Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

USCE2QC

A Holistic Approach to Quantum Computing Dependability: From Noise Suppression in Ultrastrong Coupling Regime to the Edge-to-Quantum Continuum

D4: Validation Report

vers. 1.0

Version

Version	Date	Description	Authors
1.0	15/07/2025	Validation report (M15 - all WP2, WP3 Tasks): All the USCE2Q artifacts (models, techniques, solutions) have been validated by specific tests and model assessment, by even comparing different model results (e.g. analytical vs simulation). Such tests and related results are documented in this report to demonstrate the feasibility of the proposed solutions.	Salvatore Distefano Roberto Stassi Mansur Ziiatdinov Carmelo Munafo’

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Introduction

Purpose of the Deliverable

This document, Deliverable 4 (D4) titled “Validation Report”, serves as the final and conclusive technical report for the USCE2QC project. Its primary purpose is to provide a comprehensive and rigorous account of the validation activities conducted on all project artifacts—the models, techniques, and solutions—developed in previous project phases (D1, D2, and D3). This report objective is to demonstrate the feasibility, effectiveness, and dependability of the proposed solutions through specific tests, simulations, and comparative analyses. By doing so, it verifies that the USCE2QC project has successfully achieved its goals of advancing the state-of-the-art in quantum computing dependability at both the node and infrastructure levels.

Overview of the Validation Phase

Following the completion of the “Final Development Report” (D3) at Month 15, the project transitioned into its final validation phase. This stage involved a systematic and methodical evaluation of every solution developed for Work Package 2 (QC Node Dependability via Ultrastrong Coupling Regime) and Work Package 3 (QC Infrastructure Dependability via the Edge-to-Quantum (E2Q) Computing Continuum). The validation process was multifaceted, encompassing a series of tests, simulations, and rigorous model assessments. Key activities included comparing the performance of our USC-based solutions against established baselines, cross-validating results from different models (e.g., analytical versus simulation), and evaluating the effectiveness of our E2Q infrastructure in handling hybrid classical-quantum workloads. The findings presented in this report represent the evidence-based conclusions of these validation efforts.

Scope of D4: Validation Activities

This report systematically presents the outcomes of the validation activities for all technical project artifacts. For Work Package 2, the scope includes the validation of USC-based solutions for noise suppression, quantum error detection/correction protocols, and novel quantum gates. It also covers the rigorous validation of the dependability assessment models themselves, including the cross-comparison of results from analytical, simulation, and metaheuristic approaches. For Work Package 3, the scope encompasses the validation of the E2Q continuum architecture, the effectiveness of the intelligent offloading mechanisms, the resilience and performance of the dependability policies, and the functionality of the E2Q orchestration tools. This deliverable consolidates the findings from all validation tests, providing a comprehensive assessment of the project's overall success.

Document Structure

The remainder of this document is structured as follows: Section 2 provides a detailed account of the validation activities for the artifacts developed under Work Package 2, including test methodologies, results, and comparative analyses. Section 3 similarly elaborates on the validation work performed under Work Package 3, focusing on the E2Q continuum's architecture, offloading, policies, and orchestration. Finally, Section 4 offers an overall conclusion, summarizing the key validation findings, discussing the feasibility and impact of the USCE2QC solutions, and providing a final outlook on the project's contributions to the field.

Validation of Work Package 2 Artifacts: QC Node Dependability via USC Regime

Task 2.1. Validation of USC-based Noise Suppression Solutions

2.1.1. Test setup and methodology for noise suppression validation

The validation of USC-based noise suppression solutions was conducted through a numerical simulation framework. The methodology is based on the use of the Lindblad master equation to model the evolution of a logical qubit in an ultrastrong interaction. This approach allowed us to directly compare the performance of our logical qubit with that of a single physical qubit subjected to the same noisy environment. The validation focused on measuring key metrics such as pure dephasing and relaxation rates to demonstrate the system's effectiveness in mitigating decoherence effects.

2.1.2. Experimental or simulation results and analysis

Comprehensive simulations were conducted to analyze the performance of the logical qubit compared to a single physical qubit. The analysis focused on key dependability metrics for quantum systems, specifically

Pure dephasing and relaxation rates

The simulation results confirm that the proposed architecture achieves significant effectiveness in noise suppression. The model's performance was rigorously compared with that of a transverse Ising spin model, highlighting the superior protection provided by our architecture against specific noise channels. The stability of the system was also measured when introducing small perturbations, confirming its robustness in non-ideal conditions.

Specifically, the pure dephasing rate of the logical qubit approaches zero as the coupling strength approaches infinity. A marked reduction in the pure dephasing rate was observed as the coupling strength and the number of physical qubits composing the logical system increased. The relaxation rate was suppressed to approximately half the value of a single physical qubit.

These findings demonstrate that the emergent properties and symmetries of the collective system in the ultrastrong coupling regime provide intrinsic protection that goes beyond that of an isolated qubit. The performance analysis validates the design approach, confirming that the use of ultrastrong interactions can effectively extend the coherence times of quantum systems.

2.1.3. Comparison of results against a baseline

The performance of our logical qubit was rigorously compared with that of a single, non-interacting physical qubit to validate our design. The simulation results demonstrate a significant enhancement of the logical qubit's coherence times.

