

Reliable Quantum Communication

Masab Iqbal*, Morteza Ahmadian, Luis Velasco, and Marc Ruiz

Optical Communications Group (GCO), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain

**e-mail: masab.iqbal@upc.edu*

ABSTRACT

The quantum internet, which will be a hybrid of quantum and classical networks, is expected to provide information-theoretic security for data transmission. Classical networks have well-established protocols for reliable end-to-end transmission that use duplicating the classical bits implicitly. However, due to the no-cloning theorem, quantum bits (qubits) cannot be copied. In this paper, we propose to use a Universal Quantum Copying Machine (UQCM) to create imperfect clones and summarizes the Quantum Automatic Repeat Request (QARQ) protocol, which is inspired by its classical counterpart. To investigate the viability of QARQ, a simulation platform is created considering Nitrogen-vacancy (NV) center qubit platform that implements QARQ for quantum communication. The results explore the applications it is suitable for while maintaining enough quality of the qubit state. Two major quantum technologies are studied for these protocols: Direct Transmission (DT), and Teleportation (TP). It has been shown that for short distance communication DT provides better fidelity than TP while for long-distance communication TP outperforms DT and hence improves the QARQ performance as well.

Keywords: reliable quantum communication, qubit retransmission, universal quantum cloning machine.

1. INTRODUCTION

Quantum computing is a highly promising technology for advanced computing with remarkable capabilities in the future. Its growth is accelerating rapidly, and soon quantum computers will be able to communicate with each other through a quantum Internet, enabling distributed quantum computing. These computers can be used for various applications, including quantum key distribution (QKD) [1] and specialized quantum computing tasks [2]. Additionally, quantum mechanics ensures information-theoretic security, offering perfect security compared to classical approaches [3]. Nonetheless, the no-cloning theorem [4], which prohibits the perfect duplication of qubits, presents a fundamental obstacle in some quantum communication paradigms, such as qubit retransmission.

Quantum computers are currently in the Noisy Intermediate Scale Qubits (NISQ) era [4] and can only operate with a limited number of noisy qubits. The presence of noise in the system limits the functionality of quantum devices and poses a significant challenge for near-term quantum networks, specifically qubit loss. There are several factors that can cause qubit loss, including the generation of imperfect entangled pairs, which are crucial for qubit transport. Entanglement refers to the relationship between two particles that remain correlated regardless of the distance between them. Other factors that contribute to qubit loss include imperfect quantum memories and gate operations, as well as lossy quantum channels.

One potential approach to address qubit loss is to utilize error-correcting codes [6], although their efficacy may be limited in cases where errors exceed the level that can be corrected. Alternatively, in [7], the authors suggest a secure connection method that employs secret sharing. Nevertheless, this solution is only practical for quantum networks that experience low levels of transmission errors.

The Transmission Control Protocol (TCP) in classical packet networks uses an error-control mechanism that relies on the Automatic Repeat Request (ARQ) protocol to store and resend packets or bits. In quantum networks, it might seem feasible to develop similar protocols based on storing and resending qubits to ensure the reliability of quantum messages. However, this approach is not possible because the no-cloning theorem prevents the duplication of perfect quantum bits.

A different approach to ensuring reliability in quantum communications is to create imperfect copies of qubits using quantum cloning machines. Several types of these machines have been suggested in literature (e.g., [8]). One such machine, called the Universal Quantum Copying Machine (UQCM) [9], generates imperfect but optimal copies of the original qubits, regardless of the input state, and it can produce multiple imperfect copies of qubits.

In this research article, we build upon our previous work in [10] and suggest using the UQCM for reliable quantum communications. Our contributions are: i) introducing the Quantum Automatic Repeat Request (QARQ) protocol, which combines classical and quantum channels for reliable transmission. Here, clones can be created and stored in quantum memories that can be utilized in case of qubit loss. ii) we have developed a simulation platform to evaluate the feasibility of the QARQ protocol under different sources of noise. These protocols are analyzed for two distinct quantum technologies: i) direct transmission (DT), which uses a quantum channel for qubit transmission, and ii) teleportation (TP), which employs entanglement to transfer qubits.

