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USCE2QC

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

D2: Initial development report

vers. 1.0

Version

Version	Date	Description	Authors
1.0	15/05/2025	Initial development report (M10 - all WP2, WP3 Tasks): This deliverable documents the initial development of project solutions, models, techniques and artifacts. Specifically, a first version of USC regime-based solutions for quantum noise suppression and error detection/correction of WP2 is delivered, as well as WP3 E2Q architecture, models and mechanisms.	Salvatore Distefano Roberto Stassi Mansur Ziiatdinov Carmelo Munafo’

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Introduction

Purpose of the Deliverable

This document, Deliverable 2 (D2) titled “Initial Development Report”, serves as a key milestone in the USCE2QC project. Its primary purpose is to document and report on the initial progress of the implementation and development activities carried out since the completion of the “Analysis and Design Report” (D1) at Month 5. This report provides a detailed account of the first version of the solutions, models, and techniques developed within 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). It highlights the initial results, challenges encountered, and the overall trajectory of the project's development phase, ensuring a transparent and verifiable record of progress.

Overview of Project Progress since D1

Following the comprehensive analysis and design documented in D1, the USCE2QC project has transitioned into the implementation phase. The first five months were dedicated to establishing the theoretical and architectural foundations for enhancing quantum computing dependability at both the node and infrastructure levels. Since then, the project team has focused on translating these designs into tangible, functional components. This includes the initial coding and testing of solutions for quantum noise suppression, error correction, and novel quantum gates. Simultaneously, the team has begun building the foundational architecture for the E2Q continuum, including the first versions of offloading mechanisms, dependability policies, and orchestration tools. The progress outlined in this report demonstrates the project commitment to moving from conceptualization to practical development, laying the groundwork for the final solutions to be presented in subsequent deliverables.

Scope of D2: Initial Development Activities

This report systematically presents the outcomes of the initial development activities for the technical tasks within Work Packages 2 and 3. For Work Package 2, the scope encompasses the initial implementation of USC-based noise suppression techniques, quantum error correction protocols, and novel quantum gates. It also includes the initial application of dependability assessment models developed for evaluating these USC solutions. For Work Package 3, the scope covers the first version of the E2Q continuum architecture, including its offloading mechanisms, dependability policies and strategies, and orchestration tools. The report details the initial results and observations from these early implementations, providing a concrete measure of progress against the designs outlined in D1.

Document Structure

The remainder of this document is structured as follows: Section 2 provides a detailed account of the initial development activities carried out within Work Package 2, covering the implementation of USC-based solutions for node dependability and their initial assessment. Section 3 similarly elaborates on the initial development work performed under Work Package 3, focusing on the E2Q continuum architecture, offloading mechanisms, policies, and orchestration. Finally, Section 4 offers an overall conclusion, summarizing the initial development milestones, outlining the remaining challenges, and detailing the next steps leading to the final deliverables (D3 and D4).

Work Package 2: QC Node Dependability via Ultrastrong Coupling (USC) Regime — Initial Development

Task 2.1. Initial Development of USC-based Solutions

This section outlines the initial development progress of the solutions and techniques for Work Package 2 (WP2), as defined in Deliverable D1. The focus is on the advancement of noise suppression methods, Quantum Error Correction (QEC) protocols, and novel quantum gates, all leveraging the Ultrastrong Coupling (USC) regime.

2.1.1. Implementation progress of the USC-based noise suppression techniques designed in D1

The initial development of noise suppression techniques is centered around the theoretical framework proposed in the document "Noise Protected Logical Qubit in a Spin Chain with

Ultrastrong Interactions." This work serves as the conceptual implementation for Task 2.1. The approach involves creating a logical qubit composed of a chain of physical qubits with interactions in the USC regime. This scheme is designed to be intrinsically protected from decoherence by exploiting the symmetries of the system. This method differs from other approaches by embedding the logical qubit within a strongly-interacting system rather than relying on isolated qubits.

2.1.2. Initial simulation results and performance observations

Initial simulations were conducted using the Lindblad master equation to evaluate the effectiveness of the proposed spin chain model. The preliminary results show a significant suppression of both the pure dephasing rate and the relaxation rate compared to a single, non-interacting physical qubit. Key observations include:

Pure Dephasing: The pure dephasing rate of the logical qubit approaches decreases as the coupling strength (λ) or the number of physical qubits (N) in the chain increases.

Relaxation: The relaxation rate is reduced to approximately half that of a single physical qubit.

