Continuous-variable quantum repeaters based on bosonic error-correction and teleportation: architecture and applications

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Abstract: We report a teleportation-enabled continuous-variable quantum-repeater architecture assisted by the Gottesman-Kitaev-Preskill code to significantly suppress the physical noise. This architecture significantly improves the performance of three representative use cases for quantum communication and sensing. © 2022 The Author(s)

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Photons are ideal information carriers for long-haul quantum communications by virtue of their robustness against environmental noise but are susceptible to loss. Such a restriction places a fundamental rate-loss trade-off between entanglement-distribution rate and transmission distance. To circumvent the rate-loss trade-off, a long-distance quantum link is divided into shorter and less lossy links via introducing intermediate quantum repeater (QR) nodes. Although the mainstream QR architectures have been dedicated to discrete-variable quantum states, continuous-variable (CV) quantum states underpins a variety of quantum-enhanced sensing and communication capabilities. Quantum error correction (QEC) is an essential ingredient for QRs to reliably relay quantum information. QEC for QRs, however, requires an additional framework to account for the infinite dimensional Hilbert space that photons reside in. In this regard, bosonic QEC has emerged as a powerful paradigm to protect photonic quantum information. Most bosonic codes have been designed to protect qubits by encoding them into bosonic modes, but a QR based on bosonic QEC to transmit CV quantum information, which will significantly benefit a wide range of quantum-enhanced applications, remains elusive.

We proposed a CV QR architecture, in Fig. 1, based on the Gottesman-Kitaev-Preskill (GKP) QEC [1, 2], combined with CV teleportation, and show the boosted performance of entanglement-assisted (EA) communication [3], quantum illumination (QI) [4], and CV quantum key distribution (QKD) [5].

![Fig. 1. Scheme of m-relay repeaters based on CV error-correction protocol. ENC: encoding. DEC: decoding. L is the physical distance between Alice and Bob. LΔ is the inter-repeater spacing.](Image)

To establish CV entanglement in the form of two-mode squeezed vacuum (TMSV) pairs, we focus on the following scenario: Alice generates a TMSV state (i.e. squeezing level r) consisting of signal and idler modes, and attempts to transmit the idler mode to Bob via a series of teleportation enabled QRs while locally retaining the signal mode. In Fig 2, we evaluate the performance of the QR in terms of the fidelity of the established TMSV to the ideal TMSV across different physical parameters, r, s, s(Δ) and L, and conclude that s(Δ) > s > r is required for effective teleportation-enabled QEC.

Preshared entanglement between distant parties underpins numerous quantum applications. Nonetheless, establishing entanglement at a distance is impeded by the loss of the entanglement-distribution channel. The proposed GKP-assisted QEC can correct the Gaussian errors to enhanced the performance of a multitude of applications. Moreover, the multilayer QEC is proved to boost its correction capabilities [6] and is applied to our QEC protocol in the following applications.
Fig. 2. Fidelities of teleportation-enabled repeater based on imperfect GKP. $r = 15$ dB, $L_\Delta = 1$ km and (a) $s = 10$ dB , (b) $s = 15$ dB, (c) $s = 20$ dB, (d) $s = 25$ dB.

Fig. 3. Application performances with $s^{(G)} = 25$ dB. (a) EA Communication: the Holevo capacity over classical one versus $\log_{10} N_s$, where $N_s$ is the mean photon number of input TMSV. (b) QI: The Quantum Chernoff bound, $P_e$, versus $\log_{10} M$, where $M$ is mode number of QI. (c) CV QKD: the secret key rate versus the distribution length.

1. EA communication

In EA communication [3], Alice performs phase encoding on the signal mode of a preshared TMSV state and sends it to Bob over a lossy and noisy channel. Bob then performs a joint measurement on the received signal with preshared idler. The quantum capacity (i.e. Holevo information) over classical capacity of different distribution channels are shown in Fig. 3(a).

2. Quantum illumination

QI is a paradigm for quantum-enhanced target detection through a lossy and noisy environment [4]. The QI transmitter prepares TMSV states and distributed the idler modes to receiver over a channel while transmits the signal modes to interrogate a target residing in an environment. The Quantum Chernoff bound of error probabilities of different distribution channels are shown in Fig. 3(b).

3. CV QKD

CV-QKD enables two distant parties, Alice and Bob, to securely share a common binary random key despite the adversary, Eve, mounts the optimal attack to capture the communicated information [5]. The secret key rate of CV-QKD protocols is analyzed by upper bounding the maximal accessible information to Eve, and the secret key rates, corresponding to different distribution strategies, are shown in Fig. 3(c).

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