A Vision for Integrated Quantum-Classical Network Operations

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ABSTRACT

We propose qcNOC, a next-generation hybrid quantum-classical Network Operations Center. qcNOC introduces a unified framework that encompasses hybrid performance metrics, real-time observability, advanced fault detection and localization, and operator training tailored to the hybrid network environment. This work outlines the architectural vision and strategic roadmap for qcNOC, with the goal of democratizing access to quantum networking capabilities and ensuring that research and education networks (RENs) and campus networks can actively participate in and benefit from the quantum revolution.

CCS CONCEPTS

• **Networks → Network architectures**.

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1 INTRODUCTION

Recent efforts in quantum networking (e.g., ongoing work on the quantum Internet at the NSF-funded Center for Quantum Networks [13], DOE's Quantum Application Network Testbed for Novel Entanglement Technology (QUANT-NET) [3, 24], DARPA's Quantum-Augmented Network (QuANET) [6]) have unveiled its remarkable transformative potential, promising revolutionary breakthroughs that could redefine the landscape of information processing and secure communication across several domains (e.g., chemistry, material science, among others).

As quantum networking research progresses, a holistic approach to effectively and efficiently integrate, operate and mange both quantum networks and classical packet-switched networks becomes increasingly important in research and educational networks (RENs) in general and campus networks in particular. This integration will give rise to what we call the *hybrid quantum-classical networks*, which is defined as the co-existence of classical packet-switched networks with quantum networking infrastructures. Hybrid quantum-classical networks aim to leverage the strengths of both paradigms to surpass what either could accomplish on its own for several motivating applications (e.g., Quantum-Enhanced Traffic Engineering).

This integration presents unique challenges that current network operation centers (e.g., [16]) are ill-equipped to handle. Concretely, the operators are currently facing an intensifying "quantum divide", where only a small, privileged subset of research groups within the industry are able to harness quantum-related advancements for competitive advantage and business growth [12]. This growing disparity highlights an urgent problem that demands immediate and coordinated action from the campus networking and REN communities. In fact, it is no longer feasible to passively rely on industry-led solutions (e.g., IQM [8]), which risk being either financially unviable or inadequate to meet the specific needs of these networks. Without a proactive and collaborative "quantum transition plan," RENs and campus networks will be left at a significant disadvantage, struggling to keep pace in a future where quantum technologies are critical for advancing research and operational capabilities.

Addressing this gap requires overcoming key limitations in current NOCs (e.g., [16]) including a lack of performance metrics capable of capturing the complex interplay between quantum and classical elements, paucity of tools for real-time monitoring and visualization of both classical and quantum-specific metrics, exponentially more complex fault detection and localization processes due to the subtle and distributed nature of quantum errors, and a significant knowledge gap among network operators regarding quantum-specific concepts and protocols. These limitations collectively hinder operators' ability to accurately assess health, gain a holistic view of performance, identify and isolate faults effectively, and understand the unique operational underpinnings of hybrid quantum-classical network. These limitations also underscore the urgent need for specialized tools, techniques, and training programs tailored to the demands of hybrid quantum-classical network management.

2 qcNOC: QUANTUM-CLASSICAL NETWORK OPERATIONS CENTER

Recognizing the above-mentioned fundamental limitations of the state of the art, this work envisions qcNOC, a next-generation quantum-classical network operations center (qcNOC) aimed at revolutionizing hybrid quantum-classical network management. The vision is structured around four components, encompassing development, research, and training efforts.

(1) Metrics. qcNOC proposes *novel metrics for hybrid quantum-classical networks that provide real-time, intuitive insights into the performance and health of both quantum and classical network components*. These metrics, to be extracted from layer1 and layer2 of the testbed, are intended to enable seamless monitoring of quantum network states from, e.g., QUANT-NET, alongside their classical counterparts by aligning quantum-specific phenomena with analogous classical measures. At layer1, Fidelity would quantify how

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closely a transmitted qubit matches its original state, analogous to *bit error rate (BER)* but accounting for quantum effects like superposition and entanglement. Quantum Bit Error Rate (QBER) would reflect the fragility of quantum states, paralleling *classical BER*. Photon Loss/Channel Attenuation would measure transmission loss, similar to *signal attenuation*, though more impactful due to the no-cloning theorem. Quantum Channel Polarization Drift Rate would track birefringence-induced changes in qubit polarization, and Decoherence Time would capture how long a qubit remains coherent (a uniquely quantum property with no classical analog). At layer2, proposed metrics include Link Layer Entanglement Fidelity to assess entanglement quality, Link Layer Entanglement Generation Rate to measure the speed of entanglement establishment, and Quantum Error Correction Overhead to quantify the extra qubits required to protect information, in contrast to *classical error correction codes*.

