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Quantum Text Teleportation Protocol for Secure Text Transfer by using Quantum Teleportation and Huffman Coding

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***Abstract*—In this work, the authors present Quantum Text Teleportation Protocol (QTTP) that uses Quantum Teleportation (QT) technique and Huffman Coding for secure text transfers. The QTTP enables the teleportation of quantum states of text (for example, email) in a secure manner, while simultaneously encrypting and decrypting them using Huffman Coding since data can only be retrieved or decoded if the prefix codes are known. The Huffman Coding approach offers the benefit of compressing the entire text, resulting in faster transmission of large amounts of information. For proof of concept, the authors experimentally evaluated both of the proposed QTTPs (Standard QTTP and QTTP with Huffman Coding) using Quantum Information Science Kit (Qiskit), a quantum computing platform and simulated on IBM QASM Simulator and on IBM real quantum hardware.**

***Index Terms*—Huffman Coding, No-Cloning Theorem, Quantum Computing, Quantum Gates, Quantum Information Science Kit, Quantum Teleportation**

I. Introduction

Among the many quantum information processing (QIP) tasks, quantum entanglement is essential for quantum teleportation (QT) [1], [2], quantum key distribution (QKD) [3], [4], distributed quantum computation [5], quantum networks [6].

QT, a remarkable feature of quantum entanglement, is a technique that provides a means of sending quantum information, which is embedded in an unknown quantum state, from one place to another using shared entangled states between the sender and the receiver, as well as local operations and classical communications [2]. The theoretical idea of QT was first proposed in 1993 by Bennett *et al.* [2] who used a Bell state maximum entanglement to implement a scheme to transmit an arbitrary single-qubit state to a remote location. Researchers have since then been paying much attention to this, both theoretically [7]–[12] and experimentally [13]–[18].

QT technique allows us to teleport only the quantum state of information from one qubit (Alice, the sender) to another qubit (Bob, the receiver), which is entangled and separated by an intermediate qubit (Telamon). To the best of the authors' knowledge, this is the first work that demonstrated successful teleportation of Quantum state of text using the proposed Quantum Text Teleportation Protocols (QTTPs) based on two principles: QT technique and Huffman Coding.

This work proposed two QTTPs: (i) Standard QTTP (ii) QTTP with Huffman Coding. The first text teleportation protocol is the Standard QTTP that can be performed with a minimum of three qubits, with one qubit each for Alice, Bob and Telamon, respectively. The Standard QTTP has the drawback, however, that when employing three qubits and teleporting quantum state of a single bit at a time, it takes longer to teleport quantum state using conventional QT technique, which utilizes quantum superposition principles. Next, the same Standard QTTP was employed with twenty-four qubits for shorter teleportation time, with eight qubits in each. However, this method has the disadvantage of using a higher number of qubits.

The second text teleportation protocol is QTTP with an additional encoding technique known as Huffman Coding, that compresses the text almost up to 50 percent and then teleports the quantum state of binary data using a minimum of three qubits, whereby each compressed binary string is transmitted at a time. Following successful teleportation, the data is decompressed again to retrieve the original text contents. It should be noted that the quantum state of binary data is teleported using QTTP with Huffman Coding when both Alice and Bob possess the prefix codes.

The rest of the paper is structured as follows: Section II provides an insight into basic quantum states and quantum gates, explains QT technique and Huffman Coding. Section III discusses the proposed Standard QTTP and QTTP with Huffman Coding. Section IV discusses an evaluation study of both of the proposed QTTPs and teleporting quantum state of secured email text transfer using IBM Quantum Simulator and real quantum hardware via IBM Quantum Experience (IBM QX) [19] and followed by conclusions in Section V.

II. Background

A. Quantum States

The quantum states $|0\rangle$ and $|1\rangle$ can be represented in mathematical form as two orthogonal vectors [20]:

$$|0\rangle = \begin{pmatrix}1\\0\end{pmatrix}, \quad |1\rangle = \begin{pmatrix}0\\1\end{pmatrix} \tag{1}$$

An arbitrary quantum state $|\psi\rangle$ can be represented in terms of linear combination of $|0\rangle$ and $|1\rangle$ (since they are in orthonormal basis) as

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle \tag{2}$$

Here, α and β are probability amplitude values that are complex and follows the normalization constraint:

$$|\alpha|^2 + |\beta|^2 = 1 \tag{3}$$

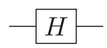
The multi-qubit quantum states can be represented as the tensor product of individual basis states [20], [21].

