Quantum Bit Retransmission Using Universal Quantum Copying Machine

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***Abstract*— Quantum internet, which is expected to be a combination of quantum and classical networks, promises to provide information theoretic security for data exchange. Classical networks have well established protocols for reliable end-to-end transmission that implicitly make use of duplicating the classical bits. However, quantum bits (qubits) cannot be copied due to no-cloning theorem. In this paper, we take advantage of the principle of creating imperfect clones using Universal Quantum Copying Machine (UQCM) and propose the Quantum Automatic Repeat Request (QARQ) protocol, inspired by its classical equivalent. A simulation platform has been developed to study the feasibility of QARQ and results show that our proposal is well suited for applications where the requirement of fidelity is low.**

Keywords—reliable transmission, quantum communication, quantum automatic repeat request, universal quantum copying machine

I. Introduction

Quantum computing is turning to be the next generation of advanced computing with enormous computing capabilities. The technology is growing fast, and soon quantum computers would exchange quantum messages among them thus, enabling distributed quantum computing. Such quantum computers connected by quantum internet can be used for various applications, ranging from quantum key distribution (QKD) to special quantum computation, while guaranteeing information theoretic security governed by the laws of quantum mechanics. The real challenge in near-term quantum networks is the degradation of the quality of quantum bits (qubits), measured as *fidelity*, and even the loss of qubit caused by their interaction with environment. The degraded fidelity of qubits is not an issue as quantum devices can deal with imperfect qubits as long as the fidelity is above application-specific thresholds (e.g., fidelity threshold for QKD is 80% [1]). Therefore, the main issue is qubit loss, which can happen because of several reasons, including: *i*) entanglement pair generation which is fundamental for transporting qubits, however, imperfect entanglement results in qubit loss; *ii*) the quantum memories and gate operations are not perfect, which introduce decoherence in qubits; and *iii*) a lossy quantum channel can also be the cause of qubit loss, if the transmission is not entanglement assisted.

In classical packet networks, Transmission Control Protocol (TCP) implements error-control mechanism for reliable and error-checked transmission of messages based on a variant of the Automatic Repeat Request (ARQ) protocol. One could expect the development of similar protocols to guarantee reliable delivery of quantum messages, however, such approach is not possible because of the fundamental differences between classical and quantum bits. Packet retransmission is the basic mechanism that ensures reliable communication in classical networks, where classical bits are copied and retransmitted again if a loss occurs during the transmission; copying a qubit, however, is against the no-cloning theorem [2], a fundamental law of quantum physics which makes qubit retransmission impossible.

A possible solution to recover a qubit loss might be to use error correcting codes [3], but these cannot recover the information if errors are beyond the error correcting capability. In this regard, authors have proposed a technique in [4] for reliable connection based on secret sharing scheme, but this is for packet quantum networks that is suitable only when transmission error rate is low. Another approach consists of making clones of the received qubit. Several different types of quantum cloning machines have been studied in the literature, both theoretically and experimentally (see, e.g., [7]-[8]), Among them, Universal Quantum Copying Machine (UQCM) [5] creates the imperfect clones of qubits closer to the state of original qubits, provides high fidelity independently of the input state, and it can be used to generate multiple copies.

In this paper, we assume that quantum applications can be dealt with imperfect qubits. Although, no perfect clone of qubits can be made, we can clone quantum states with approximately the optimal fidelity. In this paper, we propose making clones of quantum states by using UQCM. Although such clones are imperfect, the mechanism gives the opportunity to retransmit qubits in case of loss. Then, we propose combining classical and quantum channels to provide reliable transmission, thus implementing the Quantum Automatic Repeat Request (QARQ) protocol. We have developed a simulation platform using NetSquid [6] to evaluate the feasibility of the QARQ protocol when qubit decoherence occurs due to the time the qubit has to wait in a quantum memory, as well as to the quantum transmission channel in case of non-entanglement assisted quantum communication. Simulation results show the potential of the proposed QARQ protocol for short distance communication where the fidelity requirement is low and the errors in transmission are high.

