstract framework should subsequently be tested using a more detailed simulator when the relevant physical and protocol mechanisms are supported.

F. Graph-Based Learning and Routing Intelligence

Graph-based learning methods are relevant to routing because a network naturally consists of interconnected nodes and edges. Graph convolutional networks use graph structure to aggregate information from neighbouring nodes [19], while message-passing frameworks generalise neighbourhood-based information exchange to a range of graph-learning tasks [20], [21]. Reinforcement-learning approaches have also been explored for decision-making in quantum-repeater networks [22].

However, graph-based visualisation, graph-based feature aggregation, and trained graph-learning policies are technically distinct. A graph visualisation may expose connectivity and route structure without learning from data. A trained graph neural network requires a defined model, training procedure, data or interaction process, and evaluation protocol. A reinforcement-learning policy requires an appropriate state representation, action space, reward function, and training or adaptation procedure.

The current framework includes a graph-message-passing-inspired visual layer to make network relationships easier to inspect. This component should be described as an interpretable visualisation unless a trained model is actually implemented and evaluated. It does not establish that graph learning improves route quality, nor does it support claims about prediction accuracy or generalisation.

A future extension could evaluate a learned routing policy against the current utility-based method and established baselines. Such a study would need to specify the training data or interaction environment, define the reward in terms of relevant quantum-network objectives, and test performance on unseen topologies and failure conditions. These experiments would provide evidence for the value of learned routing beyond the visual explanation of network structure.

G. Synthesis and Implications for the Proposed Framework

The reviewed research addresses complementary layers of quantum-network operation. Repeater studies establish the mechanisms and physical constraints of entanglement distribution [7], [10], [24]–[26]. Routing research investigates path selection, entanglement-generation rates, multi-path operation, and concurrent requests [11]–[15]. Capacity analysis and distributed protocols address resource limits and network organisation [5], [16]–[18]. Detailed simulation platforms support protocol and hardware-oriented investigations [8], [9], while graph-learning research offers alternative approaches to exploiting network structure [19]–[22].

These bodies of work indicate that no single capability comparison can establish the scientific value of a routing framework. A method must be assessed in relation to its objective, assumptions, and baseline. In particular, fidelity-aware routing is an established research direction; incorporating fidelity into a composite utility is not sufficient by itself to establish algorithmic novelty. Likewise, topology visualisation and failure injection demonstrate useful software functionality but do not independently establish improved network performance.

The contribution of the proposed laboratory is therefore positioned as an integrated experimental workflow for examining route quality, topology, resource constraints, and failure resilience. It combines eight topology families with a configurable multi-factor utility, abstract entanglement-generation and swapping models, interactive monitoring, and CSV-based experiment export. This combination supports controlled investigations of how structural and operational conditions affect the behaviour of a specified routing policy.

To substantiate the contribution, experiments should compare the proposed policy with shortest-path routing and at least one appropriate quality-aware baseline. All policies should use identical network configurations, link parameters, traffic patterns, and failure scenarios. Multiple independent runs should be used to estimate variability, and reported outcomes should include request success rate, delivered fidelity, latency, and entanglement distribution rate where these quantities are implemented and measured. Weight sensitivity, targeted hub failures, and depleted-resource scenarios should be analysed separately so that the causes of observed differences can be identified.

The resulting evidence would establish the framework's usefulness as a reproducible environment for comparative routing analysis. Claims about physical quantum-network performance would still require validation against more detailed models or experimental systems. This distinction defines both the intended scope of the present work and the pathway for extending it into a more comprehensive study of fidelity-aware quantum-network routing.

IV. Comparison with Existing Approaches

Existing quantum-network research addresses several complementary challenges, including entanglement generation and swapping, fidelity-aware path selection, network-resource allocation, and the simulation of quantum communication protocols. However, these approaches differ in their primary

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objectives, modelling granularity, evaluation capabilities, and intended applications. A meaningful comparison must therefore consider not only routing performance but also network modelling, resource monitoring, failure analysis, and experimental reproducibility.

This section compares conventional routing strategies, established quantum-network simulation platforms, graph-learning-based routing methods, and the proposed interactive fidelity-aware entanglement-routing framework. The comparison focuses on methodological scope and functional capabilities rather than assuming a performance advantage without experimental evidence.

A. Conventional and Fidelity-Aware Routing Approaches

Conventional shortest-path routing selects a route by minimising a defined cost, such as hop count or physical distance. Although computationally simple and useful as a baseline, this approach does not inherently account for quantum-specific characteristics, including entanglement fidelity, probabilistic swapping operations, or finite entanglement resources. Consequently, the shortest route may not necessarily provide the most reliable or suitable quantum connection.

Fidelity-aware routing addresses this limitation by incorporating quantum-state quality into path selection. Depending on the algorithm, fidelity may be used as an optimisation objective, a feasibility constraint, or one component of a multi-criteria decision process. Success-aware routing further considers the probability that the required entanglement-generation and swapping operations will succeed. These criteria represent distinct aspects of route quality: high estimated fidelity does not necessarily imply a high establishment probability, and a route with a high success probability may still incur substantial latency or resource consumption.

The proposed framework adopts a composite route-utility concept that considers end-to-end fidelity, estimated success probability, residual capacity, path latency, and link utilisation. By considering these factors within a common decision framework, the approach aims to facilitate the inspection of trade-offs between communication quality, reliability, and resource availability. However, the inclusion of multiple metrics alone does not establish algorithmic novelty or superiority. The mathematical formulation, normalisation procedure, feasibility constraints, and comparative evaluation must demonstrate the value of the proposed combination.

For experimental validation, the proposed routing policy should be compared against a shortest-path baseline, a fidelity-constrained baseline, and a success-aware baseline. All methods should use consistent network configurations, request sequences, resource assumptions, and failure conditions wherever applicable. This design would help determine whether the composite policy provides measurable improvements over simpler routing strategies.

B. Comparison with Quantum-Network Simulation Platforms

Quantum-network simulation platforms provide environments for investigating network protocols, entanglement distribution, quantum operations, and resource-management strategies. NetSquid supports detailed simulation of quantum-network systems, while SeQUeNCe provides a discrete-event simulation framework for studying quantum-network operation. Their suitability for particular experiments depends on the models, protocols, and routing algorithms configured by the researcher.

The proposed framework has a different intended emphasis. Rather than claiming to replace detailed quantum-network simulators, it focuses on interactive network-level exploration, topology comparison, route-quality inspection, resource monitoring, controlled failure scenarios, and metric export. These capabilities are intended to help users examine how routing decisions and network conditions interact across different network structures.

This distinction concerns scope rather than demonstrated superiority. The availability of an interactive dashboard does not establish greater simulation accuracy, lower computational complexity, or better routing performance. Such claims would require direct experiments under equivalent assumptions and documented evaluation procedures. Furthermore, the extent to which the proposed framework reproduces physical quantum-network behaviour must be assessed against its implemented models and stated abstractions.

C. Graph-Learning-Based Routing Approaches

Graph-based learning methods provide another direction for quantum-network routing research. Graph representations can encode network connectivity and node or link characteristics, while learning algorithms can use these representations to identify routing policies suited to specified objectives. Depending on their design, these methods may incorporate fidelity, success probability, resource availability, and latency into their input features, reward functions, or optimisation objectives.

However, learning-based routing introduces additional requirements, including training data or simulation experience, model configuration, evaluation against unseen scenarios, and appropriate baseline comparisons. Its performance cannot be established merely by representing a network as a graph or displaying graph-related information.

The proposed framework includes graph-message-passing-inspired visualisation to support the inspection of network structure and routing behaviour. This visualisation should not be interpreted as a trained graph neural network or a learned routing policy unless such a model has been implemented and experimentally validated. The framework's contribution is therefore positioned around interactive, multi-criteria network analysis rather than an unverified claim of graph-learning capability.