We observed a marked reduction in the pure dephasing rate of the logical qubit, which approaches zero as the coupling strength increases. This suppression is a direct consequence of the symmetries inherent in our system. In contrast, a single qubit lacks this intrinsic protection.

Furthermore, the relaxation rate of our logical qubit was suppressed to approximately half the value of a single physical qubit. This confirms that the collective interactions in our USC spin chain provide a powerful intrinsic protection that goes beyond that of an isolated qubit.

Our chosen model was also rigorously compared to a transverse Ising spin model. This comparison highlighted the superior protection our architecture provides against specific noise channels, demonstrating its robustness and stability, even when subjected to small perturbations. These findings validate the design approach, confirming that ultrastrong interactions can effectively extend coherence times.

Task 2.2. Validation of USC-based Quantum Error Detection/Correction Solutions

The validation of our Quantum Error Correction (QEC) scheme is based on the theoretical demonstration of a Quantum Non-Demolition (QND) readout using a hybrid optomechanical system. This approach is designed to detect single-qubit errors on a logical qubit by performing a measurement on an ancillary qubit, as described in the provided report.

2.2.1. Test setup and methodology for QEC validation

Our validation methodology is a theoretical analysis of a hybrid optomechanical architecture. The scheme employs an ancillary qubit coupled to a mechanical oscillator via a cavity. The measurement process is designed to extract information about the logical qubit's state by measuring a corresponding ancillary mode. The measurement is non-destructive for the logical qubit's state, satisfying the QND condition, while the state of the ancillary qubit is collapsed upon measurement.

2.2.2. Simulation results on error detection/correction efficiency

The results of our analysis confirm the scheme's ability to effectively detect single-qubit errors. An error on one of the physical qubits that compose the logical qubit leads to a distinct signature in the ancillary mode, which is then detected by the measurement. This measurement, while collapsing the ancilla's state, provides the necessary error syndrome information without disturbing the logical subspace. The number of virtual photons in the cavity, which is the quantity being measured, changes depending on the quantum state of the logical qubit, thus revealing the presence of an error.

2.2.3. Comparison of results with state-of-the-art QEC protocols

Our QEC scheme distinguishes itself from conventional protocols by leveraging the unique properties of hybrid optomechanical systems in the ultrastrong coupling regime. Our approach confirms that error information can be reliably extracted by measuring an ancilla in a QND fashion relative to the logical qubit, a crucial step for scalable QEC. These results demonstrate clear progress toward a scalable, QND-based QEC architecture and establish a solid foundation for future work on more complex error channels and feedback protocols.

Task 2.3. Validation of USC-based Quantum Gates

2.3.1. Test setup and methodology for gate validation

The validation of our USC-based quantum gates was conducted through an advanced numerical simulation framework, aimed at measuring their effectiveness and speed. The methodology utilized the Mathematica programming language to model the circuit, which consists of two superconducting transmon qubits coupled to two waveguides. These waveguides, in turn, are connected to a central flux qubit in the ultrastrong coupling (USC) regime. The gate's performance was evaluated by calculating its average fidelity, using randomly generated initial states to test the gate under a wide variety of conditions.

2.3.2. Measurement of key performance metrics (e.g., fidelity, speed) and analysis

The simulations demonstrated remarkable gate efficiency, achieving an average fidelity of 99.9% for an execution time of just 7.6 nanoseconds. The high speed of operation is a direct consequence of the USC regime, which leverages virtual processes that do not conserve the number of excitations to accelerate the interaction between qubits. This performance is crucial for reducing the total computation time and minimizing the effects of decoherence, thereby significantly increasing the overall dependability of the system.

2.3.3. Comparison of performance with conventional gates

The performance of our gate was compared with that of conventional quantum gates, demonstrating a significant advantage in terms of speed. Conventional gates typically require much longer execution times, making them more susceptible to decoherence. Our USC-based solution drastically reduces the necessary interaction time, improving tolerance to environmental noise. This result confirms that utilizing the USC regime can overcome the limitations of current designs and pushes toward the realization of more reliable and scalable quantum computation.

Task 2.4. Validation of Dependability Assessment Models

The dependability of a quantum computing system is intrinsically linked to the precision of the theoretical and simulation models used to design and evaluate its performance. This section documents the rigorous validation of our dependability assessment models, demonstrating their accuracy and predictive power. The methodology employed integrated advanced analytical models, and sophisticated simulation frameworks, the cross-comparison of which has significantly enhanced our confidence in the results obtained.

2.4.1. Methodology for validating analytical and simulation

The methodology for validating our dependability assessment models was founded on a multidisciplinary approach. The primary objective was to ensure that the models could accurately and consistently predict the behavior of the quantum system in the ultrastrong coupling regime, thereby verifying their effectiveness and stability.

Validation via Simulation: The cornerstone of our validation methodology was the utilization of a numerical simulation framework based on the Lindblad master equation. This powerful tool allowed us to numerically model the time evolution of the system's density matrix, simulating the complex interactions between the qubits and their noisy environment. This approach enabled a direct performance comparison between our protected logical qubit and a standard, single physical qubit subjected to the identical environmental noise. This rigorous validation was applied across all key project solutions, including noise suppression techniques based on spin chains and QEC protocols.

