Efficient long distance quantum communication (Extended abstract)

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I. INTRODUCTION

First developed in the 1970s, fiber-optic communication systems have boosted the rate of classical information transfer and played a major role in the advent of the information age. The possibility to encode information in quantum states using single photons and transmit them through optical channels has led to the development of quantum key distribution systems[1]. However, the intrinsic channel attenuation becomes a major barrier for efficient quantum communication over continental scales, due to the exponential decay of communication rate [2]. In addition, due to quantum no-cloning theorem[3], quantum states of photons cannot be amplified without any disturbance in contrast to classical communication. To overcome these challenges, quantum repeaters (QRs) have been proposed for the realization of long-distance quantum communication[4].

The essence of QRs is to divide the total distance of communication into shorter intermediate segments connected by QR stations, in which both loss errors from fiber attenuation and operation errors from operation imperfections can be corrected. Loss errors can be suppressed by either heralded entanglement generation (HEG)[4, 5] or quantum error correction (QEC)[6–10] as listed in Fig. 1. During HEG, quantum entanglement can be generated with techniques such as two-photon interference, the success of which, is conditioned on the click patterns of the detectors in between. Loss errors are suppressed by repeating this heralded procedure until the two adjacent stations receive the confirmation of certain successful detection patterns via *two-way* classical signaling. Alternatively, one may encode the logical qubit into a block of physical qubits that are sent through the lossy channel and use QEC to restore the logical qubit with only *one-way* signaling from the intermediate stations to the destination. Quantum error correcting codes can correct no more than 50% loss rates deterministically due to the no-cloning theorem [10, 11].

To suppress operation errors, one may use either heralded entanglement purification (HEP)[12, 13] or QEC[6–8, 10] as listed in Fig. 1. In HEP, multiple low-fidelity Bell pairs are consumed to probabilistically generate a smaller number of higher-fidelity Bell pairs. The high fidelity Bell pairs can be then used for state transmission or key generation. Like HEG, to confirm the success of purification , *two-way* classical signaling between repeater stations for exchanging measurement results is required. Alternatively, QEC can correct operation errors using only *one-way* classical signaling.

II. THREE GENERATIONS OF QUANTUM REPEATERS

Based on the methods used to suppress loss and operation errors, we can classify various QRs into three generations[14]. The first generation of QRs uses HEG and HEP to suppress loss and operation errors, respectively[4, 5]. It starts with purified high-fidelity entangled pairs with separation $L_0 = L_{tot}/2^n$ created and stored in adjacent stations. At k-th nesting level, two entangled pairs of distance $L_{k-1} = 2^{k-1}L_0$ are connected to extend entanglement to distance $L_k = 2^k L_0$ [15]. As practical gate operations and entanglement swapping inevitably cause the fidelity of entangled pairs to drop, HEP can be incorporated at each level of entanglement extension[12, 13]. With n nesting levels of connection and purification, a high-fidelity entangled pair over distance $L_n = L_{tot}$ can be obtained. The first generation of QRs reduces the exponential overhead in direct state transfer to only polynomial overhead, which is limited by the two-way classical signaling required by HEP between non-adjacent repeater stations. The communication rate still decreases polynomially even after optimization [16] with distance and thus

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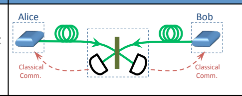
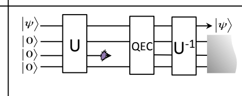
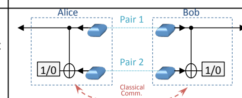
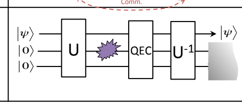
Errors	Approaches	Examples	Classical signaling	1G	2G	3G
Loss Error	Heralded Entanglement Generation (HEG)		Two way signaling (neighboring stations)	✔	✔	
	Quantum Error Correction (QEC)		One way signaling			✔
Operation Error	Heralded Entanglement Purification (HEP)		Two way signaling (Remote stations)	✔		
	Quantum Error Correction (QEC)		One way signaling		✔	✔

FIG. 1: A list of methods to correct loss and operation errors. Depending on the methods used to correct the errors, QRs are categorized into three generations.

becomes very slow for long distance quantum communication. The communication rate of the first generation of QRs can be boosted using temporal, spatial, and/or frequency multiplexing associated with the internal degrees of freedom for the quantum memory[5, 17].

The second generation of QRs uses HEG to suppress loss errors and QEC to correct operation errors[6, 7]. First, the encoded states $|0\rangle_L$ and $|+\rangle_L$ are fault-tolerantly prepared using the Calderbank-Shor-Steane (CSS) codes and stored at two adjacent stations. Then, an encoded Bell pair $|\Phi^+\rangle_L = \frac{1}{\sqrt{2}}(|0,0\rangle_L + |1,1\rangle_L)$ between adjacent stations can be created using teleportation-based non-local CNOT gates[18, 19] applied to each physical qubit in the encoded block using the entangled pairs generated through HEG process. Finally, QEC is carried out when entanglement swapping at the encoded level is performed to extend the range of entanglement. The second generation uses QEC to replace HEP and therefore avoids the time-consuming two-way classical signaling between non-adjacent stations. The communication rate is then limited by the time delay associated with two-way classical signaling between adjacent stations and local gate operations and it decreases poly-logarithmically with total distance of communication. Note that If the probability of accumulated operation errors over all repeater stations is sufficiently small, we can simply use the second generation of QRs *without* encoding.

