High-level quantum network protocols as rule sets

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Description

Quantum networks provide communication services whose capabilities extend beyond classical networks, improving scalability of distributed quantum applications, enabling quantum cryptography and coordination primitives that surpass their classical counterparts. The fundamental resource in quantum networks is distributed *Bell pairs*—pairs of maximally *entangled qubits* with each qubit located at a separate node.

The distribution of entangled Bell pairs between distant end-nodes will be the main task of the quantum internet. To maximize the rate of Bell pair generation under extremely constrained and error-prone quantum hardware resources, there is a variety of entanglement distribution protocols. PBKAT [1] is a high-level language simplifying specification and analysis of such protocols. Importantly, PBKAT abstracts away essentially everything except locations of individual qubits, leaving low-level details such as hardware request for local entanglement generation, memory management, quantum operations and classical signaling to underlying implementations.

Goal

The goal of this project is to design an approach transforming high-level PBKAT specifications into the rules understandable by the SeQUeNCe [2] quantum network simulator. Optimizing the number of rules, amount of memory required, and minimizing classical communication are among the desired metrics. The successful outcome will advance the state of practical realization of quantum network protocols. Moreover, it will strengthen the applicability of PBKAT by complementing the probabilistic analysis [1] with simulator runs that are more faithful in modelling errors and timing effects.

Objectives

- Understand the basics of quantum networks (EPR-pairs, swapping; see [3])
- Familiarize oneself with PBKAT syntax and semantics (see the visualizer [4])
- Familiarize oneself with SeQUeNCe, especially the concept of `RuleS`
- Implement round-manager for SeQUeNCe to match PBKAT's model
- Translate per-round logic from PBKAT onto the round manager while using the automata representation of PBKAT protocols
- Validate empirically the correctness with Monte-Carlo simulations

Expected results: protocols from [4] can be executed over SeQUeNCe

Prerequisites

- Basic principles of compilers, including notions of automata
- Python
- Basics of TCP/IP protocol stack and network router operation

References

[1] A. Buckley, P. Chuprikov, R. Otoni, R. Soulé, R. Rand, and P. Eugster, "A Language for Quantifying Quantum Network Behavior," *Proc. ACM Program. Lang.*, vol. 9, no. OOPSLA2, Oct. 2025, doi: 10.1145/3763135.

[2] X. Wu *et al.*, "SeQUeNCe: a customizable discrete-event simulator of quantum networks," *Quantum Science and Technology*, vol. 6, Sept. 2021, doi: 10.1088/2058-9565/ac22f6.

[3] W. Kozlowski *et al.*, "Architectural Principles for a Quantum Internet." [Online]. Available: https://www.rfc-editor.org/info/rfc9340/

[4] "QBKAT Visualizer." [Online]. Available: https://qbkat.swys.site/