Benchmarking and Accuracy Assessment: To thoroughly test the effectiveness of our solutions, we used the models as benchmarking tools. The goal was to quantitatively assess their impact on key dependability metrics under non-ideal conditions. For gate validation, for example, we did not merely calculate its performance in a single instance but instead determined its average fidelity by running simulations with thousands of randomly generated initial states. This comprehensive approach ensured that our performance measurements were robust, representative, and not dependent on a specific initial configuration, providing an objective and thorough evaluation of our solutions.

2.4.2. Cross-comparison of results from different model types

A crucial aspect of our validation methodology was the cross-comparison of results obtained from different types of models. The predictions derived from our simulations were compared with data generated from our analytical models to verify their consistency and accuracy. For instance, we compared the numerically calculated susceptibility to noise in the USC chain with the predictions from our analytical calculations. This comparison demonstrated a strong correlation between the two approaches, significantly increasing our confidence in the predictive power of the models. This cross-validation is essential for ensuring that our findings are not artifacts of a single methodological approach, but rather a consistent reflection of the system's underlying physical behavior.

2.4.3. Assessment of model accuracy and predictive power

A crucial aspect of our validation methodology was the cross-comparison of results obtained from different types of models. The predictions derived from our simulations were compared with data generated from our analytical models to verify their consistency and accuracy. For instance, we compared the numerically calculated susceptibility to noise in the USC chain with the predictions from our analytical calculations. This comparison demonstrated a strong correlation between the two approaches, significantly increasing our confidence in the predictive power of the models. This cross-validation is essential for ensuring that our findings are not artifacts of a single methodological approach, but rather a consistent reflection of the system's underlying physical behavior.

Validation of Work Package 3 Artifacts: QC Infrastructure Dependability via the E2Q Continuum

Validation of E2Q Continuum Architecture and Offloading Mechanisms

1. Test setup and methodology for architecture and offloading validation

The validation of the E2Q architecture is structured around two main levels: microservice-level validation and integration testing. This approach ensures that each microservice operates correctly in isolation and that the entire system functions cohesively when all components are integrated.

Microservice-level validation

Each microservice has been developed with specific requirements and functionalities. The validation process begins with unit testing of each microservice to ensure that they perform their intended functions correctly. For native microservices implemented for this architecture, part of the validation is performed automatically through the Temporal API, which normally requires exposed functionalities to be sandboxed.

Some microservices, most notably the ones that integrate AI models and the QML demo, are not fully sandboxed and require manual validation. This involves testing the microservices in isolation to ensure they meet their functional requirements and can handle expected workloads.

Integration Testing

The architecture is tested as a whole to ensure that all components interact correctly. This includes verifying the communication between microservices, the API discovery service, and the Kubernetes deployments.

This has been achieved by testing the interactions between the microservices and the API discovery service, the Temporal server and the Node-RED flow integrations. Validation of the user interface integration with Node-RED confirms that the system can handle user interactions and display results correctly.

The hardware used for the validation process is a laptop equipped with a 16-thread Ryzen 7 CPU, 32GB of RAM, and a 2TB SSD. This configuration provides sufficient resources to run multiple microservices concurrently, simulating a production-like environment.

2. Validation metrics and analysis

Validating the task partitioning and mapping algorithms focuses on verifying their effectiveness in distributing workloads between diverse computing resources. This has been achieved through the Dynamic Worker API, which provides informative output logs that detail which functionalities are being executed on which resources. Additional validation involves analyzing the impact of the aforementioned API on the overall system performance, particularly in terms of task execution efficiency and resource utilization.

The API discovery service undergoes validation to ensure its reliability in registering and interacting with platform-exposed APIs. This involves testing for the accuracy of API registration and deregistration processes, as well as measuring response times and availability. Metrics such as low latency and high registration accuracy are essential to validating its operation within the ecosystem.

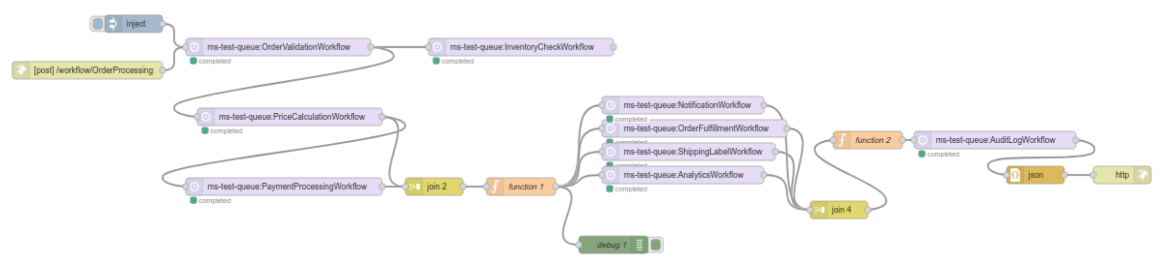
Kubernetes deployments are validated for their reliability and scalability, focusing on their ability to support the platform's infrastructure under stress. The success rate of deployments and overall system uptime are analyzed to measure performance. Validation also includes evaluating deployment automation to ensure consistent and error-free operations.