D. Resource Awareness and Network Resilience

Quantum-network routing decisions are influenced by finite entanglement resources, link quality, repeater availability, and

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the probabilistic nature of entanglement operations. A routing strategy that considers only path length may overlook resource depletion or the degradation of links along the selected route. Resource-aware approaches seek to account for these constraints when selecting or maintaining communication paths.

Network resilience is similarly important because a route that is suitable under normal operating conditions may become infeasible following link degradation, repeater failure, capacity exhaustion, or a disruption affecting a central network node. The ability to study these conditions depends on the network model and the failure scenarios supported by the evaluation environment.

The proposed framework is designed to support the examination of residual capacity, link utilisation, and configurable failure conditions alongside route-quality indicators. These features can provide a common environment for investigating how different routing strategies respond to changing network conditions. Nevertheless, the presence of failure-injection controls does not itself demonstrate improved resilience. Resilience must be evaluated through measurable outcomes, such as request success rate, recovery behaviour where implemented, and performance degradation under consistently defined failure scenarios.

E. Comparative Evaluation and Research Positioning

The main distinction of the proposed framework is its intended integration of fidelity-aware routing, estimated operation success, resource indicators, topology exploration, failure analysis, and interactive metric inspection. Whereas routing algorithms primarily define path-selection decisions and detailed simulators support configurable protocol-level investigations, the proposed framework aims to make network-level behaviour accessible through a unified exploratory workflow.

To determine whether this integration offers measurable benefits, the experimental evaluation should examine end-to-end fidelity, request success rate, path latency, entanglement distribution rate, resource consumption, and network performance under defined failures. Metric definitions must remain consistent across the evaluated methods. Where stochastic operations are modelled, repeated runs with multiple random seeds should be conducted, and results should include appropriate summary statistics and uncertainty measures.

The evaluation should also distinguish functional verification from performance validation. Functional verification establishes whether the implemented routing logic, resource updates, failure mechanisms, and exported metrics behave as specified. Performance validation determines whether the routing policy provides measurable improvements over selected baselines. These are separate objectives and should be reported accordingly.

Illustrative Scenario

Consider a student team investigating why an entanglement request succeeds in one quantum-network topology but fails in another. Both networks contain the same number of repeaters and have comparable individual link fidelities; however, their connectivity structures differ. In the ring topology, alternative routes are available between connected nodes, whereas the star topology depends heavily on a central hub.

When a link in the ring is disabled, an alternative route may remain available, provided the failure does not disconnect the relevant endpoints. This alternative can introduce additional hops, increased latency, and further fidelity degradation. In contrast, failure of the central hub in the star topology can disconnect peripheral nodes from one another, making requests that depend on the hub infeasible.

Although these differences can be analysed mathematically, an interactive network representation can make their practical implications easier to observe. By displaying the network structure, highlighting the selected route, and updating relevant performance indicators after a simulated failure, the proposed laboratory aims to help users investigate the relationship between topology, path diversity, and routing outcomes. This scenario illustrates the framework's intended educational and exploratory value rather than constituting a claim of experimentally measured performance.

VI. RESEARCH GAP

The reviewed literature establishes important foundations for quantum-network simulation, entanglement routing, resource management, and network resilience. Nevertheless, several opportunities remain for improving the integration, accessibility, and evaluation of these capabilities.

1. Fragmented network-analysis workflows. Topology generation, routing-policy evaluation, failure modelling, and performance reporting may be implemented as separate components in research workflows. Integrating these functions into a common environment could simplify scenario configuration and facilitate more consistent comparisons across network conditions.

2. Limited integration of multiple routing criteria. Routing algorithms may prioritise particular objectives, such as entanglement-generation rate, connection success probability, or fidelity constraints. However, practical route selection can also depend on latency, residual capacity, and link utilisation. A unified evaluation framework can help investigate the trade-offs among these criteria. The extent to which existing methods already address such combinations must be established through a careful comparison of specific algorithms rather than a general claim that multi-metric routing is absent from the literature.

3. Insufficiently accessible interactive resilience analysis. Network topology influences the consequences of link and node failures. Established complex-network research has examined the relationship between structural properties and tolerance to random failures or targeted attacks [30]. An interactive quantum-network environment could extend this perspective by enabling users to examine how selected routing policies respond to controlled link degradation, repeater failure, and connectivity disruption.

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4. Accessibility challenges in detailed simulation. Configuring quantum-network simulations may require familiarity with programming, protocol models, and simulation parameters. Although detailed simulators are essential for investigating protocol-level behaviour, an interactive network-level interface can complement them by supporting preliminary exploration, teaching, and rapid inspection of routing scenarios. Such an interface should be understood as complementary to, rather than a replacement for, detailed simulation tools.

5. Limited interpretability of routing guidance. Learning-based routing methods can potentially incorporate complex relationships among network structure, link quality, and resource availability. However, the usefulness of such methods depends on how their decisions are evaluated and explained. There is an opportunity to develop evaluation environments that expose relevant route-quality indicators and uncertainty information. In the present framework, any confidence-based or learning-based guidance should be claimed only if the corresponding mechanism has been implemented and validated; graph-inspired visualisation alone does not establish this capability.

6. Reproducibility and experiment-data export. Comparing routing strategies requires consistent configuration records, clearly defined metrics, and accessible experimental outputs. Exporting simulation results in a structured format, such as CSV, can support subsequent analysis and benchmarking. However, export functionality alone does not guarantee reproducibility; the experimental configuration, random seeds where applicable, routing-policy settings, and failure conditions must also be recorded.

Research Opportunity

These gaps motivate the development of an interactive framework that combines network-topology exploration, multi-criteria route evaluation, resource monitoring, controlled failure scenarios, and structured metric export. The intended contribution is the integration of these capabilities into a common workflow for examining quantum-network routing behaviour.

The framework's effectiveness must be established through implementation verification and controlled experiments. In particular, comparisons against shortest-path, fidelity-constrained, and success-aware routing baselines are necessary to determine whether the proposed composite utility offers measurable benefits. This evaluation should assess end-to-end fidelity, request success rate, path latency, resource consumption, and behaviour under defined failure conditions.

Accordingly, the research gap is framed as an opportunity for integrated, accessible, and experimentally testable network-level analysis, rather than an assertion that the individual routing, simulation, resilience, or multi-criteria concepts have not previously been studied.

VII. PROPOSED SIMULATION FRAMEWORK

A. Framework Overview

The proposed simulation framework provides an interactive environment for investigating fidelity-aware entanglement routing, network-resource utilisation, and resilience under changing network conditions. As illustrated in Fig. 1, the framework follows a seven-stage processing pipeline: user configuration, topology generation, node and link modelling, failure injection, candidate-route evaluation, entanglement simulation, and performance monitoring with data export.

The process begins when the user specifies the network topology, network size, and source–destination pair. The topology generator constructs the corresponding graph, after which node and link attributes are assigned. Configured failure conditions are then applied, and the routing engine evaluates feasible candidate paths using the implemented route-scoring mechanism. The selected path is passed to the entanglement simulation module, which models probabilistic generation and swapping events. Finally, the resulting outcomes are recorded and presented through the dashboard, while supported experiment data are exported for subsequent analysis.

The framework is organised into three logical layers. The presentation layer provides the browser-based dashboard, network visualisation, configuration controls, and performance indicators. The simulation layer contains the graph representation, routing logic, failure handling, entanglement-event modelling, and metric computation. The data layer manages structured simulation information and stores experimental outputs in CSV format. This separation supports modular development and allows individual components to be modified without requiring corresponding changes throughout the entire system.

