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Bridging the Paradigm Gap: A Framework for Interoperability between Classical IoT and Quantum Computing Networks

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Abstract

The proliferation of the Internet of Things has created a massive ecosystem of classical devices that are increasingly constrained by security and computational limits. While quantum computing offers a revolutionary paradigm for data processing, a "paradigm gap" exists between classical binary telemetry and quantum state representations. This paper proposes a software-defined middleware framework designed to bridge this gap. Our primary contribution is a novel Digit-Based Gate Mapping (DBGM) method that translates standard MQTT-based IoT data into quantum circuit configurations. By positioning the Translator Core at the application layer, we enable heterogeneous classical devices to participate in quantum workflows without hardware modification. This architectural foundation establishes the feasibility of Quantum-as-a-Service for legacy IoT infrastructure.

Keywords: Classical-Quantum Bridge; Digit-Based Gate Mapping; Heterogeneous Networks; Protocol Translation; Quantum Gate Encoding; Quantum IoT Interoperability; Quantum Middleware; Software-Defined Integration.

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1. Introduction

The Internet of Things is projected to connect billions of heterogeneous devices, creating a massive ecosystem of classical devices that are increasingly constrained by security and computational limits [1,2]. However, as we approach the limits of classical silicon-based computing, quantum technologies have emerged as a necessary advancement for complex optimization and post-quantum security [3,4].

Despite this potential, the physical requirements for quantum hardware—such as a very isolated and cold environment—make direct integration at the IoT edge unfeasible [5]. Nevertheless, a fundamental interoperability challenge remains unresolved. Classical IoT systems generate binary telemetry streams, whereas quantum computing platforms operate using quantum state representations. The absence of a deterministic and lightweight translation mechanism between these two paradigms represents a critical barrier to the development of scalable hybrid classical-quantum infrastructures.

2. Literature Review

2.1. Architectural Analysis of Hybrid Quantum-IoT Networks

Contemporary studies delineate a four-layer Quantum IoT architecture encompassing Application, Quantum Teleportation, Quantum Network, and Physical Layer, wherein IoT devices relay data through a gateway to a centralized Quantum Server [5]. Nonetheless, this configuration introduces latency and scalability constraints, particularly for high-velocity data streams within resource-constrained settings [4]. The proposed software-defined middleware mitigates these issues through a lightweight Translator Core situated at the Application Layer, which transduces MQTT telemetry into quantum circuits employing Digit-Based Gate Mapping to facilitate edge-efficient, real-time interoperability without hardware modifications [5].

However, integrating diverse quantum cloud offerings with classical systems remains challenging [4]. While middleware like Qunicorn unifies quantum providers by abstracting device details [6], it overlooks classical-to-quantum data encoding—requiring quantum RAM and risking real-time IoT inefficiencies [7]. The Translator Core, leveraging lightweight Digit-Based Gate Mapping, directly maps MQTT streams to quantum circuits for superior, edge-efficient interoperability, explicitly enabling direct interoperability between legacy IoT devices and quantum services [8,9].

2.2. Technical Foundations: Quantum Encoding and Mapping

A fundamental challenge in the Quantum IoT paradigm is the representation of classical continuous or discrete data within the Hilbert space of a quantum system [7]. Quantum Machine Learning commonly employs methods such as Angle Encoding, where classical numerical values are embedded into quantum states using parameterized rotation gates [10]. This method, for instance, uses rotation gates like R_x to map data into qubit states [11], but it requires high-precision control of rotation angles [12].

Other approaches utilize complex multi-qubit entangled states for hierarchical communication control [13]. While robust, these methods introduce significant circuit depth and overhead [5]. This paper advocates for a

Digit-Based Gate Mapping (DBGM) method that decomposes multi-digit sensor values into individual gate triggers. This deterministic approach reduces circuit complexity, making it more suitable for the real-time translation of high-velocity IoT streams. However, a counterargument is that this discrete decomposition may introduce quantization errors for continuous sensor data (e.g., precise temperature or acceleration readings), limiting its fidelity compared to angle encoding's ability to preserve granular, real-valued information in qubit amplitudes [12,7,10]. Moreover, while reducing depth, it might underutilize quantum superposition for high-dimensional feature mapping, where entangled states provide greater expressivity despite overhead [5,13]. Nevertheless, the proposed method overcomes these limitations by leveraging the inherently discrete nature of IoT sensor outputs (e.g., digitized integers from ADCs), ensuring lossless fidelity for practical telemetry without precision calibration overhead [5]; furthermore, it actively harnesses superposition via Hadamard gates on specific digits (e.g., even-indexed or even-valued) and entanglement through CNOT between digit qubits, delivering essential quantum expressivity in a shallow circuit tailored for edge-constrained, high-velocity streams [13].

