

Topological Q-JSON Protocol (TQP): A Hybrid Architecture for Deterministic Quantum Data Transfer

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Abstract

The transition from classical networking to a secure Quantum Internet is currently bottlenecked by the exponential degradation of fragile quantum states when transmitted over long physical distances. Traditional models rely on quantum teleportation and physical entanglement swapping, which are highly susceptible to channel noise and require massive hardware redundancy. The Topological Q-JSON Protocol (TQP) proposes a novel, hybrid network architecture that bypasses the need to physically transmit complex quantum states through noisy fiber-optic channels. TQP utilizes a bifurcated model: it establishes an unconditionally secure classical channel using Differential Phase Shift Quantum Key Distribution (DPS-QKD), and transmits a classical, machine-readable “topological recipe” formatted as a JSON payload. The receiving node uses this payload to locally reconstruct a deterministic, hype rentangled cluster state within a gauge-invariant subspace. This architecture bridges the gap between high-level software engineering and low-level physical quantum hardware.

Keywords: Quantum Networking, QKD, Stabilizer Formal-ism, JSON API, Effective Field Theory, Colored Multi graph.

1. Introduction

The realization of a scalable Quantum Internet promises unprecedented advancements in unconditionally secure communication, distributed quantum computing, and high-precision metrology [1]. However, the transition from theoretical models to viable physical infrastructure is currently bottlenecked by a fundamental physical limitation: the exponential degradation of fragile quantum states (quits or quits) when transmitted over long-distance optical fibers. Unlike classical signals, which can be easily amplified to combat channel loss, quantum states are strictly governed by the No-Cloning Theorem. An unknown quantum state cannot be copied or deterministically amplified without collapsing its superposition or destroying its entanglement. Consequently, long-distance transmission suffers from exponential photon loss and severe environmental decoherence. While traditional quantum repeater architectures attempt to solve this via probabilistic entanglement swapping and quantum teleportation, these methods require massive physical hardware redundancy, highly coherent quantum memories, and are highly susceptible to cumulative channel noise.

To circumvent the physical hostility of long-distance quantum state transmission, this paper proposes novel hybrid architecture: the Topological Q-JSON Protocol (TQP). TQP introduces a paradigm shift in quantum network routing by abandoning the physical transmission of the operational quantum state itself. Instead, TQP bifurcates the network into two distinct operational

layers: an unconditionally secure classical transport channel, and a deterministic local quantum hardware layer [2]. Rather than forcing a fragile multiparticle state through hundreds of kilometers of noisy fiber, the source node compiles the target entanglement topology into a classical, machine-readable format—the Q-JSON payload. This topological recipe is transmitted over a secure quantum key distribution (QKD) channel. Upon receipt, the target node utilizes this payload to deterministically reconstruct a hyper entangled cluster state within a protected, local gauge-invariant subspace.

2. The Classical Transport Layer: DPS-QKD

To guarantee the privacy of the topological recipe (the Q-JSON payload), TQP utilizes the Differential Phase Shift Quantum Key Distribution (DPS-QKD) protocol [4]. The security of this transport layer is grounded in the foundational postulates of quantum mechanics [3]. In DPS-QKD, information is encoded in the relative phase between sequential coherent pulses.

It is critical to note that the DPS-QKD quantum channel does not transmit the Q-JSON payload itself. Rather, it generates an unconditionally secure symmetric key via quantum phase transmission. Any interception by an eavesdropper collapses the state and spikes the Quantum Bit Error Rate (QBER) [5], aborting the protocol. Once the secure key is established, it is used to encrypt the classical Q-JSON payload via a One-Time Pad for transmission over a standard classical TCP/IP network, ensuring that physical channel interception yields no topological data.

To ensure the viability of the TQP architecture over existing infrastructure, the physical limits of the fiber-optic channel must be addressed [6]. Following empirical results demonstrating DPS-QKD viability over standard telecom-grade fiber, this protocol relies on baseline error optimization [7]. The total Quantum Bit Error Rate (QBER), denoted as E_{total} , is modeled as:

$$E_{total} = \frac{p_{dark} + p_{opt}(L)}{p_{signal}(L) + p_{dark}}$$

Where p_{dark} is the probability of a dark count in the superconducting nanowire single-photon detectors (SNSPDs), $p_{opt}(L)$ represents the optical errors accumulated over distance L , and $p_{signal}(L)$ is the probability of a successful photon detection event [8].

