A complete linear optic Bell measurement for long distance quantum communication

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There are two major obstacles for the realization of photonic quantum communication over long distance: one is *'photon loss'* during the transmission, due to which the probability that a photon survives decays exponentially with distance so that the communication rate becomes significantly low. The other is the upper limit of *'the success probability of Bell measurement'*. It is well known that the standard scheme of Bell measurement, an essential task in quantum communication protocols, allows to discriminate only two out of the four Bell states encoded in photon pairs with linear optics, so that its success probability has the upper limit 50% [1].

The 'photon loss' during the communication over long distance can be suppressed by using quantum repeaters. A quantum repeater, working at the intermediate nodes that divide the entire distance by a shorter one, can correct the effect of losses during the transmission. While its earlier versions employ heralded entanglement generation scheme that requires two-way signaling, purification, and long-lived quantum memories, some recent proposals do not require them as developed based on quantum error correction resulting in dramatically enhanced communication rates. However, they still require efficient matter-light interactions [2], complicated feedforwards [3], or ideal resource preparation in repeaters [4]. Meanwhile, it has been shown that the low 'success probability of Bell measurement' can be resolved by employing ancillary photons, in-line squeezing, or multiphoton entanglement encoding. While a recent proposal attains the highest success probability $1-2^{-N}$ using total N photons per qubit, under photon losses it requires additional error correcting schemes [5].

We here introduce a complete Bell measurement scheme with linear optics, discriminating Bell states not only near-deterministically but also loss-tolerantly. Our scheme is 'complete' in the sense that it attains two fundamental bounds limited by i) linear optics and ii) no-cloning theorem: It reaches the upper bound of the success probability $1-2^{-N}$ limited by linear optics and the number of photons N used per qubit. It can also tolerate up to 50% loss in a single qubit, fundamentally limited by no-cloning theorem. We employ a photonic qubit encoded in the quantum parity code QPC(n,m), containing total $N=nm$ photons [6]. The Bell measurement scheme is performed based on the standard linear optic Bell measurement in a concatenated manner. It plays a role as the logical Bell measurement in QPC(n,m). The success probability of Bell measurement increases to unit as increasing the encoding size N even under losses. It is notable that all the photons contained in a qubit contribute to either increase the success probability or tolerate losses. This is contrast to the other recent proposals consuming a lot redundant photons for protecting a qubit from losses [4]. Remarkably, our scheme achieves much higher success probabilities than the others under the same loss rate when the same number of photons are used in the process.

An efficient all optical quantum repeater can be developed based on our Bell measurement scheme. It does not require long-lived quantum memory, photon-matter interaction [2], and complicated feedforwards [3]. We note that our scheme can tolerate some imperfections during the preparation and measurement process as well as the losses during the transmission, in contrast to the scheme in Ref. [4]. We optimize the protocol to find a best strategy for long distance quantum communication by numerical search over the encoding size (n,m) and the distance between nodes L_0. Finally, we demonstrate that an ultrafast and efficient quantum communications over 10,000 km is possible with our scheme.

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