These metrics would be exposed to the observation system described below via lightweight, north-bound interfaces. A key requirement is the ability to capture quantum and classical metrics from campus CI (e.g., EMERGE [21, 23]) and deliver real-time, actionable insights. qcNOC is envisioned to implement persistent, event-driven interfaces using Socket.IO [15] and SignalR [11], avoiding polling inefficiencies. This setup is intended to ensure that state changes in the hybrid quantum-classical network are immediately relayed to the observation system, maintaining an accurate, up-to-date view of network health.

(2) Observation System. qcNOC envisions an *advanced network observation system that captures, integrates, and analyzes both classical and quantum network metrics in real time*. Designed to work with the proposed hybrid metrics, this system would enable holistic monitoring of the network. Central to this effort is a real-time data fusion engine envisioned to gather and integrate quantum and classical metrics using Apache Kafka [2] for scalable, low-latency data streaming. Metrics would then be processed via Apache Flink [1], enabling real-time analytics, complex event processing, and dynamic pattern detection essential for understanding hybrid system behavior. To enhance observability, service mesh tools like Istio [9] and Linkerd [10] would track service-level metrics such as latency, packet loss, and failures. Together, these components are intended to form a responsive fusion pipeline supporting tasks like fault localization and enabling real-time insight into hybrid network performance.

To ensure accuracy and robustness, the data fusion engine would be calibrated through a multi-phase validation process. This process would begin with simulation environments such as QuISP [26], SeQUeNCe [27], and NetSquid [19], which model hybrid behaviors (e.g., congestion, decoherence, and node failure) under varied conditions. Using techniques such as *Monte Carlo simulations* and *discrete event simulations*, these tools would stress-test the engine's ability to process dynamic, cross-domain metrics in real time. Tools like Wireshark [17] and QubiCSV [18] would monitor classical traffic and qubit states, respectively, to ensure fidelity and integrity during live operations. This combined approach aims to ensure the system is scalable, resilient, and capable of delivering high-fidelity observability in hybrid quantum-classical networks.

(3) Use Cases. As a potential use case, qcNOC envisions *advanced fault detection and localization techniques using innovative visualization methods and predictive algorithms, enabling precise identification of faults and performance issues*. To support such techniques, a unified visualization library and interactive dashboard would be developed for monitoring hybrid quantum-classical networks. Built using Cytoscape.js [4], the system would depict layered network topologies (quantum nodes, classical routers, and entangled qubits), highlighting interdependencies. Quantum-specific visualizations would include interactive Bloch sphere models via Three.js [7] and an entanglement map rendered with Sigma.js [14] and D3.js [5], illustrating coherence strength and decay. A quantum error correction (QEC) module would visualize real-time correction performance for bit- and phase-flip errors, while time-series and latency models would track delays in quantum operations. Together, these components aim to offer comprehensive observability and alerting within a dynamic dashboard.

To enable predictive fault localization, the system would integrate real-time insights from the fusion engine and dashboard to detect and mitigate faults proactively. Moving beyond static heuristics, qcNOC envisions the use of machine learning with Apache Spark and MLlib [28] (e.g., decision trees, SVM, K-means) and deep learning models via PyTorch to analyze streaming and historical metrics such as QBER, latency, bandwidth, and topological changes. Techniques like data windowing [25] would be used to balance detection latency and accuracy, while hyperparameter tuning would ensure performance efficiency. This multi-model approach aims to support real-time fault prediction, root-cause analysis, and adaptive response strategies, improving the reliability, resilience, and security of hybrid quantum-classical networks.

(4) Operator Training and Outreach. qcNOC is intended to serve as a *platform for developing training programs to equip NOC operators with the skills required to effectively manage both quantum and classical networks*. To this end, qcNOC proposes a hybrid training curriculum that blends foundational quantum topics such as qubit manipulation, entanglement, and QEC with classical networking principles. Emphasis would be placed on interpreting and responding to domain-specific metrics like fidelity, QBER, BER, and signal attenuation through scenario-based exercises. Operators would learn to diagnose cross-domain issues (e.g., latency-induced qubit degradation) and apply predictive fault detection using quantum-classical data fusion. The curriculum would also include interactive modules, virtual labs, and real-world case studies (e.g., from the QUANT-NET testbed) to ensure both theoretical understanding and hands-on competence.

In future iterations, qcNOC aims to deliver an immersive simulation environment offering hands-on experience with managing hybrid networks under realistic conditions. By integrating quantum simulators with classical tools such as Mininet [22] and GNS3 [20], the platform would simulate complex scenarios requiring operators to balance quantum properties (e.g., coherence, fidelity) with classical network challenges (e.g., latency, packet loss). Participants would navigate fault conditions, optimize parameters, and observe real-time outcomes via interactive dashboards from (3). Gamification elements, such as scoring and badges, would enhance engagement and provide measurable progress tracking, fostering the development of a next-generation, hybrid-ready operations workforce.

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