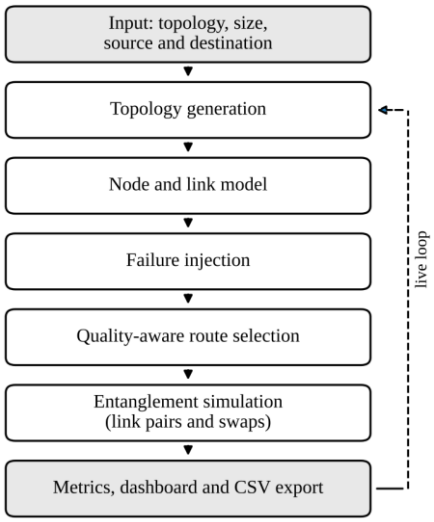


Fig. 1. Block diagram of the proposed simulation framework.

B. Network Topology Generation

Network topology determines the connectivity between repeaters, the availability of alternative routes, and the potential consequences of link or node failures. To investigate these structural effects, the framework supports eight topology families: ring, star, linear chain, grid, mesh, random, small-world, and scale-free networks.

A ring topology provides alternative directions between connected nodes, whereas a star topology concentrates

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connectivity around a central hub. A linear chain represents a sequential repeater arrangement with limited path diversity. Grid and mesh topologies provide additional connectivity, although their actual redundancy depends on the graph configuration. Random graphs exhibit connectivity patterns influenced by their generation parameters, while small-world networks combine local clustering with long-range shortcuts [33]. Scale-free networks exhibit heterogeneous degree distributions and may contain highly connected hubs as a consequence of preferential attachment [31]. Random-graph generation follows the selected graph model [32], with graph construction implemented using standard graph-library routines [34].

The framework uses these topology families to examine how structural differences influence routing decisions and network behaviour under failure conditions. The expected characteristics described below are qualitative hypotheses based on network structure; their implications for the simulated quantum-network performance must be established experimentally.

Table III summarises the qualitative expectations for each family. These are structural expectations drawn from complex-network theory, to be confirmed by experiments with the laboratory.

TABLE III. STRUCTURAL CHARACTERISTICS OF THE TOPOLOGY FAMILIES

Topology	Path diversity	Expected behaviour under failure
Ring	Two alternative directions between node pairs	A single link failure may leave an alternative route, potentially with increased path length
Star	Routes between peripheral nodes depend on the hub	Hub failure can disconnect peripheral nodes from one another
Linear chain	A single route between the endpoints	Failure of an intermediate link can disconnect the endpoints
Grid	Multiple routes may be available	Alternative paths may support gradual performance degradation
Mesh	High connectivity, depending on network size	Multiple alternatives may improve tolerance to individual link failures
Random	Depends on the generated graph and connectivity	Outcomes vary with the connectivity structure
Small-world	Local connections supplemented by long-range shortcuts	Shortcuts may reduce path length, but their failure can affect route availability
Scale-free	Heterogeneous connectivity with potentially influential hubs	May tolerate some random failures but can be vulnerable to targeted hub removal [30]

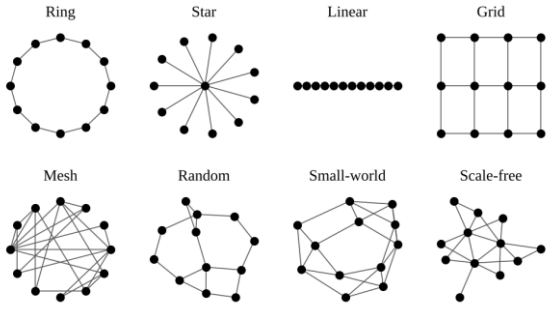


Fig. 2. The eight topology families offered by the laboratory.

C. Repeater and Link Modelling

The framework represents the quantum network as a graph in which vertices correspond to quantum repeaters and edges represent optical-fibre links. Each component is associated with attributes that influence its eligibility for routing and its contribution to the simulated communication process.

Repeater attributes include capacity, fidelity-related state information, operational status, neighbouring links, and traffic participation. Link attributes include capacity, fidelity, attenuation, length, utilisation, and operational status. Depending on its current state, a component may participate in routing, incur a penalty during route evaluation, or be excluded from the set of feasible components.

TABLE IV. ATTRIBUTES AND STATES OF NETWORK COMPONENTS

Component	Attributes	Status states
Repeater (node)	Capacity, fidelity, status, neighbouring links, traffic participation	Active, degraded, failed, overloaded, on selected route
Link (channel)	Capacity, fidelity, attenuation, length, utilisation	Active, degraded, failed

Link length and attenuation influence the modelled quality and availability of entanglement generation. Longer links may exhibit lower generation success or degraded pair quality according to the selected simulation parameters. The framework includes a simplified quantum-memory model intended to represent the effect of storage time on simulated entanglement quality. The model's behaviour depends on the memory parameters and decay rule implemented in the simulation. It is a computational abstraction rather than a calibrated representation of a specific physical quantum-memory technology; its assumptions and parameter values should therefore be documented when interpreting the results.

The decay behaviour is controlled by an initial fidelity and a memory-lifetime parameter.

This memory model is intended as a computational abstraction for exploring the influence of storage time on simulated entanglement quality. It should not be interpreted as a calibrated representation of a specific physical quantum-memory technology. The assumptions and parameter values must therefore be documented when interpreting the resulting performance metrics.

D. Failure Injection and Resilience Analysis

To investigate network resilience, the framework allows network conditions to change during simulation. Four failure scenarios are considered: link loss, channel degradation or resource depletion, repeater failure, and routing disruption.

Link loss removes a connection from the active network graph. Channel degradation or depletion modifies the relevant link attributes, such as available capacity or fidelity, according to the implemented failure model. Repeater failure makes the affected node unavailable for subsequent routing decisions. Routing disruption occurs when a previously preferred path becomes infeasible because one or more of its components fail or no longer satisfy the routing constraints.

Failures can be introduced individually through the dashboard or generated randomly for repeated experiments, where supported by the implementation. The interface provides link

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information, including source, destination, length, fidelity, pair capacity, and status. Following a state change, the routing engine reevaluates feasible paths using the remaining eligible network components.

The purpose of this mechanism is to facilitate controlled investigation of the relationship between topology, resource availability, and route feasibility. Quantitative conclusions about resilience require consistent failure definitions and repeated measurements of outcomes such as request success rate, end-to-end fidelity, and latency.

E. Quality-Aware Route Selection

For each entanglement request, the routing engine identifies candidate paths between the specified source and destination using the currently eligible network components. Each feasible path is evaluated using the composite scoring mechanism implemented in the framework. The criteria include end-to-end fidelity, estimated operation-success probability, link availability, capacity utilisation, path latency, and reliability under the current network conditions.

The routing engine selects the feasible candidate with the highest calculated utility and forwards it to the entanglement simulation module. This approach extends conventional cost-aware path selection [27] by incorporating quantum-network quality and resource-related criteria, consistent with the routing considerations discussed in [11].

The composite score is a heuristic decision mechanism rather than an exact global optimisation method. Its behaviour depends on the definitions and normalisation of the individual criteria, their weights, and the constraints applied during candidate-path selection. These details must be specified in the mathematical formulation and kept consistent with the implementation to support reproducibility and fair comparison with alternative routing strategies.

The selected route should not be interpreted as globally optimal solely because it achieves the highest score among the candidates evaluated. Any claim of improved routing performance requires controlled comparison with suitable baseline methods using clearly defined metrics.

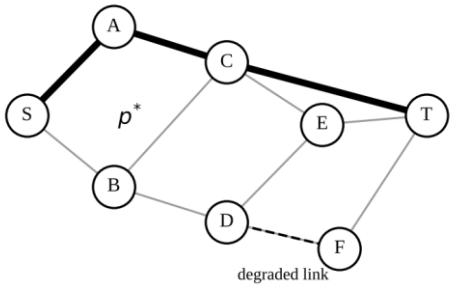


Fig. 3. Example of route selection. The highlighted path p* has the highest utility; the dashed link is degraded.