2. BACKGROUND

Quantum communication is an alternate of the classical forms of communication that takes advantage of the principles of quantum mechanics. In contrast to classical computers, which transmit data as discrete bits of either

0 or 1, quantum computers use qubits to convey information. Qubits utilize a superposition of 0 and 1 to represent data, and like classical logic gates, quantum gates are used to manipulate and transform the qubits to achieve the desired output state.

Various quantum computing platforms exist, including superconducting qubits, trapped ions, and NV-centers in diamond. Each has strengths and weaknesses, such as fast gate operations for superconducting qubits but requiring extreme cold temperatures. Trapped ions have longer decoherence times and can operate at room temperature, but are slower and still require cooling. NV-centers have long coherence periods and high gate decoherence, operate at room temperature, and interact with photons for long-distance communication, making them suitable for quantum internet. Diamond spin qubits can establish robust entanglement links quickly, but further research may be necessary to determine the best platform for different applications, and new technologies may improve performance.

In order to evaluate the effectiveness of any quantum network protocol, it is important to consider fidelity as a metric, which is a purely quantum phenomenon. Fidelity is a measure of the state's quality and ranges from 0 to 1, where a value of 1 indicates that the state is in the desired state, while a value equal to or below 0.5 means that the state is unusable. In contrast to classical networks where data must be delivered error-free, quantum networks can operate with imperfect quantum states as long as the fidelity is greater than a specific threshold that depends on the application. For basic quantum key distribution (QKD), the threshold fidelity is typically around 0.8. In this paper, we will be using fidelity as a metric to evaluate the performance of the proposed protocols for the three different quantum technologies we have studied.

There is a relationship between fidelity and decoherence-which is a major challenge in quantum networks. Loss of qubit coherence can lead to a reduction in quantum state fidelity, which can occur in several ways such as environmental effects during transmission, imperfect entanglement in entanglement distribution networks, coherence degradation during qubit storage, and imperfect implementation of quantum gates during qubit processing. The paper considers all these factors when evaluating the loss of quantum state fidelity in a quantum network.

3. IMPLEMENTING QARQ

In Fig. 1, the QARQ protocol is presented for a quantum communication system consisting of two nodes named Alice (A) and Bob (B). To transmit qubits from A to B , quantum channels (solid lines) are used via either DT or TP, while classical channels (dashed lines) are utilized to exchange classical messages between them. QARQ protocol, like classical ARQ, utilizes acknowledgement (ACK) and timeout messages to accomplish reliable quantum communication over an unreliable quantum system. A can transmit quantum data with error detection codes such as repetition codes to confirm whether the data is received accurately or not. If B receives the quantum data with no errors, a positive ACK (PACK) is sent to A via the classical channel, and the quantum memory is cleared (Fig. 1a). However, if an error is detected that cannot be rectified, B discards the quantum data and sends a negative ACK (NACK) to A (Fig. 1b). If A receives the NACK, the cloned quantum data stored in the quantum memory is sent to B . Further retransmissions can be conducted if more clones are produced, but the cost is the degradation of the qubit fidelity. In QARQ, timeouts are set for retransmission, and if no ACK is received after a specified time period, A uses the stored qubits (as shown in Fig. 1c).

Figure 2 illustrates the basic principle of QARQ and how to set up a quantum communication channel for it. The UQCM generates multiple clones for retransmission, but this comes at the expense of degrading the qubit's state, and the number of clones generated depends on the quantum application.

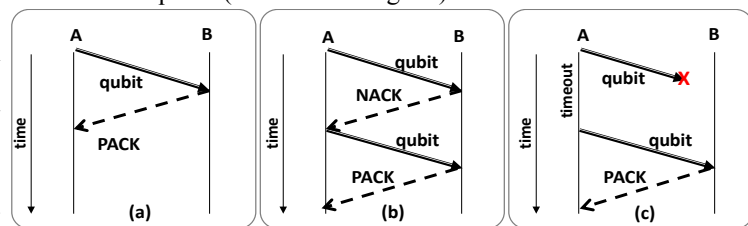


Figure 1. The QARQ protocol.