These early results are critical as they provide a solid theoretical basis for the final solutions. They demonstrate the potential of USC-based schemes to extend the coherence times of quantum systems and are a key milestone in the project's development.

Task 2.2. Initial Development of USC Quantum Error Detection/Correction

2.2.1. Study and Exploration Phase for the Implementation of USC-based Quantum Error Correction (QEC) Protocols

Initial progress on the implementation of Quantum Error Correction (QEC) protocols is focused on the study and exploration of the USC regime. This work investigates the use of virtual photons generated by the ultrastrong coupling between qubits and resonators to protect quantum computations from noise-induced errors. While full-scale implementation is ongoing, initial testing and analysis have been conducted to assess the feasibility of these protocols. The main objective at this stage is to lay the groundwork for a comprehensive evaluation of their efficiency in detecting and correcting quantum errors, which is crucial for achieving fault-tolerant quantum computing.

2.2.2. Initial Study of Quantum Nondemolition (QND) Measurement

The foundational work for developing robust readout mechanisms has begun with a deep dive into the principles of Quantum Nondemolition (QND) Measurement. This type of measurement is essential because it allows for the repeated measurement of a specific observable without disturbing its value, thereby avoiding back-action on the system. The study focuses on:

- Identifying an observable that commutes with the free Hamiltonian ([O^1,H0]=0).
- Designing an interaction Hamiltonian that also commutes with the observable ([O^1,HI]=0).

This ensures that the measurement process does not alter the state of the observable being measured. This principle is being explored as a core component for future readout schemes, particularly in cavity quantum electrodynamics (QED), where the interaction between a qubit and a probe field can be designed to perform a QND measurement of the qubit's state.

2.2.3. Exploration of Coherent State Preparation for Readout

A complementary area of study is the preparation of coherent states, which are fundamental for quantum measurement and readout. A coherent state is a quantum state that most closely resembles a classical state, mimicking the behavior of a classical oscillator. The project is exploring the conceptual procedure for generating these states for use as classical probe fields in readout and amplification.

The procedure involves:

- Applying a resonant coherent drive to a quantum system (e.g., a cavity mode).
- Allowing the drive to act for a finite time (tP).
- Stopping the drive to "freeze" the amplitude at a desired value.

This method is crucial for preparing the classical fields used in homodyne or heterodyne detection, which are standard techniques for extracting the state of a quantum bit. The exploration of this procedure is a foundational step in ensuring that the measurement process itself is reliable and precise.

Task 2.3. Initial Development of USC Quantum Gates

2.3.1. Implementation progress of novel quantum gates and preliminary performance metrics

The development of novel quantum gates operating in the USC regime is proceeding as planned. The theoretical framework suggests that the strong interactions between qubits will enable the creation of faster and more robust gates. Preliminary simulations, which isolate gate performance from decoherence effects, have yielded an average gate fidelity of 99.99% for both single- and two-qubit gates. The gate operations are performed by applying pulses to, or modulating the frequency of, individual physical qubits or by inducing inductive coupling between them. These initial performance metrics are promising and serve as the baseline for further optimization and validation in the later stages of the project.

Task 2.4. Dependability Assessment for USC Solutions

2.4.1. Initial development of analytical and simulation models for assessing USC solution dependability

The foundational work for assessing system dependability has begun with the initial development of analytical and simulation models. The primary tool for this is the Lindblad master equation, which allows us to numerically simulate the evolution of a logical quantum state under the ultrastrong coupling (USC) regime. This framework is being designed to directly compare the performance of our logical qubit with that of a single, non-interacting qubit subjected to the same noisy environment. The goal is to model how USC interactions can enhance the system's coherence time and suppress noise rates, laying the groundwork for a more robust quantum architecture.

2.4.2. Application of these models to the first developed USC solutions

We have applied our preliminary models to the first USC solutions developed. The focus has been on evaluating the impact of decoherence channels, specifically relaxation and pure dephasing processes. This initial application aims to demonstrate the theoretical feasibility of using the USC regime to suppress these noise rates, providing a solid theoretical foundation for subsequent development activities. These early results, which show significant suppression of both pure dephasing and relaxation rates, serve as a key milestone in the project's development.

Work Package 3: QC Infrastructure Dependability via the Edge-to-Quantum (E2Q) Computing Continuum — Initial Development

Task 3.1. Initial Development of the E2Q Continuum Architecture and Offloading Mechanisms

3.1.1. Implementation of the first version of the E2Q architecture and protocols

The initial version of the E2Q architecture marked a pivotal step in establishing a robust framework for integrating edge and quantum computing resources. At this stage, the architecture was designed to support a wide range of computational tasks, from classical edge computing to quantum processing, while ensuring efficient resource management and task orchestration.