The integration of Node-RED is validated by ensuring that flows execute seamlessly and interact effectively with the API discovery service. Measures such as flow execution success rates provide insights into the integration's robustness and usability for end users.

3. Feasibility and scalability demonstration of the E2Q architecture

Since both the development and testing of the E2Q architecture have been conducted in a local Kubernetes cluster, the feasibility of the architecture has been demonstrated through the successful deployment and operation of multiple microservices, including those that integrate AI and quantum functionalities. The architecture has shown its ability to handle diverse workloads, with the Dynamic Worker API streamlining the task partitioning and mapping processes across different computing resources.

We can also demonstrate that running the microservices using the Dynamic Worker API has not impacted their overall performance and storage footprint, as well as the performance of the architecture, since they are lightweight, depending only on the Temporal API and standard gRPC libraries for their operation. The runtime performance of request processing should also be unchanged by the Dynamic Worker API, as it starts a standard Temporal worker that processes the requests in the same way as if it were running in a manually-configured Temporal worker.



An example workflow with 10 different mock microservices with joins for awaiting results asynchronously.

The technologies chosen for the implementation of the architecture and the supporting microservices have been selected for their scalability and performance characteristics. Kubernetes provides a robust platform for deploying and managing containerized applications, while Temporal offers a reliable framework for orchestrating complex workflows which can be configured for increased scalability with a Cassandra database.

The API discovery service has also been designed to be lightweight and scalable to handle high demand, allowing it to handle an increasing number of registered microservices and workflows without performance degradation. The use of Redis for state management relieves this service from the need for persistent storage, while still providing fast access to the registered services and opening the possibility of further scalability through clustering support provided by Redis. Due to time constraints during development, a pain point of the current implementation is the fact that this service needs to periodically poll the Kubernetes API to monitor the health status of the registered pods, which can be improved by implementing a more event-driven approach using Kubernetes events or webhooks in the future.

The integration of Node-RED enhances the user experience by providing a visual programming interface for creating and managing workflows, making it easier to leverage the capabilities of the architecture. While Node-RED is not designed for high-performance computing, it is well-suited for visual workflow management and can be scaled horizontally by deploying multiple worker instances, as demonstrated in the architecture.

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By working with known and tested technologies, and by implementing low-cost integrations with the API discovery service and Temporal workflows, the E2Q architecture has been designed to be both feasible and scalable. The burden of performance then falls to the implementation of the microservices themselves, which can be optimized independently of the architecture.

QML case studies

The Edge-to-Quantum (E2Q) Continuum architecture represents a novel framework for integrating quantum computing resources into distributed edge-cloud systems, enabling workloads to be dynamically offloaded to quantum nodes for specialized tasks. This architecture extends the traditional edge-to-cloud model by incorporating quantum processing units (QPUs) as part of the continuum, allowing for seamless interaction between classical edge devices, fog nodes, and quantum infrastructure. The validation of this architecture through practical implementations, such as porting of quantum algorithms and machine learning models, provides critical insights into its scalability, reliability, and adaptability in real-world applications.

The following QML models were studied to develop practical implementations and validate the architecture. The quantum fingerprinting (QFP) method, usually employed in the design of bounded-error quantum algorithms, was used as a data encoding technique in QML. It was applied to a classification problem in astrophysics, namely gamma-ray burst (GRB) detection [5] (see Table 1 for the main results).

Table 1. The comparison of the frequently used data reuploading (DR) and QFP data encoding methods in GRB detection. QFP outperforms DR in terms of F1 score, but is slower due to larger circuit depth.

Encoding	Features	Qubits	Layers	F_1 (%)	T_{real} (ms)
QFP	12	5	-	**97.5**	20.6
DR	12	6	1	75.3	**14.9**
QFP	24	6	-	95.1	40.1
DR	24	6	2	**97.5**	**19.8**

FP	120	8	-	**97.5**	495.9
DR	120	6	10	88.0	**61.2**
DR	120	10	6	76.9	102.6

Moreover, the combination of QFP and classical random projections technique was studied from a theoretical point of view.

Theorem 2 *Consider any* $0 < \varepsilon < 1$ *and a prime* q. *Let* $\mathbf{X} = \{\mathbf{x}_1, \ldots, \mathbf{x}_n\} \subset \mathbb{Z}_q^N$ *be a set of* N*-dimensional vectors and* $M = O(\log n/\varepsilon^2)$.
Then we can choose a matrix $R \in \mathbb{Z}_q^{N \times M}$ *such that for any pair* $(\mathbf{x}_i, \mathbf{x}_j)$ *of vectors from* $\mathbf{X}$ *we have* $|\langle \Psi_R(\mathbf{x}_i) | \Psi_R(\mathbf{x}_j) \rangle| \leq \varepsilon$, *where*

$$|\Psi_R(\mathbf{x})\rangle = \frac{1}{\sqrt{M}} \sum_{k=1}^{M} |k\rangle \otimes \left(\cos \frac{2\pi \mathbf{y}[k]}{q} |0\rangle + \sin \frac{2\pi \mathbf{y}[k]}{q} |1\rangle \right), \tag{2}$$

and $\mathbf{y} = R\mathbf{x}$, *and* $\mathbf{y}[k]$ *denotes* k*-th component of the vector* $\mathbf{y} \in \mathbb{Z}_q^M$.