B. Quantum Gates

The matrix representations of quantum gates [20] using the computational basis of $|0\rangle$ and $|1\rangle$ are as follows:

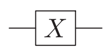
1) H gate (puts the qubit in uniform superposition):

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \tag{4}$$



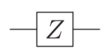
2) X gate (flips the state of qubit):

$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \tag{5}$$



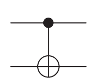
3) Z gate (flips the phase of qubit around Z-axis):

$$Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \tag{6}$$



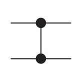
4) CX gate (flips the state of qubit when the control qubit is in $|1\rangle$ state):

$$CX = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \tag{7}$$



5) CZ gate (flips the phase of qubit when the control qubit is in $|1\rangle$ state):

$$CZ = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \tag{8}$$



C. Quantum Teleportation (QT) Technique

Quantum Teleportation (QT) is a technique [22] for transferring quantum information from a sender at one location to a receiver at some remote location. For better understanding of QT technique, let us consider a scenario with three persons Alice, Bob, and Telamon. Here, Alice is the sender, Bob is the receiver and Telamon is the intermediate channel or person. Alice want to communicate quantum information to Bob. Let us assume Alice wishes to convey the arbitrary qubit state $|\psi\rangle$ to Bob in particular that requires disseminating information.

But, the no-cloning theorem in quantum physics states that it is impossible to generate a duplicate of an unknown quantum state [20]. Hence, Alice cannot simply produce a copy of $|\psi\rangle$ and transfer it to Bob. It is only possible to replicate classical states (not superpositions).

The quantum state $|\psi\rangle$ of Alice can be transmitted to Bob by two classical bits and an entangled pair of qubit. This can be referred to as teleportation since, in the end, Bob will have the same quantum state $|\psi\rangle$ and Alice will not. In order to transmit a quantum bit, Alice and Bob must rely on a third party (Telamon) to provide them with an entangled qubit pair. Following that, Alice performs certain operations on her qubit and transmits the results to Bob by way of classical communication channel, after which Bob performs some operations on his end to acquire Alice's qubit.

Following are the basic steps for teleporting a quantum state:

1) ***Step I****:* The beginning of quantum teleportation is when Alice needs to send Bob an arbitrary quantum state $|\psi\rangle$ which Bob is unaware of. Alice and Bob enlist the support of a third party (Telamon) to make this happen. Telamon prepares an entangled pair of qubit $|e\rangle$ for Alice and Bob expressed as

$$\begin{aligned} |e\rangle &= \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \\ |e\rangle &= \frac{1}{\sqrt{2}}(|0\rangle_{Alice}\,|0\rangle_{Bob} + |1\rangle_{Alice}\,|1\rangle_{Bob}) \end{aligned} \tag{9}$$

Both Alice and Bob possess a qubit from the entangled pair, but they have no way to split up the entangled pair. The result is a three-qubit quantum system given as

$$\begin{aligned} |\psi\rangle_{123} &= |\psi\rangle \otimes |e\rangle \\ &= (\alpha\,|0\rangle + \beta\,|1\rangle) \otimes \frac{1}{\sqrt{2}}(|0\rangle\,|0\rangle + |1\rangle\,|1\rangle) \\ &= \frac{1}{\sqrt{2}}(\alpha\,|000\rangle + \alpha\,|011\rangle + \beta\,|100\rangle + \beta\,|111\rangle) \end{aligned} \tag{10}$$

with Alice controlling the first two qubits and Bob controlling the third qubit.

2) ***Step II****:* The protocol says Alice now applies the CNOT gate to her two qubits, followed by the Hadamard gate to the first qubit. Thus, Alice's state is as follows:

$$\begin{aligned} &= (H \otimes I \otimes I)(CNOT \otimes I)(|\psi\rangle \otimes |e\rangle) \\ &= \frac{1}{2}((\alpha(|000\rangle + |011\rangle + |100\rangle + |111\rangle) \\ &\qquad + (\beta(|010\rangle + |001\rangle - |110\rangle - |101\rangle) \end{aligned} \tag{11}$$

This can be further be simplified to

$$\begin{aligned} = \frac{1}{2}(&|00\rangle\,(\alpha\,|0\rangle + \beta\,|1\rangle) + |01\rangle\,(\alpha\,|1\rangle + \beta\,|0\rangle) \\ &+ |10\rangle\,(\alpha\,|0\rangle - \beta\,|1\rangle) + |11\rangle\,(\alpha\,|1\rangle - \beta\,|0\rangle)) \end{aligned} \tag{12}$$