Kubernetes Proof-of-Concept

A proof-of-concept deployment on Kubernetes was implemented to enable container orchestration, showcasing the feasibility of managing diverse computational workloads within a unified platform. The deployment includes a set of microservices that handle various aspects of the E2Q architecture, such as task scheduling, resource management, and workflow execution.

Microservices are deployed as Docker containers, allowing for easy scaling and management of resources. The Kubernetes cluster is configured to support both classical and quantum workloads, with dedicated namespaces for each type of task.

Temporal

The Temporal orchestration framework was integrated by keeping the configuration as simple and in line with the official documentation as possible. This includes the server container, the

PostgreSQL database for state management, and the web UI for easy access to the bookkeeping features.

Separating tasks by resource requirements

The quantum prototype based on Shor's algorithm has been further developed to isolate tasks based on their resource requirements and allowing for the explicit execution of each step of the algorithm through the Temporal framework. This will allow for a more granular control over the execution of quantum and classical tasks, as well as the initialization of the workers exposing each functionality with the Temporal framework.

Node-RED Integration

Node-RED was integrated into the E2Q architecture to provide a user-friendly interface for workflow management and task orchestration. Node-RED is a platform that allows users to visually design flows prominently for IoT integrations and REST services. Our goal is bringing this kind of user-friendly workflow to the architecture, in such a way that the user can use microservices in the architecture (be they quantum or classical tasks) as they would regular Node-RED nodes, facilitating rapid development and testing of new task partitioning strategies.

An initial Node-RED plugin implementation introduces a simple node that can be configured to start a Temporal workflow with a given task queue by wrapping the Temporal client TypeScript SDK. This node allows the user to trigger a Temporal workflow from Node-RED and integrate it into their flows.

3.1.2. Implementation of the first version of intelligent task partitioning and resource mapping algorithms

The first version of the intelligent task partitioning and resource mapping algorithms was implemented, focusing on optimizing the execution of tasks across the E2Q continuum and providing a foundation for future enhancements, along with the integration of a user interface for workflow management.

Dynamic Worker Integration

To support the hybrid nature of the E2Q workloads and facilitate the integration of new microservices, a dynamic worker convention was established through a custom API that manages the initialization of the Temporal worker. The objective is speeding up the development of new microservices by allowing developers to focus on their specific tasks without worrying about the underlying orchestration details, which are to be standardized across microservices introduced in the E2Q architecture.

Microservices are to be developed as Python packages that expose ordinary Temporal activities and workflows, which will be tagged with the task queues that they are intended to serve by using the custom decorators provided by the dynamic worker package. This approach allows for a clear separation of concerns and enables the Temporal framework to handle the orchestration of tasks across different computational domains.

Execution of the microservices then requires the creation of a Docker image that includes the application package and its dependencies (one of which is the dynamic worker package). The entrypoint is set to the dynamic worker module, which will automatically crawl the application package for Temporal activities and workflows tagged with the decorators and register them with the Temporal server. Parameters such as the target application package and the task queues the worker should listen to are provided through environment variables for easy reconfiguration of worker instances through container orchestration solutions. The main goal of this approach is to avoid the need for developers to explicitly register their activities and workflows, but rather to let the package structure and decorators handle the registration process by registering all activities and workflows in a set of categories specified through environment variables, for better flexibility and ease of configuration in Kubernetes.

This integration, albeit convoluted at first glance, is expected to significantly streamline the development process of new microservices by providing a standardized way to register and manage Temporal activities and workflows. Additional features such as future integration with services exclusive to the E2Q architecture could further prove the benefits of avoiding the need for developers to rewrite the interaction with the Temporal framework for each new microservice.

Experimental Node-RED worker instances

An experimental implementation of Node-RED worker instances was introduced, allowing users to create Node-RED flows, deploy them and execute them as part of the E2Q architecture, eventually by taking advantage of features offered by container orchestration frameworks, such as replication and load balancing.

The worker instances are designed to be compatible with the user-facing Node-RED instance, and their flows are to be updated automatically every time the user modifies the flows in the user-facing Node-RED instance. This integration aims to provide a seamless experience for users who want to leverage Node-RED for workflow management while ensuring that the underlying orchestration and execution mechanisms remain consistent with the E2Q architecture.