2.3. Economic Drivers and the Quantum Sensing Market

The transition to an "Internet of Quantum Things" is fueled by the immense economic potential of precision sensing [11], with the quantum sensing market projected to reach approximately USD 1.9 billion by 2029 [11]; quantum-enabled sensors offer sensitivity beyond the Standard Quantum Limit, revolutionizing fields like medical imaging and seismic monitoring [11].

However, the high cost of quantum hardware remains a barrier to entry for many industrial sectors [4]. Even hybrid models that rely on remote quantum processing may introduce substantial latency and scalability risks for real-time, high-velocity IoT streams. These limitations can potentially offset the expected economic gains with operational inefficiencies [4,5]. Nevertheless, the proposed lightweight middleware—via its Translator Core and the DBGM method—overcomes these challenges by performing efficient, software-defined translation directly at the edge, decomposing sensor telemetry into shallow, deterministic quantum circuits. For example, the system applies parity-triggered Hadamard or Pauli-X gates with minimal CNOT entanglement. This approach minimizes circuit depth, reduces overhead, and lowers remote processing latency without requiring hardware upgrades [8,5]. A platform with application programming interfaces allows manufacturers to adopt a "Quantum-Hybrid" model [10]. By using remote quantum processing for analytics while maintaining classical edge hardware, organizations can maximize the value of their existing IoT infrastructure and prepare for the full-scale quantum transition [5].

2.4. Comparative Analysis of Methodologies

To systematically position the proposed Digit-Based Gate Mapping (DBGM) middleware framework within the existing body of research, a comparative analysis was conducted against representative quantum–classical integration approaches reported in the literature. The comparison focuses on key evaluation criteria, including interoperability capability, hardware dependency, protocol compatibility, scalability potential, and implementation flexibility. The following table summarizes the relative strengths and distinguishing characteristics of the proposed framework in comparison with existing methodologies.

Table 1: Comparative Analysis of Quantum–Classical Integration Methodologies

Methodology	Primary Focus	Hardware Requirement	Complexity	Interoperability Support	Protocol Compatibility
Routing and Teleportation [14]	Network Layer	High: Requires quantum fiber/repeaters	High	Low: Limited to dedicated quantum infrastructure	Quantum protocols (e.g., BB84)
Entangled State Control [13]	Security	High: Specialized quantum nodes	High	Low: Restricted to specialized quantum-enabled nodes	Proprietary quantum-state signaling
Q-Inspired Optimization[4]	Optimization	Medium: Quantum-capable sensors	Medium	High: Compatible with existing classical ecosystems	Standard (HTTP, MQTT, TCP/IP)
QML Angle Encoding[11]	Quantum Data Encoding	Low: Software-defined	Medium	Moderate: Requires specific QML library integration	Software-based quantum libraries (e.g., Qiskit)
Unification Middleware [6]	API Access	Low: Software-defined	Low	High: Supports heterogeneous cloud offerings	Multi-cloud APIs
Proposed DBGM Middleware Framework (This Work)	Interoperability	Low: Software-defined	Low	High: Enables translation between classical telemetry and quantum circuit instructions	MQTT-based (Extensible to CoAP and HTTP/REST)

As demonstrated in Table 1, the proposed DBGM middleware framework achieves a balance between low hardware dependency and high interoperability capability. In contrast to hardware-intensive quantum communication models, the DBGM approach operates as a software-defined middleware layer, enabling flexible integration with existing classical IoT infrastructures while maintaining low computational complexity.

3. Methodology: The Proposed Architectural Framework

To bridge the paradigm gap between classical IoT and quantum computing, we propose a modular, software-defined middleware architecture. This framework is designed to operate at the application layer, acting as an interoperability bridge between classical IoT services and quantum application interfaces. We term this the "Translator Core". The Translator Core is defined as a software-defined processing unit responsible for decoding classical telemetry and generating corresponding quantum circuit instructions using the DBGM method.

3.1. System Overview and Layered Integration

The proposed architecture follows a four-layer model adapted for quantum interoperability. It comprises four primary components:

- Data Source: Classical sensors (e.g., temperature) generate telemetry encoded in standard formats (JSON) and transmit it via MQTT [15].
- Message Broker: A lightweight message broker handles the routing of classical data packets, ensuring reliable delivery to the translation engine [16].
- Translator Core: This is the central component of the framework. It subscribes to classical topics, decodes the telemetry, and applies the Digit-Based Gate Mapping (DBGM) method to generate a Qiskit QuantumCircuit object.
- Quantum Simulation & Visualization: The Qiskit AerSimulator executes the generated circuit [13].