We apply the Shannon-Schumacher entropy bounds [10] to define the asymptotic secure key rate (R_{secure}). Using the Binary Entropy Function, $H_2(E) = -E \log_2(E) - (1 - E) \log_2(1 - E)$ the key generation rate is [9]:

$$R_{secure} \geq R_{sift} [1 - f(E)H_2(E) - H_2(E_{ph})]$$

Where R_{sift} is the raw sifted key rate, $f(E) \geq 1$ is the inefficiency function of the classical error correction algorithm, and $H_2(E_{ph})$ bounds the maximum information leaked via phase errors. For the TQP architecture to successfully route a target graph state, the total size of the compiled Q-JSON file must satisfy $S_{JSON} \leq \int \Delta t R_{secure}(t) dt$.

3. The Data Layer: Q-JSON and Hyper entangled Hilbert Space

Rather than using simple 2-level quits, TQP increases information density by utilizing higher-dimensional quits ($d > 2$) [11]. By encoding information across multiple physical degrees of freedom (such as spin, path, time-bin, and orbital angular momentum), the localized quantum hardware generates a composite multidimensional Hilbert space $H^{(i)}$ capable of bypassing standard bipartite entanglement monogamy limits [12, 13].

A core innovation of TQP is how classical binary data is translated into the quantum domain [14]. Rather than encoding data into the local amplitude of a single quit, TQP encodes data directly into the entanglement geometry of the degrees of freedom, conceptually mirroring chemical molecular bonds. The network of N qudits forms a Colored Multigraph. The “color” of an edge represents the specific Degree of Freedom used to entangle two nodes. If the architecture utilizes k distinct Degrees of Freedom, each pair of qudits possesses k addressable entanglement “slots,” representing k bits of classical data. For a cluster state of N nodes, the total binary capacity encoded strictly within the topological structure is:

$$C_{bits} = k \frac{N(N-1)}{2}$$

Consequently, a classical binary sequence is algorithmically mapped to a unique multidimensional graph state. As N increases, the information capacity scales quadratically, allowing massive datasets to be compressed into the geometric arrangement of a highly dense, local cluster [15].

To standardize the translation of these multidimensional topologies into classical routing data, the protocol defines the Q-JSON schema. This payload dictates the exact instructions required for Node B to compile the target cluster state.

Listing 1. Topological Q-JSON Payload Schema

```
{
  "q_json_version": "1.0",
  "payload_id": "TQP-784-OMEGA",
  "network metadata": {
    "source": "Novena",
    "target": "Node",
    "protocol": "DPS-QKD"
  },
  "Hilbert_Space_Definition": {
    "quits": [
      {"id": "q0", "dimensions": 4, "doff": ["spin", "oak"]},
      {"id": "q1", "dimensions": 2, "doff": ["path"]}
    ]
  },
  "Adjacency Matrix": {
    "edges": [
      {"source": "q0", "target": "q1", "gate": "CZ_d4"}
    ]
  },
  "Gauge Constraints": {
    "stabilizers": [
      {"node": "q0", "operator": "X_0 * Z_1"}
    ]
  }
}
```

3.1 Fundamental Concepts of the Quantum Data Layer

The quantum data layer provides a way to represent, organize, and manage information used in quantum computing systems. Unlike classical computers, which store information as bits with values of 0 or 1, quantum computers use qubits that can exist in a combination of quantum states. The data layer must therefore consider not only the information itself but also the properties of quantum states, such as superposition and entanglement. A well-designed quantum data layer can help connect quantum information with software applications, simulation tools, and classical data-processing systems.

3.2 Q-JSON: Structure, Representation, and Encoding of Quantum Data

Q-JSON can be introduced as a proposed JSON-based format for describing quantum information in a structured and readable form. JSON is widely used in software applications because its data can be organized into objects, arrays, and key-value pairs. A quantum-oriented extension could use a similar structure to record details such as qubit identifiers, quantum circuit operations, state descriptions, measurement results, and entanglement relationships.