Additionally, the Node-RED worker instances are expected to integrate with the Temporal framework to allow for the execution of their flows via the Temporal API, and by extension, the rest of the E2Q architecture. This will enable users to create complex workflows that can span both classical and quantum tasks, leveraging the capabilities of the architecture while maintaining the user-friendly interface provided by Node-RED.

3.1.3. Progress on the development of resource discovery mechanisms

The development of resource discovery mechanisms for the E2Q architecture was initiated, focusing on enabling efficient identification and utilization of available resources across the edge and quantum computing continuum.

Initial developments of API discovery solutions through Node-RED

One approach explored was the use of existing Node-RED plugins for API discovery, which mainly focus on REST APIs. This approach was deemed insufficient for the E2Q architecture, as it did not provide the necessary flexibility and extensibility required for the diverse range of resources and services involved in edge and quantum computing.

Integration with Temporal Nexus

The Temporal Nexus API was explored as a potential solution for orchestrating resource discovery processes, offering advanced features for state synchronization and event-driven updates, though it was not fully implemented in the first version of the E2Q architecture. The focus remained on ensuring that the discovery mechanisms were robust and could adapt to the dynamic nature of the E2Q workloads.

Quantum Machine Learning as a Case Study for Testing

Quantum machine learning (QML) represents a transformative intersection of quantum computing and classical machine learning, leveraging quantum principles such as superposition, entanglement, and quantum parallelism to enhance computational efficiency and solve complex problems beyond the reach of classical systems. At its core, QML employs quantum algorithms to process and analyze data, often polynomial speedups for specific tasks, such as optimization, pattern recognition, and data classification. For instance, quantum neural networks (QNNs) use quantum circuits to model nonlinear relationships in data, while variational quantum algorithms (VQAs) combine classical optimization with quantum computation to train models on hybrid quantum-classical hardware. Quantum kernel methods, another prominent example, utilize quantum feature maps to compute similarity measures in enabling more effective classification in machine learning tasks. These models are particularly relevant for applications requiring high computational power, such as drug discovery, financial modeling, and real-time data analysis, where classical systems face limitations in scalability and speed.

The edge-to-quantum (E2Q) continuum architecture extends the traditional edge-to-cloud model by integrating quantum nodes, allowing workloads to be offloaded to quantum processors for specialized tasks. As it can be seen from the short description above, a lot of currently used QML models are naturally divided into quantum and classical parts, thus serving an ideal testbed because of their ubiquity and diversity. For example, a classical preprocessing part of a QML model could be deployed on edge devices for initial data preprocessing, with quantum nodes in the cloud handling computationally intensive tasks like optimization. This workflow validates the E2Q continuum's ability to dynamically allocate resources, manage latency, and ensure seamless communication between classical and quantum components. By testing QML models in this hybrid environment, dependability can be evaluated, such as how effectively it handles quantum noise, error correction, and the synchronization of classical and quantum workflows. This is critical for the USCE2QC project, which aims to enhance quantum computing dependability through ultrastrong coupling regimes and robust orchestration tools.

In the context of the USCE2QC project, QML models provide a practical framework to test and refine the E2Q continuum's offloading mechanisms and dependability policies. For instance quantum algorithms, which are sensitive to noise and require precise control, can be used to assess the reliability of quantum nodes in the E2Q architecture. Similarly, quantum kernel methods can be used to evaluate how well the E2Q continuum manages data transfer between edge devices and quantum nodes, ensuring minimal latency and maximal throughput. These tests align with the project's objectives outlined in Work Package 3, which focus on the development of orchestration tools. By iteratively refining QML-based workflows within the E2Q framework, the project can demonstrate the feasibility of integrating quantum computing into distributed systems, paving the way for scalable, dependable quantum-edge infrastructures.

The initial development activities described in Deliverable 2 (D2) of the USCE2QC project lay the groundwork for such QML-driven testing. For example, the development of dependability assessment models for E2Q solutions can be applied to QML tasks, measuring how well the architecture handles failures or resource constraints. By embedding QML core components to the E2Q testbed, the project not only advances quantum computing's practical applicability but also establishes a robust framework for future innovations in edge-quantum hybrid systems.

The astrophysical data (simulated signal and background noise from gamma-ray bursts) was analyzed using quantum machine learning. Specifically, a four-step QML workflow was proposed encompassing data encoding, quantum circuit design, model training, and evaluation.

The starting point of the workflow focuses on data processing, i.e. the quantum encoding. Different quantum encoding techniques can be adopted to obtain a quantum representation, e.g. basis-, amplitude- or angle-based ones, strongly depending on the dataset X size n and number of features f, resulting in a q-qubit representation. In the following, some of the most relevant ones are described.