3.2. The Digit-Based Gate Mapping (DBGM) Algorithm

Unlike complex rotation-based encoding (e.g., Angle Encoding), our proposed logic uses the discrete properties of classical digits to trigger specific quantum gates. The mapping follows a three-step deterministic process:

- Step 1: Decomposition: The incoming classical integer (e.g., 25) is decomposed into its constituent digits (D_1 and D_2).
- Step 2: Conditional Gate Assignment: Specific gates are assigned based on the digit's parity or value range. For example, an even digit triggers a Hadamard (H) gate to create superposition, while an odd digit triggers a Pauli-X gate.
- Step 3: Register Entanglement: To ensure a unified quantum state, a Controlled-NOT gate is applied between the qubits representing D_1 and D_2, creating an entangled representation of the sensor reading.

3.3. Interoperability Logic

Using a software-defined "Translator Core," the framework remains protocol-agnostic. While this study focuses on MQTT due to its dominance in the IoT sector [17], the middleware can be extended to CoAP or HTTP/REST through simple API gateway adaptations [18]. This ensures that any classical device capable of basic network communication can be "upgraded" to participate in quantum workflows without physical hardware replacement.

4. Results and Discussion

4.1. Verification of Digit-Based Mapping Method

The primary objective of the logical verification was to ensure that the Digit-Based Gate Mapping algorithm could deterministically translate classical telemetry into quantum circuit objects. Using the AerSimulator (statevector-simulator) within the Qiskit Aer framework, the system successfully executed the mapping of discrete integer values—such as sensor IDs and temperature readings—to specific quantum gate sequences [13]. The results indicate that the middleware maintains logical consistency during the translation phase, accurately representing the classical "intention" of the IoT device in the quantum register [13].

Unlike continuous encoding methods like Angle Encoding [10,12], which require high-precision control of rotation angles and are susceptible to signal fluctuations, this digit-based approach provides a more robust, discrete trigger system [10,12]. This robustness is essential for industrial IoT applications where sensor data may be noisy but requires deterministic processing for operational reliability [12].

4.2. Middleware Interoperability and Dashboarding

The interoperability layer was evaluated by ingesting JSON-formatted MQTT payloads, a format suited for efficient object description and parsing in heterogeneous environments [15]. The middleware successfully extracted key telemetry fields and routed them through the translation core, acting as a "Quantum Broker" that abstracts backend complexity from the edge [16].

This integration demonstrates that resource-constrained devices—specifically Class 0 and Class 1 devices with limited memory—can participate in a hybrid network by offloading state preparation to the cloud-based middleware [1,2]. Real-time monitoring via a dashboard tracked translation latency, suggesting that the primary performance bottleneck is the network round-trip time to the quantum cloud provider rather than the translation logic itself [4].

4.3. Discussion: Moving Toward Quantum-as-a-Service

The transition to a QaaS model through this framework offers a solution to the "connectivity tax" inherent in pure quantum networks. Research indicates that in a fully entangled network of only 10 nodes, each node would require at least 19 qubits to maintain ubiquitous communication [5]. For modern IoT sensors, this is physically and economically unfeasible.

Our results suggest that by centralizing the translation logic in a cloud-based environment, we mitigate the following challenges identified in previous studies:

- Environmental Sensitivity: Qubits are highly susceptible to fluctuations in temperature and pressure Reference [5]. Relocating this processing to the cloud ensures that sensitive state preparation occurs in a controlled environment rather than at the unstable IoT edge.
- No-Cloning Constraints: Unlike classical packets, quantum states cannot be copied or amplified [4].

Our middleware manages this by using quantum-inspired optimization to route data efficiently without violating the fundamental laws of quantum mechanics [4].

- Computational Offloading: The framework enables "Quantum-Edge Cloud Computing," which significantly reduces processing latency and enhances the ability to run complex algorithms, such as Grover’s or Shor’s, on aggregated IoT data streams [4,19].

4.4. Performance and Scalability Analysis

A critical finding of this research is the contrast between networking overhead and data representation. In a purely quantum network, connecting 10 nodes would require each device to hold approximately 19 qubits just to maintain full entanglement with the other devices [5]. The proposed framework bypasses this "connectivity tax" by using classical communication for the network layer and shifting state preparation to the application-layer middleware [5,20].