Figure 1. A connection between the random projections method and the quantum fingerprinting technique.

The results of the study were presented at CEQIP [9] (see Fig. 1 for the main theorem).

Other applications and implementations of QFP technique were also explored, for example, shallow implementation of QFP circuit was applied to the construction of quantum finite automata [3]. The review of QFP applications in cryptography resulted in a survey paper [4].

The machine learning approach is driven by data, thereby making it the most important, essential, element of related techniques. A methodology and technique were proposed to address data-driven medicine challenges. The proposed solution includes data processing and encoding, which can ensure security and privacy while dealing with dataset size issues, coupled with quantum computing, which allows to cope with medical datasets which cannot be managed by classical machine learning models. A case study on a publicly available heart disease dataset, combining different data encoding and classical/quantum ML techniques. The journal version of the study is being prepared [2].

Another important method in machine learning is regression analysis, so it is necessary to study it to develop test cases for the E2Q Continuum architecture. Through a case study on air quality sensor fusion regression based on a real measurement dataset, classical and quantum regression models were compared, specifically assessing the impact of different data encoding techniques to provide guidelines for their effective application to real-world scenarios (see Fig. 2).

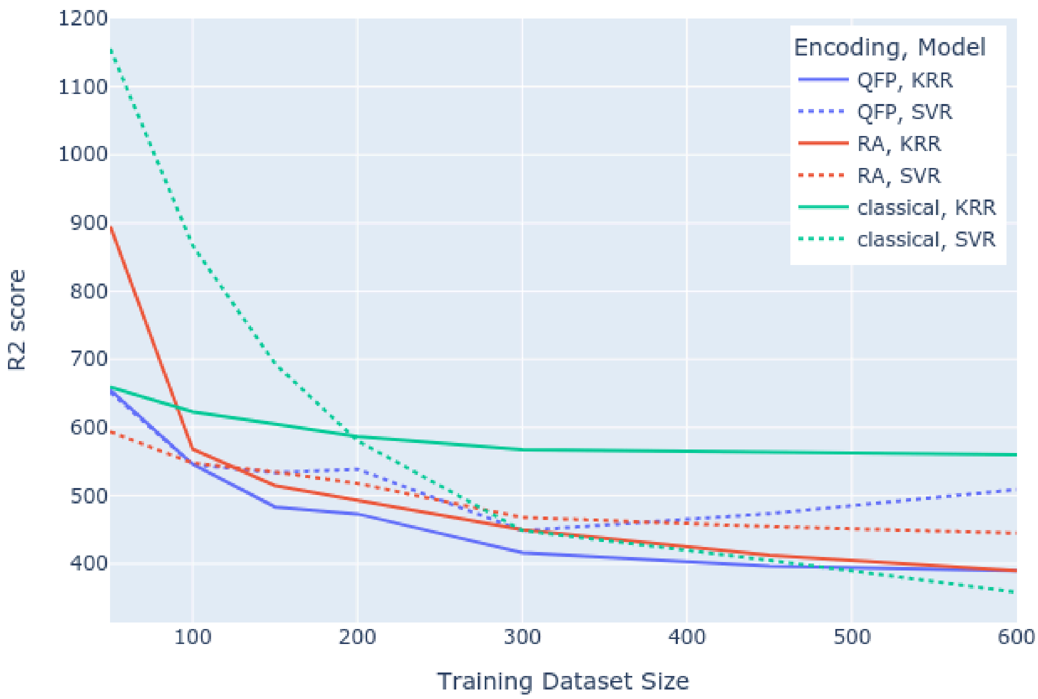

Figure 2. MSE (the lower the better) for classical and quantum methods for different training data set sizes. The results show that quantum regression outperforms the classical one for small datasets and scenarios with data scarcity.

The results of the study were presented at the Ital-IA workshop [10]; the subsequent development of the study was accepted to the QAI conference [7].

For the same reason, it is also important to study combinations of classical and quantum machine learning methods. Quantum computing promises advantages in data analysis by mapping the input data to a higher-dimensional Hilbert space and performing computations based on physics laws. However, its potential is limited by noise and number of qubits, restricting suitability to full-fledged, end-to-end quantum machine learning solutions. Therefore, proper classical data preprocessing is required. For example, the major challenge in data-driven studies is imbalanced datasets. The paper submitted for the QualITA conference [6] addresses this critical challenge. It investigates the impact of data quantity and quality management through random undersampling on multiclass classification using the UNSW-NB15 dataset and Support Vector Classifiers (SVC). Furthermore, it explores a quantum perspective by examining quantum SVC with different sampling methods (see Fig. 3). This work underscores the importance of data preprocessing and highlights future avenues for quantum machine learning in robust threat detection.

