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 classical bits. However, quantum bits (qubits) cannot be copied due to the no-cloning theorem. In this paper, we take advantage of the principle of creating imperfect clones using a 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. Results show that our proposal is well suited for applications that are compatible with low fidelity requirements.**

Keywords— Reliable quantum communication, Universal Quantum Copying Machine.

I. INTRODUCTION

Quantum computing is a promising solution for the next generation of advanced computing with enormous computing capabilities. The technology is developing rapidly and soon quantum computers will 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*, or even the loss of the qubit. The degraded fidelity of qubits may not be an issue, since quantum devices can deal with imperfect qubits as long as the fidelity is above application-specific thresholds (e.g., the fidelity threshold for QKD is 80% [1]). On the other hand, the qubit loss is critical. Several effects can lead to the loss of qubits, including *i*) imperfect entanglement pair generation (the entanglement is fundamental for transporting qubits); *ii*) imperfect quantum memories and gate operations, which introduce decoherence in qubits; and *iii*) lossy quantum channels, which is particularly relevant if the transmission is not entanglement assisted.

In classical packet networks, the Transmission Control Protocol (TCP) implements an 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 based on storing and retransmission of qubits to guarantee the reliable delivery of quantum messages. But such an approach is not possible in quantum networks due to the no-cloning theorem [2], a fundamental law of quantum physics that makes qubit duplication 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, the authors have proposed a technique in [4] for reliable connection based on a secret sharing scheme. However, such a solution is suitable for packet quantum networks only when the 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., [5]-[6]). An example of such a quantum cloning machine is the Universal Quantum Copying Machine (UQCM) [7], which creates imperfect clones of the original qubits, but still provides high fidelity independently of the input state, and can be used to generate multiple qubit copies.

In this paper, we assume that quantum applications can deal with imperfect qubits. Although no perfect clone of qubits can be made, quantum states can be cloned with approximately the optimal fidelity. We propose generating clones of quantum states by using UQCM, which would allow retransmitting the 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 [8] 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 due to the transmission in the quantum 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 transmission errors may be high.

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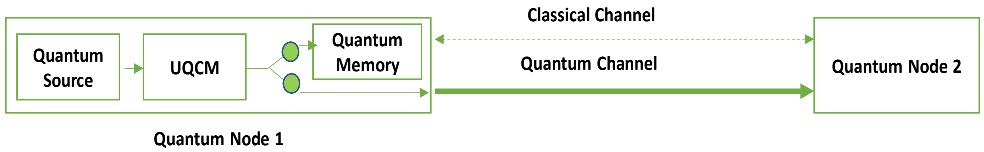

Fig. 1 Quantum Communication System

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 the UQCM before transmission to generate imperfect clones; for each received qubit, one of the clones is sent to qNode 2 and the others are stored in quantum memories. The UQCM can create multiple clones at the expense of degrading the fidelity of the qubit. The number of clones to be generated highly depends on the quantum application under consideration. For the sake of simplicity, only two clones 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.

Like the classical ARQ, QARQ uses acknowledgment (ACK) and timeout messages to achieve reliable quantum communication over an unreliable quantum system. Fig. 2 illustrates three different cases to describe the QARQ protocol, where qubits are sent through the quantum channel (continuous lines), whereas ACKs are sent through the classical channel (dashed line). When employing the QARQ protocol, 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 the classical channel and the quantum memory is flushed (Fig. 2a). Conversely, if an error is detected and it cannot be recovered because of the incapability of error correction codes in case of a high number of errors, qNode 2 discards the qubit and sends back a negative ACK (NACK) (Fig. 2b). When qNode 1 receives the NACK, the cloned qubit stored in the quantum memory is sent to qNode 2. Additional retransmissions can be done if more clones are generated but at the expense of degradation of qubit fidelity. Additionally, the QARQ sets timeouts for retransmission, where qNode 1 uses the stored qubit if no ACK is received after a specified time period (assumes that the qubit is lost (Fig. 2c)). Note that we constrained ourselves to produce just two clones of each qubit. Therefore, if the two clones are lost, the quantum source needs to be notified so to initiate a new qubit transmission.