3) ***Step III****:* Alice measures the first two qubits (which she owns) and transmits them to Bob as classical bits. During classical measurements, she always obtains one of the four standard basis states $|00\rangle$, $|01\rangle$, $|10\rangle$ and $|11\rangle$ with equal probability. According to Alice's measurement, Bob's state will be

$$\begin{aligned} |00\rangle &\rightarrow (\alpha\,|0\rangle + \beta\,|1\rangle) \\ |01\rangle &\rightarrow (\alpha\,|1\rangle + \beta\,|0\rangle) \\ |10\rangle &\rightarrow (\alpha\,|0\rangle - \beta\,|1\rangle) \\ |11\rangle &\rightarrow (\alpha\,|1\rangle - \beta\,|0\rangle) \end{aligned} \tag{13}$$

TABLE I
UNITARY TRANSFORMATION ON CLASSICAL BITS (RECEIVED FROM ALICE) BY BOB ON ENTANGLED QUBIT

Bob's State	Classical Bits	Unitary Transformations
$(\alpha \lvert 0\rangle + \beta \lvert 1\rangle)$	00	I
$(\alpha \lvert 1\rangle + \beta \lvert 0\rangle)$	01	X
$(\alpha \lvert 0\rangle - \beta \lvert 1\rangle)$	10	Z
$(\alpha \lvert 1\rangle - \beta \lvert 0\rangle)$	11	ZX

*4) **Step IV**:* Once Bob receive classical bits from Alice, he performs unitary transformations (Table I) on the entangled qubit to restore the original state $|\psi\rangle$ transferred by Alice. By the end of this fourth step, Bob will have successfully reconstructed Alice's quantum state $|\psi\rangle$.

Fig. 1 shows the quantum circuit of QT technique with Alice and Bob assigned as $|q_{Alice}\rangle$ and $|q_{Bob}\rangle$ qubits respectively and $|q_{Telamon}\rangle$ is the qubit assigned to Telamon as entangling qubit. crx and crz are the classical registers that decides when to apply X gate and Z gate (Table I) based on two-bit classical measurements, respectively.

D. Huffman Coding

The Huffman Coding is a lossless compression method that assigns input characters as variable-length codes based on their frequency [23], [24]. The character with the highest frequency is assigned the smallest code, whereas the character with the lowest frequency is assigned the greatest code. The variable-length codes assigned to input characters are called prefix codes, which implies that the codes (bit sequences) are assigned in such a way that the code assigned to one character does not form the prefix of another character's code. Decoding the resulting bit stream this way ensures that there are no ambiguities.

Here is a counterexample to help us better understand prefix codes [25]. For example, let's say there are four characters, 'e', 'f', 'g', and 'h', whose variable-length codes are '00', '01', '0', and '1'. The conventional coding approach creates uncertainty since 'g' is the prefix of 'e' and 'f' codes. The decompressed output for the compressed bit stream '0001' might be "gggd" "ggf", "egh" or "ef". To solve this ambiguity, the Huffman Coding is preferable that takes the input an array of unique characters with the frequency of their occurrences, and the output is a Huffman tree. The codes are assigned to characters by traversing or navigating the Huffman tree starting from the root node till the last node.

III. PROPOSED QUANTUM TEXT TELEPORTATION PROTOCOLS (QTTPS)

Fig. 1 shows the quantum circuit that will be employed for demonstration of the successful quantum teleportation of text file for both of the proposed QTTPs. The QTTPs are explained in the following.

A. Standard QTTP

The Standard QTTP can teleport quantum state of each bit of text file between the sender and the receiver at some remote location using the QT technique explained in Section II-C.

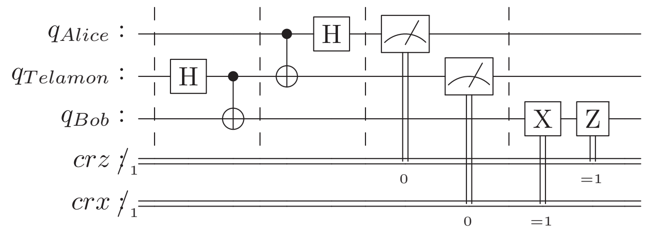


Fig. 1. Quantum Circuit of QT Technique that is employed for demonstration of both of the Proposed QTTPs [22]

The steps that need to be followed in order to teleport the quantum state of each bit of text file using the Standard QTTP can be explained in details as follows:

*1) **Step I**:* The first step is to read the text file (with a .txt extension) that has been provided by the user.

