Protocols for all-photonic quantum repeaters

Naphan Benchasattabuse*§, Michal Hajdušek*§, and Rodney Van Meter‡§

*Graduate School of Media and Governance, Keio University Shonan Fujisawa Campus, Kanagawa, Japan
‡Faculty of Environment and Information Studies, Keio University Shonan Fujisawa Campus, Kanagawa, Japan
§Quantum Computing Center, Keio University, Kanagawa, Japan
{whit3z,michal,rdv}@sfc.wide.ad.jp

2023 IEEE International Conference on Quantum Computing and Engineering (QCE) | 979-8-3503-4323-6/23/$31.00 ©2023 IEEE | DOI: 10.1109/QCE57702.2023.10259

***Abstract*—All-photonic repeater scheme based on a repeater graph state (RGS) promises tolerance to photon losses as well as operational errors. An attractive promise of this scheme is that it offers a fast Bell pair generation rate, limited only by the RGS creation time. This is in stark contrast to the traditional quantum repeater with quantum memories, where the Bell pair generation time is limited by the round-trip wait time leading to poor Bell pair generation performance and quality due to the decoherence of quantum memories. Prior research has focused on lowering the cost of RGS generation and improving upon the probabilistic generation to a deterministic generation with required photon counts to be the same as the number of qubits in the RGS. The operations of creating and manipulating the RGS into an end-to-end Bell pair are complex and have not been fully figured out in detail. Here, we focus on improving the practicality of the RGS scheme in real-world implementation and address three open questions of the RGS scheme, namely; how do end nodes participate in the connection, what classical information needs to be exchanged and processed between nodes, and how to make RGS scheme work hand in hand with the traditional quantum repeaters with memories.**

***Index Terms*—Quantum Networking, Quantum Repeaters, All-photonic Repeaters, Quantum Communication, Quantum Optics, Network Protocols, Graph State**

I. Introduction

Attenuation of optical signals in fiber leads to an exponentially vanishing probability of photon arrival as the distance between network nodes increases, limiting practical quantum communication via direct photon transmission to only a few tens of kilometers. Quantum repeaters are one of the cornerstones to realizing long-distance quantum networks and eventually a global Quantum Internet. An all-photonic quantum repeater based on *repeater graph states* (RGS) [1] is the most recent addition to the various repeater schemes, promising higher repetition rate and intrinsic tolerance to both quantum operational errors and loss errors, and most importantly, does not require quantum memories, unlike traditional quantum repeaters. Despite these attractive features, the majority of related research has been focused solely on metrics based on secret key sharing. Questions of ending the connection, details of quantum as well as classical communication between various network nodes, or integration of RGS repeater links into other architectures have gone largely underexplored.

This material is based upon work supported by the Air Force Office of Scientific Research under award number FA2386-19-1-4038.

II. RGS scheme overview

The RGS (Fig. 1(b)) comprises $2m$ physical qubits and $2m$ logical qubits forming two sets of qubits; the inner logical qubits, also called first-leaf qubits, which are all connected into a complete graph and the outer arm physical qubits, also called second-leaf qubits. RGS is defined by a parameter m which refers to the number of arms and a branching vector $\vec{b} = (b_1, b_2, \ldots, b_n)$ denoting the logical tree encoding of the first-leaf qubits for the logical tree encoding (Fig. 1(c)).

In the RGS scheme, there are two node types acting as the intermediate nodes: the RGS source (RGSS) and the adaptive measurement node or the advanced Bell state analyzer (ABSA). The RGSS's responsibility is to generate the RGS, and send one half to one ABSA and the other half to another partner ABSA, which we refer to as the left and right ABSAs. The ABSA's job is to perform a series of measurements on the incoming half-RGSs from two RGSSs, thus creating a longer distance shared entangled state (Fig. 1(e)).

III. RGS protocols

We assume that the message exchanges between two end nodes (connection setup) are completed, thus the number of RGS arms m and the branching vectors $\vec{b}$ are now known to all nodes along the connection path and that RGSS and ABSA know the photon ordering and the time between each photon. Instead of using the traditional RGS, we utilize a functionally equivalent RGS [2] created by half-RGS (Fig. 1(a)), a modified generation scheme from [3]. Then for each trial, the tasks for ABSA and RGSS go as follows.

1) ABSA sends a notification message to its neighboring RGSSs about when the first photon should arrive.
2) RGSS emits the photonic RGS and keeps the measurement results during the generation process.
3) From the measurement results, RGSS constructs a correction tree for each logical first-leaf qubit.
4) RGSS sends the correction trees (to correct physical qubit measurements), logical correction (to flip the logical first-leaf result), and correction to the second-leaf qubit of each of the m arms in a single message.
5) ABSA decides if the trial is a success or a failure. If the trial is a failure, sends a failure message to end nodes. If not, ABSA proceeds to the next step.
6) ABSA constructs its result tree from the measurements of the coming photonic qubits for each logical qubit.