In QARQ-DT (Fig. 2a), qubits go into the UQCM before transmission to generate imperfect clones, and for each received qubit, one clone is sent to B using a quantum channel while the others are stored in quantum memories. In QARQ-TP (Fig. 2b), qubits also go into the UQCM to generate clones, but instead of using the quantum channel, pre-distributed entanglement pairs are provided to A and B by an entanglement pair generator (EG) that can be present at any intermediate point. Each transmission uses these entanglement pairs to perform teleportation of qubits without traversing the quantum channel.

4. QUANTUM CIRCUITS DESIGN FOR QARQ

In Fig. 3a, there is an illustration of the UQCM producing two cloned states, namely $|\Psi^*\rangle_{q0}$ and $|\Psi^*\rangle_{q1}$, of a qubit $q0$ that initially exists in a random state $|\Psi\rangle$ ($|\Psi\rangle_{q0}$). These clones are suitable for use in either DT (Fig. 3a) or TP (Fig. 3b) in QARQ. To generate the clones, the UQCM process can be divided into two phases: a preparation

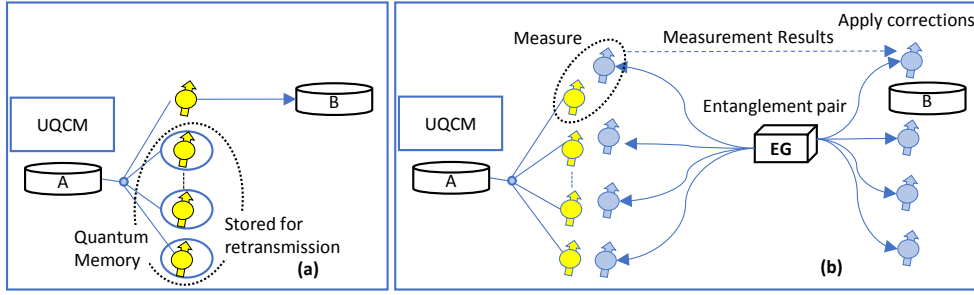


Figure 2. QARQ for: (a) direct transmission, (b) teleportation.

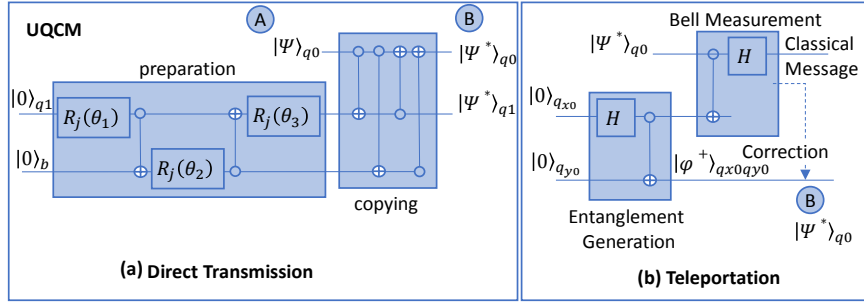


Figure 3. Quantum circuit for QARQ. Direct transmission (a), and teleportation (b).

phase and a copying phase. The input $q1$ acts as a blank page on which the information is copied, and b works as a photocopier that creates copies without retaining any knowledge of the input qubit, with both being initialized to the state $|0\rangle$.

However, before interacting with the initial qubit state $|\Psi\rangle_{q0}$, the quantum copier is first put into a particular state created during the preparation phase. The preparation block consists of three Y-rotation gates performing three rotations ($R(\theta_j)$), and two controlled-not (CNOT) gates, which enforce the desired state.