The scoring mechanism is heuristic rather than an exact global optimiser. Its behaviour depends on the mathematical definition of each metric, the normalisation method, the weights assigned to the individual criteria, and the constraints applied during candidate-path selection. These details must be specified in the mathematical-model section to ensure that the routing policy can be reproduced and evaluated consistently.

F. Entanglement Generation and Swapping Simulation

After selecting a route, the framework simulates elementary entanglement generation along the route's links and entanglement-swapping operations at intermediate repeaters. Each generation or swapping operation is represented as a probabilistic event according to the corresponding simulation parameters.

If any required event fails, the request is recorded as unsuccessful. If all required events succeed, the framework computes the resulting end-to-end fidelity according to its implemented fidelity-composition model and accumulates the modelled path latency. The request outcome and relevant performance information are then passed to the monitoring and data-recording components.

The framework also provides an illustrative representation of the four conceptual stages of entanglement swapping: Bell-state measurement, classical communication, Pauli correction, and establishment of the resulting end-to-end entangled pair. This representation supports the educational purpose of the laboratory by connecting the routing process to the principal operations involved in entanglement swapping.

Because the framework uses an abstract software model, its outcomes depend on the assumptions encoded in the generation, swapping, fidelity, and latency calculations. They should be interpreted as simulation results under those assumptions rather than direct predictions of a physical quantum-network deployment.

G. Continuous Traffic and Simulation Loop

To examine network behaviour over time, the framework supports a continuous traffic loop. During each request cycle, the system generates an entanglement request, evaluates candidate paths, selects a route, and simulates the required generation and swapping operations. The resulting success or failure is recorded, and the relevant resource-utilisation values and performance indicators are updated.

The loop allows users to observe how successive requests interact with the available network resources. When a component fails or its condition changes, subsequent routing decisions can reflect the updated network state. When a failed component is restored, the system can reevaluate the available paths and display the resulting behaviour.

The responsiveness of the dashboard depends on the implementation's request-processing and update mechanisms. Claims about real-time performance or recovery speed should therefore be supported by measurements rather than inferred solely from the presence of a continuous loop.

H. Dashboard, Routing Visualisation, and Data Export

The dashboard presents the network as a graph, visually distinguishing available links, degraded links, selected routes, active repeaters, and offline repeaters. Indicator cards display the principal network-level metrics, including entanglement distribution rate, average fidelity, request success rate, and the number of active repeaters. A timestamped event log records relevant route selections and state changes.

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A routing-decision panel provides information about the current routing decision, including the source or current repeater, destination, candidate hop sequence, calculated path cost, and estimated link-generation and swapping success information, as supported by the implementation. These visual elements are intended to make the relationship between network state and route selection easier to inspect.

The framework also includes a graph-intelligence visualisation that animates message passing over the network. The current implementation uses transparent neighbourhood averaging inspired by graph neural network concepts; it is not a trained neural-network model or a learned routing policy. Route selection is performed by the weighted-score heuristic described in Section VII-E. The visualisation therefore serves as an explanatory aid rather than evidence of machine-learning-based routing.

Finally, experiment runs and benchmark summaries can be exported in CSV format for further processing and comparison. For reproducible experimentation, exported data should be accompanied by relevant configuration information, including topology parameters, routing settings, failure conditions, and random seeds where applicable.

I. Concurrency and Resource Contention

The framework considers resource limitations associated with finite link and repeater capacities. When a request uses a selected route, the resource model accounts for the capacity consumed along the participating links and intermediate repeaters, according to the implemented reservation mechanism. The handling of reservations and their release must remain consistent with the actual request-processing logic.

As resources become less available, the resource-related component of the routing score can reduce the utility of congested paths and favour feasible alternatives. A repeater or link that no longer satisfies the implemented capacity constraints should not be treated as available for a new request until the relevant constraint is satisfied.

These mechanisms provide a simplified basis for examining resource-aware routing under changing network demand. However, the use of resource reservations does not by itself establish support for simultaneous multi-path routing. The framework selects a single route for each request; claims concerning concurrent requests, overlapping reservations, or contention should be limited to behaviours supported by the implementation and verified through testing.

The influence of resource contention should be evaluated using defined capacity constraints and repeatable request workloads. Relevant measurements may include request success rate, resource utilisation, path latency, and the frequency of requests rejected because no feasible route is available.

J. Design Rationale and Alternative Choices

Several design decisions shape the framework's scope.

First, a composite weighted score is used instead of optimising a single metric. Different quantum-network applications may assign different priorities to fidelity, success probability, latency, and resource consumption. A configurable weighted score makes these trade-offs explicit and allows alternative routing preferences to be examined without redesigning the entire simulation engine.

Second, a heuristic routing mechanism is adopted to support interactive exploration and straightforward modification of scoring criteria. Exact optimisation can be appropriate for particular formulations and constraints [12], but the proposed framework prioritises transparent decision logic and experimentation across configurable networks. This design choice does not imply that the heuristic is globally optimal or more efficient than every exact or approximate alternative; such conclusions require comparative evaluation.

Third, the framework uses an abstract software-level model rather than a fully calibrated hardware-level representation. Detailed physical modelling would require technology-specific parameters and additional modelling complexity. The abstraction makes the environment more accessible for exploratory studies and complements more detailed simulation platforms, including NetSquid and SeQUeNCe [8], [9]. Its conclusions remain bounded by the assumptions and fidelity of the implemented models.

Fourth, the graph visualisation is separated from the routing logic. This architectural separation allows the visual representation to evolve independently of the route-selection mechanism and provides a potential pathway for integrating future learning-based guidance. Such future capabilities should be distinguished from the functionality implemented and evaluated in the current framework.

K. Interaction Walkthrough

A typical interaction begins when the user opens the overview page and configures the network topology, number of repeaters, average node degree where applicable, and initial and gate fidelity parameters. The network is then generated and displayed on the graph canvas, allowing the user to inspect the available links and repeater arrangement.

The user next specifies a source–destination pair and submits an entanglement request. The routing engine evaluates the feasible candidate paths and selects the path with the highest calculated utility. The selected route is highlighted in the graph, while the routing-decision panel displays the relevant hop sequence and weighted cost.

When continuous traffic is enabled, the framework processes successive requests and updates the supported performance indicators and event log. To examine resilience, the user can disable a link on the selected route or take a repeater offline. The system updates the affected component's status and reevaluates routing feasibility for subsequent requests. The user can then observe changes in the selected route and the recorded fidelity, success-rate, and latency metrics. Restoring the component allows the network to be examined under the recovered configuration.

Finally, the user exports the experiment data in CSV format for additional analysis. This workflow is intended to support interactive investigation of topology, routing decisions, resource constraints, and failure effects within a single environment. Its practical value should be assessed through usability evaluation and reproducible experiments, while its

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routing performance should be established through controlled comparison with appropriate baseline methods.

VIII. MATHEMATICAL FORMULATION

The network is modelled as an undirected graph G = (V, E), where V is the set of repeaters and E is the set of optical links. A link ℓ has a generation probability pℓ, a fidelity Fℓ, a delay dℓ, a pair capacity, and an operational status. A path p between source s and destination d is a sequence of h links through h − 1 intermediate repeaters, each of which performs one swapping operation with success probability q.

Path success: The path delivers an end-to-end pair only if every link generates a pair and every swapping operation succeeds. Assuming independent events, the path-success probability is

$$P(p) = q^{(h-1)} \cdot \Pi\, p_\ell,\ \ell \in p \quad (1)$$

Swap fidelity: Assuming that the elementary pairs are Werner states [35], the fidelity of the pair obtained by swapping two pairs with fidelities F_1 and F_2 is

$$F = F_1F_2 + (1 - F_1)(1 - F_2) / 3 \quad (2)$$

The end-to-end fidelity of a path is obtained by applying (2) successively along the path. As the number of swapping operations increases, accumulated infidelity can reduce the quality of the resulting entangled pair, as illustrated analytically in Fig. 4.