*2) **Step II**:* Upon reading the text file, each character is converted to its corresponding ASCII value, which is then converted to its corresponding eight-bit binary string per character.

*3) **Step III**:* Next, the Standard QTTP teleports quantum state of each eight-bit binary string through a quantum circuit. During teleportation, if the hacker corrupts or attempts to hack the information, the qubits in superposition collapse, and the receiver receives a faulty output. The original data, however, will not be accessible to hackers. Additionally, the receiver will verify whether the information received is correct by checking the error rate. The higher the error rate, the higher the likelihood of hacking. However, if there hasn't been an error, the quantum state of text file has been successfully teleported.

*4) **Step IV**:* When the quantum state of binary string has been successfully teleported, it can be obtained by the receiver (Bob), which can then convert them back to ASCII values and then into characters, which can then be saved in the native text format.

By utilizing generic QT techniques, the Standard QTTP poses the trade-off between decreasing qubit counts and increasing time required (number of iterations) for teleportation.

B. QTTP with Huffman Coding

This proposed QTTP in conjunction with Huffman Coding enables shorter teleportation times while requiring fewer qubits. Following are the steps that need to be followed in order to teleport the quantum state of text file using the QTTP with Huffman Coding:

*1) **Step I**:* The first step is to read the text file (with a .txt extension) that has been provided by the user.

*2) **Step II**:* The second step is to determine the frequency of each character, that is, how often the character appears in the whole text file.

*3) **Step III**:* The next step is to generate the prefix codes for each character using Huffman Coding.

*4) **Step IV**:* Each of these prefix codes determines how the text file should be rewritten using the same prefix codes. The entire text file is then written using the prefix codes and saved in an ".bin" extension file.

*5) **Step V**:* The next step is to access the binary strings as a single binary string and then, based on the number of qubits available for Alice, Bob and Telamon, the binary string are partitioned into sub-binary strings.

*6) **Step VI**:* Next, the successful teleportation of quantum state of binary sub-strings is performed through the quantum circuit (Fig. 1). The .bin file must be reconstructed after Bob receive the teleported quantum state of binary sub-strings.

*7) **Step VII**:* Assuming that the prefix codes are already available to the sender (Alice) and the receiver (Bob), the binary strings are converted back to characters and saved into the native text format.

It is guaranteed that the proposed QTTP with Huffman Coding is faster and more efficient than the Standard QTTP (without Huffman Coding) by lowering the number of binary sub-strings without using any extra information and the number of qubits. The time will be longer when the number of qubits is reduced, but still less than the time spent by the original text file in the Standard QTTP.

IV. Evaluation Study of Proposed QTTPs

Both of the proposed QTTPs for demonstration on sample text files are simulated on IBM Quantum simulator first, and then on real quantum hardware.

A. Sample Text Files

The two sample files **(Text.txt and Email.txt) with contents** taken as inputs to the quantum circuit are:

1) Text.txt:
   Artificial Brain
2) Email.txt:
   Dear Niels Bohr,

   We are pleased to inform you that we have developed a highly efficient and secure quantum teleportation protocol to send emails. This is achieved by combining Quantum Teleportation (QT) technique with Huffman Coding. In addition to reducing the number of qubits, using the Huffman Coding approach can enable one to compress the entire file so that a large amount of information can be transmitted in a short period of time.

   We are also happy to inform you of the fact that this email was sent to you via our quantum text teleportation protocol.

   -Thanks and Regards,
   Artificial Brain Team

B. Huffman/Prefix Codes of Sample Text files

The Huffman/Prefix Codes of sample text files **(Text.txt and Email.txt) with contents in Section IV-A** are:

1) **Text.txt**:
   [‘a’: 000, ‘r’: 001, ‘A’: 0100, ‘t’: 0101, ‘ ’: 0110, ‘l’: 0111, ‘i’: 10, ‘c’: 1100, ‘n’: 1101, ‘f’: 1110, ‘B’: 1111]

TABLE II
Evaluation Study On Qiskit Simulator demonstrating the Proposed QTTPs and showing Trade-off between No. of qubits and No. of Iterations)