Once the qubit states of the quantum copier are prepared, four CNOT gates can be employed successively in the copying network to generate a duplicate of the original state. The Bloch sphere

representation of the UQCM output under optimal operating conditions is displayed in Fig. 4. The initial state $|\Psi\rangle_{q0}$ is randomly initialized and the two clones ($|\Psi^*\rangle_{q0}$ and $|\Psi^*\rangle_{q1}$) are produced with a fidelity of 83.33%. Figure 3a depicts the DT case, where $|\Psi^*\rangle_{q0}$ is transmitted to B and for QARQ, $|\Psi^*\rangle_{q1}$ is kept in quantum memory. The second circuit, Fig. 3b, depicts the quantum circuit for TP. The first step in TP is to create maximally entangled states between A and B . In the figure, one entanglement pair is generated in the state $|\varphi^+\rangle_{qx0qy0}$ by preparing qubits $qx0(A)$, and $qy0(B)$ in state $|0\rangle$ and then applying the Hadamard gate (H) followed by a CNOT gate to generate the entangled state. Then, A performs a Bell measurement on the input qubit state $|\Psi^*\rangle_{q0}$ and $|\Psi^*\rangle_{qx0}$ using a CNOT gate followed by an H gate. The measurement results are sent to B as a classical message, which applies correction in terms of Pauli Gates I, X, Z, and ZX, based on the measurement results 00, 01, 10, and 11, respectively. After corrections, the state of $qy0$ becomes equal to $|\Psi^*\rangle_{q0}$. In QARQ, $|\Psi^*\rangle_{q1}$ is stored in quantum memory and teleported later to B , if needed, using another entanglement pair.

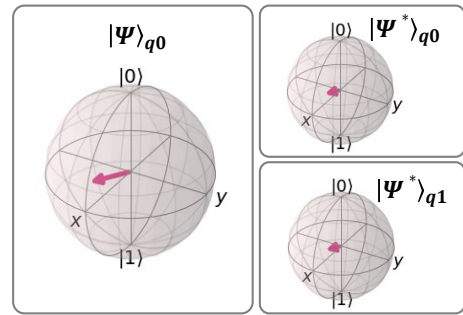


Figure 4. Bloch sphere representation of UQCM output.

5. SUMMARIZED RESULTS

This section is dedicated to assessing the performance of QARQ. To carry out this evaluation, we utilized a simulator called NetSquid, which is specifically designed to model quantum networks and allows for precise modeling of quantum physical devices. The gates used in the simulations are based on the parameters outlined in [11], which describe the NV-center implementation and are modeled as depolarizing noise. To ensure a fair comparison, we assume that the depolarization probability (dp) of all gates is 0.01. Additionally, we examine the depolarization probability per kilometer of the fiber for channel decoherence. The T1T2 noise model is employed for quantum memory, where T1 and T2 represent the decay and decoherence time constants for the NV-center platform [11] and are set to T1=10h and T2=1s. For simplicity, entanglement is generated before transmission. The maximum theoretical fidelity of UQCM is 0.833, 0.77, and 0.75 for 2, 3, and 4 clones, respectively.

Let's focus on the performance of quantum technologies for QARQ. Figure 5 presents a comparison between QARQ-DT and QARQ-TP in terms of the fidelity of the received qubit for 2 clones. This information can later

be used to analyze the benefits of implementing QARQ in quantum communication. In Fig. 5a for QARQ-DT, the fidelity of the transmitted and retransmitted qubit is observed. The fidelity of the qubit in DT is highly dependent on the length of the quantum channel and degrades rapidly as the distance increases (as seen in Fig. 5a with dp values ranging from 0.003 to 0.007). This makes QARQ-DT unsuitable for long-distance transmission. However, Fig. 5b shows that this distance degradation effect is not observed when teleportation is used, as the fidelity mainly depends on the entanglement fidelity (fe) of the entangled pairs and not on the distance. fe represents the end-to-end fidelity of the pair once it reaches its desired endpoints. However, fe depends on the distance traversed by the entangled pairs during distribution. To account for this effect, imperfect fe values (0.984 and 0.962 in the case of Fig. 5b) are considered. It is worth noting that entanglement distillation and swapping can be performed to achieve the desired entanglement, which is not discussed in this paper. These findings suggest that QARQ-TP might be a better solution for longer distances. As seen in Fig. 5c, in summary, DT provides better fidelity for short distances (up to 8km), whereas QARQ-TP is superior for longer distances.