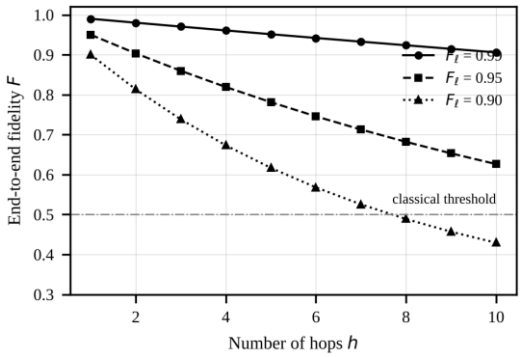


Fig. 4. End-to-end fidelity against hop count obtained by applying (2) repeatedly, for three elementary link fidelities Fℓ (analytical illustration).

Path latency: The latency of a path is the sum of the link delays plus the time spent on swapping,

$$T(p) = \Sigma\, d_\ell + (h - 1) \cdot t_{swap},\ \ell \in p \quad (3)$$

where tswap is the duration of one swapping operation.

Route utility: Each feasible path receives a composite utility in which better fidelity, success probability, and spare capacity increase the score, while latency and utilisation reduce it,

$$U(p) = w_1F + w_2P + w_3C - w_4T - w_5\rho \quad (4)$$

where C is the capacity measure of the path, ρ is its utilisation, and w_1 to w_5 are configurable weights. The capacity measure and metric scaling should be defined consistently with the implemented routing algorithm.

The selected route is

$$p^* = \text{argmax } U(p),\ p \in \Phi(s, d) \quad (5)$$

where Φ(s, d) is the set of feasible paths between source s and destination d using active links and eligible repeaters. Fig. 5 shows how the success probability in (1) falls with hop count for three link-generation probabilities when the swapping probability is fixed.

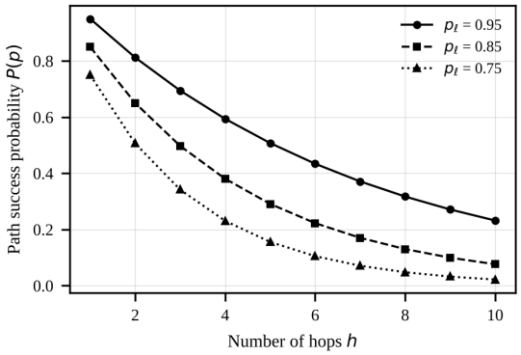


Fig. 5. Path success probability against hop count from (1) for q = 0.9 and three link probabilities (analytical illustration).

Performance indicators: Over a run of Nreq requests, of which Nok succeed, the success rate and entanglement distribution rate are

$$SR = Nok / Nreq \times 100,\ EDR = Npairs / \Delta t \quad (6)$$

where Npairs is the number of end-to-end pairs delivered in the observation window Δt, expressed in pairs per minute when Δt is measured in minutes.

Algorithm 1: Quality-Aware Route Selection and Simulation

Input: topology type, size N, source s, destination d.

- Generate the graph G(V, E) for the chosen topology.
- Assign node capacity, link fidelity, link capacity, and attenuation parameters.
- Apply failures and mark degraded or failed components.
- Enumerate feasible paths Φ(s, d) from s to d using active links.
- Score each feasible path p ∈ Φ(s, d) using the utility U(p) in (4).
- Select the best route p* ← argmax U(p), for p ∈ Φ(s, d).
- Generate elementary pairs and perform swapping along p*.
- Compute fidelity, success, and latency, and log the outcome.
- Update utilisation, performance indicators, charts, and the event stream; repeat for subsequent requests.

Complexity: Enumerating all simple paths can be exponential in the worst case. In practice, the candidate set is limited to a bounded number of short or high-quality paths. With a candidate bound K and an average path length $\bar{h}$, scoring costs

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approximately $O(K \cdot \bar{h})$ per request, excluding candidate generation and interface-rendering overhead.

Worked Example

A numerical example illustrates how the expressions combine. Consider a path of three links with elementary fidelities of 0.95, 0.94, and 0.95, link-generation probabilities of 0.9 each, a swapping success probability q = 0.9, link delays of 0.08, 0.12, and 0.10 ms, and a swapping time of 0.2 ms.

Applying (2) to the first two links gives

$$F12 = 0.95 \times 0.94 + 0.05 \times 0.06 / 3 \approx 0.894$$

Swapping this pair with the third link gives

$$Fend = 0.894 \times 0.95 + 0.106 \times 0.05 / 3 \approx 0.851$$

Therefore, the end-to-end fidelity of the path is approximately 0.851.

Using (1), the path-success probability is

$$P(p) = 0.9^2 \times 0.9^3 \approx 0.590$$

This corresponds to a success probability of approximately 59.0%, because three link-generation events and two swapping events must all succeed under the independence assumption.

Using (3), the latency is

$$T(p) = 0.08 + 0.12 + 0.10 + 2 \times 0.2 = 0.70 \text{ ms}$$

Consider a competing path with two links, each having a fidelity of 0.93 and a link-generation probability of 0.9. Its end-to-end fidelity is

$$Falt = 0.93 \times 0.93 + 0.07 \times 0.07 / 3 \approx 0.867$$

Its success probability is

$$Palt = 0.9^2 \times 0.9 = 0.729$$

The alternative path therefore has higher end-to-end fidelity and success probability in this example. However, its latency depends on its link delays and swapping duration. Its overall utility also depends on its capacity, utilisation, and the configured weights in (4). Consequently, the alternative cannot be declared the optimal route without evaluating all the utility terms. This illustrates how the routing decision depends on the relative importance of fidelity, success probability, capacity, latency, and utilisation.

Properties of the Fidelity and Success Expressions

Two properties of (1) and (2) help explain the behaviour of the routing model.

First, consider the infidelity $\varepsilon = 1 - F$ of an entangled pair. When two pairs with infidelities ε_1 and ε_2 are swapped, (2) gives

$$\varepsilon_{out} = \varepsilon_1 + \varepsilon_2 - (4/3)\varepsilon_1\varepsilon_2$$

For small infidelities, the product term is of second order and can be neglected as a first-order approximation. The output infidelity is then approximately $\varepsilon_1 + \varepsilon_2$. For a path of h links with similarly high elementary fidelities, accumulated infidelity can therefore grow approximately in proportion to the number of swapping stages, provided the total error remains small.

Applying (2) to two identical input fidelities gives

$$f(F) = F^2 + (1 - F)^2 / 3$$

The fixed points are F = 1 and F = 0.25. For $0.25 < F < 1$, this transformation produces a lower fidelity than the input fidelity under the simplified swapping model. Therefore, repeated swapping does not improve imperfect-pair fidelity without an additional mechanism, such as entanglement purification [23].

Second, the success probability in (1) depends on the product of the link-generation probabilities and the swapping success probabilities. For identical link-generation probabilities below one and a swapping probability below one, adding links introduces additional success requirements and decreases the probability that all events succeed in a single attempt. Assuming independent repeated attempts with a constant success probability P(p), the expected number of attempts until success is 1 / P(p). This expectation does not account for queueing, resource contention, memory expiration, or changing link conditions unless these effects are explicitly included in the simulation.

Together, these properties explain why longer paths can be disadvantaged by both accumulated infidelity and reduced establishment probability. Improving a weak link may benefit route quality, but the overall advantage depends on the other path characteristics and the utility weights.

