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Efficient Quantum Text Transfer Using Teleportation and Entropy-based Compression

Basma AL Kharusi[1] and Hafiz M. Asif[1*]

[1]Department of Electrical and Computer Engineering
Sultan Qaboos University, Muscat, Oman
*Email: h.asif@squ.edu.om

Abstract. In classical computing systems, the physical transfer of data (i.e., bits) is essential to transfer information from one place to another through a suitable channel (wired/wireless, etc.). Unlike classical systems, Quantum communication can take place between distant users without the physical transfer of the data, i.e., quantum bits or qubits. This paper presents how a classical compression protocol, when integrated with a quantum teleportation technique, can be utilized to transfer data between spatially distant users. The quantum text teleportation protocol (QTTP) aims to enable efficient and secure transfer of text-based data over quantum channels. Simulation programs have been carried out to gauge the performance of the proposed system under different conditions and noise levels. The simulation results indicate successful teleportation between distant users. Furthermore, the performance is enhanced when QTTP was used with Huffman coding. It has been demonstrated that the protocol is reliable especially in terms of reducing the error rate under 10% bit-flip noise from 10% to 1.11%.

1. INTRODUCTION

The integration of classical compression with quantum communication protocols offers a promising pathway to achieving both efficiency and security in data transmission. A foundational concept in this area is the hybrid Quantum Text Teleportation Protocol (QTTP), which combines the principles of quantum teleportation with a compression algorithm like Huffman coding [1]. The theoretical underpinnings of this approach rely on two landmark achievements: the ability to teleport an unknown quantum state using shared entanglement and a classical channel [2], and the development of a method for creating minimum-redundancy codes based on symbol frequency [3]. While the hybrid QTTP concept is powerful, its practical implementation requires a thorough analysis of its performance, especially in the presence of channel noise, a factor that is unavoidable in real-world systems.

Our research evaluates and extends this hybrid model by situating it within the broader landscape of secure quantum communication. Several alternative protocols have been developed, each with distinct features. For instance, Quantum Secure Direct Communication (QSDC) allows for information to be transmitted securely without requiring a pre-shared key, offering a different security framework [4]. Our work, in contrast, focuses on the teleportation-based model, which is fundamental for future distributed quantum computing networks where the transfer of quantum states, not just classical information, is required. Other hybrid protocols have been designed for different data types, such as a scheme that uses quantum chaos and teleportation to encrypt image data [5]. While effective for images, our protocol is specifically optimized for text by using Huffman coding, an entropy-based method that leverages the statistical properties of language to achieve a higher compression ratio for textual data. Furthermore, the practical feasibility of teleportation has been demonstrated over real-world metropolitan fiber networks, highlighting that noise and fidelity are the primary obstacles to deployment [6]. Our work directly addresses this challenge by quantitatively analyzing how compression reduces the protocol's vulnerability to bit-flip noise, a critical step that was not detailed in the original proposal [1].

The choice of Huffman coding is a key differentiator for our protocol's efficiency. While the original method [3] provides an optimal prefix-free code, its application in quantum protocols must be compared with other techniques. For example, more generalized quantum data compression protocols have been proposed, which aim to compress quantum states directly [7]. Our approach is distinct because it employs a classical, computationally simple compression algorithm on the data before it is encoded into qubits. This makes our method more accessible and less resource-intensive for the specific task of text transmission. The efficiency gained by this pre-compression is crucial for the scalability of the future "Quantum Internet," where minimizing qubit transmission is essential for reducing latency and error rates [8]. The development of noise-resilient and robust quantum protocols is an active area of research [9], and our work contributes by demonstrating a practical method to enhance robustness through classical means.

Therefore, a clear gap exists in the current literature. While the concept of a Huffman-coded QTTP has been introduced earlier [1], a detailed, quantitative performance evaluation under a realistic noise model is required to demonstrate the full strength of this combination of the protocols. Hence, this work fills that gap by presenting a comprehensive simulation and analysis. Our contribution is the rigorous demonstration that integrating Huffman coding not only reduces the qubit payload by up to 50% but also drastically decreases the transmission error rate from 10% to a mere 1.11% under a 10% bit-flip noise model. By providing this definitive evidence, our work confirms the protocol's real-world viability and provides a robust foundation for more scalable and reliable applications in future quantum networks [10], contributing to the broader vision for a global Quantum Internet [11].