The third generation of QRs relies on QEC to correct both loss and operation errors[8–10]. The quantum information can be directly encoded in a block of physical qubits (photons) that are sent through the lossy channel. If the loss and operation errors are sufficiently small, the received physical qubits can be used to restore the whole encoding block, which is retransmitted to the next repeater station. The third generation of QRs only needs *one-way* signaling and thus can achieve very high communication rate, just like the classical repeaters only limited by local operation delay.

III. OPTIMAL QUANTUM REPEATER SCHEMES

To present a systematic comparison of different quantum repeater protocols, we need to consider both temporal and physical resources. The temporal resource depends on the rate, which is limited by the time delay from the two-way classical signaling (first and second generations) and the local gate operation (second and third generations). The physical resource depends on the total number of qubits needed for HEP (first and second generations) and QEC (second and third generations)[10, 20].

We can compare the three generations of QRs using a cost coefficient which is the resource overhead (qubits $\times$ time) for the creation of one secret bit over 1 km. Besides the fiber attenuation L_{att}, the cost coefficient depends on generalized experimental parameters, the coupling efficiency η_c, the gate error probability ϵ_G, and the gate time t_0. We systematically compare the three generations of quantum repeaters using the cost coefficient for varying experimental parameters.

We find that the parameter space can be divided into several regions, each of which has a particular generation of QRs that performs mostly efficiently with minimum cost. These different parameter regions can be associated with drastically different architectural designs of quantum repeaters with different possible physical implementations. Our work will provide a guideline for the optimal design of quantum networks across global scales. In future, the integration of different generations of QRs will enable the creation of a secure quantum internet[21].

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[1] Lo, H.-K., Curty, M. & Tamaki, K. Secure quantum key distribution. *Nature Photon.* **8**, 595–604 (2014).
[2] Takeoka, M., Guha, S. & Wilde, M. M. Fundamental rate-loss tradeoff for optical quantum key distribution. *Nature communications* **5**, 5235 (2014).
[3] Wootters, W. K. & Zurek, W. H. A single quantum cannot be cloned. *Nature* **299**, 802–803 (1982).
[4] Briegel, H.-J., Dür, W., Cirac, J. & Zoller, P. Quantum Repeaters: The Role of Imperfect Local Operations in Quantum Communication. *Phys. Rev. Lett.* **81**, 5932–5935 (1998).
[5] Sangouard, N., Simon, C., de Riedmatten, H. & Gisin, N. Quantum repeaters based on atomic ensembles and linear optics. *Rev. Mod. Phys.* **83**, 33–80 (2011).
[6] Jiang, L. *et al.* Quantum Repeater with Encoding. *Phys. Rev. A* **79**, 32325 (2009).
[7] Munro, W. J., Harrison, K. A., Stephens, A. M., Devitt, S. J. & Nemoto, K. From quantum multiplexing to high-performance quantum networking. *Nature Photon.* **4**, 792–796 (2010).
[8] Fowler, A. G. *et al.* Surface code quantum communication. *Phys. Rev. Lett.* **104**, 180503 (2010).
[9] Munro, W. J., Stephens, A. M., Devitt, S. J., Harrison, K. A. & Nemoto, K. Quantum communication without the necessity of quantum memories. *Nat. Photonics* **6**, 777–781 (2012).
[10] Muralidharan, S., Kim, J., Lütkenhaus, N., Lukin, M. D. & Jiang, L. Ultrafast and Fault-Tolerant Quantum Communication across Long Distances. *Phys. Rev. Lett.* **112**, 250501 (2014).
[11] Stace, T. M., Barrett, S. D. & Doherty, A. C. Thresholds for Topological Codes in the Presence of Loss. *Phys. Rev. Lett.* **102**, 200501–200504 (2009).
[12] Deutsch, D. *et al.* Quantum privacy amplification and the security of quantum cryptography over noisy channels. *Phys. Rev. Lett.* **77**, 2818–2821 (1996).
[13] Dur, W., Briegel, H. J., Cirac, J. I. & Zoller, P. Quantum repeaters based on entanglement purification. *Phys. Rev. A* **59**, 169–181 (1999).
[14] Munro, W., Azuma, K., Tamaki, K. & Nemoto, K. Inside Quantum Repeaters. *IEEE Jour. Selected topics in Quantum electronics* **21**, 1–13 (2015).
[15] Zukowski, M., Zeilinger, A., Horne, M. A. & Ekert, A. K. Event-ready-detectors Bell experiment via entanglement swapping. *Phys. Rev. Lett.* **71**, 4287 (1993).
[16] Jiang, L., Taylor, J. M., Khaneja, N. & Lukin, M. D. Optimal approach to quantum communication algorithms using dynamic programming. *Proc. Natl. Acad. Sci. U. S. A.* **104**, 17291–17296 (2007).
[17] Bonarota, M., Gouet, J. L. L. & Chaneliere, T. Highly multimode storage in a crystal. *New J. Phys.* **13**, 13013 (2011).
[18] Gottesman, D. & Chuang, I. L. Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations. *Nature* **402**, 390 (1999).
[19] Jiang, L., Taylor, J. M., Sorensen, A. S. & Lukin, M. D. Distributed Quantum Computation Based-on Small Quantum Registers. *Phys. Rev. A* **76**, 62323 (2007).
[20] Bratzik, S., Kampermann, H. & Bruss, D. Secret key rates for an encoded quantum repeater. *Phys. Rev. A* **89**, 32335 (2014).
[21] Kimble, H. J. The quantum internet. *Nature* **453**, 1023–1030 (2008).