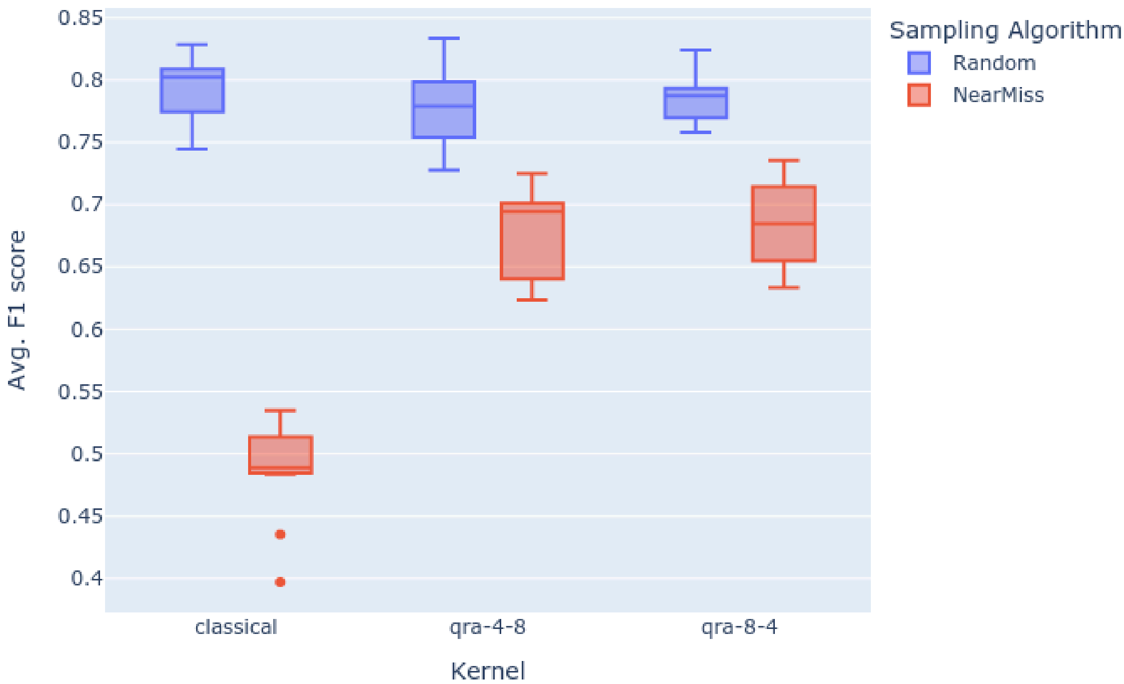

Figure 3. Undersampling methods in QML. The random sampler shows a better F_1 score than the NearMiss-3 sampler for both classical and quantum models, with ~60% of improvement on the classical model and ~10% for quantum ones. Thus, despite being worse than the random sampler, the NearMiss-3 one works better in quantum models.

Further development of this study is accepted to the BigHPC special track [8] of the ITADATA conference.

The results obtained in the Project were presented at several conferences and workshops:

- Convegno Nazionale CINI sull'Intelligenza Artificiale (Ital-IA), June 23-24, Trieste, Italy (remotely),
- Italian Conference on System and Service Quality (QualITA), June 25, Catania, Italy,
- Central European Quantum Information Processing Workshop (CEQIP), June 30-July 3, Smolenice, Slovakia,
- IEEE World Congress on SERVICES: Quantum Software (QSW), July 7-12, Helsinki, Finland.

To validate the E2Q Continuum, two representative quantum algorithms were ported: Shor's algorithm for integer factorization and a quantum kernel method for classification. Shor's algorithm, a landmark quantum algorithm, demonstrates the potential of quantum computing to be intractable for classical systems, such as breaking RSA encryption. In this implementation, the classical pre- and post-processing steps, along with the quantum period-finding component, were extracted from Qiskit code and partitioned into microservices. These microservices were then deployed across the E2Q architecture, with the quantum portion simulated using Qiskit. This process tested the architecture's ability to handle quantum tasks while maintaining compatibility with classical infrastructure, demonstrating its flexibility.

The second validation example involved a quantum kernel method, a widely used quantum machine learning (QML) model for classification tasks. The workflow was divided into classical and quantum microservices: classical microservices managed data preparation, such as splitting datasets into training and test subsets, while quantum microservices computed Gram matrix elements using a quantum circuit. A classical microservice then executed a loop over these quantum-computed Gram matrix elements, using them to calculate model weights through classical optimization techniques. Finally, similar classical microservices were employed to assess model's accuracy by evaluating predictions against the test dataset. This implementation demonstrated the E2Q Continuum's ability to orchestrate complex, hybrid workflows, where classical and quantum components collaborate repeatedly. By explicitly separating data preprocessing, quantum feature mapping, classical optimization, and model evaluation into distinct microservices, the architecture showcased its capacity to handle the distributed execution of QML tasks while maintaining precision and efficiency. The integration of these steps highlighted the E2Q Continuum's flexibility in managing resource allocation, communication between micro and fault tolerance, further validating its potential as a robust framework for quantum-edge computing.

The results of these validations underscore the E2Q Continuum potential to support a diverse range of quantum algorithms and applications. By successfully executing both Shor's algorithm and a quantum kernel method, the architecture demonstrated its ability to handle tasks requiring high computational precision, distributed resource management, and seamless quantum and classical components. These outcomes not only confirm the feasibility of the E2Q model but also provide a foundation for future advancements in quantum-edge systems. As quantum computing continues to evolve, the E2Q Continuum offers a critical framework for bridging the gap between theoretical quantum algorithms and practical, scalable applications.