The key objectives of the current work are to implement the quantum teleportation protocol for text transfer, to implement the quantum teleportation protocol with Huffman coding to improve efficiency, to test the protocol under different conditions and simulated noise and identify and investigate the implementation challenges.

2. BACKGROUND

This section outlines the two fundamental concepts that form the basis of our proposed system, i.e., quantum teleportation and Huffman coding.

2.1 Quantum Teleportation

Quantum teleportation is a process by which the exact state of a quantum system can be transmitted from a sender (Alice) to a spatially distant receiver (Bob). It does not transport matter or energy; rather, it transmits quantum information. The protocol requires three qubits: the source qubit at Alice's end whose state is to be teleported, and an entangled pair of qubits (a Bell pair), with one held by Alice and the other by Bob. Alice performs a Bell-state measurement on her source qubit and her half of the entangled pair. The result of this measurement is a set of two classical bits, which she sends to Bob over a classical communication channel. Based on the classical bits he receives, Bob applies a specific set of quantum gates to his half of the entangled pair, thereby reconstructing the original quantum state of Alice's source qubit. The foundational

1993 paper on this topic established the theoretical mechanism for perfectly teleporting an unknown quantum state using dual classical and Einstein-Podolsky-Rosen channels.

The quantum state to be teleported, $|\psi\rangle$, is a general single-qubit state represented as $|\psi\rangle=\alpha|0\rangle+\beta|1\rangle$, where $|\alpha|2+|\beta|2=1$. The process begins with Alice and Bob sharing an entangled Bell pair, typically the $|\phi+\rangle$ state, defined as $|\phi+\rangle=\frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$. Alice performs a joint Bell-state measurement on her qubit $|\psi\rangle$ and her half of the entangled pair. Depending on the four possible outcomes of her measurement (corresponding to the four Bell states), Bob applies one of four Pauli operations (I, X, Z, or ZX) to his qubit to retrieve the original state $|\psi\rangle$.

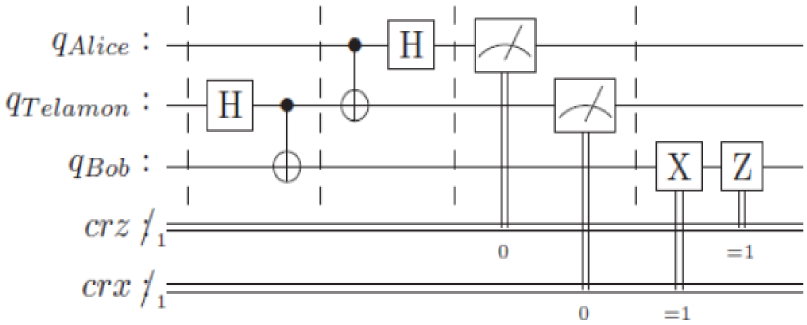

Figure 1. The quantum circuit for teleporting a single qubit state

Figure 1 shows the standard quantum circuit for teleporting a single qubit state from Alice to Bob. The circuit begins by creating a Bell state (an entangled pair) between one of Alice's ancillary qubits (q_Telamon) and Bob's qubit (q_Bob) using a Hadamard (H) gate and a CNOT gate. Alice then performs a Bell-state measurement on her input qubit (q_Alice) and her ancillary qubit. This is achieved with a CNOT gate followed by a Hadamard gate, with the results measured into two classical bits (crz and crx). These classical bits are sent to Bob, who applies conditional Pauli X and Z gates to his qubit to recover the original state.