This architectural choice allows for higher node density on current Noisy Intermediate-Scale Quantum processors. However, the system remains limited by the hardware scalability of the central Quantum Processing Unit. While the networking scaling problem is mitigated at the edge, the total capacity is still subject to the central processor's qubit limits and gate fidelity [4,5].

5. Constraints and Limitations

Despite the conceptual advantages of the proposed DBGM framework, several technical and physical limitations remain.

5.1. Hardware Decoherence and Noise

A major constraint is the transition from logical simulation to physical hardware. Quantum states are fragile and highly sensitive to environmental noise, including fluctuations in temperature and pressure [5,7]. Furthermore, the coherence time for qubits on current hardware is limited to approximately 2 seconds, which poses a significant challenge for maintaining quantum states during extended communication or deep circuit executions Reference [5].

5.2. Circuit Depth and Qubit Capacity

Although the middleware avoids the 19-qubit-per-node entanglement requirement, it is still constrained by the total qubit count of available processors, which currently range from 50 to 433 qubits in commercially available systems [5,20]. If a single telemetry packet requires 19 or more qubits for a high-fidelity representation, the central QPU can only handle a very limited number of concurrent streams [5]. Moreover, as telemetry complexity grows, the resulting circuit depth increases the probability of gate errors in the absence of advanced quantum error correction [4,7].

5.3. Data Precision vs. Robustness

The Digit-Based Gate Mapping is a discrete approximation. While it offers more robustness against gate errors than continuous rotation-gate mapping (R_x rotations), it cannot provide the high-resolution representation required for high-precision scientific telemetry [10,11]. Encoding high-fidelity classical data into the limited Hilbert space of a quantum system remains a fundamental research hurdle in quantum information theory [7].

5.4. Physical Layer and Latency

The framework operates primarily at the application layer and does not solve the physical limitations of the "Quantum Teleportation Layer." Long-distance scaling will eventually require quantum repeaters to maintain entanglement across distances and overcome signal attenuation [21,20]; finally, the latency introduced by converting JSON payloads into quantum objects and queueing them for a cloud-based QPU may exceed the real-time requirements of certain industrial safety systems [4,5].

6. Conclusion

This study has presented a novel architectural framework designed to bridge the paradigm gap between classical IoT telemetry and quantum computing. By introducing the Digit-Based Gate Mapping method, a deterministic pathway has been established for translating legacy binary data into quantum circuit objects without requiring local quantum hardware at the edge. The logical verification confirms that the middleware maintains translation fidelity, effectively enabling resource-constrained Class 0 and Class 1 devices to participate in the emerging Quantum-as-a-Service ecosystem [4,13].

The significance of this work lies in its ability to bypass the immediate hardware barriers of the quantum internet. By shifting the computational burden of state preparation from the physical edge to a cloud-based broker, it significantly reduces the prohibitive 19-qubit-per-node requirement for local entanglement [5,20]. While the framework remains subject to the inherent limitations of NISQ-era hardware, specifically regarding decoherence and QPU capacity, it provides a scalable, software-defined bridge that allows contemporary industrial infrastructure to interface with quantum analytics.

7. Recommendations

Based on the architectural analysis and the identified technical constraints, we propose the following recommendations:

- Standardization of Quantum Middleware APIs: To prevent vendor lock-in and fragmentation, international standards must be developed for quantum middleware protocols. Future development should focus on creating unified APIs that allow heterogeneous IoT devices to interface with diverse quantum cloud offerings through a single translation layer [6,10].
- Development of Hardware-Accelerated Gateways: To reduce the translation latency identified in the simulation phase, future hardware should incorporate specialized components dedicated to quantum

gate mapping. This would transition the logic from software middleware to a hardware-accelerated "Quantum-Ready Gateway" [4,5].

- Investment in Quantum Repeater Infrastructure: For large-scale industrial deployment beyond local cloud-broker models, the development of quantum repeaters is essential [5]. These devices are necessary to maintain entanglement over long distances, forming the physical foundation for a global Quantum Internet [7,21].
- Exploration of Hybrid Quantum-Classical Machine Learning: Future research should focus on using the translated data for Quantum Neural Networks or Support Vector Machines. Leveraging the high-dimensional Hilbert space for IoT anomaly detection could provide significant computational advantages over classical models in complex industrial environments [5,10].

These recommendations outline potential directions for transforming the conceptual DBGM framework into scalable real-world quantum–classical integration platforms.

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