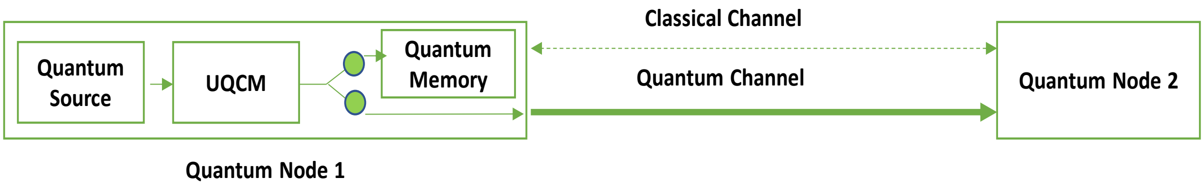

Fig. 1 Quantum Communication System

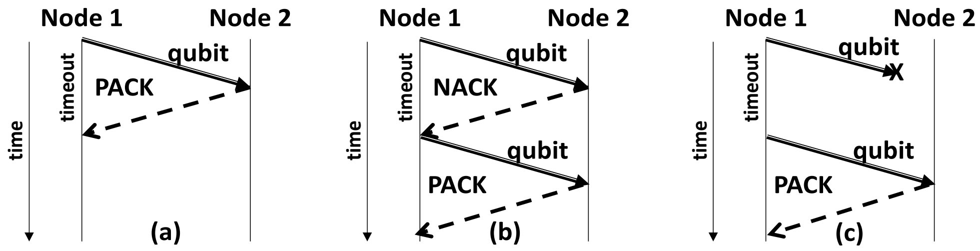

Fig. 2 Quantum Automatic Repeat Request Protocol

II. QUANTUM AUTOMATIC REPEAT REQUEST

Fig. 1 shows a quantum communication system that consists of two nodes, where Quantum Node (qNode) 1 transmits qubits to qNode 2. Qubits go into UQCM before transmission where imperfect clones are generated; for each received qubit, one of the clones is sent to qNode 2 and the others are stored into quantum memories. UQCM can create multiple clones at the expense of degrading fidelity of qubit. Choosing the number of clones highly depends on the quantum-application under consideration. For the sake of simplicity, only two copies are considered in this paper. The quantum channel is used for the transmission of qubits, while the classical channel is utilized to exchange classical messages between qNode 1 and qNode 2.

Similarly, as the classical ARQ, QARQ uses acknowledgements (ACK) and timeouts to achieve reliable quantum communication over an unreliable quantum system. Fig. 2 illustrates three different cases to describe the protocol, where qubits are sent through the quantum channel (continuous lines), whereas ACKs are sent through the classical channel (dashed line). In QARQ, qNode 1 sends the quantum data with error detection codes, e.g., repetition codes to check whether the quantum data is received correctly. If no error is detected by qNode 2, it notifies qNode 1 using a positive ACK (PACK) via classical channel and the quantum memory is flushed (Fig. 2a). Conversely, if error is detected and it cannot be recovered because of the incapability of error correction codes, qNode 2 discards the qubit and sends back a negative ACK (NACK) (Fig. 2b). When qNode 1 receives NACK, the cloned qubit stored in the quantum memory is sent to qNode 2. More retransmissions can be corrected if more clones are generated but at the expense of degradation of qubit fidelity. Additionally, QARQ uses timeouts for retransmission, where qNode 1 uses the stored qubit if no ACK is received after a specified time period, timeout, assuming that the qubit is lost (Fig. 2c).

Note that by this we constrained ourselves to producing just two clones of each received qubit, therefore, if the two produced clones are lost, the quantum source needs to be notified so as it can initiate a new qubit transmission.

III. DESIGN OF QARQ ENABLED QUANTUM NODES

The proposed QARQ protocol is based on creating the copies of the received qubits, where their output states remain closer to the original qubit. In this section, we describe the necessary steps to generate clones by UQCM; please refer to [5] for further details.

The UQCM output (cloned) state is universal to the input state. Fig. 4 shows the UQCM network. The system represented by $a_{0_{in}}$ is 'original qubit', while a_1 represents a 'blank paper' where information is copied and system b can be considered as a 'photocopier machine' and helps to create copies which does not contain any information regarding $a_{0_{in}}$. In principle the UQCM network has two phases, preparation and copying. In the preparation step before interacting with the original qubit $a_{0_{in}}$ in state $|\Psi\rangle_{a_{0_{in}}}$, first the quantum copier that consists of two qubits a_1 and b needs to be prepared in a specific state generated by the preparation block which consists of three rotations ($R(\theta_j)$) that can be implemented by three Y-Rotation gates and two controlled-not ($CNOT_{CT}$) gates. The rotation angles can be found by

$$cos\theta_1 = \frac{1}{\sqrt{5}}; cos\theta_2 = \frac{\sqrt{5}}{3}; cos\theta_3 = \frac{2}{\sqrt{5}} \qquad (1)$$

In the copying network, after the preparation of qubit states of quantum copier, four $CNOT_{CT}$ gates can be used sequentially to obtain the copy of initial state $|\Psi\rangle_{a_{0_{in}}}$. The quantum circuit will give two clones, each with a fidelity of 83.33% that will provide the basis of the retransmission protocol described in Section II.