2.2 Huffman Coding

Huffman coding is a leading entropy-based, lossless data compression technique [3]. It functions by examining the frequency of characters within a text; characters that appear more frequently receive shorter binary codes, while those that are less common are assigned longer codes. This creates a variable-length, prefix-free codebook, which ensures that no code for one character is the prefix of another character's code. This property allows for clear and unambiguous decoding at the receiver's end. By compressing text data with Huffman coding prior to encoding it into quantum states, we can greatly minimize the number of qubits that need to be transmitted. This reduction in data size directly improves transmission speed and lowers the overall error rate, as fewer qubits are exposed to noise in the quantum channel.

While Huffman coding is a classical algorithm, its integration with quantum protocols presents unique challenges. A primary difficulty lies in the variable length of the codes, which can complicate the quantum state encoding process. In a quantum system, the length of the encoded signal can become a quantum mechanical variable, leading to a superposition of different length eigenstates. Measuring this length would disturb the quantum state, so the sender and receiver must operate without this information. This is analogous to the synchronization problem in a quantum computer, where different computational paths may have varying lengths [12].

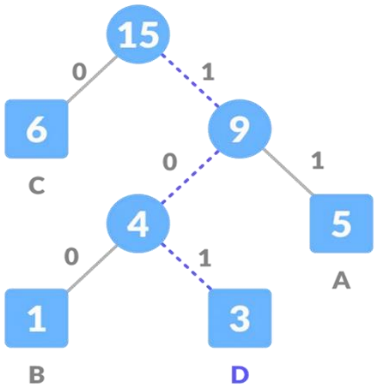

Figure 2. Example of Huffman coding

Figure 2 illustrates the Huffman coding algorithm for a sample text with character frequencies: C=6, A=5, D=3, and B=1. The algorithm constructs a binary tree by iteratively merging the two nodes with the lowest frequencies. For example, 'B' (frequency 1) and 'D' (frequency 3) are combined first to form a new node with a weight of 4. This process continues until all nodes are merged into a single root node (with a total frequency of 15). Binary codes are generated by traversing the tree from the root to each leaf, typically assigning '0' to a left branch and '1' to a right branch. This process yields the variable-length, prefix-free codes: C = '0', A = '11', D = '101', and B = '100'. Notably, the most frequent character 'C' receives the shortest code, while the least frequent character 'B' receives the longest code, which is the core principle behind the compression.

3. METHODOLOGY

For the current work, we designed and implemented a simulation setup in MATLAB to evaluate the performance of the Quantum Text Teleportation Protocol (QTTP). We chose a simulation environment known for its robust capabilities in modelling quantum operations, data encoding, and custom noise channels. Our methodology assessed the protocol's reliability under two distinct scenarios: a standard implementation without compression and an enhanced version using Huffman coding. For both scenarios, a bit-flip noise model was introduced to simulate realistic channel conditions.

We chose the bit-flip noise model for our simulations due to its simplicity and relevance in representing a common and fundamental type of error in quantum communication channels. In this model, a qubit has a certain probability of flipping its state (from $|0\rangle$ to $|1\rangle$ or vice versa), which is analogous to bit-flip errors in classical communication. While more complex noise models exist, the bit-flip channel provides a clear and understandable baseline for evaluating the impact of noise on our protocol and demonstrating the effectiveness of our proposed solution [12].

3.1 The standard Quantum Text Teleportation Protocol (QTTP)

The first scenario evaluated the baseline performance of the standard QTTP. This method transmits a quantum state from a sender (Alice) to a receiver (Bob) using a shared entangled pair. The process in our simulation was as follows:

First, the protocol converted each character of the input text into its corresponding 8-bit ASCII binary string. Next, we simulated the transfer of this uncompressed quantum state through a quantum circuit. To model a realistic channel, we subjected the transmission to a 10% bit-flip noise rate. Finally, upon reception, the protocol at the receiver's end (Bob) converted the state back into ASCII characters to reconstruct the original message, allowing us to measure the transmission fidelity.

3.2 QTTP with Huffman Coding

The second scenario integrated Huffman coding to improve transmission efficiency. In this enhanced method, the protocol first compresses the source text before teleportation. This creates a variable-length, prefix-free codebook, which significantly reduces the total number of qubits required for transmission and, in turn, the number of simulation iterations.