For example, a Q-JSON record might contain the number of qubits in a circuit, the sequence of quantum gates, and the required measurement settings. This could make quantum information easier to exchange between compatible applications. However, the format would need clearly defined rules for data types, state representation, validation, and interoperability. Q-JSON should be described as a proposed format unless its use as an established standard can be supported by a reliable source

3.3 Mathematical Representation of Hyper entangled Hilbert Space

A Hilbert space is a mathematical space used to describe the possible states of a quantum system. Each qubit is represented by a two-dimensional complex Hilbert space. When multiple qubits are combined, the overall state space is formed using the tensor product of their individual spaces [16].

3.4 Quantum State Encoding and Multidimensional Entanglement

Quantum state encoding describes how information is represented in the states of a quantum system. In a basic quantum computer, information can be encoded in the states of individual qubits or in the joint state of several qubits. In systems that support hyper entanglement, multiple physical properties may be used together to represent a more complex quantum state.

For example, a photon may carry information through its polarization while also using its spatial mode as another degree of freedom. When these properties are entangled with corresponding properties of another photon, the resulting system can support more complex correlations. Such encoding may be useful in quantum communication and quantum information experiments. Its practical benefits depend on the physical implementation, measurement techniques, noise levels, and available control methods.

3.5 Data Integrity, Scalability, and Challenges in Quantum Information Representation

Representing quantum information in a structured data format introduces several technical challenges. Quantum states may require complex-valued amplitudes, and their descriptions can become large as the number of qubits increases. Entangled states are especially difficult to represent efficiently because the state of the complete system may not be described independently by assigning a separate state to each qubit. Another challenge is maintaining the distinction between a

mathematical description of a quantum state and the information that can actually be measured. A data format can store circuit instructions, state parameters, or experimental measurement results, but storing a description does not itself create or preserve the corresponding physical quantum state.

A practical quantum data format should therefore define clear validation rules, consistent conventions, and suitable methods for representing uncertainty and measurement outcomes. It should also support interoperability between classical software and quantum-computing platforms. Addressing these issues would make the data layer more useful for quantum simulations, communication systems, and research applications.

4. Microscopic Physical Layer: The Stabilizer Hamiltonian

In the TQP architecture, the local cluster state $|G\rangle$ at Node B is deterministically constrained by the Q-JSON payload [17]. The graph state $|G\rangle$ is uniquely defined as the simultaneous $+1$ eigenstate of a set of commuting stabilizer operators S_i .

To physically compile this state without direct measurement of the data qubits, we define a Stabilizer Hamiltonian:

$$H_{NodeB} = -\Delta \sum_{i \in V} S_i$$

Where Δ is the energy gap protecting the ground state? Because $S_i |G\rangle = +1 |G\rangle$ for all i , the state $|G\rangle$ resides exactly in the gauge-invariant subspace (the non-degenerate ground state) of this Hamiltonian. Node B's hardware is tasked with driving the local qubits into this invariant subspace.

A critical vulnerability in standard quantum networking is measurement-induced decoherence. If Node B directly measures the data qubits to verify the topology, the operational quantum state collapses. To circumvent this, TQP utilizes Quantum Non-Demolition (QND) parity measurements [18]. Node B introduces initialized ancilla qubits $(0)_A$. The measurement protocol proceeds via a sequence of unitary operations for each stabilizer S_i , utilizing a generalized Controlled-Unitary operation:

$$CU = |0\rangle_A \langle 0|_A \otimes I + |1\rangle_A \langle 1|_A \otimes S_i$$

By measuring only the ancilla on the computational basis following a Hadamard interference sequence, Node B extracts the topological structure (the graph parity) while remaining completely decoupled from the encoded operational quantum information.

Within standard Quantum Field Theory (QFT), these stabilizer conditions function as local gauge constraints. Environmental noise interacting with Node B's hardware acts as a perturbation E_k . If an error occurs that anti-commutes with a stabilizer ($\{E_k, S_i\} = 0$), it violently kicks the state out of the $+1$ eigenspace:

$$S_i(E_k |G\rangle) = -E_k S_i |G\rangle = -(E_k |G\rangle)$$

Because Node B continuously executes Ancilla-Mediated Parity Extraction, these local gauge violations manifest instantly as -1 parity readings. The protocol then applies feed-forward Pauli corrections to push the system back into the gauge-invariant ground state, effectively mitigating the local decoherence rate (Γ_{tot}) derived via the Optical Theorem [21].