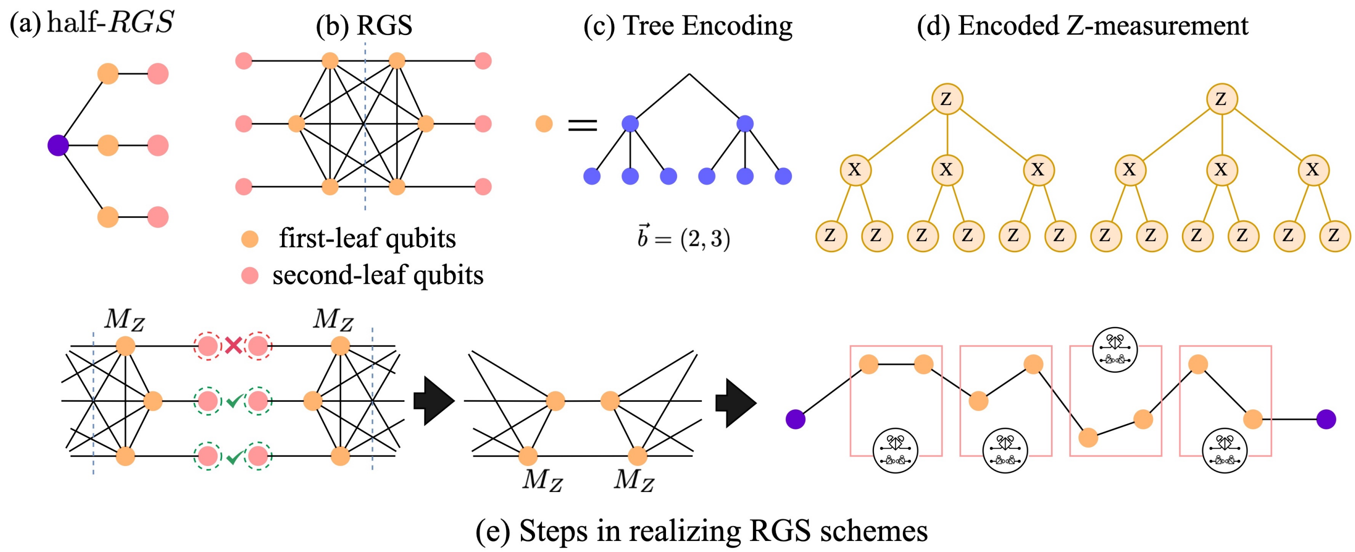

Fig. 1. (a) half-RGS. (b) RGS. (c) Tree-encoding of a first leaf logical qubit. (d) Measurement bases for encoded Z-measurement, Z and X are swapped for encoded X-measurement. (e) Steps in realizing RGS schemes.

7) For each of the RGSS's message, ABSA merges the information of the correction tree and its own measurement result tree and computes the logical measurement result of each of the first-leaf qubit.
8) ABSA uses logical correction to decide if the first-leaf qubit result should be flipped or stay as is.
9) ABSA uses the second-leaf correction and the logical result to compute the correction at end nodes and sends a message to the end nodes, indicating that the trial is successful at this segment of the path and what Pauli correction should be done from this segment.

IV. Amount of Information Needed for Correction

It is clear that we need every measurement result performed at RGSSs and ABSAs, every logical tree (Fig. 1(d)) for each logical qubit, to correct the final Bell pair. For each trial, every RGSS and ABSA needs to send out b_{RGSS} and b_{ABSA} bits of information to the end nodes, where these values can be given by

$$b_{RGSS} = 2 + 2m\left(2 + \sum_{k=0}^{n-2}\prod_{j=0}^{k} b_j\right) \tag{1}$$

and

$$b_{ABSA} = 2m\left(2 + \sum_{k=0}^{n-1}\prod_{j=0}^{k} b_j\right), \tag{2}$$

where b_j refers to the branching factor at index j of vector $\vec{b}$.

Depending on the structure of the RGS, this can be quite a large amount of information that should be sent to get a single Bell pair. In fact, we can do better, by having each RGSS send their measurement result to the ABSA they are connected to, instead of directly to end nodes. The ABSA can then combine the information it receives and send just 2 bits of information to the end nodes.

V. Integration with Memory-Based Architectures

The traditional RGS scheme has been introduced as an alternative to conventional memory-based repeaters. This view may be appropriate in the context of QKD applications but requires reconsideration if the desired distributed states are correctable Bell pairs. In light of our current discussion, with our introduction of half-RGS, it is straightforward to see that by swapping the anchor qubits to a quantum memory, RGS scheme can be treated as a link-level connection, which leads to far greater flexibility. In particular, the RGS scheme can be used to connect any two nodes, not necessarily only end nodes. The Bell pairs created from the RGS scheme at the link level can be treated the same way as link-level resources created from other link architectures, such as Meet-in-the-Middle, Memory-Memory, Memory-Source-Memory, or Sneakernet links, and later can be allocated to the resource management software of the quantum nodes. This is in the spirit of heterogeneity and interoperability of the future quantum internet [4].

References

[1] K. Azuma, K. Tamaki, and H.-K. Lo, "All-photonic quantum repeaters," *Nature Communications*, vol. 6, no. 1, p. 6787, Apr. 2015. doi:10.1038/ncomms7787
[2] N. Benchasattabuse, M. Hajdušek, and R. Van Meter, "Architecture and protocols for all-photonic quantum repeaters," 2023. doi:10.48550/arXiv.2306.03748
[3] P. Hilaire, E. Barnes, and S. E. Economou, "Resource requirements for efficient quantum communication using all-photonic graph states generated from a few matter qubits," *Quantum*, vol. 5, p. 397, Feb. 2021. doi:10.22331/q-2021-02-15-397
[4] R. Van Meter *et al.*, "A Quantum Internet Architecture," in *2022 IEEE International Conference on Quantum Computing and Engineering (QCE)*. Broomfield, CO, USA: IEEE, Sep. 2022, pp. 341–352. doi:10.1109/QCE53715.2022.00055