The compressed bitstring was then encoded into quantum states and transmitted through the identical quantum circuit and noise model as the standard protocol. For the receiver (Bob) to successfully decode the message, it is essential that he has access to the same Huffman codebook used by the sender (Alice) to encode the message [1].

The simulations were performed on a standard desktop computer. The runtime of the simulation is primarily dependent on the number of qubits being transmitted. For the uncompressed QTTP, the computational complexity is (n), where n is the number of bits in the message. For the QTTP with Huffman coding, the complexity is (m + k log k), where m is the number of bits in the compressed message and k is the number of unique characters, with the k log k term arising from the construction of the Huffman tree. Since m is generally much smaller than n, the overall runtime for the compressed protocol is significantly lower.

4. RESULTS AND DISCUSSION

This section presents the simulation results, first for the standard QTTP and then for the enhanced QTTP with Huffman coding, followed by a comparative analysis.

4.1 QTTP without Huffman Coding

The simulation of the standard Quantum Text Teleportation Protocols (QTTP) began by converting each character into a standard 8-bit binary string. The results showed a proportional relationship between the number of qubits (input text size) and the number of simulation iterations. Consequently, a larger input text resulted in a longer execution time. To simulate a realistic channel, we introduced a 10% bit-flip noise model. This noise slightly affected the transmitted data; for shorter texts, the impact was minimal. However, as the message size increased, the number of errors also increased. Fig. 4 illustrates the relationship between the simulation time and the number of qubits, showing that longer messages incur a higher time cost. Although the curve appears non-monotonic for very short messages due to simulation overhead, a comparison with the compressed protocol (Fig. 5) confirms that this standard method is less time efficient. Fig. 3 shows that under these conditions, the error probability was approximately 10% (0.1), resulting in a valid transmission probability of 90% (0.9). The primary drawback of the standard QTTP, therefore, is its inefficiency and vulnerability to noise, especially for longer messages that require more qubits.