A further consideration is the fidelity threshold. If the simulator adopts $Fend \geq 0.5$ as a route-feasibility condition, any path whose composed fidelity falls below this value can be excluded by the routing policy. This threshold should be treated as a model-specific assumption rather than a universal limit for all quantum-network applications. If the laboratory models memory decay over time, the corresponding decay equation and lifetime parameters should also be specified so that the influence of storage time can be reproduced and evaluated.

IX. IMPLEMENTATION

A. Technology Stack

The laboratory is implemented as a modular software pipeline corresponding to the stages illustrated in Fig. 1. The backend uses Python and the Flask framework to provide application programming interface (API) endpoints and server-side logic. A custom Python simulation engine handles graph construction, route selection, failure management, and performance-metric computation. The frontend is developed using HTML, CSS, and JavaScript, with canvas-based network visualisation, charts, and indicator cards. Simulation state is

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exchanged through JSON, while experiment results can be exported in CSV format.

The system is designed as a software-based research and teaching environment for exploring quantum-network behaviour. It is a conceptual simulation rather than a physical quantum-network testbed, and its outputs depend on the assumptions and models implemented in the simulation engine.

B. Dashboard Pages

The interface is organised into several workspaces that provide access to network configuration, simulation, visualisation, and analysis. The overview page combines the network topology, configuration controls, routing-request form, performance indicators, and event log. The quantum-network page displays optical links and provides controls for disabling or restoring links where supported. The live-routing page presents routing decisions for individual requests. The graph-intelligence page visualises message-passing operations, while the quantum-physics page presents fidelity-related illustrations and memory-age effects where implemented.

Additional workspaces support traffic and concurrency simulations, resilience analysis, telemetry, benchmarking, and experiment export. These interface components are intended to make the relationship between network configuration, routing decisions, and observed simulation metrics easier to inspect.

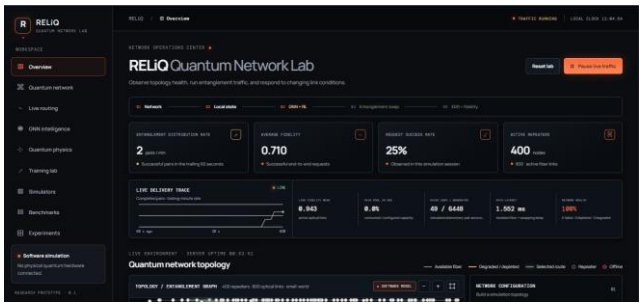


Fig. 6. dashboard during one live session: entanglement distribution rate, average fidelity, request success rate, and active repeaters.



Fig. 7. Live topology view

C. Experiment Workflow

A typical experiment begins by selecting the network topology, number of repeaters, average node degree, and initial link and gate fidelities. The graph is then generated, and source and destination nodes are selected for a routing request. Traffic is initiated, and the performance indicators are monitored over the observation period. A failure scenario can subsequently be introduced, after which the changes in route selection and performance indicators are recorded.

The resulting experiment data can be exported as a CSV file when this functionality is available in the implementation. Repeating the procedure across different topology families using consistent parameters provides a basis for comparative evaluation. For reproducibility, the experiment configuration, random seed, traffic conditions, and failure settings should be recorded for each run.

D. Server-Side Modules and Data Flow

The server-side architecture consists of cooperating modules with distinct responsibilities. The graph generator creates the selected topology and assigns its link and node attributes. The state manager maintains the operational status of network components and applies failure or recovery events. The routing engine identifies feasible candidate paths and evaluates them using the configured routing criteria. The simulation engine models link-generation and swapping outcomes and calculates the corresponding fidelity, success probability, and latency. A metrics aggregator updates the performance indicators, while the exporter writes supported experiment records to CSV.

For each routing request, the dashboard or traffic generator submits the request to the backend. The state manager provides the current network state to the routing engine, which returns a selected route when a feasible path exists. The simulation engine then evaluates the route and produces the request outcome. The metrics aggregator updates the corresponding indicators, and the resulting state is returned to the frontend as structured JSON for visualisation.

Separating these responsibilities allows individual components, such as the routing strategy or failure model, to be modified without redesigning the entire application. The actual degree of modularity depends on the interfaces and dependencies in the implemented source code.

E. Recorded Data and Export Fields

For reproducible evaluation, each experiment record should include the run identifier and random seed, topology family, number of repeaters, average degree, source and destination, selected route, hop count, request outcome, end-to-end fidelity, modelled latency, routing weights, and failure configuration. These fields provide the information needed to associate an observed outcome with the network configuration and routing conditions under which it was obtained.

The success field records whether an end-to-end pair was delivered, while fidelity and latencyms record the corresponding simulated outcome when available. The weights field records the utility parameters used for route selection, and failurestate identifies the active failure scenario and its severity. Fields that are not currently produced by the implementation should be added before they are described as available export outputs. Recording a random seed is useful only if the simulation actually uses it to control its random processes.

F. Extensibility

The modular design provides opportunities for extending the laboratory. A new topology can be introduced through a generator that returns a graph with the required attributes.

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Additional routing metrics can be incorporated into the utility function and metrics aggregator, provided that their definitions and scales are specified. New failure scenarios can be added through operations that modify and restore component states.

Entanglement purification could be introduced as an additional simulation operation with an explicitly defined success probability and fidelity model. Similarly, a learned routing policy could be evaluated as an alternative to the weighted-score method if it accepts the same network state and returns a feasible route. Integration with a more detailed quantum-network simulator could provide a further means of validating selected scenarios. These are potential extensions unless they have already been implemented and tested.

G. Testing and Consistency Checks

Before conducting comparative experiments, the implementation should be checked against hand calculations and basic network properties. The expressions in (1)–(3) should reproduce the worked-example values under the same assumptions. Repeated runs with identical inputs and controlled random seeds should behave consistently to the extent permitted by the simulation's stochastic processes.

The calculated success probability should remain between zero and one. A request between nodes in disconnected components should be reported as infeasible, and a failed link should not appear in the selected route. Restoring a failed link should return it to the eligible network state. Fidelity calculations should also be checked against the implemented swapping model and its assumptions, rather than relying on a universal monotonicity rule for every possible quantum-state model.

These checks help identify errors in route selection, state management, and metric calculation. They should be repeated whenever the routing policy, failure model, topology generator, or physical abstraction is modified. Any reported testing outcome should be supported by actual test execution rather than inferred from the design description alone.

X. Experimental Setup and Evaluation Metrics

A. Simulation Environment and Parameter Configuration

The proposed quantum-network simulation laboratory was evaluated using a configurable graph-based simulation environment. The experiments were designed to examine routing performance under different network topologies, utility-weight configurations, component failures, and network sizes. A small-world topology was used as the primary configuration, while additional topology families were considered for comparative evaluation. The simulation parameters are summarised in Table VI.

TABLE VI. SIMULATION PARAMETERS

Parameter	Symbol	Value
Primary topology	—	Small-world
Number of repeaters	N	400
Average node degree	k	4
Initial link fidelity	F_0	0.95
Gate fidelity	—	0.98
Memory lifetime	τ	512 ms
Link length range	—	14.4–33.6 km
Swapping success probability	q	0.92
Link pair capacity	—	8 pairs per link
Requests per repetition	Nreq	20
Repetitions per setting	R	30
Base random seed	—	20261017

The average degree is a configuration parameter; the realised degree distribution may differ between topology families. Link lengths are generated within the specified range. Unless otherwise stated, the same parameter configuration is used across comparable experiments to reduce variation caused by changes unrelated to the factor being investigated.

To support repeatability, the base random seed is set to 20261017. The seed for repetition (r) is calculated as the base seed plus the repetition number. This procedure provides a reproducible seed schedule, provided that the simulation implementation uses these seeds consistently for topology generation, parameter assignment, and stochastic events.

B. Routing Utility Weight Configurations

The routing model selects a feasible path using the composite utility defined in Section VIII. To investigate the influence of routing preferences, four weight configurations are considered: fidelity-dominated, success-dominated, latency-dominated, and balanced. Their values are listed in Table VII.