Consider a dataset X, the amplitude encoding converts the dataset to a state

$$|\psi(\mathbf{X})\rangle = \frac{1}{\|\mathbf{X}\|} \sum_{i=1}^{n} \sum_{j=1}^{f} x_{i,j} \, |i\rangle \, |j\rangle \, ,$$

The angle encoding represents a data item using different qubit rotations, for example:

$$|\psi(x_i)\rangle = \prod_{j=1}^{f} R_Y^{(j)}(x_{i,j}) \left|0^{\otimes f}\right\rangle ,$$

The data reuploading encoding uses single-qubit gates to encode classical features and repeats this process interspersing encoding and some computation. The motivation behind the data reuploading method is to circumvent the No-Cloning theorem, and to allow the quantum neural network to take the same input several times. Usually, one layer of data reuploading uses single-qubit gates to encode the features and then entangles all qubits, so, in some sense, it is a generalization of the angle encoding since it applies this technique in a different basis.

Consider a data item with f features and choose a number of qubits q and a number of layers l such that f = lq. The state is then obtained by using the following transformation:

$$\begin{aligned} |\psi(x_i)\rangle &= \prod_{k=l}^{1} U_{l-k+1}(x_{i,f-kq+1}, x_{i,f-kq+2} \dots, x_{i,f-kq+q}) \, |0\rangle \\ &= U_l(x_{i,f-q+1}, \dots, x_{i,f}) U_{l-1}(x_{i,f-2q+1}, \dots, x_{i,f-q}) \times \\ &\times \dots \times U_1(x_{i,1}, \dots, x_{i,q}) \, |0\rangle \,, \end{aligned} \tag{1}$$

where k-th layer is described by:

$$U_k(z_0, \dots, z_{q-1}) = \Big(\otimes_{j=1}^{q} R_Y^{(j)}(z_j) \Big) V_k,$$

and V_k is a unitary transformation that entangles all qubits.

Another research direction was to explore whether methods from long-term quantum algorithm design can be used to enhance dependability of short-term quantum methods, such as QML. Particularly, the quantum fingerprinting (QFP) method, usually employed in the design of bounded-error quantum algorithms, was used as a data encoding technique in QML.

Two types of data encoding are considered based on the quantum fingerprinting technique. Starting from $\theta = (\theta_0, \ldots, \theta_{f-1})$ coefficients, quantum fingerprinting encoding for a data item $x_i = (x_{i,1}, \ldots, x_{i,f})$ can be defined as

$$|\psi_\theta(x_i)\rangle = \frac{1}{\sqrt{f}} \sum_{j=1}^{f} |j\rangle \Big(\cos(\theta_j x_{i,j}) \, |0\rangle + \sin(\theta_j x_{i,j}) \, |1\rangle \Big).$$

In other words, different subspaces (indexed by j) are adopted to encode features $x_{i,j}$ of the data item x_i using different rotations θ_j for each feature. This puts the quantum fingerprinting encoding in between the amplitude and angle encodings.

Table I: Data encoding comparison			
Encoding	**Parameters**	**Qubits q**	**Description**
Amplitude	n, f	log (nf)	
Angle	f	f	
Data reuploading	f, l	f / l	
Fingerprinting	f	log f + 1	

The encoding techniques discussed above are summarized and compared in Table I in terms of the number of qubits q based on relevant parameters, i.e. the dataset size n, the number of features f, and the number of levels l (for data reuploading). This comparison highlights that the best encoding techniques, in terms of q, are the hybrid ones, i.e. data reuploading and fingerprinting.

Conclusions and Next Steps

The USCE2QC project has achieved significant progress in both Work Packages 2 and 3. In Work Package 2 (QC Node Dependability via Ultrastrong Coupling), key milestones include the development of USC-based noise suppression techniques, successful simulations demonstrating reduced dephasing and relaxation rates, initial implementation correction (QEC) protocols using virtual photons, and the creation of quantum gate architectures with high fidelity. Dependability models leveraging the Lindblad equation were established to assess system resilience. In Work Package 3 (QC Infrastructure Dependability via E2Q Continuum), the E2Q architecture was implemented with Kubernetes for orchestration, Temporal for workflow management, and Node-RED for user-friendly interfaces. Resource discovery mechanisms, dynamic worker integration, and experimental Node-RED worker instances were developed, with quantum machine learning (QML) serving as a case study to test hybrid classical-quantum laid the groundwork for scalable, dependable quantum-edge infrastructures.