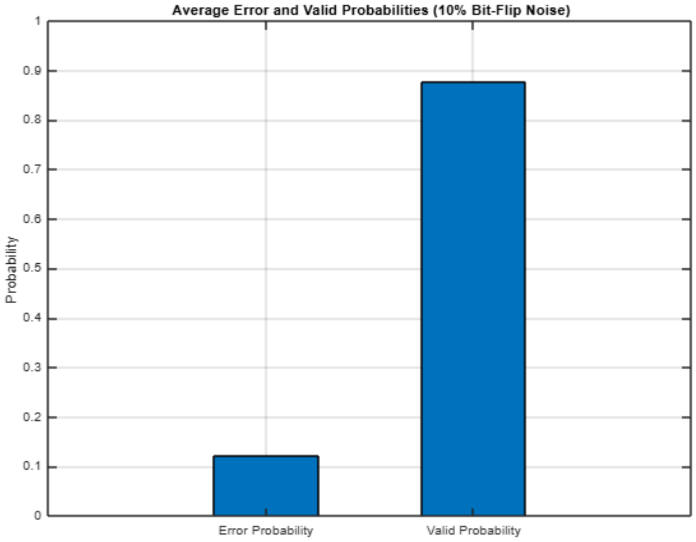

Figure 3. Analysis of the message length for uncompressed QTTP

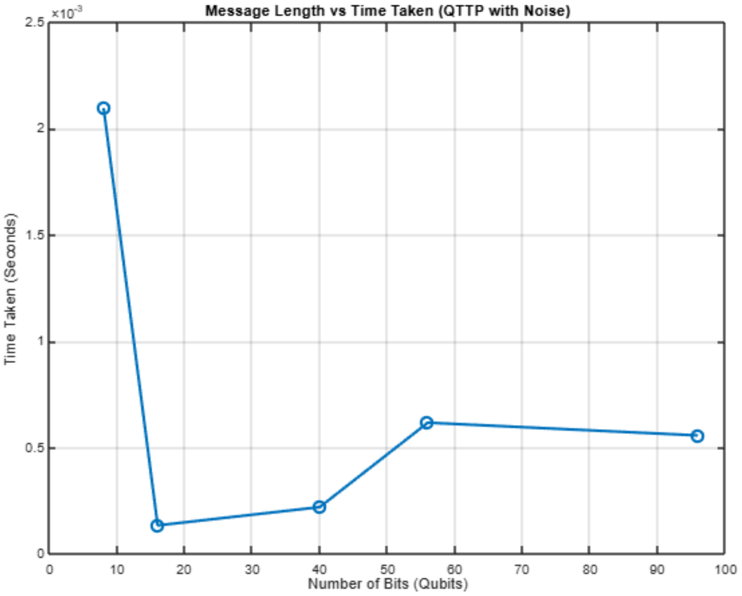

Figure 4. Transmission probabilities for uncompressed QTTP under a 10% bit-flip noise model

4.2 QTTP with Huffman Coding

Integrating Huffman coding significantly enhanced the efficiency of text message transmission. As a lossless compression algorithm, it assigns shorter to more frequent characters, reducing the total number of required qubits by up to 50%. This reduction in qubits leads directly to fewer teleportation iterations and shorter execution time, as shown by the results in Fig. 5. For example, our protocol achieved the following compression:

- “HELLO” was reduced to 10 bits.
- “QUANTUM” was reduced to 18 bits.
- “ENTANGLEMENT” was reduced to 32 bits

Consequently, the protocol's execution time was lower, even for longer messages. In addition, Figure 6 shows that the error rate remained low at approximately 1.11%, with a corresponding valid transmission probability of 98.89%. Overall, Huffman coding improved the protocol's efficiency and helped reduce the impact of noise. By transmitting fewer qubits through the noisy channel, it effectively mitigated the chances of bit-flip errors.

The significant reduction in the error rate from 10% to 1.11% can be directly attributed to the compression achieved by Huffman coding. With a 10% bit-flip probability per qubit, a message with more qubits has a higher overall probability of experiencing at least one error. By reducing the number of transmitted qubits, the protocol lowers the number of opportunities for errors to occur, thus decreasing the overall error rate for the entire message.