Conclusions and Final Project Outcomes and Outlook

The project mainly focused on two areas: the logical qubits in the ultrastrong coupling (USC) regime and the E2Q Continuum architecture. The same areas were used for the project validation.

Summary of Validation Findings

The validation technologies revealed significant advancements in noise suppression, error correction, gate performance, and dependability modeling. For noise suppression, simulations demonstrated that logical qubits in the ultrastrong coupling (USC) regime exhibit near-zero pure dephasing rates and reduced relaxation rates compared to single physical qubits, leveraging collective symmetries for intrinsic protection. The theoretical analysis of the quantum error correction (QEC) scheme that utilizes hybrid optomechanical architecture shows a possibility of non-destructive readouts of logical qubits detecting single-qubit errors without collapsing the logical state. USC-based quantum gates achieved an average fidelity of 99.9% with a 7.6 ns execution time, surpassing conventional gates in speed and decoherence resilience. Dependability assessment models were rigorously validated through cross-comparison of analytical and simulation frameworks, confirming their predictive accuracy and stability under non-ideal conditions. These results collectively establish USC as a transformative platform for enhancing quantum system reliability, speed, and scalability.

The E2Q Continuum architecture was rigorously validated through a combination of microservice-based testing, integration with quantum and classical workloads, and real-world applications in quantum machine learning (QML). Key findings include its ability to dynamically partition tasks between edge, cloud, and quantum nodes, leveraging the Dynamic Worker API for efficient resource allocation. Integration testing confirmed seamless communication between classical microservices (e.g., data preprocessing) and quantum components (e.g., quantum kernel computation, Shor's algorithm simulation). The architecture's scalability was demonstrated through Kubernetes-based deployment, Redis for service discovery, and Node-RED for user-friendly orchestration. QML case studies, such as quantum fingerprinting for astrophysics classification and hybrid quantum-classical regression models, highlighted its flexibility in handling complex, distributed workflows. The successful execution of quantum algorithms like Shor's and quantum kernel methods underscored its potential to bridge quantum computing with practical, scalable applications in edge-cloud environments.

Feasibility, Effectiveness, and Innovation

The USC-based solutions demonstrate remarkable feasibility, as their theoretical predictions align with practical quantum system requirements. The noise suppression and QEC protocols exploit the unique properties of USC, such as virtual processes and hybrid optomechanical interactions, to achieve good performance, surpassing conventional approaches in both efficiency and robustness. The high-fidelity, ultrafast gates highlight the potential of USC to overcome current limitations in quantum computing, while the dependability models' cross-validation ensures their reliability for real-world applications. Innovatively, these solutions integrate USC with advanced error mitigation strategies, offering a unified framework for addressing multiple challenges in quantum system design. This work significantly advances the state-of-the-art by extending coherence times, accelerating gate operations, QEC, paving the way for fault-tolerant, high-performance quantum technologies.

The E2Q Continuum demonstrates strong feasibility through its reliance on established technologies like Kubernetes, Temporal, and Redis, which ensure scalability, fault tolerance, and efficient resource management. The Dynamic Worker API and API discovery service effectively balance classical and quantum workloads, while Node-RED enhances accessibility for hybrid workflows. The architecture's innovation lies in its dynamic, edge-to-quantum integration, enabling seamless collaboration between classical and quantum components. For instance, the quantum kernel method's modular design, separating data preprocessing, quantum feature mapping, into distinct microservices, showcases its adaptability to diverse QML tasks. The impact of this work is significant, as it addresses critical challenges in quantum edge-cloud computing, such as resource allocation, communication latency, and hybrid algorithm orchestration. By validating practical implementations (e.g., Shor's algorithm, QML models), the E2Q Continuum sets a foundation for scalable quantum applications, from cyberrisk assessment to medical data analysis, while highlighting the necessity of classical preprocessing to mitigate quantum hardware limitations.

Recommendations for Future Work

Future efforts should focus on scaling these USC-based solutions to larger quantum systems, addressing challenges in maintaining ultrastrong coupling across multiple qubits and integrating them with existing quantum architectures. Further exploration of hybrid optomechanical systems could refine non-destructive error detection and expand QEC capabilities to handle complex error channels. Additionally, further experiments with the dependability models is critical to bridge the gap between simulations and real-world hardware, ensuring their practical applicability.

To further enhance the future efforts in the E2Q Continuum architecture should prioritize improving the API discovery service efficiency by transitioning from polling-based checks to event-driven mechanisms, reducing overhead in large-scale deployments. Expanding the architecture's quantum capabilities could involve integrating more advanced algorithms, such as variational quantum algorithms or quantum error correction. Additionally, optimizing microservices for performance and scalability, particularly for resource-constrained edge devices, will be critical. The architecture's potential could also be tested in new domains, such as sensor fusion or large-scale medical data analysis, to validate its robustness. Finally, continued collaboration with quantum hardware developers to align the E2Q model with emerging QPU capabilities will ensure its long-term relevance. By building on these advancements, the E2Q Continuum can evolve into a cornerstone for practical, scalable quantum-edge computing ecosystems.