4.1 Fundamental Principles of Stabilizer Hamiltonians

A stabilizer Hamiltonian is a mathematical model used to describe the energy and behaviour of a quantum system. It helps researchers understand how quantum states can be maintained and how various parts of a quantum system interact with one another. In quantum computing, stabilizers are particularly useful because they help identify whether a quantum state satisfies specific conditions

required for reliable computation. These conditions also play a key role in protecting quantum information against certain types of errors.

4.2 Mathematical Formulation of the Stabilizer Hamiltonian

The stabilizer Hamiltonian can be expressed mathematically as a combination of stabilizer operators. Each operator represents a condition that the quantum system is expected to satisfy. The negative sign is commonly used when the desired states correspond to the lowest energy. This formulation provides a useful starting point for studying quantum states and their stability.

4.3 Pauli Operators and Stabilizer Generators

Pauli operators are basic mathematical tools used to describe operations on qubits. The three main Pauli operators are (X), (Y), and (Z). The (X) operator changes the computational basis state of a qubit, the (Z) operator changes its phase, and the (Y) operator combines aspects of both operations. Stabilizer generators are constructed using these operators, sometimes acting on several qubits at the same time. They define the conditions that a valid quantum state must satisfy. By measuring or evaluating these conditions, researchers can detect certain errors without directly measuring all the information stored in the quantum state.

4.4 Ground States, Energy Spectrum, and System Stability

The ground state is the lowest-energy state of a quantum system. In a stabilizer-based system, the ground state is often designed to satisfy all the required stabilizer conditions. The energy spectrum describes the different energy levels available to the system.

Studying these energy levels helps researchers understand how the system responds to disturbances. For example, an energy gap between the ground state and excited states can be important when analysing stability. However, an energy gap alone does not guarantee protection against every type of noise or information loss. The actual level of protection depends on the system design and its physical environment [19].

4.5 Quantum Noise, Decoherence, and Error Correction

Quantum systems are sensitive to disturbances from their surroundings. These disturbances may change a qubit's state or destroy the quantum coherence needed for computation. This process is known as decoherence. Other errors may occur because of imperfect operations or inaccurate measurements.

Stabilizer-based quantum error correction helps detect certain errors by checking whether the system continues to satisfy its stabilizer conditions. A change in a stabilizer measurement can indicate that an error has occurred. A suitable error-correction procedure can then use this information to identify and correct the error while preserving the encoded quantum information. This approach is an important foundation for developing more reliable quantum computing systems [20].

5. Conclusion and Scalability

The Topological Q-JSON Protocol offers a fundamentally more resource-efficient path to the Quantum Internet. Table 1 summarizes the structural advantages of TQP compared to traditional architecture. By utilizing DPS-QKD for the long-haul transport layer, the network sidesteps the need for probabilistic entanglement swapping across multiple intermediate nodes.

Table 1: Comparison of Quantum Network Architectures

Feature	Traditional Repeaters	TQP (Proposed)
Transmission	Fragile Quantum State	Classical Q-JSON
Protocol	Entanglement Swapping	DPS-QKD + TCP/IP
Redundancy	High (multi-node)	Low (Node-localized)
Data Density	Qubit-limited (N)	Multigraph (C_{bits})
Noise Defense	Continuous QEC	Gauge-invariant subspace

While the generation of massive cluster states is experimentally demanding, the TQP architecture is grounded in verified hyper entanglement paradigms. Current state-of-the-art photonic experiments have successfully demonstrated 18-qubit entanglement utilizing only 6 photons across three Degrees of Freedom (polarization, spatial mode, and orbital angular momentum). Because TQP relies on a composite multidimensional Hilbert space $H^{(t)}$ bounded by the Stabilizer Hamiltonian, the generation of a 30-qubit target topology does not require 30 distinct physical particles. It merely requires the deterministic scaling of DoF entanglement on a smaller photonic cluster, making TQP highly feasible for near-term Noisy Intermediate-Scale Quantum (NISQ) optical hardware.

Beyond physical advantages, TQP provides a critical bridge between quantum hardware and classical software engineering. The standardization of multidimensional topology into the Q-JSON format allows quantum network operations to be seamlessly integrated into modern, full-stack web infrastructure. By abstracting the heavy lifting of quantum field theory and local gauge constraints into a standardized JSON API, TQP provides a highly scalable, mathematically rigorous blueprint for routing data across the future Quantum Internet using existing telecom grids.

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All of the authors Contribute equally in all phase.

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Conflicts of Interest

The authors declare no conflicts of interest.

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