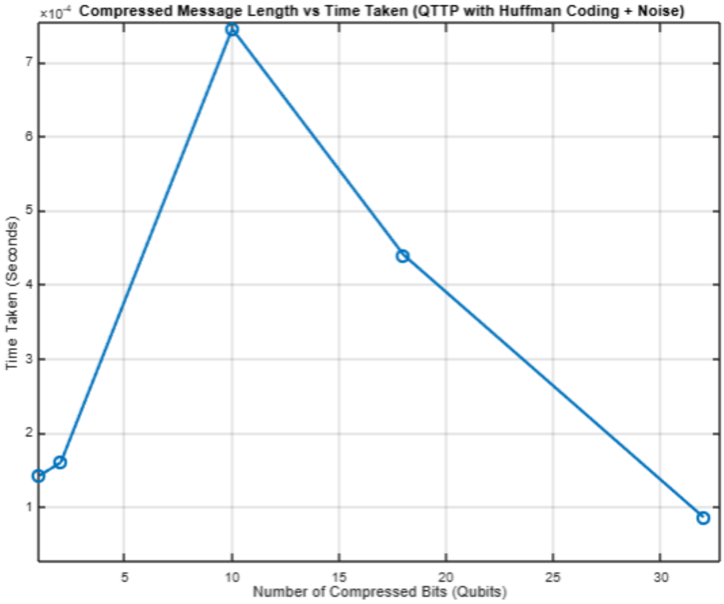

Figure 5. Analysis of the number of compressed bits for QTTP with Huffman coding

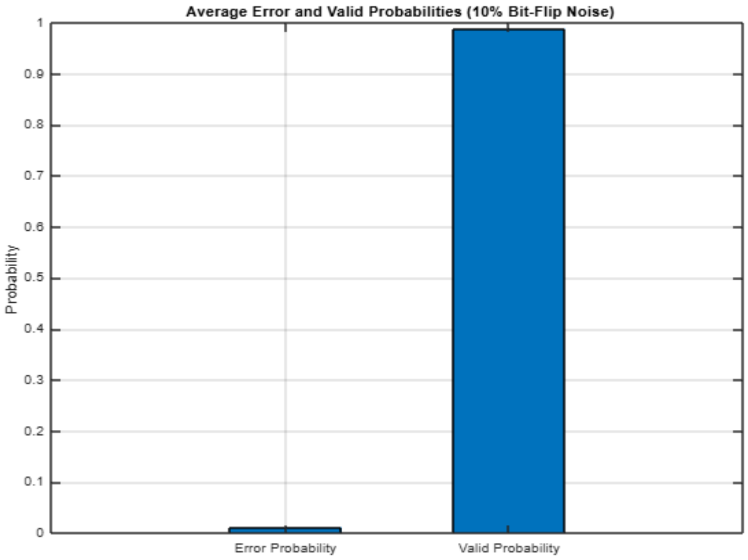

Figure 6. Transmission probabilities for QTTP with Huffman coding under a 10% bit-flip noise model

4.3 Comparative analysis

Table 1. Comparative analysis of QTTP with and without HUFFMAN coding under a 10% bit-flip noise model

Protocol	**Avg. Qubit**	**Avg. Time**	**Avg. Error Rate**	**Fidelity**	**Resource Overhead**
QTTP without Huffman	High	Higher	10%	90%	Higher
QTTP with Huffman	Lower	Faster	1.11%	99%	Lower

[a] Table footnote.

As summarized in Table 1, the comparative results clearly favor the Huffman-enhanced protocol. The standard QTTP required a high number of qubits and more time, resulting in a 10% error rate. In contrast, the QTTP with Huffman coding used fewer qubits, was faster, and achieved a significantly lower error rate of 1.11%.

To further contextualize our results, we compare our protocol with other quantum communication schemes. For instance, some direct communication protocols might offer higher transmission rates for uncompressed data but are more susceptible to noise. Quantum data compression protocols that operate directly on quantum states can be more efficient in terms of qubit usage but are also more complex to implement [7]. Our hybrid approach offers a balance between efficiency, ease of implementation, and robustness against noise, making it a practical solution for near-term quantum communication applications.

Conclusion

This study has addressed the dual issues of security and efficiency that currently impede the practical use of quantum communication protocols. By focusing on a significant gap in the existing literature, specifically the absence of quantitative performance evaluations for hybrid protocols in realistic noise conditions, we have presented clear, empirical evidence supporting our proposed solution. Our simulations, which operated under a 10% bit-flip noise model, revealed that the combination of Huffman coding with a Quantum Text Teleportation Protocol (QTTP) led to a reduction in average message size by as much as 50%. This integration significantly lowered the transmission error rate, decreasing it from 10% in the standard protocol to just 1.11%.

However, we would like to highlight that the availability of quantum hardware is currently limited by the number of qubits, often restricted to small-scale systems (e.g.,5-qubits). Additionally, the noise observed in testing highlights challenges for practical implementation. Moreover, the dependence on classical channels to exchange the Huffman prefix Code led to potential vulnerabilities. Furthermore, the absence of quantum error correction techniques can affect the protocol's reliability in adverse conditions.

The results of this study have direct implications for the implementation of quantum communication protocols on real-world quantum devices. The demonstrated reduction in qubit requirements and error rates through classical compression can help mitigate the effects of decoherence and gate errors, which are significant challenges in current quantum hardware. By reducing the number of quantum operations needed, our protocol can be more readily implemented on noisy intermediate-scale quantum (NISQ) devices, bringing practical quantum communication a step closer to reality.

In future works, the security of the classical channel used for exchanging Huffman codes could be strengthened by incorporating a Quantum Key Distribution (QKD) protocol. This integration would establish a fully quantum-secured communication system.

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