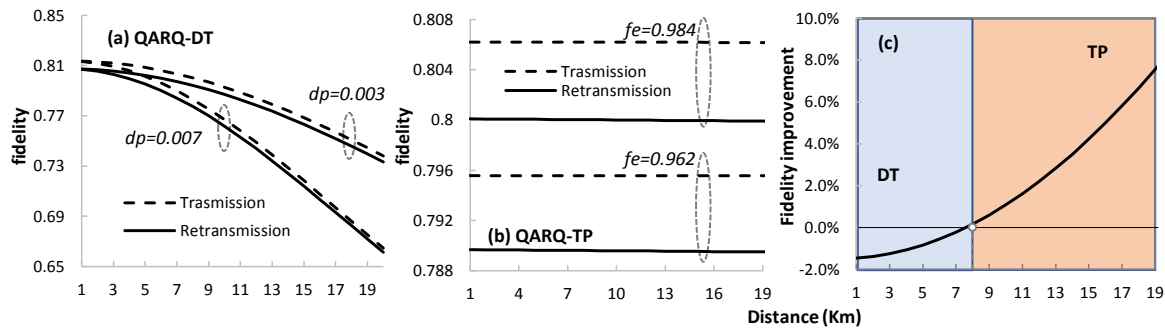


Figure 5. QARQ quantum technologies performance comparison.

6. CONCLUSION

In this paper, the authors propose the use of a Universal Quantum Copying Machine (UQCM) to create imperfect clones to enable the reliable transmission of quantum bits (qubits) in the quantum internet. They also introduce the Quantum Automatic Repeat Request (QARQ) protocol, inspired by its classical counterpart, which is used to ensure reliable transmission of qubits over long distances. The paper includes a simulation platform that investigates the viability of QARQ, considering a Nitrogen-vacancy center qubit platform.

The study compares two major quantum technologies, Direct Transmission (DT) and Teleportation (TP), and shows that for short distance communication, DT provides better fidelity than TP. However, for long-distance communication, TP outperforms DT and improves the QARQ performance. The results suggest that QARQ is suitable for specific applications while maintaining an acceptable level of qubit state quality.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the MSCA REAL-NET (G.A. 813144) HORIZON ALLEGRO (G.A. 101092766) and the AEI IBON (PID2020-114135RB-I00) projects and from the ICREA institution.

REFERENCES

- [1] M. Ahmadian, M. Ruiz, J. Comellas, and L. Velasco, "Cost-effective ML-powered polarization-encoded quantum key distribution," *IEEE/OPTICA Journal of Lightwave Technology (JLT)*, 2022.
- [2] S. Wehner, D. Elkouss, and R. Hanson, "Quantum internet: A vision for the road ahead," *Science*, vol. 362, pp. eaam9288, 2018.
- [3] M. Iqbal, L. Velasco, N. Costa, A. Napoli, J. Pedro, and M. Ruiz, "LPsec: A fast and secure cryptographic system for optical connections," *IEEE/OPTICA J. of Optical Communications and Networking*, vol. 14, pp. 278-288, 2022.
- [4] W. Wootters and W. Zurek, "A single quantum cannot be cloned," *Nature*, vol. 299, pp. 802-803, 1982.
- [5] J. Preskill, "Quantum computing in the NISQ era and beyond," *Quantum*, vol. 2, pp. 79, 2018.
- [6] P. Shor, "Scheme for reducing decoherence in quantum computer memory," *Physical Review A*, vol. 52, pp. 2493-2496, 1995.
- [7] N. Yu, C. Lai, L. Zhou, "Protocols for packet quantum network," *arXiv:1903.10685*.
- [8] E. Woodhead, "Quantum cloning bound and application to quantum key distribution," *Physical Review A*, vol. 88, p. 012331, 2013.
- [9] V. Buzek, M. Hillery, "Universal optimal cloning of qubits and quantum registers," *Quantum Computing and Quantum Communications*, vol. 1509, pp. 235-246, 1998.
- [10] M. Iqbal, L. Velasco, M. Ruiz, A. Napoli, J. Pedro, and N. Costa, "Quantum bit retransmission using universal quantum copying machine," in *Proc. International Conference on Optical Network Design and Modelling (ONDM)*, 2022.
- [11] C. Liao, S. Bahrani, F. Silva, and E. Kashefi, "Benchmarking of quantum protocols," *Scientific Reports*, vol.12, 2022.