TABLE VII. UTILITY WEIGHT PRESETS USED IN SCENARIO 2

Configuration	w_1: Fidelity	w_2: Success	w_3: Capacity	w_4: Latency	w_5: Utilisation
Fidelity-dominated	0.60	0.10	0.10	0.10	0.10
Success-dominated	0.10	0.60	0.10	0.10	0.10
Latency-dominated	0.10	0.10	0.10	0.60	0.10
Balanced	0.20	0.20	0.20	0.20	0.20

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The fidelity-dominated configuration assigns the largest weight to end-to-end fidelity, whereas the success-dominated configuration prioritises path-establishment probability. The latency-dominated configuration gives greater importance to reducing path delay. In the balanced configuration, all five terms receive equal weights.

Because the utility expression combines metrics with different units and numerical ranges, the metric-normalisation procedure must be specified and applied consistently before interpreting these configurations. In particular, latency and utilisation are penalty terms in the utility function, whereas fidelity, success probability, and capacity contribute positively. The weight settings alone do not establish which configuration performs best; this must be determined from simulation results.

C. Experimental Scenarios

Five experimental scenarios are defined to evaluate the behaviour of the routing framework. The first scenario compares routing performance across eight topology families while maintaining comparable network-size and link-quality settings. The second scenario investigates the influence of routing preferences using four utility-weight configurations: fidelity-dominated, success-dominated, latency-dominated, and balanced. Where feasible, the same request set and random-seed schedule are used across configurations to support paired comparisons and reduce the influence of random variation.

The third scenario evaluates routing performance under component failures. The standard failure level is set to 10% of eligible links or nodes, depending on the experiment. Additional failure percentages must be specified when conducting a complete failure-level analysis. The fourth scenario examines targeted failures by disabling a single link on a selected route or a selected hub node. These outcomes are compared with random failures using consistently documented failure-selection procedures. The fifth scenario evaluates scalability by varying the number of repeaters while keeping other parameters as comparable as possible. The tested network sizes and measured execution times should be reported after the corresponding experiments have been conducted.

D. Evaluation Metrics

The framework uses five evaluation metrics to characterise request completion, quantum-pair quality, delay, throughput, and network availability. The request success rate measures the percentage of requests successfully completed and is calculated as:

$$SR = Nok / Nreq \times 100$$

where Nok represents the number of successful requests and Nreq denotes the total number of evaluated requests.

Average end-to-end fidelity is calculated as the arithmetic mean of the final fidelity values obtained for successful requests. Failed requests do not produce a delivered-pair fidelity value and should not be assigned an arbitrary fidelity unless the implementation explicitly defines and justifies such a convention.

Path latency represents the modelled end-to-end delay and is calculated from the link-delay and swapping-delay terms specified in Section VIII. Unless measurements from physical quantum-network hardware are available, this metric is interpreted as simulated latency rather than experimentally measured physical-network delay.

The entanglement distribution rate (EDR) measures the number of end-to-end entangled pairs delivered during a

specified observation interval. It is calculated as:

$$EDR = Npairs / \Delta t$$

where Npairs denotes the number of end-to-end pairs delivered and Δt represents the observation duration. When the observation duration is expressed in minutes, EDR is reported in pairs per minute.

Network health measures the fraction of network components that remain operational during a simulation. The component set used in this calculation must be explicitly defined, including whether it comprises links, nodes, or both. The same definition should be applied consistently across all experimental scenarios.

E. Repetition and Statistical Analysis

Each experimental setting is configured for 30 repetitions, with 20 requests per repetition. Therefore, up to 600 request outcomes may be obtained for each setting if all requests are executed. However, requests within the same repetition may share network conditions and random processes, so they should not automatically be treated as 600 independent experimental runs.

For each setting, the mean and standard deviation of the relevant metrics should be calculated across the 30 repetitions. When configurations are evaluated using matched random seeds and comparable request sets, paired differences should be calculated to support more consistent comparisons. A 95% confidence interval may be estimated using an appropriate t-distribution procedure, treating the repetition as the unit of analysis when the run-level observations satisfy the relevant independence assumptions.

The analysis should report observed effect sizes and uncertainty estimates alongside the mean performance values. Any claim that a particular topology, routing-weight configuration, or failure-handling strategy performs better than another must be supported by recorded simulation results rather than inferred from the parameter settings alone.

F. Reproducibility and Reporting

To support reproducibility, each experimental run should record its random seed, topology family, number of repeaters, degree configuration, source and destination nodes, selected route, route length, component failures, request success outcome, end-to-end fidelity, path latency, and relevant throughput and network-health metrics. The recorded fields must correspond to the data actually generated and exported by the implementation.

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Experimental findings should be presented using figures or tables containing the measured results for each scenario. The topology comparison should report the selected performance metrics for each evaluated topology, while the weight-sensitivity analysis should compare the four routing configurations. Similarly, the failure-level, targeted-failure, and scalability experiments should report their tested configurations alongside their observed outcomes.

The experimental parameters and evaluation protocol establish a consistent basis for assessing the proposed simulation laboratory. However, these settings alone do not demonstrate performance improvements or experimental superiority. Conclusions should therefore be drawn only after the relevant simulations have been executed, the resulting data have been recorded, and the observations have been analysed using the defined evaluation metrics.

XI. EXPERIMENTAL VALIDATION AND RESULTS

A. Simulation Environment and Experimental Configuration

The proposed quantum-network simulation laboratory integrates network topology generation, repeater and optical-link modelling, multi-criteria route selection, simplified entanglement-generation and swapping models, component-failure handling, and performance-metric computation. The framework is designed to investigate how network connectivity, link quality, resource availability, and component failures influence simulated entanglement distribution.

The documented experimental configuration specifies a small-world network comprising 400 repeater nodes and 800 optical links, with an average node degree of 4. The configured parameters include an initial link fidelity of 0.95, a gate fidelity of 0.98, a quantum-memory lifetime of 512 ms, link lengths ranging from 14.4 to 33.6 km, a swapping-success probability of 0.92, and a pair capacity of 8. The traffic configuration specifies 20 requests per repetition, 30 repetitions per setting, and a base random seed of 20261017.

These parameters define a reproducible configuration for evaluating the proposed routing framework. However, experimental conclusions must be based on completed simulation runs and recorded outputs rather than configured values alone. The results discussed in this section therefore distinguish the analytical behaviour implied by the mathematical model from quantitative performance outcomes that require verified experimental data.

B. Model and Functional Validation

The framework is intended to support topology construction, source–destination selection, candidate-route evaluation, resource-aware routing, component-failure scenarios, and computation of network-performance indicators. Functional validation should establish that these operations behave consistently with their specified design.

The principal verification requirements include checking whether generated networks satisfy their configured structural constraints, whether failed links and repeaters are excluded or handled appropriately during route selection, and whether the reported route metrics correspond to the selected paths. The consistency of resource updates and exported experimental records should also be checked against the corresponding simulation outputs.

These checks are important because a routing decision is meaningful only when the underlying topology, resource state, and metric calculations are consistent. Nevertheless, the availability of a particular function does not independently establish its numerical accuracy. Functional correctness and comparative routing performance must therefore be evaluated as separate aspects of the framework.

C. Analytical Interpretation of Routing Behaviour

The mathematical formulation provides a basis for examining how route characteristics influence simulated entanglement distribution. Under the assumptions adopted by the model, the probability of successfully establishing an end-to-end connection depends on the success probabilities assigned to the constituent elementary links and entanglement-swapping operations. When these events are treated as independent, the estimated path-success probability is represented by the product of their individual success probabilities.