Proposed QTTPs	No. of Qubits	No. of Iterations	
		Text.txt	**Email.txt**
Standard QTTP	24	16	604
	12	32	1208
	6	64	2416
	3	**128**	**4832**
QTTP with Huffman Coding	24	8	337
	12	16	674
	6	32	1348
	3	**64**	**2696**

2) **Email.txt**:
   [‘e’: 000, ‘p’: 00100, ‘c’: 00101, ‘’: 001100, ‘q’: 0011010, ‘.’: 0011011, ‘d’: 00111, ‘C’: 01000000, ‘)’: 010000010, ‘I’: 010000011, ‘x’: 010000100, ‘-’: 010000101, ‘H’: 01000011, ‘g’: 010001, ‘f’: 01001, ‘W’: 01010000, ‘D’: 010100010, ‘N’: 010100011, ‘(’: 010100100, ‘k’: 010100101, ‘R’: 010100110, ‘A’: 010100111, ‘B’: 01010100, ‘Q’: 01010101, ‘v’: 0101011, ‘l’: 01011, ‘m’: 01100, ‘u’: 01101, ‘n’: 0111, ‘i’: 1000, ‘h’: 10010, ‘s’: 10011, ‘o’: 1010, ‘a’: 1011, ‘ ’: 110, ‘t’: 1110, ‘T’: 1111000, ‘,’: 11110010, ‘w’: 11110011, ‘b’: 1111010, ‘y’: 1111011, ‘r’: 11111]

C. Experimental Results

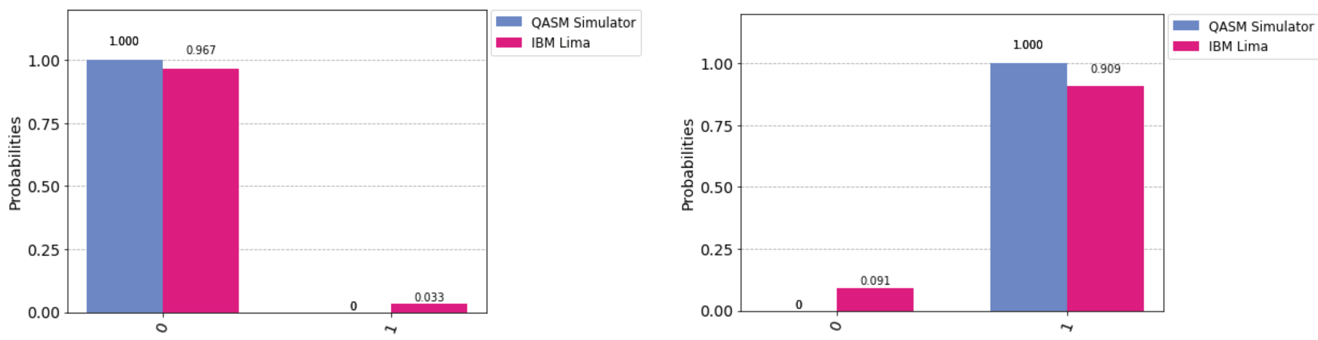
*1) **On IBM Quantum Simulator:**:* The binary data of the input text file was transferred as a list of elements directly to the specifically developed quantum circuit and ran via ”32-qubit IBM QASM simulator” for different number of qubits: 24, 12, 6 and 3 qubits with Alice, Bob and Telamon each having 8, 4, 2 and 1 qubits, respectively. The same binary list of elements was obtained as output after successful teleportation.

Table II shows evaluation study of both of the proposed QTTPs and summarizes how the total number of qubits used by Alice, Bob and Telamon results into variation in the number of iterations for teleporting the quantum state of two sample files: **Text.txt and Email.txt**. Simulations on IBM QASM simulator shows a 100 percent probability for teleporting each binary bit (or iteration) for both the files: **Text.txt and Email.txt**.

Thus, the authors conclude that, as the number of qubits decreases, the number of iterations also increases, which is indirectly proportional. Even though the number of iterations increases with decrease in number of qubits, the proposed QTTP with Huffman Coding shows fewer iterations for the same number of qubits than the Standard QTTP.

*2) **On IBM Quantum Hardware**:* Currently, IBM quantum hardware is accessible to the general public with only five qubits; therefore, experiments on real quantum hardware were performed with three qubits only: one each for Alice, Bob, and Telamon (Fig. 1).