IV. RESULTS

To evaluate the performance of our proposed protocol, we have implemented the protocol in a purpose-built simulator for simulating quantum networks called NetSquid ((Python/C++)) [5]. The simulator is built to give accurate modeling of physical devices that incudes decoherence, fiber losses, propagation delay, quantum gate operations and their time dependencies. The simulation platform is created in python environment. In our simulation for the protocols, we are just considering decoherence that occurs due to waiting time of qubit in quantum memory and decoherence because

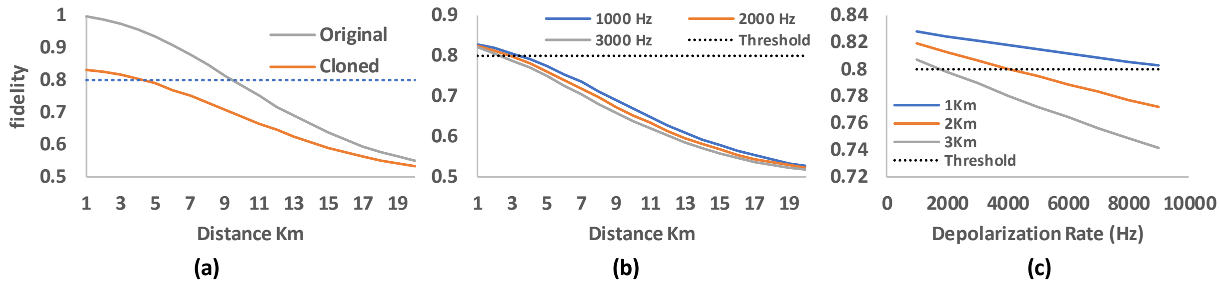

Fig. 3 Effects of depolarization on fidelity of qubit

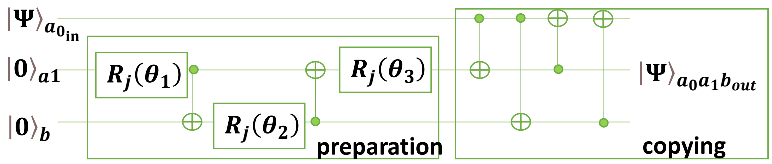

Fig. 4 Schematic of UQCM

of the transmission of qubit in the fiber channel. The generation of clones through UQCM is created ideally with optimal fidelity without considering losses. For fiber channel decoherence probability of depolarization per km of fiber is considered as 0.025 per km.

Fig. 5 shows the Bloch sphere representation of working of the UQCM, where the initial state of $|\Psi\rangle_{a_{0_{in}}} = |0\rangle$ is used to create two clones with optimal fidelity of 83.33%. We can see that $|\Psi\rangle_{a_{0_{out}}}$ and $|\Psi\rangle_{a_{1_{out}}}$ are the same while $|\Psi\rangle_{b_{out}}$ does not contain any information regarding $|\Psi\rangle_{a_{0_{in}}}$.

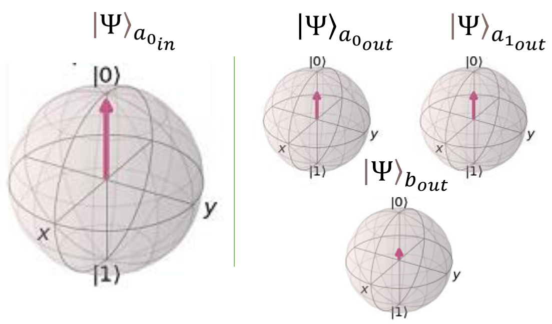

Fig. 5 Bloch sphere representation of output of UQCM

For the testing of protocol three cases as shown in Fig. 2 are considered. Fig. 3 shows that how the fidelity of qubit is affected in each case while considering the threshold fidelity of qubit as 80%. Fig. 3 (a) describes the case (a) of Fig. 2 in which the cloned qubit is perfectly received by the receiver and the fidelity is compared with the original qubit when it is sent without cloning. In this case only depolarization due to channel will affect the fidelity of qubit We can see that initially the loss in fidelity of 16.67% is observed in cloned qubit that decreases the communication range which is the main drawback of using UQCM. However, it provides the reliable communication in case of loss of qubit. If the goal is just to achieve the fidelity above the application specified threshold, then, entanglement assisted teleportation of cloned qubits can achieve long distances which is not discussed in this paper.

Fig. 3 (b) and Fig. 3 (c) show how the fidelity of cloned bit is affected in the cases (b) and (c) of Fig. 2. In these two cases cloned qubit rests in quantum memory during the time until NACK is received and then sent to quantum node 2. Here depolarization due to channel and due to waiting time in quantum memory both affects the fidelity of qubit. Fig. 3 (b) describes that fidelity decrease as the distance increases at different values of depolarization rates of quantum memory. While Fig. 3 (c) plots the fidelity as a function of memory depolarization rates for different cases of distances. Note that, the depolarization rates for quantum memory and depolarization probabilities of fiber channel are taken randomly for readers to understand the pros and cons of the protocol and they don't represent any physical devices.

V. Conclusion and Future Work

In this paper, we have devised a unique protocol called QARQ for reliable quantum communication. We have simulated the network on NetSquid and discussed the pros and cons of this protocol. In this work ideal generation of clones through UQCM is considered and only depolarization of channel and quantum memory is studied. As a part of the future work, we plan to incorporate other noises such as noise due to gate operations and study the protocol for entanglement assisted teleportation.

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