III. Design of QARQ-Enabled Quantum Nodes

The proposed QARQ protocol is based on creating the clones of the received qubits, where their output states remain close to the original qubit. To design the QARQ based qNodes two fundamental blocks are UQCM and Quantum memory. Let us discuss the necessary steps to design the UQCM; the reader is referred to [7] for further details. The UQCM output (cloned) state is independent i.e. universal to the input state. Fig. 3 shows the UQCM network. The system represented by $a_{0_{in}}$ is the

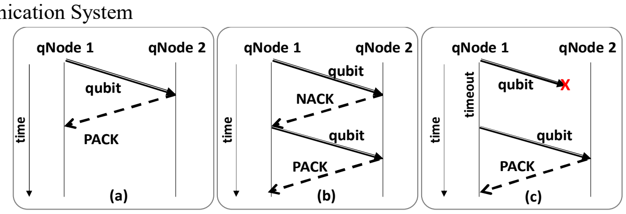

Fig. 2 Quantum Automatic Repeat Request Protocol

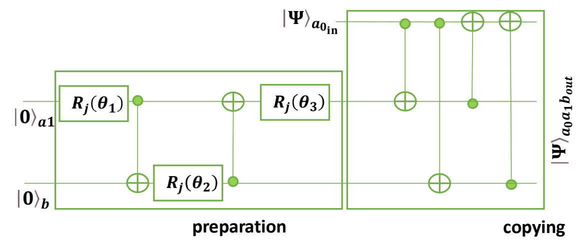

Fig. 3 Schematic of UQCM

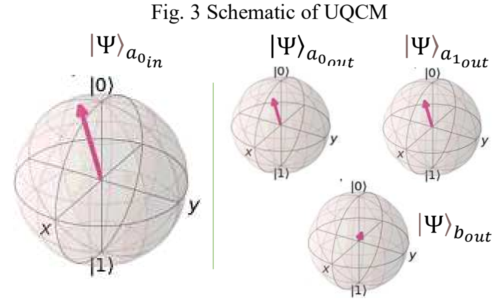

Fig. 4 Bloch sphere representation of the output of UQCM

'original qubit', while a_1 represents a 'blank paper' where information is copied and system b can be considered as a 'photocopier machine' that helps to create copies but 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 $|\Psi\rangle_{a_{0_{in}}}$, the quantum copier that consists of two qubits a_1 and b, both initialized with state $|0\rangle$ needs to be set in a specific state generated by the preparation block. The preparation block 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:

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

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 generate two clones, each with fidelity of 83.33% that will provide the basis of the retransmission protocol described in Section II.

Once the clones are generated, these clones must be stored in a quantum memory. Quantum memories are available with typical memory lifetimes ranging from few microseconds to one second [1] and can be used to store the cloned qubits.

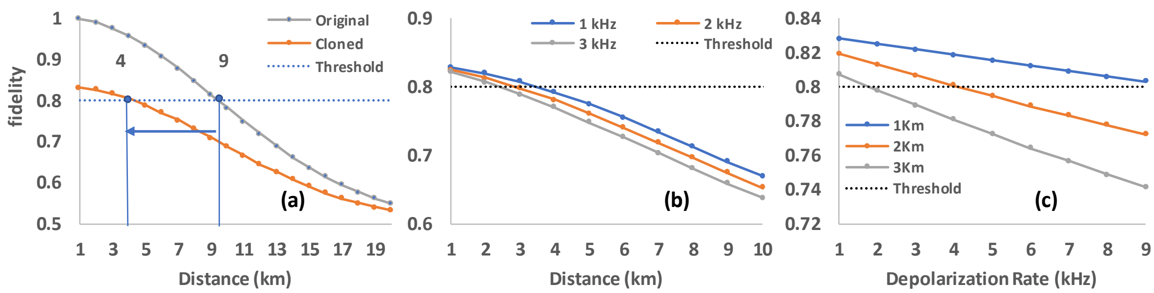

Fig. 5 Effects of depolarization on fidelity of qubit

IV. Results

To evaluate the performance of our proposed QARQ protocol, we have implemented the protocol in a purpose-built simulator for simulating quantum networks called NetSquid [8]. The simulator provides accurate modeling of physical devices. In our simulation for the protocols, we are considering decoherence resulting from the waiting time of qubit in quantum memory and the transmission of qubit in the fiber channel only. The generation of clones through the UQCM is assumed ideal with optimal fidelity and without considering losses. For fiber channel decoherence probability of depolarization per km of fiber is considered as 0.025. This length property is used to calculate depolarization probability that is applied to the qubit. Quantum memory depolarizes the qubit for a delay with a given depolarization rate.