This relationship implies that a route involving more probabilistic operations may have a lower overall establishment probability when other relevant conditions remain unchanged. The actual outcome depends on the assigned probabilities, path structure, and resource constraints. This is a model-derived expectation rather than a claim of experimentally measured improvement.

End-to-end fidelity is likewise influenced by the initial link fidelity and the operations performed along the selected path. Under the state and swapping assumptions adopted in the model, successive operations can reduce the fidelity of the resulting entangled pair. The extent of this reduction depends on the model parameters and the number of operations involved. Consequently, estimated fidelity values should be interpreted within the scope of the simulation assumptions rather than as direct predictions of physical quantum-network performance.

These relationships demonstrate why hop count alone may be insufficient for evaluating candidate routes. A route with fewer hops is not necessarily preferable when competing paths differ in fidelity, operation-success probability, residual capacity, latency, or link utilisation. The proposed multi-criteria formulation provides a structured means of representing these competing factors, provided that the metrics are defined consistently and their weights are appropriately normalised.

However, the analytical formulation alone does not establish that the proposed routing policy outperforms shortest-path routing or other quality-aware strategies. Such a conclusion requires comparative simulation results obtained under equivalent experimental conditions.

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D. Quantitative Evaluation and Reproducibility

Quantitative evaluation should compare the proposed routing policy with appropriate baseline strategies using consistent network configurations, traffic conditions, link parameters, resource constraints, and failure scenarios. Conventional shortest-path routing provides a useful baseline, while fidelity-constrained or success-aware routing can serve as additional comparators where implemented.

The primary evaluation metrics should include request success rate, average end-to-end fidelity, path latency, and entanglement distribution rate, provided that these quantities are implemented, calculated, and recorded correctly. Resource utilisation and active-repeater measurements may also be included where supported by the simulation.

Topology comparisons should evaluate the selected network structures under equivalent operating conditions. Routing-weight sensitivity experiments should examine how route selection changes when the relative importance of fidelity, success probability, capacity, latency, and utilisation is varied. Failure-resilience experiments should record the affected components, resulting connectivity changes, and request outcomes. Scalability experiments should report tested network sizes and measured execution times rather than infer computational efficiency from configuration settings.

To support reproducibility, each completed run should record its random seed, topology configuration, source–destination pair, routing weights, traffic conditions, failure settings, selected route, request outcome, and available performance measurements. Repeated runs should be summarised using appropriate descriptive statistics, including means and measures of variability where applicable. Metric calculations and exported records should be verified before aggregate results are reported.

The available documented configuration does not provide sufficient verified aggregate outputs to establish numerical performance gains, statistically significant differences, a definitive ranking of topology families, or a quantified improvement in failure resilience. These claims are therefore not made in the present study.

E. Discussion

The proposed laboratory brings together topology exploration, configurable route-quality assessment, abstract entanglement operations, resource-aware routing, component-failure analysis, and performance-metric computation within a common software framework. Its principal research value lies in providing a structured environment for examining how network structure and routing criteria interact under explicitly defined simulation assumptions.

The mathematical formulation highlights the limitations of relying exclusively on hop count and motivates the consideration of fidelity, estimated establishment probability, resource availability, latency, and link utilisation. By allowing these factors to be examined within a common framework, the approach supports systematic investigation of routing trade-offs in multi-hop quantum-repeater networks.

The practical effectiveness of the proposed routing policy, however, remains to be established through verified quantitative comparisons. The documented configuration and analytical relationships provide a basis for further experimentation but do not demonstrate superior performance over existing routing methods or quantum-network simulators.

Future evaluation should prioritise completed simulation runs, verification of metric calculations, baseline comparisons, controlled component-failure experiments, and statistical analysis. These steps are necessary to determine whether the proposed approach offers measurable benefits under specific network conditions while maintaining a clear distinction between simulation-level findings and the behaviour of physical quantum networks.

XII. THREATS TO VALIDITY AND LIMITATIONS

Several limitations should be considered when interpreting the results obtained from the proposed laboratory. First, the laboratory operates at a high level of software abstraction and does not model photon-level hardware behaviour, detector noise, or the physical characteristics of specific quantum memories. Therefore, its results should not be used to predict the performance of real quantum devices directly. Second, the Werner-state assumption used in Equation (2) simplifies the representation of quantum states. Since real quantum states may exhibit more complex characteristics, the resulting fidelity values should be interpreted as model-dependent estimates. Third, the routing engine uses a weighted-score heuristic that is transparent and computationally efficient but does not guarantee an optimal route. Its decisions depend on the selected utility weights and the normalisation of the scoring terms. The graph intelligence view is based on neighbourhood averaging and serves as an interpretability aid rather than a trained machine-learning model; consequently, it should not be treated as evidence of learned routing capability. In addition, topology generation and probabilistic events introduce stochastic variation, making repeated simulations with recorded random seeds necessary for reliable comparisons. Large networks and heavy concurrent traffic may also require further optimisation of path enumeration and resource management. Finally, the laboratory represents a software abstraction rather than a physical quantum-network testbed. Publications and presentations based on the laboratory should clearly state its modelling assumptions, parameter settings, and limitations, and should avoid generalising conclusions from a single topology, routing configuration, or simulation run.

XIII. PRACTICAL RECOMMENDATIONS AND CHECKLIST

Experiments conducted using the proposed laboratory should begin with clearly defined topology parameters, link fidelity, and swapping success probability. When comparing routing policies, researchers should change one experimental factor at a time wherever possible and maintain consistent conditions

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across comparisons. The scoring terms in Equation (4) should be normalised to comparable ranges before applying utility weights, and the selected weights should be reported alongside the experimental results. Each topology should be evaluated under consistent failure scenarios and failure levels to support meaningful comparisons. Every configuration should be repeated using multiple random seeds, with the mean and variability of the evaluation metrics reported. Request success rate should be considered alongside average end-to-end fidelity because successful delivery alone does not establish that the delivered quantum states meet the required quality. Experimental configurations and recorded results should be exported as CSV files whenever supported by the implementation, allowing other researchers to inspect and reproduce the experiments. Researchers should also explicitly identify the software abstraction level and validate promising findings using detailed quantum-network simulators such as those discussed in [8] and [9] before drawing conclusions about physical hardware performance.

XIV. CONCLUSION

This paper presented an interactive software simulation laboratory for studying fidelity-aware entanglement routing and failure resilience in multi-hop quantum repeater networks. The framework integrates configurable network topologies, a multi-factor route-selection heuristic, abstract entanglement-generation and swapping operations, controlled component failures, performance monitoring, network visualisation, and CSV-based data export. Its routing formulation considers modelled end-to-end fidelity, estimated request success probability, residual capacity, path latency, and link utilisation, providing a structured way to examine trade-offs that cannot be represented by hop count alone.

The mathematical model describes how route characteristics and probabilistic operations may influence entanglement distribution under the assumptions adopted by the simulation. The configurable environment also provides a basis for investigating how topology, resource availability, and component failures affect route feasibility and request outcomes. However, these capabilities and model-derived expectations should not be interpreted as empirical evidence that the proposed heuristic outperforms existing routing strategies. Establishing such a conclusion requires completed simulation runs, verified metric calculations, consistent baseline comparisons, and appropriate statistical summaries.

Future work should prioritise systematic evaluation across the supported topologies and failure scenarios. Comparisons with clearly defined baseline strategies, including shortest-path routing, would help establish the conditions under which the multi-factor heuristic provides measurable benefits. Further work should also examine sensitivity to routing weights, network size, traffic demand, link quality, and resource constraints. Where greater physical fidelity is required, selected experiments could be validated using established quantum-network simulation platforms with more detailed component and protocol models.

Overall, the proposed laboratory provides a configurable foundation for exploratory investigation and reproducible experimentation in quantum-network routing. Its scientific contribution should ultimately be assessed through transparent implementation details and verified experimental evidence, rather than assumed performance advantages.

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