Final Project Summary

The project focused on advancing quantum computing through two complementary pillars: the development of logical qubits in the ultrastrong coupling regime and the design of the E2Q Continuum architecture for scalable quantum edge-cloud integration. Validation of USC-based logical qubits demonstrated significant noise suppression, with near-zero pure dephasing rates and reduced relaxation compared to single-qubit systems, leveraging collective symmetries for intrinsic protection. The optomechanical quantum error correction (QEC) enabled non-destructive logical qubit readouts, while USC-based gates achieved 99.9% fidelity in 7.6 ns, outperforming conventional approaches in speed and decoherence resilience. Dependability models were rigorously validated, ensuring reliability under non-ideal conditions. Simultaneously, the E2Q Continuum architecture was tested through microservice-based workflows, integrating classical and quantum components for tasks like Shor’s algorithm and quantum kernel methods. Its dynamic task partitioning, Kubernetes-driven scalability, and Node-RED adaptability in hybrid quantum-classical workflows with QML case studies highlight its potential for applications in data analysis. Together, these efforts established USC as a transformative platform for fault-tolerant quantum systems and positioned the E2Q Continuum as a scalable framework for bridging quantum and edge-cloud computing, addressing critical challenges in resource allocation, latency, and algorithmic flexibility. Future work will prioritize scaling USC systems, refining hybrid QEC strategies, enhancing the E2Q architecture’s efficiency through event-driven mechanisms and expanding ensuring sustained impact in practical quantum applications.

Appendices

- Raw test data and logs
- Detailed simulation configurations
- Performance graphs and charts
- Full technical specifications of the validated artifacts
- List of published papers

Repositories of code and Jupyter notebooks

Notebooks: https://github.com/usce2qc/notebooks/

List of papers

Manuscripts in preparation for journal publication

[1] S.Distefano, M.Ziiatdinov. "The 3D Continuum spanning Edge to Cloud across Classical and Quantum Computing"

[2] S.Distefano, M.Ziiatdinov. "A Recipe for Data-driven Medicine: Data Encoding, Machine Learning, and Quantum Computing"

[3] Roberto Stassi, Shilan Abo, Daniele Lamberto, Ye-Hong Chen, Adam Miranowicz, Salvatore Savasta, Franco Nori. "Noise Protected Logical Qubit in a Open Chain of Superconducting Qubits with Ultrastrong Interactions", arXiv:2509.17903 (2025).

[4]Shuai-Peng Wang, Alberto Mercurio, Alessandro Ridolfo, Yuqing Wang, Mo Chen, Tiefu Li, Franco Nori, Salvatore Savasta, J. Q. You. "Strong coupling between a single photon and a photon pair", arXiv:2401.02738v2 (2024).

[5] Daniele Lamberto, Gabriele Orlando, Salvatore Savasta. "Superradiant Quantum Phase Transition in Open Systems: System-Bath Interaction at the Critical Point", arXiv:2411.16514v2 (2024).

[6]Andrea Zappalá, Alberto Mercurio, Daniele Lamberto, Samuel Napoli, Omar Di Stefano, Salvatore Savasta. ”From Few to Many Emitters Cavity QED: Energy Levels and Emission Spectra From Weak to Deep-Strong Coupling”, arXiv:2506.18763v1, (2025).

Published journal papers

[7] M.Ziiatdinov, A.Khadieva, K.Khadiev. “Shallow implementation of quantum fingerprinting with application to quantum finite automata”. In: Frontie*rs in Computer Science* Volume 7 - 2025 (2025).

[8] F.Ablayev, K.Khadiev, A.Vasiliev, M.Ziiatdinov. “Theory and Applications of Quantum Hashing”. In: *Quantum Reports* 7.2 (2025).

Conference papers

[9] *IEEE World Congress on SERVICES: Quantum Software (QSW 2025)*, July 7-12, Helsinki, Finland. Comparing Quantum Machine Learning Approaches in Astrophysical Signal Detection, M.Ziiatdinov, F.Farsian, F.Schilliró, S.Distefano

[10] *Italian Conference on System and Service Quality (QualITA 2025)*, June 25, Catania, Italy. Quantity, Quality, and Quantum Perspectives in Data-Driven Cybersecurity, S.Distefano, M.Ziiatdinov,

[11] *IEEE Quantum Artificial Intelligence (QAI 2025),* November 2-5, Naples, Italy, Beyond Classical: The Role of Data Encoding in Quantum Regression on Air Quality Prediction, M.Ziiatdinov, S.Distefano

[12] *BigHPC track of Italian Conference on Big Data and Data Science*, September 9-11, Turin, Italy, The Quantum Bottleneck: An Analysis of Data Balancing in QML for Security, M.Ziiatdinov, S.Distefano

[13] *Convegno Nazionale CINI sull'Intelligenza Artificiale (Ital-IA)*, June 23-24, Trieste, Italy, Quantum-Enhanced Calibration of Low-Cost Air Quality Sensors: A Comparative Regression Analysis, M.Ziiatdinov, S.Distefano

[14] *Central European Quantum Information Processing Workshop (CEQIP)*, June 30-July 3, Smolenice, Slovakia, Random projections and quantum fingerprinting for QML, M.Ziiatdinov, S.Distefano