Fig. 4 shows the Bloch sphere representation of the operation of the UQCM, where a random initial state of $|\Psi\rangle_{a_{0_{in}}}$ 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 $|\Psi\rangle_{a_{0_{in}}}$.

For the testing of the QARQ protocol the three cases as shown in Fig. 2 are considered. Fig. 5 shows the impact on fidelity of the qubit in each transmission scenario (the threshold fidelity of qubit was set 80%). Fig. 5(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 transmission will affect the fidelity of the qubit Indeed, we observe loss in fidelity of 16.67% in the cloned qubit which decreases the transmission reach which is the main drawback of using UQCM. Nevertheless, it provides reliable communication in case of loss of qubit. In fact, if the goal is just to achieve the fidelity above the application specified threshold, then entanglement assisted teleportation of cloned qubits can be used to reach long transmission distances.

Fig. 5(b) and Fig. 5(c) show how the fidelity of cloned bit is affected in the cases (b) and (c) of Fig. 2. In these two cases the cloned qubit is stored in a quantum memory until NACK is received or a timeout occurs. When one of these scenarios occurs, the cloned qubit is sent to the qNode 2. Here depolarization due to channel transmission and due to the waiting time in the quantum memory both affect the fidelity of the qubit. Fig. 5(b) and (c) show the fidelity decrease as a function of the transmission distance and depolarization rate of the quantum memory. A distance of 4 km can be achieved for depolarization rate of 1 kHz (Fig. 5 (b)) while a 1 km link can sustain depolarization rate of up to 9 kHz (Fig. 5 (c)) considering 80% fidelity threshold. 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 specific physical devices as these are still under investigation.

Another important issue while developing quantum networks is memory life time. In Fig. 5(b) for depolarization rate of 1 kHz, 4 km distance can be achieved which entails the waiting time of cloned qubit in quantum memory to be around 0.04 ms (considering speed of light in fiber as 2 x 10^5.km/s) As discussed earlier that quantum memories with storage time of up to one second are available, lifetime of quantum memories don't limit the simulation results even for a distance of 10 km which results in the waiting time of 0.1 ms.

V. Conclusion and Future Work

In this paper, we have proposed a novel QARQ protocol for reliable quantum communication. We have run a set of simulations using a purpose-built simulator NetSquid and discussed the pros and cons of this protocol. The ideal generation of clones through UQCM is considered and only depolarization of channel and quantum memory is studied to extract the fundamental limitations of the proposed approach while providing the advantage of retransmission of a qubit. For future work, we plan to incorporate other noise sources such as noise due to gate operations and study the protocol for entanglement assisted teleportation.

References

[1] W. Kozlowski, A. Dahlberg S. Wehner, “Designing a quantum network protocol.” in Proc. of CoNEXT, ACM, 2020.

[2] W. Wootters and W. Zurek, “A single quantum cannot be cloned,” Nature, vol. 299, pp. 802–803, 1982.

[3] P. Shor, “Scheme for reducing decoherence in quantum computer memory.”, Physical Review A, vol. 52, pp. R2493–R2496, 1995.

[4] N. Yu, C. Lai and L. Zhou, "Protocols for Packet Quantum Network Intercommunication," IEEE Transactions on Quantum Engineering, vol. 2, pp. 1-9, 2021.

[5] E. Woodhead, “Quantum cloning bound and application to quantum key distribution.”, Phys. Rev. A, vol. 88, pp. 012331, 2013.

[6] S. Iblisdir et al., “Multipartite asymmetric quantum cloning.” Phys. Rev. A, vol. 72, pp. 042328, 2005.

[7] Buzek, R. Vladimír and M. Hillery. “Universal Optimal Cloning of Qubits and Quantum Registers.”, QCQC, 1998.

[8] QuTech. 2020. NetSquid. [Online]. Available: https://netsquid.org/