The quantum state of binary elements were teleported directly from the input file (.bin file) to the quantum circuit



(a) Quantum State teleported is of bit ‘0’

(b) Quantum state teleported is of bit ‘1’

Fig. 2. Experimental Measurements of the quantum circuit on real quantum hardware (IBM Lima- 5 qubits [26]) for both of the two proposed QTTPs with 8192 shots (quantum states on the horizontal axis and probabilities on the vertical axis) when the quantum state teleported is of (a) Bit ‘0’ and (b) Bit ‘1’

running on real quantum hardware. In the process of teleporting the quantum state on quantum hardware, the authors successfully obtained the same binary list as an output.

There are some errors on the histograms of probabilities with real quantum hardware when compared to results with no hardware noise (from IBM QASM simulator). This could be due to various hardware noise from the quantum device.

For better illustration, Fig. 2(a) and Fig. 2(b) shows the histogram with different quantum state probabilities when the teleportation of the quantum state are for the bit ‘0’ and ‘1’, respectively. In the end, the authors do not obtain a probability of 100 percent for the specified binary string or binary digit as in IBM QASM simulator. Hence, based on the histogram or measurements, it may be concluded that the real result or probability with the desired bit at Bob will have a greater likelihood than the rest probabilities. It is still likely that Bob, regardless of the error rate on the hardware, will get the teleported quantum state of bit in each of the possible combinations, even if there is an error rate on the hardware.

Note: The entire quantum experiment on real quantum hardware are based solely on counts, not on probabilities. As a result, we do not obtain a probability of 100 percent for the specified binary string or binary digit. However, even if there is an error rate in real hardware for a desired binary digit or string, there is a large likelihood of alternative possibilities, where Bob will have the teleported quantum state of bit in each of the possible combinations.

D. Discussions

The Standard QTTP does not require prefix codes to be created by the sender and sent to the receiver before teleportation begins, so it can be used repeatedly. However, the Standard QTTP approach has the drawback of rapidly increasing the number of iterations as the amount of the text increases.

The QTTP with Huffman Coding offers one major advantage over the Standard QTTP is that the number of iterations can be reduced even if the input file size increases. The Huffman codes/Prefix codes also increase data security, since decrypting data is difficult. Due to its unique prefix codes, only it can be decoded and encoded by the sender and the receiver.

It is assumed that the sender will send the prefix codes to the receiver via the classical channel in order to conduct this experiment, then switches to a quantum channel to send the actual encoded data (using Huffman/Prefix codes). Even if the third-party eavesdrops the classical channel in order to obtain Huffman Codes/Prefix codes, the data would still be safe since the encoded data transmission takes place over a quantum channel in which all quantum states are in superposition. Consequently, any attempt to measure it will result in the quantum state collapsing. Even if the eavesdropper has the Huffman codes, it will be useless without the actual encoded data, which is transferred using the quantum channel (Fig. 1).

Upon successfully receiving quantum states from the sender, the receiver will perform some quantum operations (X and Z gates) based on classical information to obtain encoded binary values (Fig. 1). After that, the receiver converts encoded data into actual binary data using the Huffman/Prefix codes communicated over the classical channel.

There is no need to send prefix codes over and over if the sender use the same quantum state of a file teleported through the quantum channel but simply increase or decrease the number of qubits used, because the prefix codes for a text file will be the same even if we use different qubits as shown in Table II. In the Standard QTTP and QTTP with Huffman Coding, one can increase or decrease the number of qubits for teleportation. However, if one reduce the number of qubits in the standard QTTP, this will increase the number of iterations. But for QTTP with Huffman Coding, however, this is not the case. Anyway, one can increase or decrease the number of qubits in both the Standard QTTP and QTTP with Huffman Coding. But there are few constraints with Standard QTTP.

V. Conclusion

This work detailed the design of two proposed Quantum Text Teleportation Protocols (QTTPs) for secure text transfer using Quantum Teleportation (QT) and Huffman Coding. Both of the two proposed QTTPs (Standard QTTP and QTTP with Huffman Coding) are explained in a detailed manner. Demonstration of quantum state transfer of two samples files (Text.txt and Email.txt) using both of the proposed QTTPs are also successfully shown on IBM Quantum Experience

(IBM QX) using IBM QASM simulator and on real quantum hardware. Future works call for quantum teleportation of secure email transfer including attachments using the proposed QTTPs.

VI. Acknowledgements

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